# Energy Efficient Scheduling and Time-Slot Sharing for Hyper-Dense D2D Networks Using mmWave

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**Abstract.** This paper targets on improving the efficiency of the concurrent transmissions for the hyper-dense device-to-device (D2D) networks using the millimeter wave (mmWave) transmission technology. To this end, the increment of the multiple access interference is well controlled by the proposed energy-efficient (EE) power adjustment scheme. Therein, the nonlinear fractional programming technique is firstly applied to transform the nonlinear optimization problem into the linear from. Then, the transmission power of the D2D pairs is formulated as the noncooperative Game. Via the well-known Karush-Kuhn-Tucker condition, the optimal transmission power can then be decided. With the aid of the EE power adjustment, we modify the conventional vertex multi-coloring concurrent transmission scheme to accommodate more D2D pairs. The main concept is to judge the feasibility of the concurrent transmission based the increase of sum data rate rather than the individual rate. The superiority of the proposed scheme is verified by simulations in terms of the EE and data rate.

**Keywords:** Concurrent transmission · mmwave · D2D · Energy efficiency · Game theory

## 1 Introduction

Nowadays, the device-to-device (D2D) communication has been widely recognized as a promising technology to enhance the performance of the spectrum efficiency, energy efficiency (EE), network overloading, and transmission delay. However, in the hyper-dense D2D networks, the co-layer interference could be a fatal problem which limits the data rate and wastes energy. Fortunately, the millimeter wave (mmWave) with highly directional transmission characteristic can alleviate the problem of co-layer interference. Moreover, the directionality property can facilitate the concurrent transmissions such that the overall spectrum can be utilized in a more efficient way.

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In the literature, several concurrent transmissions schemes have been proposed for the mmWave-based communication systems. In [1], a joint beamwidth selection and scheduling algorithm was proposed to accommodate more users; and consequently the overall network throughput can be boosted. In [2], the concurrent beamforming problem was decomposed into multiple single-link beamforming problems. Via an iterative searching algorithm, the suboptimal beam sets can be obtained such that the system throughput and EE can be improved. In [3], a long-hop transmission path can be divided into multiple short-hop transmissions using the properly selected relay nodes. In this fashion, not only the high rate but also several non-interfering concurrent transmissions can be achieved. In [4], the concurrent transmissions for the backhauling of the multiple small cells was formulated as a mixed integer nonlinear programming (MINLP) problem. By solving the MINLP problem, the scheduling as well as the EE power control algorithm for the concurrent transmissions can be developed.

In addition to the above literatures, the concurrent transmission technique is also an important area for the mmWave-based D2D communications. For example, in [5], the radio accesses and backhauls of the small cells were jointly scheduled to fully exploit the spatial resources. In [6], a transmission path selection method for the multi-hop D2D mmWave communications was designed so that its associated scheduling algorithm can carry out the concurrent transmission using the minimum time slots. Moreover, in [7], the directionality property and the concept of time division multiple access (TDMA) were utilized to carry out the concurrent transmissions. Firstly, the exclusive region (ER) was defined to evaluate the tolerable amount of interference. Based on the ER evaluation, the so-called conflict matrix as well as the graph of vertex coloring (VC) was constructed to describe the ability of concurrent transmission for two arbitrary D2D pairs.

Motivated by [7], we wonder whether the spectrum resources can be shared by more users (i.e. the D2D pairs) by properly adjusting the transmission power such that the additional amount of interference can be tolerable. To this end, different from [7], the sum rate rather than the individual rate is used as the criterion for the concurrent transmission. To be specific, a group of users can be scheduled to share the same time slots if the overall sum rate can be larger than that achieved by using the vertex multi-coloring concurrent transmission (VMCCT) scheme in [7]. Note that in [7], a group of users can share a time slot if each of them can reach higher transmission rate than that using the solely TDMA scheme. Additionally, an EE power control under the sum rate constraint is designed to make the multiple access interference (i.e. the multiple access interference (MAI) caused by sharing the time slot) tolerable so as to accommodate more users during a time slot. Via the simulation results, the superior performance of the proposed concurrent transmission scheme can be verified in terms of the EE and effective user data rate. Although the proposed scheme can only incur a minor improvement of the sum data rate, the EE and effective user data rate can be enhanced by 20.3% and 11.9%, respectively, in one of our considered cases.

The remainder of this paper is organized as follows. Section 2 introduces the system model, including the signal model and time-slotted operation of the

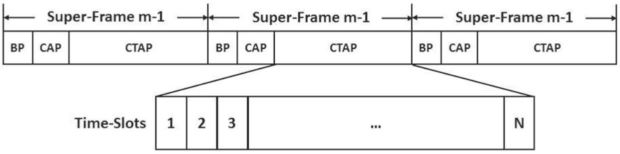

**Fig. 1.** The super-frame structure for the IEEE 802.15.3c piconet system.

WPAN network. In Sect. 3, the concurrent transmission problem is formulated, and then solved by the proposed EE scheduling and time-slot sharing strategy. Section 4 demonstrates the simulation results, while the concluding remarks as well as some suggestions for future works are given in Sect. 5.

## 2 System Model

In this paper, the mmWave-based D2D network is developed on top of the IEEE 802.15.3c piconet system [8]; therein, $K$ D2D pairs (denoted by $\mathbf{K} = \{D_i\}\ \forall i = 1, \cdots, K$) are uniformly distributed over the piconet's coverage area of $L \times L\ m^2$. Among the $K$ pairs, one is selected to be the piconet controller (PNC) which arranges all the other pairs to access the network as what follows.

First of all, the D2D network operates according to the time-slotted super-frame (SF) structure. As shown in Fig. 1, an SF can be divided into the beacon period (BP), contention access period (CAP) and channel time allocation period (CTAP). Note that, according the contention result, the PNC can allocate the time slots in the CTAP to the devices who win during the CAP. We name these devices the winning D2D pairs.

In our consider scenario, each device is equipped with an adaptive antenna array such that the beam can be directed toward the receiver. Referring to [9], the cone plus sphere model is applied to generate the radiation beam pattern as

$$G_A(\theta) = \begin{cases} \nu \frac{2\pi}{\theta} & , |\theta| \leq \theta_m \\ (1-\nu)\frac{2\pi}{2\pi-\theta} & , |\theta| > \theta_m \end{cases} , \tag{1}$$

where $\theta$ is the incident angle; $\theta_m$ is the beamwidth of the mainlobe; $\nu$ is the radiation efficiency. Let the $i$-th D2D pair is the one of interest. Assume that the mainlobes of the transmitting and receiving ends of the $i$-th D2D pair are aligned with each other. Then, the average receiving power $P_R(i)$ can be written as

$$P_R(i) = k_1 G_T(i) G_R(i) d_i^{-\alpha} P_T(i) , \tag{2}$$

where $k_1 \propto (\lambda/4\pi)^2$ is a constant coefficient dependent on the wavelength; $P_T(i)$ denotes transmitting power; $G_T(i)$ and $G_R(i)$ represent the antenna gain for the transmitting and receiving ends; $d_i$ stands for the distance between the two ends of the $i$-th D2D pair; $\alpha$ is the path loss exponent. To ease the presentation, let

$g_i = k_1 G_T(i) G_R(i) d_i^{-\alpha}$ and $p_i = P_T(i)$, respectively. Then, the corresponding end-to-end capacity $R_i$ at the $n$-th time slot can be expressed as

$$R_i(n) = \varphi_i(n) W \log_2 \left[ 1 + \frac{p_i g_i}{[N_0 W + \Sigma_{i \neq j} I_{i,j}(n)]} \right] , \tag{3}$$

where $W$ and $N_0$ denote the channel bandwidth and one-sided power spectral density of the additive white Gaussian noise, respectively; $\varphi_i(n) = 1$ if the $D_i$ is scheduled to transmit during the $n$-th time slot, otherwise $\varphi_i(n) = 0$; $I_{i,j}(n) = \phi_{i,j}(n) p_j g_j$ is the experienced interference from the $D_j$ at the $n$-th time slot; and $\phi_{i,j}(n) = 1$ means the $D_i$ suffers the MAI from the $D_j$ at the $n$-th time slot, otherwise $\phi_{i,j}(n) = 0$.

Accordingly, the average data rate of for the $i$-th D2D pair $D_i$ can be defined as

$$\overline{R}_i = \sum_{n=1}^{N} \frac{R_i(n)}{N} , \tag{4}$$

which leads to the sum data rate as

$$\overline{R} = \sum_{i=1}^{K} \overline{R}_i . \tag{5}$$

Moreover, the utility function of the EE for the $i$-th pair can be defined as the ratio of the spectrum efficiency (SE) $R_i/W$ over its power consumption $P_i$ as

$$EE = U_i(n, p_i, p_{-i}) = \frac{1}{W} \frac{R_i(n)}{P_i} = \frac{1}{W} \frac{R_i(n)}{\frac{1}{\eta} p_i + 2 p_{cir}} \text{ (bits/J/Hz)} , \tag{6}$$

where $p_{-i}$ stands for the transmission power for all the other D2D pairs; $\eta \in (0, 1)$ is the efficiency of the power amplifier; $p_{cir}$ denotes the circuit power and it is assumed to be the same for all the devices. For simplicity, the index of time slot "$n$" is omitted in the following equations.

## 3 EE Scheduling and Time-Slot Sharing

### 3.1 Problem Formulation

Assume that the contention process during the CAP has finished, and the $M \leq N$ winning D2D pairs has been allocated time slots for transmission during the CTAP by using the TDMA scheme, as illustrated in Fig. 1. Let $\mathbf{M}$ denotes the set of these $M$ winning D2D pairs. Then, in the conventional VMCCT algorithm, whether a subset of the D2D pairs (say $\mathbf{m} \subset \mathbf{M}$) can share their $|\mathbf{m}|$ time slots or not (where $|\mathbf{m}|$ measures the volume of the subset $\mathbf{m}$) can be judged according to the following rule

$$|\mathbf{m}| \, R_i \geq R_{i,o} \; \forall i \in \mathbf{m} , \tag{7}$$

where $R_{i,o}$ is the attainable transmission rate by using the TDMA scheme and it can be written as

$$R_{i,o} = W \log_2 \left(1 + \frac{p_i g_i}{N_0 W}\right) . \tag{8}$$

Moreover, the satisfaction of (7), indicates that the MAI $\Sigma_{i \neq j} I_{i,j}$ in (3) can be tolerable (or even negligible). However, we wonder that whether the MAI can further be controlled by using a certain power control mechanism so that more D2D pairs can share their time slots according to the following criterion

$$\sum_{i \in \mathbf{m}'} R_i \geq \sum_{i \in \mathbf{m}} R_i , \tag{9}$$

where $\mathbf{m} \subset \mathbf{m}'$. To this end, we propose the EE scheduling and time slot sharing scheme as follows.

### 3.2 Scheduling and Time Sharing

Now, we develop the two-step EE scheduling and time-slot sharing algorithm. For each time slot, the conventional VMCCT algorithm is firstly applied to select the set of users $\mathbf{m}$ in (7) to transmit concurrently. Then, the second step is to decide the additional users $\mathbf{m}'/\mathbf{m}$ to share the time slot with the current users belonging to $\mathbf{m}$, where $\mathbf{A}/\mathbf{B}$ removes the set $\mathbf{B}$ from the set $\mathbf{A}$.

**Step 1: VMCCT Algorithm** To easy the presentation, let's define some terminologies as follows.

1. $D_{ti}$: The transmitting end of the pair $D_i$.
2. $D_{ri}$: The receiving end of the pair $D_i$.
3. $D_{ti} \Rightarrow D_{rj}$: The radiation beams of $D_{ti}$ and $D_{rj}$ are aligned.
4. $D_{ti} \nRightarrow D_{rj}$: The radiation beams of $D_{ti}$ and $D_{rj}$ are not aligned.
5. $D_i \Leftrightarrow D_j$: $(D_{ti} \Rightarrow D_{rj})$ or $(D_{tj} \Rightarrow D_{ri})$
6. $D_i \nLeftrightarrow D_j$: $(D_{ti} \nRightarrow D_{rj})$ and $(D_{tj} \nRightarrow D_{ri})$
7. $d(D_{ti}, D_{ri})$: Distance between $D_{ti}$ and $D_{ri}$.
8. $ER_i$: The radius of the ER centered at $D_{ti}$.

Also, according to [9], the $ER_i$ can be defined as

$$ER_i = \left(\frac{k_1 G_T(i) G_R(i) P_T(i)}{N_0 W}\right)^{1/\alpha} . \tag{10}$$

Then, any two arbitrary D2D pairs (say pairs $(D_{ti}, D_{ri})$ and $(D_{tj}, D_{rj})$) are allowable to share a time slot if one of the following two conditions (i.e. $\mathcal{C}_1$ and $\mathcal{C}_2$) can be satisfied; otherwise the pairs of $\mathcal{D}_i$ and $\mathcal{D}_j$ conflict with each other.

$$\begin{cases} \mathcal{C}_1 : D_i \nLeftrightarrow D_j \\ \mathcal{C}_2 : (d(D_{ti}, D_{rj}) > ER_i) \,\&\, (d(D_{tj}, D_{ri}) > ER_j) \end{cases} . \tag{11}$$

For the purpose of systematically describing the conflicts between the D2D pairs, the conflict matrix $\mathbf{C} = [\zeta_{i,j}]$ for $i, j \in \mathbf{M}$ can be constructed according to

$$\begin{cases} \zeta_{i,j} = 1 : (D_{ti} \Rightarrow D_{rj}) \& \left(d(D_{ti}, D_{rj}) \leq ER_i\right) \\ \zeta_{i,j} = 0 : \text{otherwise;} \end{cases} , \tag{12}$$

where $\zeta_{i,j}$ is the element at the $i$-th row and $j$-th column. Take the following conflict matrix as an example:

$$\mathbf{C} = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & \textcircled{1} \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ \textcircled{1} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \end{bmatrix} . \tag{13}$$

The terms $\zeta_{1,6} = 1$ and $\zeta_{5,1} = 1$ represent the conflict conditions of $(D_{t1} \Rightarrow D_{r6}) \& \left(d(D_{t1}, D_{r6}) \leq ER_1\right)$ and $(D_{t5} \Rightarrow D_{r1}) \& \left(d(D_{t5}, D_{r1}) \leq ER_5\right)$, respectively. Then, based on the matrix $\mathbf{C}$, the pairs without conflicts can be scheduled to transmit concurrently. For example, the pairs $\mathcal{D}_2$, $\mathcal{D}_5$ and $\mathcal{D}_6$ can share a time slot. In other words, for the subset of $\mathcal{D}_2$, $\mathcal{D}_5$ and $\mathcal{D}_6$, the criterion of (7) can be satisfied.

Moreover, in order to optimize the concurrent transmission and maximize the utilization of the CTAP, the main task of the VMCCT algorithm is to organize all possible subsets (denoted by $\mathbf{M}'_n \subseteq \mathbf{M}$ for $n = 1, \cdots, M'$) of the D2D pairs such that a time slot can be shared among each subset $\mathbf{M}'_n$. Accordingly, each subset can occupy a duration of $N'T_s = \lfloor N/M' \rfloor T_s$, where $T_s$ is the time slot duration. Equivalently, the time slots during the CTAP are reshaped to have $M'$ time slots and each of which is with a duration of $N'T_s$. In addition, to prioritize each D2D pair, the distance weight can be defined as

$$\omega(i) = \frac{\sum_{i \in \mathbf{M}} d(D_{ti}, D_{ri})}{d(D_{ti}, D_{ri})} . \tag{14}$$

Note that the pair with higher weight can be scheduled with higher priority.

**Step 2: EE Power Adjustment** To facilitate the presentation, the following terminologies are defined.

1. $\mathcal{V}_n$ for $n = 1, \cdots, M'$: the set of the winning D2D pairs which are arranged to transmit during the $n$-th time slot by using the VMCCT algorithm; also $\mathcal{V}_n(i)$ denotes the $i$-th member of the set $\mathcal{V}_n$, which can also be denoted by $\mathcal{V}_n = \{\mathcal{V}_n(i)\}\ \forall i \in \mathcal{V}_n$.
2. $\mathcal{W}_n$ for $n = 1, \cdots, M'$: the set of the winning D2D pairs which are not arranged to transmit during the $n$-th time slot; also $\mathcal{W}_n(i)$ denotes the $i$-th member of the set $\mathcal{W}_n$, i.e. $\mathcal{W}_n = \{\mathcal{W}_n(i)\}\ \forall i \in \mathcal{W}_n$. Moreover, $\mathcal{W}_n(i)\ \forall i \in \mathcal{W}_n$ are sorted according to the $w(i)$ of (14).
3. $\mathcal{I}_n$ for $n = 1, \cdots, M'$: the set of the D2D pairs among which the MAI exists during the $n$-th time slot;

4. $\mathcal{V}_n \Leftrightarrow \mathcal{I}_n$: the MAI exists between any particular element of $\mathcal{V}_n$ and any particular element of $\mathcal{I}_n$, i.e. $\mathcal{V}_n(i) \Leftrightarrow \mathcal{I}_n(j)$ $\forall i \in \mathcal{V}_n$ and $\forall j \in \mathcal{I}_n$.

Now, we aim to properly select the aforementioned $\mathbf{m}'/\mathbf{m}$ users from the set $\mathcal{W}_n$ so that the sum rate (as list in (9)) can be maximized. To achieve this goal, the EE power adjustment is proposed to alleviate the extra amount of interference caused by accommodating the additional $\mathbf{m}'/\mathbf{m}$ users. Note that accommodating more users may lead to the violation of the two conditions $\mathcal{C}_1$ and $\mathcal{C}_2$ in (11).

According to the $\omega(i)$, let's consider the first candidate D2D pair (i.e. $\mathcal{W}_n(1)$) belonging to $\mathcal{W}_n$. Assume that accommodating the $\mathcal{W}_n(1)$ can cause some extra interference to a subset of the D2D pairs (say $\mathcal{V}'_n \subseteq \mathcal{V}_n$), which leads to $\mathcal{I}_n = \mathcal{W}_n(1) \cup \mathcal{V}'_n$. Then, the optimization problem (denoted by $P1$) of the EE power adjustment can be defined as

$$\begin{aligned} &\max_{p_i} \quad U_i(p_i, p_{-i}) \ , \ \forall \ i \in \mathcal{I}_n \quad \text{(P1)} \\ &s.t. \qquad 0 \le p_i \le p_{max} \\ &\qquad\qquad R'_{sum} \ge R_{sum} \ , \end{aligned} \tag{15}$$

where $R'_{sum} = \sum_{i \in \mathcal{W}_n(1) \cup \mathcal{V}_n} R_i$ and $R_{sum} = \sum_{i \in \mathcal{V}_n} R_i$. To solve this optimization problem, the nonlinear fractional programming (NFP) [10,11] is firstly applied to transform P1 into its linear version (denoted by P2) as

$$\begin{aligned} &\max_{p_i} \quad C_i(p_i, p_{-i}) - q_i^* P_i(p_i) \ , \ \forall \ i \in \mathcal{I}_n(k) \quad \text{(P2)} \\ &s.t. \qquad 0 \le p_i \le p_{max} \\ &\qquad\qquad R'_{sum} \ge R_{sum} \ , \end{aligned} \tag{16}$$

where $q_i^* = U_i(p_i^*, p_{-i}) = \max_{p_i} U_i(p_i, p_{-i})$ and $p_i^*$ is the transmission power which optimizes $U_i(p_i, p_{-i})$ [10]. Also, it leads to

$$\max_{p_i} C_i(p_i, p_{-i}) - q_i^* P_i(p_i) = C_i(p_i^*, p_{-i}) - q_i^* P_i(p_i^*) = 0 \ . \tag{17}$$

Now, the $P2$ problem can be solved by two phases: (1) determine $p_i^*$ by relaxing $R'_{sum} \ge R_{sum}$; (2) check $R'_{sum} \ge R_{sum}$ to determine whether the D2D pair $\mathcal{W}_n(1)$ can share the time slot with the D2D pairs belonging to $\mathcal{V}_n$.

***Phase 1.*** In fact, the relaxed $P2$ problem (i.e. relaxing $R'_{sum} \ge R_{sum}$) can be modeled by a noncooperative game; and accordingly using the Karush-Kuhn-Tucker condition gives the following Lagrangian function.

$$\begin{aligned} L_{EE}(p_i, p_{-i}, \mu_i) = C_i(p_i, p_{-i}) - q_i^* P_i(p_i) \\ - \mu_i(p_i - p_{max}) \ , \end{aligned} \tag{18}$$

**Algorithm 1.** EE Scheduling and Time-Slot Sharing

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Initialize: $\mathcal{V} = \mathcal{I}_n = \mathcal{P} = \mathcal{P}' = \emptyset$
Apply the VMCCT algorithm to obtain $\mathcal{V}_n$ $\forall n \in M'$
for $n \in M'$ do
    $\mathcal{W}_n = \mathbf{M}/\mathcal{V}_n$
    for $i \in \mathcal{W}_n$ do
        $\mathcal{I}_n = \mathcal{W}_n(i)$
        $\mathcal{P} = \mathcal{V}_n$
        while $\mathcal{P} \Leftrightarrow \mathcal{I}_n$ do
            $\mathcal{P}' = \{\mathcal{P}(j)\}$ with $\mathcal{P}(j) \Leftrightarrow \mathcal{I}_n(k)$ $\forall j \in \mathcal{P}$ and $\forall k \in \mathcal{I}_n$
            $\mathcal{I}_n = \mathcal{I}_n \cup \mathcal{P}'$
            $\mathcal{P} = \mathcal{P}/\mathcal{P}'$
        end while
        Apply the EE power adjustment for all the D2D pairs belonging to $\mathcal{I}_n$
        if $R'_{sum} > R_{sum}$ for $\mathcal{V}_n = \mathcal{V}_n \cup \mathcal{W}_n(i)$ then
            $\mathcal{V}_n = \mathcal{V}_n \cup \mathcal{W}_n(i)$
        end if
    end for
end for
```

where $\mu_i$ is the Lagrange multiplier. Moreover, the equivalent dual problem can be decomposed into the following min max problem as:

$$\min_{\mu_i} \max_{p_i} \; L_{EE}(p_i, p_{-i}, \mu_i) \; . \tag{19}$$

After some derivations, the optimal transmission power $p_i^*$ can be obtained as

$$p_i^* = \left[ \frac{\eta \log_2 e}{q_i^* + \eta \mu_i} - \frac{\sum_{i \neq j} I_{i,j} + N_0 W}{g_i} \right]^+ \; , \; \forall \; i \in \mathcal{I}_n \; , \tag{20}$$

where $j \in \mathcal{I}_n$ and $[x]^+ = \max\{0, x\}$. Note that (20) is indeed the well-known water-filling algorithm and the water level can be decided by the the Lagrange multiplier $\mu_i$. Also, $\mu_i$ can be updated by using the gradient method as:

$$\mu_i(\tau + 1) = [\mu_i(\tau) + \epsilon_i(\tau)(p_i^*(\tau) - p_{max})]^+ \; , \; \forall \; i \in \mathcal{I}_n \; , \tag{21}$$

where $\tau$ is the iteration index; $\epsilon_i$ is a positive step size. It should be noticed that the power adjusting iteration can be terminated when two conditions are reached: (1) $|p_i(\tau + 1) - p_i(\tau)| \leq \varepsilon$, $\forall i \in \mathcal{I}_n$; or (2) $\tau > \tau_{\max}$, where $\varepsilon$ is the convergence threshold.

***Phase 2.*** Check $R'_{sum} \geq R_{sum}$ for the candidate D2D pair $\mathcal{W}_n(1)$. If it can be satisfied, the $\mathcal{W}_n(1)$ can share the time slots with the D2D pairs belonging to $\mathcal{V}_n$, which leads to $\mathcal{V}_n = \mathcal{V}_n \cup \mathcal{W}_n(1)$.

Based on the above description, the Algorithm 1 summarizes the proposed EE scheduling and time-slot sharing scheme.

**Table 1.** Simulation parameters.

| Parameter | Value |
|---|---|
| System bandwidth ($W$) | 500 MHz |
| Number of winning D2D Users ($M$) | $20 \sim 80$ |
| Antenna beamwidth ($\theta_m$) | 30°, 60° |
| Pathloss exponent ($\alpha$) | 4 |
| Constant coefficient $k_1$ in (2) | −51 dB |
| PA efficiency $\eta$ in (6) | 35% |
| Background noise ($N_0$) | −114 dBm/MHz |
| Max transmission power ($P_{\max}$) | 23 dBm |
| Constant circuit power ($P_{cir}$) | 20 dBm |
| Radiation frequency ($\nu$) | 0.9 |
| Step size $\epsilon_i$ in (21) | $10^{-4}$ |
| Convergence threshold $\varepsilon$ for (20) | $10^{-5}$ |
| Maximum allowable iterations $\tau_{\max}$ for (21) | 100 |
| Number of time slot during CTAP ($N$) | 1000 |

## 4 Simulation Results

In this section, the proposed scheme and conventional VMCCT algorithm in [7] are compared in terms of the effective D2D data rate of (4), power consumption, EE of (6) and average time utilization for each winning D2D pairs $\mathcal{T}_w$, respectively. To be clear, $\mathcal{T}_w$ can be defined as

$$\mathcal{T}_w = \frac{1}{M}\sum_{i=1}^{M}\frac{1}{N}\sum_{n=1}^{N}\varphi_i(n) \ . \tag{22}$$

Note that $\varphi_i(n)$ is defined in (3); $M'$ and $\mathbf{M}'_n$ are defined in Sect. 3(B.1). Also, in order to focus on the performance of the concurrent transmission schemes, the impacts of the BP and CAP sessions are omitted. Thus, only the winning D2D pairs are considered to share the time slots during the CTAP. Furthermore, to verify the effectiveness in controlling the incremental interference for the proposed scheme, the impact of the antenna beamwidth is taken into account as well. Note that the VMCCT algorithm used the fixed transmission power, which is taken as the maximum power ($P_{\max}$) for the proposed scheme. The simulations are conducted according to the system descriptions in Sect. 2 and simulation parameters listed in the Table 1, are selected according to [9,10]. All the simulation results are obtained by averaging over 1,000 randomly generated topologies.

Fig. 2 shows the (a) time utilization; and (b) effective D2D data rate with respective to the number of winning D2D pairs $M$ for the antenna beamwidths of 30° and 60°. Thanks to the serious MAI caused by accommodating more D2D

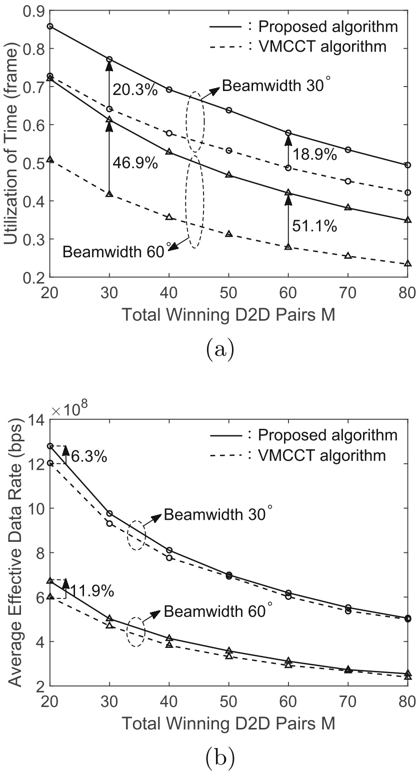
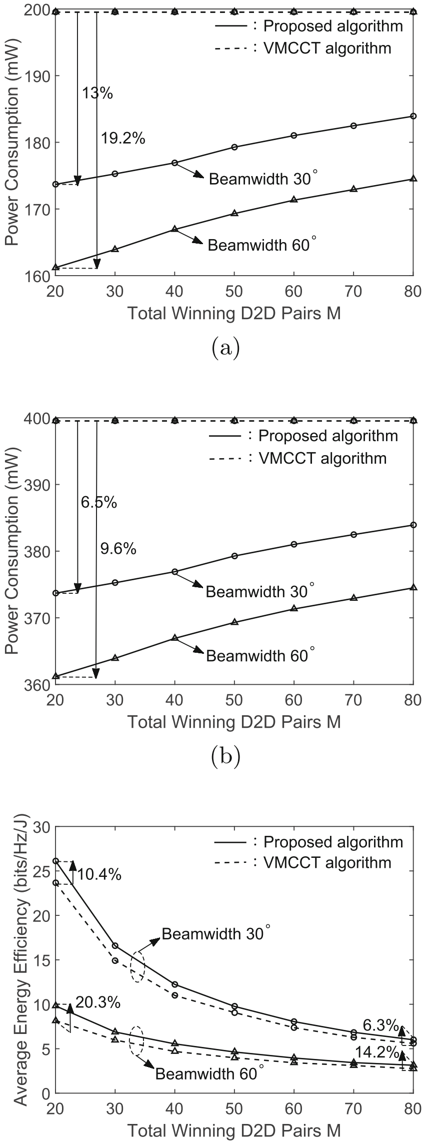


**Fig. 2.** (a) time utilization; and (b) effective D2D data rate with respective to the number of winning D2D pairs $M$ for the antenna beamwidths of 30° and 60°.

pairs, it is intuitional to expect the lower average data rate of (4) for each D2D pair. Fortunately, the loss of the data rate can be compensated by the higher time utilization. Figure 2 reflects this phenomenon. As shown in Fig. 2(a), the higher time utilization of the proposed scheme does successfully compensate the degraded data rate such that the 11.9% higher effective D2D data rate can be achieved (as illustrated in Fig. 2(b)).

Moreover, it is important to find that the proposed scheme can significantly outperform the VMCCT counterpart in the aspect of power consumption and EE. As shown in Fig. 3(a), the decrement of the transmission power can be 19.2% for the case with $\theta_m = 60°$ and 20 D2D pairs. However, taking the circuit power into consideration, this decrement reduces to 9.6%, as demonstrated in Fig. 3(b). In this case, the corresponding EE can be increased by 20.3%, as shown in Fig. 3(c). It should be noticed that the circuit power is fixed, while the transmission power can be adjusted; and the proposed scheme aims to reduce the transmission power rather than the circuit power.



(a)

(b)

(c)

**Fig. 3.** (a) Power consumption (without consideration of the circuit power); (b) power consumption (with consideration of the circuit power); and (c) average EE with respective to the number of winning D2D pairs $M$ for the antenna beamwidths of 30° and 60°.

## 5 Conclusions and Future Works

In this paper, we have proposed the EE scheduling and time-slot sharing algorithm for the hyper-dense D2D networks based on the mmWave transmission technology. In principle, the proposed algorithm consists of two steps. Firstly, the conventional VMCCT algorithm is applied to carry out the concurrent transmission on the premise of no intolerable MAI. Then, in the second step, the proposed EE power adjustment method can effectively alleviate the increment of MAI such that more D2D pairs can be accommodated without causing any loss of the transmission rate. Most importantly, the EE can be significantly improved. In one of our consider cases, the EE can be remarkably raised by 20.3%. Some suggestions for future works include: (1) the fairness issue in the concurrent transmission scheme; (2) some sophisticated MAI elimination schemes to optimize the efficiency of the concurrent transmission; (3) extension of the proposed scheme to the relay-assisted D2D networks.

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