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Reliable Multicast D2D Communication Over Multiple Channels in Underlay Cellular Networks

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***Abstract*—Multicast device-to-device (D2D) communications operating underlay with cellular networks is a spectral efficient technique for disseminating data to the nearby receivers. However, due to critical challenges such as, mitigating mutual interference and unavailability of perfect channel state information (CSI), the resource allocation to multicast groups needs significant attention. In this work, we present a framework for joint channel assignment and power allocation strategy to maximize the sum rate of the combined network. The proposed framework allows access of multiple channels to the multicast groups, thus improving the achievable rate of the individual groups. Furthermore, fairness in allocating resources to the multicast groups is also ensured by augmenting the objective with a penalty function. In addition, considering imperfect CSI, the framework guarantees to provide rate above a specified outage for all the users. The formulated problem is a mixed integer nonconvex program which requires exponential complexity to obtain the optimal solution. To tackle this, we first introduce auxiliary variables to decouple the original problem into smaller power allocation problems and a channel assignment problem. Next, with the aid of fractional programming via a quadratic transformation, we obtain an efficient power allocation solution by alternating optimization. The solution for channel assignment is obtained by convex relaxation of integer constraints. Finally, we demonstrate the merit of the proposed approach by simulations, showing a higher and a more robust network throughput.**

***Index Terms*—D2D multicast communications, resource allocation, imperfect CSI, fractional programming.**

I. Introduction

Multicast D2D communication represents the operation of directly disseminating the data to nearby devices without passing the packets through the base station (BS). Some important applications include: (i) dissemination of marketing/advertisement data in the commercial networks; (ii) device discovery, clustering, co-ordination in self organizing networks; (iii) dissemination of critical information such as police, fire, ambulance, etc. in the public safety networks [1]. In these scenarios, D2D multicast in underlay configuration is a promising approach to improve spectrum utilization as it allows simultaneous transmissions of existing cellular network and multicast groups in the same spectrum [2]. However, unlike the unicast D2D communication, multicast D2D communication has its own challenges in terms of heterogeneous channel conditions for individual receivers in the multicast group, thus, achievable performance of the multicast group is generally limited by the receiver with the worst channel conditions. In addition, similar to underlay unicast D2D communications, simultaneous transmissions in the same spectrum bands increases interference at the respective receivers and may adversely reduce the overall network performance. Further, acquiring perfect CSI for optimizing network performance poses critical challenges in practical networks. Thus, it is necessary to devise a judicious and reliable resource allocation algorithm which can maximize the overall network performance.

Resource allocation problems for underlay unicast D2D communications have been extensively investigated in [3]–[5]. In D2D multicast settings, previous work in [1] has exploited concepts of stochastic geometry to model and derive the analytical expressions for performance metrics under the overlay communication framework. For the underlay framework, a resource allocation problem is formulated in [6] to maximize the sum throughput of multicast groups while restricting interference to cellular users (CUs) below a certain specified threshold. Similarly, a sum throughput maximization problem is formulated in [2] with constraints on minimum signal to interference plus noise ratio (SINR) requirements. Moreover, a channel assignment scheme to maximize the sum effective throughput is proposed in [7] under partial information of the device location. It can be noted that most of the above work on multicast D2D communication consider perfect CSI. Further, the optimizations for channel and power allocation are done separately and most of the times also limiting multicast groups to access more than one channel. In addition, fairness in allocation resources to the multicast groups is also ignored.

In this work, we investigate the sum rate maximization problem for underlay multicast D2D communication under the assumption of imperfect CSI. The main contributions of this work can be summarized as follows:

1) We formulate a joint power allocation and channel assignment problem to maximize the sum rate of all D2D multicast groups and CUs with a probabilistic constraint on the minimum SINR for both receivers in multicast groups and CUs. The objective function is also augmented to include penalty on the unfairness in channel assignment to D2D multicast groups. Further, the formulation ensures higher throughput to multicast groups by allowing simultaneous access of multiple channels to the respective groups.
2) The formulation is a mixed integer non-convex problem, for which we first introduce auxiliary variables to decou-

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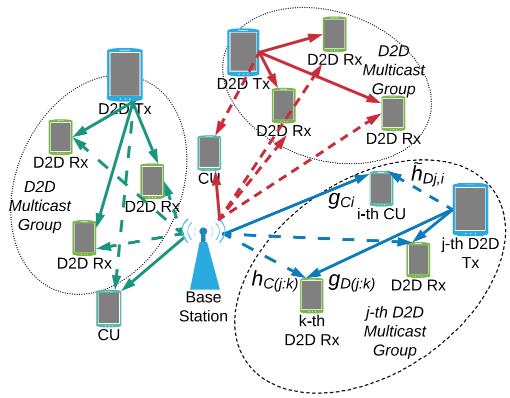

Fig. 1: Illustration of the overall system model.

ple without loosing optimality, the original problem into multiple power allocation subproblems and a channel assignment subproblem. The non-convex power allocation subproblems are handled by fractional programming via quadratic transformation followed by alternating optimization. The channel assignment subproblem is solved by integer relaxation.

3) Evaluation of the algorithm is presented on the basis of Matlab simulations to demonstrate the merits, showing a superior and more robust and performance.

The rest of this paper is structured as follows. Sec. II describes the system model. Sec. III introduces the joint channel assignment and resource allocation problem. Sec. IV proposes an efficient algorithm to solve it. Finally, Sec. V provides the simulations and Sec. VI summarizes conclusions.

II. System Model

Consider a multicast D2D communications scenario which underlays over the downlink spectrum[1] of cellular communication as shown in Fig. 1. We assume that the BS communicates with the associated CUs over N_C orthogonal downlink channels. Further, we consider a fully loaded network condition with N_C active downlink CUs. In order to avoid confusion in notation, active CUs (equivalently, downlink channels) are indexed by $\mathcal{C} = \{1, ..., N_C\}$. The D2D multicast groups wishing to communicate over the aforementioned N_C channels are indexed by $\mathcal{D} = \{1, ..., N_D\}$. The j-th D2D muticast group ($\forall j \in \mathcal{D}$) is assumed to have one transmitter and M_j receivers; the receivers in the j-th D2D muticast group are indexed by $\mathcal{M}_j = \{1, 2, \cdots, M_j\}$. Further, to provide higher throughput among D2D multicast groups, we allow simultaneous access of multiple channels to D2D multicast groups; however, to restrict interference among the D2D multicast groups, access of more than one multicast group is not allowed over a particular channel.

[1]Without loss of generality, the same formulation and algorithm design developed here, can be also applied to the uplink spectrum.

In this setup, consider the generic scenario where the i-th cellular user (CU) shares the channel resource with j-th D2D multicast group. Then, the expressions for the respective SINR's observed by i-th CU and k-th receiver of j-th D2D multicast group can be stated as:

$$\Gamma_{C_{i,j}} = \frac{g_{C_i} p_{C_i}}{N_0 + \tilde{h}_{D_{j,i}} p_{D_{j,i}}}, \quad \Gamma_{D_{(j:k),i}} = \frac{g_{D_{(j:k)}} p_{D_{j,i}}}{N_0 + h_{C_{(j:k)}} p_{C_i}} \tag{1}$$

where, g_{C_i}, $g_{D(j:k)}$ denote[2] the channel gains, respectively, between BS and i-th CU and transmitter and k-th receiver in the j-th multicast group; $h_{C_{(j:k)}}$, $h_{D_{j,i}}$ denotes the interference channel gain between BS and k-th receiver of the j-th D2D multicast group and transmitter of j-th multicast group and the i-th CU; and p_{C_i}, $p_{D_{j,i}}$ denote respectively the transmit powers of BS for the i-th CU and transmitter of j-th multicast group over i-th channel.The additive noise is assumed to have one sided power spectral density N_0.

In this analysis, channel gains g_{C_i}, $g_{D(j:k)}$ and $h_{C_{(j:k)}}$ are assumed to be perfectly known during the computation of the resource allocation. However, as expected in practice, we consider limited cooperation from CUs in estimating the interference channel gain. Thus, we assume that the statistical characterization of $h_{D_{j,i}}$ (based on channel-gain maps, pilot signal transmission, etc.) is known during the computation resource allocation. The imperfect CSI nature of $h_{D_{j,i}}$ is denoted by $\tilde{h}_{D_{j,i}}$.

Let $R^{LB}_{C_{i,j}}$ denote the lower bound on the rate of the i-th CU, which must be achieved $(1-\epsilon)$ portion of the time, and can be expressed as:

$$\begin{aligned} &R^{LB}_{C_{i,j}} = W \log_2 \left(1 + \Gamma^{LB}_{C_{i,j}}\right) \\ &\text{where,} \quad \Gamma^{LB}_{C_{i,j}} : \Pr\left\{\Gamma^{LB}_{C_{i,j}} \leq \frac{g_{C_i} p_{C_i}}{N_0 + \tilde{h}_{D_{j,i}} p_{D_{j,i}}}\right\} = 1 - \epsilon \end{aligned} \tag{2}$$

Here W denotes the allocated bandwidth for the downlink channel. For the D2D multicast group, the maximum achievable rate is determined by the SINR of worst case receiver; thus, the corresponding achievable rate can be stated as:

$$R_{D_{j,i}} = W \log_2 \left(1 + \min_{k \in \mathcal{M}_j} \Gamma_{D_{(j:k),i}}\right) \tag{3}$$

For the case where the i-th CU does not share any resource with D2D multicast groups, the maximum achievable rate for the i-th CU is given by:

$$R_{C_{i,0}} = W \log_2 \left(1 + \Gamma_{C_{i,0}}\right), \quad \text{where} \quad \Gamma_{C_{i,0}} = \frac{g_{C_i} p_{C_{max}}}{N_0} \tag{4}$$

Here $p_{C_{max}}$ is the maximum transmit power of the BS. Denoting $\beta_{i,j}$ as the binary variable which takes value 1 when the i-th CU shares channel with the j-th multicast group and 0 otherwise; the minimum sum rate that can be achieved over the i-th downlink channel (under the assumption of restricted D2D interference, i.e., $\sum_{j \in \mathcal{D}} \beta_{i,j} \leq 1$), can be expressed as:

$$R_i = \left(1 - \sum_{j \in \mathcal{D}} \beta_{i,j}\right) R_{C_{i,0}} + \sum_{j \in \mathcal{D}} \beta_{i,j} (R_{D_{j,i}} + R^{LB}_{C_{i,j}}) \tag{5}$$

[2]In principle, $g_{D_{(j:k)}}$ and $h_{C_{(j:k)}}$ should also depend on the operated channel i, however, this subscript is dropped as the proposed scheme carries over immediately to accommodate such dependence.

The minimum sum rate of the whole multicast D2D network underlayed over the cellular downlink channels is $R = \sum_{i\in\mathcal{C}} R_i$. In the next section, we discuss the problem formulation to maximize the sum rate subjected to several quality of service (QoS) constraints.

III. Problem Formulation

The objective of this work is to maximize the minimum sum rate of all underlay D2D multicast groups and the CUs. In addition, our objective is also to ensure fairness in channel assignment to the D2D multicast groups. Thus, we define the unfairness measure $\delta(\mathbb{B}) = 1/(N_D c^2)\sum_{j=1}^{N_D}(x_j - c)^2$ along similar lines to [8], [9], where $x_j := \sum_{i=1}^{N_C} \beta_{i,j}$ is the number of channels assigned to the j-th D2D multicast group; $c := N_C/N_D$ is the fairest assignment; and $\mathbb{B}$ denotes the discrete channel assignment matrix. Finally, the sum rate maximization problem with fairness in the channel assignment can be expressed as:

$$\underset{\mathcal{P}_C,\mathcal{P}_D,\mathbb{B}}{\text{maximize}} \quad R - \gamma\delta(\mathbb{B}) \tag{6a}$$

$$\text{subject to:} \quad \beta_{i,j} \in \{0,1\}, \qquad \sum_{j\in\mathcal{D}} \beta_{i,j} \le 1 \tag{6b}$$

$$p_{C_i} \le p_{C_{max}}, \qquad p_{D_{j,i}} \le p_{D_{max}} \tag{6c}$$

$$W\log_2\left(1 + \Gamma^{LB}_{C_{i,j}}\right) \ge \beta_{i,j}\eta_{C_{min}} \tag{6d}$$

$$W\log_2\left(1 + \min_{k\in\mathcal{M}_j} \Gamma_{D_{(j:k),i}}\right) \ge \beta_{i,j}\eta_{D_{min}} \tag{6e}$$

$$\forall j \in \mathcal{D},\ i \in \mathcal{C}$$

where $\mathcal{P}_C$ and $\mathcal{P}_D$ denote the set of continuous power allocation variables for CUs and D2D multicast groups, respectively. The regularization parameter $\gamma \ge 0$ in the objective (6a) is selected to balance the trade-off between sum rate and fairness in channel assignment. Constraint (6b) is an integer constraint, restricting interference among D2D multicast groups. Constraint (6c) specifies, respective, transmit power limits $p_{C_{max}}$ and $p_{D_{max}}$ for BS and transmitters of D2D multicast groups[3]. Constraint (6d) and (6e) specifies the respective minimum rate requirements $\eta_{C_{min}}$ and $\eta_{D_{min}}$ under sharing of resources between the CU and the D2D multicast group.

Note that the optimization problem (6a) is a non-convex mixed-integer program, which involves exponential complexity. In addition, due to imperfect CSI, objective (6a) and constraint (6d) involve stochastic terms. In the next section, we discuss the relaxation techniques to derive a tractable solution of (6a) with guaranteed polynomial run-time complexity.

IV. Proposed Convex Relaxation Approach

The first challenge to obtain a tractable solution of (6a) is the joint optimization over integer variables ($\mathbb{B}$) and continuous variables ($\mathcal{P}_C$ and $\mathcal{P}_D$). Thus, in the next subsection, we decouple without loss of optimality of the problem (6a) to separate power allocation and channel assignment sub-problems.

[3]In general, constraining the transmit power in each band is more restrictive than restricting the total sum of transmitting power over all bands. Moreover, this allows a more balanced transmit power among different channels.

A. Decoupling Resource Allocation Problem

We first re-express the sum rate R in (6a) as:

$$R(\mathbb{B},\mathcal{P}_C,\mathcal{P}_D) = \sum_{i\in\mathcal{C}}\left[\sum_{j\in\mathcal{D}} \beta_{i,j} v_{i,j}(p_{C_i}, p_{D_{ji}}) + R_{C_{i,0}}\right] \tag{7}$$

where $v_{i,j}(p_{C_i}, p_{D_{ji}}) := R^{LB}_{C_{i,j}} + R_{D_{j,i}} - R_{C_{i,0}}$ represents the rate increment due to the assignment of channel i to the D2D pair j relative to the case where the channel i is only used by the CU. Next, notice that the objective of (6a) with the substitution of (7) can be equivalently expressed by replicating $\{p_{C_i}\}$ with multiple auxiliary variables $\{p_{C_{i,j}}\}$ and removing the constant terms from the objective function. The resulting problem can be stated as:

$$\underset{\mathbb{B},\mathcal{P}_C,\mathcal{P}_D}{\text{maximize}} \quad \sum_{i\in\mathcal{C}}\sum_{j\in\mathcal{D}}\left[\beta_{i,j} v_{i,j}(p_{C_{i,j}}, p_{D_{j,i}})\right] - \gamma\delta(\mathbb{B})$$

$$\text{subject to:} \quad \text{(6b)}, \text{(6c)}, \text{(6d)}, \text{ and (6e)} \tag{8}$$

To recover the optimal $\{p^*_{C_i}\}$ of (6a) from the optimal $\{p^*_{C_{i,j}}\}$ of (8), one only needs to find, for each i, the value of j such that $\beta_{i,j} = 1$ and set $p^*_{C_i} = p^*_{C_{i,j}}$. If no such a j exists, i.e. $\beta_{i,j} = 0\ \forall j$, then channel i is not assigned to any D2D pair and the BS can transmit with maximum power $p^*_{C_i} = p_{C,\max}$.

In addition, we can also notice that (8) decouples across i and j into $N_C \times N_D$ power allocation sub-problems and a final channel assignment problem. Then, for each i, j, the power allocation sub-problem can be stated as:

$$\underset{p_{C_{i,j}},p_{D_{j,i}}}{\text{maximize}} \quad R^{LB}_{C_{i,j}} + R_{D_{j,i}}$$

$$\text{subject to:} \quad 0 \le p_{C_{i,j}} \le p_{C_{max}}, \qquad 0 \le p_{D_{j,i}} \le p_{D_{max}}$$

$$W\log_2\left(1 + \Gamma^{LB}_{C_{i,j}}\right) \ge \eta_{C_{min}}$$

$$W\log_2\left(1 + \min_{k\in\mathcal{M}_j} \Gamma_{D_{(j:k),i}}\right) \ge \eta_{D_{min}} \tag{9}$$

Denoting $\Gamma_{C_{min}} := 2^{\frac{\eta_{C_{min}}}{W}} - 1$ and $\Gamma_{D_{min}} := 2^{\frac{\eta_{D_{min}}}{W}} - 1$, the optimization problem (9) can be re-expressed in-terms of optimization variables $p_{C_{i,j}}$ and $p_{D_{j,i}}$ as follows:

$$\underset{p_{C_{i,j}},p_{D_{j,i}}}{\text{maximize}} \quad \log_2\left(1 + \Gamma^{LB}_{C_{i,j}}\right) + \log_2\left(1 + \min_{k\in\mathcal{M}_j} \frac{g_{D_{(j:k)}} p_{D_{j,i}}}{\sigma^2 + h_{C_{(j:k)}} p_{C_{i,j}}}\right) \tag{10a}$$

$$\text{subject to:} \quad \Pr\left\{\Gamma^{LB}_{C_{i,j}} \le \frac{g_{C_i} p_{C_i}}{N_0 + \tilde{h}_{D_{j,i}} p_{D_{j,i}}}\right\} = 1 - \epsilon \tag{10b}$$

$$0 \le p_{C_{i,j}} \le p_{C_{max}} \qquad 0 \le p_{D_{j,i}} \le p_{D_{max}} \tag{10c}$$

$$\Pr\left\{\frac{g_{C_i} p_{C_{i,j}}}{\sigma^2 + \tilde{h}_{D_{j,i}} p_{D_{j,i}}} \ge \Gamma_{C_{min}}\right\} \ge 1 - \epsilon \tag{10d}$$

$$\frac{g_{D_{(j:k)}} p_{D_{j,i}}}{\sigma^2 + h_{C_{(j:k)}} p_{C_{i,j}}} \ge \Gamma_{D_{min}} \quad \forall k \in \mathcal{M}_j \tag{10e}$$

Next, under the assumption that the statistical distribution of interference channel gain $h_{D_{j,i}}$ is pre-specified, the probabilistic constraint (10b) can be restated as:

$$\Pr\left\{\tilde{h}_{D_{j,i}} \le \frac{g_{C_i} p_{C_i} - \Gamma^{LB}_{C_{i,j}} N_0}{p_{D_{j,i}} \Gamma^{LB}_{C_{i,j}}}\right\} \ge 1 - \epsilon$$

$$\implies \Gamma^{LB}_{C_{i,j}} \le \frac{g_{C_i} p_{C_i}}{N_0 + F^{-1}_{h_{D_{j,i}}}(1-\epsilon) p_{D_{j,i}}} \tag{11}$$

where $F^{-1}_{h_{D_{j,i}}}(\cdot)$ is the inverse cumulative distribution function of $h_{D_{j,i}}$. Similarly, constraint (10d) can be expressed as,

$$\frac{g_{C_i} p_{C_i}}{N_0 + F^{-1}_{h_{D_{j,i}}}(1-\epsilon) p_{D_{j,i}}} \geq \Gamma_{C_{min}} \tag{12}$$

It can be noted that the objective (10a) and the modified constraint (11) involve ratio between two convex functions which is not convex in general. Hence, in the next subsection, we use fractional programming [10] to relax the non convexity due to these ratios.

B. Fractional Programming via Quadratic Transformation

Introducing the auxiliary variable $\Gamma^{LB}_{D_{j,i}}$ as the lower bound on achievable SINR over all receivers in the j-th multicast group, the power allocation problem (10a) can be re-stated as:

$$\underset{p_{C_i}, p_{D_{j,i}}}{\text{maximize}} \quad \log_2\left(1+\Gamma^{LB}_{C_{i,j}}\right) + \log_2\left(1+\Gamma^{LB}_{D_{j,i}}\right) \tag{13a}$$

$$\text{subject to:} \quad \Gamma^{LB}_{D_{j,i}} \leq \frac{g_{D_{(j:k)}} p_{D_{j,i}}}{N_0 + h_{C_{(j:k)}} p_{C_{i,j}}} \quad \forall k \in \mathcal{M}_j \tag{13b}$$

$$(11), (10c), (12) \text{ and } (10e) \tag{13c}$$

Taking a partial Lagrangian of (13a) by considering only the constraints related to the auxiliary variables $\Gamma^{LB} := \{\Gamma^{LB}_{C_{i,j}}, \Gamma^{LB}_{D_{j,i}}\}$ in (11) and (13b), respectively, we obtain

$$\begin{aligned} L(\mathbf{p}, \Gamma^{LB}, \lambda) &= \log_2\left(1+\Gamma^{LB}_{C_{i,j}}\right) + \log_2\left(1+\Gamma^{LB}_{D_{j,i}}\right) \\ &- \lambda_C\left(\Gamma^{LB}_{C_{i,j}} - \frac{g_{C_i} p_{C_{i,j}}}{N_0 + F^{-1}_{h_{D_{j,i}}}(1-\epsilon) p_{D_{j,i}}}\right) \\ &- \sum_{k\in\mathcal{M}_j}\left(\lambda_{D_k}\left(\Gamma^{LB}_{D_{j,i}} - \frac{g_{D_{(j:k)}} p_{D_{j,i}}}{N_0 + h_{C_{(j:k)}} p_{C_{i,j}}}\right)\right) \end{aligned} \tag{14}$$

At a stationary point, $\frac{\partial L}{\partial \Gamma^{LB}} = 0$; thus, the optimal values of the Lagrange variables can be computed as $\lambda_C = \frac{1}{1+\Gamma^{LB}_{C_{i,j}}}$ and $\sum_{k\in\mathcal{M}_j} \lambda_{D_k} = \frac{1}{1+\Gamma^{LB}_{D_{j,i}}}$. Note that the optimal value of the Lagrange variable λ_C is achieved when the inequality constraints (11) is satisfied with equality. Furthermore, by complementary slackness at optimality, $\lambda_{D_k} = 0$ for all relaxed constraints and $\lambda_{D_k} \geq 0$ for tight constraint in (13b). Here, a tight constraint applies to the receiver with *lowest* SINR; thus, if $(j:l)$ denotes the receiver in the multicast group j which observes the *lowest* SINR, then the optimal value is $\lambda_{D_l} = \frac{1}{1+\Gamma^{LB}_{D_{j,i}}}$. Next, by calculating λ^*_C and $\lambda^*_{D_l}$ and substituting them in problem (13a), we obtain:

$$\begin{aligned} \underset{p_{C_i}, p_{D_{j,i}}}{\text{maximize}} \quad & \log_2\left(1+\Gamma^{LB}_{C_{i,j}}\right) + \log_2\left(1+\Gamma^{LB}_{D_{j,i}}\right) \\ & - \Gamma^{LB}_{C_{i,j}} + \frac{(1+\Gamma^{LB}_{C_{i,j}}) g_{C_i} p_{C_{i,j}}}{g_{C_i} p_{C_{i,j}} + N_0 + F^{-1}_{h_{D_{j,i}}}(1-\epsilon) p_{D_{j,i}}} \\ & - \Gamma^{LB}_{D_{j,i}} + \frac{(1+\Gamma^{LB}_{D_{j,i}}) g_{D_{j,l}} p_{D_{j,i}}}{g_{D_{j,l}} p_{D_{j,i}} + N_0 + h_{C_{(j:l)}} p_{C_{i,j}}} \\ \text{subject to:} \quad & (10c), (12) \text{ and } (10e) \end{aligned} \tag{15}$$

Next, we transform the fractions in the objective by introducing auxiliary variables y_C and y_D through a quadratic transformation [10], obtaining:

$$\begin{aligned} \underset{p_{C_{i,j}}, p_{D_{j,i}}}{\text{maximize}} \quad & \log_2\left(1+\Gamma^{LB}_{C_{i,j}}\right) + \log_2\left(1+\Gamma^{LB}_{D_{j,i}}\right) \\ & - \Gamma^{LB}_{C_{i,j}} + 2y_C\sqrt{(1+\Gamma^{LB}_{C_{i,j}}) g_{C_i} p_{C_{i,j}}} \\ & - y_C^2\left(g_{C_i} p_{C_{i,j}} + N_0 + F^{-1}_{h_{D_{j,i}}}(1-\epsilon) p_{D_{j,i}}\right) \\ & - \Gamma^{LB}_{D_{j,i}} + 2y_D\sqrt{(1+\Gamma^{LB}_{D_{j,i}}) g_{D_{j,l}} p_{D_{j,i}}} \\ & - y_D^2\left(g_{D_{j,l}} p_{D_{j,i}} + N_0 + h_{C_{(j:l)}} p_{C_{i,j}}\right) \\ \text{subject to:} \quad & (10c), (12) \text{ and } (10e) \end{aligned} \tag{16}$$

The optimal values of the auxiliary variables y_C and y_D can be readily computed as:

$$\begin{aligned} y_C^* &= \frac{\sqrt{(1+\Gamma^{LB}_{C_{i,j}}) g_{C_i} p_{C_{i,j}}}}{g_{C_i} p_{C_{i,j}} + N_0 + F^{-1}_{h_{D_{j,i}}}(1-\epsilon) p_{D_{j,i}}} \\ y_D^* &= \frac{\sqrt{(1+\Gamma^{LB}_{D_{j,i}}) g_{D_{j,l}} p_{D_{j,i}}}}{g_{D_{j,l}} p_{D_{j,i}} + N_0 + h_{C_{(j:l)}} p_{C_{i,j}}} \end{aligned} \tag{17}$$

Notice that for the given values of slack variables $\Gamma^{LB}_{C_{i,j}}$ and $\Gamma^{LB}_{D_{j,i}}$ and auxiliary variables y_C and y_D, the optimization problem (16) is jointly convex in $p_{C_{i,j}}$ and $p_{D_{j,i}}$. Hence, in the next subsection, we propose to perform alternating optimization in (16) between $p_{C_{i,j}}$ and $p_{D_{j,i}}$.

C. Alternating Optimization

Optimization problem (16) is solved by alternating maximization with respect to the individual $\Gamma^{LB}_{C_{i,j}}$, $\Gamma^{LB}_{D_{j,i}}$, y_C, y_D. $p_{C_{i,j}}$ and $p_{D_{j,i}}$ variables. At each step, all iterates can be obtained in closed form by taking the partial derivative with respect to each variable and setting it to 0, and projecting the solution onto the feasible set. The overall iteration can be expressed as:

- Compute $\Gamma^{LB}_{C_{i,j}}$ following tight constraint (11). Compute $\Gamma^{LB}_{D_{j,i}}$ following tight constraint for receiver $(j:l)$ with *lowest* SINR in (13b).
- Compute auxiliary variables y_C and y_D from equation (17).
- Updates for $p_{C_{i,j}}$ and $p_{D_{j,i}}$ can be computed as:

$$\begin{aligned} p_{C_{i,j}} &= \text{Proj}_{\mathcal{S}_1}\left(\frac{y_C^2(1+\Gamma^{LB}_{C_{i,j}}) g_{C_i}}{(y_C^2 g_{C_i} + y_D^2 h_{C_{(j:l)}})^2}\right) \\ p_{D_{j,i}} &= \text{Proj}_{\mathcal{S}_2}\left(\frac{y_D^2(1+\Gamma^{LB}_{D_{j,i}}) g_{D_{j,l}}}{(y_D^2 g_{D_{j,l}} + y_C^2 F^{-1}_{h_{D_{j,i}}}(1-\epsilon))^2}\right) \end{aligned} \tag{18}$$

  where, $\text{Proj}_{\mathcal{A}}(*)$ is a projection of $*$ onto the set $\mathcal{A}$; $S_1 \triangleq \{p_{C_{i,j}} : (p_{C_{i,j}}, p_{D_{ji}})\}$ satisfy (10c), (12), and (10e) for specified last update of $p_{D_{j,i}}$. $S_2 \triangleq \{p_{D_{j,i}} : (p_{C_{i,j}}, p_{D_{j,i}})\}$ satisfy (10c), (12), and (10e) for specified last update of $p_{C_{i,j}}$.

The convergence analysis of above alternating optimization is omitted due to lack of space; however, the analysis can be easily performed by following the extensive discussion in our previous work [11]. Once (9) is solved $\forall i \in \mathcal{C}$ and $\forall j \in \mathcal{D}$, the next step is to perform channel assignment to D2D pairs, as explained in the next section.

D. Channel Assignment via Integer Relaxation

For the channel assignment to D2D pairs, the resulting values $\tilde{v}_{i,j}$ (solution obtained after solving (9) $\forall i \in \mathcal{C}, \forall j \in \mathcal{D}$) are substituted into (8) and then we need to maximize the objective of (8) with respect to $\mathbb{B}$. The resulting channel assignment sub-problem can be stated as:

$$\begin{aligned} &\underset{\mathbb{B}}{\text{maximize}} \quad \sum_{i\in\mathcal{C}}\sum_{j\in\mathcal{D}} \beta_{i,j}\tilde{v}_{i,j} - \gamma\delta(\mathbb{B}), \qquad (19) \\ &\text{subject to} \quad \beta_{i,j} \in \{0,1\} \;\; \forall i,j, \quad \sum_{j\in\mathcal{D}} \beta_{i,j} \le 1 \;\; \forall i. \end{aligned}$$

Due to the integer constraints, solving (19) involves prohibitive computational complexity even for reasonable values of $N_C,\ N_D$. Similar to [9], we relax the integer constraints to $\beta_{i,j} \in [0,1]\ \forall i,j$ to obtain a differentiable Lipschitz smooth objective function with linear constraints, which can be efficiently solved using the Projected Gradient Descent algorithm. The obtained solution is finally discretized back to satisfy the original constraints $\beta_{i,j} \in \{0,1\}\ \forall i,j$. In our approach, this is done by setting the highest positive value in every row of $\mathbb{B}$ to 1 while setting other values in the same row to 0. This relaxation yields good solutions with low computational complexity (as compared to other types of relaxations [9]) and the performance of this relaxation has been extensively discussed in [9].

V. Simulations

The simulation setup comprises a circular cell of 500 m radius in which the CUs and D2D transmitters are placed uniformly at random. Each D2D receiver is placed uniformly at random inside a circle of radius 5 m centered at the corresponding transmitter. The channel gains are calculated using a path loss model with exponent 2 and gain -5 dB at a reference distance of 1 m. We assume $\tilde{h}_D$ to be exponentially distributed with the mean value obtained from the mentioned path-loss model. Averages are calculated over 400 independent realizations of the user locations with parameters BW$=$ 15 kHz, $\epsilon = 0.1,\ N_D = 3,\ N_C = 6,\ M_j = 3,\ N_0 = -70$ dBW. The proposed algorithm is compared with the unicast method in [11] when each D2D group is considered as M_J D2D pairs. Other works that focus on multicast D2D communications have very different network assumptions (e.g. perfect CSI in the case of [2] and network assisted transmission in the case of [1]) and can not be directly compared to our proposed method.

Fig. 2 shows that the proposed method achieves slightly lower rate compared to the unicast method in [11]. However, in the multicast case, the number of transmitted signals is much smaller than the unicast case. When γ increases, the rate decreases in all methods while the unfairness decreases. This is expected because γ controls the trade-off between the rate and fairness, high γ will force the solution to have better

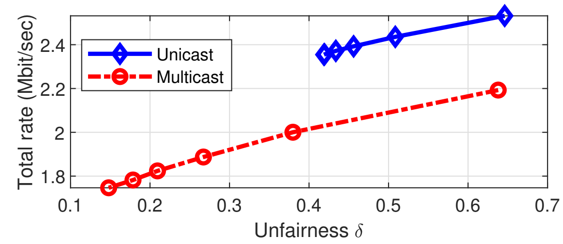

Fig. 2: Total average rate R vs. Unfairness δ (γ from 10 to 100)

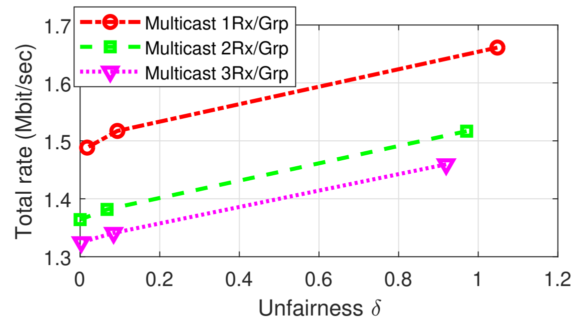

Fig. 3: Total average rate R vs. Unfairness δ (γ from 10 to 100)

fairness (lower unfairness) on the expense of achieving lower rate.

Fig. 3 shows the performance of the proposed method when changing the number D2D receivers in each multicast group. The total network rate decreases with each additional receiver in the group, since the rate in each group is determined by the receiver with the worst communication conditions. As before, increasing the value of γ decreases the rate while decreasing the unfairness.

Fig. 4 shows the achieved outage probability of the multicast case compared to the unicast case for different values of ϵ and $\gamma = 100$. It can be seen that the proposed multicast algorithm is very conservative and achieves very small outage probabilities compared to the unicast method which achieves outage probability that is very close to the desired outage ϵ.

VI. Conclusion

This paper presented a reliable algorithm for joint channel assignment and power allocation in multicast underlay D2D cellular networks that ensures (i) reliability by probabilistically constraining the SINR for both CUs and D2D to guarantee the desired outage probability, (ii) the fairness among D2D pairs by penalizing unfair assignments.

In general, multicast communications allow sending the same information to several receivers with the same network resources. Our proposed algorithm achieves this goal while ensuring the reliability of cellular communication. Moreover, our algorithm provides an additional freedom by selecting a trade-off parameter to balance between rate and fairness.

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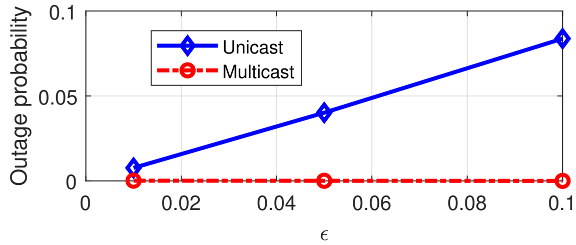

Fig. 4: Outage probability vs. ϵ.

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