A Distributed Power Control Scheme for Cellular Network Assisted D2D Communications

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***Abstract*—Device-to-device (D2D) communications underlaying a cellular infrastructure has recently been proposed as a means of increasing the resource utilization, improving the user throughput and extending the battery lifetime of user equipments. In this paper we propose a new distributed power control algorithm that iteratively determines the signal-to-noise-and-interference-ratio (SINR) targets in a mixed cellular and D2D environment and allocates transmit powers such that the overall power consumption is minimized subject to a sum-rate constraint. The performance of the distributed power control algorithm is benchmarked with respect to the optimal SINR target setting that we obtain using the Augmented Lagrangian Penalty Function (ALPF) method. The proposed scheme shows consistently near optimum performance both in a single-input-multiple-output (SIMO) and a multiple-input-multiple-output (MIMO) setting.**

I. Introduction

Device-to-device (D2D) communications supported by a cellular infrastructure holds the promise of three types of gains. The *reuse gain* implies that radio resources may be simultaneously used by cellular as well as D2D links thereby tightening the reuse factor even of a reuse-1 system [1], [3]. Secondly, the proximity of user equipments (UE) may allow for extreme high bit rates, low delays and low power consumption [4]. Finally, the *hop gain* refers to using a single link in the D2D mode rather than using an uplink and a downlink resource when communicating via the access point in the cellular mode. Additionally, D2D communications may also facilitate new types of wireless peer-to-peer services [1], [2].

However, D2D communications utilizing cellular spectrum poses new challenges, because relative to cellular communication scenarios, the system needs to cope with new interference situations. For example, in an orthogonal frequency division (OFDM) system in which D2D communication links may reuse some of the OFDM physical resource blocks (PRB), intra-cell interference is no longer negligible [5]. Solution approaches to deal with this problem include power control [6], [7], various interference avoiding multiple-input-multiple-output (MIMO) techniques [8] that can be combined with proper mode selection [9] and advanced (network) coding schemes [4]. However, to our best knowledge, prior works have not proposed a distributed power control scheme for D2D communications that minimizes the sum power subject to a sum rate constraint.

Therefore, the purpose of the current paper is to develop a power control scheme that minimizes the used sum power in an OFDM system that may reuse PRBs for D2D links. In particular, we are interested in a scheme that does not require fast scale channel information, but relies on the D2D geometry only and want to compare the performance of such a scheme with that of the optimal (centralized) power control scheme. We are also interested in gaining insight in the potential gains of using the direct D2D link as compared to using cellular links between two communicating UEs (Tx UE - Rx UE) when employing such power control in both (i.e. cellular and D2D) operational modes. In particular, we focus on scenarios in which the same PRB may be used simultaneously for a cellular and a D2D link tightening the reuse factor below 1 (as in Figure 1). For a particular UE pair, this sum power minimizing scheme may be combined with mode selection that determines whether the UE pair (Tx UE - Rx UE of Figure 1) should use the direct D2D link or they should communicate via the cellular access point. Therefore, we compare the performance of these two communications modes when the positions of both the D2D pair and the interfering cellular UE vary within the cell.

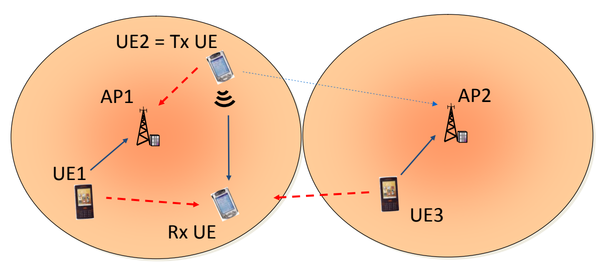

Figure 1. Illustration of D2D communications, when a user equipment (UE1) and a D2D pair (Tx UE - Rx UE) may use the same OFDM PRB. Due to the D2D link, intracell interference as well as intercell interference between D2D and cellular links (UE3 to Rx UE) can be very high. (In this example assuming that the D2D link uses cellular UL resources.)

We structure the paper as follows. The next section describes our system model and formulates the D2D power control problem as an optimization task. Next, in Section III, we propose an iterative power control scheme to meet predefined SINR targets. A second algorithm is presented in Section IV that aims to set the SINR targets that help to minimize the overall used power in the system. Section V discusses numerical results and Section VI highlights our findings.

II. System Model

A. Modeling the Received Signal

We focus on the case in which a cellular and a D2D link are multiplexed on the same uplink OFDM PRB. Due to intercell interference, cellular or D2D links in neighboring cells may cause additional interference to the received signal. Thus, the received signal at the k^{th} receiver (i.e. cellular AP or the Rx UE of a D2D pair) can be modelled as:

$$\mathbf{y}_k = \alpha_{k,k}\mathbf{H}_{k,k}\mathbf{T}_k\mathbf{x}_k + \sum_{j\neq k}\alpha_{k,j}\mathbf{H}_{k,j}\mathbf{T}_j\mathbf{x}_j + \mathbf{n}_k, \qquad (1)$$

where

- $\alpha_{k,j} = \sqrt{P_j d_{k,j}^{-\rho}\chi_{k,j}/N_t}$ is a scalar coefficient depending on the total transmit power P_j for user j, the log-normal shadow fading $\chi_{k,j}$ and distance $d_{k,j}$ between the k-th receiver and the j-th transmitter with path loss exponent ρ;
- $\mathbf{x}_k \in \mathbb{C}^{N_t\times 1}$ is the data vector that is assumed to be zero-mean, normalized and uncorrelated, $\mathbb{E}\left(\mathbf{x}_k\mathbf{x}_k^{\dagger}\right) = \mathbf{I}_{N_t}$;
- $\mathbf{H}_{k,j}$ denotes the $(N_r \times N_t)$ channel transfer matrix; and
- $\mathbf{T}_k$ is the UE-k $(N_t \times N_t)$ diagonal power loading matrix. To keep the total transmit power constant, $\mathbf{T}_k$ must satisfy
$$\text{trace}\left(\mathbf{T}_k\mathbf{T}_k^{\dagger}\right) = \sum_{i=1}^{N_t}|\mathbf{T}_k^{(i,i)}|^2 = N_t \quad \forall k;$$
- $\mathbf{n}_k$ is a $N_r \times 1$ additive white Gaussian noise vector at the k-th receiver with zero mean and covariance matrix $\mathbf{R}_{n_k} = \mathbb{E}\left(\mathbf{n}_k\mathbf{n}_k^{\dagger}\right) = \sigma_n^2\mathbf{I}_{N_r}\forall k$.

We rewrite the signal model (1) in a compact form as

$$\mathbf{y}_k = \alpha_{k,k}\mathbf{H}_{k,k}\mathbf{T}_k\mathbf{x}_k + \mathbf{z}_k + \mathbf{n}_k, \qquad (2)$$

where $\mathbf{z}_k = \sum_{j\neq k}\alpha_{k,j}\mathbf{H}_{k,j}\mathbf{T}_j\mathbf{x}_j$ denotes the $(N_r \times 1)$ interference vector with covariance matrix

$$\mathbf{R}_{z_k} = \mathbb{E}\left(\mathbf{z}_k\mathbf{z}_k^{\dagger}\right) = \sum_{j\neq k}\alpha_{k,j}^2\mathbf{H}_{k,j}\mathbf{T}_j\mathbf{T}_j^{\dagger}\mathbf{H}_{k,j}^{\dagger}. \qquad (3)$$

For ease of notation, we define an *equivalent* noise vector that accounts both inter-cell interference and background noise

$$\mathbf{v}_k = \mathbf{z}_k + \mathbf{n}_k$$

It is easy to show that $\mathbf{v}_k$ is zero-mean with covariance $\mathbf{R}_{v_k} = \mathbf{R}_{z_k} + \mathbf{R}_{n_k}$.

B. MMSE Receiver Error Matrix and the Effective SINR

We assume that the received signal both at the AP and the Rx UE is filtered through a linear MMSE receiver with weighting matrix $\mathbf{G}_k$ to obtain the estimate

$$\widehat{\mathbf{x}}_k = \mathbf{G}_k\mathbf{y}_k.$$

where the $(N_t \times N_r)$ linear MMSE weighting matrix $\mathbf{G}_k$ is given as:

$$\mathbf{G}_k = \frac{1}{\alpha_{k,k}}\mathbf{T}_k^{\dagger}\mathbf{H}_{k,k}^{\dagger}\left(\mathbf{H}_{k,k}\mathbf{T}_k\mathbf{T}_k^{\dagger}\mathbf{H}_{k,k}^{\dagger} + \frac{1}{\alpha_{k,k}^2}\mathbf{R}_{v_k}\right)^{-1}$$
$$= \left(\mathbf{I} + \mathbf{T}_k^{\dagger}\mathbf{R}_{H_k}\mathbf{T}_k\right)^{-1}\alpha_{k,k}\mathbf{T}_k^{\dagger}\mathbf{H}_{k,k}^{\dagger}\mathbf{R}_{v_k}^{-1},$$

where $\mathbf{R}_{H_k} = \alpha_{k,k}^2\mathbf{H}_{k,k}^{\dagger}\mathbf{R}_{v_k}^{-1}\mathbf{H}_{k,k}$, see e.g. [10, Chapter 12]. To derive the stream-wise SINRs at base station k, we will need the diagonal elements of the error matrix of the MMSE filtered signal. To this end, the following proposition is useful. (The proof is omitted due to space constraint.)

***Proposition** 1:* The MMSE estimation error matrix $(N_r \times N_r)$ for the k-th base station is :

$$\mathbf{E}_k = \left(\mathbf{I} + \mathbf{T}_k^{\dagger}\mathbf{R}_{H_k}\mathbf{T}_k\right)^{-1}. \qquad \blacksquare$$

We are now in the position to calculate the SINR for the signal model (2) assuming a linear MMSE receiver. Using the linear MMSE weighting matrix $\mathbf{G}_k$, the MSE and SINR expressions can be rewritten respectively as

$$MSE_{k,s} \triangleq (\mathbf{E}_k)_{(s,s)} = \left\{\left(I + \mathbf{T}_k^{\dagger}\mathbf{R}_{H_k}\mathbf{T}_k^{\dagger}\right)^{-1}\right\}_{(s,s)} \qquad (4)$$

$$\gamma_{k,s} \triangleq \frac{1}{MSE_{k,s}} - 1. \qquad (5)$$

C. Summary

In this section we defined the multicell MIMO received signal model (2) and, assuming a linear MMSE receiver, derived the associated effective SINR ($\gamma_{k,s}$) for each stream of the received signal. Equations (4) and (5) are important because they capture the dependence of the SINRs on the transmission powers of the own UE *and* the interfering UEs through the $\mathbf{R}_{H_k}$'s and the $\mathbf{R}_{v_k}$'s. Thus, these relations serve as the basis for the optimization problems of the next section.

III. An Iterative D2D Power Control Scheme

From the signal model (1), when transmitter k uses a diagonal power loading matrix $\mathbf{T}_k \in C^{N_t\times N_t}$ with $\sum_{s=1}^{N_t} \mid \mathbf{T}_k^{(s,s)} \mid^2 = N_t$, the post-processing SINR of its s^{th} stream becomes [11]:

$$\gamma_{k,s} = \frac{P_k \mid \mathbf{T}_k^{(s,s)} \mid^2}{\zeta_{k,s}} - 1, \qquad (6)$$

where

$$\zeta_{k,s} = \left\{\left(\left(d_{k,k}^{-\rho}\chi_{k,k}\mathbf{H}_{k,k}^{\dagger}\left(\sum_{j\neq k}P_j d_{k,j}^{-\rho}\chi_{k,j}\mathbf{H}_{k,j}\mathbf{T}_j\mathbf{T}_j^{\dagger}\mathbf{H}_{k,j}^{\dagger}\right.\right.\right.\right.$$
$$\left.\left.\left.\left. + N_t\sigma_n^2\mathbf{I}\right)^{-1}\mathbf{H}_{k,k} + \frac{1}{P_k}\mathbf{I}\right)^{-1}\right\}^{(s,s)} \qquad (7)$$

denotes the effective interference after MMSE processing. In [11], a heuristic algorithm for distributing the transmit power over different streams was presented. By inverting

Algorithm 1: Iterative transmit power and power loading optimization.

Given $t = 0$, P_{tot}, ε_{gap} and $\mathbf{T}_k^{(0)} = \mathbf{I}_{N_t}\ \forall\ k$.
Initialize SINR targets $\mathbf{\Gamma}^{(0)} = \text{diag}(\gamma_k^{\text{tgt}})$ and transmission powers $\mathbf{p}^{(0)}$.
repeat
1) $t = t + 1$.
2) **for** *k=1 to K* **do**
Receiver-k measures the effective interference $\zeta_{k,s}$ and feeds it back to Transmitter-k;
Calculate the optimum loading matrix $\mathbf{T}_k^{(t)}$ and P_k as:

$$\left(\mathbf{T}_k^{(t)}\right)^{(s,s)} = \sqrt{\frac{\zeta_{k,s} N_t}{\sum_{j=1}^{N_t} \zeta_{k,j}}}\ \forall s \in [1, N_t];$$

$$P_k^{(t)} = \max_s \left\{ \frac{\zeta_{k,s}}{|(\mathbf{T}_k^{(t)})^{(s,s)}|^2} (\gamma_k^{(t)} + 1) \right\} \quad \forall k, s \tag{8}$$

end
until $\mid P_k^{(t)} - P_k^{(t-1)} \mid \leq \varepsilon_{\text{gap}}, \quad \forall\ k;$

equation (6) for fixed SINR targets, the algorithm finds a near optimal (sum power minimizing) power loading matrix for these given SINR targets assuming perfect knowledge of the own and cross channel matrices $\mathbf{H}_{k,j}$.

In this paper, we relax the assumption on the knowledge of all the $\mathbf{H}_{k,j}$ channel matrices at all transmitters. Our assumption is that the receivers measure the received effective interference ζ and feed it back to their respective transmitters (Algorithm 1).

IV. A Heuristic SINR Target Setting Algorithm

A. Determining the Optimum SINR Target

Determining the optimum SINR target is useful for benchmarking purposes. Finding the SINR targets that minimize the overall used power involves solving the following optimization problem:

$$\begin{array}{ll} \underset{\mathbf{\Gamma},\mathbf{p}}{\text{minimize}} & \sum_k P_k \\ \text{subject to} & \sum_k c_k(\gamma_k^{\text{tgt}}) \geq c_{\text{m}} \\ & \gamma_k^{\text{tgt}} \leq \underline{\gamma}_k(\mathbf{p}) \qquad \forall k, \end{array} \tag{9}$$

in the optimization variables $\mathbf{\Gamma}$ (SINR targets) and $\mathbf{p}$ (power). We propose to solve this problem through the augmented Lagrangian penalty function (ALPF) method. In this method, the constrained non-linear optimization task is transformed into an unconstrained problem by adding a penalty term to the Lagrangian function. The details of this method are omitted and we refer to [12] for details.

It is important to realize that solving (9) by ALPF requires a central entity with access to the full channel matrix, so it is hardly feasible in practice. However, finding the optimal SINR targets is useful for benchmarking our proposed heuristic algorithm that we describe in the next subsection.

B. A Distributed Algorithm to Set the SINR Targets

Algorithm 2 tries to successively increase the SINR targets until a predefined C^{sum} capacity target is reached. In each iteration it increases the SINR target of the one user that contributes the most to the sum capacity increase by calculating a *benefit* value b_k. The calculation of the power increase is detailed in the Appendix.

Algorithm 2: Greedy iterative SINR target setting

Input: $C^{\text{sum}}, \text{SINR}^{\min} > 0, \Delta > 1, \rho, \epsilon > 0, \sigma_n^2$ and $g_{k,j} = d_{k,j}^{-\rho}\chi_{k,j}$, $k = 1, \ldots, K, j = 1, \ldots, J$, where K and J are the number of receivers and transmitters, respectively.
Output: $\Gamma^{(t)}$
Given $t = 0, \mathbf{b}^{(0)} = [b_1^{(0)}, \ldots, b_k^{(0)}] = \mathbf{0}$, and $\gamma_k^{(0)} = \text{SINR}_{\min}$, $p_k^{(0)} = \gamma_k^{(0)} \cdot \sigma_n^2 / g_{k,k}$, $k = 1, \ldots, K$.
repeat
1) **for** *k=1 to K* **do**
Calculate the approximated transmit power required to increase SINR by Δ (see Appendix A) as:

$$\Delta \mathrm{P}_k^{(t)} = \frac{\gamma_k^{(t)}(\Delta - 1)\left(\sum\limits_{j \neq k}^{K} p_j^{(t-1)} g_{k,j} + \sigma_n^2\right)}{g_{k,k}};$$

Calculate the capacity increase achieved by the increased SINR as:

$$\text{capInc}_k^{(t)} = \log_2\left(1 + \gamma_k^{(t)} \cdot \Delta\right) - \log_2\left(1 + \gamma_k^{(t)}\right);$$

Calculate the benefit value $b_k^{(t)} = \frac{\text{capInc}_k^{(t)}}{\Delta \mathrm{P}_k^{(t)}}$.
end
2) Select user with the highest benefit value as:
if $(|b_i^{(t)} - b_j^{(t)}| < \epsilon, \forall i, \forall j, i \neq j)$ **then**

$$\text{bestUE}^{(t)} = \text{argmax}\left\{g_{1,1}, \ldots, g_{k,k}\right\}$$

else $\text{bestUE}^{(t)} = \text{argmax}\left\{\mathbf{b}^{(t)}\right\}$
3) Update SINR target for the user with the highest benefit as:

$$\gamma_{\text{bestUE}^{(t)}}^{(t+1)} = \gamma_{\text{bestUE}^{(t)}}^{(t)} \cdot \Delta.$$

4) Calculate current sum capacity as:

$$C^{(t+1)} = \sum_{s=1}^{N_t} \log_2 (1 + \gamma_k^{(t+1)}).$$

5) t=t+1;
until $C^{\text{sum}} \geq C^{(t)}$;

C. Summary

While the previous section proposed a heuristic algorithm that allocates transmit powers and tunes the power loading matrix at the transmitter such that a predefined SINR target vector is reached, in this section we considered the problem of setting the SINR targets that minimize the sum power subject to a target capacity constraint. To this end, we proposed a heuristic algorithm that requires the slow changing path loss and shadowing matrix knowledge at each transmitter. The availability of this information can be assumed in systems with an inter-base station backhaul network or with a central node such as a radio network controller.

V. Numerical Results

We consider two sets of numerical results. The first set focuses on the performance of Alg 1 given a fixed set of SINR targets. The second set shows the gains when setting the SINR targets in an optimal or heuristic fashion.

A. Simulation Scenarios

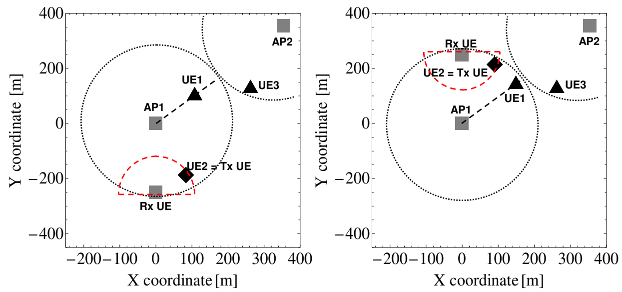

Figure 2. Simulation scenarios. In Scenario 1 (left) the D2D pair is randomly dropped in an area that is "on the other side" of the access point than UE1. In Scenario 2, the D2D pair is randomly dropped in an area close to UE1. In both scenarios, UE1 moves from the cell center to the cell edge (Position 1...Position 10). UE2 is the transmitting UE of the D2D pair. UE3 is a stationary interfering UE in the neighbor cell.

We consider two simulation scenarios as shown in Figure 2, which are basically two instances of the scenario shown in Figure 1. We denote with UE1 the user equipment transmitting to its serving base station. We let UE1 move from a position close to the base station (UE1 Position 1) towards the cell edge (UE1 Position 10). We use the UE1 position along the x axis of all our plots. UE2 denotes the transmitting user equipment (Tx UE) of the D2D pair. Finally, UE3 denotes an interfering user equipment in a neighbor cell served by access point AP2. The D2D pair is dropped within the half circle areas denoted in Figure 2 in 40000 Monte Carlo experiments. The D2D pair can communicate in two modes:

1) **D2D mode**: The two UEs of the D2D pair communicate via a direct link. In this mode, the D2D link uses the same OFDM resource blocks as the UE1 uses to communicate with its serving AP.
2) **Cellular mode**: The two UEs of the D2D pair communicate via the serving AP. In this case the UE1 and UE2 use orthogonal uplink resources (either in the time or in the frequency domain). For example, assuming a time domain separation, during first period only UE1 transmits to AP1 followed by a period when only UE2 transmits to AP1.

The two performance measures of interest are the sum power for a given sum capacity target (UE1+UE2+UE3) and the probability that the (fixed or set) SINR targets are infeasible. Some of the simulation parameters are listed in Table I.

Table I
Simulation Input Parameters

Input Parameters	
Inter Site Distance [m]	500
Path loss exponent	3.07
Shadow fading	Lognormal; st. dev: 5 dB
Fast fading model	Rayleigh flat
AWGN noise power	−60 dBm
Max. per user transmit power	250 mW
Antenna configurations	1x2 SIMO and 2x4 MIMO

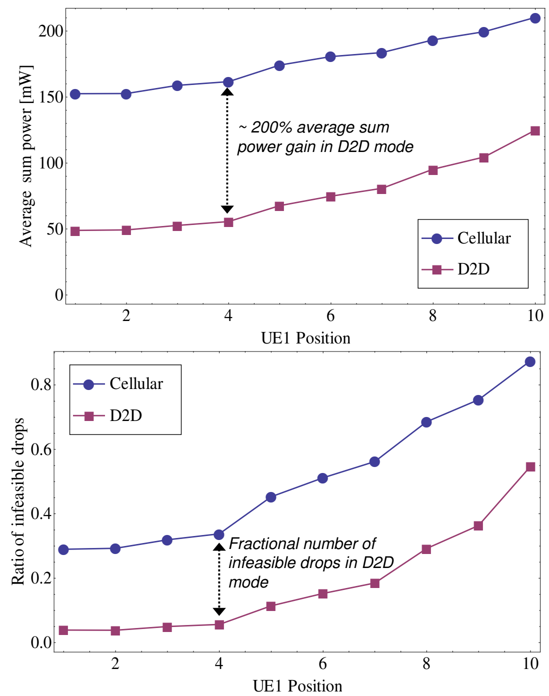

Figure 3. Required sum power and probability of infeasibility with fixed SINR targets (1x2 SIMO). When the D2D pair communicates in D2D mode, the average sum power is significantly lower than the average sum power in cellular mode. This SINR target is also more often feasible in D2D mode than in cellular mode.

B. Results for Predefined SINR Targets

Figures 3 and 4 present results for the fixed SINR target case and compare the performance of D2D mode and cellular mode between the D2D pair in terms of the performance measures of interest. The SINR target for D2D mode is set to $\gamma_{D2D}^{tgt} = 4dB$ for all 3 links (UE1, UE2 and UE3). For the cellular mode, the SINR target is set such that the total capacity be the same as in the D2D mode. Since in the cellular mode there is only one communication link (apart from the interfering neighbor, UE3) at a time, the SINR target is set such that $3 \cdot \log_2(\gamma_{D2D}^{tgt}+1) = 2 \cdot \log_2(\gamma_{Cell}^{tgt}+1)$ (that is: $\gamma_{Cell}^{tgt} = 7.47dB$).

The upper graph of Figure 3 shows the sum power results for the 1x2 SIMO case. As UE1 moves from its cell center position towards the cell edge, the average sum power (on the 3 links) required to reach their respective SINR targets gradually increases both when the D2D pair communicates in D2D mode and when they communicate in cellular mode. Recall that in cellular mode, we first assume that only UE1

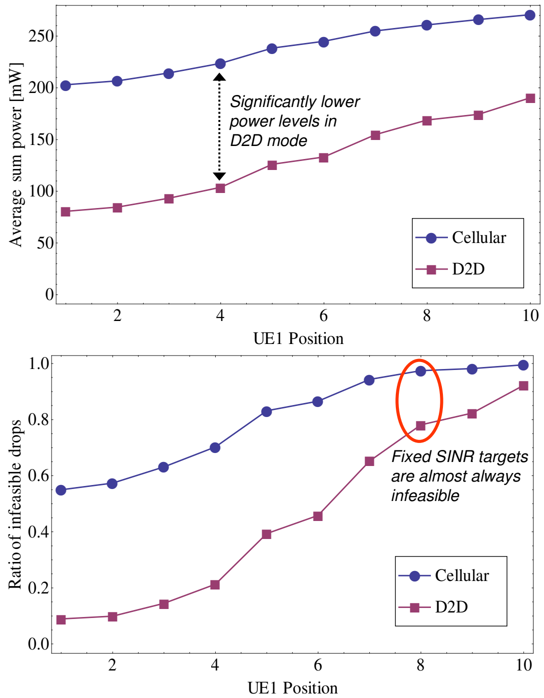

Figure 4. Required sum power and probability of infeasibility with fixed SINR targets (2x4 MIMO). This figure is similar to Figure 3. In this case the SINR targets are typically not feasible except when the UE1 is in the cell center.

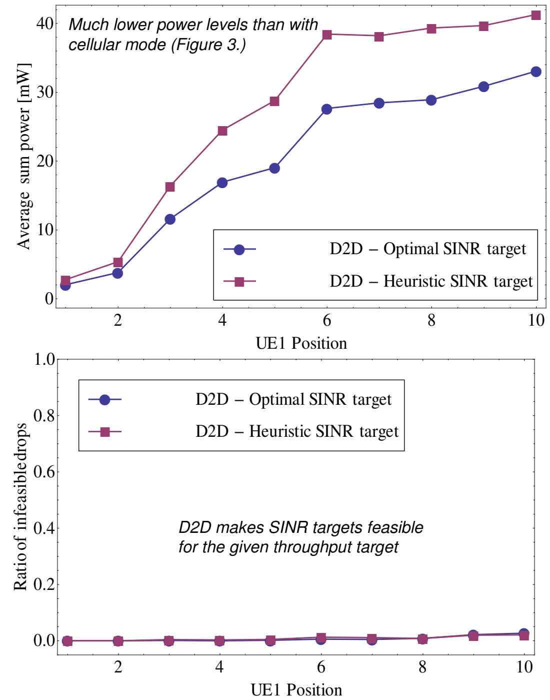

Figure 5. Performance measures of interest in D2D mode with optimized and heuristically set SINR targets (1x2 SIMO). The target sum rate is the same as in Figure 3, but the required sum power is just a fraction of that with fixed SINR targets. In addition, the probability of infeasibility is very low, even when UE1 approaches the cell edge.

transmits and then only UE2 transmits to the AP (when only UE2 transmits, the required power is obviously independent from the UE1 position, since UE1 does not transmit). What is important to notice here is that the sum power is always lower (roughly 30% of the average power used in cellular mode) in the D2D mode than in cellular mode due to the reuse and proximity gains in D2D mode.

The lower graph of Figure 3 shows the probability that in a Monte Carlo experiment the SINR targets are infeasible. As expected, the probability of infeasibility increases as UE1 moves towards the cell edge, but this probability is significantly lower (typically half or less) in D2D mode.

Figure 4 shows the sum power and the probability of infeasibility for the 2x4 MIMO case and setting the SINR target per stream to 4 dB (that is setting the sum capacity target to twice of that required in Figure 3). This high SINR per stream target is basically only feasible when UE1 is in the cell center, but also in this case the D2D mode between UE2 and its D2D pair is clearly superior to the cellular mode both in terms of sum power and feasibility.

C. Results for Optimal and Heuristic SINR Targets

In the section we discuss the results when the SINR targets are not fixed, but set optimally or by means of our proposed heuristic SINR target setting algorithm such that the sum rate capacity is the same as in the fixed SINR target case of the previous section (that is 5.44 bps/Hz in the 1x2 SIMO case and 2x5.44 bps/Hz in the 2x4 MIMO case).

First, we consider the results for the 1x2 SIMO case (Figure 5). In this case, the required sum power is drastically lower than in the fixed SINR target case. For example, when UE1 is at the cell edge, the required sum power in D2D mode is only around 30 mW (with optimal SINR targets) and around 40 mW (heuristic SINR targets) as compared to 125 mW with the fixed SINR targets (of Figure 3). We also notice that virtually all drops turn out to be feasible, both with optimal SINR targets and with our proposed SINR target setting algorithm.

The results for the 2x4 MIMO case without and with power loading are shown in Figures 6 and 7. Recall from Figure 4 that in this case the fixed SINR targets were typically infeasible. With optimal and heuristic SINR targets, the same sum rate becomes feasible except when UE1 is close to the cell edge. Also the sum power in the feasible drops becomes only a fraction of what is required in the fixed SINR case.

In both the 1x2 SIMO and the 2x4 MIMO case we also notice that D2D mode provides better performance than cellular mode.

VI. Conclusions

In this paper we developed a distributed power control algorithm applicable in network assisted D2D communication scenarios that relies on the slow scale path loss measurements rather than requiring full channel states. The algorithm consists of an SINR setting part that aims to set the individual SINR targets such that the required sum power is minimized with respect to a sum rate target and a power allocation part that sets the power levels and power loading matrices over multiple MIMO streams. We compared the performance of

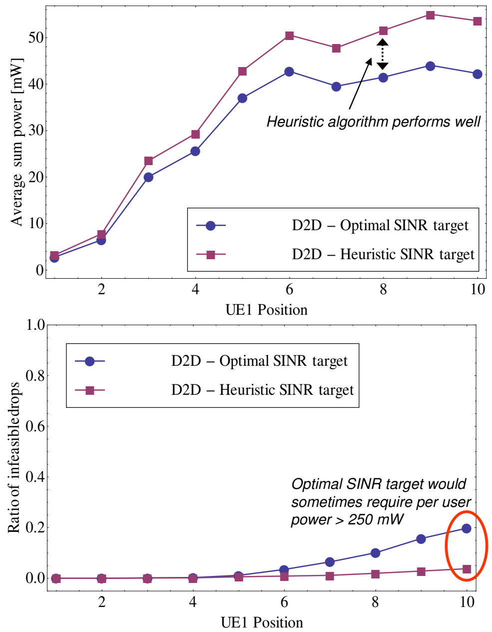

Figure 6. Performance measures of interest in D2D mode with optimized and heuristically set SINR targets (2x4 MIMO) without power loading optimization. Compared with the results of Figure 4, we notice the dramatic decrease in the required power and the improved feasibility probability. Except for the UE1 cell edge positions, the same sum rate that is typically infeasible with fixed SINR targets becomes typically feasible with proper SINR target setting.

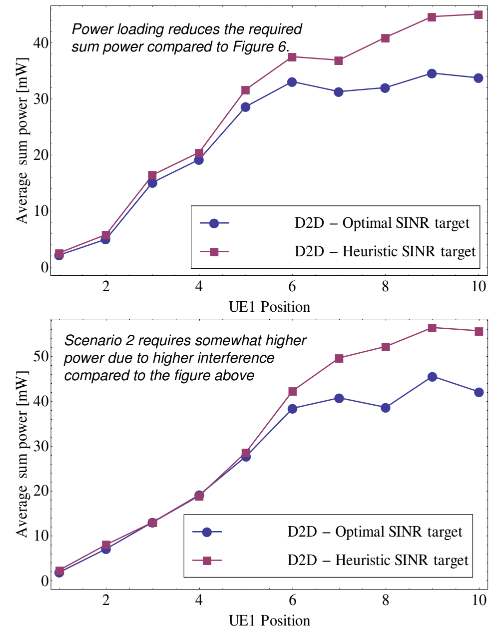

Figure 7. Average sum power in D2D mode with optimized and heuristically set SINR targets (2x4 MIMO) and with power loading optimization in Scenario 1 (upper) and Scenario 2 (lower). Power loading helps further reduce the required power to reach the sum rate target (the feasibility probability is roughly the same as without power loading (Fig. 6) in both scenarios.) In Scenario 2, the average sum power is increased since UE1 and UE3 are closer to Rx UE and thus, the received interference is higher than in Scenario 1.

the proposed scheme with the power minimizing SINR target setting that uses full channel knowledge and a centralized execution. Our simulation results indicate that the proposed scheme performs close to the optimum both in terms of the required sum power and the probability of infeasibility. The results also show that with proper power allocation, network assisted D2D communications can increase the resource utilization in cellular networks.

Appendix

Derivation of ΔP in Algorithm 2:

$$\gamma_k^{(t)} \approx \frac{p_k^{(t)} g_{k,k}}{\sum_{j\neq k}^{K} p_j^{(t-1)} g_{k,j} + \sigma_n^2}$$

$$p_k^{(t)} \approx \frac{\gamma_k^{(t)}\left(\sum_{j\neq k}^{K} p_j^{(t-1)} g_{k,j} + \sigma_n^2\right)}{g_{k,k}} \tag{10}$$

$$\gamma_k^{(t)}\Delta \approx \frac{p_k^{(t)'} g_{k,k}}{\sum_{j\neq k}^{K} p_j^{(t-1)} g_{k,j} + \sigma_n^2}$$

$$p_k^{(t)'} \approx \frac{\gamma_k^{(t)}\Delta\left(\sum_{j\neq k}^{K} p_j^{(t-1)} g_{k,j} + \sigma_n^2\right)}{g_{k,k}} \tag{11}$$

The approximated transmission power needed to increase the SINR by Δ can be calculated from (10) and (11) as $\Delta \mathrm{P}_k^{(t)} = p_k^{(t)'} - p_k^{(t)}$.

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