Joint Optimization of Transmission-Order Selection and Channel Allocation for Bidirectional Wireless Links—Part II: Algorithms

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***Abstract*—This is the second in a two-part series of papers on transmission order (TO) optimization in the presence of channel allocation (CA), i.e., *joint* optimization of the TO selection and CA problem, for interfering bidirectional wireless links. Part I of this paper thoroughly analyzes the *joint* optimization problem from a game theoretic perspective for a general deterministic setting. Here in Part II, we present novel distributed and centralized CA-TO algorithms, together with their performance analysis, for Device-to-Device (D2D) communications underlaying cellular networks based on the findings in Part I of this paper. Here, TO is a novel dimension for optimization. In Part II, we propose and analyze novel two distributed and one centralized *joint* CA-TO algorithms. Our investigations show that: i) our algorithms contain many of the existing TO algorithms and CA algorithms as its special cases and can thus be considered as a general framework for the *joint* CA and TO optimization. The computer simulations for TDD-based D2D communications underlaying cellular network show that the proposed distributed and centralized *joint* CA-TO algorithms remarkably outperform the reference algorithms.**

***Index Terms*—Device-to-device (D2D) communications underlaying TDD cellular network, transmission order optimization, channel allocation problem, GADIA.**

I. Introduction

IN Part I of this two-part series [54], we consider a system consisted of bidirectional wireless links that interfere with each other, and thoroughly analyze the *joint* transmission order (TO) selection and channel allocation (CA) problems from a game theoretic perspective. Here, in Part II, we focus on Device-to-Device (D2D) communications underlaying cellular networks, and present distributed and centralized *joint* CA-TO algorithms based on the findings in Part I [54], and examine their system performances. The results of this paper can readily be applied to emerging Small Cell Networks (SCNs) and heterogeneous small-cell networks (Het-SNets) as well. Because this two-part paper is an extension of [51], and paper [51] focuses on the D2D communications underlay, we consider the D2D communications in Part II for the sake of consistency.

In D2D communications using cellular radio resources, spatially isolated Mobile Stations (MSs) are engaged in a direct communication without being relayed by a centralized unit like Base Station (BS), although the D2D communication is controlled by the BS. Due to its many advantages over the traditional cellular networks, the research on the D2D communications has proliferated in recent years. In fact, D2D communications under the control of cellular radio systems has been proposed since late 1990s by various works for different systems (e.g., [2]–[4], [6], [8], [15], [18], [32], [34], [35], [39]–[42], etc). In [4], the serving BS maintains control over the D2D call, and preserves billing information for the direct D2D communication between the mobiles. For conceptual and implementation details for FDMA and CDMA systems, see [4]. A D2D communication underlaying TD-SCDMA (Time Division-Synchronous Code Division Multiple Access) system, and a D2D communication underlaying TDD CDMA can be found in [39] and [40], respectively. The authors in [42] propose D2D communications (also named as ad-hoc comm.) underlaying OFDM/TDMA TDD cellular system. The authors in [29] show how the D2D can be implemented in 3GPP LTE-Advanced networks in details. The advantages of the D2D communications underlaying cellular radio networks are as follows: reducing the minimum co-channel reuse distances within the same cell and thus improving spectral efficiency in terms of [b/Hz/km2] (see, e.g., [40], [41], [52]), reduction of transmit power requirements, and thus improving battery life, e.g., [2], [5]–[8], [10], [16], [27], [39], [43], providing more efficient radio resource use because D2D communications requires only half the amount of resources compared to communication through the BS (e.g., [5], [7], [10]–[13]), reducing the interference in the cellular network e.g., [2], [4], [7], [19], providing infrastructure off-loading (i.e., reduces the loading of the network) in enterprise, campus, stadium, metro, shopping malls, airports, home environments, etc. [3], [32], [33], increasing the bit rate compared to cellular link due to enhanced channel characteristics ([5], [12]), increasing communication throughput of D2D as compared to the cellular transmission (e.g., [2], [32], [39], [40], [42]), increasing network efficiency and thus supporting more services, including today's "hot" social networking applications like facebook, youtube or myspace [26], improving network performance in shadow fading [7], [9],

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improving performance of delay-sensitive applications [12], [32], bringing the mobile operator some further revenue [2], [4], [14], [39]. Because a serving BS continues to control mobile-to-mobile (i.e., D2D) calls, billing information is handled by the operator [2], [4], [14].

There are various interference avoidance methods developed for D2D communications underlay for various scenarios, see, e.g., [23], [30] (LTE onel-cell), [24] (LTE multi-cell), [17], [22], [38] (LTE), [31], [32] (UMTS system), [36] (teletraffic approach by clustering), [21] (rate splitting for a two-link case), [28], [37] (multi-user diversity), [25] (several D2D pairs case), [20] (fractional frequency reuse), [15] (capacity tradeoff between cellular network and D2D communications). A recent and extensive literature review on D2D solutions can be found in [51]. In almost all these works, D2D communications can use only the UL resources of the cellular system because BSs have more possibilities to tackle the D2D interference than MSs could, and none of these and other similar works examine *explicitly* the transmision-order (TO) optimization problem. To our best knowledge, the authors in [51] have recently, as a first time, *explicitly* analyzed the TO problem in D2D communications underlaying TDD cellular networks, which is an NP-complete problem. In Part II, we greatly extend the results in [51] by taking also the CA problem into account.

In our approach in this paper, i.e., Part II of the two-part series, we allow as many D2D pairs as possible as long as they are spatially distributed such that the D2D pairs are relatively far from each other, and the interference is managed by a power control mechanism. For example, the average number of supported D2D users per cell can be as high as 40 for a D2D-average-distance of 100 m in a cell whose radius of 1 km in [39], and over 100 D2D users for D2D-average-distance of 100 m in a single cell in [40]. Furthermore, in our two-part paper, the (co-channel) D2D pairs do not have to be in the same cell, but can be distributed over all the cells throughout the network. We consider TDD network, as in many other papers mentioned above, and focus on the case where cellular and D2D MSs use the same air interface and the same radio resources simultaneously.

A. Contribution of Part II of This Two-Part Paper

In Part I [54], we thoroughly analyze the TO optimization problem in the presence of the CA, i.e., the *joint* CA-TO optimization problem using a game theoretic approach. Using the results in Part I [54], the contributions of Part II are as follows:

i) We propose and analyze two novel distributed joint CA-TO algorithms called Non-greedy and Greedy joint CA-TO Algorithms (called as N-CATO and G-CATO), and a centralized joint CA-TO algorithm (called as CG-CATO).

ii) There are various CA algorithms in wireless communications literature. The proposed joint algorithms introduce a novel dimension to be optimized in the presense CA: TO dimension. This new dimension brings a remarkable performance improvement. On the other hand, comparing with [51] which is the first paper analyzing *explicitly* the TO optimization in the context of D2D communications, this two-part paper takes the CA optimization into account as well, which is a much more difficult optimization problem than in [51].

iii) The proposed N-CATO and G-CATO include some interference reduction algorithms and the TO optimization algorithms in literature as its special cases such as the GADIA in [49], the second phase of the N-GAIR in [44], the ABCAMiC and CABCAMiC in [51], etc.

iv) A shortened version of N-CATO greatly simplifies the original N-GAIR in [44] which yields a great relief in its computational complexity.

v) A shortened version of the G-CATO extends the GADIA [49] to asymmetric link-gains case.

vi) Detailed computer simulations for TDD-based D2D underlaying cellular network show that the proposed distributed and centralized joint algorithms remarkably outperform the reference cases, and, give near global optimal solution to the *joint* optimization problem.

The rest of this paper is arranged as follows: We present the novel *joint* CA and TO algorithms in Section II. Performance analysis results for D2D communication underlays are shown in Section III, followed by the conclusions in Section IV.

II. Joint CA-TO Algorithms

In order to set up the discussions in this paper, we briefly reiterate some definitions and the *joint* CA-TO optimization problem in Part I [54]: For any D2D pair, we call the D2D user which "mimics the BS" as in [4] as First Radio (FR), and the other user as Second Radio (SR). For any cellular MS-BS pair, the FR and SR denotes the BS, and MS, respectively. Let's assume that there are N FR-SR pairs, and L channels. The FRs are indexed from 1 to N, and corresponding SR's are indexed as $N+1$ to $2N$, respectively. Let's denote the set of indices of transmitters (txs) and receivers (rxs) in channel l by TO-dependent sets S_1^l and S_2^l, respectively, where $l=1,\ldots,L$, and $S_1^l(TO(t)),\ S_2^l(TO(t)) \in \{1,\ldots,N,N+1,\ldots,2N\}$. Then, once N FR-SR pairs are allocated to L channels, and their TOs are determined, then the sum of $UL+DL$ total network interference at time t is

$$I^{tot,DL+UL}\left(\left\{S_1^l(t),S_2^l(t)\right\}_{l=1}^{L}\right) = \sum_{l=1}^{L}\left(\sum_{i\in S_2^l(t)}\left(\sum_{j\in\left\{S_1^l(t)-i_T\right\}} r_{ij}^l + r_{ji}^l\right)\right) \quad (1)$$

where i_T is the index for the own-signal, and r_{ij}^l is the received (interfering) signal power from j to i. In Part I [54], we formulate a *joint* TO and CA optimization game as finding the optimum TO-dependent sets S_1^l and S_2^l, where $l=1,2,\ldots,L$, which minimizes the sum of total network interference power in (1). The network utility $U(t)$ of the game is chosen as (1): $U(t)=I^{tot,DL+UL}(\{S_1^l(t),S_2^l(t)\}_{l=1}^{l})$. A player is an FR-SR pair. And its action is either to change its channel, or to change its TO, or to remain as it is. Let $\Xi=\{1,2,\ldots,N\}$ represent the set of indexes of players (FR-SR pairs). We represent the set of action profile indexes of player i as $A_i\equiv\{1,2,\ldots,L+1,L+2\}$, where actions 1 to L correspond to channels; and action $L+1$ stands for TO UL, and action $L+2$ stands for TO DL. Let $a_i \in A_i$ denote an action of player i, and let a_{-i} represent an action profile of all users except player i. In Part I [54], we define the joint CA-TO game by $\Gamma = (\Xi, A_i, a_i)$. We define the utility function u_i of the player (FR-SR pair) i as follows [Part I [54], eq. (14)]:

$$u_i\left(a_i(t), a_{-i}\right) = \sum_{j \in \bar{S}^{a_i}(t)} \left(r_{j,i}^{c_i} + r_{i,j}^{c_i}\right) + \sum_{j \in S^{a_i}(t)} \left(r_{j,i+N}^{c_i} + r_{i+N,j}^{c_i}\right) \quad (2)$$

where $S^{a_i}(t)$ represents the set to which the i'th player belongs to at time t, and $\bar{S}^{a_i}(t)$ denotes the other set which includes its SR $(i+N)$ at time t, and index c_i shows its CA. Thus, the joint TO and CA optimization game can be expressed as $\Gamma : \min_{a_i \in A_i} u_i(a_i, a_{-i})$, $\forall i \in \Xi$, and $a_i \in \{1, 2, \ldots, L+1, L+2\}$ [Part I [54], eq. (10)]. In what follows, we propose two distributed and one centralized algorithms for joint CA and TO optimization based on the results in Part I [54].

A. Non-Greedy Joint CA and TO Algorithm (N-CATO)

Every FR and its SR measures the corresponding interferences from other SRs and FRs. Let the action of the i'th FR-SR pair (player) at time t be $a_i(t) = a_i^p \in A_i$, and $A_i = \{1, 2, \ldots, L+1, L+2\}$. The FR i and its SR $i+N$ calculates its individual utility function $u_i(a_i^p, a_{-i})$ according to (2), and checks if there exists another action $a_i(t+1) = a_i^n \in A_i$ which would give a smaller individual utility function satisfying

$$a_i^n = \arg\left\{u_i\left(a_i^n, a_{-i}\right) < u_i\left(a_i^p, a_{-i}\right)\right\} \quad (3)$$

for the i'th FR-SR pair (player). Whenever such an action is determined, then the i'th FR-SR pair (player) updates its action as a_i^n (either CA or TO). All the players update their actions sequentially (asynchronously) exactly in the same way. Because the D2D communications is performed under the control of central BS, the central BS coordinates the sequential updates by giving a unique order number to every pair when establishing the connection. Throughout the connection, these order numbers are fixed. Accordingly every pair sequentially updates its TO and CA. Let's denote the channel of player i at time t as $c_i(t)$, and its TO as $M_i(t)$ (and thus its reverse $\bar{M}_i(t)$). The *N-CATO* algorithm for D2D communication underlaying TDD based cellular network is presented by Table I.

Corollary 1: Consider D2D communication underlaying TDD based cellular system with N FR-SR pairs over possibly different cells. The N-CATO summarized in Table I converges to a minimum of the total network interference $I^{tot,DL+UL}$ in (1) for any initial CAs and TOs within a finite number of iterations for the complete action set $A_i = \{1, 2, \ldots, L+1, L+2\}$.

Proof: The proof is obvious due to Theorem 1 in Part I [54]: From (3) above and the eq. (27) in Part I [54], we conclude that $I^{tot,DL+UL}(t+1) < I^{tot,DL+UL}(t)$. And because the number of possible combinations is limited, the proposed algorithm *N-CATO* converge within a finite number of iterations. ∎

TABLE I
PROPOSED N-CATO ALGORITHM

1. Every FR and its SR measures the corresponding interferences from its neighboring FRs/SRs.
2. For every FR-SR: Let a_i^p represent its action at time t:
   - i'th FR-SR pair (FR i and its SR $j+N$) calculates their individual utility function $u_i(a_i^n, a_{-i})$ and $u_i(a_i^p, a_{-i})$ according to (2).
   - The first a_i^n which satisfy (3) (if there is any) is performed. If a_i^n represents a channel then $c_i(t+1) = a_i^n$. If a_i^n represents the TO then $M_i(t+1) = \bar{M}_i(t)$.

   end
3. The loop in step 2 is run until there is no further CA and TO updates (i.e., until the algorithm converges).

B. Greedy Joint CA and TO Algorithm (G-CATO)

Every FR and its SR measures the corresponding interferences from other SRs and FRs. Let the action of the i'th FR-SR pair (player) at time t be $a_i(t) = a_i^p \in A_i$. The FR i and its SR $i+N$ calculates their individual utility function $u_i(a_i^p, a_{-i})$ according to (2). The basic idea of the proposed Greedy joint CA and TO Algorithm (G-CATO) is that the FR i (and its SR $i+N$) chooses the best possible action in the set $A_i = \{1, 2, \ldots, L+1, L+2\}$ in the sense that the its individual utility function in (2) is decreased the most according to

$$a_i^{n^*} = \arg\max\left\{u_i\left(a_i^p, a_{-i}\right) - u_i\left(a_i^n, a_{-i}\right)\right\} \quad (4)$$

for a particular i. When such an action is determined for the i'th FR-SR pair (player), then it updates its action as $a_i^{n^*}$ (either CA or TO). All the players update their actions sequentially (asynchronously) according to (4) exactly in the same way. The G-CATO algorithm for D2D communication underlaying TDD based cellular network is presented by Table II.

Corollary 2: Consider D2D communication underlaying TDD based cellular system with N FR-SR pairs over possibly different cells. The G-CATO summarized in Table II converges to a minimum of the total network interference $I^{tot,DL+UL}$ in (1) for any initial CAs and TOs within a finite number of iterations for the action set $A_i \equiv A_{CA} \cup A_{TO} = \{1, 2, \ldots, L+1, L+2\}$.

Proof: From (4) above and the Theorem 1 and eq. (27) in Part I [54], we conclude that $I^{tot,DL+UL}(t+1) < I^{tot,DL+UL}(t)$. And because the number of possible combinations is limited, the proposed algorithm *N-CATO* converge within a finite number of iterations. ∎

Proposition 1: Consider D2D communication underlaying TDD based cellular network with N FR-SR pairs over possibly different cells. The proposed algorithms N-CATO and G-CATO can be implemented in a distributed manner.

Proof: Because the same frequencies are used in both UL and DL in a TDD system, the channels are reciprocal (e.g., [1]), which means that for the link gains are symmetric.

Case 1) The transmit powers of all FRs/SRs are the same: If the transmit powers of all FRs/SRs are the same

TABLE II
PROPOSED DISTRIBUTED G-CATO ALGORITHM

1. Every FR and its SR measures the corresponding interferences from its neighboring FRs/SRs.
2. For every FR-SR pair: Let a represent its action at time *t*.
   Let a_i^p represent either the TO ($M_i(t)$) or CA ($c_i(t)$) for *i*'th FR-SR pair at time *t*.
   - *i*'th FR-SR pair (FR *i* and its SR *j+N)* calculates its individual utility function $u_i(a_i, a_{-i})$ for all possible actions according to (2).
   - The $a_i^{n^*}$ which satisfy (4) (the best action) is performed. If $a_i^{n^*}$ represents a channel then $c_i(t+1) = a_i^{n^*}$. If $a_i^{n^*}$ represents the TO then $M_i(t+1) = \overline{M}_i(t)$.

   end
3. The loop in step 2 is run until there is no further CA and TO updates (i.e., until the algorithm converges).

in channel c_i, then using the reciprocity condition gives

$$r_{ij}^{c_i} = g_{ij}^{c_i} p_j^{c_i} = g_{ji}^{c_i} p_i^{c_i} = r_{ji}^{c_i} \tag{5}$$

where $g_{ij}^{c_i}$ is the link gain (see eq.(3) in Part I [54]) from tx j to rx i; and $p_i^{c_i}$ is the transmit power of tx i in channel c_i. Note that in (5), $r_{ij}^l = 0$ for those links which do not correspond to interference signals. So, (5) implies that $r_{j,i}^{c_i} = r_{i,j}^{c_i}$ and $r_{j,i+N}^{c_i} = r_{i+N,j}^{c_i}$ in (2), which yields that the utility function of the player i in (2) can be written as

$$u_i\left(a_i(t), a_{-i}\right) = 2 \sum_{j \in \bar{S}^{a_i}(t)} \left(r_{i,j}^{c_i}\right) + 2 \sum_{j \in S^{a_i}(t)} \left(r_{i+N,j}^{c_i}\right) \tag{6}$$

where $i = 1, 2, \ldots, N$. The sum $\sum_{j \in \bar{S}^{a_i}(t)} (r_{i,j}^{c_i})$ and $\sum_{j \in S^{a_i}(t)} (r_{j,i+N}^{c_i})$ are nothing but the measured interference powers by the FR i and its SR $i+N$ in channel c_i. Therefore, the Theorem 1 in Part 1 [54], and thus the proposed N-CATO and G-CATO in Tables I and II can be implemented in a fully distributed manner.

Case 2) the transmit powers of all FRs/SRs are not the same: We assume that the FRs and SRs transmit a constant-power pilot signals in a its control channel so that the other FRs and SRs estimate the interfering link gains $g_{i,j}^{c_i}$. So, the FR i and its SR $i+N$ estimates $g_{i,j}^{c_i}$ and $g_{i+N,j}^{c_i}$, $i = 1, 2, \ldots, N$, respectively, from the pilot signals. Because all FRs are responsible to send their measurement reports, which include also their current transmit power information to its BS, the BS can signal the information of p_l to the i'th FR. Then, the i'th FR-SR pair has all the information to calculate its own utility function $u_i(a_i(t), a_{-i})$ in (2) in a distributed manner, which completes the proof considering the Tables I and II. ■

TABLE III
PROPOSED CENTRALIZED G-CATO ALGORITHM (CG-CATO)

1. Every FR and its SR estimates the link gains and measures the interferences from other FRs/SRs.
2. All measurement reports are sent to the serving BS.
3. The utility function of each FR-SR pair $u_i(a_i, a_{-i})$ is calculated by the central BS.
   - The best FR-SR i^* and its action $a_i^{n^*}$ according to (7) is determined. Only the best FR and its action $a_i^{n^*}$ is informed by the central FR. The best FR executes its best action $a_i^{n^*}$.
4. The loop in step 3 is run until there is no further CA and TO updates (i.e., until the algorithm converges).

C. Centralized G-CATO Algorithm (CG-CATO)

Every FR and its SR estimates the link gains and measures the interferences from other SRs and FRs. The basic idea of the proposed Centralized Greedy joint CA and TO Algorithm (CG-CATO) is that the serving BS determines both the best FR-SR pair and its best action according to (7). And the BS performs this by using all the FRs' measurement reports, and calculating each of the individual utility functions $\{u_i(a_i^p, a_{-i})\}_{i=1}^{i=N}$ and $\left\{\{u_i(a_i^n, a_{-i})\}_{a_i^n=1}^{a_i^n=L+2}\right\}_{i=1}^{i=N}$, according to (2) in a centralized manner

$$\left(i^*, a_i^{n*}\right) = \arg\max \left\{u_i\left(a_i^p, a_{-i}\right) - u_i\left(a_i^n, a_{-i}\right)\right\}_{i=1}^N. \tag{7}$$

When such an action is determined, then only the best FR-SR pair i^* (player i^*) updates its action as $a_i^{n^*}$ (either CA or TO). The computational complexity of (7) linearly increases with L and N. The *CG-CATO* algorithm for D2D communication underlaying TDD based cellular network is presented by Table III.

In N-CATO, G-CATO and CG-CATO algorithms, the measurements are performed only for neighboring transmitters, and *not* for all transmitters in the system. Therefore, in all proposed algorithms in Tables I–III, the computational complexity does not increase exponentially with increasing L and N. This is organized by the central BS in such a way that every transmitter sends a pilot signal in a designated channel, and the neighboring pairs then measure the received signal strength (RSS) of the received pilot signal. This is similar to the standard measurement operation performed by the MSs in cellular networks. The measurements are conducted as standard received signal strength measurements as in, for example, [47]. In N-CATO, G-CATO and CG-CATO algorithms, the CA and TO updates are done sequentially (as in hill-climbing algorithms [55]).

Corollary 3: Consider D2D communication underlaying TDD based cellular system with N FR-SR pairs over possibly different cells. The CG-CATO summarized in Table III converges to a minimum of the total network interference $I^{tot,DL+UL}$ in (1) for any initial CAs and TOs within a finite number of iterations for the action set $A_i = \{1, 2, \ldots, L+1, L+2\}$.

Proof: From (7) above and the Theorem 1 and eq. (27) in Part I [54], we conclude that $I^{tot,DL+UL}(t+1) < I^{tot,DL+UL}(t)$. And because the number of possible combinations is limited, the proposed algorithm *N-CATO* converge within a finite number of iterations. ■

Furthermore, we also observe that the proposed algorithms N-CATO and G-CATO, both of which are based on the proposed game Γ, include some interference reduction algorithms and the TO optimization algorithms in literature as its special cases such as the GADIA in [49], the second phase of the N-GAIR in [44], the ABCAMiC and CABCAMiC in [51], etc.

Corollary 4: If $N \times N$ UL and DL System-Interference-Matrix are symmetric for a given fixed TO (i.e., $TO(t) = TO$), and if the set of action profile indexes of i'th player is $A_i = A_{CA} \equiv \{1, 2, \ldots, L-1, L\}$, which includes only CAs, then the proposed G-CATO becomes equal to the GADIA in [49].

Corollary 5: If the set of action profile indexes of i'th player is $A_i = A_{CA} \equiv \{1, 2, \ldots, L-1, L\}$, which includes only CAs, then the N-CATO becomes equal to the second phase of the N-GAIR in [44].

Corollary 6: If the set of action profile indexes of i'th player is $A_i = A_{TO} \equiv \{L+1, L+2\}$, which includes only TOs, then the N-CATO and G-CATO become equal to the ABCAMiC and CABCAMiC in [51], respectively.

The proofs of Corollary 4, 5 and 6 are based on the following observation: Theorem 1 in Part 1 [54] is proved for any arbitrary action (CA/TO) $a_i \in A_i$ for the joint CA and TO optimization. The results of Theorem 1 in Part I [54], and thus Corollary 1, 2 and 3 above are true for not only the complete set of CA-TO action profile indexes $A_i = \{1, 2, \ldots, L-1, L, L+1, L+2\}$ but also any possible subset of A_i. This yields Corollary 4, 5 and 6.

D. Brief Comparison of the Proposed N-CATO and G-CATO, With the GADIA [49], N-GAIR [44], and ABCAMiC-CABCAMiC [51]

i) *G-CATO and GADIA* [49]: The basic heuristics that each radio is sequentially allocated to the channel where it experiences the least interference has been used for a long time [45]–[49], etc. Babadi and Tarokh was the first one who thoroughly analyzed such a distributed minimum-interference algorithm in [49] for *symmetric* link-gains case. In [53], the GADIA for symmetric link gains case is proved to be a potential game with half of the weighted aggregate interference serving as the potential function. In this paper, we present a generalized framework for joint optimization of CA and TO optimization in D2D communication from game theoretic perspective. The proposed G-CATO with $A_i = A_{CA} \equiv \{1, 2, \ldots, L-1, L\}$ (i.e., a shortened version of the G-CATO) is for *asymmetric* link-gains case, and therefore includes the basic GADIA as its special case. While the GADIA checks only the total interference received from others at each channel, the G-CATO takes not only the total interference received from others but also the interference caused to others at each channel. Let's call this shortened version of the G-CATO which extends the GADIA [49] to *asymmetric* link-gains case as Generalized-GADIA (G-GADIA).

ii) *N-CATO and the second phase of the N-GAIR in* [44]: The N-GAIR (Non-Greedy Asynchronous Interference Reduction Algorithm) in [44] is a hybrid algorithm and has two phases: It first performs the spectral clustering algorithm and then a non-greedy asynchronous interference reduction algorithm for *asymmetric* link gain matrix case. As shown in Corollary 5, the proposed N-CATO with $A_i = A_{CA} \equiv \{1, 2, \ldots, L-1, L\}$ gives the second phase of the N-GAIR in [44]. This implies that we greatly simplify the original N-GAIR in [44] as applied to the CA problem in D2D communication underlaying TDD based cellular system. Let's call this simplified algorithm as N-GAIR2 because it exactly corresponds to the second phase of the original N-GAIR in [44]. The N-CATO with $A_i = A_{CA} \equiv \{1, 2, \ldots, L-1, L\}$ exactly corresponds to the second phase of the hybrid algorithm N-GAIR [44].

iii) *N-CATO/G-CATO and ABCAMiC/CABCAMiC* [51]: To our best knowledge, recently proposed algorithm ABCAMiC and CABCAMiC in [51] is the first work which *explicitly* addresses the TO optimization in D2D communication underlaying cellular network. The work in [51] focuses on the TO optimization problem for *only* one-channel case (using a graph theoretic approach). In this two-part paper we greatly extend the results in [51] taking also the CA problem into account and using a game theoretic approach, which yields several interesting results. Thus the proposed N-CATO and G-CATO in this paper are the CA extension of the TO algorithms ABCAMiC and CABCAMiC in [51], respectively.

All these algorithms and various other CA algorithms (like [47], etc) can be considered in the class of so-called "hill climbing" algorithms. In computer science, hill climbing [55] is a mathematical optimization technique, which belongs to the family of local search. For further details, see, e.g., [55]. In this two-part paper, we device some novel algorithms, which can be considered in the family of "hill-climbing" methods, for a completely new problem: TO optimization (together with the CA optimization). The TO option has recently been included into the 3GPP standard.

III. Simulation Results

We compare the performances of the proposed N-CATO, G-CATO and CG-CATO with various reference algorithms. For a complete comparison, the reference algorithms are taken as Random-CA (RCA) without TO, RCA with TO, the basic GADIA in [49], the G-GADIA, and the N-GAIR2. Without loss of generality, a direct-sequence (W)CDMA/TDD wireless network is considered in all examples. For link gain modeling, attenuation factor $\beta = 3$, the log-normally distributed s_{ij} in (3) in Part I [54] is generated according to the model in [50], and the lognormal variance is 10 dB. The transmit powers of FRs and SRs are between [1.9–2.1] mW and [1.8–2.0] mW, respective. In what follows, we first provide an illustrative example to motivate the TO optimization for co-channel FR-SR pairs.

Example 1—Analysis of a Snapshot for $N = 2$ Case: The aim of this illustrative example is to analyze a simple 2-FR-SR co-channel pairs case in details in order to give an insight

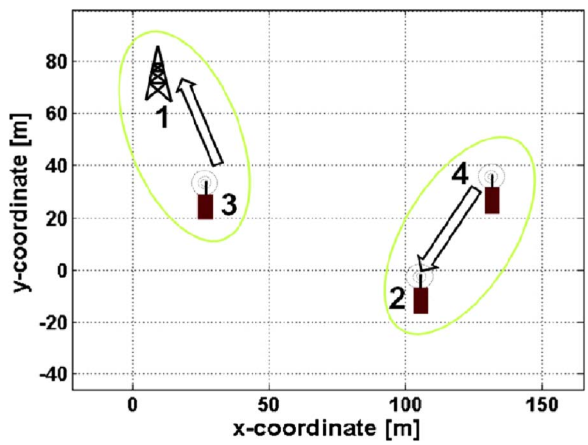


Fig. 1. Reference case (all TOs are UL) for the snapshot in Ex. 1.

into why the TO optimization can greatly improve the system performance of the network. This example shows that the TO optimization for co-channel pairs not only can greatly decrease the total network interference but also improve the SINRs. A snapshot of the network is shown in Fig. 1. The FRs are numbered as 1 and 2; and SR2s as 3 and 4. In Fig. 1, the TOs are UU, which represents the reference case.

The interfering link gains of the TDD system in Fig. 1 are given as $g_{12} = g_{21} = 0.3890 \times 10^{-6}$, $g_{14} = g_{41} = 0.8355 \times 10^{-6}$, $g_{23} = g_{32} = 0.9931 \times 10^{-6}$, and $g_{34} = g_{43} = 0.8355 \times 10^{-6}$. The symmetry of the link gains come from the reciprocity of the channels in TDD systems. The own-link gains g_{13} and g_{24} for SR1 and SR2 are $10^{-4} \times 0.0791$ and $10^{-4} \times 0.1307$, respectively. All the transmit powers are 2 mW. From Proposition 1 in Part I [53], this means $I_{tot}^{ntw,DL+UL} = 2I_{tot}^{ntw,DL} = 2I_{tot}^{ntw,UL}$.

Taking the reference case as the initial condition, we determine the TOs by the ABCAMiC (a special case of the N-CATO) algorithm. The evolution of the total network interference $I_{tot}^{ntw,DL+UL}$ calculated from eq. (1) is shown in Fig. 2(a). After one update, the algorithm converges.

The N-CATO algorithm results in DU as shown in Fig. 2(b) for the initial condition UU. The total network interference power for the reference case (UU) in Fig. 1 and the N-CATO case (DU) is -85.0812 dBm and -86.1102 dBm, respectively. This means -1.029 dBm interference power reduction for this particular example just by optimizing the TOs with the proposed N-CATO as shown by comparing Figs. 1 and 2(b). As shown in Section II, the promise of the ABCAMiC is to effectively reduce the total network interference $I_{tot}^{ntw,DL+UL}$ from eq. (1). From Corollary 1, the N-CATO guarantees that the total network interference power is further decreased for each and every TO update sequentially. How about the interference power, SINR at the rx? Using the link gains, and own-link gains, we calculate those entities and present them in Table IV. As seen from Table IV, the link-specific interference power is reduced 0.7505 dBm for the link of FR1; and 1.5729 dBm for the link of FR2 by the N-CATO as compared to the reference case. The SINR is increased $+1.4731$ dB and $+9.8218$ dB for the link of FR1 and FR2, respectively, by the proposed N-CATO. This translates into a channel capacity increase of $+0.2212$ [bits/Hz] and of $+0.4946$ [bits/Hz] for the link of FR1 and FR2, respectively. In short, as seen from Table IV,

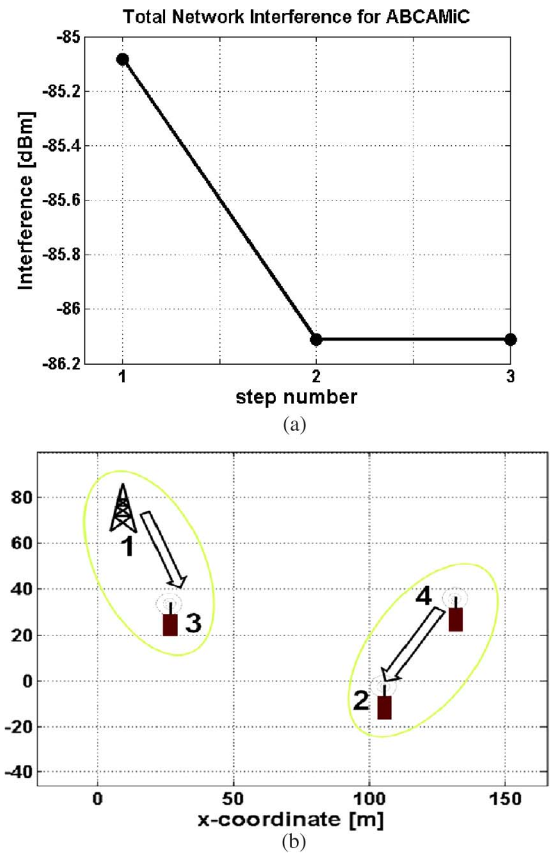


Fig. 2. (a) Total network UL Interference for the N-CATO for the snapshot in Example 1 with respect to step number. (b) Result of the N-CATO algorithm.

TABLE IV
INTERFERENCE POWERS ([dBm]), SINRS ([dB]) AND CORRESPONDING CAPACITIES (bits/Hz) FOR THE CO-CHANNEL PAIRS IN EXAMPLE 1

FR-SR pair		Interf. [dBm]	SINR [dB]	Capacity [bits/Hz]
1-3	ref	-7.0197	7.8920	3.1525
	ABC.	-7.7702	9.3651	4.5860
	diff.	**-0.7505**	**+1.4731**	**+0.2212**
2-4	ref	-9.5177	23.0180	3.3737
	ABC.	-1.0906	32.8397	5.0806
	diff.	**-1.5729**	**+9.8218**	**+0.4946**

the N-CATO not only reduces remarkably the link-specific interference powers but also improves drastically the SINRs of both links in the network for this specific example.

Example 2—$N = 10$ Case: In this example, there are 10 FR-SR pairs and 2 channels. A snapshot of the network is given in Fig. 3. For the sake of brevity, the FR locations are indicated as squares in black, and the SR locations are shown as upward and downward triangles indicating their TOs. Upward and downward triangles represent UL and DL, respectively. Different colors represent different channels. So, blue color and red color represents channel 1 and 2, respectively. Thus, for example, blue upward triangle means that corresponding SF is allocated to channel 1 and its TO is UL. The results of the basic GADIA [49] and the proposed N-CATO are presented in Fig. 3(a) and (b), respectively, for the same initial conditions (the same TO initial and random CA initial conditions). As seen from Fig. 3, circled four pairs out of ten in the proposed N-CATO are different in their CAs and/or TOs as compared to the basic GADIA, in this particular snapshot. The $I_{tot}^{ntw,UL+DL}$

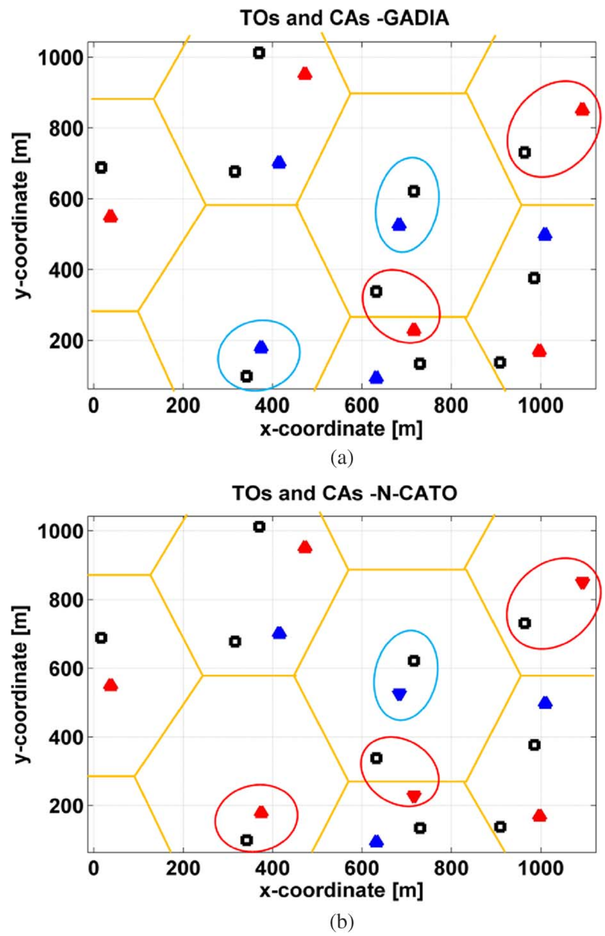


Fig. 3. Snapshot for Example 2. (a) CA results of the basic GADIA and (b) CA-TO results of N-CATO.

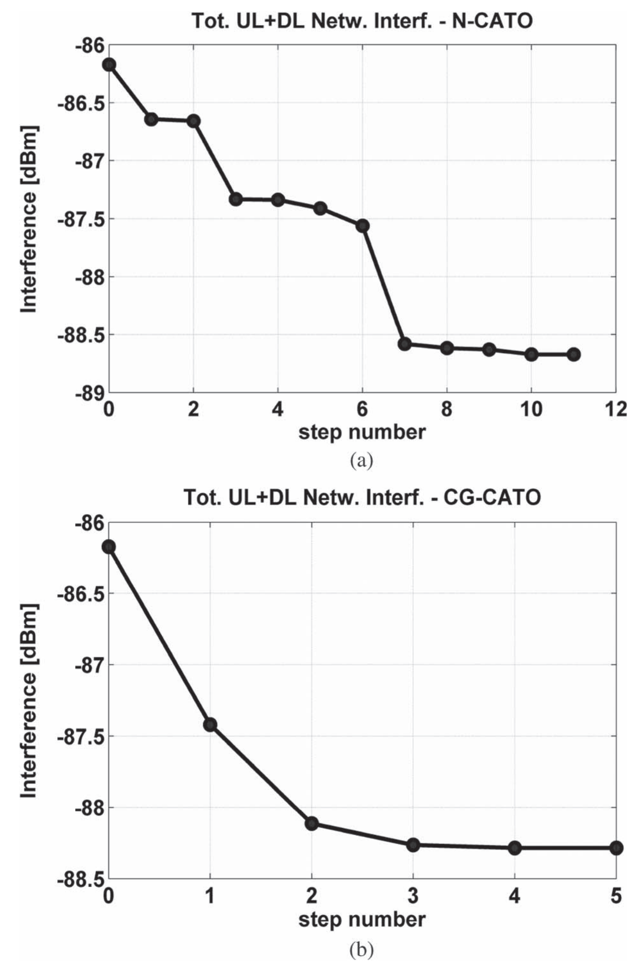


Fig. 4. Evolution of the total UL + DL network interference [dBm] for (a) the N-CATO and (b) the CG-CATO for the snapshot in Fig. 3.

in (1) with respect to the step number for the N-CATO and the CG-CATO is shown in Fig. 4(a) and (b), respectively. As seen from Fig. 4, the proposed N-CATO and CG-CATO reduces the total network interference at each step whenever either a CA or a TO is changed. The N-CATO converges fast, only within 10 steps. In Fig. 5(a) and (b), we present the $I_{tot}^{ntw,UL+DL}$ in (1) with respect to the step number and epoch number for the G-CATO. Epoch here means one complete cycle period during which all N pairs perform their TO and CA allocations sequentially. The Fig. 5 shows that the G-CATO converges already within 12 steps in four epochs for this particular example.

In order to evaluate the system performance of the proposed N-CATO, G-CATO, and CG-CATO, we calculate the related statistics over 10.000 independent random snapshots from the network. In all cases, the initial CAs are such that the FR-SR pairs are randomly allocated to channels evenly, i.e., the number of FR-SR pairs in every channel is the same. In order to examine how the proposed algorithms' performances depend on the initial TOs, we run the proposed algorithms twice for each same snapshot by taking the initial condition as 1) the TOs are all-DL and all-UL; and 2) the initial TOs are random. In presenting the average results over the 10.000 snapshots, we use the following notation:

R0 Reference-Random-CA (RCA): The CAs are randomly chosen, (and the number of FR-SR pairs in every channel is the same), and TOs are all-DL or all-UL. There is neither CA nor TO optimization.
R1 Reference-TO: The CAs are randomly chosen, and TOs are optimized by ABCAMiC [51].
R2 Reference-Basic GADIA, R3: Reference-G-GADIA, R4: Reference-N-GAIR2,
A1 N-TACO with initial TOs are all-DL (and all-UL),
A1r N-TACO with random initial TOs.
A2 G-TACO with initial TOs are all-DL (and all-UL),
A2r G-TACO with random initial TOs.
A3 CG-TACO with initial TOs are all-DL (and all-UL),
A3r CG-TACO with random initial TOs.

The average network interference in DL and in UL given by (4) and (5), respectively, together with their average variances over the 10.000 snapshots are presented in Fig. 6. The figure shows that *i)* All proposed algorithms, the N-CATO, the G-CATO and the CG-CATO, effectively reduce the average network interference both in DL and in UL. *ii)* Comparing A1 with A1r, A2 with A2r, and A3 with A3r in Fig. 6(a), all three proposed algorithms perform almost about the same regardless of the initial TOs. This implies that the average performance does not depend on the initial TOs and CAs. Furthermore, Fig. 6(b) shows that all the proposed algorithms remarkably reduce the variance of the network interference.

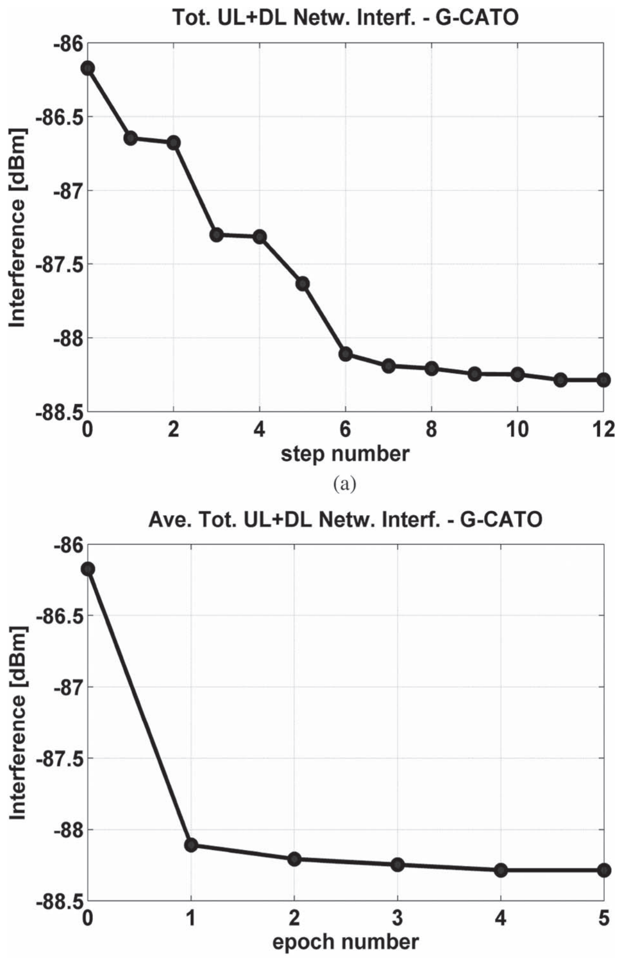


Fig. 5. Evolution of the total UL + DL network interference [dBm] in (1) by G-CATO for the snapshot in Fig. 3 with respect to (a) step number and (b) epoch number.

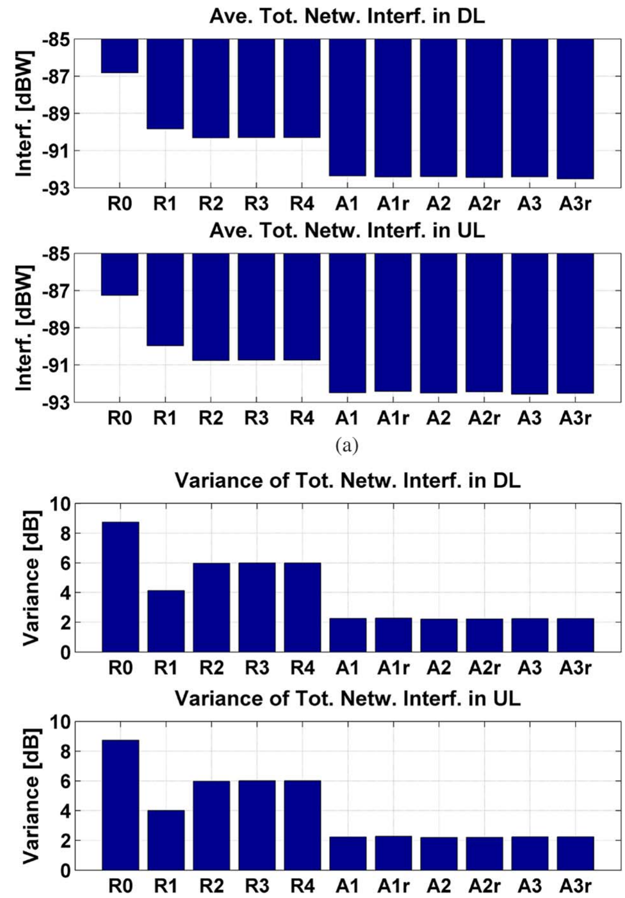


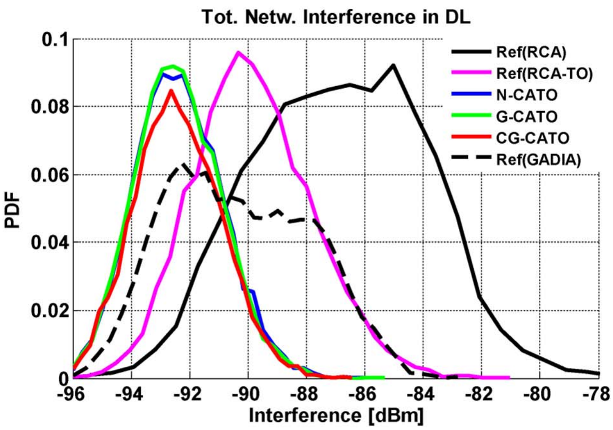
Fig. 6. (a) Average network interference [dBm] in DL ($I^{tot,DL}$ in (4) of Part I [54]) and in UL ($I^{tot,UL}$ in (5) of Part I [54]) and (b) their average variances in Example 2 over 10.000 snapshots.

The PDFs of the total network interference in DL and UL are presented in Fig. 7. The figure show the remarkable superiority of the proposed algorithms N-CATO, the G-CATO and the CG-CATO as compared to all the reference algorithms. From Fig. 7, all three proposed algorithms (N-CATO, the G-CATO and the CG-CATO) perform almost the same in all interference regimes.

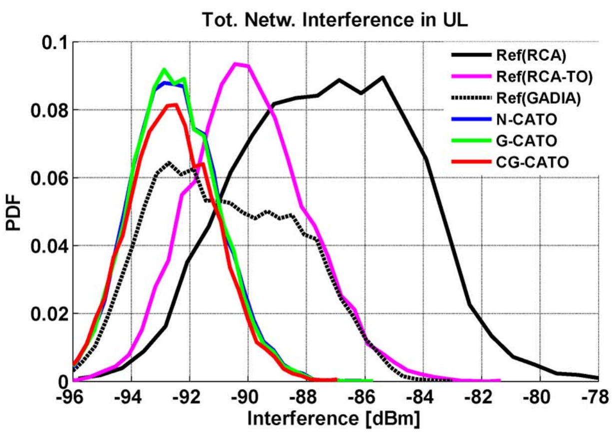
Link-wise average SINR results [dB] in DL in UL in Example 2 over 10.000 snapshots are presented in Fig. 8. From the figure, the average SINR gains in UL obtained by the proposed N-CATO, the G-CATO and the CG-CATO are +1.0108, 1.0265, and 1.0367 dB higher, respectively, than the best reference cases.

Furthermore, we also examine the performances of the proposed algorithms in the presence of measurement error. The simulation results suggest that the performances of all algorithms degrade about in the same order in the presence of measurement error [for example see Figs. 6(a) and 9]. This result is in line with the result that the proposed algorithm includes the reference CA algorithms and TO algorithms as its special cases. Fig. 9 shows the performances of all algorithms in the presence of a Gaussian measurement error whose standard deviation is 90% of the actual measurement value. Here, we examine the case where the measurement errors only affect the TO-CA selections, so the results in Fig. 9 is calculated with the actual measurement values after the TO-CA selections are determined in the presence of measurement errors.

Example 3—$N = 100$ Case: In this example, there are 100 FR-SR pairs, whose locations are randomly chosen in such a way that the pairs are relatively "isolated". As in Example 2, the FR locations are indicated as squares in black, and the SR locations are shown as upward and downward triangles indicating their TOs, and in different colors indicating their CAs. The results of the basic GADIA [49] and the proposed N-CATO are presented in Fig. 10(a) and (b), respectively, for the same initial conditions (i.e., the same TO and same random CA initial conditions). As seen from Fig. 10, circled 30 pairs out of 100 in the proposed N-CATO remain the same in both CAs and TOs as compared to the reference GADIA, in this particular snapshot. Each of the rest (70 out of 100) is different in its CA and/or its TO. The $I_{tot}^{ntw,UL+DL}$ in (1) with respect to the step number and epoch number for the N-CATO is shown in Fig. 11(a) and (b), respectively. As seen from Fig. 11, the proposed N-CATO reduces the total network interference at each step whenever either a CA or a TO is changed. The N-CATO converges only within 6 epochs as seen from Fig. 11(b). In Fig. 12(a) and (b), we present the $I_{tot}^{ntw,UL+DL}$ in (1) with respect to the step number and epoch number for the



(a)



(b)

Fig. 7. PDF of average network interference [dBm] in Example 2 over 10.000 snapshots in (a) DL ($I^{tot,DL}$ in in (4) of Part I [54]), and (b) UL ($I^{tot,UL}$ in (5) of Part I [54]).

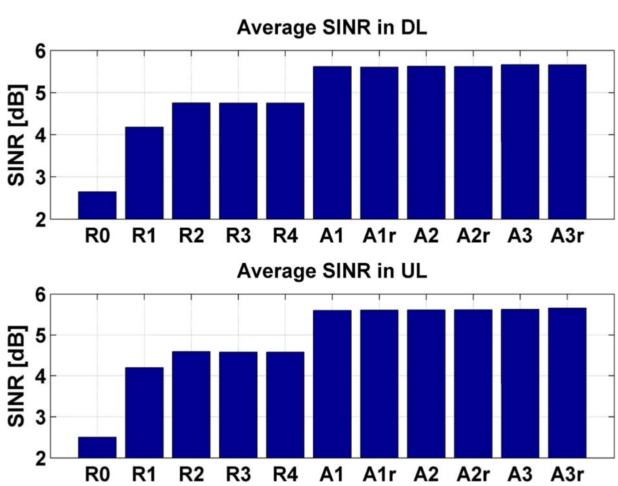


Fig. 8. Average SINR [dB] in DL and in UL in Example 2 over 10.000 snapshots.

G-CATO. The figure shows that G-CATO effectively reduces the total network interference and converges already within 5 epochs for this particular example. The evolution of the CG-CATO is shown by Fig. 13 showing how the total network interference is effectively reduced.

We evaluate the system performance of the proposed N-CATO, G-CATO, and CG-CATO over 1000 independent random snapshots from the network. The average network in-

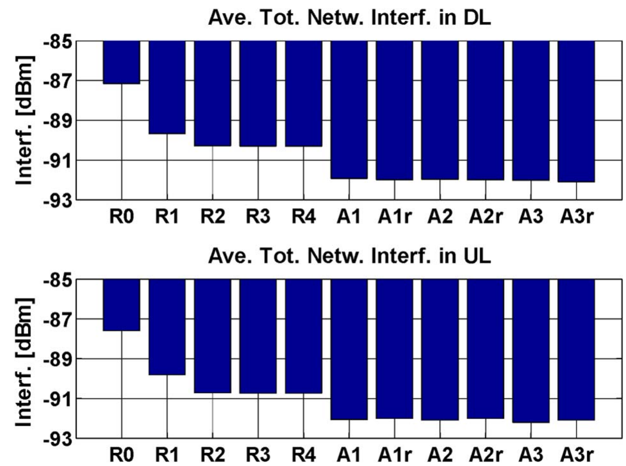
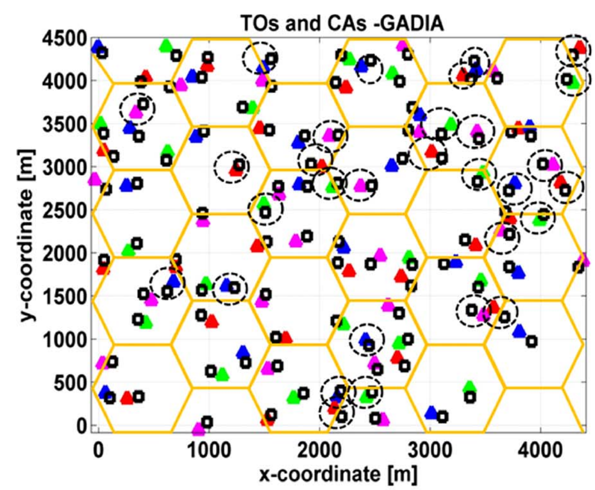
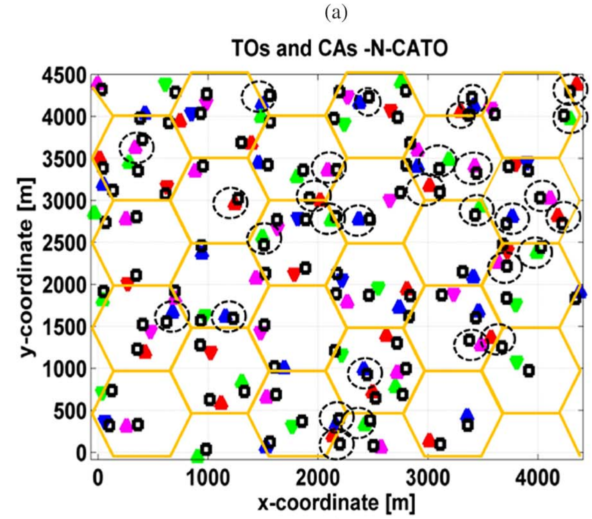


Fig. 9. Average network interference [dBm] in DL and in UL in the presence of measurement error in Example 2 over 10.000 snapshots.



(a)



(b)

Fig. 10. Snapshot for Example 3. (a) CA results of the basic GADIA and (b) CA and TO results of the N-CATO.

terference in DL and in UL given by (4) and (5) are presented in Fig. 14(a). Average linkwise SINRs are presented in Fig. 14(b). The figure confirms the findings in Example 2, i.e.,: Fig. 14 hows that *i)* all proposed algorithms, the N-CATO, the G-CATO and the CG-CATO effectively reduce the average network interference both in DL and in UL. *ii)* the performances of all three

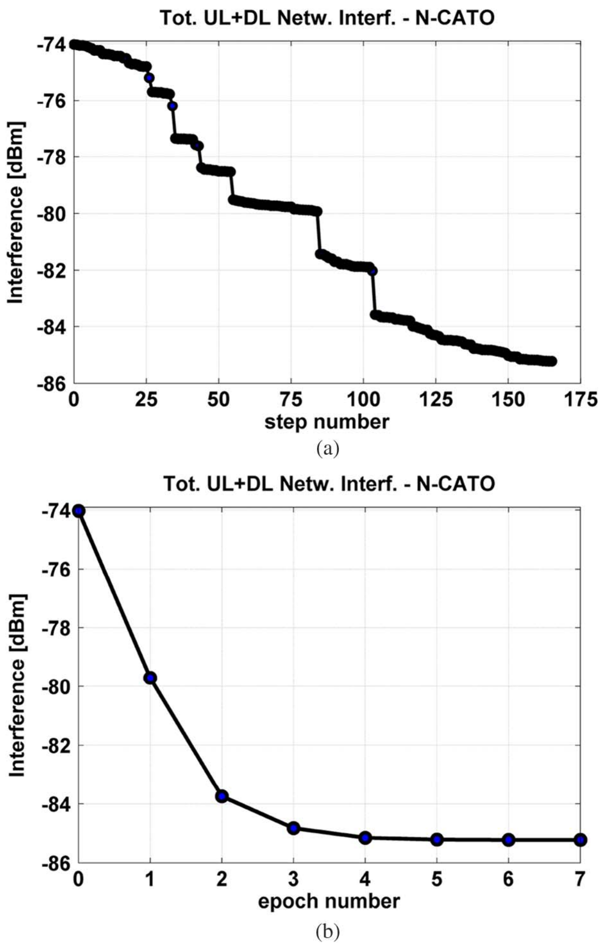


Fig. 11. Evolution of the total UL + DL network interference [dBm] in (1) by the N-CATO for the snapshot in Fig. 10 with respect to (a) step number and (b) epoch number.

proposed algorithms are close to each other regardless of their initial TOs. This implies that the average performance does not depend on the initial TOs and CAs. Comparing Fig. 14(a) with Figs. 6(a) and 8(a), the gains due to the TOs in the case $N = 100$ is smaller than those of the case $N = 10$ in Example 2. The reason is because the parameter setting in Example 3 for $N = 100$ is such that the every FR-SR pair is exposed to relatively high number of interfering FR-SR pairs regardless of the TOs. From Fig. 14(b), the average SINR gains in UL by the proposed algorithms are about $+0.3$ dB, respectively, higher than the best reference cases. Assuming that the interference is Gaussian due to the central limit theorem, this translates into $+0.0478$ [bits/Hz] higher average (Shannon) channel capacity gains per link. (For a 5 MHz channel, these would correspond to $+239$ kbits average link capacity increase). Similar but little lower gains are obtained in DL as well.

Comparing Figs. 6(a) and 14(a), we see that the average interference reduction gain by the proposed methods depend on the number of co-channel FR-SR pairs and the locations of the FR-SR pairs. While the gain for the scenario $N = 10$, $L = 2$ in Fig. 6(a) is about 2–3 dB, it is about 1 dB in the scenario $N = 100$, $L = 4$. The reason why the gain is decreased when going from $N = 10$, $L = 2$ to $N = 100$, $N = 4$ is because for this specific scenario of $N = 100$, $L = 4$, there is much less room in the TO dimension for performance improvement. This is because when the number of co-channel pairs in the neighborhood is relatively high (e.g., 25), then no matter how we optimize the TOs, there will be almost always some relatively strong interfering transmitters in the close neighborhoods due to the location distribution. This yields less room for the overall performance improvements.

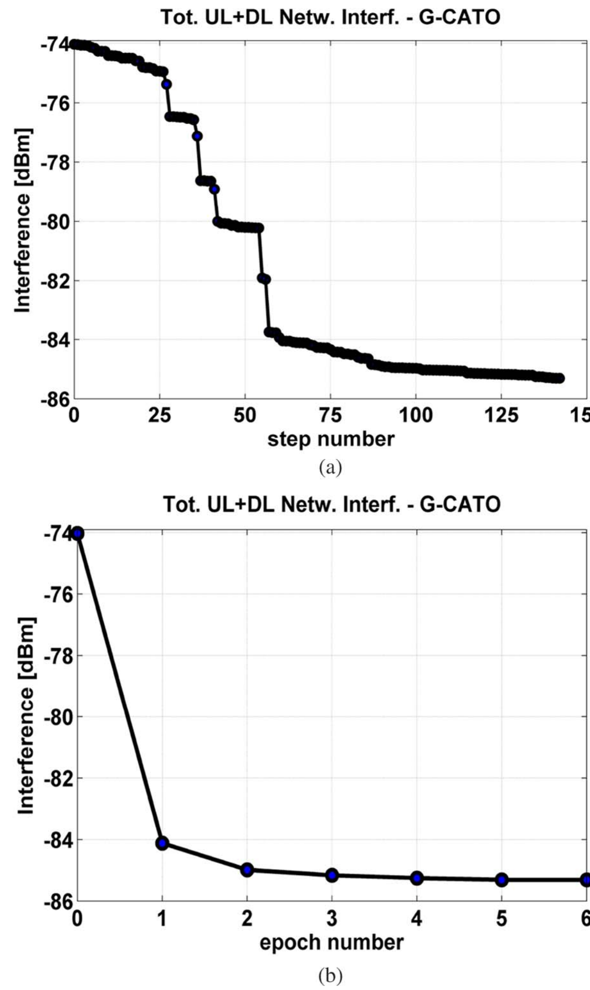


Fig. 12. Evolution of the total UL + DL network interference [dBm] in (1) by the G-CATO for the snapshot in Fig. 10 with respect to (a) step number and (b) epoch number.

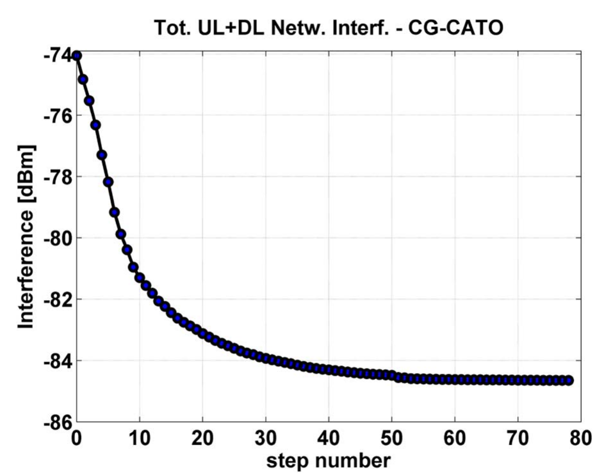


Fig. 13. Evolution of the total UL + DL network interference [dBm] in (1) by the CG-CATO for the snapshot in Fig. 10 with respect to step number.

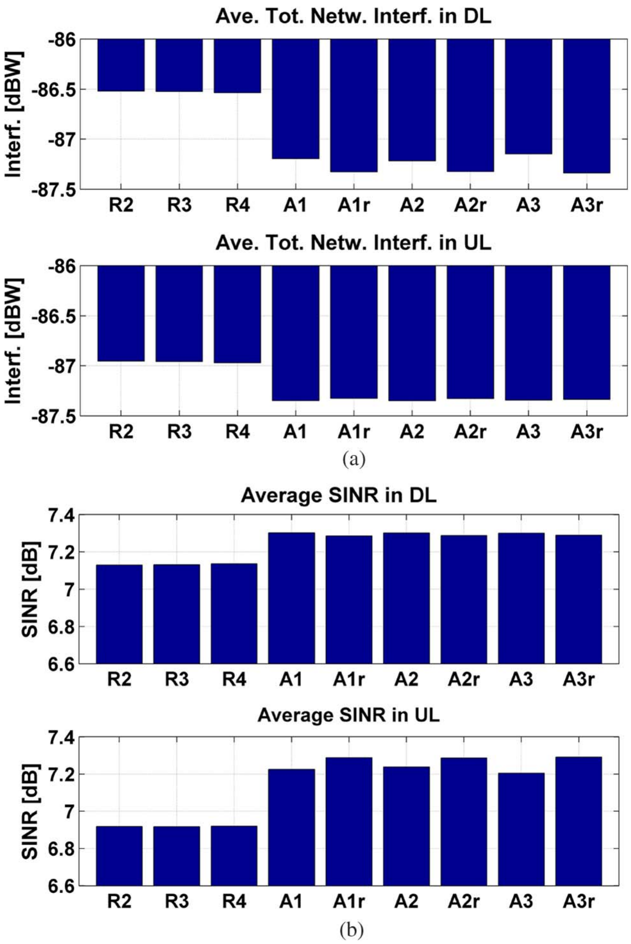


Fig. 14. (a) Ave. total network interference power [dBm], (b) Ave. SINR [dB] in Example 3 over 1.000 snapshots.

IV. Conclusion

In this paper, i.e., Part II of the two-part series, we focus on D2D communications underlaying cellular networks: *i)* we propose and analyze two distributed *joint* CA-TO algorithms, called N-CATO and G-CATO, and one centralized *joint* CA-TO algorithm called CG-CATO (using the findings in Part I [54]). *ii)* the proposed N-CATO and G-CATO include some interference reduction algorithms and the TO optimization algorithms in literature as its special cases such as the basic GADIA in [49], the second phase of the N-GAIR in [44], the ABCAMiC and CABCAMiC in [51], etc. *iii)* The proposed CA and TO game is equal to the max-cut of a proposed TO-dependent graph. *iv)* A special case of the N-CATO greatly simplifies the original N-GAIR in [44] which yields a great relief in its computational complexity. *v)* A shortened version of the G-CATO extends the basic GADIA [49] to asymmetric link-gains case.

The computer simulations for TDD-based D2D underlaying cellular network show that the proposed distributed and centralized joint algorithms, i) remarkably outperform all the reference cases, and, ii) converge within a small number of epochs (only few to several epochs) even for large number of cells and D2D pairs, and, iii) give near global optimal solution to the joint optimization problem. Although the focus of this paper is D2D communications underlaying TDD based cellular networks, the results can be readily applied to emerging heterogeneous networks, and small-cell networks.

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