Near-Optimal Practical Power Control Schemes for D2D Communications in Cellular Networks

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Abstract—**Device-to-device (D2D) communication has the potential of increasing the system capacity, energy efficiency and achievable peak rates while reducing the end-to-end latency. To realize these gains, recent works have proposed resource allocation (RA) and power control (PC) approaches that show near optimal performance in terms of spectral or energy efficiency. However, the proposed schemes either consider a single cell environment or assume instantaneous channel state information (CSI) and/or rely on iterative algorithms that require excessive inter-node message exchange and suffer from slow convergence time. For D2D user equipment (UE), we propose a distributed utility optimization based PC scheme that relies on locally available measurement data and is made practical by constraining the number of iterations and the interference caused to the cellular receiver, while legacy UEs employ the standard Long Term Evolution (LTE) PC. We investigate the performance of the proposed PC scheme when combined with two RA schemes that differ in terms of the required channel state information. We find that when properly tuned, this practical PC scheme combined with a RA algorithm that requires limited channel knowledge, not only shows near optimal performance, but it also constraints the impact of D2D communications on the cellular layer.**

I. INTRODUCTION

Device-to-device (D2D) communication in cellular networks can increase spectral and energy efficiency of the system and at the same time reduce the latency and increase the peak rate of user equipment (UE) that are in the proximity of each other [1]. However, resource sharing between the cellular and the D2D layers implies potentially strong interference levels both at cellular and D2D receivers that makes harvesting the potential gains of D2D communication non-trivial [2]. Recognizing the importance of proper radio resource management in the integrated D2D and cellular environment, the research community has proposed a number of mode selection (MS) [3], [4], power control (PC) [1], [5] and resource allocation (RA) schemes [6], [7], [8], that can optimize the system performance in terms of sum rate, energy efficiency or some other suitable performance measure such as reliability or quality of service [9].

Optimization based approaches to the D2D system design are attractive, but their practical applicability is limited due to two reasons. Some of the proposed schemes assume either full and instantaneous channel state information (CSI) at a central entity such as the base station (BS) and/or disregard intercell (D2D or cellular) interference [1], [3], [5], [6], [7], [9], [10]. Additionally, these works assume the deployment of new power control mechanisms by the cellular (non-D2D) UEs that may be difficult to justify in practice. According to an alternative approach, MS, RA and PC are performed in a distributed fashion and rely on partial CSI and locally available measurement data [11], [12]. These iterative distributed schemes are advantageous in terms of required CSI and associated signaling, but they suffer from a potentially large number of iterations and associated convergence time.

In this paper, we first develop a model that gives us an insight in the performance of a power control scheme in which UEs of the cellular layer employ the fractional path loss compensation PC of the Long Term Evolution (LTE) type of radio access networks, while D2D UEs use a utility maximizing iterative distributed algorithm originally proposed in [11], but with a limited number of iterations. This operation requires the use of cellular protection since the distributed scheme of the D2D layer may tend to cause unacceptable interference to cellular users. While limiting the number of iterations and imposing a cap on the interference caused to the cellular layer reduces the spectral efficiency at the D2D layer, it improves the performance of the cellular users. Thus, the proposed scheme is not only feasible by both the cellular and the D2D UEs, it also provides a tool to network operators to tune the inherent D2D-cellular performance trade-off. This set of results indicate that the constrained hybrid scheme is capable of approaching the utility optimal scheme with an iteration number that is feasible in real systems.

II. SYSTEM MODEL

We model the hybrid cellular-D2D network as a set of L transmitter-receiver pairs that include both cellular UEs transmitting to their respective serving BSs and D2D pairs communicating in cellular uplink spectrum.

The network topology is represented by a directed graph with links labelled with $l = 1, \ldots, L$ indexing the transmitter-receiver pairs in the network. Any transmitter, i.e. either cellular or D2D transmitter, operating in the link l is assumed to have data to send to the corresponding receiver at a transmission rate s_l. Associated with each link l is a function $u_l(\cdot)$, which describes the *utility* of communicating at rate s_l. The utility function u_l is assumed to be increasing and *strictly concave*, with $u_l \to -\infty$ as $s_l \to 0^+$. We let $\mathbf{c} = [c_l]$ denote the vector of link capacities, which depend on the

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system bandwidth W, the achieved SINR of the links (γ_l) as well as the specific modulation and coding schemes used for the communication. A feasible rate vector $\mathbf{s}$ must fulfill the following set of constraints:

$$\mathbf{s} \preceq \mathbf{c}(\mathbf{p}), \qquad \mathbf{s} \succeq 0,$$

where $\mathbf{p}$ is the transmit power vector. In this formulation, it is convenient to look at the $\mathbf{s}$ vector as the vector of the rate *targets* directly derived from a corresponding vector of SINR *targets*, while the capacity vector $\mathbf{c}$ depends on the specific powers $\mathbf{p}$ selected by the transmitters. Specifically, each link can be seen as a Gaussian channel with Shannon-like capacity $c_l(\mathbf{p}) = W \log_2\big(1 + \gamma_l(\mathbf{p})\big)$ which represents the maximum rate that can be achieved on link l, and $\gamma_l(\mathbf{p})$ represents the SINR perceived at the receiver of link l.

G_{lm} denotes the effective link gain between the transmitter of pair m and the receiver of pair l (including the effects of path-loss and shadowing [1]) and let σ_l be the thermal noise power at the receiver of link l, and P_l be the transmission power. The SINR of link l is

$$\gamma_l(\mathbf{p}) = \frac{G_{ll} P_l}{\sigma_l + \sum\limits_{m \neq l} G_{lm} P_m} \tag{1}$$

where $\mathbf{p} = [P_1, ..., P_L]$ is the power allocation vector, and $\sum_{m \neq l} G_{lm} P_m$ is the interference experienced at the receiver of link l. Equation (1) can also be written as

$$\gamma_l(P^{tot}_{l_{Rx}}, P_l, G_{ll}) = \frac{G_{ll} P_l}{(P^{tot}_{l_{Rx}} - G_{ll} P_l)} \tag{2}$$

where $P^{tot}_{l_{Rx}}$ represents the total received power (including σ_l) measured by the receiver of link l. Hence, the SINR in (2) can be computed by the receiver-l without direct knowledge of any of the channel gains, except the one related to its corresponding transmitter-l.

III. POWER CONTROL SCHEMES

In our design, cellular UEs employ the standard LTE open loop fractional path loss compensating PC scheme, whereas D2D users may use other LTE based PC schemes or an iterative scheme that maximizes a utility function (to be introduced in this section). In this section we start by explaining the basics of LTE based PC and utility-maximizing PC, and then introducing our proposed PC scheme—partial utility-maximization—and its practical considerations.

A. LTE Power Control Schemes

The LTE open loop PC can be summarized as:

$$P = \min\{P_{max}, P_0 + 10\log_{10} M + \alpha L\},$$

where P_{max} is the maximum UE transmit power, P_0 is a device-specific UE transmit power parameter, M is the number of assigned resource blocks, L is the measured downlink path loss, and α is the path-loss compensation factor and P_0 is set with respect to a predefined SNR target (γ^{tgt}) according to: [2]

$$P_0 = \alpha \cdot (\gamma^{tgt} + P_{IN}) + (1-\alpha) \cdot (P_{MAX} - 10 \cdot \log_{10} M). \tag{3}$$

Alternatively, an LTE PC scheme can be carried out with a closed-loop operation. In this case, a variable Δ is introduced such that $P = \min\{P_{max}, P_0 + 10\log_{10} M + \alpha L + \Delta\}$ where Δ represents a tuning step, which can be either fixed or dynamic.

B. Utility-Maximization Power Control

Utility-maximization power control is able to maximize the total utility of the system and minimize the total transmit power at the same time. The utility itself is logarithmically proportional to the transmission rate of link-l defined as $u_l(x) = \ln(x), \forall l$. The objective of the utility maximizing power control scheme is expressed by

$$\begin{array}{lll} \underset{\mathbf{p},\mathbf{s}}{\text{maximize}} & \sum\limits_l u_l(s_l) - \omega \sum\limits_l P_l & \\ \text{subject to} & s_l \leq c_l(\mathbf{p}), & \forall l, \\ & \mathbf{p}, \mathbf{s} \succeq 0 & \end{array}$$

where $\mathbf{p}$ and $\mathbf{s}$ represent UE transmit powers and transmission rates respectively and ω is a design parameter that can tune the spectral versus power efficiency tradeoff—lower ω promotes higher spectral efficiency in exchange of higher transmit power. This problem is solved by an iterative approach using nested loops [12], such that the so called *inner loops* calculate the optimum transmit power for a given SINR target while the *outer loops* update the SINR targets based on local measurements by the receivers.

C. Proposed Scheme: Partial Utility-Maximization PC

To facilitate the introduction of utility maximizing power control by D2D users in evolving LTE systems, our design allows (1) legacy UEs to use LTE power control, (2) constraining the impact of the D2D layer on the cellular layer and (3) limiting the number of iterations performed by the D2D users while calculating the utility optimizing transmit power levels.

In contrast to [12], our design allows significantly lower number of iterations and assumes that LTE based PC can still be applied by some UEs in the system.

Specifically, to protect the cellular layer, we introduce a threshold parameter I_{th} which limits the D2D transmit power, such that $P_l = \min\{I_{th}/G_{BS,l}; P_l^{opt}\}$, where P_l is the power allocated to link-l's transmitter, $G_{BS,l}$ is the channel gain between link-l's transmitter and the base station, I_{th} is a design parameter limiting the D2D signal at the BS and P_l^{opt} is the transmit power that maximizes the u_l utility function. We refer to constraining the D2D transmit power by means of imposing a maximum transmit power limit as the *partial* utility maximizing (PUM) power control.

In addition to introducing a power-limiting parameter, we propose executing the utility-maximization power control with a reduced number of iterations (denoted by n_{OL}), i.e. below what would be needed to reach optimality.

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[1] We assume that the G matrix is obtained after Layer-1 filtering, that is typically used for open loop power control, mobility management and other purposes in LTE.

[2] Note that (3) is valid only in the case when a γ^{tgt} value is defined. Typically, γ^{tgt} is set between 10 . . . 15 dB.

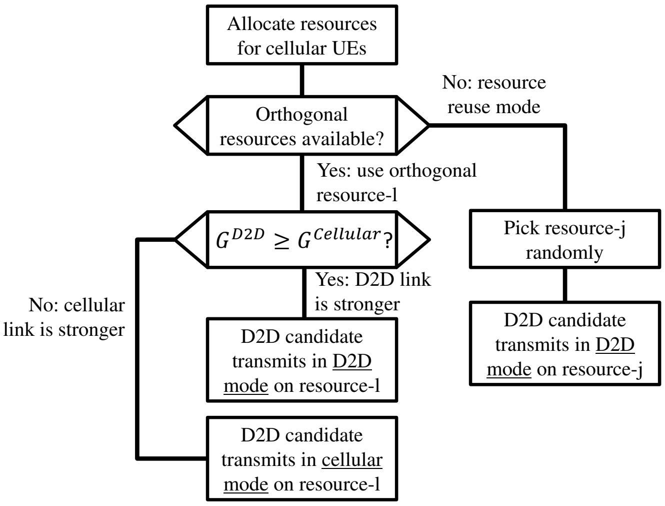

Fig. 1. Mode selection and random resource allocation, where G^{D2D} is the direct link gain and $G^{cellular}$ is the cellular link gain.

IV. MODE SELECTION AND RESOURCE ALLOCATION

Mode selection and resource allocation are intertwined, because the availability of orthogonal resources has an impact on what communication modes (cellular or D2D mode) can be chosen for D2D candidates. This is because of the fundamental requirement of maintaining orthogonality among cellular UEs while allowing for resource reuse between the cellular and D2D layers [3], [7], [10]. In particular, the work in [12] has proposed the so called *MinInterf* joint mode selection and resource allocation algorithm that takes into account both the caused and suffered interference levels by the cellular and D2D layers. MinInterf has been reported to increase the capacity of *both* the cellular and the D2D links at the cost of full gain matrix availability at the cellular BS. Here we propose an alternative resource mode selection and allocation scheme that relaxes the need for full gain matrix knowledge at the BS at the expense of potential performance degradation (Figure 1).

This algorithm requires the availability of CSI between the D2D candidates and between the BS and all (cellular and D2D) transmitters. This set of CSI reports is already maintained by cellular BSs to support mobility (handover) decision. This information is required for the MS decision, whereas resources are allocated by selecting randomly out of the available resource blocks. The rationale for this RA for the D2D layer is that RA to D2D pairs by the BS in practice is expected to operate on a much coarser time scale (e.g. 500 ms) than what is used for physical resource block scheduling in LTE systems [2].

V. NUMERICAL RESULTS

A. Simulation Parameters

In this section we consider the uplink (UL) of a 3-cell system, in which the number of resource blocks (RBs) is 8 (per cell). In each cell, there are 6 cellular UEs transmitting to their respective serving base stations using a cellular UL RB and 6 D2D pairs also communicating in the uplink band. Since intracell orthogonality has to be maintained between the cellular UEs, 6 distinct RBs are needed to support the cellular traffic implying that 4 D2D candidates must select *direct mode with resource reuse*, while two D2D transmitters have the possibility to choose between *cellular mode*, *direct mode with dedicated resource* and *direct mode with resource reuse* (see Figure 1).

TABLE I
SIMULATION PARAMETERS

System bandwidth	5 MHz
Carrier frequency	2 GHz
Thermal noise per MHz	-114 dBm
Path loss coefficient	3.5
Lognormal shadow fading σ	6 dB
Number of cells	3
Cell radius	500 m
Number of RBs per cell	8
Number of cellular UEs per cell	6
Number of D2D candidate pairs per cell	6
Maximum interference caused by each D2D pair at the cellular BS	-144 dB
Number of resource blocks requested by each user	1
Maximum number of iterations used by D2D pairs for PC	30, 60, 100
Number of Monte Carlo simulations	100
Path loss compensation factor (LTE PC), α	0.8
Closed loop iterations (LTE PC)	40
Closed loop tuning step (LTE PC), Δ	1 dBm
Utility-maximization parameter ω	0.1

We perform Monte Carlo experiments to build statistics over the used transmit power and achieved SINR by cellular UEs and D2D pairs when employing the LTE-based power control algorithms and the distributed optimization-based power control scheme with a constrained number of iterations and an imposed interference cap. In each Monte Carlo experiment, all users are dropped randomly within the cell according to a surface uniform distribution. D2D candidates (i.e. UE pairs subject to mode selection according to Figure 1) are dropped such that the maximum D2D distance is $0.2 \cdot R$, where R is the cell radius. The main simulation parameters are given in Table I. We note that P_0 is set according to Equation (3) to correspond to $\gamma^{tgt} = 12.5$ dB.

B. PC Schemes and Their Practical Implementation

To gain insight in the performance limits of the LTE and utility maximizing PC schemes, in Figures 2-5 we employ our proposed random resource allocation described in Figure 1, whereas Figure 6 compares the performance of the random RA with the interference minimizing RA (MinInterf) [11].

Figure 2 shows the distribution of the power levels used by the cellular UEs. Recall that the cellular UEs employ the LTE open loop PC independently of the PC scheme by the D2D layer. Figure 3 shows the SINR distribution at the cellular layer. Here we clearly see the impact of the PC scheme employed by the D2D users. Limiting the number of iterations of the iterative D2D power control scheme from a near optimal $n_{OL} = 100$ to $n_{OL} = 30$ or imposing the power-limiting threshold I_{th} allows the cellular users to reach higher SINR than when D2D users use LTE power control. On the other

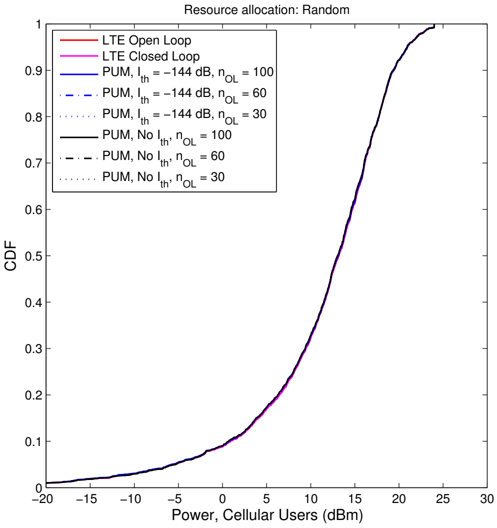

Fig. 2. Power distribution of cellular users where different PC schemes are used by the D2D users. In our design cellular users use LTE PC with open loop operation regardless of the PC scheme used by D2D users.

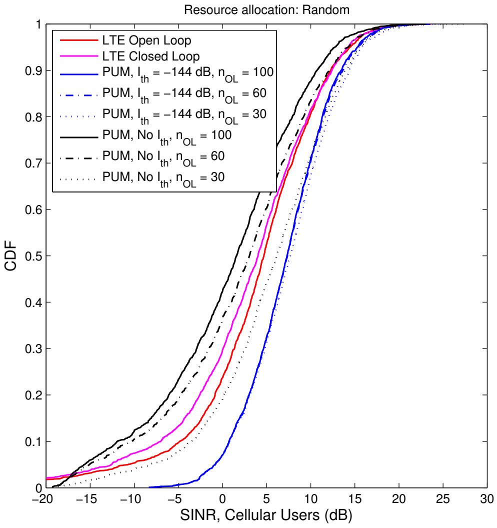

Fig. 3. SINR distribution of cellular users where different PC schemes are used by the D2D users. PUM with I_{th} yields high cellular SINR because the D2D users transmit with low power (see Figure 4).

hand, letting the D2D layer employ utility optimizing transmit power levels causes a slight SINR performance degradation of the cellular UEs. For example setting $n_{OL} = 60$ (without I_{th}) causes a 1-2 dB loss in the SINR performance of the cellular users. Based on these results we argue that when the D2D layer employs a limitation on the number of PC iterations, there is no need to introduce I_{th}, since D2D users tend to use suboptimal (low) transmit power levels.

The D2D transmit power levels are shown by Figure 4, comparing the 8 PC schemes under study. The utility maximizing PC scheme yields the rightmost curve whereas the other PC schemes limit the D2D transmit power levels either by limiting the number of power control iterations (achieving fast convergence) or by imposing I_{th} (achieving cellular layer protection). For example, setting $n_{OL} = 60$ (without I_{th}) results in somewhat higher D2D transmit power levels than when using LTE based power control, but this increase would hardly be noticeable by D2D users.

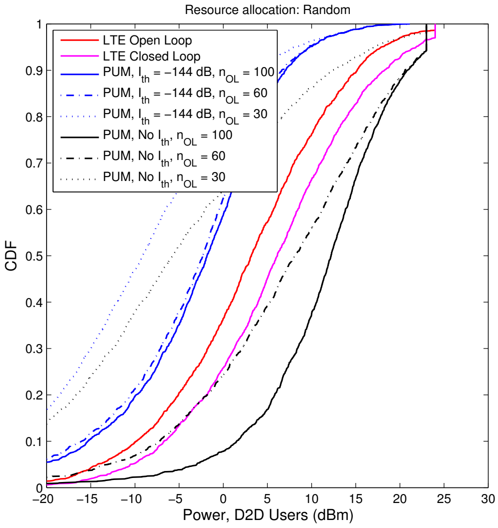

Fig. 4. Power distribution of D2D users with different PC schemes. The power allocated by PUM is higher than with LTE power control because setting $\omega = 0.1$ of PUM pushes the D2D users to be spectral efficient. With I_{th}, the D2D users transmit with low power, which effectively improves the cellular SINR at the cost of lower D2D SINR.

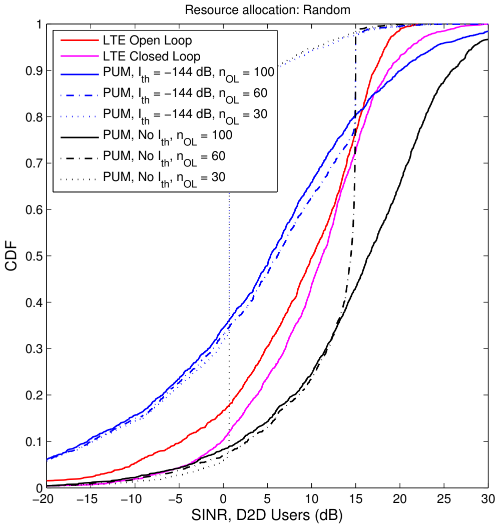

Fig. 5. SINR distribution of D2D users with different PC schemes. It is interesting to note that in the high SINR region, PUM with I_{th} outperforms LTE PC, despite the fact that PUM allocates lower power to the D2D transmitters.

The SINR distribution at the D2D layer is shown by Figure 5. Limiting the number of iterations to $n_{OL} = 60$ (without I_{th}) substantially improves the D2D performance as compared to LTE power control, except in the high SINR regime. On the other hand, imposing I_{th} causes a noticeable SINR degradation at the D2D layer, even when the utility

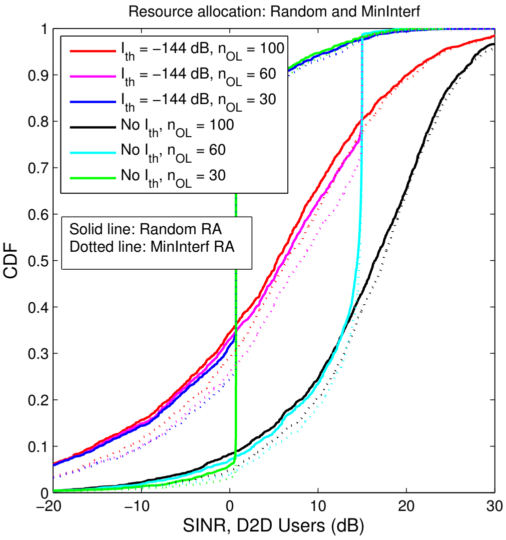

Fig. 6. SINR distribution of D2D users with Random and MinInterf resource allocation. The two RA schemes show 1-2 dB performance difference, justifying the use of the low complexity RA scheme.

maximizing iterative scheme is allowed to use full number of iterations. In our setting the I_{th} is tight and it is intuitively clear that by tuning the I_{th} cap the D2D layer performance can be improved without noticeable performance impact on the cellular UEs.

C. Resource Allocation

Figure 6 compares the SINR of D2D users when (partial) utility maximizing PC is used with the MinInterf and random resource allocation schemes. In terms of D2D SINR, our proposed random scheme yields only 1-2 dB lower SINR than MinInterf RA, while the SINR degradation of the cellular UEs is even smaller. Recall that as opposed to the random scheme, MinInterf requires full gain matrix in order to decide which resource a D2D link should *reuse*. Therefore, we conclude that the low complexity RA scheme (with limited channel state information) performs close to MinInterf. Figure 6 also shows that the slightly lower performance of random RA can be compensated by a PC scheme which manages well the system performance in terms of invested transmit power levels and achieved SINR.

VI. CONCLUSIONS

We proposed a power control scheme in which the cellular UEs continue to use the legacy LTE PC scheme, while the D2D UEs are allowed to use either LTE PC scheme or a utility-optimal PC scheme [12] with additional practical constraints: a power-limiting threshold and/or reduced iterations. Our proposed solution is a mix of optimal and legacy PC schemes presented in [12], which results in a practical but well-performing PC scheme. We found that these practical constraints, while having limited impact on the D2D performance, can in fact protect the cellular layer. In addition, we proposed a low-complexity RA scheme which provides similar performance as a more complex resource allocation scheme previously proposed in the literature.

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