Cooperative Device-to-Device Communications in the Downlink of Cellular Networks

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Abstract—**We propose a cooperative device-to-device (D2D) communications framework in order to combat the problem of congestion in crowded communication environments. The idea is to allow a D2D transmitter to act as an in-band relay for a cellular link and at the same time transmit its own data by employing superposition coding in the downlink. Cooperation between the cellular link and D2D transmitter eases down the requirement on the interference. The main benefit of the proposed method is in increasing the number of connections per unit area with the same spectrum usage. It could also be beneficial to offload over-loaded cells. We formulate our problem to minimize the assigned power for cooperation while making sure the cellular user's performance does not degrade. Our results show that cooperation possibilities and improvement in overall cell capacity increase with the number of cellular users within the cell as well as the cell size.**

I. INTRODUCTION

The amount of data traffic to be treated by cellular networks is increasing with the popularity of multimedia services. In order to accommodate this huge multimedia traffic, the capacity of cellular networks should be enhanced by new spectrum and novel spectrum sharing techniques. Existing infrastructure will not be able to support the required data rates to mobile users in crowded areas such as open air festivals and shopping malls. Therefore, spectral efficient networks and energy efficient devices are needed. Spectrum sharing is an efficient way of improving the spectral efficiency of cellular networks. As a way of spectrum sharing, device-to-device (D2D) communications has recently been proposed as an underlay for cellular networks. In the D2D communication mode, transmission is done using a direct link from one device to its receiver as opposed to the traditional cellular users where all transmissions go through the base station [1], [2].

The advantages of D2D communications are manifold: offloading the cellular system, reduced battery consumption, increased bit-rate, robustness to infrastructure failures and thereby also enabling new services [2]. Contrary to competing D2D technologies such as Bluetooth and Wireless LANs, cellular D2D communications can give local service providers access to licensed spectrum with a controlled interference environment. However, the design of an efficient D2D communication mode as underlay to a cellular network is a key problem to be solved. For underlay systems, both cellular and D2D links employ the same radio resources creating mutual interference. This mutual interference may limit the achievable data rates of different links. Therefore, interference management, mode selection, and efficient resource scheduling are important issues in cellular networks with underlay D2D communications.

The rest of the paper is organized as follows. In the remainder of this section, we review the related work and present our contributions. The system model is described in Section II. We formulate the problem in Section III and present the numerical results in Section IV. Finally, we conclude in Section V.

A. Related Work and Our Contributions

In order to manage the interference of D2D links to the cellular network, one approach is to limit the maximum transmit power of the D2D users as considered in [3] and [4]. Another approach is to minimize the received interference while maximizing the number of D2D links in the cell [5]. Interference from the cellular users to D2D links can also be critical as it limits the reliability of transmission for D2D users. In [6], authors employ different interference regime knowledge in the receiver to ensure lower outage probability for D2D communications. Minimizing the sum power with regard to the sum rate constraint with mode selection is addressed in [7], [8]. Proper pairing, in order to maximize the network capacity while minimizing the interference, is considered in [9]. Hence, interference management is a key issue for allowing underlay D2D communications in cellular systems. By introducing cooperation between the cellular links and the D2D links, we may avoid the mutual interference and improve the system capacity.

Cooperative communications in wireless networks have shown good potential in improving coverage, increasing link reliability, and reducing costs [10], [11]. Cooperation can be used to share the spectrum, this can be done through superposition coding or orthogonal splitting [12], [13] . Authors in [14] proposed to use the known nearby idle users as multihop relays

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for the D2D transmission in order to improve the reliability and rate of D2D users in an uplink underlay scenario. As the relays in this work are idle users, there is actually no cooperative transmission for the cellular users. However, [15] considered the bidirectional relaying scenario where the relay assists both base station and the cellular user simultaneously. The achievable rate region of the sum rate for the D2D user versus the cellular user was investigated for a scenario with one D2D pair and one cellular user.

In this paper, we consider using the idea of cooperative communications, route selection, and interference cancelation as a framework for multi-link communications in cellular systems. The idea is to allow the D2D transmitter to act as an in-band relay to a cellular link. The D2D link shares the radio resources with the cooperating cellular link in the downlink. The D2D transmitter employs the superposition coding scheme in which it transmits a linear combination of its own information superimposed with the decoded information from the cellular user. Such cooperation can be useful for the cellular link when the cellular mobile user is far away from its serving base station, or when it is located indoor while the D2D transmitter is outdoor. Cooperative D2D communications can free some radio resources to other users and increase the data rate of users in bad spots. Another immediate benefit can be reducing the infrastructure costs as opposed to fixed relaying solution for the cellular networks.

Our objective is to minimize the assigned power for cooperation while cellular user can achieve at least its direct link rate. Our results show that such cooperation improves the overall cell capacity while providing the possibility of direct D2D communications. This improvement increases with the number of cellular mobile users within the cell and also with the cell size.

II. SYSTEM MODEL

We consider a single cell of a cellular network, as depicted in Fig. 1. There are M cellular users (CUEs) that communicate in the conventional way through the base station. Let $\mathcal{M} = \{1, \ldots, M\}$ define the set of these users. Besides, there exists an extra transmitter-receiver pair in the cell which is already operating in the D2D transmission mode. There is no dedicated channel for direct communications between devices. Therefore, the D2D user cooperates with one of the cellular users in order to transmit its own data while relaying the cellular data simultaneously in the downlink, provided that the cellular user's rate is not degraded. It is assumed that the D2D transmitter uses the decode-and-forward (DF) relaying protocol. When the DF scheme is employed, the relay node decodes the message broadcasted by the source node, then, transmits the decoded message to the destination. We assume that the D2D transmitter is operating in the half-duplex mode in which it cannot transmit and receive at the same time. The transmission scheme is the time division multiple access (TDMA) technique. In case of cooperation, two consequent and equal-sized time slots are used as one transmission frame, and we assume that the frame length is normalized ($T = 1$) as shown in Fig. 2. The first time slot is used for transmission of the base station in which a complex-valued signal x_{c_i} is broadcasted using the power p_i. In the next time slot, the D2D transmitter employs superposition coding in order to transmit a linear combination of its own signal x_d and the ith cellular user's signal, i.e., $x_i^{\text{sc}} = \sqrt{p_d \nu_i} x_{c_i} + \sqrt{p_d(1-\nu_i)} x_d$, where ν_i is the fraction of the D2D user's total transmit power p_d assigned to the ith cellular user's signal with $0 < \nu_i < 1$. Note that $\nu_i = 1$ corresponds to the case of selfless relaying and $\nu_i = 0$ to the case of transmission only to the D2D receiver. Since there is no incentive in these two cases, no cooperation would be formed. We consider the transmitted signals to be zero-mean and uncorrelated with normalized power, i.e., $\mathbb{E}[x_{c_i}] = \mathbb{E}[x_d] = 0$ and $\mathbb{E}[|x_{c_i}|^2] = \mathbb{E}[|x_d|^2] = 1$. We assume that there exits identical additive white Gaussian noise in each receiver with power N_0. Let $h_{k,j}$ be the channel between the transmitter $k \in \{b, d_{\text{tx}}\}$ and the receiver $j \in \{1, \cdots, M, d_{\text{rx}}\}$ that accounts for the effects of path loss, shadowing, and Rayleigh fading. We assume that the channel is constant over one time slot and all channels are known in the base station.

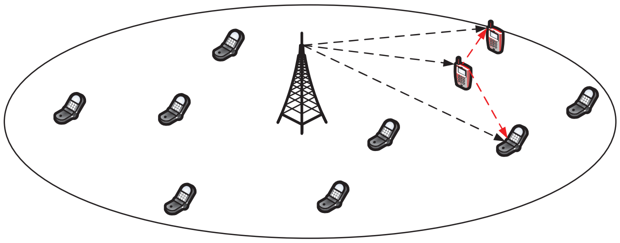

Fig. 1. System model with one D2D link and M cellular users uniformly distributed over the cell area.

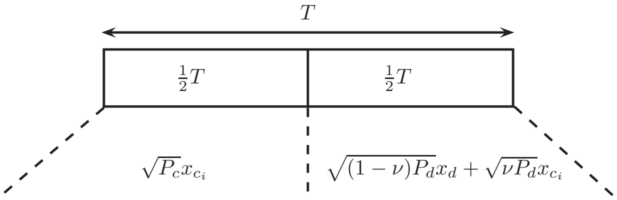

Fig. 2. Frame structure with two equal sized time slot.

III. PROBLEM FORMULATION

In order to formulate our problem, we consider the achievable rate under capacity-achieving coding as our performance metric. The achievable cellular user data rate in the direct link, denoted by R_{dir} and measured in bit/s/Hz, is

$$\begin{aligned} R_{\text{dir}} &= \frac{1}{2} \log_2 (1 + \Gamma_{b,i}^{(1)}) + \frac{1}{2} \log_2 (1 + \Gamma_{b,i}^{(2)}) \\ &= \frac{1}{2} \log_2 (1 + \Gamma_{b,i}^{(1)})(1 + \Gamma_{b,i}^{(2)}), \end{aligned} \tag{1}$$

where $\Gamma_{k,j}^{(t)} = \frac{p_k |h_{k,j}|^2}{N_0}$ is the received signal-to-noise ratio (SNR) from transmitter k to receiver j in transmission time slot $t \in \{1, 2\}$. Furthermore, the factor $\frac{1}{2}$ in front of each rate term corresponds to the length of the transmission slot. Note that no power control is performed for the cellular user's power and the base station employs its maximum power to transmit.

The end-to-end achievable rate for the ith cellular user R_{c_i} when it cooperates with the D2D user is limited by the minimum rate in the two transmission phases [10], i.e.,

$$R_{c_i} = \min\{R^{(1)}_{b,d_{\text{tx}}}, R^{(2)}_{d_{\text{tx}},i}\}, \quad i \in \mathcal{M}, \tag{2}$$

where $R^{(1)}_{b,d_{\text{tx}}}$ is the rate between the base station and the D2D transmitter in the first time slot, and $R^{(2)}_{d_{\text{tx}},i}$ is the achievable rate at the ith cellular user. It is assumed that the cellular receiver employs maximum ratio combining (MRC) in order to detect its own signal. When MRC is used, the receiver combines the received SNR from the first time slot with the one from the second time slot. The rates in (2) are given by

$$R^{(1)}_{b,d_{\text{tx}}} = \frac{1}{2}\log_2\left(1+\Gamma^{(1)}_{b,d_{\text{tx}}}\right), \tag{3}$$

$$R^{(2)}_{d_{\text{tx}},i} = \frac{1}{2}\log_2\left(1+\Gamma^{(1)}_{b,i} + \frac{\nu_i}{1-\nu_i+\frac{1}{\Gamma^{(2)}_{d_{\text{tx}},i}}}\right). \tag{4}$$

Now the problem is how the D2D user and CUEs should cooperate to be beneficial for both systems. That is, which CUE should be selected for cooperation. Furthermore, how much of the D2D user's transmit power (ν_i) should be assigned to the CUE? In order to answer these questions, first we notice that the cellular system can benefit from cooperation if and only if the CUE's achievable rate with cooperation is at least equal to their direct link rate, i.e,

$$R_{c_i} \geq R_{\text{dir}}. \tag{5}$$

Since R_{c_i} is the minimum of two terms, both should be higher than the rate of the direct link which implies

$$R^{(1)}_{b,d_{\text{tx}}} \geq R_{\text{dir}}, \tag{6}$$

$$R^{(2)}_{d_{\text{tx}},i} \geq R_{\text{dir}}. \tag{7}$$

$R^{(1)}_{b,d_{\text{tx}}}$ is not a function of ν_i and is determined by the channel gains and the base station's power. On the other hand, the condition in (7) can be written as

$$\left(1+\Gamma^{(1)}_{b,i} + \frac{\nu_i}{1-\nu_i+\frac{1}{\Gamma^{(2)}_{d_{\text{tx}},i}}}\right) \geq \left(1+\Gamma^{(1)}_{b,i}\right)\left(1+\Gamma^{(2)}_{b,i}\right). \tag{8}$$

By simplifying (8) with respect to ν_i, we obtain

$$\nu_i \geq \left(1+\frac{1}{\Gamma^{(2)}_{d_{\text{tx}},i}}\right)\left(\frac{1}{1+\frac{1}{\Gamma^{(2)}_{b,i}(1+\Gamma^{(1)}_{b,i})}}\right) \triangleq \nu_i^{lb}. \tag{9}$$

Note that the lower bound on ν_i given in (9) is always a positive value, i.e., $\nu_i^{lb} > 0$.

For the D2D user to be able to cooperate with the ith cellular user, it should be able to decode the CUE's signal. This is possible if

$$R^{(1)}_{b,d_{\text{tx}}} \geq R^{(2)}_{d_{\text{tx}},i}. \tag{10}$$

The condition in (10) not only ensures the decoding in the D2D transmitter, but also ensures that the link between the base station and the D2D transmitter does not limit the CUE's achievable rate in (2).

Substituting (3) and (4) in (10), we get

$$\Gamma^{(1)}_{b,d_{\text{tx}}} - \Gamma^{(1)}_{b,i} \geq \frac{\nu_i}{1-\nu_i+\frac{1}{\Gamma^{(2)}_{d_{\text{tx}},i}}}. \tag{11}$$

If $\Gamma^{(1)}_{b,d_{\text{tx}}} - \Gamma^{(1)}_{b,i} \geq 0$, we obtain an upper bound on ν_i by simplifying (11) as

$$\nu_i \leq \frac{1+\frac{1}{\Gamma^{(2)}_{d_{\text{tx}},i}}}{1+\frac{1}{\Gamma^{(1)}_{b,d_{\text{tx}}}-\Gamma^{(1)}_{b,i}}} \triangleq \nu_i^{ub}. \tag{12}$$

The set of cellular users that can cooperate with the D2D transmitter should satisfy

$$0 < \nu_i^{lb} \leq \nu_i^{ub} < 1. \tag{13}$$

Denote this set of CUEs by $\mathcal{A}$. From the D2D user's point of view, it is desirable to spend as less power as possible for the CUE's signal, and therefore, our objective with respect to the constraints in (5) and (10) is

$$\min_{i\in\mathcal{A}} \quad \nu_i. \tag{14}$$

For each CUE that satisfy (13), the smallest power fraction for relaying is

$$\nu_i^* = \nu_i^{lb}, \quad i \in \mathcal{A}. \tag{15}$$

The user that needs the least power to fulfill its requirements is selected for cooperation as such choice is more beneficial for the D2D user, i.e.,

$$r = \arg\min_{i\in\mathcal{A}} \nu_i^*, \tag{16}$$

where r is the index of the cellular user which is chosen for cooperation.

The D2D user can achieve capacity gain if its receiver has the capability of interference cancelation. The condition for the D2D receiver to be able to cancel the intended signal for cellular user r is

$$R_{d_{\text{rx}}} \geq R_{c_r}. \tag{17}$$

Note that $R_{c_r} \geq R^{(2)}_{d_{\text{tx}},r}$ implies that $R_{d_{\text{rx}}} \geq R^{(2)}_{d_{\text{tx}},r}$. Thus, we have

$$\Gamma^{(1)}_{b,d_{\text{rx}}} + \frac{\nu_r}{1-\nu_r+\frac{1}{\Gamma^{(2)}_{d_{\text{tx}},d_{\text{rx}}}}} \geq \Gamma^{(1)}_{b,r} + \frac{\nu_r}{1-\nu_r+\frac{1}{\Gamma^{(2)}_{d_{\text{tx}},r}}}. \tag{18}$$

Therefore, the rate of the D2D user is given based on the condition in (18) as

$$R_{\text{d2d}} = \begin{cases} \frac{1}{2}\log_2\left(1+(1-\nu_r)\Gamma^{(2)}_{d_{\text{tx}},d_{\text{rx}}}\right), & \text{with IC,} \\ \frac{1}{2}\log_2\left(1+\frac{1-\nu_r}{\nu_r+\frac{1}{\Gamma^{(2)}_{d_{\text{tx}},d_{\text{rx}}}}}\right), & \text{without IC.} \end{cases} \tag{19}$$

IV. NUMERICAL STUDY

We evaluate the cooperation performance between CUEs and the D2D user, and the achievable gain of the D2D user

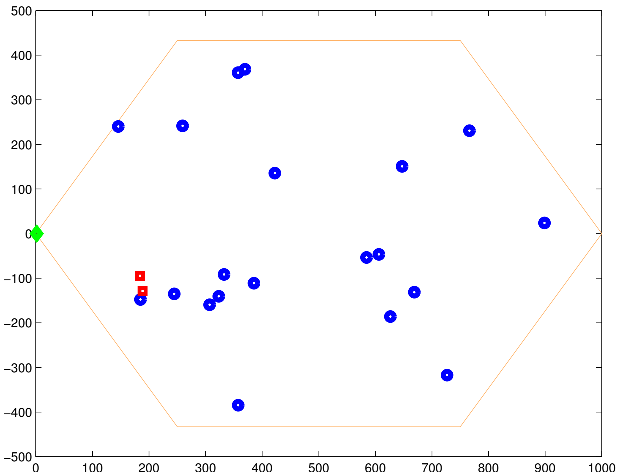

Fig. 3. Cell layout for $M = 20$ and one D2D pair.

in crowded environments for different system parameters by means of Monte-Carlo simulations. A single hexagonal cell with radius R is considered where the base station lies in the corner of the cell as depicted in Fig. 3. In each realization, M CUEs and one D2D pair are generated randomly and uniformly distributed over the cell area. The distance of the D2D receiver from its transmitter lies in range $20 < d_{\text{d2d}} < 50$ meters. Both base station and D2D transmitter use their maximum power for transmission. The fraction of the D2D transmit power that is assigned to either of the cooperative users is optimized. Simulation parameters are given in Table I.

The channel model accounts for the effects of path loss, multi-path fading, and shadowing. The path loss model for D2D communications has not been standardized yet and we use the model described in [16] which is based on the ITU recommendations for micro urban environment [17]. The path loss model is defined as

$$\text{PL} = C + 10\alpha \log_{10}(d), \tag{20}$$

where d is the distance between the transmitter and the receiver measured in meter. C and α are path loss coefficient and path loss exponent, respectively. As shown in [16], C is a function of the carrier frequency (f_c). The values of C and α are given in Table II for both line-of-sight (LoS) and non-line-of-sight (NLoS) scenarios. The average path loss is calculated as [16]

$$\overline{\text{PL}} = \beta \text{PL}_{\text{LoS}} + (1 - \beta)\text{PL}_{\text{NLoS}}, \tag{21}$$

where β is the probability of line-of-sight which for outdoor users, between the base station and a device is defined as

$$\beta = \min\left(\frac{18}{d}, 1\right)\left(1 - \exp\left(\frac{-d}{36}\right)\right) + \exp\left(\frac{-d}{36}\right), \tag{22}$$

and between devices as

$$\beta = \begin{cases} 1, & d \leq 4, \\ \exp(-(d-4)/3), & 4 < d < 60, \\ 0, & d \geq 60. \end{cases} \tag{23}$$

TABLE I
SIMULATION PARAMETERS.

Description	Parameter	Value
Max. UE TX power	P^d_{max}	24 dBm
BS TX power	P_{max}	41 dBm
Cell radius	R	$200, 500$ m
Noise power	N_0	-100 dBm
Carrier frequency	f_c	2 GHz
D2D pair distance	d_{d2d}	$20 - 50$ m
Shadowing (BS and devices)	σ_{sh}	10
Shadowing (devices)	σ_{sh}	12
Correlation distance	d_{cor}	20 m
Monte-Carlo runs	MC	20000

TABLE II
PATH LOSS PARAMETERS.

Device	type of PL	α	C
BS - UE	PL_{LoS}	2.2	34.04
BS - UE	PL_{NLoS}	3.67	30.55
UE - UE	PL_{LoS}	1.69	38.84
UE - UE	PL_{NLoS}	4	28.03

The log-normal shadowing $\mathcal{X} \sim \mathcal{N}(0, \sigma_{\text{sh}})$ is generated based on a correlated model described in [18], [19]. The multi-path fading component is distributed as $\mathcal{CN}(0, 1)$, where both its real and imaginary components are i.i.d. Gaussian distributed with $\mathcal{N}(0, \frac{1}{\sqrt{2}})$ [18]. We assume a Rayleigh block fading channel where the channel is constant during one time slot, but varies over different time slots.

Fig. 4 shows the CDF of the optimal fractional power that is assigned to the D2D links for its own communication, i.e., $1 - \nu_r$, versus different number of cellular users in the cell with radius $R = 200$ m. As the results indicate, the cooperation opportunities increase with the number of users. For low density of users, e.g., $M = 20$, in almost 60% of realizations the cooperation is impossible, and for the rest, high values of power are needed to be allocated to the cellular user for cooperation to be possible. On the contrary, when the user density in the cell is high, e.g., $M = 200$, the cooperation can be formed in 98% of instances. In the small cell, since we do not use power control for the base station's transmit power, the direct link data rate is high and satisfying (8) is difficult. Consequently, the feasible set $\mathcal{A}$ shrinks. Note that in this case, average received SNR at the cell border is 26 dB.

In Fig. 5, we change the cell radius to $R = 500$ m which shows that increasing the cell size increase the cooperation opportunities, especially when the number of cellular users in the cell is low. This is due to the fact that in such a scenario the condition (8) is easier to satisfy. Basically, the effect of cell size on the number of cooperation instances is similar to increasing the expected capacity gain by the cellular user. That is, if the cellular user puts more demand on the D2D user, the cooperation probability would be decreased and also the required power for cooperation would be increased.

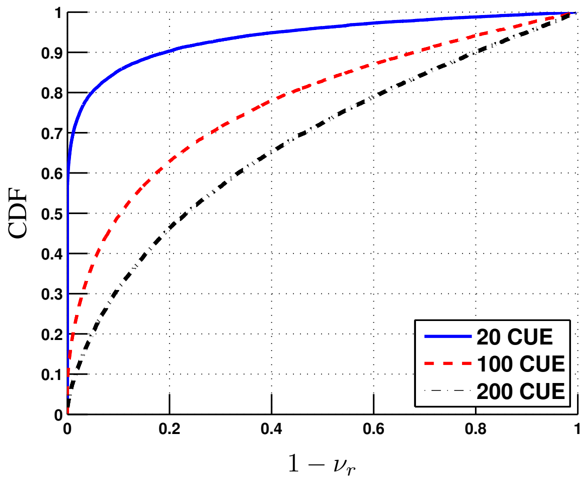

Fig. 4. CDF of $1 - \nu_r$ when $R = 200$ m.

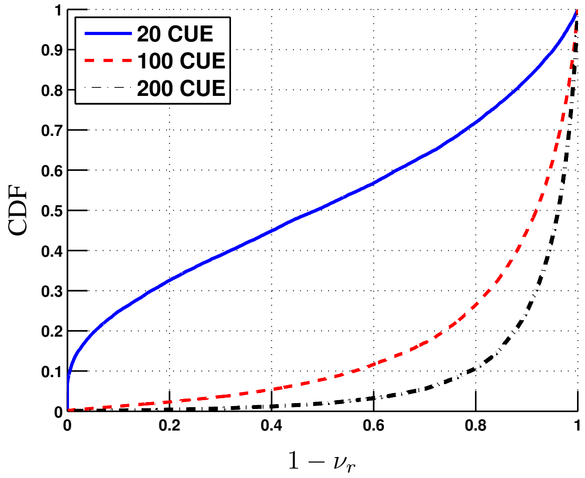

Fig. 5. CDF of $1 - \nu_r$ when $R = 500$ m.

Fig. 6 shows the achievable data rates for both cooperative cellular and D2D users when $R = 500$ m and $M = 20$. In case of cooperation in our model, the cooperative CUE always achieves the direct link data rate while the D2D user can also transmit with high data rate if interference cancelation condition (17) is satisfied. The cooperative D2D communication not only provides opportunities for transmission in high density areas, but also a high data rate for the D2D user leading to an increase in cell capacity.

Note that, our problem is modeled in a way that the CUE achieves at least its direct link rate. This is beneficial in cases where the network is overloaded in crowded areas. If cooperation should be used as a means of capacity improvement in bad spots, an extra capacity gain for cellular user should be defined, i.e., the CUE should achieve at least its direct link rate multiplied by the required gain factor. However, requiring a higher gain is equivalent to having a smaller cell size with the stronger direct link as we have considered in our results here. Therefore, if any cooperation is formed, the D2D user needs to invest more in the power assigned for the cellular user.

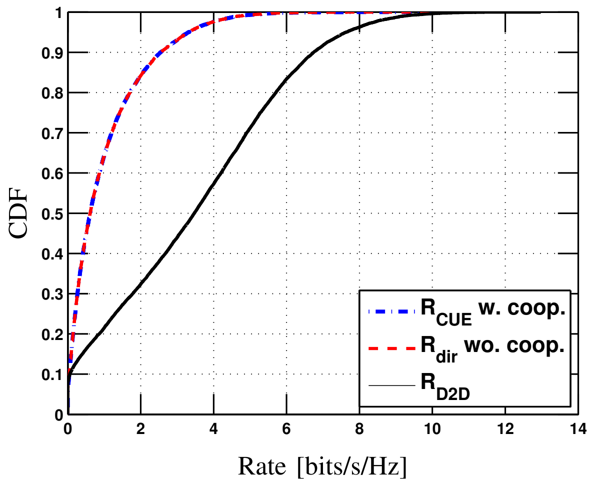

Fig. 6. CDF of data rates when $R = 500$ m and $M = 20$.

Fig. 7 depicts the probability of interference cancelation as a function of the number of CUEs in the cell for two cases. In the first case, we count the number of realizations in which the interference cancelation condition in (17) is satisfied only when cooperation between the D2D user and a cellular user is formed. That is, it shows when a cooperation is formed, the D2D receiver can cancel the interference from the cellular user in almost 90% of the instances. However, in the second case, we count the number of instances with satisfied condition for cancelation in all Monte-Carlo realizations, without considering if a cooperation is actually formed. This probability is seen to be high especially in denser cells. This is beneficial in terms of the D2D achievable rate.

In Fig. 8 the average rates of the cooperative CUE and D2D user are shown as a function of the number of CUEs in the cell with $R = 200$ m and $R = 500$ m. It can be observed that when the number of CUEs increases, the D2D user can find a cellular user that needs lower power to cooperate and as a result the D2D user can achieve higher data rates. Comparing the rates in the two cell sizes, we observe higher CUE rates in the smaller cell, which is expected since if any cooperation is formed in the smaller cell, the D2D user needs to assign higher fractional power ν_r to the cellular signal in order to satisfy the condition for cooperation. This leads to lower achievable rates for the D2D user.

V. CONCLUSIONS

We investigated the problem of cooperative D2D communications where one D2D pair co-exits with many CUEs in the cell. This framework allows the D2D transmitter to act as a relay for a cellular link and at the same time transmit its own data by employing superposition coding in the downlink. This problem targets crowded areas such as open air festivals and shopping malls where current infrastructure cannot support too

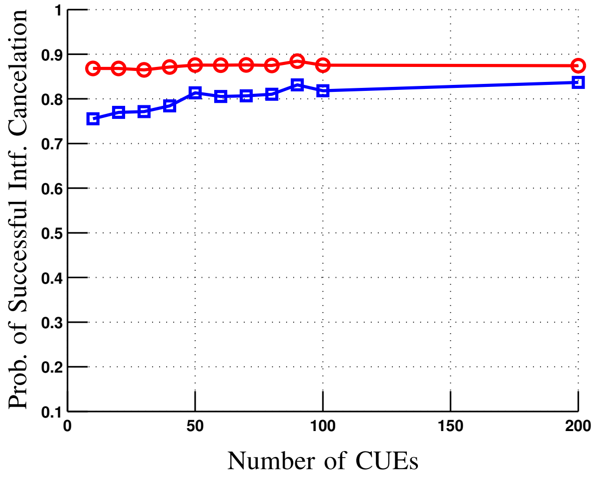

Fig. 7. Probability of interference cancelation for $R = 500$ m.

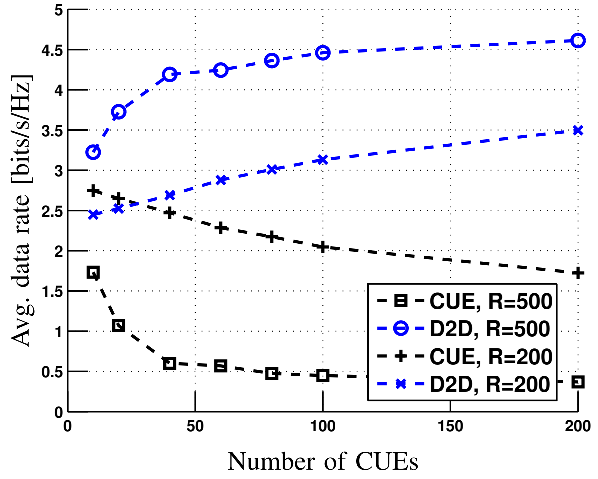

Fig. 8. Average rates vs. different number of CUEs for $R = 200, 500$ m.

many connections per unit area. We formulate our problem in order to minimize the assigned power for cooperation while achieving the direct link capacity for the cellular user. We assumed that the D2D receiver has the interference cancelation capability. The system performance is evaluated by means of Monte-Carlo simulations. Our results showed that cooperative D2D communications in a single cellular network are possible where D2D links can share the spectrum with cellular users without affecting their performance. We found that the cooperation possibilities increase with the number of cellular users willing to cooperate within the cell as well as the cell size. The achieved data rate of the cooperating D2D link increases with the number of cellular users willing to cooperate within the cell. We also observed that the D2D receiver is able to cancel the cellular user signal in most cases which can improve the achieved data of the D2D link.

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