Sum-Rate Maximization for Energy Harvesting-Aided D2D Communications Underlaid Cellular Networks

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Abstract—This paper investigates the beamforming design for sum-rate maximization in energy harvesting (EH)-aided device-to-device (D2D) communications underlaid cellular networks. In the considered system, each receiving cellular or D2D user performs EH while decoding information from the base station (BS) or the paired transmitting D2D user. The objective is to derive optimal beamforming strategies at the BS and power allocations at transmitting D2D users, such that the network sum rate is maximized under EH and transmit power constraints. The original nonconvex problem is convexified by the semidefinite relaxation technique and a reformulation of the objective function with first-order approximation in each algorithm iteration, and solved by an iterative algorithm, based on the concept of the Frank-Wolfe algorithm. Simulation provides numerical validation of the proposed method from various perspectives.

Index Terms—Sum-rate maximization, cellular networks, device-to-device (D2D) communications, energy harvesting (EH).

I. INTRODUCTION

In recent years, spectrum congestion has been a main concern in cellular networks due to the dramatically growing bandwidth demand. Device-to-device (D2D) communication underlaying cellular networks is a promising technology to offload the network traffic and also improve the spectral efficiency. The main feature is that D2D users are allowed to use the spectrum occupied by cellular users for signal transmission (i.e., underlay). However, the mutual interference between cellular users and D2D links will degrade the system throughput [1], [2]. Many approaches to this problem have been proposed in the literature, e.g., [3], [4].

Typically, the receivers of either cellular users or D2D links are powered by pre-charged batteries. This implies

that the lifetime will be a bottleneck for the power-limited devices. Energy harvesting (EH) has been considered an emerging solution to address the lifetime issue. Several designs for EH-aided transmitters or receivers have been studied in prior works. In [5], the modeling and analysis for the random and prioritized access protocols have been proposed for cognitive and EH-based D2D communications. In [6], a system with user-equipment relaying was considered. In [7], the security issue in D2D communication was studied. It is known that beamforming is an effective method to improve the system performance. In [8], D2D relays are equipped with EH to compensate and forward data for machine-type communications. Combined with radio resource allocation, a power allocation scheme that maximizes the sum-rate was developed in [9]. Note that power allocation can be viewed as a special case of beamforming. In [10], beamforming for D2D communication was studied; however, EH was not considered.

To the best of our knowledge, the beamforming design for specifically EH-aided D2D communications underlaid cellular networks is previously unexamined, and is the objective of this paper. In the considered system, all receivers of the cellular and D2D links are assumed capable of EH. It can be observed that there exists a tradeoff between the sum-rate performance and harvested energy. With the observation, the design goal is to find the beamforming vectors at the BS and power allocations at transmitting D2D users that maximize the network sum rate under EH and transmit power constraints. Unfortunately, the resultant problem is difficult to solve due to nonconvexity. To overcome the difficulty, we propose a novel scheme to efficiently derive the solution. We first reformulate the objective function with first-order approximation and then apply semidefinite relaxation by dropping the rank-one constraint in the problem. Consequently, a convex optimization problem is yielded and can be solved efficiently with existing
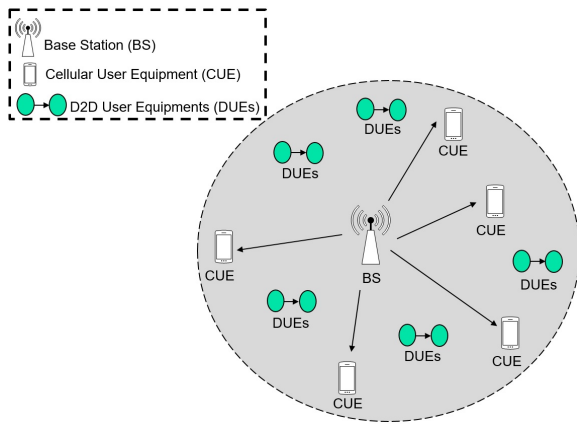
Fig. 1. An EH-aided D2D communications underlaid cellular network.

tools. From simulations, we see that the relaxation is tight since the obtained solution is of rank one with high probability. In addition, the sum-rate performance is indeed significantly improved by our design.

Notations: Matrices and vectors are typefaced using bold uppercase and lowercase letters, respectively. We use $(\cdot)^H$ and $\text{Tr}(\cdot)$ to denote Hermitian transpose and trace, respectively. $\boldsymbol{A} \succeq 0$ indicate that $\boldsymbol{A}$ is a positive semidefinite matrix. $\mathbb{C}^{m \times n}$ is used to describe the complex space of $m \times n$ matrices.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

We consider a D2D communications underlaid downlink cellular network with one base station (BS), K cellular user equipments (CUEs), and L pairs of D2D user equipments (DUEs), as depicted in Fig. 1. The BS is equipped with N antennas and each CUE/DUE is equipped with a single antenna. Let $\mathcal{K} = \{1, \ldots, K\}$ and $\mathcal{L} = \{1, \ldots, L\}$ be the index set of CUEs and DUE pairs, respectively. Each CUE/DUE is capable of harvesting energy as well as receiving information from the BS. Thus, the BS and each CUE/DUE link forms a multiple-input single-output (MISO) simultaneous wireless information and power transfer (SWIPT) system.

Cellular user information rate: Let $\sum_{k=1}^{K} \boldsymbol{w}_k s_k^{\text{C}}$ be the broadcast signal from the BS for all K CUEs, where $s_k^{\text{C}} \in \mathbb{C}$ is a zero-mean, unit-variance signal destined for the kth CUE, and $\boldsymbol{w}_k \in \mathbb{C}^N$ is the associated beamforming vector. The received signal at the kth CUE is given by

$$y_k^{\text{C}} = (\boldsymbol{h}_{k,\text{BS}}^{\text{C}})^H \sum_{k=1}^{K} \boldsymbol{w}_k s_k^{\text{C}} + \sum_{\ell=1}^{L} h_{k,\ell}^{\text{C}} \sqrt{p_\ell^{\text{D}}} s_\ell^{\text{D}} + n_k^{\text{C}},$$
$$k \in \mathcal{K} \quad (1)$$

where $\boldsymbol{h}_{k,\text{BS}}^{\text{C}} \in \mathbb{C}^N$ is the channel vector from the BS to the kth CUE, $h_{k,\ell}^{\text{C}}$ is the channel from the transmitter

of the lth DUE pair to the kth CUE, p_ℓ^{D} and s_ℓ^{D} are the transmit power and transmit signal of the transmitter of the lth DUE pair, respectively, and $n_k^{\text{C}} \sim \mathcal{CN}(0, \sigma_k^2)$ is the complex additive white Gaussian noise (AWGN). The second term in (1) corresponds to the interference from the D2D transmitters.

Each receiving CUE/DUE adopts a power-splitting-based SWIPT scheme, with power-splitting factor for information decoding denoted by ρ_k^{C} for the kth CUE and ρ_ℓ^{D} for the receiver of the lth DUE pair (thus, the power-splitting factor for EH at the corresponding receiver is $1 - \rho_k^{\text{C}}$ and $1 - \rho_l^{\text{D}}$). The received signal at the information decoder of the kth CUE is expressed as

$$\widetilde{y}_k^{\text{C}} = \sqrt{\rho_k^{\text{C}}} y_k^{\text{C}} + \widetilde{n}_k^{\text{C}}, \ k \in \mathcal{K} \quad (2)$$

where $\widetilde{n}_k^{\text{C}} \sim \mathcal{CN}(0, \widetilde{\sigma}_k^2)$ is the complex AWGN introduced in the RF-to-baseband conversion in the decoding process, which is independent of n_k^{C}. The signal-to-interference-plus-noise ratio (SINR) at the kth CUE is given by

$$\text{SINR}_k^{\text{C}}$$
$$= \frac{|(\boldsymbol{h}_{k,\text{BS}}^{\text{C}})^H \boldsymbol{w}_k|^2}{\sum_{i \neq k} |(\boldsymbol{h}_{k,\text{BS}}^{\text{C}})^H \boldsymbol{w}_i|^2 + \sum_{\ell=1}^{L} |h_{k,\ell}^{\text{C}}|^2 p_\ell^{\text{D}} + \sigma_k^2 + \frac{\widetilde{\sigma}_k^2}{\rho_k^{\text{C}}}}$$
$$= \frac{(\boldsymbol{h}_{k,\text{BS}}^{\text{C}})^H \boldsymbol{W}_k \boldsymbol{h}_{k,\text{BS}}^{\text{C}}}{\sum_{i \neq k} (\boldsymbol{h}_{k,\text{BS}}^{\text{C}})^H \boldsymbol{W}_i \boldsymbol{h}_{k,\text{BS}}^{\text{C}} + \sum_{\ell=1}^{L} |h_{k,\ell}^{\text{C}}|^2 p_\ell^{\text{D}} + \sigma_k^2 + \frac{\widetilde{\sigma}_k^2}{\rho_k^{\text{C}}}}$$
$$(3)$$

where $\boldsymbol{W}_k = \boldsymbol{w}_k \boldsymbol{w}_k^H, k = 1, \ldots, K$. The weighted sum information rate for all K CUEs is given by[1]

$$R_{\text{C}} = \sum_{k=1}^{K} \alpha_k \log(1 + \text{SINR}_k^{\text{C}}) \quad (4)$$

where α_k is the weight associated with the kth CUE accounting for the priority of the kth CUE in the system.

D2D user information rate: The received signal at the receiver of the lth DUE pair is given by

$$y_\ell^{\text{D}} = \sum_{j=1}^{L} h_{\ell,j}^{\text{D}} \sqrt{p_j^{\text{D}}} s_j^{\text{D}} + (\boldsymbol{h}_{\ell,\text{BS}}^{\text{D}})^H \sum_{k=1}^{K} \boldsymbol{w}_k s_k^{\text{C}} + n_\ell^{\text{D}},$$
$$\ell \in \mathcal{L} \quad (5)$$

where $h_{\ell,j}^{\text{D}}$ is the channel from the transmitter of the jth DUE pair to the receiver of the ℓth DUE pair, $\boldsymbol{h}_{\ell,\text{BS}}^{\text{D}}$ is the channel from the BS to the receiver of the ℓ DUE pair, and $n_\ell^{\text{D}} \sim \mathcal{CN}(0, \sigma_l^2)$ is the complex AWGN. The received signal at the information decoder of the receiver of the lth DUE pair is

$$\widetilde{y}_\ell^{\text{D}} = \sqrt{\rho_\ell^{\text{D}}} y_\ell^{\text{D}} + \widetilde{n}_\ell^{\text{D}}, \ \ell \in \mathcal{L} \quad (6)$$

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[1]We use natural logarithm for the sake of mathematical convenience. However, the weighted sum information rate is calculated with base-2 logarithm in the simulation results section.

where $\widetilde{n}_\ell^D \sim \mathcal{CN}(0, \widetilde{\sigma}_\ell^2)$ is the complex AWGN introduced in the RF-to-baseband conversion in the decoding process, which is independent of n_ℓ^D. The SINR at the receiver of the lth DUE pair is expressed as

$$
\begin{aligned}
&\mathrm{SINR}_\ell^D \\
&= \frac{|h_{\ell,\ell}^D|^2 p_\ell^D}{\sum\limits_{j\neq\ell}^{L} |h_{\ell,j}^D|^2 p_j^D + \sum\limits_{k=1}^{K} (\boldsymbol{h}_{\ell,\mathrm{BS}}^D)^H \boldsymbol{W}_k \boldsymbol{h}_{\ell,\mathrm{BS}}^D + \sigma_\ell^2 + \frac{\widetilde{\sigma}_\ell^2}{\rho_\ell^D}}.
\end{aligned}
\tag{7}
$$

Hence, the weighted sum information rate for all L receiving DUEs is given by

$$
R_D = \sum_{\ell=1}^{L} \beta_\ell \log(1 + \mathrm{SINR}_\ell^D)
\tag{8}
$$

where β_ℓ is the weight associated with the lth receiving DUE.

Harvested energy for cellular and D2D users: Each receiving CUE/DUE harvests energy from the useful signal as well as interference. The harvested energy at the kth CUE and at the receiver of the lth DUE pair are given respectively by

$$
\begin{aligned}
E_k^C = (1 - \rho_k)\bigg(&\sum_{i=1}^{K} (\boldsymbol{h}_{k,\mathrm{BS}}^C)^H \boldsymbol{W}_i \boldsymbol{h}_{k,\mathrm{BS}}^C \\
&+ \sum_{\ell=1}^{L} |h_{k,\ell}^C|^2 p_\ell^D + \sigma_k^2 \bigg) + \widehat{\sigma}_k^2,
\end{aligned}
\tag{9}
$$

$$
\begin{aligned}
E_\ell^D = (1 - \rho_\ell)\bigg(&\sum_{j=1}^{L} |h_{\ell,j}^D|^2 p_j^D \\
&+ \sum_{k=1}^{K} (\boldsymbol{h}_{\ell,\mathrm{BS}}^D)^H \boldsymbol{W}_k \boldsymbol{h}_{\ell,\mathrm{BS}}^D + \sigma_\ell^2 \bigg) + \widehat{\sigma}_l^2
\end{aligned}
\tag{10}
$$

where $\widehat{\sigma}_k^2$ and $\widehat{\sigma}_l^2$ are the variance of the complex AWGN noise introduced at the energy harvester of the kth CUE and of the receiver of the lth DUE pair, respectively.

B. Problem Formulation

Our design objective is to maximize the network sum information rate with BS transmission power, D2D transmission power, and harvested energy constraints. The power-splitting factors ρ_k^C and ρ_l^D are assumed to be predetermined constants [11]. The design problem is formulated as

$$
\max_{\{\boldsymbol{W}_k\}, \{p_\ell^D\}} \quad R_C + R_D
\tag{11a}
$$

$$
\mathrm{s.t.} \quad E_k^C \geq E_{\min}^C, \forall k \in \mathcal{K},
\tag{11b}
$$

$$
E_\ell^D \geq E_{\min}^D, \forall \ell \in \mathcal{L},
\tag{11c}
$$

$$
\sum_{k=1}^{K} \mathrm{Tr}(\boldsymbol{W}_k) \leq P_{\max}^C,
\tag{11d}
$$

$$
0 \leq p_\ell^D \leq P_{\max}^D, \forall \ell \in \mathcal{L},
\tag{11e}
$$

$$
\boldsymbol{W}_k \succeq 0, \forall k \in \mathcal{K},
\tag{11f}
$$

$$
\mathrm{rank}(\boldsymbol{W}_k) = 1, \forall k \in \mathcal{K}
\tag{11g}
$$

where constraints (11b) and (11c) ensure that the harvested energy at the kth CUE and at the receiver of the lth DUE pair be higher than some constant $E_{\min}^C$ and $E_{\min}^D$, respectively; (11d) and (11e) represent the total BS transmit power constraint and the transmit power constraint for each transmitting DUE, respectively; (11f) and (11g) are established because $\boldsymbol{W}_k = \boldsymbol{w}_k \boldsymbol{w}_k^H$.

Problem (11) is nonconvex due to the fractional form of the objective function and the rank constraint. To deal with the nonconvexity for the considered problem, we reformulate the objective function into the subtractive form with first-order approximation, and apply rank constraint relaxation, resulting in a tractable optimization problem. The proposed solution method is described in the following.

III. PROPOSED ALGORITHM

Without loss of generality, we consider equal weights for all users, i.e., $\alpha_k = \beta_\ell = 1, \forall k \in \mathcal{K}, \forall \ell \in \mathcal{L}$. The objective function (11a) in the current fractional form is first reformulated into the difference of two concave functions. Specifically, we can write $R_C + R_D = h(\boldsymbol{W}, \boldsymbol{p}^D) - g(\boldsymbol{W}, \boldsymbol{p}^D)$, where

$$
\begin{aligned}
&h(\boldsymbol{W}, \boldsymbol{p}^D) \\
&= \sum_{k=1}^{K} \log \bigg(\sum_{i=1}^{K} (\boldsymbol{h}_{k,\mathrm{BS}}^C)^H \boldsymbol{W}_i \boldsymbol{h}_{k,\mathrm{BS}}^C + \sum_{\ell=1}^{L} |h_{k,\ell}^C|^2 p_\ell^D \\
&\quad + \sigma_k^2 + \frac{\widetilde{\sigma}_k^2}{\rho_k^C} \bigg) + \sum_{\ell=1}^{L} \log \bigg(\sum_{j=1}^{L} |h_{\ell,j}^D|^2 p_j^D \\
&\quad + \sum_{k=1}^{K} (\boldsymbol{h}_{\ell,\mathrm{BS}}^D)^H \boldsymbol{W}_k \boldsymbol{h}_{\ell,\mathrm{BS}}^D + \sigma_\ell^2 + \frac{\widetilde{\sigma}_\ell^2}{\rho_\ell^D} \bigg),
\end{aligned}
\tag{12}
$$

$$
\begin{aligned}
&g(\boldsymbol{W}, \boldsymbol{p}^D) \\
&= \sum_{k=1}^{K} \log \bigg(\sum_{i\neq k} (\boldsymbol{h}_{k,\mathrm{BS}}^C)^H \boldsymbol{W}_i \boldsymbol{h}_{k,\mathrm{BS}}^C + \sum_{\ell=1}^{L} |h_{k,\ell}^C|^2 p_\ell^D \\
&\quad + \sigma_k^2 + \frac{\widetilde{\sigma}_k^2}{\rho_k^C} \bigg) + \sum_{\ell=1}^{L} \log \bigg(\sum_{j\neq\ell} |h_{\ell,j}^D|^2 p_j^D \\
&\quad + \sum_{k=1}^{K} (\boldsymbol{h}_{\ell,\mathrm{BS}}^D)^H \boldsymbol{W}_k \boldsymbol{h}_{\ell,\mathrm{BS}}^D + \sigma_\ell^2 + \frac{\widetilde{\sigma}_\ell^2}{\rho_\ell^D} \bigg)
\end{aligned}
\tag{13}
$$

and $\boldsymbol{W}$ and $\boldsymbol{p}^{\mathrm{D}}$ are symbolic notations that denote the set of optimization variables $\{\boldsymbol{W}_k\}$ and $\{p_\ell^{\mathrm{D}}\}$, respectively. Then, problem (11) is reformulated into the following problem by removing the rank constraints (11g) [12]:

$$\max_{\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}}} \ h(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}}) - g(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}}) \tag{14a}$$

$$\text{s.t.} \ (11b), (11c), (11d), (11e), (11f). \tag{14b}$$

Note that problem (14) is still nonconvex, since the sum of a concave function and a convex function, as in the objective function, does not guarantee convexity [13]. To proceed, we apply the first-order Taylor series on $g(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}})$, i.e., [13]

$$g^{(n)}(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}}) = g(\boldsymbol{W}^{(n)}, \boldsymbol{p}^{\mathrm{D}(n)})$$
$$+ \sum_{k=1}^{K} \sum_{i \neq k}^{K} \left[(\Psi_k^{(n)})^{-1} (\boldsymbol{h}_{k,\mathrm{BS}}^{\mathrm{C}})^H (\boldsymbol{W}_i - \boldsymbol{W}_i^{(n)}) \boldsymbol{h}_{k,\mathrm{BS}}^{\mathrm{C}} \right]$$
$$+ \sum_{k=1}^{K} \sum_{\ell=1}^{L} \left[(\Psi_k^{(n)})^{-1} |h_{k,\ell}^{\mathrm{C}}|^2 (p_\ell^{\mathrm{D}} - p_\ell^{\mathrm{D}(n)}) \right]$$
$$+ \sum_{\ell=1}^{L} \sum_{j \neq \ell}^{L} \left[(\Theta_\ell^{(n)})^{-1} |h_{\ell,j}^{\mathrm{D}}|^2 (p_j^{\mathrm{D}} - p_j^{\mathrm{D}(n)}) \right]$$
$$+ \sum_{\ell=1}^{L} \sum_{k=1}^{K} \left[(\Theta_\ell^{(n)})^{-1} (\boldsymbol{h}_{\ell,\mathrm{BS}}^{\mathrm{D}})^H (\boldsymbol{W}_k - \boldsymbol{W}_k^{(n)}) \boldsymbol{h}_{\ell,\mathrm{BS}}^{\mathrm{D}} \right] \tag{15}$$

where $g^{(n)}(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}})$ and $g(\boldsymbol{W}^{(n)}, \boldsymbol{p}^{\mathrm{D}(n)})$ denote the first-order Taylor series expansion of $g(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}})$ and the approximation value of $g(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}})$ at the nth iteration in the algorithm step, respectively; and $\Psi_k^{(n)}$ and $\Theta_l^{(n)}$ are defined as

$$\Psi_k^{(n)} = \sum_{i \neq k} (\boldsymbol{h}_{k,\mathrm{BS}}^{\mathrm{C}})^H \boldsymbol{W}_i^{(n)} \boldsymbol{h}_{k,\mathrm{BS}}^{\mathrm{C}} + \sum_{\ell=1}^{L} |h_{k,\ell}^{\mathrm{C}}|^2 p_\ell^{\mathrm{D}(n)}$$
$$+ \sigma_k^2 + \frac{\widetilde{\sigma}_k^2}{\rho_k^{\mathrm{C}}}, \tag{16}$$

$$\Theta_\ell^{(n)} = \sum_{j \neq \ell}^{L} |h_{\ell,j}^{\mathrm{D}}|^2 p_j^{\mathrm{D}(n)} + \sum_{k=1}^{K} (\boldsymbol{h}_{\ell,\mathrm{BS}}^{\mathrm{D}})^H \boldsymbol{W}_k^{(n)} \boldsymbol{h}_{\ell,\mathrm{BS}}^{\mathrm{D}}$$
$$+ \sigma_\ell^2 + \frac{\widetilde{\sigma}_\ell^2}{\rho_\ell^{\mathrm{D}}}. \tag{17}$$

Next, we approximate problem (14) by substituting $g^{(n)}(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}})$ for $g(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}})$ in the objective function so that the objective function is now the sum of a concave function and a linear function, which results in a convex program at each iteration, i.e.,

$$\max_{\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}}} \ h(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}}) - g^{(n)}(\boldsymbol{W}, \boldsymbol{p}^{\mathrm{D}}) \tag{18a}$$

$$\text{s.t.} \ (11b), (11c), (11d), (11e), (11f). \tag{18b}$$

We propose an iterative algorithm based on the Frank-Wolfe algorithm [14], [15] to solve problem (18). First,

the initial values of $\boldsymbol{W}_k^{(0)}$ for $k = 1, \ldots, K$ and $p_\ell^{\mathrm{D}(0)}$ for $\ell = 0, \ldots, L$ are arbitrarily chosen. Then, in the nth iteration, the optimal solution is obtained by solving problem (18) and denote the optimal solution as $(\boldsymbol{W}^\star, \boldsymbol{p}^{\mathrm{D}\star})$. The accuracy convergence stopping criterion is defined as

$$\text{The stopping criterion} = \frac{|\mathrm{C}_{\mathrm{opt}}^{\star\,(n+1)} - \mathrm{C}_{\mathrm{opt}}^{\star\,(n)}|}{\mathrm{C}_{\mathrm{opt}}^{\star\,(n)}} < 0.01 \tag{19}$$

where $\mathrm{C}_{\mathrm{opt}}^{\star\,(n+1)}$ and $\mathrm{C}_{\mathrm{opt}}^{\star\,(n)}$ denote the optimal value at the the $(n+1)$th and nth iteration, respectively. Finally, we perform Gaussian randomization [12] on the solution $\boldsymbol{W}^\star$ to problem (18) to obtain a rank-one solution to the original problem (11). The proposed algorithm is summarized in Algorithm 1.

Algorithm 1 Algorithm to Solve Problem (11)

1: Initialize $n = 0$.
2: Generate initial values for $\boldsymbol{W}_k^{(n)}$ for $k = 1, \ldots, K$ and $p_\ell^{\mathrm{D}(n)}$ for $\ell = 0, \ldots, L$.
3: Generate initial value for $\mathrm{C}_{\mathrm{opt}}^{\star\,(n)}$.
4: **repeat**
5:    Solve (18) for $(\boldsymbol{W}^\star, \boldsymbol{p}^{\mathrm{D}\star})$ and $\mathrm{C}_{\mathrm{opt}}^\star$.
6:    $n \leftarrow n + 1$.
7:    Update: $\boldsymbol{W}_k^{(n+1)} = \boldsymbol{W}^\star$; $\boldsymbol{p}^{\mathrm{D}(n+1)} = \boldsymbol{p}^{\mathrm{D}\star}$; and $\mathrm{C}_{\mathrm{opt}}^{\star\,(n+1)} = \mathrm{C}_{\mathrm{opt}}^\star$
8: **until** Convergence $:= \frac{|\mathrm{C}_{\mathrm{opt}}^{\star\,(n+1)} - \mathrm{C}_{\mathrm{opt}}^{\star\,(n)}|}{\mathrm{C}_{\mathrm{opt}}^{\star\,(n)}} < 0.01.$
9: Obtain $\boldsymbol{w}_k^*$ by decomposition of $\boldsymbol{W}_k^* = \boldsymbol{w}_k^*(\boldsymbol{w}_k^*)^H$ for all k, if $\boldsymbol{W}_k^*$ are all of rank one; otherwise perform Gaussian randomization [12] to obtain a rank-one approximate solution to problem (11).

IV. SIMULATIONS RESULTS

We simulate a D2D-underlaid cellular network where $K = 5$ CUEs and $L = 5$ pairs of DUEs are uniformly distributed in a 160×160 m^2 area, as depicted in Fig. 2. The distance between paired DUEs is set to 10 m. We consider small-scale Rayleigh fading as well as large-scale path loss model [16] $-90.4 - 43.3 \log_{10}(R)$ dB, where the distance R is measured in kilometer. We set thermal noise variances $\sigma_k^2 = \sigma_l^2 = -83$ dBm, $\forall k, l$ (thermal noise density -143 dBm/Hz and channel bandwidth 1 MHz [3]), variances of the circuit noises introduced at the information decoder $\widetilde{\sigma}_k^2 = \widetilde{\sigma}_l^2 = -80$ dBm and at the energy harvester $\widehat{\sigma}_k^2 = \widehat{\sigma}_l^2 = -80$ dBm, $\forall k, l$, and the power-splitting factor at all devices $\rho_k^{\mathrm{C}} = \rho_l^{\mathrm{D}} = 0.5, \forall k, l$. Unless otherwise stated, we set $N = 7$ antennas at the BS, the maximum transmit power at the BS $P_{\max}^{\mathrm{C}} = 25$ dBm, the maximum transmit power at each transmitting DUE $P_{\max}^{\mathrm{D}} = 10$ dBm, and the target harvested energy $E_{\min}^{\mathrm{C}} = E_{\min}^{\mathrm{D}} = -20$ dBm. All
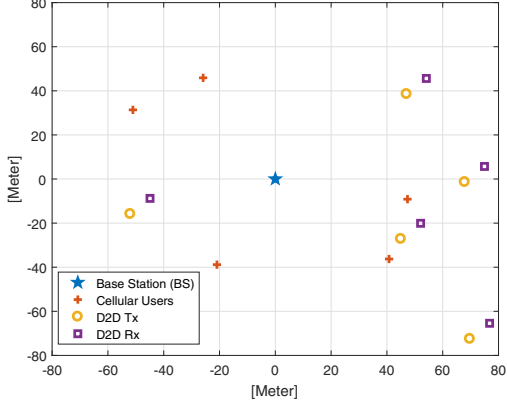
Fig. 2. Network topology with $K = 5$ and $L = 5$.

Fig. 4. Sum rate vs. the maximum transmit power at the BS $P_{\max}^{C}$ performance, with $P_{\max}^{D} = 10$ dBm, $N = 7$, $K = 5$, $L = 5$, and various target harvested energy thresholds.
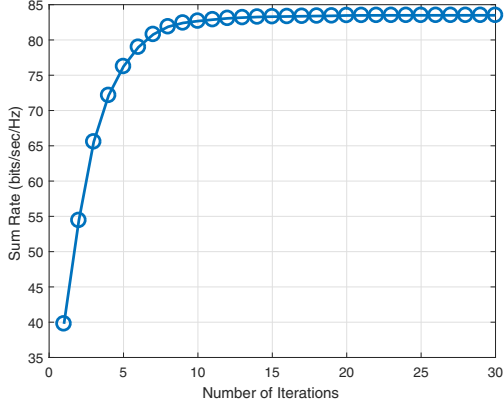

Fig. 3. Convergence behavior of the proposed algorithm, with $P_{\max}^{C} = 25$ dBm, $P_{\max}^{D} = 10$ dBm, $E_{\min}^{C} = E_{\min}^{D} = -20$ dBm, $N = 7$, $K = 5$, and $L = 5$.

the results are obtained by averaging a sufficient number of vector channel realizations.

Fig. 3 illustrates the convergence behavior of Algorithm 1. As can be seen, Algorithm 1 exhibits fast convergence behavior. Convergence to an optimum is guaranteed since problem (11) is bounded above due to the power constraints (11d) and (11e).

Fig. 4 plots the network sum rate vs. the maximum transmit power at the BS $P_{\max}^{C}$ performance. The figure shows a monotonical increase in the sum rate with an increasing transmit power at the BS. Also, it shows the tradeoff between the sum rate and the target harvested energy; specifically, when $E_{\min}^{C} = E_{\min}^{D}$ increases, the sum rate decreases. When $E_{\min}^{C} = E_{\min}^{D}$ is small, i.e., at $E_{\min}^{C} = E_{\min}^{D} = -40$ dBm, the resulting sum rate overlaps with that yielded by "No EH constraint" which corresponds to solving problem (11) with EH constraints (11b) and (11c) removed. When the target harvested energy is higher, the sum rate decreases more
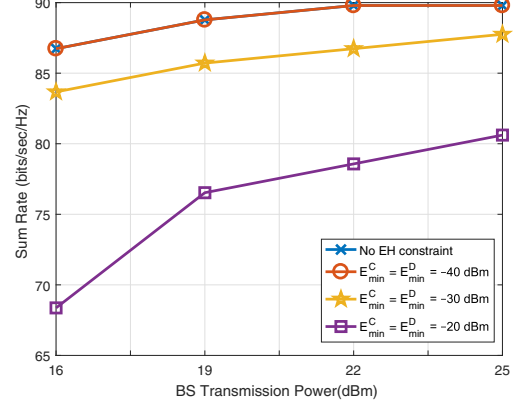
dramatically.

Fig. 5 plots the network sum rate vs. the distance between paired DUEs performance. We fix the locations of CUEs and transmitting DUEs, while varying the locations of receiving DUEs to create different distances between paired DUEs. It is observed, again, the tradeoff between the sum rate and the target harvested energy. Furthermore, the network sum rate decreases as the distance between paired DUEs increases, because the sum rate of DUEs decreases. The sum rate of CUEs does not change significantly.

Fig. 6(b) shows the network sum rate results corresponding to the topology in Fig. 6(a) constructed to illustrate the effect of beamforming. Here, we set $N = 6$, $K = 2$, $L = 2$, $P_{\max}^{C} = 20$ dBm, $P_{\max}^{D} = 10$ dBm, and $E_{\min}^{C} = E_{\min}^{D} = -30$ dBm. As can be seen, the sum rate decreases when the DUE pairs move near the spatial direction at which the BS beamformer is directed (i.e., toward the CUEs), in which case both CUE and DUE sum rates tend to decrease due to interference.

V. CONCLUSION

We have considered the beamforming design and power allocation problem for EH-aided D2D communications underlaid cellular networks in this paper. The objective was to find the beamforming vectors at the BS and power allocations at transmitting D2D users that maximize the network sum rate under EH and transmit power constraints. The optimization problem was formulated as a rank-constrained optimization problem. By applying the semidefinite relaxation technique and convexifying the nonconvex objective function in each iteration of the algorithm based on the concept of the Frank-Wolfe algorithm, we arrived at a tractable problem that was solved by the proposed algorithm. Numerical experiments demonstrated the tradeoff between the network sum rate and the target harvested energy. Moreover,
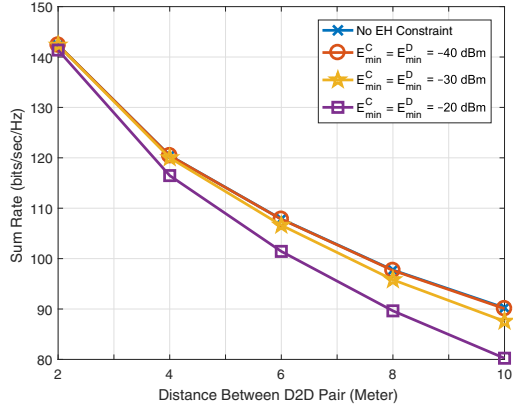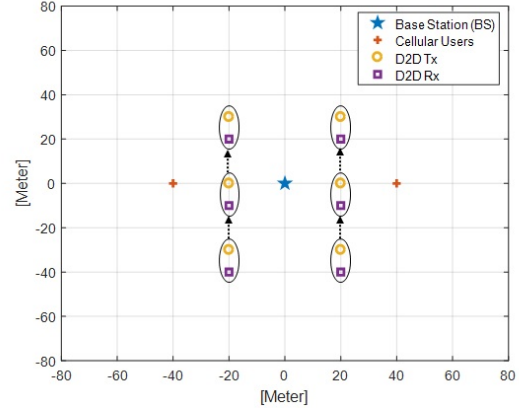
Fig. 5. Sum rate vs. the distance between paired DUEs performance, with $P_{\max}^C = 25$ dBm, $P_{\max}^D = 10$ dBm, $N = 7$, $K = 5$, $L = 5$, and various target harvested energy thresholds.
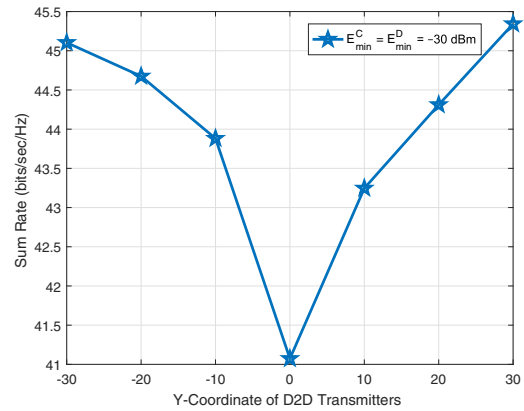
we observed the effect of beamforming and the distance between each D2D pair on the network sum rate.

(a)

(b)

Fig. 6. (a) Network topology with $K = 2$ and $L = 2$. The two pairs of DUEs are moved simultaneously from $(-20, -30)$ and $(20, -30)$ (referring to the coordinates of the transmitting DUEs), respectively, all the way to $(-20, 30)$ and $(20, 30)$, respectively. The transmitter and receiver in each DUE pair is 10 m apart. (b) Sum rate vs. the y-coordinate of the transmitting DUEs.

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