Performance Analysis of Power Control for Device-to-Device Communication in Cellular MIMO Systems

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***Abstract*—The Device-to-Device (D2D) communication can increase data rates and resource utilization in cellular networks. However, the direct application of the D2D communication can cause harmful interference to the cellular network. Therein, power control algorithms become essential tools to keep interference controlled and to ensure improved system performance. In this paper, we study two power control strategies for D2D communication within Multiple Input Multiple Output (MIMO) cellular networks. In the first strategy, each user achieves a certain target Signal to Interference-plus-Noise Ratio (SINR) while minimizing the total transmit power. In the second one, the target SINR varies with user's transmit power. Simulation results show that system capacity can be improved only if D2D communication and power control are appropriately combined.**

I. INTRODUCTION

With the growth of several kinds of multimedia services, such as Multimedia Message Service (MMS), mobile TV, mobile video telephony, etc., the requirement for higher data rate has exponentially increased. In this context, network-assisted D2D communication promises to improve the resource utilization in cellular networks, building an underlay that allows for direct and low-power communication among devices, reduced cellular network overloading, improved radio resource sharing, lower delays and increased network capacity compared to networks using conventional cellular communications only [1].

D2D communications can profit from the proximity between User Equipments (UEs) to attain higher data rates and/or use lower transmit powers. This direct communication mode can use dedicated resources or share resources with cellular communications [2] and in this last case the spectrum efficiency can be increased. Besides that, D2D communication uses a single link rather than using an uplink and a downlink resource as in traditional cellular networks.

However, the inadequate application of the D2D communication can cause severe interference to conventional cellular networks, which in turn can lead system performance losses. Therefore, Radio Resource Management (RRM) techniques take a key role to ensure improved performance. In [3], the authors propose a joint optimization framework for mode selection, resource assignment and power allocation. The results indicate that the resource allocation combined with mode selection can play a key role in the system performance.

Power control is one of these RRM techniques which balances the power levels of all system communication links, thus providing capacity enhancements while meeting the Quality of Service (QoS) requirements. Several works have discussed power control schemes for D2D communication. 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. More recently, [6] analyzed different power control schemes for D2D communication in the Uplink (UL) of a 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) system.

In this paper, we analyze a cellular system in which the resources can be used for D2D and cellular communications simultaneously. In particular, we considered the UL of an LTE-like system. Differently from previous works, we consider the use of two power control strategies with MIMO antennas. Both strategies try to minimize the power consumption while meeting minimum SINR requirements. In the former, each user achieves a certain target SINR while minimizing the total transmit power. In the latter, the UEs' target SINR is not a fixed value, but it varies with their required transmit power.

In addition to [7], where we investigate mode selection and resource allocation algorithms, this work focuses on the benefits of the D2D communication when jointly applied with power control algorithms. We are interested in modeling situations in which D2D communications are expected to take place and, therefore, we consider the existence of a large amount of UEs concentrated in a same area.

The remainder of this paper is organized as follows. In Section II, we describe the system model. In Section III, we describe the two MIMO power control strategies considered in our analysis. In Section IV, the performance of the proposed power control algorithms is discussed. Finally, conclusions are presented in Section V.

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II. System Modeling

In this section, we detail the scenario and models considered in our analysis. We consider a multi-user scenario where multiple cellular and D2D users are present. Besides that, we assume the existence of a *hotspot*. The idea of the *hotspot* is to take advantage of the cases where a pair of D2D-capable UEs are closer to each other, far from the Evolved Node B (eNB), and willing to communicate directly. Thus, in our analysis we uniformly drop D2D users over the *hotspot* area and cellular users over the whole cell area. In fact, in [7] we have shown that in cases presenting D2D nodes in hotspots it is much more advantageous to set up a D2D communication than a cellular one.

In our model, two D2D-capable UEs within the hotspot area are paired randomly to build a D2D pair. Analogously, two cellular UEs within the cell area are also randomly paired. Then, we took one D2D pair and one pair of cellular UEs to form a group of four UEs. Such a four-UE group can be assigned for one or more specific Physical Resource Block (PRB) depending on the adopted Radio Resource Allocation (RRA) scheme. After performing the resource allocation, we analyze the power control strategies on the UL connections of D2D and cellular users. The details of the resource allocation considered in our analysis can be found in [7].

Figure 1 shows the interest and interfering links when one cellular and a D2D pair share the same resources in the UL. Our study scenario consists of two circular cells, each one having one eNB at its center. Notice that in the multiple user case in the UL, groups consisting of one cellular UE and one pair D2D will be sharing resources in first cell. In the second cell, we model an interfering link considering one fixed cellular UE, namely UE_2. The positions of eNB_1, eNB_2, and UE_2 are fixed while the positions of the UEs in the first cell are uniformly distributed.

Our system model assumes the use of multiple antennas at both transmitters and receivers. Therefore, we need to calculate the SINR of each stream for each receiver in order to estimate data rates. The SINR of stream s of receiver k on a given PRB is calculated as

$$\gamma_{k,s} = \frac{p_{k,s}|\mathbf{r}_{k,s}\mathbf{H}_{k,k}\mathbf{t}_{k,s}|^2}{\sum\limits_{m\neq s} p_{k,m}|\mathbf{r}_{k,s}\mathbf{H}_{k,k}\mathbf{t}_{k,m}|^2 + \sum\limits_{j\neq k}\sum\limits_{n} p_{j,n}|\mathbf{r}_{k,s}\mathbf{H}_{k,j}\mathbf{t}_{j,n}|^2 + \sigma^2} \tag{1}$$

where $\mathbf{H}_{k,j}$ is the channel matrix between a receiving node k and a transmitting node j, $\mathbf{r}$ and $\mathbf{t}$ represent respectively the receiver and transmitter precoding filters associated to stream s, and $p_{k,s}$ stands for the power allocated to stream s of receiver k. For simplicity of notation, no index for PRB is used in (1). Moreover, the first term of the denominator of (1) shows the interference that the other streams of the link of interest cause in the receiver itself, the second term shows the interference caused by all the streams of the other links and, finally, σ^2 denotes the average noise power.

In this work, the rates achieved by a receiving node are determined by mapping SINR values to rate values considering ideal link adaptation according to the link level results from [8]. A total of 15 different Modulation and Coding Schemes (MCSs) are considered and after defining the MCS based on the SINR value, we consider that the communication occurs error-free. Two communication modes are defined:

- **D2D mode in UL**: D2D UEs can communicate with each other directly. The D2D pair share the same resources with the cellular UEs. For the D2D link, we call the transmitting UE as $D2D_{Tx}$ and the receiving UE as $D2D_{Rx}$. In this communication mode, UE_1 transmits to eNB_1, $D2D_{Tx}$ to $D2D_{Rx}$, and UE_2 to eNB_2. The sum rate for D2D mode is calculated on the rates at the eNB_1, eNB_2 and $D2D_{Rx}$;
- **Cellular mode in UL**: UEs communicate with each other via conventional cellular network, i. e., always through a eNB. As the UEs use orthogonal resources in the same cell, there are two phases in this mode. In phase 1, UE_1 transmits to eNB_1. In phase 2, the $D2D_{Tx}$ transmits to eNB_1. In both phases, the UE_2 transmits to eNB_2. The rates are calculated at the eNB_1 and eNB_2 per phase. The sum rate for cellular mode is obtained by averaging the sum rate of the two phases.

III. Power Control Strategies

In this section, our goal is to describe two power control strategies: one with fixed target SINR value and another with variable target SINR values. In the first strategy, each user achieves a certain target SINR while minimizing the sum power. In the second one, the target SINR is not a fixed value, but varies with user's required transmit power decreasing as the demanded power increases.

A. Power Control with Fixed Target SINR

The power control problem in MIMO systems that aims at minimizing the total transmit power while ensuring minimum target SINR values per stream can be stated as

$$p^{\star}_{k,s} = \arg\min_{\mathbf{P}} \sum_{k=1}^{K}\sum_{s=1}^{S_k} p_{k,s} \tag{2a}$$

subject to

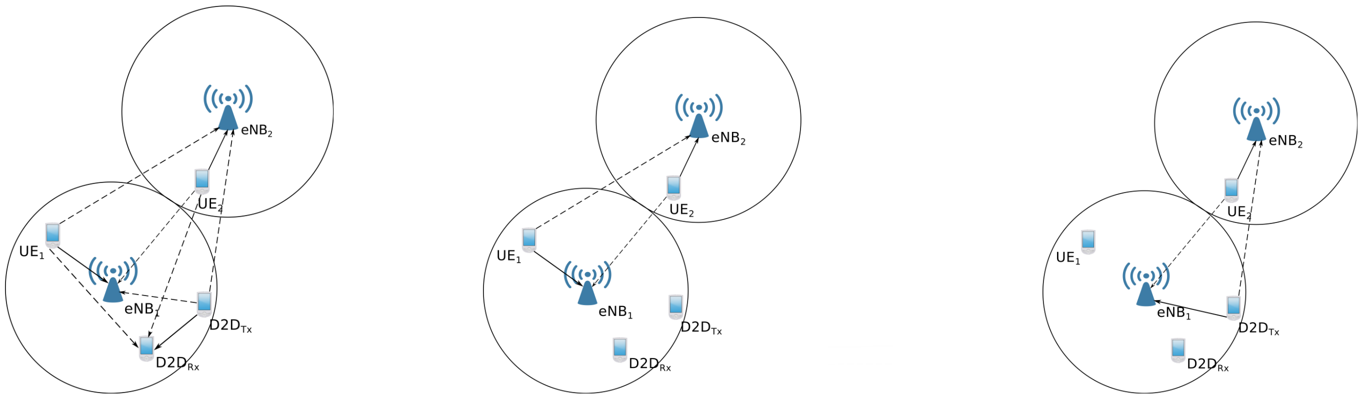
$$\gamma_{k,s} \geq \mathit{\Gamma}_{k,s}, \tag{2b}$$

$$\sum_{s=1}^{S_k} p_{k,s} \leq P_k, \quad \forall k \in \{1,\ldots,K\} \tag{2c}$$

$$p_{k,s} \geq 0, \quad \forall k \in \{1,\ldots,K\} \text{ and } s \in \{1,\ldots,S_k\} \tag{2d}$$

where $\mathit{\Gamma}_{k,s}$ is the target SINR value of the stream s of the UE k, S_k is the number of streams of UE k, which is limited by minimum number of transmit and receive antennas, and P_k is the maximum sum power constraint of UE k.

The fundamental idea here is to sequentially update each $p_{k,s}$ by treating interference as fixed at each time, so that each stream s of each UE k achieves its target SINR. Power optimization is conducted according to the channel inversion principle as to minimize the power of each single UE. It corresponds to allocate power proportionally to the inverse of the effective channel gain so that links with good channels are



(a) D2D Mode. (b) Cellular Mode – Phase 1. (c) Cellular Mode – Phase 2.

Figure 1. Study scenario with the interest (solid lines) and interference links (dashed lines) for both D2D and cellular communication modes in UL.

allocated less power, while links in deep fading are allocated more power to achieve their target SINR values. This is a well-known approach in the power control literature for maximizing the minimum SINR among co-channel links. The power allocation process is repeated iteratively until a fixed point be reached and at which the sum power is minimized.

The principle previously mentioned is describe in the Algorithm 1. This algorithm considers multi-antenna nodes and is derived from power control algorithms based on *interference functions* proposed by [9]. Starting from an initial power vector, the algorithm iteratively updates the power of each stream as shown in Algorithm 1, where the term $\zeta_{k,s}$ represents the effective interference perceived by the stream s of the UE k. This procedure is repeated until the convergence be reached.

Algorithm 1 Iterative Channel Inversion Power Control

1) Let $t \leftarrow 0$
Set $\mathbf{p}^0$
2) Let $t \leftarrow t+1$
for $k = 1 \rightarrow K$ **do**
  for $s = 1 \rightarrow S_k$ **do**
    a) Compute $\zeta_{k,s} = f(\mathbf{p}^{(t-1)})$
    b) Calculate $p_{k,s}^{(t)} = \Gamma_{k,s}\zeta_{k,s}$
  end for
end for
3) If $\frac{|p_{k,s}^{(t)} - p_{k,s}^{(t-1)}|}{p_{k,s}^{(t-1)}} \leq \eta, \quad \forall k, s$, stop, otherwise go to step 2), where η is a small scalar value used to determine if the convergence has been reached.

Assuming that the power control problem is feasible and $\gamma_{k,s} \geq \Gamma_{k,s}$, it is intuitive that the sum power of UE k is minimized by enforcing $\gamma_{k,s} = \Gamma_{k,s}$ for each stream. Otherwise, the power of UE k can be lowered while meeting $\Gamma_{k,s}$. According to [9], if the target SINR values are jointly feasible, the Algorithm 1 converges to the optimum power allocation $p_{k,s}^{\star}$.

B. Power Control with Variable Target SINR

An alternative approach to increase feasibility of power control problems is to use a variable target SINR going from a maximum value Γ_{max} to a minimum value Γ_{min} as the required transmit power goes from a minimum value P_{min} to a maximum P_{max}. In this way, when a link raises its transmit power, it will low its target SINR. As a consequence, the variable target SINR algorithm encourages a link to aim at lower target SINR values and so increases the likelihood that all co-channel links be supported and that a feasible power control problem be configured. This approach in which target SINR gradually decreases as the required transmit power rises is called soft dropping in [10].

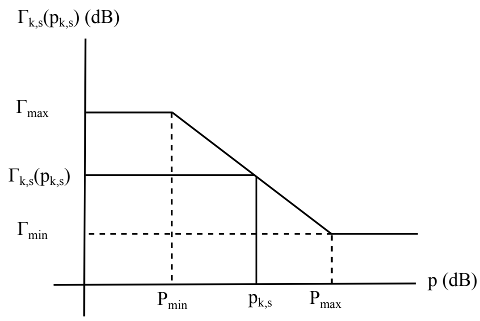


Figure 2. The variable target SINR.

The principle of the soft dropping algorithm is illustrated in the Figure 2. The SINR of the stream s of UE k must satisfy

$$\gamma_{k,s}(\mathbf{p}) \geq \Gamma_{k,s}(p_{k,s}) \tag{3}$$

where $\Gamma_{k,s}(p_{k,s})$ is the target SINR for stream s of UE k which varies according to the required transmit power $p_{k,s}^{(t)}$. For $p_{k,s}^{(t)} \leq P_{min}$, one attempts to maintain a high quality connection by aiming for a target SINR Γ_{max}. For $p_{k,s}^{(t)} \geq P_{max}$, one aims at a target SINR Γ_{min} which is relatively easier to reach when channel conditions are bad. Finally, for $P_{min} < p_{k,s}^{(t)} \leq P_{max}$, one aims for a target SINR $\Gamma_{k,s}(p_k)$ that linearly trades SINR for transmit power in dB scale as illustrated in Figure 2. Thus, the variable $\Gamma(\cdot)$ can be written

$$\Gamma_{k,s}(p_{k,s}^{(t)}) = \begin{cases} \Gamma_{max}, & p_{k,s}^{(t)} \leq P_{min} \\ \Gamma_{max}\left(\dfrac{p_{k,s}}{P_{min}}\right)^{\rho}, & P_{min} < p_{k,s}^{(t)} < P_{max} \\ \Gamma_{min}, & p_{k,s}^{(t)} \geq P_{max}, \end{cases} \tag{4}$$

where

$$\rho = \frac{\log_{10}(\Gamma_{min}/\Gamma_{max})}{\log_{10}(P_{max}/P_{min})}, \tag{5}$$

is slope of the power-target SINR curve of Figure 2.

From [10], the soft dropping algorithm can be written as

$$p_{k,s}^{(t+1)} = p_{k,s}^{(t)}\left(\frac{\Gamma_{k,s}(p_{k,s}^{(t)})}{\gamma_{k,s}(\mathbf{p}^{(t)})}\right)^{\beta_k} \tag{6}$$

where $0 < \beta_k \leq 1$ is a control parameter.

By adapting taking into account the variable target SINR values as described in this section, the same algorithm of section III-A is straightforwardly modified and applied to our scenario.

IV. Results and Analyses

In this section, we show the results for the two power control strategies described in Section III when simultaneously applied to D2D and cellular communication modes. The Round Robin (RR) criterion described in [7] has been chosen as resource allocation algorithm with the aim of being fair by assigning the same number of PRBs to every group of UEs. This resource allocation scheme generates a list with all groups of UEs and assigns randomly one PRB to each group following the list order and the process starts again from the beginning of the list once all groups received one PRB. Nevertheless, other RRA criteria can be equally applied to the strategies studied in this work.

Herein, non-feasibility is assumed to occur if the power control algorithm does not converge to a feasible solution after 50 iterations. The parameter of convergence of the fixed SINR power control algorithm is $\eta = 10^{-4}$. A total of 100 UEs, of which 50% are D2D-capable UEs, were randomly distributed in the first cell and 1,000 Monte Carlo realizations have been performed. In our results, we investigated the Single Input Single Output (SISO) and 2×4 MIMO antenna configuration with Singular Value Decomposition (SVD)-based spatial filtering. The others simulation parameters used for obtaining power control results are summarized in Table I.

The factor β used for the power control algorithm with variable SINR has been set to $\beta = 0.3$. One can show that $\beta \leq 1/(1-\rho) = 0.5$ is required for the convergence of the power control iteration. In general the higher the value of β, the faster the algorithm converges.

Figure 3 compares the probability of feasibility of the power control algorithms for cellular and D2D communication modes when SISO and MIMO antenna configurations are considered. Therein, we have set the target SINR of the fixed SINR power control algorithm (FSPCA) to the value of 15 dB. From the results, we observe that the variable SINR power control algorithm (VSPCA) substantially increases the feasibility of the power control to D2D and cellular communication modes.

Table I
Simulation Parameters Values

Parameter	Value
Number of Resource Blocks	25
Number of subcarriers per Resource Block	12
Channel Model	3GPP Typical Urban (TU)
Path loss model for cellular links	$128.1 + 37.6\log_{10}(d)$, d in km
Path loss model for D2D links	$127 + 30\log_{10}(d)$, d in km
Cell Radius	250 m
Inter site distance	500 m
Hotspot radius	50 m
Noise power	-116.4 dBm
Standard deviation of shadowing	8 dB
Total simulation time	1 TTI
Maximum transmission power	24 dBm
Minimum transmission power	-6 dBm
Maximum target SINR	20 dB
Minimum target SINR	-5 dB

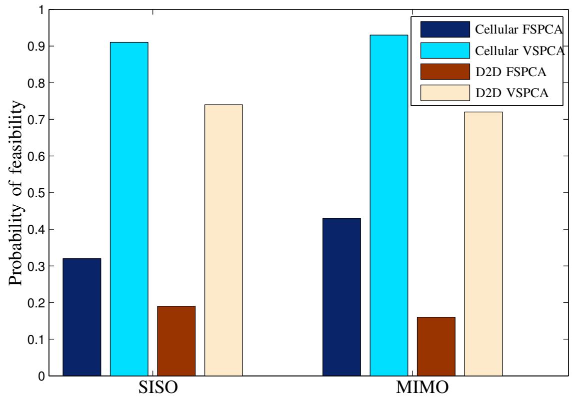


Figure 3. Probability of feasibility for cellular and D2D modes.

Looking at Figure 3, we can also see that the percentage of feasible realizations for cellular mode is higher than that achieved using D2D mode in both SISO and MIMO cases. For example, when the strategy with variable target SINR is applied for MIMO case, we have that $72,82\%$ of the Monte Carlo realizations are feasible in the D2D mode while this percentage increases to $93,83\%$ in the cellular mode.

The reason to the high percentage of feasible cases in the cellular mode is associated with the lower interference found in this communication mode. In the D2D mode, the D2D-capable UEs share resources with the cellular UEs, which in turn causes higher interference and higher occurrence of infeasible cases. However, it is important to investigate the overall system capacity when D2D mode is performed. In the following, we evaluated the system performance in terms of sum rate.

Figure 4 compares the sum rate for both communication modes when the two power control strategies are employed in the SISO configuration. We only considered the sum rate when the power control is feasible. The sum rate is defined to be zero in case of non-feasibility. Note that the fixed target SINR approach, when feasible, only achieves the target SINR value of 15 dB. From the curves, we can see that for fixed SINR,

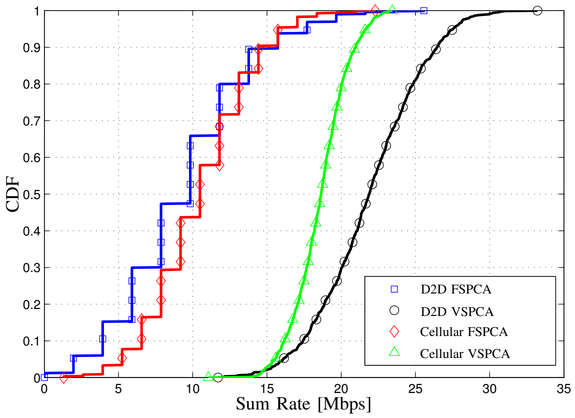


Figure 4. Sum rate comparison for SISO configuration.

the cellular mode has better performance than D2D mode. However, when the power control algorithm with variable SINR is performed, the D2D mode outperforms the cellular mode for nearly 100% of the cases. The higher sum rates obtained by the D2D mode with variable target SINR are mainly an effect of the adjustment of the target SINR values, which leads to higher feasibility and better exploitation of advantages of the D2D communication mode.

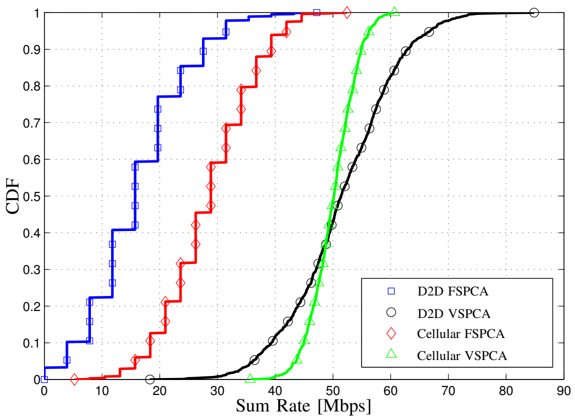


Figure 5. Sum rate comparison for MIMO configuration.

Figure 5 presents a similar analysis to preceding, but now for MIMO configuration. Again, we can see that cellular sum rate is always higher that the sum rate obtained by D2D mode for FSPCA. This behavior changes when the power control algorithm with variable SINR is applied. In this case, the D2D mode overcomes the cellular mode in most of the sum rate values. It is worth to highlight that in the D2D mode there are more interfering sources which makes it harder to profit from spatial filtering ability of multi-antenna systems. These results reveal that power control algorithms with variable SINR become a key factor to ensure improved system performance when D2D communication mode is performed within cellular networks.

V. Conclusions

We have investigated the impact of two power control algorithms for D2D communication within cellular networks. The first aims at meeting a fixed target SINR requirement for each stream of each user, while in the second, the user's target SINR per stream varies according to its required transmit power. Due to its higher feasibility, the power control algorithm with variable SINR has shown a significant increase in sum rate when compared to power control algorithm in which the SINR is fixed. With this approach, more users can be admitted in the network and the global performance is improved. Moreover, the higher percentage of feasible case due to use of the power control with variable SINR allows to take advantage of the reuse gain of the D2D communication mode. Besides that, such a sum rate gain obtained by a power control algorithm over another can be used together with mode selection schemes to further improve the overall system capacity.

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