OPTIMAL TIME REUSE IN COOPERATIVE D2D RELAYING NETWORKS

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ABSTRACT

Device-to-device (D2D) communication has become one important part of the 5G cellular networks particularly due to the booming of proximity-based applications, e.g., D2D relays. However, the D2D relays may create strong interference to nearby users. Thus interference management in a cellular network with D2D relays is critical. In this paper, we study the optimal time reuse patterns in a cellular network with cooperative D2D relays and derive the corresponding optimized relaying strategies. Due to the binary association constraints and the fact that the total number of feasible time reuse patterns increase exponentially with the number of users, we have a large scale integer programming problem which is formidable to solve. However, we show that we just need to activate a few time reuse patterns in the order of the number of users. Accordingly, a low-complexity algorithm is proposed to find the set of active time reuse patterns and solve this problem in an approximated way. Numerical simulations demonstrate that our scheme can efficiently allocate the time resources and determine the relaying strategies. Furthermore, the proposed scheme offers significant gains relative to the existing ones.

Index Terms— Cooperative network, device-to-device relay, time reuse, resource allocation, user association.

1. INTRODUCTION

With the ever-increasing mobile data traffic demands, the proximity-based communication through the device-to-device (D2D) links is regarded as one promising technology in 5G cellular networks\textsuperscript{[1]}. Different from the base station (BS)-based links, D2D links usually appear in short-range scenarios and can significantly enhance the network throughput performance without interfering distant users\textsuperscript{[2]}. In a cooperative D2D network, when both types of links share the same time or spectrum resources, severe interference can still occur among nearby users without careful resource management\textsuperscript{[3]}.

To make full use of the limited resources, a lot of works have been done to optimize D2D-enabled cellular networks\textsuperscript{[4-8]}. In particular, the spectrum allocation and power control were jointly optimized in\textsuperscript{[4] to maximize different network utility metrics under QoS constraints, while D2D relays were not modeled in\textsuperscript{[4]}. Recent works in\textsuperscript{[5-8]} emphasized the importance of D2D relays and recommended some D2D user equipments (DUEs) to serve as D2D relays for other DUEs experiencing poor BS-based links. Orthogonal resource allocations and corresponding relaying strategies were optimized jointly under different constraints in\textsuperscript{[5-8]}.

Fig. 1. A cooperative network with D2D relays. DUE 1 is served by DUE 2 since its BS-based link is blocked. Both DUE 4 and DUE 5 are served by DUE 3 for similar reasons.

As shown in Fig. 1, a downlink shared cooperative network\textsuperscript{[6]} is considered here, where a number of nodes coexist including the DUEs and the BSs. The sets of BSs and DUEs are denoted by \(B\) and \(\mathcal{U}\), respectively. Meanwhile, we define \(B := |B|\) and \(\mathcal{U} := |\mathcal{U}|\). Each DUE is assumed to be able to act as either a relay or a user. For instance, it can act as a user to receive data either from the serving BS or from another DUE (behave as one D2D relay) in one time

Networks (HetNets) in\textsuperscript{[6-11]}. In particular, the network-wide average packet delay was minimized in\textsuperscript{[7]}, the energy efficiency was maximized in\textsuperscript{[6]}, and the network proportional fairness (PF) metric was maximized in\textsuperscript{[11]}.

In this paper, we endeavor to find the optimal resource reuse scheme in a cooperative network with D2D relays. The major contributions can be summarized as follows. Firstly, we study the optimal set of time reuse patterns and the corresponding relaying strategies such that the PF metric of the network is maximized. Even though the total number of feasible reuse patterns increases exponentially with the number of users, we show that we just need to activate a few time reuse patterns in the order of the number of users to achieve the optimal network performance. Secondly, we put forward an efficient algorithm of low complexity to identify the set of reuse patterns to be activated and solve the problem approximately. Numerical results demonstrate our scheme can offer significant gains relative to the existing solutions.

The remainder of this paper is organized as follows. Section 2 describes the system model. Section 3 formulates the problem and characterizes the optimal time reuse profile. Section 4 proposes a low-complexity algorithm. Numerical results are given in Section 5 and Section 6 concludes the paper.

Notations: Notations \(|A|\), \(\mathbf{A}^T\), \(\text{conv}(A)\), \(|A|\), and \(a \oplus b\) stand for the cardinality of the set \(A\), the convex hull of the set \(A\), the cardinality of the set \(A\), and the element-wise XOR operation of two vectors. \(1\{\cdot\}\) stands for the indicator function and takes the value of 1 (0) when the specified condition is met (otherwise). \(e_n\) denotes the unit vector with only the \(n\)-th element being 1 and all other elements being 0.

2. SYSTEM MODEL

As shown in Fig. 1 a downlink shared cooperative network\textsuperscript{[6]} is considered here, where a number of nodes coexist including the DUEs and the BSs. The sets of BSs and DUEs are denoted by \(B\) and \(\mathcal{U}\), respectively. Meanwhile, we define \(B := |B|\) and \(\mathcal{U} := |\mathcal{U}|\). Each DUE is assumed to be able to act as either a relay or a user. For instance, it can act as a user to receive data either from the serving BS or from another DUE (behave as one D2D relay) in one time
slot. In another slot, it can act as a relay to help other DUEs. Thus we assume each DUE can choose to be either a user or a relay in different time slots. The set of servers $N$ including both BSs and D2D relays is defined as follows.

$$N := \{1, \ldots, B, B + 1, \ldots, B + U\}. \quad (1)$$

Let $N := |N|$ denote the total number of servers in the set $N$. We use a vector $v_i = [v_{i,1}, \ldots, v_{i,N}]^T$ to indicate the active status of the servers in one time slot and call it the i-th time reuse pattern. The $n$-th element of $v_i$ is 1, i.e. $v_{i,n} = 1$, when server $n$ is active under time reuse pattern $v_i$. Otherwise, we have $v_{i,n} = 0$. Note when a server is active, we assume it utilizes the whole downlink bandwidth for information transmission. There are totally $2^N - 1$ feasible time reuse patterns to be considered and we do not consider the all 0 pattern, which means nobody transmits.

Let $I = \{1, \ldots, 2^N - 1\}$ denote the set of indices of all the feasible time reuse patterns. Furthermore, the set of all time reuse pattern is denoted as $\mathcal{V} = \{v_i | i \in I\}$. We also use $A_i$ to denote the set of active servers under pattern $i$, i.e. $A_i := \{n | v_{i,n} = 1, n \in N\}$. Let $x_i$ denote the fraction of the total time duration of time $T$ allocated to pattern $i$. The overall time reuse profile is thus given by the vector: $x := [x_1, \ldots, x_{2^N - 1}]^T$. In order to get the optimal network performance, we need to utilize the whole time duration, i.e. $\sum_{i \in I} x_i = 1$. Furthermore, we assume time-division multiple-access (TDMA) and each server only transmits data to one served user at one time. A server needs to divide the allocated time resource under pattern $i$ orthogonally among its served users. We use $y_{u,n,i} \geq 0$ to denote the fraction of the total duration $T$ allocated to user $u$ by server $n$ under reuse pattern $i$. Clearly, it is bounded as $\sum_{u \in U} y_{u,n,i} \leq x_i$. Additionally, as in the current cellular networks, each user is allowed to be associated to a single server under each reuse pattern, which is characterized by $z_{u,n,i}$, i.e. $z_{u,n,i} = 1$ indicates user $u$ is served by server $n$ under pattern $i$ and $z_{u,n,i} = 0$ otherwise. Due to this single-server association constraint, the variables $\{z_{u,n,i}\}$ satisfy the constraint $\sum_{n \in N} z_{u,n,i} = 1$. Note the corresponding relaying strategies are also implied by $\{z_{u,n,i}\}$.

Denote the transmission power of server $n$ by $P_n$. The signal-to-interference-plus-noise ratio (SINR) of the link between user and server $n$ under pattern $i$ is denoted by $\gamma_{u,n,i}$ and can be expressed as

$$\gamma_{u,n,i} = \frac{\mathbb{I}\{n \in A_i\} P_n |g_{u,n}|^2}{\sigma^2 + \sum_{m \in A_i, m \neq n} P_m |g_{u,m}|^2},$$

where $\sigma^2$ is the power of the thermal noise at the user and $g_{u,n}$ denotes the average gain of the channel from server $n$ to user $u$. Let $c_{u,n,i}$ denote the spectral efficiency of this link. To reflect the constraint that one DUE cannot transmit and receive simultaneously, the spectral efficiency $c_{u,n,i}$ is set to be zero if server $(u + B)$ is active under reuse pattern $i$. Therefore, the spectral efficiency can be expressed as

$$c_{u,n,i} = \mathbb{I}\{u + B \in A_i\} \cdot \log_2(1 + \gamma_{u,n,i}). \quad (3)$$

Note that the actual time resource allocated to user $u$ by server $n$ under pattern $i$ is $T y_{u,n,i}$. The average data rate of user $u$ over all reuse patterns can be written as follows.

$$\bar{R}_u = \frac{1}{T} \cdot W \cdot \sum_{i \in I} \sum_{n \in N} \sum_{i \in A_i} y_{u,n,i} \cdot c_{u,n,i} \cdot T y_{u,n,i} \cdot \gamma_{u,n,i}, \quad (4)$$

where $W$ denotes the system bandwidth. Besides, we assume that the DUEs in the network demand different data. For a D2D relay, a portion of its received data are intended for others. The effective data rate of user $u$ is thus given by $R_u = \bar{R}_u - \bar{R}_{u + B}$, where $\bar{R}_{u + B}$ denotes the data rate of server $(u + B)$, i.e. user $u$ acting as a D2D relay, targeted to the served DUEs. The total rate of server $n$ serving other DUEs over all reuse patterns is given by

$$\bar{R}_n = W \sum_{i \in I} \sum_{n \in N} \sum_{i \in A_i} y_{u,n,i} \cdot c_{u,n,i}, \quad (5)$$

The single-server association rule results in a combinatorial problem and finding an optimal solution need exhaustive search. In the next section, we will relax the single-server constraint and allow one user to be served by multiple servers. This will enable low-complexity algorithms to find the optimal time reuse profile.

### 3. NUMBER OF ACTIVE TIME REUSE PATTERNS

In this section, we would like to maximize the PF metric of the network through optimizing the time reuse profile. To this end, we formulate the optimization problem $\text{P6}$, where the optimization variables $x, y, z$ are the overall time reuse profile: $\{x_i \forall i\}$, the overall user time allocation profile: $\{y_{u,n,i} \forall u, n, i\}$, and the DUE association profile: $\{z_{u,n,i} \forall u, n, i\}$ respectively. Problem $\text{P6}$ is a large knapsack problem, which is NP-hard to find its optimal solution.

By allowing fractional user association, we can drop the single-server association indicator variable $z$ and rely on $y$ to imply the fractional user association profile. Particularly, given $y_{u,n,i} > 0$, we can infer the $u$-th user is served by the $n$-th server under pattern $i$. The relaxed multi-server association problem is shown in $\text{P7}$, whose solution offers an upper bound of the problem in $\text{P6}$. Since the active servers in each pattern $i$ will use all the available time resources to optimize the network performance, the inequalities in $\text{P6}$ indeed become the equalities in $\text{P7}$.

maximize $\sum_{u \in \Upsilon} \log(R_u)$ \quad (7a)

subject to $\bar{R}_u = W \sum_{i \in I} \sum_{n \in N} y_{u,n,i} \cdot c_{u,n,i}, \forall u$ \quad (7b)

$\bar{R}_n = W \sum_{i \in I} \sum_{n \in N} y_{u,n,i} \cdot c_{u,n,i}, \forall n$ \quad (7c)

$R_u = \bar{R}_u - \bar{R}_{u + B}, R_u > 0, \forall u$ \quad (7d)

$x_i = \sum_{n \in N} y_{u,n,i}, \forall n, i$ \quad (7e)

$\sum_{i \in I} x_i = 1, \forall i, y_{u,n,i} \geq 0, \forall u, n, i$ \quad (7f)

The objective function in $\text{P7}$ is concave and all the constraints are linear. However, the amount of variables, i.e. $\{x_i\}$ and $\{y_{u,n,i}\}$,
increases exponentially with the number of servers due to the fact that we have $2^N - 1$ different time reuse patterns. For a large cooperative network, it becomes a formidable task to find the optimal solution to the convex problem in (7). Fortunately, we can show that only a very limited number of reuse patterns need to be activated without sacrificing the network throughput performance.

**Proposition 1.** There exists one optimal solution to the problem in (7) where at most $U$ out of $2^N - 1$ reuse patterns are active. Specifically, we can find one time reuse profile $x^*$ which maximizes the objective function in (7) and satisfies the following criterion:

$$||x^*||_0 \leq U.$$  \hfill (8)

**Proof.** Suppose we are given one particular optimal solution to the problem in (7), i.e., $x$ and $y$. Each element of $y$ can be re-written as $y_{u,n,i} = x_i \cdot \tau_{u,n,i}$. The rates $R_u$ and $R_n$ in (7b) and (7c) can be expressed as $R_u = \sum_{i \in \mathcal{I}} x_i R_{u,i}^*$ and $R_n = \sum_{i \in \mathcal{I}} x_i R_{n,i}^*$, where $R_{u,i}^* := \sum_{n \in \mathcal{N}} \sum_{u \in \mathcal{V}} \tau_{u,n,i} \cdot c_{u,n,i}^*$ and $R_{n,i}^* := \sum_{n \in \mathcal{N}} \sum_{u \in \mathcal{V}} \tau_{u,n,i} \cdot c_{u,n,i}^*$. Define $\mathbf{R} := [R_{u,1}, \ldots, R_{n,1}]^T$, $\mathbf{R} := [R_{u,1}, \ldots, R_{n,1}]^T$, $\mathbf{R} := [R_{1,1}, \ldots, R_{1,N}]^T$, $\mathbf{R} := [R_{1,1}, \ldots, R_{1,N}]^T$, and $\mathbf{R} := [R_{1,1}, \ldots, R_{1,N}]^T$, where $R$ can be written as $R = [\Phi^1, \Phi^2, \ldots, \Phi^{2^N-1}] x$. By defining a set $\mathcal{Q}$ as $\mathcal{Q} := \{\Phi^1, \Phi^2, ..., \Phi^{2^N-1}\}$, we see the vector $R$ lies in $\text{conv}(\mathcal{Q})$, i.e., the convex hull of $\mathcal{Q}$. Since the dimension of the vector $R$ is $U$, from the Carathéodory’s theorem [12], we know the vector $R$ must lie in the convex hull of $(p+1)$ affinely independent vector points in $\mathcal{Q}$ with $p \leq U$. Let $\mathcal{Q}'$ denote the set of those $(p+1)$ vector points and we know $R$ lies in $\text{conv}(\mathcal{Q}')$, which is a $p$-simplex. Furthermore, when the solution is optimal, the vector $R^*$ should reach the Pareto efficiency [13] given that the network utilization is measured by the PF metric in (7a), which is concave with respect to $R$. Hence we can find one optimal solution in the face of the p-simplex, which is also one q-simplex with $q < p \leq U$. Note that the constraints $R_u > 0$, $\forall u$ hold for the optimal solution $R^*$ naturally since the objective function is meaningless for any non-positive $R_u$, otherwise the problem is infeasible. As a result, we see $R^*$ can be represented by a convex combination of at most $U$ affinely independent points in $\text{conv}(\mathcal{Q})$. In summary, there exists one optimal time reuse profile $x^*$ satisfying $||x^*||_0 \leq U$, $R^* = [\Phi^1, ..., \Phi^{2^N-1}] x^*$. □

Proposition 1 indicates that we only need to turn on no more than $U$ reuse patterns to achieve the optimal network throughput performance instead of activating all the $2^N - 1$ feasible patterns.

**4. EFFICIENT PATTERN SELECTION AND RESOURCE ALLOCATION ALGORITHM**

As indicated by Proposition 1 the following optimization problem shares the same optimal objective value as the problem in (7).

\[
\begin{align*}
\text{maximize}_{x, y, \mathcal{V}} \quad P(x, y, \mathcal{V}) = & \sum_{u \in \mathcal{U}} \log(R_u) \quad \text{(10a)} \\
\text{subject to} \quad & x_i = 0, i \in \{i|u_i \notin \mathcal{V}\}, \quad (10b) \\
& |\mathcal{V}| \leq U, \quad (10c)
\end{align*}
\]

where $\mathcal{V} \subseteq \hat{\mathcal{V}}$ denotes the candidate set of reuse patterns containing at most $U$ patterns. The problem in (10) is still very hard to solve. We split it into two subproblems and solve them iteratively. In particular, during the $(t+1)$-th iteration, we carry out the following updates.

• **P1. Pattern Selection:** Determine the pattern set $\mathcal{V}^{t+1}$ such that $\mathcal{V}^{t+1} \subseteq \hat{\mathcal{V}}$ and $|\mathcal{V}^{t+1}| \leq U$;

**P2. Resource Allocation:** Update the resource allocation and the corresponding association rules as

\[
\begin{align*}
\text{maximize}_{x, y, \mathcal{V}} \quad & P(x, y, \mathcal{V}^{t+1}) \quad \text{subject to} (10a), \quad (11)
\end{align*}
\]

where $\mathcal{G}(\mathcal{V}) := \{x|\sum_{i \in \mathcal{I}} y_{u,i} \cdot x_i = 1, x_i \geq 0, \forall i\}$, and $\mathcal{F}(x) := \{y|\sum_{u \in \mathcal{U}} y_{u,n,i} = x_i, y_{u,n,i} \geq 0, \forall u, n, i\}$. The problem in (11) is convex and can be solved efficiently by general convex solvers, e.g., CVX [14]. However, the pattern selection subproblem has $\sum_{u=1}^{U} (2^N-1)$ possible solutions in theory and it is impractical to apply the exhaustive search method. Next, we propose an approximated solution enjoying low-complexity.

From $\mathcal{V}^t$, we can define a set $\mathcal{V}_t^d$ as

$$\mathcal{V}_t^d := \{v|v \in \hat{\mathcal{V}}, \exists u \in \mathcal{V}^{t+1}, D_H(v, v') \leq d\},$$

where $d \leq N$ and $D_H(v, v')$ denotes the Hamming distance between patterns $v$ and $v'$. Furthermore, we add a particular pattern set to the candidate pattern set $\mathcal{V}^t$ in the $(t+1)$-th iteration when $|\mathcal{V}^t| < U$, i.e., $\mathcal{V}^{t+1} = \mathcal{V}^t \cup \mathcal{V}_t^d$ and $\mathcal{V}^{t+1} \subseteq \mathcal{V}_t^d$ denote the pattern set to be included in the $(t+1)$-th iteration. Inspired by the pattern selection approach in [11] and the Frank-Wolfe method [12], we put forward an iterative pattern selection method according to the solution of the following problem:

$$\begin{align*}
\mathcal{V}_{t+1}^d := \{v|v \in \hat{\mathcal{V}}, \exists u \in \mathcal{V}^{t+1}, D_H(v, v') \leq d\},
\end{align*}$$

Bascially, in (12), we identify a set of reuse patterns to activate by finding the direction providing the most predominant improvement in the objective value under the specified constraints. Denoting the $(u,n,i)$-th entry of the gradient vector $[\nabla_y P(x^t, y^t, \mathcal{V}^t)]_{u,n,i}$ by $p_{u,n,i}^t$, we can have

$$p_{u,n,i}^t = W \cdot c_{u,n,i} \cdot (R_{u,i}^{t-1} - \{n > B\} \cdot R_{u,B}^{t-1}).$$

Now we can establish the following result.

**Proposition 2.** Among the solution to the problem in (13), the set $\mathcal{V}^*$ contains the following time reuse pattern:

$$v_{u,i}^* := \arg \max_{v_{u,i} \in \mathcal{V}_{t+1}^d} \sum_{i \in \mathcal{I}} p_{u,n,i}^t,$$

where $u_{n,i}^* := \arg \max_{u \in \mathcal{U}} p_{u,n,i}^t$.

**Proof.** Defining $\tau_{u,n,i} := y_{u,n,i}/x_i$, the problem in (13) can be re-written as

$$\max_{\mathcal{V} \subseteq \hat{\mathcal{V}}} \max_{x \in \mathcal{X}(\mathcal{V})} \sum_{i \in \mathcal{I}} x_i \sum_{u \in \mathcal{U}} \sum_{n \in \mathcal{N}} \sum_{i \in \mathcal{I}} \tau_{u,n,i} \cdot p_{u,n,i}^t.$$  \hfill (16)

The third maximization is a constrained linear programming (LP) problem and the optimal $\tau_{u,n,i}$ is given by

$$\tau_{u,n,i}^* := \{u = u_{n,i}^*\}, \quad u_{n,i}^* := \arg \max_{u \in \mathcal{U}} p_{u,n,i}^t.$$  \hfill (17)

The problem in (16) thus becomes

$$\max_{\mathcal{V} \subseteq \hat{\mathcal{V}}} \max_{x \in \mathcal{X}(\mathcal{V})} \sum_{i \in \mathcal{I}} x_i \sum_{n \in \mathcal{N}} p_{u,n,i}^t.$$  \hfill (18)

The solution in (18) is again a constrained LP and the solution is:

$$x_i^* = \{u = u_{n,i}^*\}, \quad v_{u,i}^* := \arg \max_{u \in \mathcal{U}} p_{u,n,i}^t.$$  \hfill □

The solution to (13) during the $(t+1)$-th iteration simply tells us to activate the particular time reuse pattern $v_{u,i}^*$ to maximize the improvement in the objective value. Clearly, the associated complexity in finding the candidate pattern set $\mathcal{V}^{t+1}$ is determined by the size of $\mathcal{V}_d$. We have the lowest complexity in the pattern selection subproblem by setting $d = 1$. To enable faster convergence, we select $N$ time reuse patterns in each iteration. Specifically, we modify the
where $d_{\text{path-loss}}$ is determined as 
walls [15].

System bandwidth is $[0,DUEs]$ uniformly dropped in a square specified by
work with only one pico-BS ($\sum n_{\text{BS}}$). 
problem in (6) can be solved with low complexity since
in (6), we simply associate the user to the server that gives the largest
$v_{\text{data rate}}$ under the particular time reuse pattern
$\epsilon$. Then we determine a new candidate reuse pattern
$(\hat{t}, n)$. In particular, let $\hat{x}^{t+1}$ be the optimal solution to the problem in (11) with
Can be derived as
$\hat{y}_{t+1} = \{v_{\text{in}}, v_{\text{out}}, v_{\text{in}} \in V_{t}, v_{\text{i}} \neq v_{\text{e}}\}$. (19)

ON/OFF state of the $n$-th server in each reuse pattern $v_{\text{in}} \in V_{t}$ as $v_{\text{in}} := v_{\text{in}} \oplus \epsilon_{\text{e}}$, and define the set $V_{t}$ as
$V_{t} = \{v_{\text{in}} \in V_{t}, v_{\text{i}} \neq v_{\text{e}}\}$. (20)

Now a temporary reuse pattern set for the $(t+1)$-th iteration, i.e.
$\hat{y}^{t+1} = \hat{y}_{t} \cup \{v_{\text{in}} \in V_{t}, n \in N\}$. (21)

Since the number of reuse patterns in $\hat{y}^{t+1}$ will become larger than $U$ when we add $N$ time reuse patterns in each iteration, we perform the following pattern trimming as well. In particular, let $x^{t+1}$ be the optimal solution to the problem in (11) with $V = \hat{y}^{t+1}$. By defining a positive threshold $\epsilon_{1} < 1$, we can delete those patterns in $\hat{y}^{t+1}$ with negligible allocated resources, i.e.
$\hat{y}_{t+1} = \{v_{\text{in}} | x_{t+1}^{v_{\text{in}}} > \epsilon_{1}, v_{\text{in}} \in \hat{y}_{t+1}\}$. (22)

Note that the solution obtained by solving (10) allows multiservier association. To meet the single-server association requirement in (6), we simply associate the user to the server that gives the largest
data rate under the particular reuse pattern $v_{\text{in}}$, i.e.
$z_{u,n,i} = \{n = n_{u,i}, i = \arg \max_{\forall n_{u,i}} y_{u,n,i} \cdot c_{u,n,i}\}$. (23)

After finalizing the user association rule as in (22), the original problem in (6) can be solved with low complexity since $z$ is given and the number of active patterns in $V_{t}$ is limited. Algorithm 1 summarizes all the steps.

5. NUMERICAL RESULTS

In this section, we test our algorithm by simulating a cooperative network
with only one pico-BS (30dBm transmission power (TxPwr)) since we focus on the relay behavior of the DUEs (20dBm TxPwr). See also Fig. 1 for one example. Other parameters are set as follows.

- DUEs are uniformly dropped in a square specified by $[0, 200]m \times [0, 200]m$ and the pico-BS is deployed at the center;
- System bandwidth is 20MHz. Noise PSD is $-174$dBm/Hz. The path-loss is determined as $37.6 \log_{10} \frac{d_{\text{m}}}{5n_{w}} + 35.3 + 5n_{w}$(dB) [4], where $d_{\text{m}}$ is the distance in meters, and $n_{w}$ stands for the number of walls [15].

Table 1 compares the geometric mean (GM) of the DUEs’
throughputs and the CPU running time between the brute-force op-
ternal solution (solve the problem in (7) directly with CVX) and our
proposed low-complexity solution. In Table 1, $\theta_{B}$ ($\theta_{L}$) denote the
GM throughput in Mbps with the brute-force solution (our proposed algorithm) and $t_{1}$ ($t_{2}$) is the consumed CPU time of the brute-force solution (our proposed algorithm) in seconds. Question mark “?” indicates the brute-force CVX solver can not be solved with our lab computer.

For a network with 5 DUEs, Fig. 4 shows the set of activated time reuse patterns and the fraction of total rate allocated to each pattern. The total number of active time reuse patterns is 4, which follows Proposition 1. It also indicates that the optimal time reuse patterns are not as those proposed in [5–8]. The orthogonal scheme in Fig. 4 considers the time reuse patterns where only the BS and one D2D relay are active, i.e. $V = \{e_{1} + e_{u+1} | u \in U\}$. In Fig. 4 it is also worth noting that the orthogonal scheme could provide higher effective rates to some DUEs than our scheme. In fact, this indicates that our proposed algorithm will ask those DUEs with high data rates to serve as D2D relays to help the DUEs with poor channel conditions. It is clear that our proposed algorithm achieves higher GM data rate than the other two existing schemes.

6. CONCLUSIONS

In this paper, we have studied the optimal time reuse patterns and the corresponding relaying strategies in a cooperative network with D2D relays. The original optimization problem is of a formidable
cost. This is due to the fact that the total number of feasible time reuse patterns scales exponentially with the number of nodes in the network. To circumvent this dilemma, we have shown that we just need to turn on a limited number of time reuse patterns without sacrific-
ing the network performance firstly. In particular, we have proved that the number of active reuse patterns can be no more than the number of users. Secondly, we have put forward a low-complexity algorithm to identify the small set of active time reuse patterns and solve the large scale optimization problem approximately. Compared to those existing schemes with orthogonal resource allocation constraints, our proposed scheme offers significant gains.
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