Scalable Device-to-Device Communications For Frequency Reuse $\gg 1$

Daniel Verenzuela, Guowang Miao

Abstract—Proximity based applications are becoming fast growing markets suggesting that Device-to-Device (D2D) communications is becoming an essential part of future mobile data networks. We present three solutions for coordinating the interferences that aim at maximizing the density of D2D links while considering different levels of complexity and available channel state information (CSI).

We analyze the performance of D2D communications in multicell environments to gain valuable insights on important limiting factors of the system scalability and spectral efficiency.

The results show that the proposed low complexity interference coordination schemes achieve high spectral efficiency and good scalability while assuring low outage probability to provide QoS for all users.

Index Terms—device-to-device communication, interference coordination, multi-cell, admission control, power control, optimization, spectral efficiency.

I. INTRODUCTION

In the last decade the global demand on mobile data traffic has increased considerably and it is expected to continue doing so for the next years [1], thus new techniques need to be developed to further increase networks capacity. Device-to-Device (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 feature provides the means of increasing both spectrum and energy efficiency, reducing delay, improving coverage and supporting new proximity based applications [2]. In addition, the emergences of new applications based on geographical proximity is becoming a fast growing market [3] suggesting that D2D communications will become an important part of future mobile data networks. Thus studying the scalability of D2D communications is of paramount importance to accommodate future traffic demands.

Allowing D2D links to share the resources with cellular user equipments (CUEs) creates two levels of networks. The first one is the primary cellular network that is comprised of the communications between CUEs and their respective base stations (BSs). In turn the secondary network is composed of the simultaneous D2D links that share the resources of the primary cellular network. The main idea is to re-utilize the resources of the primary cellular network as much as possible while minimizing the impact on its performance. For this reason we assume that D2D links will only share the uplink resources of the cellular network. Notice that when downlink resources are shared the D2D links may cause strong interference towards the CUEs whereas in the case of sharing uplink resources the interference caused by D2D links affects the BS, whose impact can be controlled by the BS [2]. To maximize the frequency reuse, thus maximizing the network performance, the resources should be reused as much as possible. However as the reutilization of resources becomes higher the interference levels may increase to a point where the performance of both cellular and D2D networks is seriously degraded. Thus one of the main limitations on the scalability of D2D communications is the interferences.

When D2D links are added to the network, two main levels of interference are found:

1) Interference caused by the cellular network
   - From CUEs towards other BSs (inter-cell interference).
   - From CUEs towards D2D links.

2) Interference caused by the D2D network
   - From D2D links towards the BSs.
   - From D2D links towards other D2D links.

We mainly have the inter-cell interference in the first level. In the uplink of the last generation cellular networks the resources within each cell are allocated orthogonally resulting in zero intra-cell interference. However the resources are shared by several cells causing inter-cell interference between the CUEs and BSs of different cells. This problem is well known and there has been important research done in the last years, e.g., in the case of the uplink of Long Term Evolution (LTE) networks the authors in [4] analyze the impact of inter-cell interference coordination (ICIC) while considering the effects of power limitations, radio resource management functions, fast retransmissions, power control and adaptive modulation and coding schemes. The work [5] proposes an adaptive soft frequency reuse scheme that decreases inter-cell interference improving the average throughput per user. In [6] the authors propose an interference aware joint scheduling scheme based on proportional fairness. The work [7] studies the problem of resource allocation considering the impact of inter-cell interference while maintaining a frequency reuse of one. The works [8] and [9] perform an evaluation the LTE open loop fractional power control (OFPC) and the closed loop power control respectively considering the impact of inter-cell interference while giving an insight to the proper configuration of the design parameters.

The second effect of the first level interference refers to the impact of cellular communications on the D2D network. Since we assume the reuse of uplink resources, the CUEs may cause
strong interference towards D2D links. However given that the cellular network is considered to have higher priority we do not consider modifying its functionality to accommodate the D2D network, rather the opposite. In addition, a D2D pair can always switch to the cellular mode if it is receiving too much interference from CUEs. Thus in this study we want to focus on the effects caused by the D2D network.

In the second level of interference we consider two main impacts. First the D2D links cause aggregated interference towards the BSs that may compromise the QoS of the uplink of CUEs. Secondly the D2D links may cause strong interference among each other limiting their QoS and reducing the spectral efficiency of the network. Thus a careful design to deal with the second level interference is needed to obtain the most benefits of D2D communications and assure the QoS of both CUEs and D2D links.

To solve the problem of coordinating the interference, dynamic resource allocation algorithms have been presented in [10], allowing an increase of capacity. Also joint resource block (RB) scheduling [11] and interference avoidance schemes [12] have been proposed to increase spectral efficiency and reduce harmful interference respectively. Power control techniques have also been proposed to coordinate the interference, the work [13] conducts a comparative study of LTE power control techniques applied to D2D communications. A double threshold power control algorithm is proposed in [14] to maximize the system throughput. The authors in [15] proposed a continuous fuzzy logic power control scheme to limit the interference and improve the QoS of D2D links. In [16] 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 network capacity can indeed be dramatically improved by allowing more D2D links in the network as it increases frequency reuse. The capacity in terms of the maximum number of D2D links that system can support has only been considered by few studies [17]–[19]. In [17] a greedy heuristic resource allocation algorithm to maximize the number of D2D links in a single-cell is presented. The results show that by allowing more D2D links to share the same resources a considerable increase in spectral efficiency can be achieved, however in this work power control is not considered. The study [18] proposes and evaluates a series of distributed power control algorithms in D2D communications. However the implementation of the admission control procedures in terms of signaling is not mentioned and the impact on network scalability is not fully addressed.

In [19], 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. Optimal and suboptimal solutions are proposed to coordinate the interference with the goal of maximizing the number of active D2D links in the system. The results show that allowing several D2D links to share the same resources with CUEs without any limitation is indeed possible and it increases network spectral efficiency.

It is worth mentioning that the studies [17]–[19] 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 comprehensive survey for D2D communications [20] is that in most available literature the existing interference coordination solutions assume full channel state information (CSI) to be known at the BS. However this is usually not practical due to the signaling overhead, especially in multi-cell environments.

This study evaluates the scalability of D2D communications in a multi-cell environment of any size and proposes interference coordination schemes with no CSI, partial CSI or full CSI available. In the first case we calculate a theoretical upper bound for the number of D2D links and implement a blind admission control (BAC) scheme considering average QoS requirements for CUE and D2D links. For the second case we present a distributed admission control (DAC) scheme to further improve the performance where each D2D pair decides its mode based on transmission power constraints to assure QoS for all users, the DAC schemes is compatible with LTE standard and can be easily implemented in 5G LTE systems. In the last case we present an optimal admission control (OAC) scheme, which is based on exhaustive search and serves as the performance benchmark.

Both BAC and DAC have extremely low signaling overhead and only semi-static network signaling is needed. They can be easily implemented in the next generation networks, e.g., LTE Release 3 and onward.

The remainder of this paper is presented as follows: section II depicts the system model; In section III a statistical model for the interference is introduced; section IV presents the analysis conducted to obtain the BAC scheme; section V shows the analysis conducted to obtain DAC scheme; section VI presents the formulation of the OAC scheme; section VII depicts the numerical results and analysis; finally section VIII concludes our work.

II. SYSTEM MODEL

Consider a multi-cell system where a number of D2D pairs are available in each cell. The D2D pairs and CUEs are randomly distributed in all cells. We focus on a single RB scenario and only one CUE is assumed to be active in each cell and no resource allocation is implemented. To maximize the network frequency reuse, 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 \( \phi_{xk} \in \{0, 1\} \) \((\forall x \in \{1, ..., N\}, \forall k \in \{1, ..., N_x\})\), as binary random variable that indicates the state of each link \( k \) in cell \( x \). The parameter \( N \) corresponds to the number of cells in the system and \( N_x \) is the number of available D2D links in cell \( x \). When \( \phi_{xk} = 1 \) the D2D link 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 communications, depicted in (1a) and (1b) respectively. We also consider an upper bound for the
transmission power of D2D links shown in  \( \text{(10)} \):

\[
\Gamma_x^0 = \frac{P_{x0} G_{x0x0}}{I_{x0}^{D2D} + I_{x0}^{CUE} + N_{BS}} \geq \gamma_{th}^x, \quad (1a)
\]

\[
\Gamma_{xk} = \frac{\phi_{xk} P_{xk} G_{xkxk}}{I_{xk}^{D2D} + I_{xk}^{CUE} + N_D} \geq \gamma_{th}^{xk}, \quad (1b)
\]

\[
\forall x \in \{1, ..., N\} \forall k \in \{1, ..., \tilde{N}_x\},
\]

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. \( N_{BS} \) and \( N_D \) 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 \( P_{max} \) is the maximum transmission power of D2D links. \( \gamma_{th}^x \) and \( \gamma_{th}^{xk} \) 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 implemented: \( G_{abij} \) corresponds to the path gain from the transmitter \( b \) in cell \( a \) to the receiver \( j \) in cell \( i \). Note that in all variables, CUE and BSs are indexed as 0 and D2D users are indexed with non-negative integer numbers. In equations \( \text{(1a)} \) and \( \text{(1b)} \), \( G_{x0x0} \) corresponds to the channel gain between the CUE and the BS of cell \( x \), while \( G_{xkxk} \) corresponds to the channel gain within the D2D pair \( k \) in cell \( x \). Thus we define the interference terms as:

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

\[
I_{x0}^{CUE} = \sum_{i=1}^{N} P_{0i} G_{i0x0}, \quad (2b)
\]

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

\[
I_{xk}^{CUE} = \sum_{i=1}^{N} P_{0i} G_{i0xk}, \quad (2d)
\]

\[
\forall x \in \{1, ..., N\} \forall k \in \{1, ..., \tilde{N}_x\}.
\]

Here we can see that the terms \( I_{x0}^{D2D} \) and \( I_{xk}^{D2D} \) correspond to the second level of interference related to the impact of the D2D network, where \( I_{x0}^{D2D} \) represents the interference caused by D2D links to BSs and \( I_{xk}^{D2D} \) the interference among different D2D links. These are the main effects that we want to control in order to provide scalable interference coordination schemes for D2D communications.

On the other hand the terms \( I_{x0}^{CUE} \) and \( I_{xk}^{CUE} \) correspond to the first level of interference that is related to the impact of the cellular network, where \( I_{x0}^{CUE} \) depicts the inter-cell interference and \( I_{xk}^{CUE} \) the interference caused by CUEs towards D2D links. Since we are not interested in modifying the functionality of the cellular networks these terms are not part of the design variables for the interference coordination schemes. Thus we redefine the SINR target for CUEs as:

\[
\gamma_{th}^{x0} = \frac{\Gamma_x^0}{\delta} = \frac{P_{x0} G_{x0x0}}{I_{x0}^{CUE} + N_{BS} + \delta}, \quad \forall \delta \in \{\mathbb{R}^+ ; \delta > 1\}, \quad (3)
\]

where \( \Gamma_x^0 \) is the SINR of CUEs before D2D links are added to the system. The parameter \( \delta \) corresponds to the desired ratio between the CUE’s SINR before and after D2D links are added, 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 parameter \( \delta \) can be broadcasted by the BS or sent to a D2D link when it is newly established.

### III. STATISTICAL INTERFERENCE MODEL

In order to simplify the analysis we also assume a fixed target SINR for all D2D links defined as \( \gamma_D \). To develop the interference coordination schemes we assume different levels of CSI to be available. For the low complexity solutions, we need to establish statistical models for the interference and channel gains in order to account for the unavailable CSI.

#### A. Interference Model

Consider a victim receiver \( v \) surrounded by \( \tilde{N} \) devices, we define the aggregated interference received at \( v \) as:

\[
I_v = \sum_{i=1}^{\tilde{N}} P_{tx_{vi}} G_{vi}, \quad (4)
\]

where \( P_{tx_{vi}} \) is the transmission power of an interfering device \( i \) and \( G_{vi} \) is the channel gain between \( v \) and \( i \). To find a statistical model for the interference we assume that the interfering devices are randomly distributed within a given area \( A \), as shown in Fig 1. Thus the channel gains can be represented as a random variable \( G_{vi} \). We also assume that the interfering devices have the same transmission power \( P_{tx_{vi}} = P_t \leq P_{max} \), where \( P_{max} \) is the maximum transmission power allowed for the devices. This assumption is made so that the transmission power of the interfering devices can be used later on as a design variable to control the interference between users. Thus we can define an expected value for the aggregated interference within \( A \) as:

\[
E[I_v] = \tilde{N}_A A P_t E[G_{vi}], \quad (5)
\]

where \( \tilde{N}_A \) is the density of interfering devices per unit area.

In order to obtain reasonable values for \( \tilde{N}_A \) the area \( A \) needs to be finite, which means that in practical applications there will be interfering devices outside of \( A \), as shown in Fig 1. Thus we define \( A = \pi (d_{uw})^2 \) as a circular interference area around \( v \) where \( d_{uw} \) is the maximum distance between \( v \) and an interfering device. Notice that the interference caused by the devices outside of \( A \) is negligible compared to the one caused by the users inside due to the path loss attenuation.

To determine the value of \( d_{uw} \) we assume that if the received power from an interfering device is lower than a threshold,
then its effect can be neglected. Notice that the received power of the interfering devices depends also on their transmission power and this is meant to be used as a design variable in the later analysis. Thus we calculate $d_w$ considering the maximum transmission power that is allowed $P_{\text{max}}$ so that the interference area $A$ is obtained for the worst interference scenario. So we consider an interferer $w$ that is located at the edge of the interference area and we define $d_w$ as:

$$P_{\text{max}}E[G_{vw}] \leq N_v,$$

$$d_{vw} \geq \left( \frac{P_{\text{max}}c_vE[|h_{vw}|^2]}{N_v} \right)^{1/\alpha_v} = d_w.$$  

(6)

where $N_v$ is the noise power at the victim receiver and $d_{vw}$ is the distance between devices $v$ and $w$. We define the channel gain between $v$ and $w$ as:

$$G_{vw} = c_v d_v^{-\alpha_v} |h_{vw}|^2,$$

(7)

where $c_v$ refers to a propagation constant and $\alpha_v$ is the path loss exponent. The effects of fast fading are represented by $|h_{vw}|^2$.

B. Channel Gain Model

If CSI is not available we can model the channel gain between two devices $v$ and $i$ as a random variable $G_{vi}$, defined in (7), where $d_{vi}$ and $h_{vi}$ are independent random variables. Thus we can calculate the expected value of $G_{vi}$ as:

$$E[G_{vi}] = c_v E[d_{vi}^{-\alpha_v}] E[|h_{vi}|^2].$$  

(8)

Notice that in our analysis we want to establish statistical models of the channel gains. So consider the channel to be invariant during the period of interest, thus we assume $E[|h_{vi}|^2] = 1$.

We also assume device $v$ to be located at a fixed point and device $i$ to be positioned randomly following a circular distribution around $v$. Thus the probability density function of $d_{vi}$ is given by a triangular distribution depicted as:

$$f_{d_{vi}}(x) = \begin{cases} \frac{2x}{(d_{\text{max}}-d_{\text{min}})^2} & \text{if } d_{\text{min}} \leq x \leq d_{\text{max}}, \\ 0 & \text{otherwise.} \end{cases}$$  

(9)

Combining (8) and (9) we have that $\forall \alpha_v \in \{ \mathbb{R}^+; \alpha_v > 2 \}$.

$$E[G_{vi}] = c_v d_{\text{min}}^{d_{\text{max}}} x^{-\alpha_v} f_{d_{vi}}(x)dx$$

$$= c_v d_{\text{max}}^{d_{\text{max}}} 2x^{(1-\alpha_v)} (d_{\text{max}})^{-\alpha_v} dx$$

$$= \frac{2c_v (d_{\text{max}}^{-\alpha_v} - d_{\text{min}}^{-\alpha_v})}{(d_{\text{max}})^{-\alpha_v} (\alpha_v - 2)}.$$  

(10)

This result is applied to model all channel gains considered in this investigation. Note also that for practical applications the probability density function of $d_{vi}$ can be changed to match real user distributions.

IV. BLIND ADMISSION CONTROL

In practical applications obtaining CSI is not always possible because of high signaling overhead. Particularly if we consider the case of D2D communications, having CSI from every D2D link in the system would considerably increase the signaling overhead. Thus we present the BAC scheme where no CSI is necessary. Admission control here refers to letting a pair of devices in proximity communicate in the D2D mode.

On the BAC scheme each BS independently estimates an upper bound for the number of D2D links that can be active in its cell by considering average constraints for the QoS of CUEs and D2D links. Then the active D2D links are selected randomly from the available ones within the cell. The transmission power of D2D links is obtained by applying the channel inversion power control algorithm which allows for a fixed received power at the receiving device. Thus the transmission power of a given D2D link $k$ in a cell $x$ is depicted as:

$$P_{zk} = P_{z2D} G_{zkk} \leq P_{D}^{\text{max}}, \quad \forall x \in \{1, ..., N\}, \quad \forall k \in \{1, ..., \hat{N_x}\},$$

(11)

where $P_{z2D}$ is the received power for all D2D links which is calculated and broadcasted by the BS. Notice that the channel gain between devices of the same pair $G_{zkk}$ is known to them from the discovery, but unknown to the BS.

To obtain an upper bound for the number of D2D links first we assume $\phi_{zk} = 1$ and calculate the expected value of interference constrains (1a) and (1b) combined with (3) and (11). As a result we have:

$$P_{x2D} G_{2D} + E[I_{x2D}] + N_{xBS} \geq \frac{\Gamma^i_{x2D}}{\delta},$$

(12a)

$$P_{x2D} G_{2D} + E[I_{x2D}] + N_{xBS} \geq \gamma_{2D},$$

(12b)

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

Since no CSI is available we consider the channel gains to be random variables, then by applying the interference model
of D2D links per unit area that can be accepted in the system.

The number of D2D links is subtracted by one because there needs to be more than one D2D link in order to satisfy both QoS constraints \( \gamma_D \) and \( \gamma_{UB} \). Thus it is possible to find \( P_{TD} \) where \( N_{UB} = N_{UB}^C = N_{UB}^D \), so that the density of D2D links is maximized. Solving for \( N_{UB}^C \), the upper bound for the density of D2D links per unit area is:

\[
N_{UB}^C = \frac{I_C \left( \frac{\mathbb{E}[G_{D2D}]}{\gamma_D} + \mathbb{E}[G_{D2D-BS}] \right)}{\mathbb{E}[G_{D2D-BS}]} \left( \frac{\mathbb{E}[G_{D2D-BS}]}{\gamma_D} + \mathbb{E}[G_{D2D-BS}] \right)
\]

where

\[
P_{TD} = \frac{\mathbb{E}[G_{D2D}] (\mathbb{E}[G_{D2D-BS}] + \mathbb{E}[G_{D2D-BS}])}{\mathbb{E}[G_{D2D-BS}]} \left( \frac{\mathbb{E}[G_{D2D-BS}]}{\gamma_D} + \mathbb{E}[G_{D2D-BS}] \right)
\]

\[\forall x \in \{1, ..., N\}, \forall k \in \{1, ..., \tilde{N}_x\}.\]

It is worth mentioning that as shown in (15c) and (15d), \( I_C \) and \( I_D \) depend on \( \mathbb{E}[I_{CU}E] \) and \( \mathbb{E}[I_{kE}] \) respectively. These terms can be calculated by applying the interference model described in section III-A. In this case the density of users per unit area is known and corresponds to 1/A_d, where A_d is the area of the cell, given that there is only one CUE per cell.

From equation (16) we can see that the expected values of the channel gains determine the maximum density of D2D links per unit area that can be allowed in the system. By implementing the model found in section III-A we define these terms as:

\[
\mathbb{E}[G_{D2D}] = 2\alpha (d_{D2D-min}^{-(\alpha_d-2)} - d_{D2D-max}^{-(\alpha_d-2)}),
\]

\[
\mathbb{E}[G_{D2D-BS}] = 2\alpha_c (d_{D2D-BS-min}^{-(\alpha_c-2)} - d_{D2D-BS-max}^{-(\alpha_c-2)}),
\]

\[
\mathbb{E}[G_{D2D-I}] = 2\alpha_c (d_{D2D-I-min}^{-(\alpha_c-2)} - d_{D2D-I-max}^{-(\alpha_c-2)}),
\]

where the distance between the D2D transmitter and receiver of the same pair is a random variable within \([d_{D2D-min}, d_{D2D-max}]\). The distance between the D2D links and the BS is randomly distributed in the interval \([d_{D2D-BS-min}, d_{D2D-BS-max}]\). Similarly the distance between D2D transmitters and receivers of different D2D pairs is randomly distributed within \([d_{D2D-I-min}, d_{D2D-I-max}]\). The term \( \alpha_c \) corresponds to the path loss exponent for the channel between devices and the BS, whereas \( \alpha_d \) corresponds to the path loss exponent for the channel between devices. Similarly the term \( \alpha_c \) refers to a propagation constant for the channel.

These upper bounds depend on the received power of D2D links \( P_{TD} \), Fig 2 depicts a numerical example of \( \tilde{N}_x^{UB} A \) and \( \tilde{N}_x^{UB} C \) as the upper bounds for the number of D2D links in a circular area \( A \) of radius \( R \). The term \( d_{D2D} \) is a random variable that represents the distance between the transmitter and receiver of a given D2D pair. \( N_{UB}^C \) is monotonically decreasing with respect to \( P_{TD} \), \( \tilde{N}_x^{UB} \) increases until it reaches a saturation point, which means that after certain value of \( P_{TD} \), the density of D2D links per unit area cannot increase if a target SINR \( \gamma_D \) wants to be provided.

The overall upper bound for the density of D2D links is given by the minimum between \( N_{UB}^C \) and \( N_{UB}^D \) in order to satisfy both QoS constraints \( \gamma_D \) and \( \gamma_{UB} \). Applied (13) and (14) to constraints (12a) and (12b) allows the overall upper bound for the density of D2D links is maximized. Solving for \( \tilde{N}_x^{UB} \), the upper bound for the density of D2D links per unit area is:

\[
\tilde{N}_x^{UB} = \frac{I_C \left( \frac{\mathbb{E}[G_{D2D}]}{\gamma_D} + \mathbb{E}[G_{D2D-BS}] \right)}{\mathbb{E}[G_{D2D-BS}]} \left( \frac{\mathbb{E}[G_{D2D-BS}]}{\gamma_D} + \mathbb{E}[G_{D2D-BS}] \right)
\]

\[\forall x \in \{1, ..., N\}, \forall k \in \{1, ..., \tilde{N}_x\}.\]
between devices and the BS, and \( c_d \) corresponds to a propagation constant for the channel between devices.

Notice that the maximum limit for the distribution of the distances \( d_{D2D-BS} \) and \( d_{D2D-I} \) are given by the definition of the interference area (see section II-A, eq. 6). In practical applications more sophisticated spatial distributions of users can be obtained in order to have more accurate values for the expectations of the channel gains.

At this point we are able to estimate the maximum number of D2D links that can be allowed in the system without considering any CSI. In order to implement this result each BS estimates independently the number of D2D links that can be active in its cell as:

\[
\hat{N}_x = \min\{\lfloor \tilde{N}^{UB} A_{cl_x} \rfloor, \tilde{N}_x \}, \forall x \in \{1, ..., N\}.
\]

The term \( A_{cl_x} \) is the area of cell \( x \) and \( \tilde{N}_x \) is the number of available D2D links in the cell. Once the BS calculates the number of active D2D links \( \hat{N}_x \), it simply selects them randomly from the available ones and broadcasts the received power parameter \( \hat{P}_{D2D} \) for the power control of D2D links, which can be done in the admission control of D2D communications.

V. DISTRIBUTED ADMISSION CONTROL

In the implementation of D2D communications there is a certain amount of CSI that is already available in the system. Thus we present the distributed admission control (DAC) scheme that makes use of the available information to better coordinate the interference between D2D links and CUEs.

The DAC scheme 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 semi-static signaling overhead. The main idea is that every D2D pair decides their own active status and transmission power based on general information parameters that are broadcasted by the BSs, e.g., number of active D2D links in the cells, path loss towards the BS, area of the cells, etc. In contrast with the BAC scheme where the admission control is done at random, this solution is able to adapt the admission and transmission power of each D2D link to better coordinate the interference.

In order to implement this scheme we use the same constraints defined in previous sections to derive an upper and lower bound 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 to the CUEs below a threshold.

To calculate the constraints for the transmission power of D2D links, we need a statistical estimation of the interference scenario given that CSI is limited. Thus we make use of the interference model found in II-A which can be applied at the D2D pairs if the BSs broadcast the numbers of active D2D links in their cells.

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.

To illustrate the implementation of the DAC scheme, let us assume 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 \( P_{ij} = \hat{P}_{D2D} \), \( \forall i \in \{1, ..., N\}, \forall j \in \{1, ..., \hat{N}_i\} \).

Initially we define an upper and lower bound for the transmission power of a D2D pair as \( \hat{I}_{D2D}^{UB} \) and \( \hat{I}_{D2D}^{LB} \) respectively. Then we compare the two sets \([-\infty, \hat{P}_{D2D}] \) and \([\hat{I}_{D2D}^{LB}, \infty]\). 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 \( \hat{I}_{x0}^{D2D} \), found in (20), as:

\[
\hat{I}_{x0}^{D2D} = \phi_{x0} P_{x0} G_{x00} + \hat{I}_{x0}^{UB} = \phi_{x0} P_{x0} G_{x00} + \hat{I}_{x0}^{D2D}.
\]

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. Thus we can calculate its expected value by applying the model found on section II-A. As a result we have:

\[
E[\hat{I}_{x0}^{D2D}] = \frac{\tilde{N}_x}{A_{cl_x}} A_{x0} P_{D2D} E[G_{D2D-BS}],
\]

where \( A_{x0} \) is the interference area and \( A_{cl_x} \) is the area of cell \( x \). The term \( E[G_{D2D-BS}] \) is the expected value of the channel gain between active D2D links and BS.

Finally we obtain a statistical upper bound for the transmission power of D2D links \( P_{D2D}^{UB} \) by combining the expected value of (1a) and (1c) with (21), thus \( P_{D2D}^{UB} \) is defined as:

\[
P_{D2D}^{UB} = \min \left\{ \frac{\hat{I}_{x0}^{UB}}{\tilde{N}_x A_{cl_x}} E[G_{D2D-BS}], P_{D2D}^{max} \right\},
\]

\[
\hat{I}_{x0}^{UB} = \left( I_{x0}^{UB} - E[I_{x0}^{CUE}] - N_{BS} \right),
\]

where \( G_{x00} \) 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 of section II-A.

The parameter \( I_{x0}^{UB} \) is the amount of interference that the D2D links can cause to the \( BS_x \) so that the QoS of the CUE can be assured. The term \( I_{x0}^{UB} \) is given by the definition of the CUE QoS based on the SINR loss, thus we have:

\[
I_{x0}^{UB} = \frac{P_{x0} G_{x00} \gamma_{x0}}{\gamma_{x0}} = \frac{\delta P_{x0} G_{x00}}{\Gamma_{x0}}, \forall x \in \{1, ..., N\},
\]

where \( \delta \) is the interference margin, \( G_{x00} \) is the channel gain between the BS and the CUE, and \( \gamma_{x0} \) is the SINR threshold.
however this information is not available at the D2D links in normal conditions, thus we assume it is broadcasted by $BS_c$.

Note that $P_{D_{zk}^{LB}}$ can be easily implemented in LTE-A system as the existing power control for D2D communications in LTE-A ensures the interference from D2D communications to the serving BSs to be at fixed tolerable levels, which are configured by the BSs \[23\]. The BSs can configure the parameters in the power control formula so that the power control value is the one in \[22\] to serve as the upperbound.

To obtain the lower bound for the transmission power we consider the constraint \[15\], where the term $I_{zk}^{D2D}$ represents the interference from active D2D links to $D2D_{zk}$. Similarly to the previous analysis we can estimate this term as:

$$\mathbb{E}[I_{zk}^{D2D}] = \frac{\hat{N}_{zd}}{A_{dk}} A_{zk} P_{D_{zk}} \mathbb{E}[G_{D2D-1}].$$  (24)

Here the parameter $A_{zk}$ is the interference area and $\mathbb{E}[G_{D2D-1}]$ is the expected value of the channel gain between an interfering D2D link (within $A_{zk}$) and $D2D_{zk}$. To estimate the number of active D2D links per unit area in the surroundings of $D2D_{zk}$ we assume that the cells can be divided into three sectors, which is highly common in practical applications. Thus $BS_c$ can know the number of active D2D links in each sector and this could be broadcasted to the users. $\hat{N}_{zd}$ represents the sum of active D2D links in the three sectors that are closer to $D2D_{zk}$ and $A_{dk}$ is the area enclosed by such sectors, as illustrated in Fig. 3 a simple way of estimating $\hat{N}_{zd}$ and $A_{dk}$ is:

$$\hat{N}_{zd} = \hat{N}_{xc} + \hat{N}_{ya} + \hat{N}_{zb},$$  (25)

$$A_{dk} = A_{xc} + A_{ya} + A_{zb}.$$  (26)

More advanced estimators can be used to obtain more accurate results.

By calculating the expected value of \[15\] and combining it with \[24\] we can obtain an statistical lower bound for the transmission power of D2D links as:

$$P_{D_{zk}^{LB}} = \frac{\left(\mathbb{E}[I_{zk}^{CUS}] + N_D\right) \gamma_D}{G_{zk} - \left(\gamma_D \frac{\hat{N}_{zd}}{A_{zk}} A_{zk} \mathbb{E}[G_{D2D-1}]\right)},$$

$$\forall x \in \{1, ..., N\}, \forall k \in \{1, ..., \hat{N}_z\}.$$  (27)

The term $G_{zk}^{2D}$ corresponds to the channel gain between the transmitter and receiver of $D2D_{zk}$, which is obtained from the discovery procedure. The parameter $I_{zk}^{CUS}$ corresponds to the interference caused by CUEs towards $D2D_{zk}$ and can be estimated by applying the interference model of section III-A.

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

$$\phi_{zk} = \begin{cases} 1 & \text{if } P_{D_{zk}^{LB}} > P_{D_{zk}^{UB}} \\ 0 & \text{if } P_{D_{zk}^{LB}} < P_{D_{zk}^{UB}} \\ \end{cases}$$  (28a)

$$P_{zk} = \phi_{zk} P_{D_{zk}^{LB}},$$  (28b)

Notice that if $D2D_{zk}$ is in active mode, the transmission power is set as lower bound. 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 density of active D2D pairs. As a result we select the active transmission power as the lower bound to minimize the interference and maximize the density of D2D links.

In this solution the BS needs to broadcast a limited number of parameters that are common to all D2D links, thus the amount of signaling overhead introduced is significantly lower compared to a solution where CSI needs to be exchanged between the BS and each D2D link. In Appendix A we give a detailed summary of the parameters that need to be calculated by the BS and D2D links to apply the algorithm.

To illustrate the main concept of the DAC scheme Fig. 4 depicts the roles of a D2D pair and its serving BS. The BS keeps track of the number of active D2D links, calculates the amount of interference that the CUE uplink can tolerate (defined as $I_{zk}^{CUS}$) and other necessary parameters so that the D2D links can calculate their transmission power constraints. 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.

Fig. 5a presents a flow chart of the specific steps of the DAC algorithm at $D2D_{zk}$. First all necessary information is collected from the BS, then $D2D_{zk}$ calculates the necessary
parameters to estimate the interference conditions and the transmission power constraints. Finally, D2D\_zk decides its active status and notifies the BS of its decision. Similarly, Fig. 5 depicts the necessary steps taken by BS\_x to support the DAC scheme. First, BS\_x collects the active status of D2D links and calculates the number of active D2D links in the cell and in each sector. Then, BS\_x calculates \( \hat{I}_{th} \) for the QoS of CUEs and \( \mathbb{E}[P_{\text{CUEk}}] \) for the expectation of the interference caused by CUEs (see Appendix A), finally it broadcasts all necessary parameters or sends them in D2D discovery messages.

VI. OPTIMAL ADMISSION CONTROL

In this section, we present the optimal admission control assuming complete CSI is available. This serves as the performance benchmark. It is based on the same approach found in [19].

The goal is to maximize the number of active D2D links in the system while providing QoS to CUEs and D2D links. So a mixed integer programming (MIP) optimization problem is formulated as follows:

\[
\begin{align*}
\max_{\phi, i \in \{0, 1\}, P_i \in \mathbb{R}^+} & \left\{ \sum_{i=1}^{N} \sum_{j=1}^{N} \phi_{ij} \right\}, \\
\text{Subject to:} & \\
\Gamma_{x0} &= \frac{P_{x0}G_{x0x0}}{I_{x0}^D + I_{x0}^C + N_{BS}}, \\
\Gamma_{zk} &= \frac{\phi_{zk}P_{zk}G_{zkxk} + (1 - \phi_{zk})M_{zk}}{I_{zk}^D + I_{zk}^C + N_{D}} \geq \gamma_{zk}, \\
\phi_{zk}P_{zk} &\leq P_{zk}^{max}, \\
\forall x \in \{1, ..., N\} \forall k \in \{1, ..., \hat{N}_k\}.
\end{align*}
\]

The optimization problem found in (33) and (34) is a mixed integer linear programming (MILP) problem and its solution can be found by using exhaustive search algorithms.

VII. NUMERICAL ANALYSIS

To evaluate the performance of the proposed interference coordination schemes we conduct extensive Monte-Carlo simulations. We consider 7 circular cells of radius \( R \) where BSs 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 within \( d_{\text{CUE}} \in [d_{\text{min}}, R] \). Also, \( \hat{N} \) D2D pairs are generated following an uniform distribution where the distance between devices of the same pair is within \( d_{D2D} \in [D_{\text{min}}, D_{\text{max}}] \). The channel model accounts for path loss and shadow fading implemented according to 3GPP specifications [22]. Table I summarizes the main parameters used in the simulations. The MILP optimization problem is solved by using the optimization software MOSEK implemented in MATLAB.
To present a comparative analysis with previous solutions we introduce two single-cell schemes provided in [19]. The first is an optimization problem formulated with full CSI within each cell and the second is a centralized solution where a statistical upper bound for the number of active D2D links is derived assuming no available CSI. The initial solution is referred 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 environment, thus we implement them independently in each cell.

The transmission power of CUEs is given by the LTE OFPC [9] depicted as:

\[
P_{x_{0,ibm}} = P_{0,ibm} - \alpha_p G_{x0,ibm},
\]

\[
P_{0,ibm} = \alpha_p \left( \gamma_{th,CUEib} + N_{BSib} \right) + (1 - \alpha_p) \left( P_{max}^{CUEib} \right),
\]

where \( \alpha_p \) is the path loss compensation factor and \( \gamma_{th,CUEib} \) is the open loop target signal-to-noise ratio (SNR). We assume that the transmission powers of CUEs are given and cannot be modified by the proposed interference coordination schemes.

Fig. 6 depicts the behavior of the theoretical upper bound for the density of D2D links derived in (16) versus the target CUE SINR loss and maximum distance between devices within the same D2D pair. In Fig. 6b as \( \delta \) increases the density of D2D links also increases until it reaches a point of saturation. This occurs because as \( \delta \) increases the constraint regarding the QoS of CUEs becomes less strict and more D2D links can be admitted in the system. However after a certain point no more D2D links can be admitted due to the interference caused by D2D links towards each other. Fig. 6a shows that as the distance \( d_{D2D_{max}} \) becomes higher the density of D2D links decreases exponentially, thus the most gain of having D2D links is obtained when the D2D transmitter and receiver of the same pair are in proximity to each other. This result shows that the distance between the transmitter and receiver of the same D2D pair and the tolerable performance loss of CUEs play a key role in the maximum density of D2D links that the system can support.

| Description | Representation and Value |
|-------------|-------------------------|
| Radius      | \( R = 400 \) [m]       |
| Noise power | \( N_D, N_{BS} = -174 \) [dBm/Hz] |
| RB bandwidth| \( B_w = 180 \) [kHz]   |
| Carrier frequency | \( f_c = 2 \) [GHz] |
| Max. transmission power | \( P^{max}_{D}, P^{max}_{C} = 23 \) [dBm] |
| Min. distance between the BS and the users | \( d_{min} = 10 \) [m] |
| D2D distance (\( d_{D2D} \)) bounds | \( D_{min} = 10 \) [m], \( D_{max} = 40 \) [m] |
| Number of cells | \( N = 7 \) |
| Available D2D pairs per cell | \( \hat{N} = 10 \) |
| Path loss coeff. (user to BS) | \( c_0 = -30.55 \) [dB] |
| Path loss coeff. (user to user) | \( c_d = -28.03 \) [dB] |
| Path loss exp. (user to BS) | \( \alpha_0 = 3.67 \) |
| Path loss exp. (user to user) | \( \alpha_d = 4 \) |
| Monte-Carlo realizations | 5000 |

Table I: Simulation parameters.

Fig. 6 depicts the behavior of the theoretical upper bound for the density of D2D links derived in (16) versus the target CUE SINR loss and maximum distance between devices within the same D2D pair. In Fig. 6b as \( \delta \) increases the density of D2D links also increases until it reaches a point of saturation. This occurs because as \( \delta \) increases the constraint regarding the QoS of CUEs becomes less strict and more D2D links can be admitted in the system. However after a certain point no more D2D links can be admitted due to the interference caused by D2D links towards each other. Fig. 6a shows that as the distance \( d_{D2D_{max}} \) becomes higher the density of D2D links decreases exponentially, thus the most gain of having D2D links is obtained when the D2D transmitter and receiver of the same pair are in proximity to each other. This result shows that the distance between the transmitter and receiver of the same D2D pair and the tolerable performance loss of CUEs play a key role in the maximum density of D2D links that the system can support.

Now we compare the overall performance of the different interference coordination schemes for a low target CUE SINR loss (\( \delta = 2 \) [dB]) and a high D2D SINR target (\( \gamma_D = 16 \) [dB]). These conditions represent the ideal case of D2D communications where the D2D links achieve high data rates while causing the least amount of disturbance towards the QoS of CUEs.

Fig. 7a and Fig. 7b show the empirical cumulative distribution function (CDF) of the SINR loss of CUEs and the SINR of active D2D links respectively. For the single-cell schemes, the SINR of D2D links is mostly below the required target \( \gamma_D \) and there is a significant CUE SINR loss when compared to the multi-cell solutions. Fig. 7c depicts the empirical CDF of the number of active D2D links with QoS and Fig. 7d shows the empirical CDF of the spectral efficiency of the system. We see that the single-cell solutions neglect the impact of inter-cell interference when coordinating the admission and power control of D2D links, thus perform poorly.

For the BAC scheme we can see that the SINR of D2D links is quite high and for over 80% of devices the required target is fulfilled, furthermore the CUE SINR loss is well below the required target for 80% of the CUEs. However the number of D2D links with QoS and the spectral efficiency are quite limited. This occurs because the BAC scheme does not control the individual admission of each D2D link, thus when their target SINR \( \gamma_D \) is high the number of D2D links that can be active is low limiting the scalability and spectral efficiency.

In the case of the DAC scheme we can see that the SINR of D2D links is more balanced around the required target with over 70% of devices above it and the CUE SINR loss is quite low, assuring the respective target for over 90% of the CUEs. Furthermore we can see a significant improvement in the number of D2D links combined with high values of spectral efficiency.

Let the outage probability be the probability of not achiev-
For the results shown in Fig. 7 we see that the outage probability of CUEs is assured by all schemes. Thus the DAC scheme is a low complexity solution suitable for a wide range of D2D SINR with a low CUE SINR loss. However as the SINR of D2D links increases the number of D2D links decays which causes the overall spectral efficiency to drop regardless of the SINR values of D2D links. As the CUE SINR loss increases more D2D links can be admitted with QoS and Fig. 10 depicts the spectral efficiency for all the evaluated schemes. We see that for the DAC scheme as the SINR of D2D links grows, the number of active pairs with QoS decreases, which causes a quasi-concave behavior for the spectral efficiency. When the SINR of D2D links is low there are more D2D links active in the system but their data rates are low as well, then as the SINR of D2D links increases the data rates also increase, resulting in higher spectral efficiency. However as the SINR of D2D links increases the number of D2D links decays which causes the overall spectral efficiency to drop regardless of the SINR values of D2D links. As the CUE SINR loss increases more D2D links can be admitted in the system which in turn increments the spectral efficiency, however after a certain point the number of D2D links reaches a saturation point along with the spectral efficiency. This means that the interference between different D2D links is becoming a more and more important limiting factor in the density of active D2D links.

Compared to the other schemes, the DAC scheme provides a significant improvement in D2D density and spectral efficiency for a wide range of D2D SINR with a low CUE SINR loss. Thus the DAC scheme is a low complexity solution suitable for practical D2D communications.

VIII. Conclusion

We have conducted a comprehensive study in the scalability of D2D communications underlay cellular networks. While there have been sophisticated ICIC techniques to handle the first level interference among cellular users, our study shows that it is of paramount importance to develop new interference coordination techniques to solve the second level interference issues, i.e., those from D2D to cellular communications and those among D2D links themselves. We have developed three
interference coordination schemes, i.e. OAC, DAC and BAC to maximize the network frequency reuse, while assuring QoS to all users.

The results show that the best performance is achieved by the OAC followed by the DAC and finally the BAC scheme. Thus we have seen that as the CSI becomes available the performance of the interference coordination is increased, however the complexity and signaling overhead is also increased. Thus a trade-off must be found in order to provide a practical solution that can be deployed in real systems.

The DAC scheme has been proven to be a good candidate for practical applications. This scheme provides good spectral efficiency and scalability for a wide range of QoS requirements for both D2D links and CUEs and can be easily implemented in 5G LTE-A systems. We can conclude that proper designs of D2D communications will result in a significant increase of spectral efficiency and it is possible to achieve this with low complexity interference coordination schemes without affecting existing cellular communications.

**APPENDIX**

**PARAMETERS OF THE DAC SCHEME**

Tables II and III depict all additional parameters that are calculated at the BS and broadcasted to the D2D links to support the DAC scheme. Similarly table III illustrates all additional parameters that the D2D links calculate in order to obtain their transmission power constraints.

![Fig. 9: Nr of active D2D links with QoS vs 5% SINR of active D2D links and 95% CUE SINR loss.](image)

![Fig. 10: Spectral efficiency [bps/Hz] vs 5% SINR of active D2D links and 95% CUE SINR loss.](image)
REFERENCES

[1] “Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update,” White Paper, Cisco, February. 2014. [Online] Available: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-520862.html.

[2] 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.

[3] Smith’s Point Analytics, “Proximity Based Mobile Social Networking: Applications and Technology, Making New Connections in the Physical World,” November. 2011. [Online] Available: http://www.researchandmarkets.com/reports/1945613/.

[4] A. Racz, N. Reider and G. Fodor, “On the Impact of Inter-Cell Interference in LTE,” Proc. IEEE Global Telecom. Conf. (CLOBECOM), New Orleans, USA. December 2008.

[5] M. Xuehong, A. Maaref and Koon Hoo Teo, “Adaptive Soft Frequency Reuse for Inter-Cell Interference Coordination in SC-FDMA Based 3GPP LTE Uplinks,” Proc. IEEE Global Telecom. Conf. (CLOBECOM), New Orleans, USA. December 2008.

[6] P. Frank, A. Muller, H. Droste and J. Speidel, “Cooperative interference-aware joint scheduling for the 3GPP LTE uplink,” Proc. IEEE Personal Indoor and Mobile Radio Comm. (PIMRC), Istanbul, Turkey. September 2010.

[7] M. Jalloul, A.M. El-Hajj and Z. Dawy, “Uplink Interference Coordination/Avoidance in LTE Systems,” Proc. IEEE Next Generation Mobile Applications, Services and Technologies (NGMAST), Amman, Jordan. July 2010.

[8] C.U. Castellanos, D.L. Villa, C. Rosa, K.I. Pedersen, F.D. Calabrese, Per-Henrik Michaellsen and J. Michel, “Performance of Uplink Fractional Power Control in UTRAN LTE,” Proc. IEEE Vehicular Technology Conf. (VTC), Singapore. May 2008.

[9] 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.

[10] 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.

[11] 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.

[12] X. Shaoyi, W. Haining 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.

[13] 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.

[14] L. Chaoeng, 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.

[15] W. Wu, L. Zhang and Z. Li, X. Sha, “Fuzzy logic power control of device to device communication underlay TD-LTE-A system,” in Proc. IEEE Int. Conf. on Elec. Commun. and Net. (CECNet), Xianning, China. November 2013.

[16] 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.

[17] H. 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.

[18] 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.

[19] 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.

[20] 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.

[21] D. Verenzuela and G. Miao “Scalable Interference Coordination for Device-to-Device Communications,” Proc. IEEE INFOCOM 2015, Hong Kong, China. April 2015.