Cooperative D2D Communication in Downlink Cellular Networks with Energy Harvesting Capability

Mohamed Seif *, Amr El-Keyi ‡, Karim G. Seddik §, and Mohammed Nafie *†

* Wireless Intelligent Networks Center (WINC), Nile University, Giza, Egypt
† EECE Dept., Faculty of Engineering, Cairo University, Giza, Egypt
‡ Department of Systems and Computer Engineering, Carleton University, Ottawa, Canada
§ Electronics and Communications Engineering Department, American University in Cairo, New Cairo 11835, Egypt
Email: m.seif@nu.edu.eg, aelkeyi@nileuniversity.edu.eg, kseddik@aucegypt.edu, mnafie@nu.edu.eg

Abstract—**Device-to-Device (D2D) communications have been highlighted as one of the promising solutions to enhance spectrum utilization of LTE-Advanced networks. In this paper, we consider a D2D transmitter cooperating with a cellular network by acting as a relay to serve one of the cellular users. We consider the case in which the D2D transmitter is equipped with an energy harvesting capability. We investigate the trade-off between the amount of energy used for relaying and the energy used for decoding the cellular user data at the relaying node. We formulate an optimization problem to maximize the cellular user rate subject to a minimum rate requirement constraint for the D2D link. Moreover, we consider the case when receiving nodes are equipped with successive interference cancellation (SIC) capability and investigate the effect of using SIC on our proposed system performance. Finally, we show via numerical simulations the benefits of our cooperation-based system as compared to the non-cooperative scenario.**

Index Terms: Cooperative D2D communication, energy harvesting, decode-and-forward, interference management.

I. Introduction

Device-to-Device (D2D) communication has been proposed as an underlay approach to facilitate local service for cellular networks by enabling the devices to communicate with each other directly without going through a cellular base station [1]. Significant research effort has been conducted to utilize D2D communication to enhance spectrum efficiency and throughput of LTE-Advanced networks. Recent work on D2D communication has resulted in promising communication protocols such as: 1) mode selection: which defines different modes of operation based on the available resources to the D2D network [2], 2) network coding: which is an elegant technique to improve the overall throughput of the network and reduce the amount of routing information required for D2D networks to achieve near optimal throughput [3], and, 3) cooperative communication: which enables D2D terminals to efficiently utilize radio resources, reduces the interference level in the network, increases D2D coverage, and enhances the overall network throughput [8].

D2D transmission is envisioned to share the same time and frequency resources with the cellular transmission. As a result, interference needs to be properly controlled in order to prevent severe performance degradation to the cellular network. Hence, D2D communication model is analogous to the concurrent spectrum access model in cognitive radio in which the secondary users have to control their interference on the primary users [4]. Two common approaches have been proposed in order to manage the interference of the D2D transmission to the cellular network. The first one is limiting the transmission power of D2D users in the cell as proposed in [5] while the second approach is minimizing the received interference power due to D2D transmission at the cellular receivers, e.g., [6].

Cooperative communication has been proposed for cellular networks to minimize the outage probability, improve the coverage, and enhance the link reliability [7]. Superposition coding and orthogonal splitting are some common techniques used in cooperation. Cooperative communication between cellular and D2D networks has also been investigated. For example, in [8], the authors have proposed a cooperative transmission scheme for D2D communication with the cellular network. In this scheme, the D2D transmitter acts as an in-band relay for the base station (BS) and the cellular network shares the radio resources with D2D links. The D2D transmitter employs a superposition coding scheme in which a linear combination of its data is sent with the decoded data from the BS. The assigned power for cooperation was minimized while achieving the direct link capacity for the cellular user where route selection was done in order to use the least power required to serve the cellular user. It was shown in [8] that the improvement in overall cell capacity due to cooperation increases with the number of cellular users within the cell as well as the cell size.

Recently, electromagnetic energy transfer techniques have attracted remarkable interest in the wireless research literature. Joint transmission of information and energy using the same waveform, which is known as simultaneous wireless information and power transfer (SWIPT), has also been proposed. For SWIPT systems, two practical signal separation schemes were considered. The first scheme is the time switching scheme where the receiver switches between information decoding (ID) and energy harvesting (EH). The second scheme is the power splitting scheme where the received signal is split into two streams; one for ID and the other for EH, i.e., a fraction $\rho \in (0,1]$ of the received signal power is used for ID while the remaining fraction $(1-\rho)$ is used for EH. The SWIPT technique for relay systems was considered in [9]–[11]. Specifically, the authors of [9] proposed a joint source and relay precoding design algorithm to achieve different

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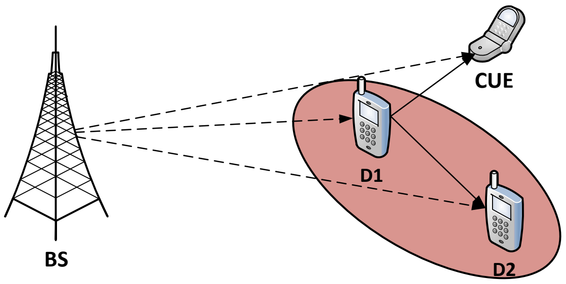

Fig. 1. Network Model: Cellular network with D2D network (shaded area). Dashed lines represent the direct channels from BS to nodes, and solid lines represent from D_1 to receiving nodes.

tradeoffs between the energy transfer and the information rate. In [10], the relay beamforming design problem for the SWIPT scheme was considered in a non-regenerative two-way multi-antenna relay network, where a global optimal solution, a local optimal solution, and a low-complexity suboptimal solution were proposed. In [11], a game-theoretical framework was developed to address the distributed power splitting problem for SWIPT in relay interference channels.

In this paper, we study a SWIPT-like technique for cooperative D2D communication where a D2D node relays the cellular network data by using superposition coding for simultaneous transmission of its own data and the relayed cellular user data. The D2D relay node is equipped with an EH capability that employs power splitting. We investigate the trade-off between the amount of energy used for decoding the cellular user data and the energy used for relaying and data transmission of the D2D node. Note that increasing the energy for decoding the cellular user data leads to increasing the rate of transmission from the cellular BS to the D2D relay node. However, it limits the amount of energy that can be used for relaying and D2D data transmission. We determine the optimal power splitting ratio and the superposition coding fraction that maximizes the achievable rate of the cellular user subject to a minimum target rate for the D2D network. We show via numerical simulations the gain of cooperation over non-cooperative transmission.

The rest of the paper is organized as follows. The system model and analysis for the achievable rates for both the direct transmission and the cooperative transmission schemes are described in Section II. In Section III, the problem formulation is presented and solved. Simulation results are presented in Section IV. Finally, we conclude the paper in Section V.

II. System Model

We consider a cellular network as shown in Fig. 1, where a BS and a cellular user equipment(CUE) are communicating with each other through a direct link. In addition, a transmitter-receiver pair operating in D2D transmission mode coexists with the cellular network. We assume that the D2D transmitter is equipped with an EH capability. We consider a time-slotted system where T denotes the duration of one time slot. Each time slot is divided into two sub-slots of equal duration. In the first time sub-slot, the BS transmits a signal x_C intended for the cellular user C with power P_B, where $E\{x_C\} = 0$ and $E\{|x_C|^2\} = 1$. In this time slot, the D2D transmitter listens to the transmission of the BS. The received signal at the D2D transmitter can be written as

$$y_{D_1} = \sqrt{P_B} h_{B,D_1} x_C + n_{D_1} \tag{1}$$

where n_{D_1} is the receiver circularly symmetric white Gaussian noise with zero mean and unit variance, i.e., $n_{D_1} \sim \mathcal{CN}(0,1)$, and $h_{X,Y}$ is the complex-Gaussian channel gain between the transmitting node X and the receiving node Y.

The D2D utilizes its received signal during the first sub-slot in EH. The second time sub-slot is dedicated for D2D transmission. We consider two transmission schemes; direct and cooperative schemes. In the direct transmission scheme, the D2D transmitter completely harvests the received energy due to the transmission of the BS in the first time slot. On the other hand, the D2D transmitter in cooperative scheme divides the received signal in the first time sub-slot both for EH and ID. In the second time slot, the D2D transmitter transmits a linear combination of the D2D signal and the decoded CUE signal. In the next two subsections, we will present the signal model for the two transmission schemes.

A. Direct Transmission Scheme

In this scheme, there is no cooperation between the D2D transmitter and the CUE. The received energy by the D2D transmitter during the first time sub-slot is completely used for transmission in the second sub-slot. The achievable rate for CUE from the direct link in bits/sec/Hz is given by

$$R_C^{\mathrm{DT}} = \frac{1}{2}\log_2(1 + \gamma_{B,C}^{\mathrm{DT}}) \tag{2}$$

where $\gamma_{B,C}^{\mathrm{DT}} = \frac{P_B |h_{B,C}|^2}{N_0}$ is the received signal-to-noise ratio (SNR) at the CUE due to the direct transmission of the BS. Similarly, the achievable rate for the D2D receiver D_2 due to the transmission of D_1 in the second sub-slot in bits/sec/Hz is given by

$$R_{D_2}^{\mathrm{DT}} = \frac{1}{2}\log_2(1 + \gamma_{D_1,D_2}^{\mathrm{DT}}) \tag{3}$$

where $\gamma_{D_1,D_2}^{\mathrm{DT}} = \frac{P_{D_1}^{\mathrm{DT}} |h_{D_1,D_2}|^2}{N_0}$ is the received SNR at receiver D_2 due to transmission of D_1 in the second sub-slot. The power $P_{D_1}^{\mathrm{DT}}$ is the harvested power at D_1 in the first time sub-slot in the direct transmission scheme, which is given by

$$P_{D_1}^{\mathrm{DT}} = P_B |h_{B,D_1}|^2 + N_0, \tag{4}$$

and is completely utilized by D_1 for transmission in the second sub-slot.

B. Cooperative Transmission Scheme

In this scheme, the D2D transmitter cooperates with the BS in order to relay the cellular data to the CUE while transmitting its own data, i.e., the D2D transmitter acts as a half-duplex cooperative decode-and-forward relay. The received signal power at D_1 is split by a power splitter as depicted in Fig. 2, where a fraction $\rho \in [0,1]$ of power is utilized for ID while the remaining power is harvested. The achievable rate at D_1 due to transmission of the BS is given by

$$R_{B,D_1} = \frac{1}{2}\log_2(1 + \rho\gamma_{B,D_1}) \tag{5}$$

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where $\rho\gamma_{B,D_1} = \frac{\rho P_B |h_{B,D_1}|^2}{N_0}$ is the received SNR at D_1 due to the transmission of the BS.

In the second time sub-slot, the D2D transmitter employs a superposition coding scheme to transmit a linear combination of the CUE data and its own data x_{D_2}. The transmitted signal by the D2D transmitter in the second sub-slot can be written as

$$x_{D_1}^{\text{CT}} = \sqrt{\alpha P_{D_1}^{\text{CT}}} x_C + \sqrt{(1-\alpha) P_{D_1}^{\text{CT}}} x_{D_2} \tag{6}$$

where $E\{x_{D_2}\} = 0$, $E\{|x_{D_2}|^2\} = 1$, $P_{D_1}^{\text{CT}}$ is the transmission power of D_1 in the cooperative transmission scheme which is given by

$$P_{D_1}^{\text{CT}} = (1-\rho)\left(P_B |h_{B,D_1}|^2 + N_0\right) \tag{7}$$

and $\alpha \in [0,1]$ is the fraction of $P_{D_1}^{\text{CT}}$ used to transmit the signal of the BS to CUE. The received signal at the D2D receiver, D_2, in the second sub-slot is given by

$$y_{D_2}^{\text{CT}} = h_{D_1,D_2} x_{D_1}^{\text{CT}} + n_{D_2}. \tag{8}$$

Similarly, the received signal at the cellular user in the second sub-slot is given by

$$y_C^{\text{CT}} = h_{D_1,C} x_{D_1}^{\text{CT}} + n_C. \tag{9}$$

*1) **No SIC case**:* The achievable rate of the D2D receiver is given by

$$R_{D_2}^{\text{CT}} = \frac{1}{2}\log_2\left(1 + \frac{1-\alpha}{\alpha + \frac{1}{\gamma_{D_1,D_2}^{\text{CT}}}}\right) \tag{10}$$

where $\gamma_{D_1,D_2}^{\text{CT}}$ is given by $\gamma_{D_1,D_2}^{\text{CT}} = \frac{P_{D_1}^{\text{CT}} |h_{D_1,D_2}|^2}{N_0}$.

The achievable rate for the CUE, when considering the cooperation, is given by [8]

$$R_C^{\text{CT}} = \frac{1}{2}\log_2\left(1 + \gamma_{B,C}^{\text{DT}} + \frac{\alpha}{1-\alpha + \frac{1}{\gamma_{D_1,C}^{\text{CT}}}}\right) \tag{11}$$

Note that it is assumed that the cellular receiver employs maximum ratio combining (MRC) in order to detect its own signal. That is, the receiver combines the received SNR from the first time slot with the one from the second time slot.

*2) **SIC case**:* The achievable rate for D_2 considering the SIC decoder will be as follows:

$$R_{D_2}^{\text{CT}} = \frac{1}{2}\log_2\left(1 + (1-\alpha)\gamma_{D_1,D_2}^{\text{CT}}\right). \tag{12}$$

Then, the achievable rate for the CUE when employing the SIC decoding is as follows:

$$R_C^{\text{CT}} = \frac{1}{2}\log_2\left(1 + \gamma_{B,C}^{\text{DT}} + \alpha\gamma_{D_1,C}^{\text{CT}}\right). \tag{13}$$

where $\gamma_{D_1,C}^{\text{CT}} = \frac{P_{D_1}^{\text{CT}} |h_{D_1,C}|^2}{N_0}$.

It is worth noting that, the achievable rate for the CUE with cooperation should be at least the same as the direct link rate, that is

$$R_C^{\text{CT}} \geq R_C^{\text{DT}}, \tag{14}$$

because the CUE will gain extra information from the relayed data, which is not the case for the direct system.

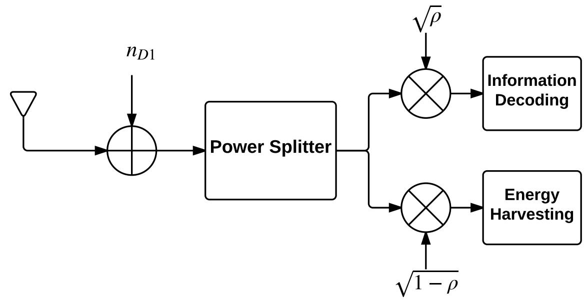

Fig. 2. Power Splitter Architecture at D_1.

Notes on SIC decoding: When both D_2 and the CUE are equipped with SIC capabilities, the following cases will specify the conditions under which using SIC will be beneficial at a certain receiving node:

A) Both D_2 and CUE employ SIC:

The condition at D_2 to use SIC will be:

$$\gamma_{B,D_2} + \frac{\alpha}{1-\alpha+\frac{1}{\gamma_{D_1,D_2}^{\text{CT}}}} \geq (\gamma_{B,C}^{\text{DT}} + \alpha\gamma_{D_1,C}^{\text{CT}}). \tag{15}$$

The condition at CUE to use SIC will be:

$$\frac{1-\alpha}{\alpha + \frac{1}{\gamma_{D_1,C}^{\text{CT}}}} \geq (1-\alpha)\gamma_{D_1,D_2}^{\text{CT}}. \tag{16}$$

B) D_2 does not employ SIC and CUE employs SIC:

The condition at CUE to use SIC will be:

$$\frac{1-\alpha}{\alpha + \frac{1}{\gamma_{D_1,C}^{\text{CT}}}} \geq \frac{1-\alpha}{\alpha + \frac{1}{\gamma_{D_1,D_2}^{\text{CT}}}}. \tag{17}$$

C) D_2 employs SIC and CUE does not employ SIC:

The condition at D_2 to use SIC will be:

$$\gamma_{B,D_2} + \frac{\alpha}{1-\alpha+\frac{1}{\gamma_{D_1,D_2}^{\text{CT}}}} \geq \gamma_{B,C}^{\text{DT}} + \frac{\alpha}{1-\alpha+\frac{1}{\gamma_{D_1,C}^{\text{CT}}}}. \tag{18}$$

D) The last case that neither D_2 nor CUE employ SIC, since it is not beneficial at any node.

Therefore, in the case of employing SIC, we will have four different cases, and for any given channel realization, we will check which of the four different cases will result in a higher CUE rate while guaranteeing the D2D rate.

III. Problem Formulation

In this section, we formulate and solve the following optimization problem to show the effectiveness of cooperation over the non-cooperative system. The problem can formulated as follows

$$\textbf{P1:} \max_{\rho,\alpha} \quad R_C^{\text{CT}}$$

$$\text{s.t.} \quad P_{D_1}^{\text{CT}} \leq P_{\text{T,max}} \tag{19}$$

$$R_{B,D_1} \geq R_C^{\text{CT}} \tag{20}$$

$$R_{D_2}^{\text{CT}} \geq \bar{R}_{D_2} \tag{21}$$

$$\rho, \alpha \in [0,1]. \tag{22}$$

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—	SIC at CUE	No SIC at CUE	—	SIC at D_2	No SIC at D_2
R_C	$\frac{1}{2}\log_2\left(1+\gamma_{B,C}^{\text{DT}}+\alpha\gamma_{D_1,C}^{\text{CT}}\right)$	$\frac{1}{2}\log_2\left(1+\gamma_{B,C}^{\text{DT}}+\frac{\alpha}{1-\alpha+\frac{1}{\gamma_{D_1,C}^{\text{CT}}}}\right)$	α_{UB}	$\frac{1}{\gamma_{D_1,C}^{\text{CT}}}(\rho\gamma_{B,D_1}-\gamma_{B,C}^{\text{DT}})$	$\frac{1+\frac{1}{\gamma_{D_1,C}^{\text{CT}}}}{1+\frac{1}{\rho\gamma_{B,D_1}-\gamma_{B,C}^{\text{DT}}}}$

TABLE I. VALUES OF DEPENDENT PARAMETERS IN **P3**.

In this problem, we aim at maximizing the achievable rate for the CUE R_C^{CT} under a minimum target rate required for the D2D link $\bar{R}_{D_2}$. Note that the constraint in (20) is added to make sure D_1 (relay) will be able to decode the CUE data in the first time slot. It is worth noting that, the constraint in (19) is set such that the transmitted power P_{D_1} from D_1 can not exceed a maximum power (which can be due to a hardware implementation constraint [12]). Note that by scanning the whole range of α and ρ from 0 to 1, we can scan the whole achievable trade-off region. Solving this problem for a given D2D rate aims at achieving a "boundary" point of this region.

Moreover, we can divide **P1** into two sub-problems[1] :

$$\textbf{P2}: \max_{\rho} \quad 1-\rho$$
$$\text{s.t. } \underbrace{(1-\rho)\left[P_B|h_{B,D_1}|^2+N_0\right]}_{P_{\text{harvested}}} - 2P_{\text{circuit}} \leq P_{\text{T,max}} \quad (23)$$
$$\rho \in [0,1] \quad (24)$$

which translates into maximizing the transmission power P_{D_1} for the second time slot while satisfying the decoding constraint. Since the constraint (23) of **P2** is active (i.e., achieved with equality), the solution can be described as follows:

$$\rho = \max\left\{0, 1-\frac{P_{\text{T,max}}}{P_B|h_{B,D_1}|^2+N_0}\right\}. \quad (25)$$

Note that $P_{\text{harvested}} = P_{D_1}^{\text{CT}} + 2P_{\text{circuit}}$. Where P_{circuit} is the circuit power of D_1 and the factor 2 is included for D_1 operation in the two time slots. Also, it is worth noting that $P_{\text{harvested}}$ must satisfy the following condition:

$$P_{\text{harvested}} \geq P_{\text{T,min}} + 2P_{\text{circuit}} \quad (26)$$

which means,

$$\rho \leq 1 - \frac{P_{\text{T,min}}+2P_{\text{circuit}}}{P_B|h_{B,D_1}|^2+N_0} \quad (27)$$

from equation (23), we constraint that $P_{D_1}^{\text{CT}} \geq P_{\text{T,min}}$ (since constraint (19) is active) to validate equation (27).

An upper bound on α from the constraint in (20) can be found as follows:

$$\alpha_{\text{UB}} = \begin{cases} \frac{1}{\gamma_{D_1,C}^{\text{CT}}}(\rho\gamma_{B,D_1}-\gamma_{B,C}^{\text{DT}}), & \text{if SIC at CUE} \\ \frac{1+\frac{1}{\gamma_{D_1,C}^{\text{CT}}}}{1+\frac{1}{\rho\gamma_{B,D_1}-\gamma_{B,C}^{\text{DT}}}}, & \text{otherwise.} \end{cases} \quad (28)$$

[1]In **P1**, the constraint in (20) will be always satisfied with equality since our objective is to minimize the consumed power for decoding at D_1.

Before we proceed to formulate **P3**, we note that **P3** is a function of the joint cases of SIC decoding capabilities at receiving nodes and hence some of the parameters of the optimization problem will depend on these cases as tabulated in Table I .

Then **P3** is defined as follows,

$$\textbf{P3}: \max_{\alpha} \mathbf{1}(A_1)g_0(\alpha) + (1-\mathbf{1}(A_1))\alpha$$
$$\text{s.t.} f_1^*(\alpha)\mathbf{1}(A_2) + f_1(\alpha)(1-\mathbf{1}(A_2)) \leq 0 \quad (29)$$
$$\alpha \in [0, \alpha_{\text{UB}}] \quad (30)$$

where,

$$f_1(\alpha) = \alpha\left(2^{2\bar{R}_{D_2}}\right) + \frac{1}{\gamma_{D_1,D_2}}\left(2^{2\bar{R}_{D_2}}-1\right) - 1 \quad (31)$$

and,

$$f_1^*(\alpha) = 2^{2\bar{R}_{D_2}} + \gamma_{D_1,D_2}^{\text{CT}}(\alpha-1) - 1 \quad (32)$$

where $g_0(\alpha) = \frac{\alpha}{1-\alpha+\frac{1}{\gamma_{D_1,C}^{\text{CT}}}}$ is a quasilinear function of the form $g_0(\alpha) = \frac{c_1\alpha+b}{c_2\alpha+d}$ on $\text{dom}f = \{\alpha | c_2\alpha + d > 0\}$, where $\text{dom}f$ is the domain of the function f over which it is defined. Moreover, $g_0(\alpha)$ and α are non-decreasing functions which yields that the optimal value of α will be the maximum value of α that satisfies all the constraints. $\mathbf{1}(E)$ is the indicator function for an event E and takes the value '1' if E is valid and '0' otherwise, where A_1 and A_2 indicate the events when CUE and D_2 will employ SIC, respectively. Since the constraint (29) of **P3** is active. The solution can be described as follows:

$$\alpha = \begin{cases} \max\{0, Y\}, & \text{if } D_2 \text{ applies SIC decoder} \\ \max\{0, 2^{-2\bar{R}_{D_2}} \times Y\}, & \text{otherwise} \end{cases} \quad (33)$$

where,

$$Y = 1 - \frac{1}{\gamma_{D_1,D_2}^{\text{CT}}}\left(2^{2\bar{R}_{D_2}}-1\right). \quad (34)$$

IV. NUMERICAL EVALUATION

In this section, we investigate the cooperation performance between the cellular network and D2D link. The locations of nodes are uniformly distributed over a single hexagonal cell with radius $S = 500$ m, where the BS lies in the center of the cell as depicted in Fig. 9. The distance of the D2D receiver from its transmitter lies in range $5 < d_{D_1,D_2} < 20$ m. Also, the BS uses its maximum power for transmission. The fraction of the D2D transmit power that is allocated for cooperation is optimized. Simulation parameters are listed in Table II.

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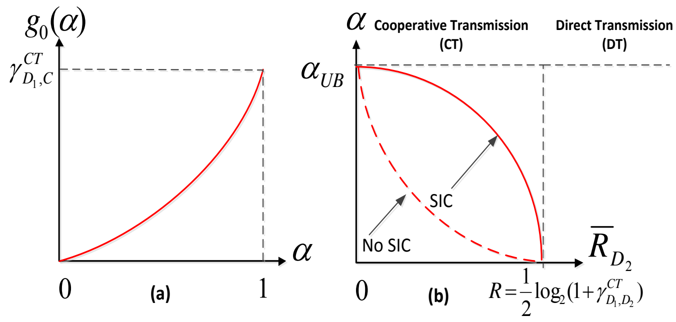

Fig. 3. Function plot for: (a) $g_0(\alpha)$ shows the quasi linearity of the function: $g_0(\alpha)$ vs α and (b) α vs $\bar{R}_{D_2}$. Beyond the point R, cooperative transmission is not beneficial. In (b), since we show only the trend of the functions, we assume in both cases they have the same α_{UB}.

Symbol	Description	Value
P_B	BS TX power	43 dBm
N_0	Noise power	-100 dBm
N_j	Noise power at node j	N_0
$P_{\text{T,min}}$	Min. TX power for D_1	-5 dBm
P_{circuit}	$0.25P_{\text{T,min}}$ [13]	—
L_{LoS}	LoS Pathloss Exponent	$2-4$
d_{B,D_1}	Distance between B and D_1	$50-500$ m
$d_{D_1,\text{C}}$	Distance between D_1 and C	$10-20$ m
d_{D_1,D_2}	Distance between D_1 and D_2	$5-20$ m
$d_{\text{B,C}}$	Distance between B and C	$200-1000$ m
σ_{sh}	UE-UE shadowing	12
σ_{sh}	BS-UE shadowing	10
f_c	Carrier frequency	2 GHz
S	Cell radius	500 m
T	No. of neighboring cells	1-2
—	No. of realizations	10000

TABLE II. SIMULATION PARAMETERS.

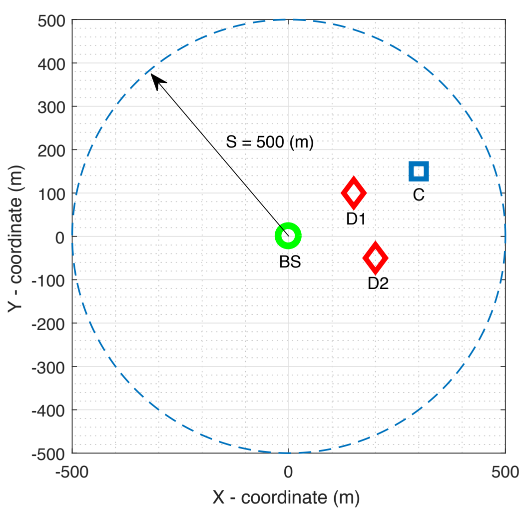

Fig. 4. Cell layout for a cellular network and one D2D pair.

—	PL	L	C
BS - UE	PL_{LOS}	2.2	34.04
BS - UE	PL_{LOS}	3.67	30.55
UE - UE	PL_{NLOS}	1.69	38.84
UE - UE	PL_{NLOS}	4	28.03

TABLE III. NOMINAL VALUES FOR PATH LOSS PARAMETERS.

A. Propagation modeling

The channel model is taking into account the effects of path loss, shadowing and multi-path fading. It is worth noting that the path loss model for D2D communications has not been standardized yet, therefore the channel model for D2D is modeled as described in [8], [12] which is based on the ITU recommendations for micro urban environment [14]. The path loss model is defined as

$$PL = D + 10L\log_{10}(d_{\text{B},i}) \tag{35}$$

where d is the distance between the BS and receiver i, where $i \in \{\text{D}_1, \text{C}\}$. D and L represent the path loss coefficient and path loss exponent, respectively. It is worth noting that D is a function of the carrier frequency f_c [12]. The values of D and α are given in Table III.

The average path loss is calculated as follows

$$\overline{\text{PL}} = \beta\text{PL}_{\text{LOS}} + (1-\beta)\text{PL}_{\text{NLOS}} \tag{36}$$

where β is the probability of LoS.

The probability of LoS between the BS and user equipment (UE) [12] is defined as follows

$$\beta = \min\left(\frac{18}{d}, 1\right)\left[1 - \exp\left(\frac{-d}{36}\right)\right] + \exp\left(\frac{-d}{36}\right) \tag{37}$$

and between devices as follows

$$\beta = \begin{cases} 1, & d \leq 4 \\ \exp\left(\frac{-(d-4)}{3}\right), & 4 < d < 60 \\ 0, & d \geq 60 \end{cases}. \tag{38}$$

For the shadowing effect is generated from Gaussian distribution with zero mean and variance σ_{sh} as described in [15].

B. Inter cell interference

It is interesting to take into account the interference caused from other cells, to model the inter cell interference we assume the T neighboring cells are downlink cellular networks and treated as noise, then we can write total effect of receiver noise and interference as follows

$$N_{\text{eff},j} = N_j + \sum_{i=1}^{T} P_{B_i}|h_{B_i,j}|^2, j \in \{D_1, D_2, C\}. \tag{39}$$

C. Simulation Results

Fig. 5 shows the relation between the achievable cellular rate R_C versus different values of the path loss exponent for a certain target rate for the D2D network. A baseline is considered for comparison purposes, which is the case of no cooperation. Moreover in Fig. 6, we see that the gain of cooperation reduces as the target rate for the D2D

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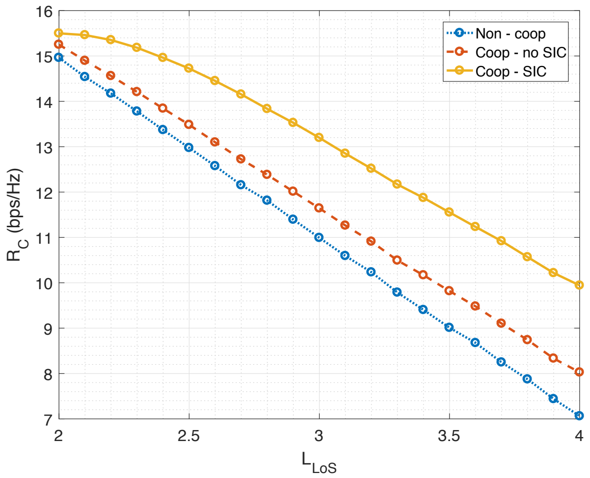

Fig. 5. R_C vs L_{LoS}: $P_{\text{T,max}} = 24$ dBm,$\bar{R}_{D_2} = 2$ bps/Hz.

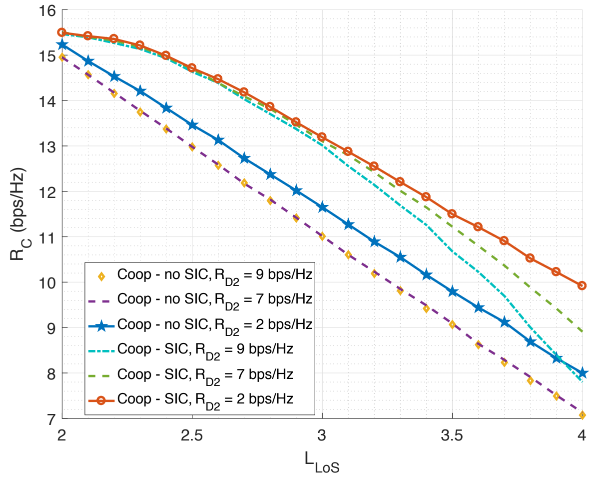

Fig. 6. R_C vs L_{LoS}: $P_{\text{T,max}} = 24$ dBm, $\bar{R}_{D_2} = 2$ bps/Hz.

network increases, which causes reducing the assigned power for cooperation to satisfy the D2D rate constraint. Also, it shows the effectiveness of employing the SIC decoding on the achievable rate for the CUE compared with the case of not employing SIC and the non-cooperative case. It worth noting that for the SIC-enabled decoding system, and for each channel realization, we check the conditions for employing SIC at both nodes (i.e., D_2 and CUE nodes) as previously discussed; we select the scheme that will result in the highest CUE rate for each realization; therefore, this SIC-enabled system will always result in a higher CUE rate as compared to the no-SIC system.

We highlight on the proximity effect on D2D network and the probability of successful interference cancellation at the cellular user and the D2D receiver. As mentioned previously, the conditions [2] of SIC is dependent on the randomness in the network. Fig. 7 shows that if the distance between D2D nodes increases, then the probability of SIC will reduce while the opposite in the case of the cellular user in which it will employ the SIC decoding with probability one.

Fig. 8 shows the tradeoff between the transmission power, whether assigned to CUE, $P_C = \alpha P_{D_1}^{\text{CT}}$ or assigned to D_2, $P_{D_2} = (1-\alpha)P_{D_1}^{\text{CT}}$, and the power splitting ratio ρ for different values of the path loss exponent. As shown, pathloss exponent reduces the transmission power at the expense of having successful decoding at D_1.

Lastly, fig. 9 shows the effect of inter cell interference on the cellular rate inside the cell of interest. We compare between three different cases: first, when there is no inter cell interference and no SIC schemes are employed for a baseline purpose. Second, when utilizing opportunistic SIC schemes and no inter cell interference. And finally, when there are T neighboring cells with SIC schemes. It is clearly seen that increasing the number of the number of neighboring cell will diminish the cellular rate R_C even with utilizing the SIC schemes.

[2]Note that the distances between nodes are generated randomly.

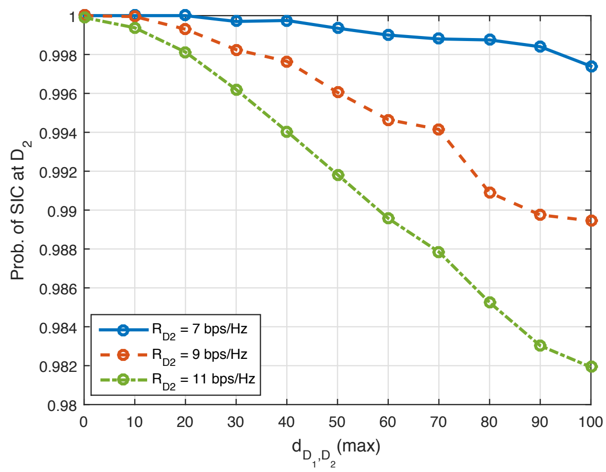

Fig. 7. Probability of SIC vs $d_{D_1,D_2}(\max)$ at D_2: $P_{\text{T,max}} = 24$ dBm, $L_{\text{LoS}} = 2.2$.

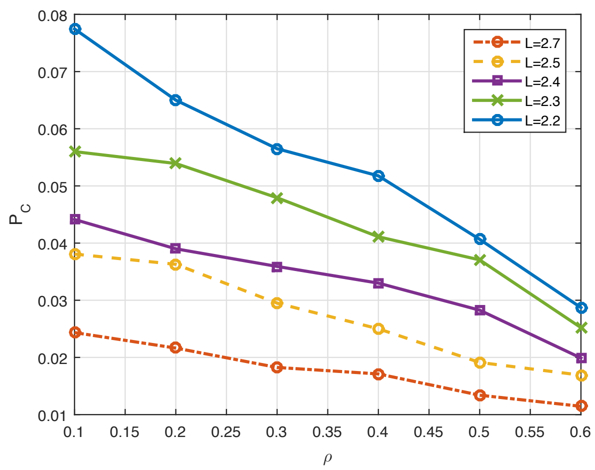

Fig. 8. Tradeoff between P_C vs ρ: $P_{\text{T,max}} = 24$ dBm, $\bar{R}_{D_2} = 7$ bits/sec/Hz.

This work was supported by a grant from the Egyptian National Telecommunications Regulatory Authority

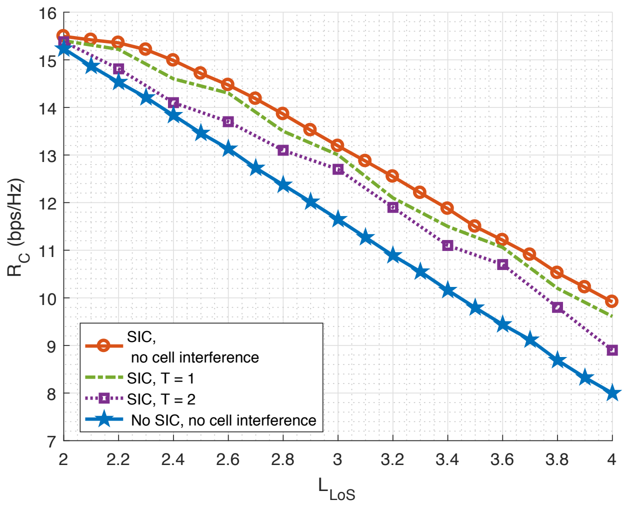

Fig. 9. Effect of inter-cell interference, $\bar{R}_{D_2} = 2$ bits/sec/Hz.

V. Conclusion

In this paper, we have investigated the benefits of the cooperation in D2D communication. We have considered a model where a D2D acts as a relay for the cellular user and is equipped with energy harvesting capability. The relaying node sends its data along with the relayed cellular user data. We have investigated the trade-off between the amount of energy used for decoding the cellular user data and the amount of energy used for relaying. An optimization problem was formulated to maximize the cellular user data rate subject to a D2D rate constraint. We have shown the gains that can be achieved by considering cooperation between the cellular network and the D2D devices as compared to the no cooperation system. Also, we have investigated the achievable gains if the receiving nodes are equipped with successive interference cancellation (SIC) capabilities.

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