On the Performance of the Device-to-Device Communication with Uplink Power Control

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Abstract— **New technologies have emerged to attend the increasing data rates demanded by multimedia services in wireless communication systems. In this context, Device-to-Device (D2D) communication appears as promising feature to improve data rates and increase spectral efficiency of wireless systems. Moreover, its combination with power control, which enables low-power communication among devices and contributes to reduce interference, can enhance even more such benefits in future wireless systems. In this work, we investigate the leverage of the uplink power control on the D2D communication underlaying cellular networks. The results show that the D2D communication applied together with power control can overcome cellular mode performance in terms of sum rate.**

Keywords— **Power control, D2D communication, sum rate.**

I. INTRODUCTION

D2D communication has received considerable attention due to the increasing need for spectrum efficiency and high data rates. Advantages of D2D communication include resource reuse and lower power consumption compared to conventional cellular systems. Thus, it is a promising technology to enhance the overall efficiency of next-generation wireless networks.

An introduction to D2D communication underlaying a cellular network is provided in [1], in which analytical expressions are derived for the probability of having D2D communication while ensuring that the resource sharing does not cause the Signal to Interference-plus-Noise Ratio (SINR) of a co-channel link to fall below a required minimum.

In [2], [3], the D2D communication as an underlay of a 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE)-Advanced network is investigated. The results show the practicability of co-existence of the D2D communication and the 3GPP LTE-Advanced network with interference constraints on the cellular communication in an interference limited scenario. In [3], it is shown that allowing D2D communications in the downlink of a cellular system is more challenging than in the uplink due to the increase in the downlink interference levels. However, the benefits of using LTE technology as a platform for D2D communication have not been sufficiently investigated. Questions as how interference margins should be controlled by the network remain open.

Few works have addressed the power control approach to D2D communication [4], [5]. In [4], the SINR distribution of D2D and cellular users is formulated and a simple power control method that limits the impact of D2D communication onto the cellular service is analyzed. In [5], two power control cases are analyzed: power optimization with greedy sum-rate maximization and power optimization with rate constraints. Nevertheless, these previous works have not considered a multi-cell scenario.

In [6], we study the role of the main link distances as a factor that could influence the mode selection in a D2D communication system underlaying a cellular system. In addition to [6], this work focuses on the benefits of the D2D communication when jointly applied with a centralized power control algorithm in a multi-cell scenario. Furthermore, our analysis considers the *feasibility* of the power control problem given the target SINR values as part of the system performance evaluation.

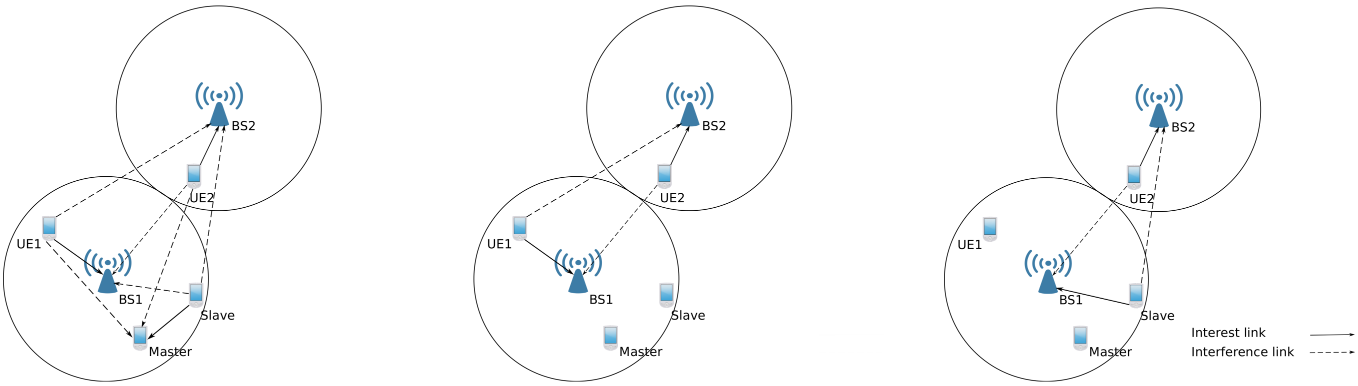
The remainder of this paper is organized as follows. In Section II, we describe our D2D communication model. Section III describes the power control algorithm employed in this work. Section IV addresses the D2D system performance with and without power control in terms of sum rates. Finally, conclusions are drawn in Section V.

II. SYSTEM MODEL

In this section, we present the proposed scenario to investigate the potential sum rate gains from D2D communication compared to conventional cellular systems.

Fig. 1 illustrates our study scenario. It consists of two circular cells, each one having one *Base Station (BS)* at its center. One *User Equipment (UE)* and one D2D pair are assigned to the first cell. In the second cell, we model an interfering link considering one cellular *UE*. We assume that the communication occurs only during the uplink frame, in which *UEs* transmit to *BSs*. Two communication modes are considered:

- D2D mode: D2D users share the same resources with the cellular users, causing interference to each other. In the D2D pair, we call the transmitting node as *Slave* and the receiving node as *Master*. In this mode, *UE1* transmits to *BS1*, *Slave* to *Master*, and *UE2* to *BS2*. We calculate rates at the *BS1*, *BS2* and *Master*;
- Cellular mode: the D2D terminals can not communicate with each other directly. The terminals use orthogonal



(a) D2D Mode. (b) Phase 1 cellular Mode. (c) Phase 2 cellular Mode.

Fig. 1. Study scenario with the interest and interference links for both communication modes: D2D and cellular.

resources in the same cell, but we assume co-channel interference among users of the different cells. There are two phases in this mode. In phase 1, *UE1* transmits to *BS1*. In phase 2, the *Slave* transmits to *BS1*. In both phases, the *UE2* transmits to *BS2*. Here we calculate rates at the *BS1* and *BS2* per phase.

Our channel model considers path loss, shadowing and fast fading. Next, we calculate the average sum rate of the D2D and cellular connections using Shannon's capacity formula considering the average *feasibility* ζ given target SINR values for each link. When no power control is assumed, full transmit power is assumed and the average sum rate C_{d2d} for the D2D mode is given by

$$C_{d2d} = \zeta \cdot \log_2((1+\gamma_1)\cdot(1+\gamma_M)\cdot(1+\gamma_2)), \qquad (1)$$

where γ_1, γ_M and γ_2 are the target SINRs at the *BS1*, *Master* and *BS2*, respectively and ζ is the average *feasibility* defined as

$$\zeta = \frac{n_f}{n_r}, \qquad (2)$$

where n_f is the number of feasible cases, i.e., in which all links reach their target SINR values, and n_r is the total number of channel realizations.

The average sum rate C_{cell} in the cellular mode is obtained by averaging the sum rate of the two phases, i.e.,

$$C_{cell} = \frac{1}{2}(C^1_{cell} + C^2_{cell}), \qquad (3)$$

where

$$C^n_{cell} = \zeta \cdot \log_2((1+\gamma^n_1)\cdot(1+\gamma^n_2)), \qquad (4)$$

where γ^n_1 and γ^n_2 are the target SINRs at the *BS1* and the *BS2* in the phase $n = 1, 2$, respectively.

When power control is considered, the average sum rate expressions for D2D and cellular modes are obtained as in (1) and (3), respectively, except that the average *feasibility* is now defined as

$$\zeta^{pc} = \frac{n^{pc}_f}{n_r}, \qquad (5)$$

where n^{pc}_f is the number of feasible cases considering a power control algorithm. A feasible case is characterized by achieving the target SINRs values in all links with powers smaller or equal to the maximum allowed power of each transmitting node.

Others parameters used in this work are shown in Table I.

Table I

SIMULATION PARAMETERS

Parameter	Value
Path loss model	128.1+37.6log(d), with d in km
Inter site distance	500 m
Shadowing standard deviation	8 dB
Noise power	-116.4 dBm
UE Maximum transmit power	24 dBm

III. POWER CONTROL ALGORITHM

In this section, we describe the power control algorithm utilized in our analysis. Power control is a resource allocation technique which adjusts the power levels of all communication links as to improve the interest link quality and decrease the interference of the others links [7]. It also promises capacity enhancements while meeting the Quality of Service (QoS) requirements and reducing battery power consumption.

Centralized power control algorithms assume that all co-channel link gains are known at a central controller, which can find the optimal solution to control the transmit power of all links. This is not suitable in real implementations due to excessive signaling, but is valuable as performance upper bound for distributed power control algorithms which use only local measurements and are, therefore, more suitable for practical implementation. A more extensive survey and more detailed analysis of power control algorithms can be found in [8].

Recently, [9] proposed two control power strategies for the uplink of a multi-cell spatial multiplexing wireless systems. In the first one, the authors present a necessary and sufficient condition on the existence of a feasible solution and develop the closed-form solution optimal in terms of an SINR lower bound. The second one develops the power control with adaptive power allocation based on game theory, where an iterative algorithm is used to sequentially update each user's power distribution.

In our analysis, we consider the first power control strategy proposed in [9], in which a SINR lower bound based on an eigenvalue approximation of the composite interference is employed. Furthermore, we start our study from a simple case where we only adopt power control on Single Input Single Output (SISO) systems. The closed-form solution for the feasible power vector $\mathbf{p}^*$ is based on the assumption that a centralized controller has perfect Channel State Information (CSI) on all links. It is derived in [9] as

$$\mathbf{p}^* = (\mathbf{I} - \mathbf{\Lambda F})^{-1} \mathbf{\Lambda n}, \tag{6}$$

where $\mathbf{I}$ is an identity matrix, $\mathbf{\Lambda}$ is a diagonal target SINR matrix for K users, $\mathbf{F}$ is a normalized gain matrix given by

$$\mathbf{F}_{k,j} = \begin{cases} 0, & \text{if } k = j, \\ \dfrac{\alpha_{k,j}\chi_{k,j}}{\alpha_{k,k}\chi_{k,k}} \mu_{max}\left(\mathbf{\Omega}_{k,j,1}\right), & \text{if } k \neq j, \end{cases} \tag{7}$$

where $\alpha_{k,j}$ and $\chi_{k,j}$ are the path loss attenuation and the log-normal shadow fading of the kth UE to the jth BS, respectively. In addition, $\mu_{max}(\cdot)$ is the maximum eigenvalue of the Hermitian matrix $\mathbf{\Omega}_{k,j,1}$, which is given by

$$\mathbf{\Omega}_{k,j,1} = \left| \frac{\mathbf{H}_{k,j}}{\mathbf{H}_{k,k}} \right|^2, \tag{8}$$

where $\mathbf{H}_{k,j}$ is the channel transfer matrix from jth UE to the kth BS and $|x|$ denotes the norm of x. Finally, $\mathbf{n}$ is a $K \times 1$ noise vector, where the kth element is $\dfrac{\sigma_n^2}{\alpha_{k,k}\chi_{k,k}} \mu_{max}\left(\mathbf{\Omega}_{k,j,2}\right)$. In addition, σ_n^2 is the noise power and $\mathbf{\Omega}_{k,j,2} = \frac{1}{|\mathbf{H}_{k,k}|^2}$. A more detailed description of this power control algorithm is out of the scope of this section. For a detailed analytical development of the referred algorithm, please refer to [9].

IV. Results and Analysis

In this section, we compare the performance of D2D and cellular communication with and without power control in terms of the achieved average sum rate. We wish to analyze the potential gains of the centralized power control algorithm proposed in [9] when simultaneously applied to D2D communication underlaying a cellular network.

We consider three case studies of the considered scenario, in which we set different positions to the D2D pair and to the *UE1* in the cell. The positions of *BS1*, *BS2* and *UE2* are fixed for the three cases. Our aim is to investigate the influence of the uplink power control on D2D communication in three different situations. A more detailed study about the key distances in D2D communication can be found in [6]. The positions of the devices in a coordinate system centered at the *BS1*'s position are given in the Table II.

Table II

Devices' positions in the three assumed cases (in meters).

Device	First Case	Second Case	Third Case
BS1	(0,0)	(0,0)	(0,0)
UE1	(0,-50)	(-30,20)	(-30,20)
Master	(-90,-130)	(-90,-110)	(-40,-130)
Slave	(20,-130)	(-90,-130)	(-140,-130)
BS2	(400,300)	(400,300)	(400,300)
UE2	(425,325)	(425,325)	(425,325)

We fix γ_2 to 10 dB and vary each component of $(\gamma_{t1}, \gamma_{t2})$ from 0 to 25 dB. The pair $(\gamma_{t1}, \gamma_{t2})$ corresponds to (γ_1, γ_M) in the D2D mode and to (γ_1^1, γ_1^2) in the cellular mode. Moreover, we consider rate mapping and select the proper Modulation and Coding Scheme (MCS) based on the Table III. Our analysis considered 1,000 channel realizations over which the obtained results are averaged.

Table III

Modulation and Coding Scheme

Modulation	BPSK	4-QAM	16-QAM	64-QAM
Data Rate (in bps)	1	2	4	6

The first case presents an unfavorable scenario to the D2D communication in which the D2D pair distance is 100 m, i.e., a large distance. We set the distance from *UE1* to *Master* to ≈120 m. Figures 2(a) and 2(b) show the D2D and cellular sum rates with and without power control, respectively. In both figures, the sum rates are conditioned to the average feasibility of the the target SINR values shown in the figure axes.

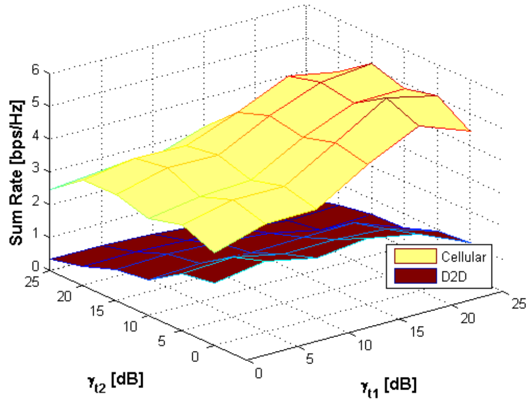
In Figure 2(a) we see that the cellular sum rate is higher than D2D sum rate for all target SINRs values. This behavior was expected due to the large distance between the nodes of the D2D pair. Figure 2(b) shows the results after applying the power control algorithm. It can be seen that the sum rate increases for both communication modes. The sum rate obtained with the cellular mode remains greater than that obtained with the D2D one in almost 100% of the cases. This result shows that, in unfavorable situations to D2D communication, power control would not be sufficient for the D2D mode to overcome the cellular mode in terms of sum rate.

In Figure 2(b), note that for the cellular mode the rate increases for large values of target SINRs. This happens because of the high percentage of feasible cases therein. For example, for the target SINR pair (25 dB, 25 dB) we have that 86% of channel realizations are feasible, while for the target SINR pair (0 dB, 0 dB) feasibility reaches 99.5%. Consequently, for this case the cellular mode is feasible and can obtain high rates for all the considered target SINR values. Similar analyses and conclusions can also be drawn for the other results in this section.

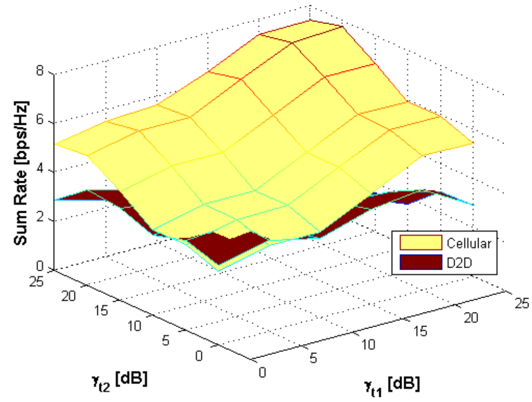
In the second case, the D2D link distance is small and a considerable gain can be achieved by D2D communication over cellular communication as illustrated in the Figures 3(a) and 3(b). In this favorable case to D2D communication, the distance between *Master* and *Slave* is 20 m. Additionally, the distance between the interfering *UE1* to *Master* is ≈143 m.

In Figure 3(a), we can see that the D2D mode sum rate is higher than that achieved using the cellular mode in most of the target SINR values. However, when the power control is utilized, Figure 3(b), this occurs for 100% of the target SINR values. Again, the sum rate increases to both communication modes. This result is different of the previous case where the power control did not give support to the D2D communication to outperform the cellular communication. The second case illustrates that the utilization of the power control can substantially enhance the D2D communication performance.

Besides the previous cases, we investigate an intermediate case that considers a D2D pair distance of 100 m. However, the *UE1* is far away (150 m) from *Master*, thus causing less

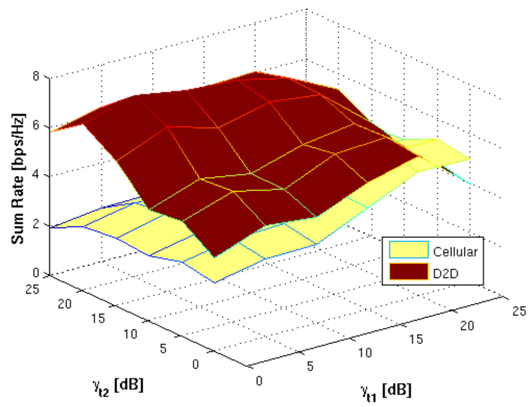


(a) Sum rate without power control.

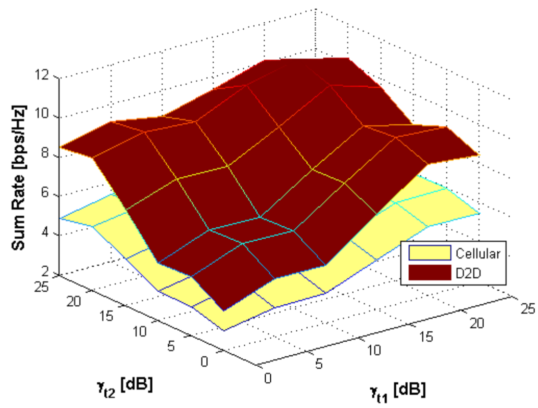


(b) Sum rate with power control.

Fig. 2. Sum rate for the first case – Unfavorable case for D2D mode.

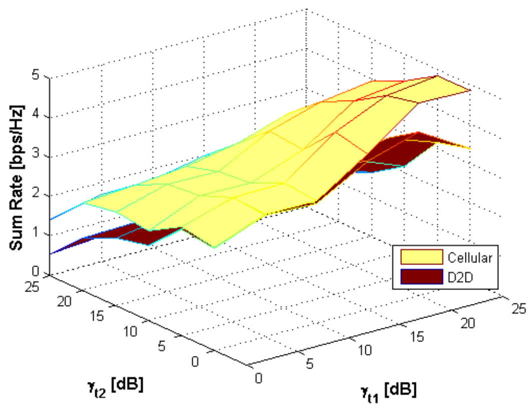


(a) Sum rate without power control.

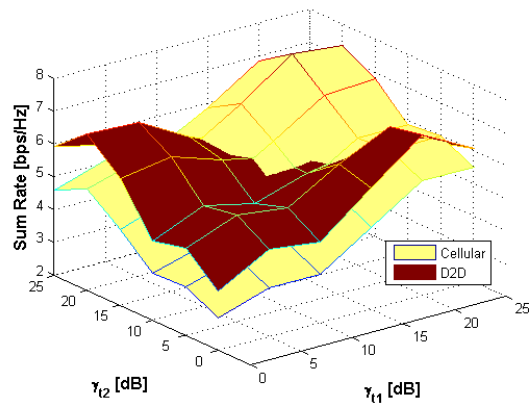


(b) Sum rate with power control.

Fig. 3. Sum rate for the second case – Favorable case for D2D mode.



(a) Sum rate without power control.



(b) Sum rate with power control.

Fig. 4. Sum rate for the third case – Intermediate case for D2D mode.

interference to the D2D communication. In Figure 4(a), we can see that the cellular sum rate is always higher than the sum rate using D2D communication when power control is not used. However, when the power control algorithm is applied, as we can see in the Figure 4(b), the sum rate achieved using the D2D mode overcomes that of the cellular mode for two thirds of the target SINR values.

In order to take more conclusions about the use of the power control with D2D communications, we keep fixed the positions of the *BS1*, *BS2* and *UE2* and vary the positions of the *Master*,

(a) Sum rate CDF without power control.

(b) Best sum rate CDF with power control.

Fig. 5. Sum rate CDF considering 100,000 position and channel realizations

Slave and *UE1* randomly. We considered 100,000 realizations of the positions and channels. In Figure 5(a) we show the sum rate Cumulative Distribution Function (CDF) of the D2D and cellular modes. As expected, see [6], the cellular mode has better performance than D2D mode when we consider a large number of position combinations. In this analysis, we find that the D2D mode outperforms the cellular mode in terms of sum rate in almost 30% of the cases.

When power control is assumed, we vary each component of $(\gamma_{t1}, \gamma_{t2})$ from 0 to 25 dB and consider the best achieved sum rates for both communication modes. In Figure 5(b), differently from the prior result, we can observe that the most of the maximum sum rates obtained by D2D mode are higher than those obtained by cellular mode. The best sum rates of D2D mode overcomes the best sum rates of cellular mode in about 55% of the cases keeping the same positions in both modes.

We can also note that the high percentage of feasible cases of the cellular mode concentrates the best sum rate CDF of this mode around 12 bps/Hz, the possible maximum sum rate for the cellular mode. Nonetheless, when the power control for D2D is feasible, the sum rate performance for D2D mode is usually better than cellular one because the D2D mode reuses radio resources.

V. Conclusions

D2D communication is a promising feature to attend the required high data-rates specified by the International Mobile Telecommunications-Advanced systems. Because of the challenges from interference in a hybrid network integrating D2D communication and conventional cellular communication, Radio Resource Management techniques, such as power control, become essential to leverage the performance of communication modes when they share the same radio resources.

In this work, we analyze the potential gains of the D2D communication when jointly applied with a centralized power control algorithm in a multi-cell scenario. We conduct our power control analysis considering the *feasibility* of the power control problem given the target SINR values as part of the system performance evaluation.

The results demonstrate that the D2D communication can overcome cellular communication performance in certain configurations for the considered scenario. Therefore, the joint consideration of the mode selection and power control would be a key point to improve the overall system performance.

As mentioned previously, several issues still need to be further investigated to identify the benefits of the co-existence of the D2D communication and the cellular network. Towards this end, we will extend this work as to encompass the gains of the Multiple Input Multiple Output transmission schemes.

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