Energy Harvesting Aided Device-to-Device Communication Underlaying the Cellular Downlink

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Abstract—The specific family of Device-to-Device (D2D) communication underlying downlink cellular networks eliminates the reliance on base stations (BS) for its transmission by allowing direct transmission between two devices in each other's close proximity that reuse the cellular resource blocks for enhancing the attainable network capacity and spectrum efficiency. By considering downlink resource reuse and energy harvesting (EH), our goal is to maximize the sum-rate of the D2D links, without degrading the quality of service (QoS) requirement of the cellular users (CUs). We formulated a sum-rate maximization problem of joint resource block and power allocation for the D2D links, which resulted in a non-convex problem that was then transformed into a more tractable convex optimization problem. Based on the results of our Lagrangian constrained optimization, we propose joint resource block and power allocation algorithms for the D2D links, when there is non-causal (off-line) and causal (on-line) knowledge of the EH profiles at the D2D transmitters. The performance of the algorithms is quantified using simulation results for different network parameters settings, where our on-line algorithm performs close to the upper-bound provided by our off-line algorithm.

I. INTRODUCTION

One of the major concerns of cellular networks is the growing demand of tele-traffic that has been enormously increased with the spread of mobile devices and mobile multimedia services. Device-to-Device (D2D) communication proves to be a promising local ad-hoc networking technology by virtue of its advantages, which include improving the area-spectral efficiency, offloading the tele-traffic of cellular base stations (BS), reducing the latency and expanding the BS's coverage, etc. D2D communication underlaying cellular networks allows a pair of closely located devices to communicate directly with each other by reusing the frequency band allocated in the existing cellular networks [1], [2]. However, D2D communication brings about new challenge, since it imposes mutual interference between the cellular users (CUs) and D2D links due to the shared cellular resources.

Therefore, conceiving efficient resource sharing schemes is essential for D2D communication, which have been studied in [3]–[8]. In [3], a maximum weight bipartite matching based scheme is designed for resource allocation for D2D to

maximise the overall network throughput. In [4], the authors provided hybrid centralised-distributed solutions for channel allocation and power control of D2D devices by formulating a graph theoretical approach and multi-agent learning game respectively. A distributed resource allocation for D2D links is proposed whilst guaranteeing the QoS of CUs by controlling interference from D2D pairs and their power in [5] . In [6], the authors proposed an efficient algorithm for jointly optimizing the D2D-CU matching and power control for multiple D2D links by judiciously re-utilising the downlink resources of multiple CUs. The resource allocation scheme of D2D communications based on the objective function (OF) of maximising the spectral efficiency in an LTE-Advanced network was proposed and analysed in [7], while that based on group sparse structure was proposed in [8].

These devices dissipate most of their energy while transmitting and processing the information signal and they are typically powered by pre-charged batteries. Once these batteries are drained, the devices become idle. An emerging solution to this impeding problem is the exploitation of energy harvesting (EH) [9]–[11] at the devices. This helps in prolonging the lifetime of the network, where the devices become capable of accommodating the random arrivals of energy and its storage for using it later [12]. Hence, different network models ranging from simple single-user communication to complex cooperative networks have been investigated with the aid of an energy harvesting capability at the transmitter node. In [13]–[15], beneficial power allocation strategies were designed under the corresponding EH constraints for a single-user EH system. These concepts were then further extended to the design of an efficient broadcast channel in [16], [17], of a two-user multiple access channel in [18], of two-way OFDM communications in [19] and of cooperative networks in [9]–[11], [20]–[22], all in the context of EH.

However the research of EH aided D2D links is in its infancy, despite having a few pioneering studies [23]–[25]. Specifically, Sakr and Hossain [23] proposed beneficial spectrum access policies for RF energy harvesting aided cognitive D2D communication underlaying the uplink and downlink channels. By contrast, Liu *et al.* [24] designed wireless power transfer policies for D2D communication underlaying a cognitive cellular network, where wireless energy is harvested from power beacons and secure transmission takes place using the spectrum of the primary BS. In [25], Yang *et al.* proposed and analysed an EH assisted

heterogeneous network relying on mobile relays harvesting energy from access points for supporting D2D communication.

Against this background, we consider a cellular network simultaneously supporting multiple EH aided D2D links that rely on reusing the downlink cellular resources of multiple CUs. We formulate our resource allocation design as a sum-rate maximization problem for the D2D links. This objective is achieved by jointly optimizing the D2D-CU matching and the power allocation of D2D links, whilst satisfying the QoS constraints of the CUs and the EH constraints of the D2D links. To the best of our knowledge, the optimization and analysis of EH aided D2D communication underlaying downlink cellular networks for radio resource and power allocation at D2D links is a relatively unexplored research area, which is the motivation behind this work.

Our sum-rate maximisation problem subjected to both QoS and EH constraints is shown to be a non-convex mixed integer problem, which is then transformed to a more tractable convex mixed integer problem used for characterising the optimal D2D-CU matching and power allocation. Additionally, we also propose efficient algorithms for the joint optimisation of D2D links for both the idealised non-causal and for the realistic causal knowledge of EH profiles, which are also often termed as off-line and on-line knowledge, respectively. These algorithms are characterised using extensive simulation results. In a nutshell, the major contributions of this work are summarised as follows:

1) **Off-line Joint Optimisation Algorithm:** It is assumed that we have prior knowledge about the energy arrivals at all the D2D links before the commencement of the communication session. In this algorithm, we employed the classic Lagrangian Multiplier method for finding the optimal D2D-CU matching, the power allocation and the transmission duration of the D2D links under the QoS constraints of the CUs and the EH constraints of the D2D links.

2) **On-line Joint Optimisation Algorithm:** In this algorithm, we considered a realistic causal energy arrival process, where there is no prior knowledge about the EH profile. We adopted the classic dynamic programming technique for simplifying the complex problem by partitioning it into smaller sub-problems which then invokes the Lagrangian multiplier method for each stage in order to find the optimal power allocation, transmission time and D2D-CU matching, whilst still satisfying the constraints.

This paper is organized as follows. In Section II, our system model and problem formulation is presented, which is then followed by the efficient design of our joint optimisation algorithms in Section III. Our performance results are discussed in Section IV, whilst our conclusions are offered in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, the system model considered is described first, which is then followed by the formulation of our sum-rate maximisation problem conceived for D2D communication.
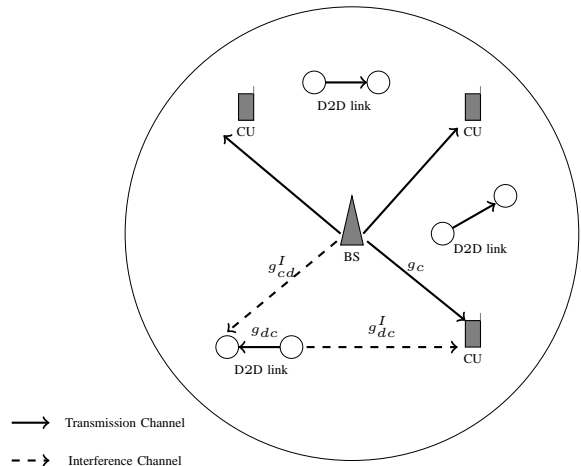
A. System Model

Figure 1. D2D Communication reusing downlink cellular resources with an illustration of interference pattern when one D2D link reuses on CU's RB

In this treatise, we consider resource sharing between two types of communication, namely the traditional cellular communication between the BS and CU as well as the direct D2D communication between two devices, where the D2D transmitters are capable of harvesting energy from the environment. In particular, a hybrid single-cell environment of Fig. 1 is considered, comprising $C = 3$ orthogonal downlink CUs and $D = 3$ energy harvesting D2D links. Each CU occupies a dedicated *resource block (RB[1])* and it is assumed that each RB can only be used by a single D2D link [3], [6], [26]. Let $y_{dc} \in \{0, 1\}$ indicate whether the D2D link d is reusing the RB of CU c. To facilitate our assumption, we stipulate $\sum_{d=1}^{D} y_{dc} = 1 \ \forall \ c$. We also assume that the D2D transmitter (TX) harvests energy from the environment, where the transmit power of the D2D link is subject to the realistic energy causality constraint. Explicitly, energy causality implies that the total energy expended by a device during its transmission session should not exceed the total energy harvested by that specific device until that particular instant in time. We represent the amount of energy harvested as $E_{d,\kappa}$ unit at time instant t_κ for $\kappa = 0, 1, ...K-1$, where we set $t_0 = 0$ and $t_K = T$. The time-interval between the two consecutive energy arrival events is termed as an *epoch*, whose length is defined as $\tau_\kappa = t_\kappa - t_{\kappa-1} \ \forall \kappa \in K$. The transmission channels as well as interference channels are considered to be independent and identically Rayleigh distributed channels. We define g_c and g_{dc} as the transmission channel gains between

[1]Resource block (RB) refers to the smallest unit of system bandwidth resource that is allocated to a CU for its communication session.

the BS and CU c, while the transmission channel gains between the D2D transmitter and the receiver (RX) of the D2D link d on the RB of CU c, respectively. Furthermore, we define g_{cd}^I and g_{dc}^I as the interference channel gains between the BS and the D2D link d on the RB of CU c as well as the interference channel spanning from the D2D link d to the CU c, respectively. These channels are clearly depicted in Fig. 1. Hence, the data rate of the D2D link d at an energy arrival instant κ can be expressed as,

$$r_{d,\kappa} = \sum_{c=1}^{C} y_{dc,\kappa} \log_2 \left(1 + \frac{p_{dc,\kappa} g_{dc}}{N_0 + g_{cd}^I p_c} \right) \qquad \forall \kappa \in K, d \in D \tag{1}$$

where $p_{dc,\kappa} \geq 0$ and $p_c \geq 0$ are the transmit power of the D2D link subject to our energy causality constraint and the transmit power of CU c, respectively on the associated RB, while N_0 is the noise power. Since D2D communication is included as a complement to the underlying cellular communication, the CUs typically have higher priority than the D2D links. Thus, in order to protect the legacy cellular communication, we impose a QoS target for each CU in terms of their minimum required data rate of R_c,

$$\sum_{d=1}^{D} y_{dc,\kappa} \log_2 \left(1 + \frac{p_c g_c}{N_0 + g_{dc}^I p_{dc,\kappa}} \right) \geq R_c \qquad \forall \kappa \in K, c \in C. \tag{2}$$

B. Problem Formulation

Our goal is to maximise the sum-rate of the D2D links by the deadline T, while satisfying the energy harvesting constraints by optimally allocating the transmit power of both the D2D link as well as of the CUs and beneficially matching each D2D link with a CU, subject to the cellular QoS constraint to be met. Explicitly, the problem can be formulated as an optimisation over $\boldsymbol{y_{dc}}$, $\boldsymbol{p_{dc}}$, $\boldsymbol{t_{dc}}$ and $\boldsymbol{p_c}$, yielding[2]:

$$\underset{\{\boldsymbol{y_{dc}}, \boldsymbol{p_{dc}}, \boldsymbol{t_{dc}}, \boldsymbol{p_c}\}}{\text{maximise}} \sum_{k=1}^{K} \sum_{d=1}^{D} r_{d,k} \tag{3a}$$

subject to :

$$\sum_{d=1}^{D} y_{dc,\kappa} \leq 1 \qquad \forall \kappa \in K, c \in C; \tag{3b}$$

$$\sum_{k=1}^{\kappa} \sum_{c=1}^{C} y_{dc,k} p_{dc,k} t_{dc,k} \leq \sum_{k=0}^{\kappa-1} E_{d,k} \qquad \forall \kappa \in K, d \in D \tag{3c}$$

$$\sum_{c=1}^{C} y_{dc,\kappa} t_{dc,\kappa} \leq \tau_\kappa \qquad \forall \kappa \in K, d \in D \tag{3d}$$

$$\sum_{d=1}^{D} y_{dc,\kappa} \log_2 \left(1 + \frac{p_c g_c}{N_0 + g_{dc}^I p_{dc,\kappa}} \right) \geq R_c \qquad \forall \kappa \in K, c \in C \tag{3e}$$

[2]Bold letters represent vectors

$$y_{dc,\kappa} \in \{0,1\}; p_{dc,\kappa} \geq 0; \tag{3f}$$
$$0 \leq t_{dc,\kappa} \leq \tau_\kappa; p_c \geq 0 \qquad \forall \kappa \in K, c \in C, d \in D,$$

where the OF in Eq. (3a) is a non-convex function. Furthermore, Eq. (3b) is the D2D-CU matching constraint, which states that only a single D2D link can reuse each RB of a CU, while Eq. (3c) defines our energy causality constraint imposed on the amount of transmit energy of each D2D link. We also have a constraint imposed on the transmission duration of each D2D link in Eq. (3d), which states that the D2D transmission takes place within each EH epoch and the QoS constraint of the CUs is given in Eq. (3e). Finally we have feasibility constraint given in Eq. (3f).

The problem defined in Eq. (3) is a mixed integer non-linear programming problem since the matching variable $y_{dc,\kappa}$ is binary, while the other variables are continuous which is combined with a non-convex OF and QoS constraint. Hence this is a complex problem that is difficult to solve in its original form. Similar to [6], we thus transform the original problem of Eq. (3) to an equivalent, but more tractable form as demonstrated below:

$$\underset{\{\boldsymbol{y_{dc}}, \boldsymbol{p_{dc}}, \boldsymbol{t_{dc}}\}}{\text{maximise}} \sum_{\kappa=1}^{K} \sum_{d=1}^{D} \tilde{r}_{d,\kappa} \tag{4a}$$

subject to :

$$\sum_{d=1}^{D} y_{dc,\kappa} \leq 1 \qquad \forall \kappa \in K, c \in C; \tag{4b}$$

$$\sum_{k=1}^{\kappa} \sum_{c=1}^{C} y_{dc,k} p_{dc,k} t_{dc,k} \leq \sum_{k=0}^{\kappa-1} E_{d,k} \qquad \forall \kappa \in K, d \in D \tag{4c}$$

$$\sum_{c=1}^{C} y_{dc,\kappa} t_{dc,\kappa} \leq \tau_\kappa \qquad \forall \kappa \in K, d \in D \tag{4d}$$

$$y_{dc,\kappa} \in \{0,1\}; p_{dc,\kappa} \geq 0; \tag{4e}$$
$$0 \leq t_{dc,\kappa} \leq \tau_\kappa \qquad \forall \kappa \in K, c \in C, d \in D,$$

where $\tilde{r}_{d,\kappa}$ is obtained using the following manipulations. Assuming that the D2D link d reuses the RB of the CU c, i.e. $y_{dc,\kappa} = 1$, from Eq. (3e) we arrive at:

$$p_c \geq \frac{\alpha_c (N_0 + g_{dc}^I p_{dc,\kappa})}{g_c}, \tag{5}$$

where $\alpha_c = 2^{R_c} - 1$.

Since the OF of Eq. (3a) is monotonically decreasing in p_c for a fixed $p_{dc,\kappa}$, in order to maximise the sum-rate of the D2D links, the optimal p_c must be achieved, when satisfying the equality of Eq. (5), i.e. for

$$p_c^* = \frac{\alpha_c (N_0 + g_{dc}^I p_{dc,k})}{g_c}. \tag{6}$$

This modification helps us in eliminating the explicit QoS constraint by integrating it into the transformed objective function that is obtained by substituting p_c^* in the objective

function of Eq. (3a) as:

$$\tilde{r}_{d,\kappa} = \sum_{c=1}^{C} y_{dc,\kappa} \log_2 \left(1 + \frac{h_{dc} p_{dc,\kappa}}{e_{dc} N_0 + f_{dc} p_{dc,\kappa}} \right), \quad (7)$$

where we have:

$$h_{dc} = g_{dc} g_c,$$
$$e_{dc} = g_c + \alpha_c g_{cd}^I,$$
$$f_{dc} = \alpha_c g_{dc}^I g_{cd}^I.$$

Note that in the equivalent problem of Eq. (4), the variables to be optimised have been reduced to $\{y_{dc}, p_{dc}, t_{dc}\}$. Now, investigating the second order derivative of the equivalent rate available for the D2D link in Eq. (7), we find that $\tilde{r}_{d,\kappa}(p_{dc,\kappa})$ is concave in $p_{dc,\kappa}$. Furthermore, the OF is the sum of the increasing and concave function of $\tilde{r}_{d,\kappa}$, hence Eq. (4a) is concave in $p_{dc,\kappa}$ following the composition rule of [27]. Since $\tilde{r}_{d,\kappa}$ is also a function of another variable $y_{dc,\kappa}$, we temporarily relax $y_{dc,\kappa}$ to be within the interval $[0, 1]$ and replace $p_{dc,\kappa}$ with a new variable $x_{dc,\kappa} = y_{dc,\kappa} p_{dc,\kappa}$. Hence, we now observe that the constraints in Eq. (4) are convex in $\{y_{dc,\kappa}, x_{dc,\kappa}\}$ and $\tilde{r}_{d,\kappa}(x_{dc,\kappa})$ is concave, since $\tilde{r}_{d,\kappa}(y_{dc,\kappa}, x_{dc,\kappa})$ is the perspective function of $\tilde{r}_{d,\kappa}(x_{dc,\kappa})$ [27]. Therefore, $\tilde{r}_{d,\kappa}$ is jointly concave in $y_{dc,\kappa}$ and $p_{dc,\kappa}$, which implies that Eq. (4) preserves the convexity of our problem. Based on the above arguments, we can analytically characterize the optimal power allocation p_{dc}, the transmission duration t_{dc} and the D2D-CU matching y_{dc} using the classic Lagrangian method of multipliers. We define the Lagrangian as:

$$\mathcal{L} = -\sum_{\kappa=1}^{K} \sum_{d=1}^{D} \sum_{c=1}^{C} y_{dc,\kappa} \log_2 \left(1 + \frac{h_{dc} p_{dc,\kappa}}{e_{dc} N_0 + f_{dc} p_{dc,\kappa}} \right)$$
$$+ \sum_{\kappa=1}^{K} \sum_{c=1}^{C} \lambda_{1,dc,\kappa} \left(\sum_{d=1}^{D} y_{dc,\kappa} - 1 \right)$$
$$+ \sum_{\kappa=1}^{K} \sum_{d=1}^{D} \lambda_{2,d,\kappa} \left(\sum_{k=1}^{\kappa} \sum_{c=1}^{C} y_{dc,k} p_{dc,k} t_{dc,k} - \sum_{k=0}^{\kappa-1} E_{d,k} \right)$$
$$+ \sum_{\kappa=1}^{K} \sum_{d=1}^{D} \lambda_{3,d,\kappa} \left(\sum_{c=1}^{C} y_{dc,\kappa} t_{dc,\kappa} - \tau_\kappa \right), \quad (9)$$

where $\lambda_{1,dc,\kappa}$, $\lambda_{2,d,\kappa}$ and $\lambda_{3,d,\kappa}$ are the Lagrangian multipliers associated with the constraints of Eq. (4b), Eq. (4c) and Eq. (4d), respectively. Now assuming that the D2D link d reuses the RB of CU c, the optimal power allocation $p_{dc,\kappa}^*$ and transmission time $t_{dc,\kappa}^*$ derived for the D2D link is given by:

$$p_{dc,\kappa}^* = \left[\frac{\lambda_{3,d,\kappa}}{\lambda_{2,d,\kappa}} \right]^+ \quad (10a)$$

$$t_{dc,\kappa}^* = \frac{h_{dc} e_{dc} N_0}{\lambda_{2,d,\kappa} \ln 2 (e_{dc} N_0 + (f_{dc} + h_{dc}) p_{dc,\kappa})(e_{dc} N_0 + f_{dc} p_{dc,\kappa})}, \quad (10b)$$

where $[a]^+$ denotes $\max\{0, a\}$. The optimal D2D-CU matching $y_{dc,\kappa}^*$ derived for a given power and transmission time allocation is:

$$y_{dc,\kappa}^* = 1, d = \underset{1 \leq \hat{d} \leq D}{\operatorname{argmax}} \lambda_{1,\hat{d}c,\kappa}; \quad y_{dc,\kappa}^* = 0, \forall \hat{d} \neq d, \quad (11)$$

where we have:

$$\lambda_{1,\hat{d}c,\kappa} = \log_2 \left(1 + \frac{h_{\hat{d}c} p_{\hat{d}c,\kappa}}{e_{\hat{d}c} N_0 + f_{\hat{d}c} p_{\hat{d}c,\kappa}} \right). \quad (12)$$

All the above-mentioned results have been obtained by investigating the KKT conditions of the optimisation problem defined in Eq. (4). *Specifically, investigating the KKT condition for Eq. (4b), we find that for the existence of optimal matching $\lambda_{1,dc,\kappa}$ has to be greater than zero, which means that the constraint is met with equality. Since according to this constraint a single RB can be reused by at most one D2D link, the CU-D2D matching yields integer indications.* Therefore we can observe from Eq. (11) that the RB of CU c can be reused by the D2D link d that has the highest $\lambda_{1,dc,\kappa}$ value and according to Eq. (12), $\lambda_{1,dc,\kappa}$ depends on the different channel gains, which are independent and identically distributed random variables. As a consequence, practically the probability of $\lambda_{1,dc,\kappa} = \lambda_{1,\tilde{d}c,\kappa}$ where $\tilde{d} \neq d$ is zero. Hence, the temporary relaxation of $y_{dc,\kappa}$ to be within $[0, 1]$ still results in an integer solution.

Now, since the expressions derived for $p_{dc,\kappa}^*$ and $t_{dc,\kappa}^*$ depend on the Lagrangian multipliers given in Eq. (10a) and Eq. (10b), we obtained the bounds of these multipliers, which will be used for the sake of faster convergence. Using the KKT conditions and letting $\lambda_{3,d,\kappa} = 0$ or $\lambda_{2,d,\kappa} = 0$ respectively, we obtain $\lambda_{2,d,\kappa}^{min}$ and $\lambda_{3,d,\kappa}^{max}$ as:

$$\lambda_{2,d,\kappa}^{min} = \min_{1 \leq c \leq C} \left(\frac{h_{dc}}{\tau_\kappa e_{dc} N_0 \ln 2} \right)$$

$$\lambda_{3,d,\kappa}^{max} = \max_{1 \leq c \leq C} \left(\frac{h_{dc} e_{dc} N_0}{\sum_{k=0}^{\kappa-1} E_{d,k} f_{dc} (f_{dc} + h_{dc}) \ln 2} \right).$$

III. JOINT OPTIMISATION ALGORITHMS

Exploiting the results derived in Section II and different EH processes, we propose a pair of different joint optimisation algorithms for optimising the power and transmission time of the D2D links as well as the D2D-CU matching, as described below.

1) **Off-line Joint Optimisation Algorithm:** An iterative algorithm has been proposed for jointly optimising the power allocation, transmission time and D2D-CU matching according to the results of Section II under the idealised simplifying assumption of non-causal knowledge of the EH process at the D2D links. This is formally defined in Algorithm 1, which assigns the available RBs to D2D links using Eq. (11) by searching for the optimal values of λ_2, λ_3 that minimise the dual problem of Eq. (4). This algorithm is comprised of two nested loops, which are responsible for updating

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the Lagrangian multipliers λ_2 and λ_3 according to the energy causality and transmission time constraints of Eq. (4c) and Eq. (4d) respectively using the Bisection search method, while the power and transmission time allocation for D2D links is obtained from Eq. (10a) and Eq. (10b) respectively.

Algorithm 1 Joint Optimisation for off-line EH D2D links

Input: R_c, g_c $\forall c$; g_{dc}, g_{dc}^I, g_{cd}^I $\forall c, d$; $E_{d,\kappa}$ $\forall d, \kappa$, t_κ $\forall \kappa$, T_{max}, K, N_0.

Output: $p_{dc,\kappa}^*$, $t_{dc,\kappa}^*$, $y_{dc,\kappa}^*$, p_c^* $\forall c, d, \kappa$.

Initialize: Set accuracy ϵ, $l_1^a = \lambda_{2,d,\kappa}^{min}$, $l_1^b = 100$; $n = 1$, $\lambda_{2,d,\kappa}(n) = \frac{(l_1^a + l_1^b)}{2}$, $\kappa = 1$.

while ($\kappa \leq K$) **do**

    while $|l_1^a - l_1^b| > \epsilon$ **do**

        Find $\lambda_{3,d,\kappa}^*$, $p_{dc,\kappa}^*$, $t_{dc,\kappa}^*$, $y_{dc,\kappa}^*$ $\forall d, c$ for a given $\lambda_{2,d,\kappa}(n)$ using Sub-Algorithm below.

        if ($\sum_{k=1}^{\kappa} \sum_{c=1}^{C} y_{dc,k} p_{dc,k} t_{dc,k} \leq \sum_{k=0}^{\kappa-1} E_{d,k}$) **then**

            $l_1^b = \lambda_{2,d,\kappa}(n)$;

        else

            $l_1^a = \lambda_{2,d,\kappa}(n)$;

        end if

        Update $n = n + 1$, $\lambda_{2,d,\kappa}(n) = \frac{(l_1^a + l_1^b)}{2}$.

    end while

    Sub Algorithm:

    Initialize: $m = 1$, $l_2^a = 0$, $l_2^b = \lambda_{3,d,\kappa}^{max}$, $\lambda_{3,d,\kappa}(m) = \frac{(l_2^a + l_2^b)}{2}$, $\tau_\kappa = t_\kappa - t_{\kappa-1}$ $\forall \kappa$.

    while $|l_2^a - l_2^b| > \epsilon$ **do**

        Calculate $p_{dc,\kappa}^*$, $t_{dc,\kappa}^*$ $\forall d, c$ with the given $\lambda_{2,d,\kappa}(n)$, $\lambda_{3,d,\kappa}(m)$ via Eq. (10a) and Eq. (10b).

        Compute $\lambda_{1,dc,\kappa}$ for any d, c via Eq. (12).

        Match D2D link d with CU c according to Eq. (11)

        if ($\sum_{c=1}^{C} y_{dc,\kappa} t_{dc,\kappa} < \tau_\kappa$) **then**

            $l_2^b = \lambda_{3,d,\kappa}(m)$;

        else

            $l_2^a = \lambda_{3,d,\kappa}(m)$;

        end if

        Update $m = m + 1$, $\lambda_{3,d,\kappa}(m) = \frac{(l_2^a + l_2^b)}{2}$.

    end while

    Finally obtain p_c^* $\forall y_{dc,\kappa} = 1$ using Eq. (6).

    $\kappa = \kappa + 1$.

end while

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2) **On-line Joint Optimisation Algorithm:** In practice, only realistic causal knowledge of the harvested energy is available and thus the off-line algorithm is not realistic, since the future harvested energy is unknown. However, the off-line EH process provides an upper-bound for the realistic scenario of causal knowledge of the EH profile. In order to implement the on-line process, we invoked the classic dynamic programming approach in conjunction with the results of Section II. Dynamic programming is the method of solving complex problems by partitioning it into simpler problems and then recursively solving these sub-problems in multiple stages. Hence, in order to

invoke dynamic programming, we have to find the sub-problems, and then their recursive relationship and finally identify the base case[3]. In our optimisation problem, different stages or sub-problems are defined as individual optimisation sub-problems of the different EH epochs, where the recursive relationship among the stages of the system are represented by the amount of unused energy available for the D2D link or the amount of energy left after transmission across the D2D link. Since the energy arrival time instances typically obey a Poisson process, at stage one, we predict the next energy arrival instant to be the one, for which the probability of occurrence is maximum. Hence the serves as the base case for our problem. This is set in order to meet the constraint of Eq. (4d) imposed on the optimisation problem of Eq. (4). At each stage, a simpler optimisation problem is solved using Algorithm 1, while the amount of unused energy is input to the next stage of the optimisation. This recursive algorithm conceived for our on-line EH process is formally described in Algorithm 2.

Algorithm 2 Joint Optimisation for on-line EH D2D links

Input: R_c, g_c $\forall c$; g_{dc}, g_{dc}^I, g_{cd}^I $\forall c, d$; K, T_{max}, N_0.

Output: $p_{dc,k}^*$, $t_{dc,k}^*$, $y_{dc,k}^*$, p_c^* $\forall c, d, k$.

Initialize: Set stage $\kappa = 1$, state $S_{d,0} = 0$ $\forall d$, initial time instant $t_0 = 0$, final time instant $t_K = T_{max}$, termination condition for recursion using $flag = 1$.

repeat

    Compute the most probable energy arrival instant, $\tilde{t}_\kappa$ following poisson distribution.

    Generate the energy harvested amount $\tilde{E}_{d,\kappa-1}$ $\forall d$ following uniform distribution

    Compute the energy harvested as $E_{d,\kappa-1} = \tilde{E}_{d,\kappa-1} + S_{d,\kappa-1}$ $\forall d$.

    Find $p_{dc,\kappa}^*$, $t_{dc,\kappa}^*$, $y_{dc,\kappa}^*$ p_c^* $\forall d, c$ using Algorithm 1 with $\tau_\kappa = \tilde{t}_\kappa - t_{\kappa-1}$, $E_{d,\kappa-1}$ & $K = \kappa$.

    if ($\sum_{c=1}^{C} y_{dc,\kappa} p_{dc,\kappa} t_{dc,\kappa} < E_{d,\kappa-1}$) **then**

        $S_{d,\kappa} = E_{d,\kappa-1} - \sum_{c=1}^{C} y_{dc,\kappa} p_{dc,\kappa} t_{dc,\kappa}$;

    end if

    if ($\sum_\kappa \tau_\kappa < T_{max}$) **then**

        Generate the next actual energy arrival instant t_κ following poisson distribution.

        $\kappa = \kappa + 1$

    else

        $flag = 0$.

    end if

until ($flag = 1$)

IV. SIMULATION RESULTS

In this section, we analyse the performance of our proposed algorithms in terms of the achievable sum-rate of the D2D links by the deadline of $T = 10$ seconds, where the D2D

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[3]base case is the trivial sub-problem, which occurs for stage 1 in our optimisation problem.
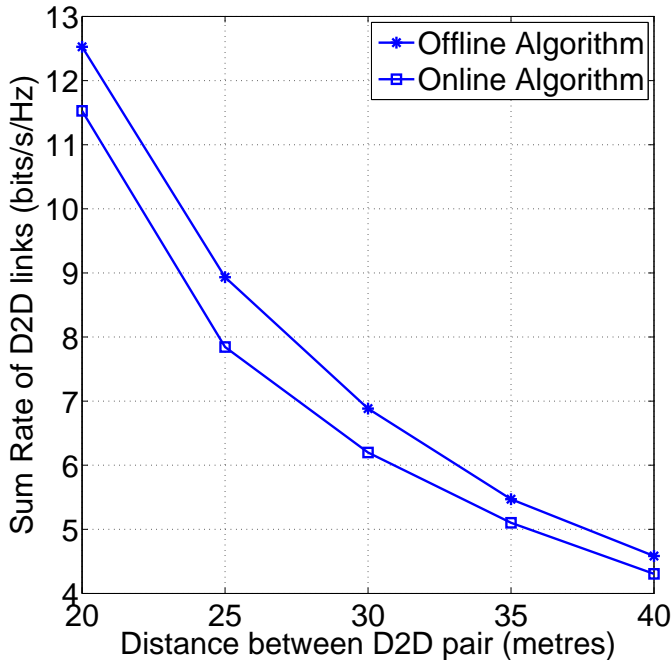
Figure 2. Sum-rate of the D2D links versus the distance between D2D pair with 10 D2D links, 10 CUs and CU QoS threshold set to 12 bits/s/Hz.

links harvest energy from the environment. The EH process of the D2D links is considered to be independent of each other with uniform distribution of the amount of energy between $[0, 100]$ mJoule arriving at Poisson distributed arrival instants t_k at a rate of $\lambda = 3$ mJoule/s. The CUs and D2D links are distributed uniformly in a cell having a radius of 1000 m and the channel spanning from the BS and D2D TXs to the CUs or D2D RXs are considered to be i.i.d. Rayleigh fading channels following a negative-exponential path-loss model. The path-loss exponent of the channels between the D2D TXs and D2D RXs or the CUs is set to $\alpha = 3$ while that between the BS and CUs or the D2D RXs is set to $\alpha = 3.5$ owing to the different propagation environments in the two scenarios. Finally, we set the thermal noise level to $N_0 = -110$ dBm/Hz. Our results quantify the sum-rate of the D2D links as a function of the QoS threshold for the CUs, of the number of CUs and of the D2D links as well as of the distance between the D2D pair for both the off-line and on-line EH processes at the D2D links.

The distance between the D2D devices is not fixed for the first set of results given in Fig. 2. Therefore, our goal is to find the optimal distance of the D2D pair that can maximise the D2D sum-rate. As expected, we can observe from the results that as the distance of the D2D pair increases, the achievable sum-rate of the D2D links is reduced. The reason behind this trend is that upon increasing the distance, the D2D transmission experiences an increased path-loss and hence requires a higher transmission power for improving the sum-rate. We can see from the figure that as the distance increases from 20 m to 25 m, there is an approximately 68% D2D sum-rate reduction for both the algorithms, hence assuming a D2D pair distance of 20 m is a reasonable choice for our

further analysis. Moreover, from Fig. 2, we can also observe that on average our on-line algorithm achieves 91% of the sum-rate attained by our off-line algorithm. This is due to the fact that our off-line algorithm provides an upper-bound for the system, since it relies on the unrealistic assumption of non-causal knowledge of the EH process of the D2D links.
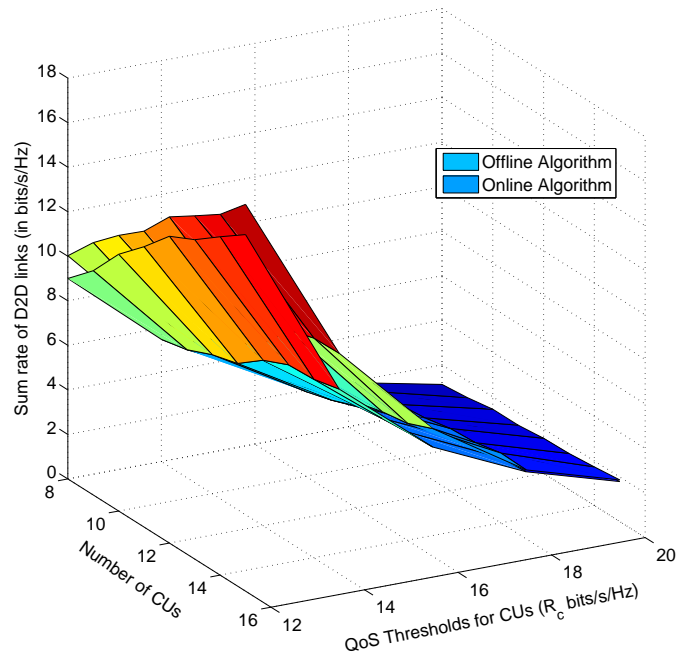

Figure 3. Sum-rate of the D2D links for varying number of CUs and QoS thresholds of CUs with 10 D2D links at 20 m distance apart.

In Fig. 3, we represent the sum-rate of the D2D links as a function of both the number of CUs and of the QoS requirement of the CUs with a fixed number of D2D links. It can be clearly observed that as the number of CUs increases, there is an increase in the sum-rate of D2D links owing to the availability of a larger number of resources (RBs) for the same number of D2D links owing to supporting a higher transmission rate for certain D2D links. However, upon increasing the QoS requirement of the CUs, we observe a diminishing trend, because increasing the QoS implies that the interference experienced by the CUs should be lower, which in turn results in a lower transmit power for the D2D TXs and hence a lower sum-rate for the D2D links. Moreover, our realistic on-line algorithm relying on causal knowledge of the EH profile performs closely to the upper-bound provided by the off-line algorithm that relies on the idealistic assumption of having non-causal knowledge of the EH profiles of D2D links. For the sake of closely analysing the impact of the number of CUs and of the QoS thresholds on the sum-rate of the D2D links, we present the 2-dimensional curves corresponding to the individual analysis of the number of CUs, while keeping the QoS requirement constant and vice versa.

The results of Fig. 4 characterize the sum-rate of D2D links as a function of the QoS requirement of the CUs for two different numbers of CUs. As the QoS threshold increases, the
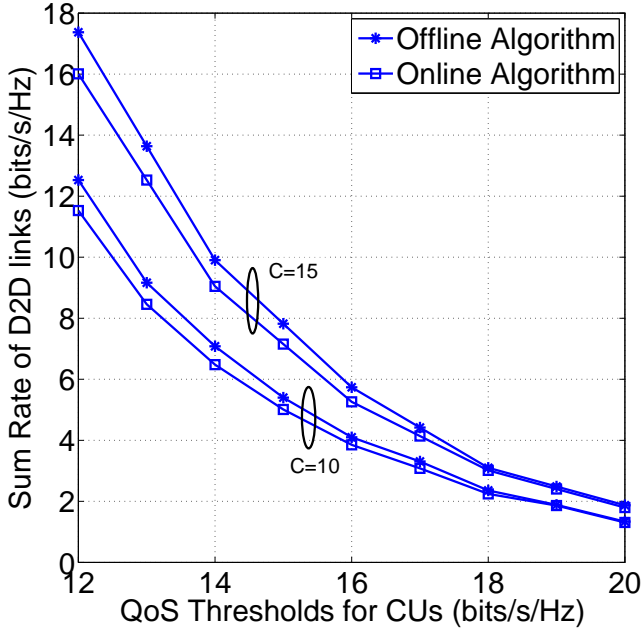
Figure 4. Sum-rate of the D2D links for different QoS thresholds of CUs for two set of values of number of CUs (10 and 15) with 10 D2D links at 20 m distance apart.
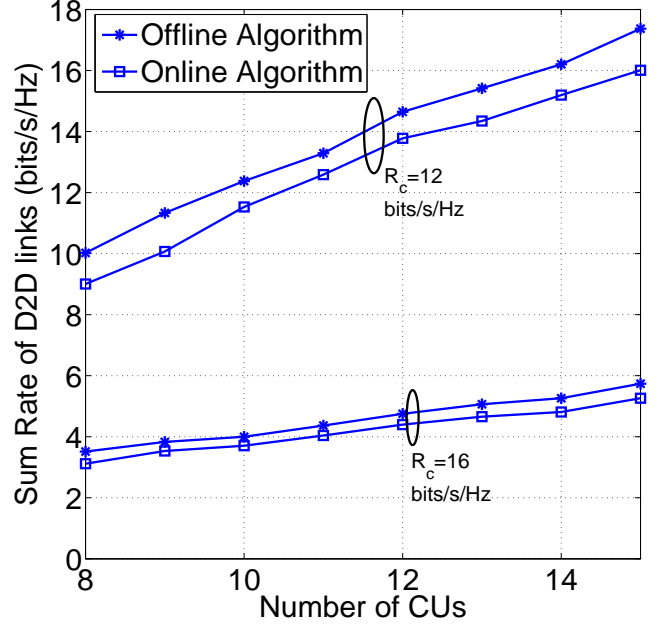

Figure 5. Sum-rate of the D2D links versus the number of CUs with 10 D2D links at 20 m distance apart and two different values of QoS threshold of 12 and 16 bits/s/Hz.

performance of both algorithms deteriorates. This implies that as the QoS requirement increases, the interference introduced by the D2D links should be low for meeting the QoS constraint of the CU, which in turn means that the transmission power and hence the rate of the D2D link will be lower. Moreover, we can see that similar trends can be observed, if we have a higher number of CUs, except that there is an overall increase in the achieved sum-rate owing to availability of a larger number of RBs to be reused by the D2D links. We can also observe from Fig. 4 that our on-line algorithm achieves approximately 94% of the off-line algorithm's sum-rate on an average. The reason behind this phenomenon is the realistic assumption of only having causal knowledge of the EH process of the D2D links in the former algorithm.

In Fig. 5, we present the D2D sum-rate as the function of number of CUs for a fixed set of QoS requirement, $R_c \in \{12, 16\}$ bits/s/Hz. Upon increasing the number of CUs, the D2D links have more cellular resources available for them and this leads to an increase in the D2D sum-rate. As in the above-mentioned results, our on-line algorithm conforms with the previous results, achieving a sum-rate of 92% of the upper-bound given by our off-line algorithm. Moreover, for a QoS threshold of 16 bits/s/Hz, similar trends are observed but the sum-rate attained is consistently lower than that, when the QoS of 12 bits/s/Hz is considered due to the reduction in the transmission power of the D2D TXs for ensuring a higher QoS requirement at the CUs.

Finally, the sum-rate of the D2D links is depicted in Fig. 6 as a function of the number of D2D links, when there are only 10 CUs in the network requiring a QoS threshold of 12
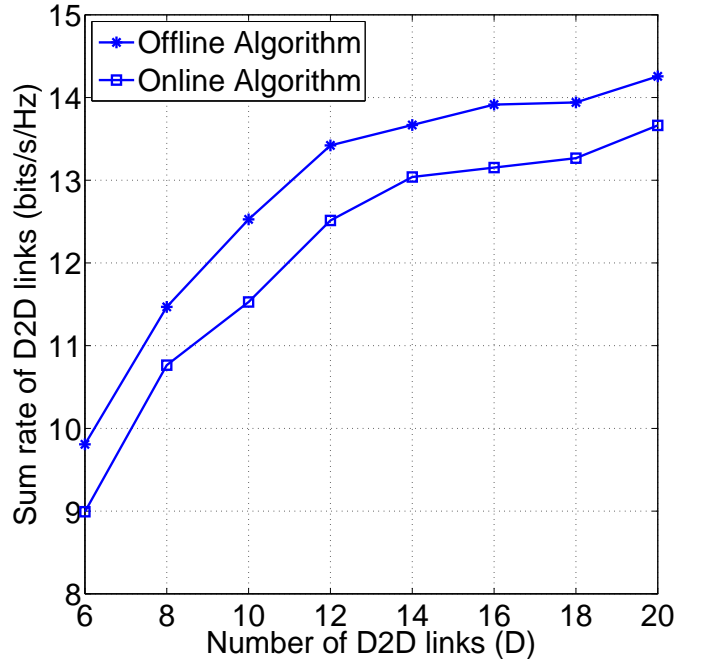
Figure 6. Sum-rate of the D2D links for varying number of D2D links with 20 m link length, 10 CUs and QoS threshold of 12 bits/s/Hz and .

bits/s/Hz . As expected, there is an increase in the sum-rate of the D2D links upon increasing in their number. It is interesting to note that the rate at which the sum-rate of the D2D links is increasing is reduced owing to the fact that upon increasing the number of the D2D links, it becomes harder to satisfy the QoS constraint for the CUs. Hence, the performance of the D2D links tends to saturate. Again, our on-line algorithm achieves 94% of the sum-rate of the upper-bound given by the off-line algorithm.

V. CONCLUSION

In this treatise, we studied a downlink resource reuse system in the presence of multiple CUs and multiple underlay D2D links that are capable of harvesting energy from the surroundings. We formulated a sum-rate maximisation problem for D2D communication, whilst protecting the cellular transmission. We first transformed our non-convex mixed integer programming problem to a more tractable convex optimisation form by obtaining the optimal CU power, whilst meeting the QoS constraints. Upon incorporating relaxed D2D-CU matching variables into the problem, we analytically characterised the optimal resource reuse, power allocation as well as the transmission duration for the D2D links using the classic Lagrangian method of multipliers for our off-line EH process. On the other hand, for on-line EH at the D2D links, we invoked a Dynamic Programming algorithm, where each stage incorporates a smaller problem solved by using the Lagrangian method. Based on the analytical results, we proposed two algorithms for the joint optimisation of the D2D-CU matching, of the power allocation and of the transmission duration for both causal and non-causal EH processes at the D2D links. Finally the proposed methods were verified using simulation results, which reveals that our proposed on-line algorithm is capable of achieving 92% of the performance achieved by the off-line algorithm, which also provides an upper-bound for our problem.

REFERENCES

[1] P. Janis, C. Yu, K. Doppler, C. Ribeiro, C. Wijting, K. Hugl, O. Tirkkonen, and V. Koivunen, "Device-to-Device Communication Underlaying Cellular Communications Systems," in *International Journal on Communications, Network and System Sciences*, vol. 2, June 2009, pp. 169–178.

[2] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Communications Magazine*, vol. 47, no. 12, pp. 42–49, Dec 2009.

[3] D. Feng, L. Lu, Y. Yuan-Wu, G. Li, G. Feng, and S. Li, "Device-to-Device Communications Underlaying Cellular Networks," *IEEE Transactions on Communications*, vol. 61, no. 8, pp. 3541–3551, August 2013.

[4] S. Maghsudi and S. Stańczak, "Hybrid Centralized-Distributed Resource Allocation for Device-to-Device Communication Underlaying Cellular Networks," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 4, pp. 2481–2495, April 2016.

[5] H. H. Nguyen, M. Hasegawa, and W. J. Hwang, "Distributed Resource Allocation for D2D Communications Underlay Cellular Networks," *IEEE Communications Letters*, vol. 20, no. 5, pp. 942–945, May 2016.

[6] D. Zhu, J. Wang, A. Swindlehurst, and C. Zhao, "Downlink Resource Reuse for Device-to-Device Communications Underlaying Cellular Networks," *IEEE Signal Processing Letters*, vol. 21, no. 5, pp. 531–534, May 2014.

[7] P. Phunchongharn, E. Hossain, and D. Kim, "Resource allocation for device-to-device communications underlaying LTE-advanced networks," *IEEE Wireless Communications*, vol. 20, no. 4, pp. 91–100, August 2013.

[8] Y. Jiang, Q. Liu, F. Zheng, X. Gao, and X. You, "Energy Efficient Joint Resource Allocation and Power Control for D2D Communications," *IEEE Transactions on Vehicular Technology*, vol. PP, no. 99, pp. 1–1, 2015.

[9] B. Medepally and N. Mehta, "Voluntary energy harvesting relays and selection in cooperative wireless networks," *IEEE Transactions on Wireless Communications*, vol. 9, no. 11, pp. 3543–3553, November 2010.

[10] I. Ahmed, A. Ikhlef, R. Schober, and R. Mallik, "Power allocation for conventional and buffer-aided link adaptive relaying systems with energy harvesting nodes," *IEEE Transactions on Wireless Communications*, vol. 13, no. 3, pp. 1182–1195, March 2014.

[11] O. Orhan and E. Erkip, "Throughput maximization for energy harvesting two-hop networks," in *2013 IEEE International Symposium on Information Theory Proceedings (ISIT)*, July 2013, pp. 1596–1600.

[12] Chandra R Murthy, Neelesh B. Metha, "Energy harvesting wireless communication systems," *Tutorial Notes, National Conference on Communications*, February 2014.

[13] J. Yang and S. Ulukus, "Optimal packet scheduling in an energy harvesting communication system," *IEEE Transactions on Communications*, vol. 60, no. 1, pp. 220–230, January 2012.

[14] K. Tutuncuoglu and A. Yener, "Optimum transmission policies for battery limited energy harvesting nodes," *IEEE Transactions on Wireless Communications*, vol. 11, no. 3, pp. 1180–1189, March 2012.

[15] P. He, L. Zhao, S. Zhou, and Z. Niu, "Recursive waterfilling for wireless links with energy harvesting transmitters," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 3, pp. 1232–1241, March 2014.

[16] J. Yang, O. Ozel, and S. Ulukus, "Broadcasting with an energy harvesting rechargeable transmitter," *IEEE Transactions on Wireless Communications*, vol. 11, no. 2, pp. 571–583, February 2012.

[17] C.-C. Kuan, G.-Y. Lin, H.-Y. Wei, and R. Vannithamby, "Reliable multicast and broadcast mechanisms for energy-harvesting devices," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 4, pp. 1813–1826, May 2014.

[18] J. Yang and S. Ulukus, "Optimal packet scheduling in a multiple access channel with energy harvesting transmitters," *IEEE Journal of Communications and Networks*, vol. 14, no. 2, pp. 140–150, April 2012.

[19] Z. Fang, T. Song, and T. Li, "Energy harvesting for two-way OFDM communications under hostile jamming," *IEEE Signal Processing Letters*, vol. 22, no. 4, pp. 413–416, April 2015.

[20] K. Tutuncuoglu, B. Varan, and A. Yener, "Throughput maximization for two-way relay channels with energy harvesting nodes: The impact of relaying strategies," *IEEE Transactions on Communications*, vol. 63, no. 6, pp. 2081–2093, June 2015.

[21] Z. Ding, S. M. Perlaza, I. Esnaola, and H. V. Poor, "Power Allocation Strategies in Energy Harvesting Wireless Cooperative Networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 2, pp. 846–860, February 2014.

[22] N. Roseveare and B. Natarajan, "An alternative perspective on utility maximization in energy-harvesting wireless sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 1, pp. 344–356, Jan 2014.

[23] A. Sakr and E. Hossain, "Cognitive and Energy Harvesting-Based D2D Communication in Cellular Networks: Stochastic Geometry Modeling and Analysis," *IEEE Transactions on Communications*, vol. 63, no. 5, pp. 1867–1880, May 2015.

[24] Y. Liu, L. Wang, S. Raza Zaidi, M. Elkashlan, and T. Duong, "Secure D2D Communication in Large-Scale Cognitive Cellular Networks: A Wireless Power Transfer Model," *IEEE Transactions on Communications*, vol. 64, no. 1, pp. 329–342, Jan 2016.

[25] H. Yang, J. Lee, and T. Quek, "Heterogeneous Cellular Network With Energy Harvesting-Based D2D Communication," *IEEE Transactions on Wireless Communications*, vol. 15, no. 2, pp. 1406–1419, Feb 2016.

[26] M. Zulhasnine, C. Huang, and A. Srinivasan, "Efficient resource allocation for device-to-device communication underlaying LTE network," in *IEEE 6th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), 2010*, Oct 2010, pp. 368–375.

[27] S. Boyd and L. Vandenberghe, *Convex Optimization*. New York, NY, USA: Cambridge University Press, 2004.
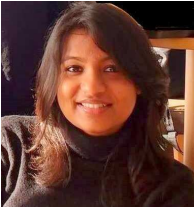
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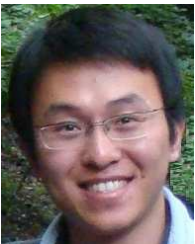
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