Throughput-Optimal D2D mmWave Communication: Joint Coalition Formation, Power, and Beam Optimization

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2022 IEEE Wireless Communications and Networking Conference (WCNC) | 978-1-6654-4266-4/22/$31.00 ©2022 IEEE | DOI: 10.1109/WCNC51071.2022.9771608

Abstract*—In this paper, we consider a device-to-device (D2D) millimeter Wave (mmWave) network that allocates a spectrum band with bandwidth B_c Hz exclusively to support communication of N cooperative D2D pairs over Rayleigh fading channels. The available bandwidth is divided into N_c non-overlapping sub-bands. Each node is equipped with a directional antenna that is capable of steering its beam within its field of view. Also, each transmitter can adjust its transmit power. Aiming at maximizing the network throughput, the cooperative D2D pairs form N_c disjoint coalitions, where the D2D pairs in a particular coalition share the same sub-band for communication and hence cause co-channel interference. We address this question: What is the best coalition among the D2D pairs, the optimal beams steering angles of directional antennas of the D2D pairs within each coalition, and the optimal transmit powers such that the network throughput is maximized? We formulate the network throughput maximization problem, subject to certain constraints, and we propose an iterative method, based on the block coordinate descent (BCD) algorithm, to solve the constrained optimization problem. Specially, we propose a coalitional game approach for coalition formation among the D2D pairs. We numerically investigate the effects of different system parameters (e.g., N, N_c, the antenna gain, the maximum allowed total transmit power), as well as the impact of optimizing coalition formation only, and optimizing transmit power only, on the network throughput maximization.

I. Introduction

Internet-of-things (IoT) is becoming a reality as smart devices, machines, sensors, and vehicles are wirelessly connected to one another and to the Internet [1]. The International Telecommunication Union (ITU) is forecasting 10,000X and 100X increases in the aggregate wireless demand by 2030, relative to 2010 and 2020, respectively [2]. The accelerating growth and penetration of wireless IoT devices into daily lives of civilians and the spiraling wireless capacity demands push for more spectral efficient solutions. The millimeter wave (mmWave) communication with directional antennas enables spatial frequency reuse in mmWave bands and is a promising solution to address the technical challenges imposed by the increasing wireless demands [3]. In addition to the mmWave directional communication, device-to-device (D2D) communication has been advocated to advance wireless innovations in spectrum utilization, via allowing many users to share the same spectrum band [4]. D2D communication can reduce the large path loss caused by long distance, cover the shaded area of mmWave communication and combat the blockage problem, and increase the communication reliability and efficiency [5].

To achieve the goals that are set for the next generation of high-speed wireless communication systems, we explore a throughput-optimal design for a D2D mmWave network, where the nodes employ *beam-steerable directional antennas* for wireless communication. In particular, we consider a mmWave network that allocates a spectrum band with bandwidth B_c Hz exclusively to support communication of N cooperative D2D pairs over Rayleigh fading channels. The available spectrum band is divided into N_c non-overlapping sub-bands, where each sub-band has a bandwidth of $W = B_c/N_c$ Hz. Also, we assume $N_c \ll N$. Each node is capable of steering its beam within the range of its field of view (FOV) [6]–[8]. Also, each transmitter node can adjust its transmit power. The D2D pairs can form up to N_c disjoint coalitions, such that the pairs in a particular coalition share the same sub-band for communication. Therefore, the pairs within a coalition cause co-channel interference, whereas the pairs in different coalitions do not interfere. The questions we address are: What is the best coalition among the D2D pairs? What are the optimal beam steering angles of directional antennas of the D2D pairs within each coalition, and what are the optimal transmit powers such that the network throughput, defined as the sum-rate of all N D2D pairs in N_c coalitions, is maximized?

Related Works: The most related literature to our work are [9]–[12], which we summarize in the following and highlight the novelty of our work with respect to these literature. The authors in [9] considered a full-duplex mmWave network, where small cells are densely deployed underlying the macrocell network, and D2D communication is adopted to enhance the resource utilization and network throughput. Each user is equipped with two directional antennas to enable full-duplex communication. The system sub-bands are shared among access links for user-BS communications, and D2D links for user-to-user communications. Given a set of sub-bands, the authors formulated the sub-band allocation problem among access and D2D links as a coalitional game, where the utility is the system throughput. Assuming that all transmitters transmit at a fixed power level and the beam steering angles of the directional antennas are fixed, [9] incorporates residual self-interference (after applying self-interference cancellation) into the system throughput. The authors in [10] considered a related model where the system consists of two types of cellular and D2D transmitter-receiver pairs and two sets of cellular and mmWave sub-bands. Each D2D pair has a directional antenna and can share either a mmWave band with other D2D pairs or a cellular band with another cellular pair. Given the two sets of sub-bands, the authors formulated the sub-band allocation problem among cellular and D2D pairs as a coalitional game, where the utility is the system throughput. The authors in [11] considered a system with two types of cellular and D2D pairs sharing a common channel, and each pair is equipped with a directional antenna. The authors formulated the beamwidth optimization of D2D pairs as a coalitional game, where the utility is the system throughput. None of the studies in [9]–[11] have considered optimizing the beam steering angles of directional antennas and transmit powers of D2D users. Taking advantage of beam steering capability of directional antennas [6], [7] to optimize the steering angles of D2D users, as well as adapting their transmit powers can play significant roles in controlling co-channel interference and hence enhancing spectrum utilization. The study in [12] considered a group of D2D pairs that share a common channel and each pair optimizes its directional antenna angles such that the rate of the pair is maximized. The study formulated the angle optimization problem as a quantum non-cooperative game.

To the best of our knowledge, our proposed problem is novel, as we combine the concepts of coalition formation among cooperative D2D pairs and the sub-band allocation problem, with adaptive beam steering and adaptive transmit power for interference management and spectral efficiency improvement.

II. System Overview

A. System Model

We consider a mmWave network, where small cells are densely deployed underlying the macrocell network. When the distance between a transmitter-receiver pair is within a certain range, they can communicate directly and establish a D2D link. If the distance is large, they communicate through the nearest base station. We assume that a total bandwidth of B_c Hz is exclusively allocated to N D2D pairs, which is not overlapping with the spectrum band allocated to cellular users. Suppose D2D link i denotes the wireless communication link between transmitter t_i and receiver r_i of pair i, for $i = 1, \dots, N$ (see Fig. 1a). Our wireless channel propagation model encompasses both Rayleigh flat fading and path loss. Suppose nodes t_i and r_j are located at Cartesian locations (X_{t_i}, Y_{t_i}) and (X_{r_j}, Y_{r_j}), respectively. Let the angles ϕ_{t_i} and ϕ_{r_j} (measured in radian) denote the the antenna orientations of nodes t_i and r_j in their local coordinates, respectively. Also, let the angle $\theta_{t_i r_j}$ denote the orientation of the line connecting nodes t_i and r_j where

$$\theta_{t_i r_j} = \tan^{-1}\left(\frac{Y_{t_i} - Y_{r_j}}{X_{t_i} - X_{r_j}}\right). \tag{1}$$

Suppose $A_\ell(\phi)$ denotes the antenna gain of node ℓ (which can be either a transmitter or receiver) at an arbitrary angle ϕ. Suppose pair i is in coalition c, i.e., the pair is communicating

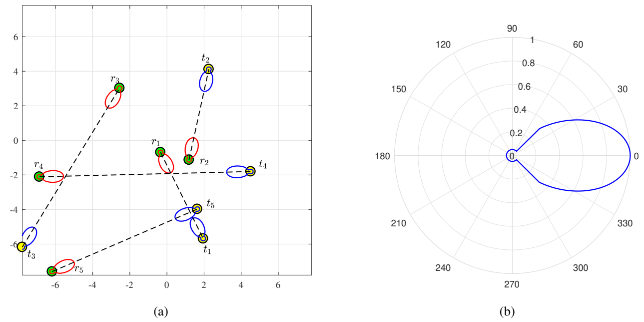

Fig. 1: (a) An example of 5 transmitter-receiver D2D pairs in a coalition. In each pair, the directional antennas of transmitter and receiver are exactly along the center of their main lobes (which is not necessarily throughput-optimal). (b) An example of $A_\ell(\phi)$.

over sub-band c, for $c = 1, ..., N_c$. The received signal power at node r_i from node t_i can be written as

$$P^c_{t_i r_i} = P^c g^c_{t_i r_i} G_{t_i r_i}(\phi_{t_i}, \phi_{r_i}), \tag{2}$$

where P^c is the transmit power of t_i, $g^c_{t_i r_i}$ is the power of fading channel between t_i and r_i corresponding to sub-band c. For Rayleigh fading channel model $g^c_{t_i r_i}$ is an Exponential random variable with mean $\mathrm{E}\{g^c_{t_i r_i}\} = \frac{d_0}{(d_{t_i r_i})^\alpha}$, where d_0 is the reference distance, $d_{t_i r_i} = \sqrt{(X_{t_i} - X_{r_i})^2 + (Y_{t_i} - Y_{r_i})^2}$ is the Euclidean distance between t_i and r_i, and α is the path loss exponent. Also, $G_{t_i r_i}(\phi_{t_i}, \phi_{r_i})$ is the product of antenna gains of t_i and r_i when the antenna orientations of t_i and r_i in their local coordinates are ϕ_{r_i} and ϕ_{r_i}, respectively. We have

$$G_{t_i r_i}(\phi_{t_i}, \phi_{r_i}) = A_{t_i}(\phi_{t_i} - \theta_{t_i r_i})\, A_{r_i}(\phi_{r_i} - \pi - \theta_{t_i r_i}). \tag{3}$$

Note that communication of pair i in coalition c causes co-channel interference on other receiver nodes in this coalition. Similarly, communication of other pairs in coalition c causes co-channel interference on node r_i in this coalition. Suppose $I^c_{t_j r_i}$ denotes the interference power imposed on r_i from t_j in coalition c. This interference power can be written as

$$I^c_{t_j r_i} = P^c g^c_{t_j r_i} G_{t_j r_i}(\phi_{t_j}, \phi_{r_i}), \tag{4}$$

where $g^c_{t_j r_i}$ is the power of fading channel between t_j and r_i corresponding to sub-band c, and

$$G_{t_j r_i}(\phi_{t_j}, \phi_{r_i}) = A_{t_j}(\phi_{t_j} - \theta_{t_j r_i})\, A_{r_i}(\phi_{r_i} - \pi - \theta_{t_j r_i}). \tag{5}$$

To simplify the presentation, we let the binary variable a^c_i indicate whether or not transmitter-receiver pair i is in coalition c, i.e., if $a^c_i = 1$ then pair i is in coalition c and thus link i operates in sub-band c, otherwise, $a^c_i = 0$. The rate of link i operating over sub-band c can be written as

$$R^c_i = W \log_2\left(1 + \frac{a^c_i P^c_{t_i r_i}}{N_0 W + \sum_{j=1,\, j \neq i}^{N} a^c_j I^c_{t_j r_i}}\right), \tag{6}$$

where N_0 is the power spectral density of the receiver additive white Gaussian noise. Then, the sum-rate of all pairs in coalition c can be written as

$$R^c = \sum_{i=1}^{N} R^c_i. \tag{7}$$

Consequently, the network throughput is $\sum_{c=1}^{N_c} R^c = \sum_{c=1}^{N_c} \sum_{i=1}^{N} R^c_i$.

Clearly, the network throughput depends on the coalition formation among the D2D pairs, beam steering angles of directional antennas of the D2D pairs within each coalition, and transmit powers. We ask the following questions: How does the throughput-optimal coalition formation look like? In other words, given each sub-band c, which D2D pairs should operate over this sub-band? Furthermore, within each coalition, what are the best beam steering angles of directional antennas of the D2D pairs and the best transmit power, in terms of maximizing the network throughput?

B. Antenna Model

Let $A_\ell(\phi)$ denote the gain of directional antenna of node ℓ (which can be a transmitter or a receiver). We express $A_\ell(\phi)$ as the following

$$A_\ell(\phi) = \begin{cases} A^\ell_{\mathrm{ml}}\, e^{-B\left(\frac{\phi}{\phi^\ell_{3\mathrm{dB}}}\right)^2}, & |\phi| \le \phi^\ell_{\mathrm{ml}} \\ A^\ell_{\mathrm{sl}}, & |\phi| > \phi^\ell_{\mathrm{ml}} \end{cases} \tag{8}$$

where ϕ denotes an arbitrary angle within the FOV range $[-\phi^\ell_{\mathrm{FOV}}, \phi^\ell_{\mathrm{FOV}}]$, ϕ^ℓ_{ml} denotes the main lobe width, $\phi^\ell_{3\mathrm{dB}}$ is the half-power beamwidth, A^ℓ_{ml} is the maximum antenna gain, A^ℓ_{sl} is the sidelobe gain and $B = \ln(2)$. We adopt our antenna gain pattern in (8) from [9]. This is a realistic model for directional antennas with sidelobe gain. Fig. 1b illustrates an example of $A_\ell(\phi)$ for $A^\ell_{\mathrm{ml}} = 1, A^\ell_{\mathrm{sl}} = 0.05, \phi^\ell_{\mathrm{ml}} = 45^\circ, \phi^\ell_{3\mathrm{dB}} = 35^\circ$.

C. Problem Formulation

To formulate the network throughput maximization problem, we need to incorporate the constraints on the binary variable a_i^c in (6). Since each transmitter-receiver pair can belong to at most one coalition, we have

$$\sum_{c=1}^{N_c} a_i^c \le 1, \quad \text{for } i = 1, ..., N. \tag{9}$$

Let $P_{\max}$ indicate the maximum allowed total transmit power of all transmitter nodes in the network. To satisfy this power constraint, we need to have

$$\sum_{c=1}^{N_c}\sum_{i=1}^{N} P^c a_i^c \le P_{\max}. \tag{10}$$

Finally, we note that the beam steering angle ϕ of node ℓ is limited to be within its field of view range $[-\phi^\ell_{\mathrm{FOV}}, \phi^\ell_{\mathrm{FOV}}]$. Therefore, the beam steering angles of nodes t_i and r_i in pair i are limited as the following:

$$\phi_{t_i} \in [\phi^{(\mathrm{low})}_{t_i}, \phi^{(\mathrm{up})}_{t_i}], \quad \phi_{r_i} \in [\phi^{(\mathrm{low})}_{r_i}, \phi^{(\mathrm{up})}_{r_i}], \quad \forall i \tag{11}$$

where

$$\begin{aligned} \phi^{(\mathrm{low})}_{t_i} &= \theta_{t_i r_i} - \phi^{t_i}_{\mathrm{FOV}}, & \phi^{(\mathrm{up})}_{t_i} &= \theta_{t_i r_i} + \phi^{t_i}_{\mathrm{FOV}}, \\ \phi^{(\mathrm{low})}_{r_i} &= \pi + \theta_{t_i r_i} - \phi^{r_i}_{\mathrm{FOV}}, & \phi^{(\mathrm{up})}_{r_i} &= \pi + \theta_{t_i r_i} + \phi^{r_i}_{\mathrm{FOV}}. \end{aligned}$$

and angle $\theta_{t_i r_i}$ denote the orientation of the line connecting nodes t_i and r_i. Our goal is to find the set of binary variables $\{a_i^c\}, \forall i, c$, the transmit powers $\{P^c\}, \forall c$, and the set of beam steering angles of directional antennas of all pairs $\{\phi_{t_i}, \phi_{r_i}\}, \forall i$ such that the network throughput is maximized, subject to the constraints in (9), (10), (11). In other words, we are interested to solve the following constrained optimization problem

$$\begin{aligned} &\underset{\{a_i^c\},\forall i,c,\{P^c\},\forall c,\,\{\phi_{t_i},\,\phi_{r_i}\},\forall i}{\text{Maximize}} \quad \sum_{c=1}^{N_c} R^c \qquad \text{(P1)} \\ &\text{s.t.} \quad \textstyle\sum_{c=1}^{N_c} a_i^c \le 1, \quad \forall i, \\ &\qquad \textstyle\sum_{c=1}^{N_c}\sum_{i=1}^{N} P^c a_i^c \le P_{\max}, \\ &\qquad \phi_{t_i} \in [\phi^{(\mathrm{low})}_{t_i}, \phi^{(\mathrm{up})}_{t_i}], \quad \phi_{r_i} \in [\phi^{(\mathrm{low})}_{r_i}, \phi^{(\mathrm{up})}_{r_i}], \quad \forall i. \end{aligned}$$

We note that (P1) is a nonlinear mixed-integer programming problem with exorbitant computational complexity [13]. Even if the binary variables $\{a_i^c\}, \forall i, c$ are relaxed to be in the interval $[0, 1]$, the optimal solution of (P1) cannot be obtained via the gradient descent algorithm, due to the constraints on a_i^c. Even if the beam steering angles $\{\phi_{t_i}, \phi_{r_i}\}, \forall i$ and the transmit powers $\{P^c\}, \forall c$ are given in (P1), still the time complexity of finding the optimal binary variables $\{a_i^c\}, \forall i, c$ is in the order of $\mathcal{O}(N_c^N)$, and the solution via an exhaustive search can only be found for a network with small N and N_c.

III. Solving Problem

We propose an iterative method based on the block coordinate descent (BCD) algorithm to solve[1] (P1) [14]. The underlying principle of the BCD algorithm is that, at each iteration one variable is optimized, while the remaining variables are fixed. The iteration continues until it converges to a stationary point of (P1) [6], [15]. To apply the principle of the BCD algorithm to (P1), we decompose (P1) into three sub-problems, which we refer to as (SP1), (SP2), and (SP3). In (SP1), we search for the binary variables $\{a_i^c\}$, $\forall i, c$, given $\{P^c\}, \forall c$ and $\{\phi_{t_i}, \phi_{r_i}\}, \forall i$. In other words, we solve the following problem

$$\begin{aligned} &\text{Given } \{P^c\}, \forall c \text{ and } \{\phi_{t_i},\, \phi_{r_i}\}, \forall i \qquad \text{(SP1)} \\ &\underset{\{a_i^c\},\forall i,c}{\text{Maximize}} \quad \sum_{c=1}^{N_c} R^c \\ &\text{s.t.} \quad \textstyle\sum_{c=1}^{N_c} a_i^c \le 1, \quad \forall i. \end{aligned}$$

To solve (SP1), we take a coalitional game approach which has a low computational complexity. The approach and the algorithm are discussed in Section III-A. In (SP2), we search for the transmit powers $\{P^c\}, \forall c$ given $\{a_i^c\}, \forall i, c$ and $\{\phi_{t_i}, \phi_{r_i}\}, \forall i$. In other words, we solve the following problem

$$\begin{aligned} &\text{Given } \{a_i^c\}, \forall i, c \text{ and } \{\phi_{t_i},\, \phi_{r_i}\}, \forall i \qquad \text{(SP2)} \\ &\underset{\{P^c\},\forall c}{\text{Maximize}} \quad \sum_{c=1}^{N_c} R^c \\ &\text{s.t.} \quad \textstyle\sum_{c=1}^{N_c}\sum_{i=1}^{N} P^c a_i^c \le P_{\max}. \end{aligned}$$

We note that (SP2) is a jointly concave function of $\{P^c\}, \forall c$. Hence, we use the Lagrange multiplier method and solve the corresponding Karush-Kuhn-Tucker (KKT) conditions to find the solution. The details are explained in Section III-B. In (SP3), we search for the beam steering angles $\{\phi_{t_i}, \phi_{r_i}\}, \forall i$, given $\{P^c\}, \forall c$ and $\{a_i^c\}, \forall i, c$. In other words, we solve the following problem

[1]Similar to [9]–[11] we assume the problem is solved at the BS and the solution is shared with D2D pairs via control channels.

$$\text{Given } \{P^c\}, \forall c, \{a_i^c\}, \forall i, c \qquad \text{(SP3)}$$

$$\underset{\{\phi_{t_i}, \phi_{r_i}\}, \forall i}{\text{Maximize}} \quad \sum_{c=1}^{N_c} R^c$$

$$\text{s.t.} \quad \phi_{t_i} \in [\phi_{t_i}^{(\text{low})}, \phi_{t_i}^{(\text{up})}], \quad \phi_{r_i} \in [\phi_{r_i}^{(\text{low})}, \phi_{r_i}^{(\text{up})}], \quad \forall i.$$

We note that (SP3) is neither a convex nor a concave function with respect to $\{\phi_{t_i}, \phi_{r_i}\}, \forall i$. We use interior-point method to solve (SP3). Section III-C provides more details on how we solve (SP3). We iterate between solving (SP1), (SP2), and (SP3) until we converge to a stationary point of (P1), which is our solution.

A. *Solving Sub-problem* (SP1)

To solve (SP1), we take a coalitional game approach, where N transmitter-receiver pairs in the mmWave network are regarded as the players of the game [9], [16]. In the following, we briefly mention some definitions of the coalitional game approach, that are important for designing the coalition formation algorithm.

Our coalitional game is defined by $(\mathcal{I}, U)$, where $\mathcal{I}$ is the set of game players (i.e., the set of N cooperative transmitter-receiver pairs) and U is the utility function (i.e., the sum-rate of the pairs in a coalition). A sub-set $S_c \subseteq \mathcal{I}$ indicates the set of transmitter-receiver pairs in coalition c which communicates over sub-band c. Then $U(S_c)$ represents the value of coalition c, i.e., $U(S_c) = R^c$ is equal to the sum-rate of the pairs in set S_c. Different coalitions in our mmWave network satisfy the following constraints:

$$\mathcal{I} = \bigcup_{c=1}^{N_c} S_c, \quad S_c \cap S_{c'} = \emptyset, \ \forall c, c' \text{ and } c \neq c'.$$

We notice that the transmitter-receiver pairs are not motivated to form a grand coalition, where all the pairs communicate over only one sub-band, since the co-channel interference will become very large and will negatively impact the coalition value. In fact, the transmitter-receiver pairs prefer to form as many disjoint coalitions as possible, to maximize the overall coalition value. Since there are N_c sub-bands in our mmWave network, the pairs are motivated to form N_c disjoint coalitions.

A coalitional partition is defined as the set $\Pi = \{S_1, \dots S_{N_c}\}$, which partitions the set of game players $\mathcal{I}$ into disjoint subsets S_c's. The total utility of this partition is

$$U(\Pi) = \sum_{c=1}^{N_c} U(S_c). \qquad (13)$$

The players of the game prefer the coalitional partition $\Pi' = \{S'_1, \dots S'_{N_c}\}$ instead of $\Pi = \{S_1, \dots S_{N_c}\}$ if the total utility achieved by Π' is strictly greater than by Π, i.e.

$$\sum_{c=1}^{N_c} U(S'_c) > \sum_{c=1}^{N_c} U(S_c). \qquad (14)$$

The players of the game decide to join or leave a coalition based on a defined *preference relation*. For any player $i \in \mathcal{I}$, the preference relation $S_p \succ_i S_q$ means player i strictly prefers being a member of coalition S_p over being a member of coalition S_q, where $S_p, S_q \subseteq \mathcal{I}$ and $S_p \neq S_q$. The preference relation $S_p \succ_i S_q$ is quantified as the following

$$U(S_p \cup i) + U(S_q \backslash i) > U(S_p) + U(S_q). \qquad (15)$$

Algorithm 1: Algorithm for Solving (SP1)

Given $\{P^c\}, \forall c$ and $\{\phi_{t_i}, \phi_{r_i}\}, \forall i$,
Initialize the system by any random partition Π_{ini}. Set the current partition $\Pi_{\text{cur}} = \Pi_{\text{ini}}$,
repeat
  Randomly choose a link $i \in \mathcal{I}$, and denote its current coalition as $S_p \in \Pi_{\text{cur}}$,
  Randomly choose another coalition $S_q \in (\Pi_{\text{cur}} \cup \{\emptyset\})$, such that $S_p \neq S_q$,
  if the switch operation from S_p to S_q satisfying $S_q \succ_i S_p$
    $\Pi_{\text{cur}} = (\Pi_{\text{cur}} \backslash \{S_p, S_q\}) \cup \{S_p \backslash \{i\}\} \cup \{S_q \cup i\}$
  else
    $\Pi_{\text{tmp}} = (\Pi_{\text{cur}} \backslash \{S_p, S_q\}) \cup \{S_p \backslash \{i\}\} \cup \{S_q \cup i\}$
    Randomly choose one link $i' \in \mathcal{I}$, and denote its current coalition as $S_{p'} \in \Pi_{\text{tmp}}$,
    Randomly choose another coalition, $S_{q'} \in (\Pi_{\text{tmp}} \cup \{\emptyset\})$, $S_{p'} \neq S_{q'}$
    Obtain the partition Π'_{tmp} as $\Pi'_{\text{tmp}} = (\Pi_{\text{cur}} \backslash \{S_{p'}, S_{q'}\}) \cup \{S_p \backslash \{i'\}\} \cup \{S_{q'} \cup i'\}$
    if $U(\Pi'_{\text{tmp}}) > U(\Pi_{\text{cur}})$
      $\Pi_{\text{cur}} = \Pi'_{\text{tmp}}$
    end
  end
until the partition converges to a final Nash-stable partition.

Given a coalitional partition $\Pi = \{S_1, \dots S_{N_c}\}$, if player i switches from coalition S_q to coalition S_p, then the current coalitional partition Π of $\mathcal{I}$ is modified into a new coalitional partition $\Pi' = (\Pi \backslash \{S_q, S_p\}) \cup \{S_q \backslash i\} \cup \{S_p \cup i\}$. Player i is allowed to switch from coalition S_q to coalition S_p (i.e., player i leaves S_q and joins S_p) if and only if $S_p \succ_i S_q$.

Algorithm 1 summarizes our approach to solve (SP1), which is based on the above definitions and the switching rule. The iterations in Algorithm 1 stop when the partition converges to the final Nash-stable coalitional partition $\Pi_{\text{Nash}} = \{S''_1, \dots S''_{N_c}\}$. The partition Π_{Nash} satisfies the following. For any player $i \in \mathcal{I}$, if i is a member of coalition S_p, then $S_p \succ_i S_q$ for any $q \neq p$. Starting from any initial coalitional partition Π, the proposed coalition game always converges to the final partition, after a finite number of switch operations. Also, the final partition is the Nash-stable coalitional partition Π_{Nash}. The convergence proof is similar to [11], and is omitted due to lack of space.

B. *Solving Sub-problem* (SP2)

We solve (SP2) using the Lagrangian multiplier method. Let $\mathcal{L}(\{P^c\}, \forall c, \lambda)$ be the Lagrangian for (SP2), where λ is the Lagrange multiplier. The Lagrangian is

$$\mathcal{L}(\{P^c\}, \forall c, \lambda) = -\sum_{c=1}^{N_c} R^c + \lambda\Big(\sum_{c=1}^{N_c}\sum_{i=1}^{N} a_i^c P^c - P_{\max}\Big), \qquad (16)$$

The optimal set $\{P^c\}, \forall c$ that minimizes (16) is the solution to the KKT optimality necessary and sufficient conditions. The

$$\partial R^c/\partial P^c = W \sum_{i=1}^{N} \frac{a_i^c g_{t_i r_i}^c G_{t_i r_i} N_0 W}{\left(N_0 W + \sum_{j \neq i} a_j^c I_{t_j r_i}^c\right)\left(N_0 W + P^c a_i^c g_{t_i r_i}^c G_{t_i r_i} + \sum_{j \neq i} a_j^c I_{t_j r_i}^c\right)} \tag{18}$$

Algorithm 2: Algorithm for Solving (SP2)

1: Given $\{a_i^c\}, \forall i, c$ and $\{\phi_{t_i}, \phi_{r_i}\}, \forall i$ and λ_{ini},
2: Set $n = 0, \lambda^{(0)} = \lambda_{\text{ini}}$,
3: **repeat**
4: Calculate $P^{c,(n)}$ by solving (17a) for $c = 1, \ldots, N_c$,
5: Calculate $\lambda^{(n+1)}$ using (19),
6: $n \leftarrow n + 1$;
7: **until** (20) is satisfied.

KKT conditions are the first derivatives of $\mathcal{L}$ with respect to P^c, λ being equal to zero. We have

$$\frac{\partial \mathcal{L}}{\partial P^c} = -\frac{\partial R^c}{\partial P^c} + \lambda \sum_{i=1}^{N} a_i^c = 0, \quad \forall c \tag{17a}$$

$$\lambda\Big(\sum_{c=1}^{N_c} \sum_{i=1}^{N} a_i^c P^c - P_{\max}\Big) = 0, \tag{17b}$$

where $\partial R^c/\partial P^c$ is given in (18). Since the closed-form analytical solution for (17a) cannot be found, we solve these equations numerically, via the following iterative method. We first initialize λ and then find P^c for $c = 1, \ldots, N_c$ using (17a). Next, we update λ using the subgradient method

$$\lambda^{(n+1)} = \Big[\lambda^{(n)} + t_0\Big(\sum_{c=1}^{N_c} \sum_{i=1}^{N} a_i^c P^c - P_{\max}\Big)\Big]^{+}, \tag{19}$$

where t_0 is the step size and $[x]^+ = \max\{x, 0\}$. Using the updated λ, we find $\{P^c\}, \forall c$ again using (17a). We repeat this procedure until λ converges, i.e., the following pre-determined stopping criterion is met for a given small number δ

$$\lambda^{(n)} \Big| \sum_{c=1}^{N_c} \sum_{i=1}^{N} a_i^c P^c - P_{\max} \Big| \leq \delta. \tag{20}$$

Algorithm 2 summarizes our approach to solve (SP2).

C. Solving Sub-problem (SP3)

Considering (SP3) we note that it is neither a convex nor a concave function with respect to $\{\phi_{t_i}, \phi_{r_i}\}, \forall i$. Since the optimization variables are continuous-valued, we can solve (SP3) using gradient descent-based algorithms. We choose interior-point method to solve (SP3). Note that the solution of interior-point method depends on the initial values for $\{\phi_{t_i}, \phi_{r_i}\}, \forall i$. Hence, we randomly choose N_ϕ sets of initial values for $\{\phi_{t_i}, \phi_{r_i}\}, \forall i$ and run the interior-point algorithm N_ϕ times and find N_ϕ sets of solutions. Among these sets, we let the set that provides the largest network throughput be the solution of (SP3).

IV. Numerical Performance Evaluations

In this section, we corroborate our analysis with Matlab simulations. We assume that the antenna gain $A_i(\phi), \forall i$ are the same. In our simulations, all transmitters and receivers are uniformly distributed in a circle with radius of 30 meters. The numerical results are averages over 100 realizations of randomly generated transmitters and receivers in the circle. The simulation parameters are given in Table I.

TABLE I: Simulation Parameters

Parameter	Value	Parameter	Value
A_{sl}	1	ϕ_{FOV}	60°
A_{ml}	0.05	N_0	-110 dBm/Hz
ϕ_{3dB}	35°	B_c	400 MHz
ϕ_{ml}	45°	δ	0.001

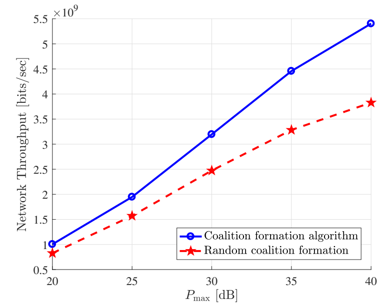

Fig. 2: Network throughput versus $P_{\max}$ for $N = 20, N_c = 4$.

• *Impact of coalition formation optimization on throughput maximization*: Fig. 2 plots the network throughput versus $P_{\max}$ for $N = 20, N_c = 4$, considering two scenarios: the scenario where Algorithm 1 is employed to optimize the coalition formation among the transmitter-receiver pairs, and the scenario where the pairs form coalitions randomly, without any optimization (i.e., the pairs are randomly assigned to a coalition). In both scenarios, the beam steering angles and the transmit powers are optimized. The gap between the two curves in Fig. 2 indicate the impact of coalition formation optimization on the throughput maximization. We note that, as $P_{\max}$ increases, this performance gap increases. For both scenarios as $P_{\max}$ increases, the throughput increases, since the transmitters in all coalitions are allowed to transmit at higher transmit powers.

• *Impact of transmit power optimization on throughput maximization*: Fig. 3a plots the network throughput versus $P_{\max}$ for $N = 20, N_c = 4$, considering two scenarios: the scenario where Algorithm 2 is employed to optimize the transmit powers, and the scenario where $P_{\max}$ is uniformly distributed among N transmitters in the network, without any optimization. In both scenarios, the coalition formation and the beam steering angles are optimized. The gap between the two curves in Fig. 3a illustrates the impact of transmit power optimization on the throughput maximization.

• *Impact of N on throughput maximization*: Fig. 3b shows the network throughput versus $P_{\max}$ for $N = 12, 16, 20, N_c = 4$. Given a $P_{\max}$ value, as N increases, the network throughput increases. We conjecture that this trend would change when N

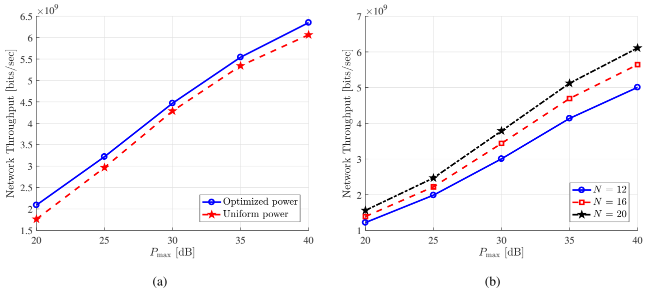

Fig. 3: (a) Network throughput versus $P_{\max}$ for $N = 20, N_c = 4$. (b) Network throughput versus $P_{\max}$ for $N_c = 4$.

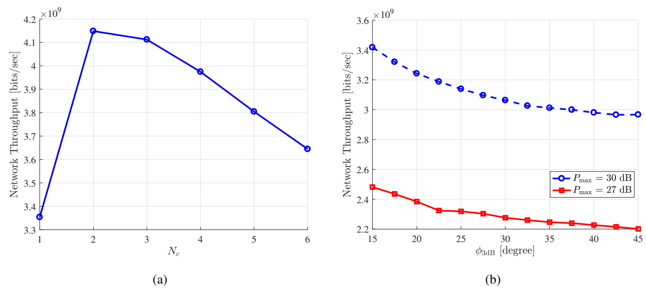

Fig. 4: (a) Network throughput versus N_c for $N = 30, P_{\max} = 30\,\text{dB}$. (b) Network throughput versus $\phi_{3\text{dB}}$ for $N = 20, N_c = 4$.

becomes very large (e.g., $N = 100$). We expect that as N increases further, the network throughput decreases (since the total transmit power and the total bandwidth are fixed). Due to time limitations, we could not increase N beyond 20.

• *Impact of N_c on throughput maximization*: Fig. 4a shows the network throughput versus N_c for $N = 30, P_{\max} = 30\text{dB}$. This figure suggests that there is a trade-off between N_c and the network throughput. On the one hand, as the number of sub-bands N_c increases, the number of coalitions increases and the co-channel interference generated in each coalition decreases, which can lead into increasing the sum-rate in each coalition and thus increasing the network throughout. On the other hand, as N_c increases, the bandwidth W of each sub-band decreases, which can lead into decreasing the network throughput. Therefore, given N one can find the optimal N_c that provides the highest network throughput. For instance, in Fig. 4a, $N_c = 2$ yields the highest network throughput.

• *Impact of half-power beamwidth $\phi_{3\text{dB}}$ on throughput maximization*: Fig. 4b shows the effect of $\phi_{3\text{dB}}$ on the network throughput for $P_{\max} = 27, 30$ dB. We note that as $\phi_{3\text{dB}}$ increases the network throughput decreases. This is because as $\phi_{3\text{dB}}$ increases, the transmitters within a particular coalition impose a stronger co-channel interference on the non-intended receivers within the same coalition.

V. Conclusion

We considered a D2D mmWave network with bandwidth of $B_c = WN_c$ Hz, where N cooperative D2D pairs form N_c disjoint coalitions and communicate over N_c non-overlapping sub-bands, each with bandwidth of W Hz. Each node is equipped with a directional antenna that has beam steering capability. Also, each transmitter can adjust its transmit power. We formulated the network throughput maximization problem, subject to certain constraints, and we proposed a BCD algorithm, to find the optimal coalition among the D2D pairs, the optimal beam steering angles of directional antennas of the D2D pairs within each coalition, and the optimal transmit powers. Through numerical simulations, we investigated the effects of $N, N_c, P_{\max}, \phi_{3\text{dB}}$ on the network throughput maximization. Our simulations show that, given $N, P_{\max}$ there is an optimal N_c value that provides the highest network throughput. Also, we showed that a lower $\phi_{3\text{dB}}$ yields a higher network throughput.

Acknowledgment

This research is supported by NSF under grant CNS-2006683.

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