<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper presented at *IEEE INFOCOM 26, April -1 May 2015, Hong Kong*.

Citation for the original published paper:

Verenzuela, D., Miao, G. (2015)

Scalable Interference Coordination for Device-to-Device Communications.

In: *IEEE INFOCOM 2015 Workshop on Mobile Cloud and Virtualization* IEEE conference proceedings

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-160726>

Scalable Interference Coordination for Device-to-Device Communications

Daniel Verenzuela, Guowang Miao
KTH Royal Institute of Technology, Stockholm, Sweden
Email: {dve, guowang}@kth.se

Abstract—Proximity based applications are becoming fast growing markets suggesting that Device-to-Device (D2D) communications is going to be an essential part of future cellular networks, thus studying the scalability of the system is of paramount importance. This paper focuses on the problem of scalability defined as finding the maximum number of D2D links that can share the same resources with cellular user equipments (CUEs) while assuring quality-of-service (QoS) to all users in cellular networks of any size. To solve this problem a careful design of interference coordination schemes is needed, thus we present two solutions namely full channel state information (CSI) optimal (F-CSIOp) scheme and partial CSI distributed (P-CSID) scheme. The first solution is based on an optimization problem that uses full CSI to maximize the number of D2D links while providing QoS to all users. However implementing this solution in real systems is infeasible due to high complexity and signaling overhead, thus we present the later solution based on a low complexity distributed algorithm that uses limited CSI. The results show that the P-CSID scheme is able to offer high spectrum efficiency and good scalability while assuring low outage probability to provide QoS for all users.

I. INTRODUCTION

D2D communications has been proposed to improve the performance of cellular networks by allowing devices to communicate directly without relaying traffic to the base station (BS). This technique has the means of increasing spectrum and energy efficiency, reducing delay, improving coverage and supporting new proximity based applications [1].

The increasing popularity of new applications based on geographical proximity [2] suggests that D2D communications will become an important part of future cellular networks. Thus studying the scalability of D2D communications is of paramount importance to accommodate future traffic demands.

We define the scalability of D2D communications underlay cellular networks as the maximum number of D2D links that can share the cellular resources while assuring QoS to both CUEs and D2D links in cellular networks of any size.

When D2D links are added to the cellular network an extra amount of interference is introduced, however since the devices are close to each other it is possible to allow several D2D links to share the same resources with a given CUE. Thus a careful design of interference coordination schemes is needed to assure the QoS of CUEs and D2D links.

To solve the problem of coordinating the interference dynamic resource allocation algorithms have been presented in [3], allowing an increase of capacity. Also joint resource block (RB) scheduling [4] and interference avoidance schemes [5]

have been proposed to increase spectrum efficiency and reduce harmful interference respectively.

Power control techniques have also been proposed to coordinate the interference, the work [6] conducts a comparative study of LTE power control techniques applied to D2D communications. A double threshold power control algorithm is proposed in [7] to maximize the system throughput. In [8] the capacity of the system is studied under cooperative and non-cooperative interference coordination schemes.

However in all of these works the number of D2D links that share the resources with the CUEs is always fixed or set. The capacity in terms of the number of D2D links that system can support has only been considered on few studies [9]–[11].

In [9] a greedy heuristic resource allocation algorithm to maximize the number of D2D links in a single-cell is presented. However in this work power control is not considered. The study [10] presents a series of distributed power control algorithms for D2D communications with the goal of achieving energy savings and spectrum efficiency in a single-cell scenario. However the impact on the scalability is not fully addressed.

In [11], we have studied the feasibility of admitting several D2D pairs to share the resources of a CUE considering only the number of D2D links in a single-cell.

It is worth mentioning that the studies [9]–[11] are all focused on a single-cell scenario neglecting the impact of inter-cell interference. However in real applications this impact can be significant and needs to be considered.

Another important remark mentioned in a survey for D2D communications [12] is that in most available literature the interference coordination solutions assume full CSI to be known at the BS. However this may not always be practical due to the signaling overhead, especially in multi-cell environments.

This work evaluates the scalability of D2D communications underlay cellular networks in a multi-cell environment considering interference coordination schemes with either full CSI or partial CSI. The full CSI optimal (F-CSIOp) scheme is based on a multi-cell optimization problem to maximize the number of D2D links while assuring QoS to all users and serves as the performance upper bound. In the second case we propose a partial CSI distributed (P-CSID) scheme based on a distributed algorithm where each D2D pair decides its active status while considering the QoS of CUEs and D2D links, thus reducing the complexity and signaling overhead.

Extensive mathematical and numerical analysis are con-

ducted to develop and evaluate the performance of the proposed schemes. The results show that the P-CSID scheme provides good scalability and spectrum efficiency while assuring low outage probability to give QoS to all users. Thus it is a good candidate for a scalable interference coordination scheme with low complexity that can be implemented in real systems.

The remainder of this paper is presented as follows: section II depicts the system model considered in the investigation; section III presents the formulation of the optimization problem with full CSI; section IV shows the analysis conducted to obtain the distributed solution with partial CSI; section V depicts the numerical results and analysis and finally section VI presents a short summary and conclusion to our work.

II. SYSTEM MODEL

This paper is focused on the scalability of D2D communications for a single RB scenario. As a result only one CUE is assumed to be active in each cell and no resource allocation is implemented. The scalability will be limited by the maximum level of interference that can be tolerated in the system so that QoS can be assured to all D2D links and CUEs.

We consider a multi-cell system where a set number of D2D pairs are available in each cell. The D2D pairs and CUEs are randomly distributed in all cells. The objective is to find the maximum number of D2D links that can be in active communications and their corresponding transmission power so that QoS could be assured to all active users.

We define $\phi_{xk} \in \{0, 1\}$ ($\forall x \in \{1, \dots, N\}, \forall k \in \{1, \dots, \hat{N}_x\}$), as a binary random variable that indicates the state of each D2D link. The parameter N corresponds to the number of cells in the system and $\hat{N}_x$ is the number of available D2D links in cell x . When $\phi_{xk} = 1$ the D2D link k in cell x is active, otherwise $\phi_{xk} = 0$.

The maximum level of interference that can be tolerated in the system is given by the signal-to-interference plus noise ratio (SINR) constraints for the CUEs and D2D links, depicted in (1a) and (1b) respectively. We also consider an upper bound for the transmission power of D2D links shown in (1c).

$$\Gamma_{x0} = \frac{P_{x0}G_{x0x0}}{I_{x0}^{D2D} + I_{x0}^{CUE} + \mathcal{N}_{BS}} \geq \gamma_{x0}^{th}, \quad (1a)$$

$$\Gamma_{xk} = \frac{\phi_{xk}P_{xk}G_{xkxk}}{I_{xk}^{D2D} + I_{xk}^{CUE} + \mathcal{N}_D} \geq \gamma_{xk}^{th}, \quad (1b)$$

$$\phi_{xk}P_{xk} \leq P_D^{max}, \quad (1c)$$

$$\forall x \in \{1, \dots, N\} \forall k \in \{1, \dots, \hat{N}_x\}.$$

The terms I_{x0}^{D2D} and I_{x0}^{CUE} correspond to the interference received at the BS of cell x , from the D2D links and CUEs respectively. Similarly I_{xk}^{D2D} and I_{xk}^{CUE} correspond to the interference received at the D2D link k of cell x from other D2D links and CUEs respectively. $\mathcal{N}_{BS}$ and $\mathcal{N}_D$ are the noise power at the BS and D2D links receivers respectively. P_{x0} corresponds to the transmission power from the CUE at cell x , P_{xk} is the power of the transmitting device of D2D pair k in cell x and P_D^{max} is the maximum transmission power of

D2D links. γ_{x0}^{th} and γ_{xk}^{th} represent the target SINR of the CUE uplink and the D2D link k in cell x respectively.

To describe the channel gains the following nomenclature is introduced: G_{abij} corresponds to the path gain from the transmitter “ b ” in cell “ a ” to the receiver “ j ” in cell “ i ”. Note that in all variables, CUEs and BS are indexed as “0” and D2D users are indexed with integer numbers greater than zero. Thus we define the interference terms as:

$$I_{x0}^{D2D} = \sum_{i=1}^N \sum_{j=1}^{\hat{N}_i} \phi_{ij} P_{ij} G_{ijx0}, \quad (2a)$$

$$I_{x0}^{CUE} = \sum_{i=1, i \neq x}^N P_{i0} G_{i0x0}, \quad (2b)$$

$$I_{xk}^{D2D} = \sum_{i=1}^N \sum_{j=1}^{\hat{N}_i} \phi_{ij} P_{ij} G_{ijxk} - \phi_{xk} P_{xk} G_{xkxk}, \quad (2c)$$

$$I_{xk}^{CUE} = \sum_{i=1}^N P_{i0} G_{i0xk}, \quad (2d)$$

$$\forall x \in \{1, \dots, N\} \forall k \in \{1, \dots, \hat{N}_x\}.$$

There are two sources of interference that affect the system, one is the D2D links and the other is the CUEs. Since this study is focused on the impact of D2D links, the SINR target for CUEs is defined as:

$$\gamma_{x0}^{th} = \frac{\Gamma_{x0}^i}{\delta} = \frac{P_{x0}G_{x0x0}}{(I_{x0}^{CUE} + \mathcal{N}_{BS})\delta}, \quad \forall \delta \in \{\mathbb{R}^+; \delta > 1\}, \quad (3)$$

where Γ_{x0}^i is the initial SINR of CUEs when no D2D links are active and δ corresponds to the desired ratio between the SINR of CUEs before and after D2D links are added to the system, i.e., the SINR loss of CUEs due to the interference caused by D2D links. This definition allows a clear evaluation of the impact of D2D links to the CUEs uplink.

The transmission power of CUEs is given by the LTE open loop fractional power control (OFPC) found in [14].

In order to simplify the analysis we also assume a fixed target SINR for all D2D links defined as $\gamma_{xk}^{th} = \gamma_D$.

III. FULL CSI OPTIMAL (F-CSIOP) SCHEME

To achieve an optimal solution we consider that full CSI regarding all users in the system is available, thus we use this result as a benchmark for the optimal performance.

We formulate a general optimization problem following the same approach depicted in [11] and expand it towards a multi-cell environment. The goal is to maximize the number of active D2D links in the system while assuring QoS for CUEs and D2D links. So a mixed integer programming (MIP) optimization problem is formulated as follows:

$$\max_{\substack{(\phi_{ij} \in \{0,1\}) \\ P_{ij} \in \mathbb{R}^+}} \left\{ \sum_{i=1}^N \sum_{j=1}^{\hat{N}_i} \phi_{ij} \right\}, \quad (4)$$

Subject to:

$$\Gamma_{x0} = \frac{P_{x0}G_{x0x0}}{I_{x0}^{D2D} + I_{x0}^{CUE} + \mathcal{N}_{BS}} \geq \gamma_{x0}^{th}, \quad (5a)$$

$$\Gamma_{xk} = \frac{\phi_{xk} P_{xk} G_{xkxk} + (1 - \phi_{xk}) M_{xk}}{I_{xk}^{D2D} + I_{xk}^{CUE} + \mathcal{N}_D} \geq \gamma_D, \quad (5b)$$

$$\begin{aligned} \phi_{xk} P_{xk} &\leq P_D^{max}, \\ \forall x \in \{1, \dots, N\} \forall k \in \{1, \dots, \hat{N}_x\}. \end{aligned} \quad (5c)$$

The constraint (5a) refers to the SINR of the uplink between the CUE and the BS of a given cell x , similarly the constraint (5b) depicts the SINR of the D2D link k in cell x . Equation (5c) shows the limit for the transmission power of active D2D links.

The term M_{xk} is a constant defined in such a way that when a D2D link is inactive $\phi_{xk} = 0$, its SINR constraint is always satisfied. By doing this we avoid the issue of having an unfeasible optimization problem because of inactive D2D links. The constraint for M_{xk} is given by:

$$\begin{aligned} M_{xk} \geq \gamma_D &\left(P_D^{max} \left(\sum_{i=1}^N \sum_{j=1}^{\hat{N}_i} G_{ijxk} - G_{xkxk} \right) \right. \\ &\left. + P_C^{max} \sum_{i=1}^N G_{i0xk} + \mathcal{N}_D \right), \end{aligned} \quad (6)$$

where P_C^{max} represents the maximum transmission power of CUEs. The optimization variables are the state of D2D links ϕ_{xk} and their transmission power P_{xk} .

The MIP optimization problem depicted in (4) and (5) cannot be solved directly because the constraint (5c) is nonlinear, given that ϕ_{xk} is a binary variable. To obtain a linear constraint we define:

$$\tilde{P}_{xk} = \phi_{xk} P_{xk} \leq P_D^{max}. \quad (7)$$

Furthermore the constraints (5a) and (5b) are also nonlinear, thus we combine (7) and (2) to rewrite the optimization problem as:

$$\max_{\substack{\phi_{ij} \in \{0,1\} \\ \tilde{P}_{ij} \in \mathbb{R}^+}} \left\{ \sum_{i=1}^N \sum_{j=1}^{\hat{N}_i} \phi_{ij} \right\}, \quad (8)$$

Subject to

$$\sum_{i=1}^N \sum_{j=1}^{\hat{N}_i} \tilde{P}_{ij} G_{ijx0} \leq \sum_{i=1}^N P_{i0} A_{ix0}^C - \mathcal{N}_{BS}, \quad (9a)$$

$$\sum_{i=1}^N \sum_{j=1}^{\hat{N}_i} \tilde{P}_{ij} A_{ijxk}^D + \phi_{xk} M_{xk} \leq B_{xk}^D, \quad (9b)$$

$$\begin{aligned} \tilde{P}_{xk} &\leq P_D^{max}, \\ \forall x \in \{1, \dots, N\} \forall k \in \{1, \dots, \hat{N}_x\}, \end{aligned} \quad (9c)$$

where

$$A_{ix0}^C = \begin{cases} \frac{G_{x0x0}}{\gamma_{x0}^{th}} & \text{if } i = x \\ -G_{i0x0} & \text{if } i \neq x \end{cases}, \quad (10a)$$

$$A_{ijxk}^D = \begin{cases} -G_{xkxk} & \text{if } (i = x \text{ and } j = k) \\ \gamma_D G_{ijxk} & \text{if } (i \neq x \text{ or } j \neq k) \end{cases}, \quad (10b)$$

$$B_{xk}^D = M_{xk} - \gamma_D \left(\sum_{i=1}^N P_{i0} G_{i0xk} + \mathcal{N}_D \right). \quad (10c)$$

The optimization problem found in (8) and (9) is a mixed integer linear programming (MILP) problem and its solution

Fig. 1. Implementation of the P-CSID scheme

can be found by using optimization solvers.

IV. PARTIAL CSI DISTRIBUTED (P-CSID) SCHEME

In practical applications having full inter-cell CSI is unfeasible because of high signaling overhead, thus we present a practical solution where we consider limited CSI available.

The solution is based on a distributed algorithm where the D2D pairs decide independently their active status and their transmission power by adding a limited amount of signaling overhead.

In order to implement this solution we define two constraints for the transmission power of D2D links based on the QoS of CUEs and D2D links. Then each D2D link decides its active status depending on the feasibility of its transmission power constraints, i.e., being able to assure QoS for itself while maintaining the aggregated interference below a threshold.

To calculate the constraints for the transmission power of D2D links we need a statistical estimation of the interference given that CSI is limited. Thus we implement an interference model based on the density of users per unit area which can be calculated at the D2D pairs if the BS broadcast the number of active D2D links in their cells. This implies that QoS of CUEs and D2D links is assured statistically with low values of outage probability. Due to space restrictions the details of the interference model calculations are not included in this paper, however more detailed information can be found in [13].

In D2D communications underlay cellular networks the BS plays a role in the discovery procedure, hence we can assume that the active status of each D2D pair can be known to its serving BS. Thus the BS would have information about the number of active D2D links in their respective cells.

Fig. 1 depicts the roles of a D2D pair and its serving BS within the implementation of the P-CSID scheme. The BS keeps track of the number of active D2D links, calculates the amount of interference that D2D links can cause to the BS (defined as $\hat{I}_{x0}^{th}$) and other necessary parameters that are broadcasted to all potential D2D links. At the same time the D2D pairs receive the parameters, calculate their transmission power constraints and notify the BS after their active status is

decided. The definition of $\hat{I}_{x0}^{th}$ and all necessary parameters is provided later on.

To illustrate the implementation of the P-CSID scheme let us consider a D2D pair k in a cell x , denoted by $D2D_{xk}$, that needs to decide its active status. Since each D2D link makes an independent decision with limited CSI, $D2D_{xk}$ assumes the same transmission power for all D2D links $P_{ij} = P_{D_{xk}}, \forall i \in \{1, \dots, N\}, \forall j \in \{1, \dots, \hat{N}_i\}$.

Initially we define an upper and lower bound for the transmission power as $P_{D_{xk}}^{UB}$ and $P_{D_{xk}}^{LB}$ respectively. Then we compare the two sets $[-\infty, P_{D_{xk}}^{UB}]$ and $[P_{D_{xk}}^{LB}, \infty]$, if their intersection is a non-empty set $D2D_{xk}$ is active $\phi_{xk} = 1$, otherwise $\phi_{xk} = 0$. This rule allows $D2D_{xk}$ to evaluate the feasibility of its link given that the upper bound limits the interference to the CUE uplink and the lower bound assures the QoS of $D2D_{xk}$ link. Notice that our objective is to maximize the number of active D2D links while assuring QoS to all users, thus $D2D_{xk}$ should only be in active mode if the two power sets intersect.

To obtain the upper bound first we redefine the term I_{x0}^{D2D} as:

$$I_{x0}^{D2D} = \phi_{xk} P_{xk} G_{xkx0} + \hat{I}_{x0}^{D2D} = \phi_{xk} P_{D_{xk}} G_{xkx0} + \hat{I}_{x0}^{D2D}, \quad (11)$$

where $\hat{I}_{x0}^{D2D}$ corresponds to the aggregated interference caused by active D2D links to the BS of cell x (BS_x). Since $D2D_{xk}$ does not have CSI to calculate $\hat{I}_{x0}^{D2D}$ we consider it to be a random variable and we can calculate its expected value following the interference model found in [13]. Thus we have:

$$\mathbb{E}[\hat{I}_{x0}^{D2D}] = \frac{\tilde{N}_x}{A_{cl_x}} A_{x0} P_{D_{xk}} \mathbb{E}[G_{D2D-BS}], \quad (12)$$

where A_{x0} is an interference area defined by the model found in [13] and A_{cl_x} is the area of cell x . The term $\mathbb{E}[G_{D2D-BS}]$ is the expected value of the channel gain between an active D2D link and a BS. The parameter $\tilde{N}_x$ is the number of active D2D links in cell x .

Then we combine the result of calculating the expected value of (1a) and (1c) with (12). Finally the upper bound is defined as:

$$P_{D_{xk}}^{UB} = \min \left\{ \frac{A_{cl_x} \hat{I}_{x0}^{th}}{G_{xkx0} A_{cl_x} + \tilde{N}_x A_{x0} \mathbb{E}[G_{D2D-BS}]}, P_D^{max} \right\}, \quad (13a)$$

$$\hat{I}_{x0}^{th} = \left(\frac{\delta P_{x0} G_{x0x0}}{\Gamma_{x0}^i} - \mathbb{E}[I_{x0}^{CUE}] - \mathcal{N}_{BS} \right), \quad (13b)$$

$$\forall x \in \{1, \dots, N\} \forall k \in \{1, \dots, \hat{N}_x\},$$

where G_{xkx0} corresponds to the channel gain between $D2D_{xk}$ and BS_x , which can be obtained by monitoring the downlink reference signals. The term I_{x0}^{CUE} is considered to be a random variable and can be estimated by applying the interference model found in [13]. The parameter $\hat{I}_{x0}^{th}$ is the amount of interference that the uplink between the CUE and BS_x can tolerate. However this information is not available at the D2D links in normal conditions, thus we assume it is broadcasted by BS_x , as shown in Fig. 1.

To obtain the lower bound of the transmission power we calculate the expected value of (1b), where the term I_{xk}^{D2D} is considered to be a random variable and its expected value can be estimated through the interference model found in [13]. Thus we have:

$$\mathbb{E}[I_{xk}^{D2D}] = \frac{\tilde{N}_{xd}}{A_{dk}} A_{xk} P_{D_{xk}} \mathbb{E}[G_{D2D-I}], \quad (14)$$

$$P_{D_{xk}}^{LB} = \frac{(\mathbb{E}[I_{xk}^{CUE}] + \mathcal{N}_D) A_{dk} \gamma_D}{G_{xkxk} A_{dk} - (\gamma_D \tilde{N}_{xd} A_{xk} \mathbb{E}[G_{D2D-I}])}, \quad (15)$$

$$\forall x \in \{1, \dots, N\} \forall k \in \{1, \dots, \hat{N}_x\},$$

where A_{xk} is an interference area defined by the model found in [13] and $\mathbb{E}[G_{D2D-I}]$ is the expected value of the channel gain between two different active D2D pairs. The term G_{xkxk} corresponds to the channel gain between the transmitter and receiver of $D2D_{xk}$ and it is assumed to be known through the discovery procedure done by the devices of pair $D2D_{xk}$.

To estimate the number of active D2D links in the vicinity of $D2D_{xk}$ we assume that the cells can be divided into three sectors, which is highly common in practical applications. Thus BS_x can know the number of active D2D links on each sector and this could be broadcasted. $\tilde{N}_{xd}$ represents the sum of active D2D links in the three sectors that are closer to $D2D_{xk}$ and A_{dk} is the area enclosed by such sectors.

The parameter I_{xk}^{CUE} is assumed to be a random variable and its expected value can be estimated by applying the interference model found in [13].

Finally the decision of $D2D_{xk}$ to be active is given by:

$$\phi_{xk} = \begin{cases} 1 & \text{if } P_{D_{xk}}^{LB} \leq P_{D_{xk}}^{UB} \\ 0 & \text{if } P_{D_{xk}}^{LB} > P_{D_{xk}}^{UB} \end{cases}, \quad (16a)$$

$$P_{xk} = \phi_{xk} P_{D_{xk}}^{LB}, \quad (16b)$$

$$\forall x \in \{1, \dots, N\}, \forall k \in \{1, \dots, \hat{N}_x\}.$$

Notice that if $D2D_{xk}$ is in active mode, the transmission power is set as the lower bound $P_{D_{xk}}^{LB}$. This is done because the lower bound is calculated by considering the estimation of the interference between different D2D links. Thus increasing the transmission power above this level would result in higher interference between D2D links limiting the number of active D2D pairs that can achieve QoS. As a result we select the active transmission power as the lower bound to minimize the interference and maximize the number of active D2D links with QoS.

In this solution each BS needs to broadcast the following information so that the D2D pairs can calculate their transmission power constraints:

- **Areas:** The area of the cell A_{cl_x} and the area of the three sectors that compose the cell, from which the D2D links can calculate A_{dk} .
- $\hat{\mathbf{I}}_{x0}^{th}$: Interference bound for the CUE's QoS.
- $\mathbb{E}[\mathbf{P}_{txCUE}]$: Expected value of the transmission power of CUEs which is used to calculate $\mathbb{E}[I_{xk}^{CUE}]$.
- **Nr of act. D2D links:** The number of active D2D links

TABLE I
SIMULATION PARAMETERS.

Description	Representation and Value
Radius	$R = 400$ [m]
Noise power	$\mathcal{N}_D, \mathcal{N}_{BS} = -174$ [dBm/Hz]
RB bandwidth	$B_w = 180$ [KHz]
Carrier frequency	$f_c = 2$ [GHz]
Max. transmission power	$P_D^{max}, P_C^{max} = 23$ [dBm]
Min. distance between the BS and the users.	$d_{min} = 10$ [m]
Bounds of D2D distance	$D_{min} = 10$ [m] $D_{max} = 40$ [m]
Number of cells	$N = 7$
Nr. of D2D pairs available per cell	$\hat{N} = 10$
Nr. of Monte-Carlo simulations	5000

in the cell $\tilde{N}_x$ and in each sector that composes the cell, from which the D2D links can calculate $\tilde{N}_{xd}$.

- **Path loss parameters:** The path loss exponents and propagation constants so that the D2D links can estimate the channel gains $\mathbb{E}[G_{D2D-BS}]$, $\mathbb{E}[G_{D2D-I}]$ and the interference $\mathbb{E}[J_{xk}^{CUE}]$.

Thus the amount of signaling overhead introduced is significantly lower compared to a solution where CSI needs to be exchanged with each individual D2D link. This makes the P-CSID scheme a low complexity scalable solution to coordinate the interference in D2D communications underlay cellular networks. More details on the calculations of all parameters can be found in [13].

V. NUMERICAL RESULTS

To evaluate the performance of the proposed schemes we conducted extensive Monte-Carlo simulations. We consider 7 circular cells of radius R where BS are located at the center of the cells. In order not to underestimate the interference conditions we only collect data from the center cell. In each realization we generate one CUE uniformly distributed per cell, where the distance to the BS is given by $d_{CUE} \in [d_{min}, R]$. Also $\hat{N}$ D2D pairs are generated following an uniform distribution where the distance between devices of the same pair is given by $d_{D2D} \in [D_{min}, D_{max}]$. The channel model accounts for path loss and shadow fading implemented according to 3GPP specifications, [15]. Table I contains the main parameters used in the simulations. The MILP optimization problem is solved by using the optimization software MOSEK implemented on MATLAB.

To present a comparative analysis we introduce two single-cell solutions provided in [11]. The first consists in an optimization problem formulated with full CSI within each cell and the second is a centralized solution where a statistical

Fig. 2. CDF of Spectrum efficiency [bps/Hz] for $\gamma_D = 16$ [dB] and $\delta = 2$ [dB].

Fig. 3. CUE outage prob. vs 5% of D2D links SINR, with $\delta = 2$ [dB].

upper bound for the number of active D2D links is derived assuming no available CSI. We refer to the initial solution as peak interference constraint (PIC) in a single-cell “PIC Single-cell” and to the later as average interference constraint (AIC) in a single-cell “AIC Single-cell”. These two solutions were developed for a single-cell case, thus we implement them independently in each cell.

Fig. 2 depicts the cumulative distribution function (CDF) of the spectrum efficiency of the system for a high SINR target of D2D links and a low target CUE SINR loss. These QoS constraints represent the ideal case of D2D communications where D2D links achieve high data rates causing a small impact on the QoS of CUEs. It can be seen that the single-cell solutions have very limited performance given that they neglect the impact of inter-cell interference. In the case of the proposed P-CSID scheme we can see that it offers near optimal performance. Notice also that there is a significant improvement in spectrum efficiency when compared to the performance of the system without any D2D links.

To evaluate the CUE QoS we define the outage as the probability of having a CUE SINR loss above the desired target δ . Fig. 3 depicts the CUE outage probability vs the 5 percentile of the SINR of active D2D links. This percentile is selected so that a strict QoS for D2D links is assured, i.e.,

Fig. 4. Nr of active D2D links with QoS vs 5% SINR of active D2D links and 95% CUE SINR loss.

95% of the D2D links have a SINR above the desired target γ_D . It can be seen that similarly to the previous results the single-cell solutions are not able to provide acceptable QoS to the CUEs. In the case of the proposed P-CSID scheme, low values of CUE outage can be guaranteed for a wide range of D2D links SINR values.

In Fig. 4 the scalability of the system is depicted as the number of active D2D links with QoS that can be supported by each scheme vs the 5 percentile of the SINR of D2D links and the 95 percentile of the CUE SINR loss. As in the case of the QoS of D2D links we introduced this percentile for the CUE SINR loss to evaluate the performance under a strict QoS requirement, i.e., 5% outage for the CUEs.

In Fig. 4 we can see that the single-cell schemes are not able to offer acceptable values of scalability for any QoS requirement whereas in the case of the multi-cell schemes good scalability is offered for different values of QoS for both D2D links and CUEs. Notice that as the SINR of D2D links increases the scalability of both P-CSID and F-CSIOP schemes is decreased and as the CUE SINR loss is decreased the scalability is also decreased, however this effect is not as prominent as in the case of the SINR of D2D links. This suggests that the interference between different D2D links is an important limiting factor in the scalability of D2D communications.

From these results we can observe that the proposed P-CSID scheme provides good scalability and high spectrum efficiency to the system. Also in Fig. 4 we see that there is still room for improvement especially when the SINR of D2D links is high.

VI. CONCLUSION

In this paper we have investigated the scalability of D2D communications underlay cellular networks by developing and evaluating two interference coordination schemes aimed at maximizing the number of D2D links that can share the resources with CUEs subject to QoS constraints in a multi-cell environment. The first scheme was based on a MILP

optimization problem with full CSI available (F-CSIOP) and the second on a low complexity distributed algorithm where D2D links decided their own active status (P-CSID).

After performing extensive numerical analysis the results show that the proposed P-CSID scheme offers high spectrum efficiency and good scalability while assuring low outage probability for all users. Thus providing a low complexity scalable solution for practical interference coordination of D2D communications underlay cellular networks. Moreover there is still room for further improvement especially for high values of D2D links SINR.

Another interesting result is that neglecting the inter-cell interference greatly decreases the performance of the system thus considering a multi-cell scenario is highly important. Also we found that the interference between different D2D links is an important limiting factor for the scalability of D2D communications.

REFERENCES

- [1] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Miklos and Z. Turanyi, "Design aspects of network assisted device-to-device communications," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 170-177, March. 2012.
- [2] Smith's Point Analytics, "Proximity Based Mobile Social Networking: Applications and Technology, Making New Connections in the Physical World," November. 2011.
- [3] S. Ferrante, Q. Zhang and B. Raghothaman, "Capacity of a Cellular Network with D2D Links," *Proc. IEEE Int. Wireless Conf. (EW)*, Guildford, UK, April 2013.
- [4] P. Phunchongharn, E. Hossain and D.I. Kim, "Resource allocation for device-to-device communications underlaying LTE-advanced networks," *IEEE Wireless Commun.*, vol. 20, no. 4, pp. 91-100, August. 2013.
- [5] X. Shao, W. Haiming and C. Tao, "Effective Interference Cancellation Mechanisms for D2D Communication in Multi-Cell Cellular Networks," in *Proc. IEEE Vehicular Technology Conf. (VTC)*, Yokohama, Japan, May 2012.
- [6] G. Fodor, D. Della Penda, M. Belleschi, M. Johansson and A. Abrardo, "A comparative study of power control approaches for device-to-device communications," in *Proc. IEEE Int. Conf. on Commun. (ICC)*, Budapest, Hungary, June 2013.
- [7] L. Chaofeng, L. Bingbing, L. Bing, Z. Yang and W. Tian, "Uplink power control for Device to Device communication underlaying cellular networks," in *Proc. IEEE Int. Conf. on Commun. and Net. in China. (CHINACOM)*, Guilin, China, August 2013.
- [8] Z. Liu, T. Peng, B. Peng and W. Wang, "Sum-capacity of D2D and cellular hybrid networks over cooperation and non-cooperation," in *Proc. IEEE Int. Conf. on Commun. and Net. in China. (CHINACOM)*, Kun Ming, China, August 2012.
- [9] S. Hongguang, S. Min, W. Xijun, Z. Yan, L. Junyu and W. Kan, "Resource allocation for maximizing the device-to-device communications underlaying LTE-Advanced networks," in *Proc. IEEE Int. Conf. on Commun. in China (CIC/ICC)*, Xi'an, China, August 2013.
- [10] R. Tang, J. Zhao and H. Qu, "Distributed power control for energy conservation in hybrid cellular network with Device-to-Device communication," *IEEE Commun. China*, vol. 11, no. 3, pp. 27-39, March. 2014.
- [11] S. Shalmashi, G. Miao, Z. Han, and S. B. Slimane, "Interference Constrained Device-to-Device Communications," in *Proc. IEEE Int. Conf. on Commun. (ICC)*, Sydney, Australia, June 2014.
- [12] A. Asadi, Q. Wang and V. Mancuso, "A Survey on Device-to-Device Communication in Cellular Networks," *IEEE Commun. Surveys & Tutorials*, vol. PP, no. 99, pp. 1-19, April. 2014.
- [13] D. Verenzuela and G. Miao, "Scalable Device-to-Device Communications in Cellular Networks," *submitted for journal publication*.
- [14] Muhammad, B and Mohammed, A, "Performance Evaluation of Uplink Closed Loop Power Control for LTE System," in *Proc. IEEE Vehicular Technology Conf. (VTC)*, Anchorage, USA, September 2009.
- [15] 3GPP TR 36.843, "Study on LTE Device to Device Proximity Services (Release 12)," v.1.2.0, February 2014, available at <http://www.3gpp.org>.