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Research Article

Performance Comparison of Practical Resource Allocation Schemes for Device-to-Device Communications

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Device-to-device (D2D) communications in cellular spectrum have the potential of increasing the spectral and energy efficiency by taking advantage of the proximity and reuse gains. Although several resource allocation (RA) and power control (PC) schemes have been proposed in the literature, a comparison of the performance of such algorithms as a function of the available channel state information has not been reported. In this paper, we examine which large scale channel gain knowledge is needed by practically viable RA and PC schemes for network assisted D2D communications. To this end, we propose a novel near-optimal and low-complexity RA scheme that can be advantageously used in tandem with the optimal binary power control scheme and compare its performance with three heuristics-based RA schemes that are combined either with the well-known 3GPP Long-Term Evolution open-loop path loss compensating PC or with an iterative utility optimal PC scheme. When channel gain knowledge about the useful as well as interfering (cross) channels is available at the cellular base station, the near-optimal RA scheme, termed Matching, combined with the binary PC scheme is superior. Ultimately, we find that the proposed low-complexity RA + PC tandem that uses some cross-channel gain knowledge provides superior performance.

1. Introduction

Device-to-device (D2D) communications in cellular spectrum assisted by a cellular network can increase the spectrum and energy efficiency of mobile broadband services, facilitate low latency machine type communications, and help extend the cellular coverage. In fact, unicasting D2D communications, as opposed to a broadcasting D2D physical layer, as in the Release 12 of Long-Term Evolution (LTE) systems, are currently studied by the 3rd Generation Partnership Project (3GPP) to facilitate proximity services (ProSe) in national security and public safety situations and vehicle-to-vehicle communication services in intelligent transportation scenarios [1–3].

As it was pointed out by several related works, D2D communications utilizing cellular spectrum pose new challenges, because, relative to cellular communication scenarios, the system needs to cope with new interference situations [4–9]. For example, in an orthogonal frequency division multiplexing (OFDM) system in which user equipment (UE) uses D2D communications, the D2D links may *reuse* some of the OFDM time-frequency physical resource blocks (PRB). Due to the reuse, intracell orthogonality is not maintained, and intracell interference can become severe due to the random positions of the D2D transmitters and receivers as well as of the cellular UEs communicating with their respective serving base stations (BS) [10, 11]. To realize the potential of D2D communications and to deal with intra- and intercell interference, the research community has proposed a number of important radio resource management (RRM) algorithms.

Although the objectives of such algorithms are different (including enhancing the network capacity [12], improving the reliability [13], minimizing the sum transmission power [7], ensuring quality of service [14], or protecting the cellular layer from harmful interference caused by the D2D layer [15]), there seems to be a consensus that the key RRM techniques include:

(1) Mode selection (MS): MS algorithms determine whether D2D candidates in the proximity of each other should communicate in *direct mode* using the D2D link or in *cellular mode* via the BS [9, 16–18].

(2) Resource allocation (RA): RA algorithms assign physical resources, such as PRBs to cellular UEs as well as D2D pairs ([10, 19–21]).

(3) Power control (PC): PC is a key technique to deal with intra- and intercell interference [14, 15, 22, 23]. References [14, 22] analyze the single (isolated) cell scenario and provide basic insights into the impact of PC and RA. The authors of [15] study a multicell system focusing on a PC scheme that helps minimize the interference from the D2D layer to the cellular users assuming that D2D users that operate in D2D mode reuse the cellular resources. The work reported in [23] evaluates the LTE PC scheme for a hybrid cellular and D2D system and concludes that PC needs to be complemented by mode selection, resource scheduling, and link adaptation to properly handle intra- and intercell interference.

Practically feasible MS, RA, and PC algorithms for D2D communications often rely on the availability of large scale channel state information, such as the large scale channel gains between transmitters and intended receivers [24, 25] as it will be discussed in detail in the next section.

This article is structured as follows. The next section describes the system model and discusses which pieces of large scale channel state information affect the performance of D2D communications. Next, Section 3 formulates the MS and RA problems. Section 4 presents three heuristics-based RA schemes that are implementable in practice and intuitively attractive and have previously been reported to provide good performance. This section also proposes an optimization-based RA scheme that utilizes cross-channel gain knowledge and is based on solving a matching problem conveniently represented by a bipartite graph. Section 5 discusses PC algorithms that differ in terms of channel gain knowledge requirement and whether they require iterations or not. Section 6 discuses numerical results and compares the signal-to-interference-plus-noise ratio (SINR) and throughput performance of the above RA and PC schemes. Section 7 draws conclusions.

2. System Model and the Role of the Large Scale Channel State Information in D2D Communications

The system we are considering is illustrated in Figure 1. Due to reusing the resources (PRBs) for cellular and D2D communications, the cellular and D2D layers cause interference to one another through the interference links $G_{d,B}$, $G_{c,d}$, and $G_{d,d}$, while the useful cellular and D2D link gains are denoted by G_c and G_d, respectively. Although in practice $G_{c,d}$ and $G_{d,d}$ are difficult to acquire either at the serving BS or at the respective transmitter and intended receiver nodes, the D2D literature seldom addresses this difficulty. To obtain the cross-channel gain $G_{d,d}$, for example, D2D Rx1 needs to know the identity and the transmit power level of D2D Tx2, measure the received power level, and report the estimated $G_{d,d}$ channel gain. Although this procedure is feasible using recently standardized D2D reference signals, measurements, and signaling, it clearly introduces some overhead. The 3GPP LTE standards suite, for example, introduced new physical layer channels, including the so-called physical sidelink control and discovery channel, as well as sidelink control information and demodulation reference signals that facilitate discovery, measurement, and channel estimation procedures for D2D communications. The sidelink control and discovery channels carry information that help peer devices to discover one another, estimate the D2D channel, and decode user data. The overhead introduced by these D2D-specific channels, control information, and signals depend on a number of configurable factors, such as the periodicity of peer discovery and the overall resources allocated for D2D communications in the cell [26, 27].

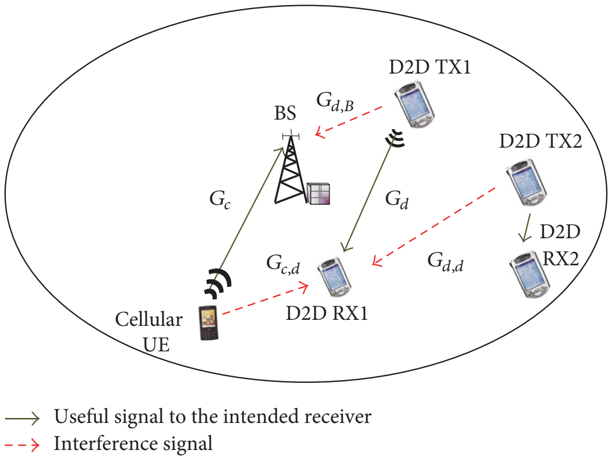


Figure 1: Channel gains in a network assisted D2D communication scenario. $G_{c,d}$ and $G_{d,d}$ (the "cross-channel gains") are more difficult to estimate in practice, although possible by using D2D reception capabilities.

In this paper, we will discuss the suitability of RA and PC algorithms depending on the availability of these channel gains and investigate the performance of practically feasible resource management schemes. To this end, we model the hybrid cellular-D2D network as a set of L transmitter-receiver pairs. A transmitter-receiver pair can be a cellular UE transmitting data to its serving BS or a D2D pair communicating in cellular uplink spectrum (Figure 1). D2D *candidates* are source-destination pairs in the proximity of each other that may communicate in direct mode, depending on the MS decision that is part of the RRM algorithm that is discussed in Section 3.

The network topology is represented by a directed graph of links labelled with $l = 1, \dots, L$ indexing the transmitter-receiver pairs in the network. Any transmitter, that is, either a cellular or D2D transmitter, operating on link l is assumed to have data to send to the intended 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 PRB bandwidth W, the achieved SINR of the links (γ_l), and the specific modulation and coding schemes used for the communication. A feasible rate vector **s** must fulfill the following set of constraints:

$$\mathbf{s} \preceq \mathbf{c}(\mathbf{p}), \qquad \mathbf{s} \succeq 0. \tag{1}$$

In this formulation, it is convenient to look at the **s** vector as the vector of the rate *targets* directly derived from a corresponding vector of SINR *targets*, while the capacity vector **c** depends on the transmit powers **p** selected by the transmitters. Specifically, each link can be seen as a Gaussian channel with Shannon-like capacity

$$c_l(\mathbf{p}) = W_l \log_2 (1 + K\gamma_l(\mathbf{p})) \tag{2}$$

that represents the maximum rate that can be achieved on link l, where K models the SINR-gap reflecting a specific modulation and coding scheme, while $\gamma_l(\mathbf{p})$ represents the SINR perceived at the receiver of link l. With no loss of generality, in this paper, we assume $K = 1$ and will set the link bandwidth to $W_l = W \ \forall l$, that is, to the bandwidth of a PRB.

Let G_{lm} denote the effective link gain between the transmitter of pair m and the receiver of pair l (including the effects of path loss and shadowing) and let σ_l be the thermal noise power at the receiver of link l, and let P_l be the transmission power. That is, G_{lm}, $l \neq m$ represents $G_{d,B}$, $G_{d,d}$, or $G_{c,d}$, while G_{ll} represents either G_c or G_d in Figure 1. The SINR of link l is

$$\gamma_l(\mathbf{p}) = \frac{G_{ll}P_l}{\sigma_l + \sum_{m \neq l} G_{lm}P_m}, \tag{3}$$

where $\mathbf{p} = [P_1, \ldots, P_L]$ 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 (3) can also be written as

$$\gamma_l\left(P_{l_{\mathrm{Rx}}}^{\mathrm{tot}}, P_l, G_{ll}\right) = \frac{G_{ll}P_l}{\left(P_{l_{\mathrm{Rx}}}^{\mathrm{tot}} - G_{ll}P_l\right)}, \tag{4}$$

where $P_{l_{\mathrm{Rx}}}^{\mathrm{tot}}$ represents the total received power (including σ_l) measured by the receiver of link l. Hence, the SINR in (4) 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. For the ease of notation, in the following we adopt $\gamma_l(\mathbf{p})$ to indicate the SINR measured at receiver-l.

In this paper, the MS and RA problems are formulated jointly, while the PC problem is formulated separately; that is, assuming that the MS and RA tasks have been solved and PRBs are assigned to the cellular UEs and the D2D pairs. Although this approach may be suboptimal, the joint MS, RA, and PC problem is more complex and may not be feasible in real time and thereby it is left for future studies. However, as we will see in Section 4.3, the particular combination of the matching-based RA scheme combined with the rate-maximizing binary power control scheme is throughput-optimal in a single-cell environment.

3. Mode Selection and Resource Allocation Algorithms

3.1. Notation and Terminology for Mode Selection and Resource Allocation. While cellular UEs communicate with their respective serving BS, D2D-capable UEs communicate with the intended peer UE either in direct mode or in cellular mode via the serving BS. In direct mode, D2D transmitters either reuse cellular PRBs (D2D reuse mode) or use orthogonal (dedicated) PRBs (D2D dedicated mode). On the other hand, when a D2D-capable UE communicates in cellular mode, D2D communication reduces to traditional cellular communication and RA follows the legacy OFDMA allocation strategy; that is, PRBs are allocated orthogonally among the cellular UEs. Therefore, three different communication modes can be considered for D2D communications: D2D mode with dedicated resources and D2D mode reusing cellular resources and cellular mode [7, 9, 25].

In general, a cellular system provides service to N cellular UEs and M D2D transmitters and the corresponding M D2D receivers that belong to the sets $\mathcal{N}$ and $\mathcal{M}$, respectively, such that the total number of served UEs in a cell is $L = N + M$. We denote with $x_{l,j}(q)$ that a transmitter-receiver pair l is assigned to PRB-j in communication mode q, where ($q = 0$) denotes cellular mode and ($q = 1$) the D2D direct mode. By definition, any cellular UE $n \in \mathcal{N}$ transmits in cellular mode ($q = 0$), while a D2D candidate can operate using the direct link ($q = 1$), or in cellular mode ($q = 0$), or adaptively switch between the direct and cellular links according to a specific MS algorithm. Using this terminology, the following resource constraints apply:

(i) *D2D mode*:

$$x_{m,j}(q) = x_{m,j}(1), \quad \forall m \in \mathcal{M}, \qquad \sum_{n \in \mathcal{N}} x_{n,j}(0) \leq 1, \quad \forall j. \tag{5}$$

(ii) *Cellular mode*:

$$x_{m,j}(q) = x_{m,j}(0), \quad \forall m \in \mathcal{M}, \qquad \sum_{n \in \mathcal{N}} x_{n,j}(0) + \sum_{m \in \mathcal{M}} x_{m,j}(0) \leq 1, \quad \forall j. \tag{6}$$

(iii) *Channel gain adaptive MS*:

$$\sum_q x_{m,j}(q) \leq 1, \quad \forall m \in \mathcal{M}, \qquad \sum_{n \in \mathcal{N}} x_{n,j}(0) + \sum_{m \in \mathcal{M}} x_{m,j}(0) \leq 1, \quad \forall j, \tag{7}$$

where the last inequality indicates that the D2D candidate pair m can be in either D2D or cellular mode when using PRB-j.

3.2. Formulating the Mode Selection and Resource Allocation Problems. The MS and RA tasks are formulated as an optimization problem that maximizes the overall spectral efficiency for a power allocation vector that is assumed to be known. As we shall see, decoupling the RA problem from the PC problem allows for combining different RA and PC approaches depending on the availability of the required channel gains. The spectral efficiency for transmitter-receiver pair l on a given PRB-j is defined as $\eta_{l,j} = \log_2(1 + G_{l,l,j}P_l/(\sigma + I_{l,j}))$. Hence, it depends on the path gain $G_{k,l,j}$ between transmitter-k and receiver-l on PRB-j and the intracell interference $I_{l,j} = \sum_{k \neq l} P_l \cdot G_{k,l,j}$, due to the possible PRB sharing between D2D pairs and cellular UEs. Thus, the joint MS and RA problem becomes *(Problem-I)*

$$\text{maximize} \quad \sum_l \sum_j \log_2\left(1 + \frac{G_{ll,j}P_l \cdot x_{l,j}(q)}{\sigma + I_{l,j}}\right) \tag{8}$$

$$\text{subject to} \quad \sum_l x_{l,j}(0) \leq 1 \quad \forall j \tag{C1}$$

$$\sum_q x_{l,j}(q) \leq 1, \quad \forall l, j \tag{C2}$$

$$x_{n,j}(1) = 0 \quad \forall n \in \mathcal{N}, j \tag{C3}$$

$$x_{l,j}(q) \in \{0, 1\}. \tag{C4}$$

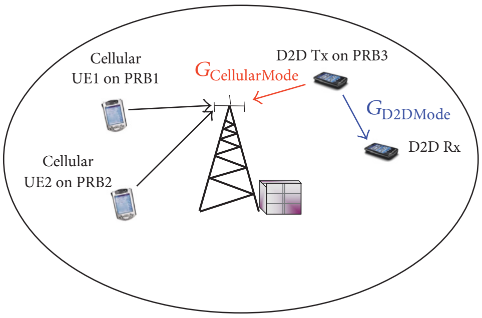
The constraints (C1) indicate that each PRB can be allocated to at most one user in cellular mode due to the orthogonality constraint. Constraints (C2) ensure that to each user only one of the two possible modes is assigned. By definition, cellular UEs must not be assigned to mode ($q = 1$) (C3).

4. Heuristic Algorithms to Solve the Resource Allocation Problem

4.1. The MinInterf Algorithm. To solve Problem (8) and to obtain benchmarking results, we first describe a centralized procedure based on the full knowledge of the channel gain measurements between all transmitters and receivers within the cell, first proposed by [25]. This scheme, that we call MinInterf, exploits the proximity between D2D candidates for MS and performs RA that aims at reducing the intracell interference by minimizing the sum of the harmful path gains as will be shown in (9) and in Algorithm 1. MinInterf is intuitively attractive because assuming that the transmit powers are set, it tries to minimize the interference due to the cross-links and serves as a good benchmarking algorithm for more practical schemes.

MinInterf involves two steps. Firstly, orthogonal resources are allocated to cellular UEs employing legacy cellular scheduling and RA schemes [28]. Next, for each D2D candidate in the cell, MinInterf considers two possible cases in the following order:

(i) *D2D transmission with dedicated resource*: if there are orthogonal resources left, they can be assigned to the D2D candidate so that the D2D transmission does not affect others within the same cell. In this case, the D2D transmitter selects the best communication mode (i.e., cellular mode or D2D mode) on the basis of the path gains towards both the D2D receiver (G_{d2dMode}) and the BS ($G_{\text{CellularMode}}$). Specifically, if $G_{\text{CellularMode}} \leq G_{\text{d2dMode}}$, then the direct mode is preferred (see Figure 2).



PRB1	PRB2	PRB3
Cellular UE1	Cellular UE2	D2D Tx (cellular mode or D2D mode)

PRB: physical resource block
BS: base station

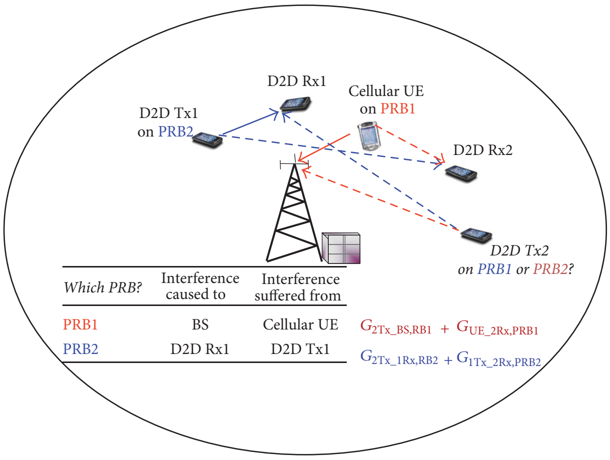
Figure 2: An example of a D2D transmission with dedicated resource. The D2D Tx node selects the transmission mode (cellular mode or D2D mode) according to the channel gain measurements towards the D2D Rx node and towards the BS. If the channel gain between the D2D pair is higher than the one towards the BS, then the D2D mode is selected.

(ii) *D2D transmission with resource reuse (as in Figure 3)*: when there are no unused RBs in the cell, the D2D pair must communicate in direct mode (D2D mode) and reuse RBs. Sharing resources with other users within the same cell produce intracell interference. To reduce this intracell interference, for each resource-j, MinInterf considers the sum

$$\mathbf{S}(j) = G_{2\text{Tx\_1Rx},j} + G_{1\text{Tx\_2Rx},j} \ [\text{dB}] \tag{9}$$

as a measure of the potential interference that assigning the D2D-pair to resource-j causes. Here $G_{2\text{Tx\_1Rx},j}$ represents the path gain between the D2D transmitter and the receiver of link(s) already allocated to resource-j, which may be the cellular BS and/or other D2D receiver(s). $G_{2\text{Tx\_1Rx},j}$ takes into account the interference that the D2D pair produces transmitting on PRB-j. $G_{1\text{Tx\_2Rx},j}$, on the other hand, is the path gain between the transmitter(s) already allocated to PRB-j (which can be both a cellular UE and/or other D2D transmitters) and the receiver of the new D2D pair to be allocated. $G_{1\text{Tx\_2Rx},j}$ is therefore related to the interference that the D2D receiver will experience due to the reuse. Once expression (9) is computed for each available resource-j, the D2D pair is assigned to that resource corresponding to the minimum value (see Figure 3).

4.2. Practical MS and RA Algorithms with Limited or No Channel State Information: BRA and CPA. While MinInterf



Which PRB?	Interference caused to	Interference suffered from
PRB1	BS	Cellular UE
PRB2	D2D Rx1	D2D Tx1

Figure 3: An example of a D2D transmission with resource reuse. The D2D Tx node communicates directly with the D2D Rx node sharing a PRB with the cellular user UE. The shared PRB is selected in a way that minimizes an estimate of the intracell interference that D2D communication might perceive (related to the gain $G_{1\text{Tx\_2Rx}}$ between the UE and the D2D Rx node) and produce (related to the gain $G_{2\text{Tx\_1Rx}}$ between the D2D Tx node and the BS); see (9).

can serve as a tool to benchmark RA algorithms, it cannot be employed in practice because it relies on a full G matrix knowledge in the "resource reuse" branch of Algorithm 1. Therefore, we seek viable alternatives to MinInterf. Our first proposed algorithm operates without any path loss knowledge but keeps track of the reuse factors ρ_j of each PRB as described by the pseudo code of the "Balanced Random Allocation" (BRA), Algorithm 2. ρ_j is a counter associated with resource-j that counts the number of intracell transmitters using that resource.

Our second proposed practical algorithm is called "Cellular Protection Allocation" (CPA). CPA takes advantage of the knowledge of the path gains between any cellular transmitter (i.e., cellular UE or D2D candidate operating in cellular mode) and the BS that is available in practice due to measurement reports by the UE. As indicated in the pseudo code of Algorithm 2, a D2D transmitter that reuses a cellular PRB is assigned to the particular PRB used by a cellular UE that has the strongest cellular link. The rationale for this heuristic is that a cellular UE with a strong cellular connection with its serving BS can be expected to tolerate intracell interference caused by D2D resource reuse.

4.3. Resource Allocation as a Matching Problem. In network assisted D2D communications, a D2D pair and a cellular UE that use the same PRB form a resource reuse pair. The transmitters of the resource reuse pair cause interference at their nonintended receivers and thereby they limit the achievable rate by one another. For example, if the D2D transmitter causes interference at the BS, this interference limits the achievable rate for the UE that uses the same (uplink) resource as the D2D pair. The matching problem is the problem of forming the resource reuse pairs (that is one pair for each PRB) and assigning an appropriate PRB to each pair, as illustrated by Figure 4. Specifically, for stating the matching problem, we will need the following indicator variable:

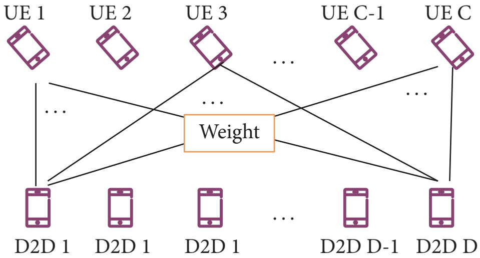


Figure 4: Matching: selecting cellular UEs and D2D pairs that share the same physical resource block. A cellular UE and a D2D pair that use the same PRB are called the resource reuse pair. Each resource reuse pair is associated with the maximum sum rate that they can achieve, and thus the system is represented by the bipartite graph shown by the figure.

$$x_{c,d} = \begin{cases} 1 & \text{if D2D link } d \text{ uses the PRB of UElink } c \\ 0 & \text{otherwise.} \end{cases} \tag{10}$$

The matching problem can then be formulated as

$$\underset{x_{c,d},P_c,P_d}{\text{maximize}} \quad \sum_{c=1}^{N} \left(u_c(d,P_c) \cdot x_{c,d} + u_d(c,P_d) \cdot x_{c,d} \right), \tag{11}$$

subject to

$$\begin{aligned} &\sum_d x_{c,d} = 1 \quad \forall c, \\ &\sum_c x_{c,d} = 1 \quad \forall d, \\ &0 \le P_c \le P_c^{\max}, \\ &0 \le P_d \le P_d^{\max}, \end{aligned} \tag{12}$$

where $u_c(d,P_c)$ is the throughput of cellular link c, when it uses the same PRB (matched with) D2D pair d and transmits with power P_c. Similarly, $u_d(c,P_d)$ is the throughput of D2D link d when it uses the same PRB (matched with) cellular link c and transmits with power P_d.

4.4. Throughput Maximization by Solving the Matching Problem. Solving the matching problem of (11) requires the generation of the weight matrix $\mathbf{W} \in \mathbb{R}^{c \times d}$ whose (c,d) entry contains the achievable sum throughput of the resource reuse pair of cellular UE c and D2D link d, where $c = 1 \cdots N$, and $d = 1 \cdots M$. The achievable sum throughput on a shared PRB obviously depends on the PC algorithm employed by the resource reuse pair, but for a given PC scheme solving the matching problem maximizes the sum throughput, as discussed below. In particular, if the PC scheme maximizes the throughput on a PRB by appropriately setting P_c and P_d,

```
Allocate orthogonal resources (PRB) to cellular-UEs (using legacy algorithms)
for Each D2D candidate do
    if there is an orthogonal resource-$l$ left then
        if $G_{\text{CellularMode}} \leq G_{\text{d2dMode}}$ then
            D2D candidate transmits in D2D-Mode on resource-$l$
        else
            D2D candidate transmits in Cellular-Mode on resource-$l$
        end if
    else
        /* Resource Reuse */
        for Each available resource-$j$ do
            $\mathbf{S}(j) = [G_{2\text{Tx\_1Rx},j} + G_{1\text{Tx\_2Rx},j}]$
        end for
        D2D candidate transmits in D2D-Mode on resource-$j$ corresponding to the
        minimum value of $\mathbf{S}$
    end if
end for
```

Algorithm 1: MinInterf.

Table 1: Large scale CSI required by RA algorithms.

RA scheme	Channel gain knowledge	Complexity	Comment
MinInterf	G_c, G_d, $G_{d,B}$, $G_{d,d}$, $G_{c,d}$	$O(MR)$	All cross-channel gains are needed to minimize the sum interference
Balanced random allocation (BRA)	G_c, G_d, $G_{d,B}$	$O(MR)$	$G_{d,B}$ and G_d are needed for MS
Cellular protection allocation (CPA)	G_c, G_d, $G_{d,B}$	$O(MR)$	$G_{d,B}$ and G_d are needed for MS
Matching	G_c, G_d, $G_{d,B}$, $G_{c,d}$	$O(\varrho^3)$ where $\varrho = \max(N, M)$	$G_{d,B}$ and $G_{c,d}$ are needed for generating the weight matrix

then solving the matching problem provides a throughput-optimal solution to the joint RA and PC problem. This observation is important, since from [29, 30] we know that the binary power control scheme is throughput optimal as long as there are two transmit-receive pairs on the same PRB and close-to-optimal if there are more than two transmit-receive pairs on the same PRB. To generate the weight matrix $\mathbf{W}$, the BS needs to know the cross-channel gains $G_{c,d}$, since the sum throughput depends on the SINR levels at the respective receivers as indicated in the Weight Matrix Generation (Algorithm 3).

Once the weight matrix associated with the bipartite graph is available, the matching problem can be solved by the Hungarian algorithm.

4.5. Summary: Channel Gain Knowledge Needed by RA Algorithms. In this section, we discussed three heuristics-based and a novel near-optimal (sum rate maximizing) RA schemes. From the perspective of channel gain knowledge, these algorithms are summarized in Table 1.

Compared with BRA and CPA, the Matching RA scheme requires somewhat more cross-channel gain knowledge ($G_{c,d}$); Acquiring of $G_{c,d}$ would be possible in practice since D2D-capable UEs can readily perform measurements on uplink signals. "In return," Matching achieves near-optimal sum rate performance and, as we shall see, in this respect it is a natural RA counterpart of the binary power control scheme.

5. Power Control Algorithms

5.1. Power Control Options Based on LTE Mechanisms. It is natural to base a PC strategy for D2D communications underlying an LTE network on the LTE standard uplink PC mechanisms that require the useful channel gain only (that is, it does not require the cross-channel gains) [28]. Also, building on standardized and widely deployed schemes facilitates a smooth introduction of D2D-capable user equipment (UE) and helps to develop interoperable solutions between different devices and network equipment. However, due to intracell interference and new intercell interference scenarios, the question naturally arises whether the available LTE PC is suitable for D2D communications integrated in an LTE network. Also, the ad hoc networking community has proposed efficient distributed schemes suitable for D2D communications, including situations with or without the availability of a cellular infrastructure (see, e.g., [22, 23, 31]). Such schemes can also serve as a basis for D2D PC design [24, 32].

The LTE PC scheme can be seen as a "toolkit" from which different PC strategies can be selected depending on

```
BS maintains variables $\rho_j$ and $\rho_{\mathrm{MIN}}$ as explained below
BS maintains (from e.g. D2D discovery algorithms) the
D2D candidates for mode selection and
the value of large scale fading (path gain) $G_{\mathrm{d2dMode}}$
between each D2D candidate, which
can be updated on the slow time scale (e.g. 500 ms).
$\rho_j = 0$ for all resource blocks PRB-$j$ ($j = 1 \cdots R$)
if there are cellular UEs in the cell then
    Allocate orthogonal resources (PRB) to cellular-UEs
    (using legacy algorithms)
    Set $\rho_j = 1$ for PRB:s assigned to UEs
    /* For CPA: Store $g(j)$, where $g(j)$ is the path gain
    between cellular UE using PRB-$j$ and the serving
    BS */
end if
for each D2D candidate do
    $\rho_{\mathrm{MIN}} := \min_{j=1\cdots R} \rho_j$ where $R$ is the total number of
    resource blocks
    if $\rho_{\mathrm{MIN}} == 0$ then
        /* there is an orthogonal resource-$l$ left: Schedule
        D2D on orthogonal resource-$l$ */
        if $G_{\mathrm{CellularMode}} \leq G_{\mathrm{d2dMode}}$ then
            D2D candidate transmits in D2D-Mode on
            resource-$l$
        else
            D2D candidate transmits in Cellular-Mode on
            resource-$l$
            /* For CPA: Store $g(l)$, where $g(l)$ is the path
            gain between the D2D transmitter in cellular
            mode using PRB-$l$ and the serving BS */
        end if
    else
        /* Resource Reuse */
        Select a resource-$j$ out of the resources for which
        $\rho_j == \rho_{\mathrm{MIN}}$
        /* For the CPA algorithm: Substitute the above by:
        Pick the resource-$j$ out of the resources for which
        $\rho_j == \rho_{\mathrm{MIN}}$ for which $j = \arg\max g(j)$, where
        $g(j)$ is the path gain between the cellular
        transmitter using PRB-$j$ and the BS */
        D2D candidate transmits in D2D-Mode on
        resource-$j$
    end if
    Increment $\rho_j$
end for
```

Algorithm 2: Balanced random allocation (BRA) and cellular protection allocation (CPA).

the deployment scenario and operator preference [33]. It employs a combination of open-loop (OL) and closed-loop (CL) control to set the UE transmit power (up to a maximum level of $P_{\mathrm{MAX}} = 24$ dBm) as follows:

$$P^{\mathrm{UE}} = \min\left[P_{\mathrm{MAX}}, \underbrace{P_0 - \alpha \cdot G}_{\text{OL operating point}} + \underbrace{\Delta_{\mathrm{TF}} + f\left(\Delta_{\mathrm{TPC}}\right)}_{\text{dynamic offset}} + \underbrace{10 \cdot \log_{10} M}_{\text{BW factor}}\right], \tag{13}$$

```
Allocate orthogonal resources (PRB) to cellular-UEs
(using legacy algorithms)
for Each UE link $c$ do
    for Each D2D link $d$ do
        Calculate and store the estimated SINRs and sum
        throughput $w_{c,d}$ for the two-link system of UE link $c$
        and D2D link $d$ by some suitable PC algorithm such
        as the Binary Power Control scheme that maximizes
        the sum throughput for any given UE-D2D pair
        sharing the same PRB;
    end for
end for
Output: Weight Matrix W associated with the Bipartite
Graph of Figure 4.
```

Algorithm 3: Weight matrix generation.

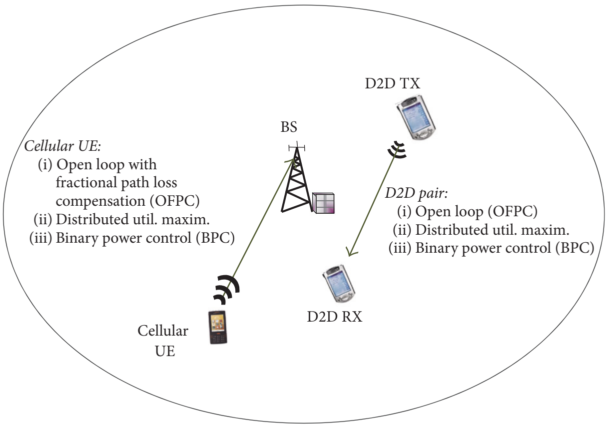


Figure 5: The UE communicating in cellular mode with its serving BS as well as the D2D pair using the same PRB as the cellular UE can use the de facto standard LTE open-loop with fractional path loss compensation (OFPC), but also utility maximizing PC and BPC are viable alternatives.

where G is the path gain between the UE and the BS. The OL operating point allows for *path loss (PL) compensation* and the dynamic offset can further adjust the transmit power taking into account the current modulation and coding scheme and explicit transmit power control (TPC) commands from the network. The bandwidth factor takes into account the number of scheduled RBs (M). For the OL operating point, P_0 is a base power level used to control the SNR target and it is calculated as [34]

$$P_0 = \alpha \cdot \left(\gamma^{tgt} + P_{\mathrm{IN}}\right) + (1 - \alpha) \cdot \left(P_{\mathrm{MAX}} - 10 \cdot \log_{10} M\right), \tag{14}$$

where α is the PL compensation factor and P_{IN} is the estimated noise and interference power. For the dynamic offset, Δ_{TF} is the transport format dependent component, and $f(\Delta_{\mathrm{TPC}})$ represents the explicit TPC commands.

For the integrated D2D communications scenario, the PC options are illustrated by Figure 5. With UEs communicating

Table 2: Large scale CSI required by PC algorithms.

PC scheme	Channel gain knowledge	Comment
LTE OFPC	G_c, G_d	OFPC is a simple one-shot suboptimal scheme that needs its own channel gain only
Utility maximizing PC	G_c, G_d	Iterative optimal scheme, where the Tx needs the current SINR level at the receiver
BPC	$G_c, G_d, G_{d,B}, G_{c,d}$	One-shot optimal scheme: $G_{d,B}$ and $G_{c,d}$ are needed for estimating the SINR

in cellular mode with their respective serving base stations, OFPC provides a well-proven alternative, typically used in practice. It avoids the complexity and overhead associated with the dynamic offset of the CL scheme but makes use of the fractional path loss compensation balancing between overall spectrum efficiency and cell edge performance [33]. When the cellular spectrum hosts D2D communications, the distributed utility maximizing PC and the BPC schemes are also viable options. Figure 5 also illustrates the PC options for the D2D link.

5.2. Utility Maximization Power Control. In this section, we assume that MS has already been performed for the D2D candidates and a RA algorithm has already assigned certain PRBs for communication to cellular and D2D links. From the concept of D2D communications reusing cellular spectrum, it is clear that a given PRB may be used by a cellular and multiple D2D transmitters even within the same cell, which causes intracell interference.

Utility maximization PC has been introduced in [35] and successively extended to the field of radio resource management in multihop wireless networks in [36, 37] and specifically to cellular networks supporting D2D communications in [25, 32]. This PC scheme is attractive, because it achieves utility optimal performance but requires a typically prohibitive amount of iterations in practice [24]. However, previous works did not combine this scheme with different RA schemes and did not compare its performance with the much simpler binary power control scheme discussed in the next subsection.

For the set of interfering links sharing the same PRB and thereby causing interference to one another, the utility maximization PC formulates the problem of target SINR setting and PC as *(Problem-II)*

$$\begin{aligned} \underset{\mathbf{p},\mathbf{s}}{\text{maximize}} \quad & \sum_l u_l(s_l) - \omega \sum_l P_l \\ \text{subject to} \quad & s_l \leq c_l(\mathbf{p}), \quad \forall l, \\ & \mathbf{p}, \mathbf{s} \geq 0 \end{aligned} \tag{15}$$

which aims at maximizing the utility while taking into account the transmit powers by means of a predefined weight $\omega \in (0, +\infty)$ [37], so as to both increase spectrum efficiency and reduce the sum power consumption over all transmitters sharing a specific PRB. The predefined weight 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. The constraints in Problem (15) formally ensure that the rate allocation does not exceed the link capacities that in turn depends on the transmit powers on the given PRB. As shown in [25], Problem (15) can be decomposed into two separate problems (Problem-I and Problem-II) that need to be executed recursively until convergence to the optimum of Problem (15). Specifically, Problem-I selects the transmit rate target, while Problem-II selects the transmit power that fulfills the desired transmit rate target, that is, the SINR target. As such, Problem-I and Problem-II resemble an outer-loop and an inner-loop mechanism, respectively, where the inner-loop power allocation ensures that the target rate **s** reduces to the optimal capacity vectors (**c**) at convergence of the outer/inner-loop routine.

5.3. Binary Power Control. Binary power control (BPC) is known to maximize the capacity of a two-cell interference limited system and performs near optimally for larger systems [29]. Recently, it has been proven that when D2D communication underlying the cellular layer is supported, BPC remains utility optimal when the weight of the overall power consumption in the utility function is bounded [30].

From a system design and operation perspective, BPC is easier to implement than iterative algorithms, since BPC does not require lengthy iterations and frequent channel state information updates and can achieve near utility optimal performance (Algorithm 4). In particular, when two transmit-receive pairs share the same resource, BPC is sum throughput optimal, similar to a two-cell interference limited system in which the PRBs are reused by neighbor cells.

5.4. Summary: Channel Gain Knowledge Needed by PC Algorithms. In this section, we discussed three PC algorithms including the LTE OFPC scheme, an iterative utility maximization scheme, and the sum rate optimal BPC scheme. From the perspective of channel gain knowledge, these algorithms are summarized in Table 2. BPC requires some cross-channel gain knowledge (similar to Matching), out of which $G_{d,B}$ is typically available at the cellular serving BS, since all served UEs regularly report their current channel gain (path loss) for mobility management purposes. Acquiring of $G_{c,d}$ would also be possible in practice since D2D-capable UEs can readily perform measurements on uplink signals. "In return," BPC achieves near-optimal sum rate performance without lengthy iterations.

6. Numerical Results

6.1. Cell and UE Placement. To answer the question whether acquiring more CSI can be translated to performance gains, we experiment with the meaningful combinations of the RA and PC schemes discussed above. We consider a 7-cell system,

```
Assumption: Resources (PRB) are allocated to cellular UEs and D2D pairs. (At most 1 UE
and 1 D2D pair per PRB.)
    for Each PRB-$j$ in each cell do
        Something
        if PRB-$j$ is used by a cellular UE only (i.e. PRB-$j$ is not reused by a D2D pair) then
            Let the cellular UE using PRB-$j$ transmit with maximum power
    else
        Assume $P_{\mathrm{D2D}} = P_{\mathrm{D2D}}^{\max}$ and $P_{\mathrm{UE}} = P_{\mathrm{UE}}^{\max}$
        Estimate $\mathrm{SNR}_{\mathrm{D2D}}$, $\mathrm{SINR}_{\mathrm{D2D}}$, $\mathrm{SNR}_{\mathrm{UE}}$ and $\mathrm{SINR}_{\mathrm{UE}}$
        $s_{\mathrm{MAX}} = \mathrm{maximize}\{s(\mathrm{SNR}_{\mathrm{D2D}}), s(\mathrm{SNR}_{\mathrm{UE}}), s(\mathrm{SINR}_{\mathrm{D2D}}) + s(\mathrm{SINR}_{\mathrm{UE}})\}$
        if $s_{\mathrm{MAX}} == s(\mathrm{SNR}_{\mathrm{D2D}})$ then
            $P_{\mathrm{D2D}} = P_{\mathrm{D2D}}^{\max}$, $P_{\mathrm{UE}} = 0$
        else
            if $s_{\mathrm{MAX}} == s(\mathrm{SNR}_{\mathrm{UE}})$ then
                $P_{\mathrm{D2D}} = 0$, $P_{\mathrm{UE}} = P_{\mathrm{UE}}^{\max}$
            end if
        else
            $P_{\mathrm{D2D}} = P_{\mathrm{D2D}}^{\max}$, $P_{\mathrm{UE}} = P_{\mathrm{UE}}^{\max}$
            end if
    end if
end for
```

ALGORITHM 4: Binary power control for D2D communications.

TABLE 3: System parameters.

Parameter	Value
System bandwidth	5 MHz
Carrier frequency	2 GHz
Number of cells	7
Radius of cells	500 m
Number of cellular UEs per cell	8 or 6
Number of D2D pairs per cell	8 or 6
Distance between D2D transmitter and receiver	30–70 m
Standards deviation of errors in G matrix	10 dB
Range of the errors in G matrix	[−6 dB, 6 dB] or [−3 dB, 6 dB]
Number of simulations	100
Maximal transmission power of all UE	24 dBm
Noise power	174 dBm/Hz
Path loss coefficient, α	3.5
Lognormal shadow fading, σ	6 dB
Compensation factor of LTE open loop	0.8
Weight ω for utility maximizing PC according to (15)	1

in which cellular UEs and D2D pairs are dropped randomly in a series of Monte Carlo experiments as illustrated by Figure 6. In this paper, we assume a truncated Gaussian distribution for the errors in the G matrix, where the finite support of the measurement error along with other relevant system parameters is summarized in Table 3.

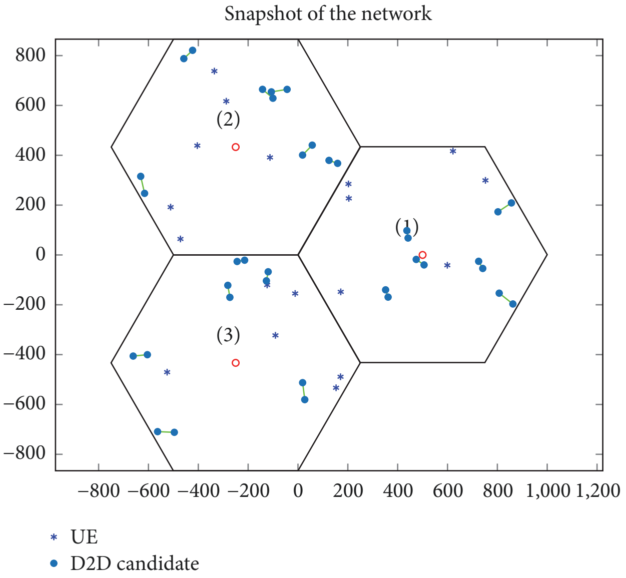


FIGURE 6: A sample Monte Carlo drop of UEs and D2D pairs in a 3-cell portion of the simulated network. Each cell has 6 cellular UEs and predefined D2D candidates pairs. The red circle in the middle represents the serving BS.

6.2. Comparing the Resource Allocation and Power Control Schemes.

Figures 7 and 8 compare the performance of various combinations of RA and PC schemes. For the utility maximizing PC algorithm, we set $\omega = 1$ in the utility function of (15), because it represents a reasonable tradeoff between spectral and energy efficiency [32]. The performance gap between the different algorithms indicates that more channel

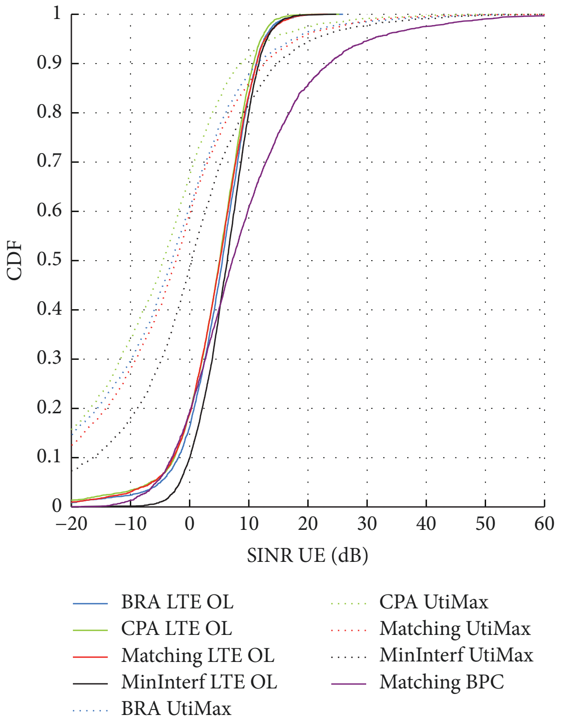


Figure 7: SINR distribution of the cellular UEs. The Matching RA scheme with BPC provides good performance for all UEs.

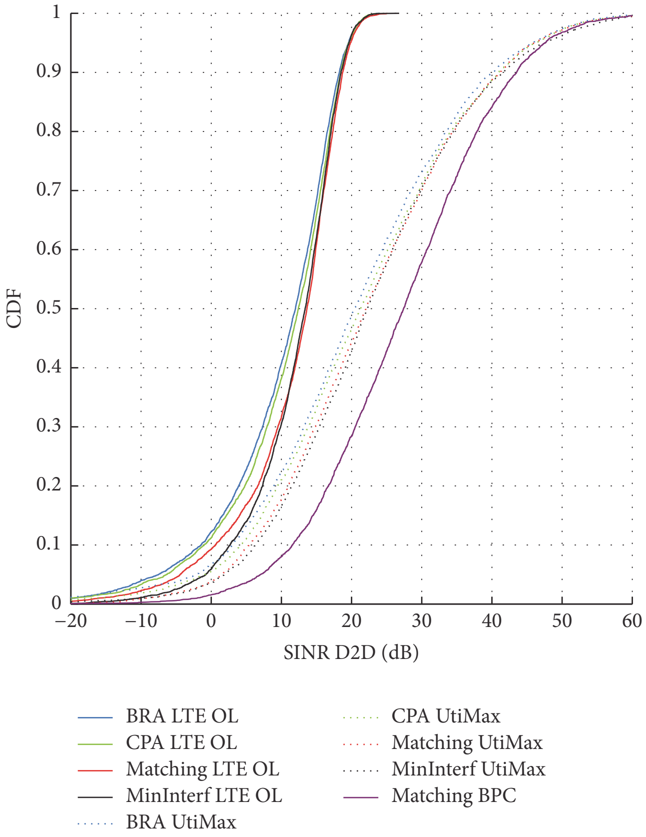


Figure 8: SINR distribution of the cellular D2D pairs. The effect of PC is decisive: BPC is superior, and utility maximization outperforms the LTE OL PC scheme.

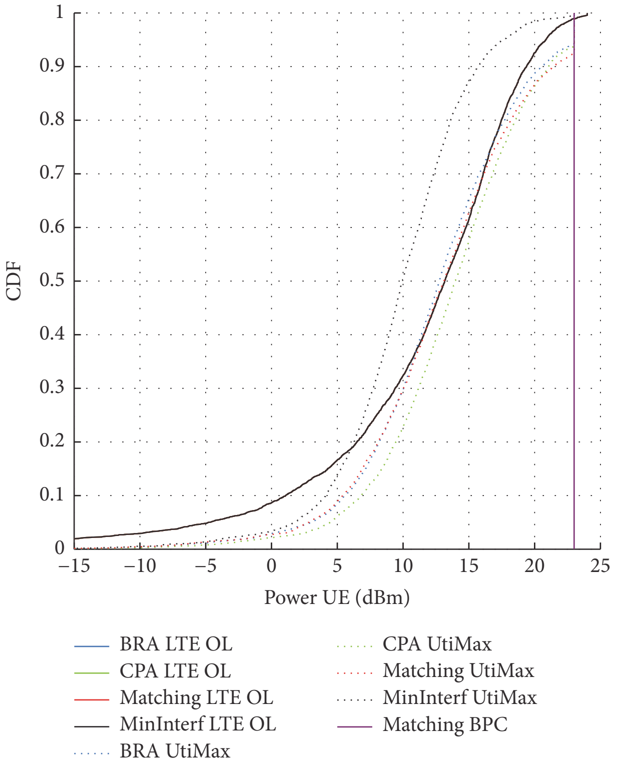


Figure 9: Power distribution of the cellular UEs. BPC transmits either with the maximum power level (24 dBm) or with zero power.

Table 4: Throughput degradation due to errors in the G matrix.

Case	Cellular layer	D2D layer	Overall
Perfect CSI	100%	100%	100%
[−6 dB, 6 dB]	95.4%	92.5%	93.8%
[−3 dB, 6 dB]	92.1%	91.3%	91.8%

gain (CSI) knowledge increases the performance. Specifically, combining the matching algorithm with BPC yields superior SINR performance for both the cellular and the D2D layer.

Figures 9 and 10 compare the power consumption of various combinations of RA and PC schemes. The performance gap between the different algorithms indicates that more channel gain (CSI) knowledge increases the performance. Specifically, combining the matching algorithm with BPC yields superior power consumption performance for both the cellular and the D2D layer.

The impact of large scale fading measurement and estimation errors on the MS performance is shown by Figure 11. The estimation errors may lead to selecting the cellular mode for a D2D pair, or to selecting the direct (that is D2D) mode, when it would be more beneficial to communicate in cellular mode. We can see that the mode selection error rate increases when the D2D distance increases.

To gain insight into the impact of large scale fading estimation errors, Table 4 shows the throughput degradation due to errors in G matrix. We can observe that an asymmetric distribution of the errors cause more severe throughput degradation than a symmetric error distribution.

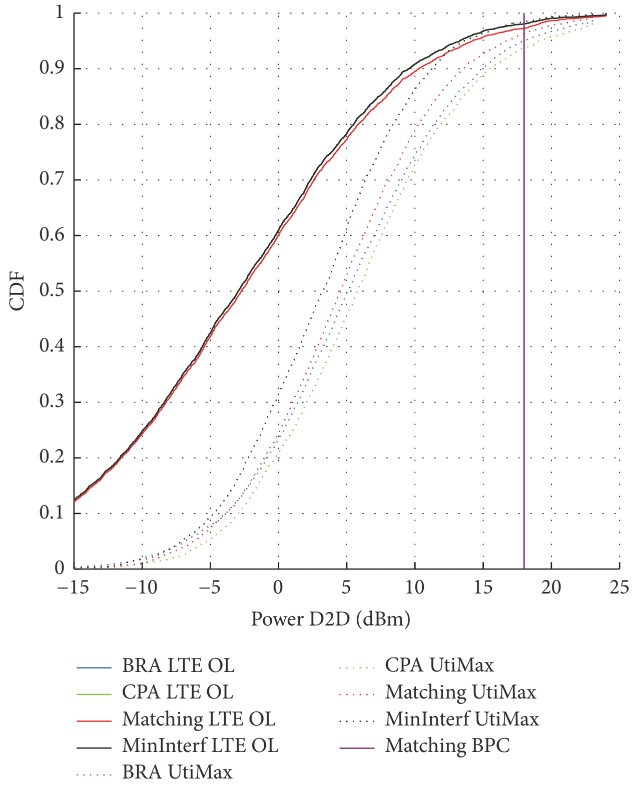


FIGURE 10: Power distribution of the cellular D2D pairs. BPC transmits either with the maximum power level (24 dBm) or with zero power.

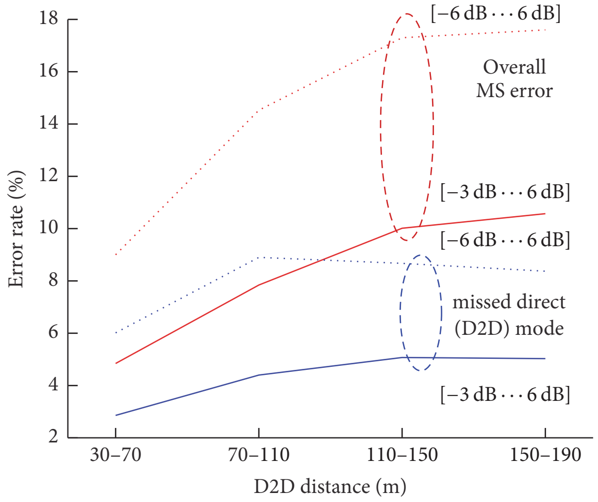


FIGURE 11: Mode selection error as a function of the D2D distance and the error range in the G matrix.

Table 5 shows the relative throughput that can be achieved by employing RA and PC schemes that require more channel gain information than the baseline scheme represented by the BRA resource allocation scheme and the LTE open-loop PC algorithm. This throughput comparison indicates the following:

TABLE 5: Throughput enhancement of the baseline LTE open loop with the BRA resource allocation scheme achieved by alternative RA and PC schemes.

Algorithms	Cellular layer	D2D layer	System
LTE open loop			
BRA	100.00%	100.00%	100.00%
CPA	94,47%	103,26%	99,96%
Matching	96.69%	110.89%	105.56%
MiniInterf	109.54%	111.65%	110.85%
Utility maximization			
BRA	109.69%	188.64%	159.05%
CPA	94.62%	197.32%	158.82%
Matching	115.88%	212.34%	176.19%
MiniInterf	132.05%	204.83%	177.54%
Binary power control			
Matching	138.20%	230.09%	195.65%

(i) When the LTE open-loop PC scheme is used, the overall system throughput can be increased by employing the Matching or the MinInterf resource allocation schemes.

(ii) The utility maximizing PC scheme improves the system throughput by at least 58.82%, and with the MinInter RA scheme, it improves the throughput by 77.54%.

(iii) The combination of the BPC and Matching almost doubles the overall throughput, showing that making good use of additional CSI information largely improves the system performance.

6.3. Binary Power Control: Transmission Probabilities. Due to its superior performance and its simple on-off type of operation, BPC is a strong PC scheme candidate in cellular networks supporting D2D communications. Since BPC can switch off either a D2D transmitter or a cellular UE, evaluating the probability of the "on" state that is when a transmitter is allowed to transmit (and then with maximum power) becomes very important.

Figures 12 and 13 compare the transmission probabilities for cellular UEs depending on the position of the cellular UE within the cell, when BPA is combined with the BRA and Matching RA schemes, respectively. In these figures, the x-axis and y-axis represent the position of the cellular UE, while the different shades represent the probability of transmission for a cellular UE at that specific position. Compared with BRA, the Matching algorithm extends the high probability region (the red area) within the cell. With Matching, a large portion of cellular UEs have a transmission probability ("on" state) higher than 0.8. However, with BRA, cellular UEs outside the cell center have a transmission probability lower than 0.5, which in practice would need to be managed by some suitable scheduling algorithm (outside the scope of this article).

Figures 14 and 15 show the probability of transmission ("on" state) for D2D transmitters. Similar to the simulation

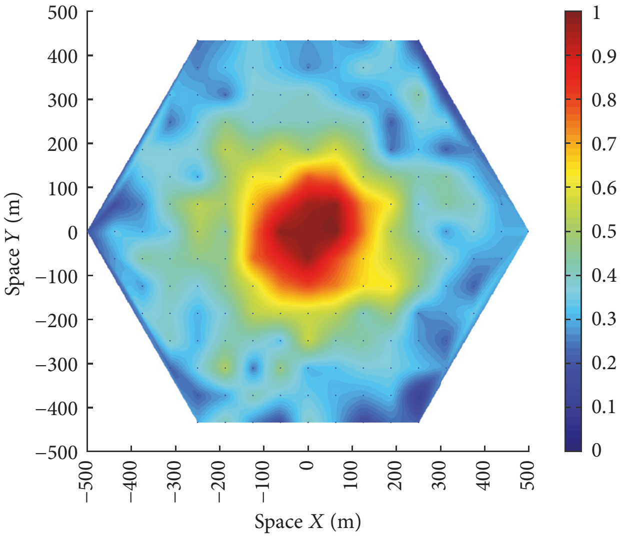


FIGURE 12: BRA with BPC: transmission probabilities of the cellular UEs.

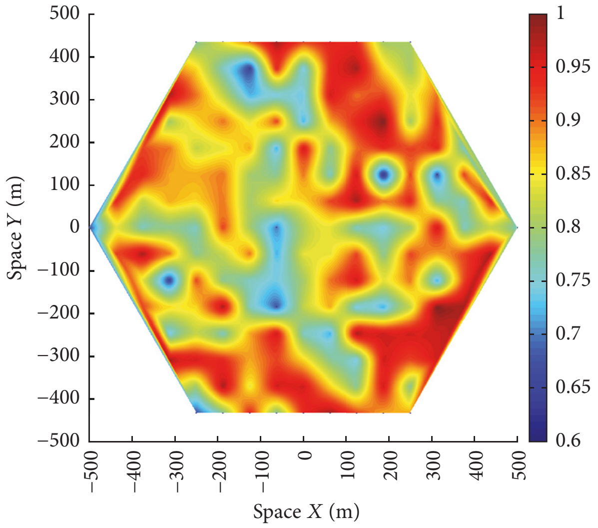


FIGURE 14: BRA with BPC: transmission probabilities of the D2D transmitters.

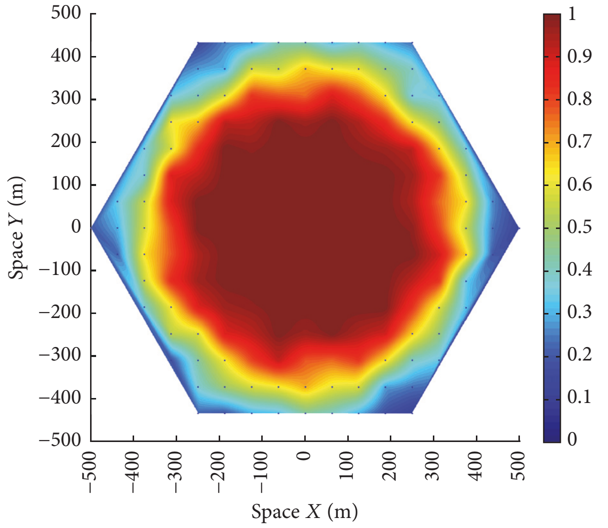


FIGURE 13: Matching with BPC: transmission probabilities of the cellular UEs.

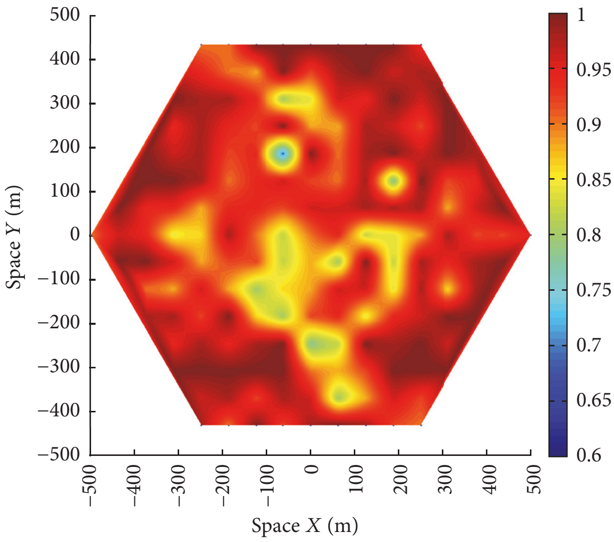


FIGURE 15: Matching with BPC: transmission probabilities of the D2D transmitters.

results for the cellular UEs, the Matching algorithm extends the area of the high transmission probability region. These figures do not indicate strong relation between the D2D position within the cell and the transmission probability. The difference of transmission probability is mainly caused by the different D2D distance: a shorter D2D distance leads to stronger path gains, and thus a higher transmission probability is possible.

It is worth noting that, in terms of the required CSI knowledge, BPC needs the channel gain between the cellular UE and the D2D receiver on the same PRB within the same cell. To perform matching, the channel gains between each cellular UE and each D2D receiver within the same cell are required. Although Matching does not yield notable throughput and SINR gains over those achieved by BRA, the improved fairness is an important advantage of having more CSI knowledge and makes BPC feasible in practice (the investigation of fairness in D2D networks supporting elastic services [38, 39] is an important topic for future research).

7. Conclusions

In this paper, we considered a small set of viable (heuristics and optimization-based) RA and PC schemes for cellular network assisted D2D communications and compared their performance. This comparative study was motivated by the observation that in practice the required CSI information in terms of large scale channel gain knowledge is a very important but often overlooked design consideration.

Our numerical results indicate that acquiring more CSI, and in particular acquiring the channel gain of the cross-channels, can indeed help to improve the SINR performance of both the cellular and D2D layers. Specifically, our simulation results indicate that when large scale CSI about the useful as well as interfering channel gains are available at the cellular base station, the binary power control scheme combined with the near-optimal matching-based resource allocation scheme is superior in terms of SINR and throughput. We also found that the matching-based (low complexity) RA scheme is a very attractive companion of the throughput-optimal binary power control scheme, not only because they together maximize the throughput, but also because matching ensures a high transmission ("on") probability for both the cellular UEs and the D2D transmitters. Luckily, Matching and the BPC scheme require similar large scale CSI, and therefore they together offer an attractive RA and PC solution for cellular networks supporting unicast D2D communications.

Large Scale CSI in a D2D Communication Scenario

G_c:	Channel gain between the cellular UE and its serving BS
$G_{d,B}$:	Channel gain between the D2D transmitter and the serving BS in the cell
G_d:	Channel gain between the D2D transmitter and the intended D2D receiver
$G_{d,d}$:	Channel gain between a D2D transmitter and a nonintended (victim) D2D receiver
$G_{c,d}$:	Channel gain between the cellular UE and the D2D receiver.

Disclosure

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Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this article.

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References

[1] M. S. Corson, R. Laroia, J. Li, V. Park, T. Richardson, and G. Tsirtsis, "Toward proximity-aware internetworking," *IEEE Wireless Communications Magazine*, vol. 17, no. 6, pp. 26–33, 2010.

[2] K. Zheng, F. Hu, W. Wang, W. Xiang, and M. Dohler, "Radio resource allocation in LTE-advanced cellular networks with M_2M communications," *IEEE Communications Magazine*, vol. 50, no. 7, pp. 184–192, 2012.

[3] R. Baldemair, E. Dahlman, G. Fodor et al., "Evolving wireless communications: Addressing the challenges and expectations of the future," *IEEE Vehicular Technology Magazine*, vol. 8, no. 1, pp. 24–30, 2013.

[4] P. Janis, C.-H. Yu, and K. Doppler, "Device-to-device communication underlaying cellular communications systems," *International Journal of Communications, Network and System Sciences*, vol. 2, no. 3, pp. 169–178, 2009.

[5] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hug, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Communications Magazine*, vol. 47, no. 12, pp. 42–49, 2009.

[6] G. Fodor, E. Dahlman, G. Mildh et al., "Design aspects of network assisted device-to-device communications," *IEEE Communications Magazine*, vol. 50, no. 3, pp. 170–177, 2012.

[7] M. Belleschi, G. Fodor, and A. Abrardo, "Performance analysis of a distributed resource allocation scheme for D2D communications," in *Proceedings of the 2011 IEEE GLOBECOM Workshops, GC Wkshps 2011*, pp. 358–362, USA, December 2011.

[8] G. Fodor and N. Reider, "A distributed power control scheme for cellular network assisted D2D communications," in *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM '11)*, pp. 1–6, Houston, Tex, USA, December 2011.

[9] N. Reider and G. Fodor, "A distributed power control and mode selection algorithm for D2D communications," *EURASIP Journal on Wireless Communications and Networking*, vol. 2012, article 266, 2012.

[10] T. Peng, Q. Lu, H. Wang, S. Xu, and W. Wang, "Interference avoidance mechanisms in the hybrid cellular and device-to-device systems," in *Proceedings of the IEEE 20th Personal, Indoor and Mobile Radio Communications Symposium (PIMRC '09)*, pp. 617–621, September 2009.

[11] P. Janis, V. Koivunen, Ć. Ribeiro, J. Korhonen, K. Doppler, and K. Hugl, "Interference-aware resource allocation for device-to-device radio underlaying cellular networks," in *Proceedings of the IEEE 69th Vehicular Technology Conference (VTC '09)*, pp. 1–5, April 2009.

[12] H. Min, J. Lee, S. Park, and D. Hong, "Capacity enhancement using an interference limited area for device-to-device uplink underlaying cellular networks," *IEEE Transactions on Wireless Communications*, vol. 10, no. 12, pp. 3995–4000, 2011.

[13] H. Min, W. Seo, J. Lee, S. Park, and D. Hong, "Reliability improvement using receive mode selection in the device-to-device uplink period underlaying cellular networks," *IEEE Transactions on Wireless Communications*, vol. 10, no. 2, pp. 413–418, 2011.

[14] X. Xiao, X. Tao, and J. Lu, "A QoS-aware power optimization scheme in OFDMA systems with integrated device-to-device (D2D) communications," in *Proceedings of the IEEE 74th Vehicular Technology Conference, VTC Fall 2011*, USA, September 2011.

[15] J. Gu, S. J. Bae, B.-G. Choi, and M. Y. Chung, "Dynamic power control mechanism for interference coordination of device-to-device communication in cellular networks," in *Proceedings of the 3rd International Conference on Ubiquitous and Future Networks (ICUFN '11)*, pp. 71–75, June 2011.

[16] K. Doppler, C.-H. Yu, C. B. Ribeiro, and P. Jänis, "Mode selection for device-to-device communication underlaying an LTE-advanced network," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC '10)*, pp. 1–6, Sydney, Australia, April 2010.

[17] S. Hakola, C. Tao, J. Lehtoma, and T. Koskela, "Device-to-device (D2D) communication in cellular network—performance analysis of optimum and practical communication mode selection," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC '10)*, pp. 1–6, April 2010.

[18] G. Fodor and N. Reider, "A distributed power control and mode selection scheme for device-to-device communications," in *Proceedings of the IEEE Globecom*, vol. December 2011.

[19] B. Wang, L. Chen, X. Chen, X. Zhang, and D. Yang, "Resource allocation optimization for Device-to-Device communication underlaying cellular networks," in *Proceedings of the Proceeding of the 73rd IEEE Vehicular Technology Conference (VTC '11)*, pp. 1–6, Budapest, Hungary, May 2011.

[20] C. Yu, K. Doppler, C. B. Ribeiro, and O. Tirkkonen, "Resource sharing optimization for device-to-device communication underlaying cellular networks," *IEEE Transactions on Wireless Communications*, vol. 10, no. 8, pp. 2752–2763, 2011.

[21] S. Racz, M. Telek, and G. Fodor, "Link capacity sharing between guaranteed- and best effort services on an ATM transmission link under GoS constraints," *Telecommunication Systems*, vol. 17, no. 1-2, pp. 93–114, 2001.

[22] C.-H. Yu, O. Tirkkonen, K. Doppler, and C. Ribeiro, "Power optimization of device-to-device communication underlaying cellular communication," in *Proceedings of the IEEE International Conference on Communications (ICC '09)*, pp. 1–5, IEEE, Dresden, Germany, June 2009.

[23] H. Xing and S. Hakola, "The investigation of power control schemes for a device - To-device communication integrated into OFDMA cellular system," in *Proceedings of the 2010 IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications, PIMRC 2010*, pp. 1775–1780, Turkey, September 2010.

[24] A. Pradini, G. Fodor, G. Miao, and M. Belleschi, "Near-optimal practical power control schemes for D2D communications in cellular networks," in *Proceedings of the 2014 European Conference on Networks and Communications, EuCNC 2014*, Italy, June 2014.

[25] M. Belleschi, G. Fodor, D. D. Penda, A. Pradini, M. Johansson, and A. Abrardo, "Benchmarking Practical RRM Algorithms for D2D Communications in LTE Advanced," *Wireless Personal Communications*, vol. 82, no. 2, pp. 883–910, 2015.

[26] X. Lin, J. G. Andrews, A. Ghosh, and R. Ratasuk, "An overview of 3GPP device-to-device proximity services," *IEEE Communications Magazine*, vol. 52, no. 4, pp. 40–48, 2014.

[27] J. Lee, Y. Kim, Y. Kwak et al., "LTE-advanced in 3GPP Rel -13/14: An evolution toward 5G," *IEEE Communications Magazine*, vol. 54, no. 3, pp. 36–42, 2016.

[28] S. Sesia, I. Toufik, and M. Baker, *LTE-The UMTS Long Term Evolution: Form Theory to Practice*, Wiley, 2011.

[29] A. Gjendemsjø, D. Gesbert, G. E. Øien, and S. G. Kiani, "Binary power control for sum rate maximization over multiple interfering links," *IEEE Transactions on Wireless Communications*, vol. 7, no. 8, pp. 3164–3173, 2008.

[30] J. M. B. Da Silva and G. Fodor, "A binary power control scheme for D2D communications," *IEEE Wireless Communications Letters*, vol. 4, no. 6, pp. 669–672, 2015.

[31] C. Yu, O. Tirkkonen, K. Doppler, and C. Ribeiro, "On the performance of device-to-device underlay communication with simple power control," in *Proceedings of the IEEE Vehicular Technology Conference (VTC Spring)*, 5, 1 pages, April 2009.

[32] G. Fodor, D. D. Penda, M. Belleschi, M. Johansson, and A. Abrardo, "A comparative study of power control approaches for device-to-device communications," in *Proceedings of the 2013 IEEE International Conference on Communications, ICC 2013*, pp. 6008–6013, Hungary, June 2013.

[33] A. Simonsson and A. Furuskar, "Uplink power control in lte overview and performance," in *Proceedings of the in IEEE Vehicular Technology Conference Spring. 1em plus 0.5em minus 0*, March 2007.

[34] 3GPP, *Uplink Power Control for E-UTRA, R1-074850*, vol. RAN WG1, Jeju, Korea, 2007.

[35] F. P. Kelly, A. K. Maulloo, and D. Tan, "Rate control for communication networks: Shadow prices, proportional fairness and stability," *Journal of the Operational Research Society*, vol. 49, no. 3, pp. 206–217, 1997.

[36] M. Chiang, "Balancing transport and physical layers in wireless multihop networks: jointly optimal congestion control and power control," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 1, pp. 104–116, 2005.

[37] J. Papandriopoulos, S. Dey, and J. Evans, "Optimal and distributed protocols for cross-layer design of physical and transport layers in MANETs," *IEEE/ACM Transactions on Networking*, vol. 16, no. 6, pp. 1392–1405, 2008.

[38] M. Pioro, P. Nilsson, E. Kubilinskas, and G. Fodor, "On efficient max-min fair routing algorithms," in *Proceedings of the ISCC 2003 - International Symposium on Computers and Communications*, pp. 365–372, Kemer-Antalya, Turkey.

[39] G. Malicskó, G. Fodor, and M. Pióro, "Link capacity dimensioning and path optimization for networks supporting elastic services," *IEEE International Conference on Communications*, vol. 4, pp. 2304–2311, 2002.