Energy-Efficient D2D Communications Underlaying NOMA-Based Networks With Energy Harvesting

Lu Pei, Zhaohui Yang, Cunhua Pan, Wenhuan Huang, Ming Chen, Maged Elkashlan, and Arumugam Nallanathan

***Abstract*—This letter investigates the resource allocation problem in device-to-device (D2D) communications underlaying a nonorthogonal multiple access based cellular network, where both cellular users (CUs) and D2D users harvest energy from the hybrid access point in the downlink and transmit information in the uplink. We propose a low-complexity iterative algorithm to maximize the energy efficiency of the D2D pair while guaranteeing the quality of service of CUs. In each iteration, by analyzing the Karush–Kuhn–Tucker conditions, the globally optimal solution can be derived in the closed form despite the nonconvexity. Simulation results validate the superiority of the proposed scheme over the existing schemes.**

***Index Terms*—D2D, NOMA, energy harvesting, resource allocation.**

I. Introduction

DEVICE-to-device (D2D) communications, which share the same resources with cellular users (CUs) under control of the cellular network, have been considered as a promising technology to alleviate the explosive traffic growth in wireless communications [1], [2].

The system throughput in D2D underlaying networks is limited by the battery lifetime budget. To prong the lifetime of networks, energy harvesting has been applied to D2D underlaying networks [3]–[5]. In [3], joint power control and time allocation was considered in a D2D underlaying cellular network, where D2D users are powered by energy harvested from the uplink transmission of a CU. However, the harvested energy is confined by the limited transmit power, and the lifetime of the CU is limited without energy harvesting. We consider a scheme where both CUs and the D2D-transmitter (Tx) harvest energy from a hybrid access point (HAP).

In [5], all users are powered by the power station in the downlink and time division multiple access (TDMA) is adopted for multi-user transmission in the uplink. In TDMA, the transmit time of each user is seriously limited, which leads to low individual data rates. Recently, non-orthogonal multiple access (NOMA) has received extensive attention due to its advantage in improving the spectral efficiency by allowing multiple users sharing the same resource and adopting successive interference cancellation (SIC) in decoding [6], [7]. Consequently, the combination of NOMA technology and energy harvesting is a promising method to improve the performance in D2D underlaying cellular networks.

We consider joint power control and time allocation problem in a NOMA-based cellular network with energy harvesting. Our target is to maximize the energy efficiency of the D2D pair while guaranteeing the quality of service of CUs. We introduce NOMA in a D2D underlaying network with energy harvesting, and propose an energy-efficient algorithm. We obtain the globally optimal solution of D2D power and time allocation in closed form despite the nonconvexity. Simulation results show that the proposed scheme outperforms the conventional representative schemes.

II. System Model and Problem Formulation

Consider a NOMA-based cellular network with one HAP, K CUs and one pair of D2D users. The HAP plays the role of energy broadcasting in the downlink and information receiving in the uplink. The CUs are multiplexed on the same uplink resource with the underlaid D2D pair. Two-phase transmission with periodicity T is adopted. The CUs and D2D-Tx harvest energy from the HAP with broadcast power P_0 in the first phase with allocated time τ_e. During the second phase with allocated time τ_i, all CUs simultaneously transmit information to the HAP while the D2D-Tx communicates with the D2D-receiver (Rx). Obviously, $\tau_e+\tau_i \leq T$ should be satisfied.

Perfect channel state information obtained via pilot sequences is assumed to be known and constant during time T. Denote $\mathcal{K} = \{1, \cdots, K\}$ as the set of CUs. In the first phase, the harvested energy of CU k or the D2D-Tx is $E_u^h = \tau_e \eta P_0 \, h_u, \quad \forall u \in \mathcal{K} \cup \{d\}$, where h_k denotes the channel gain from the HAP to CU k, h_d is the channel gain from the HAP to the D2D-Tx, and η is the energy transformation efficiency.

For all users, energy consumption should not exceed the harvested energy. During the first phase, only the constant circuit power is consumed for user u, i.e., p_u^r. During the second phase, the transmit power and the constant circuit power of user u are denoted by p_u and p_u^c, respectively. In practice, $p_u^c \geq p_u^r$ due to the fact that the circuits of information transmission are more complex than that of energy harvesting [5]. Consequently, the energy consumption constraints are given by:

$$\tau_e p_u^r + \tau_i p_u + \tau_i p_u^c \leq E_u^h, \quad \forall u \in \mathcal{K} \cup \{d\}. \tag{1}$$

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In the NOMA-based uplink cellular network, K CUs are multiplexed on the same resource, and SIC is adopted at the HAP side. With SIC, the information of CUs is decoded in a decreasing order of the channel gain. Let g_{kB} denote the uplink channel gain from CU k to the HAP. Assume that $g_{1B} \geq g_{2B} \geq \cdots \geq g_{KB}$. The SINR of CU k is

$$\mathrm{SINR}_k = \frac{p_k g_{kB}}{\sum_{j=k+1}^{K} p_j g_{jB} + p_d g_{dB} + \sigma^2}, \quad \forall k \in \mathcal{K} \setminus \{K\}, \tag{2}$$

and when $k = K$, the SINR is given by

$$\mathrm{SINR}_K = \frac{p_K g_{KB}}{p_d g_{dB} + \sigma^2}, \tag{3}$$

where g_{dB} is the channel gain from the D2D-Tx to the HAP. Since the D2D pair reuses the resource of CUs, the achievable throughput of the D2D pair is given by

$$R_d = \tau_i W \log_2\left(1 + \frac{p_d g_{dd}}{\sum_{k=1}^{K} p_k g_{kd} + \sigma^2}\right), \tag{4}$$

where W is the system bandwidth, g_{kd} is the channel gain from CU k to the D2D-Rx, and g_{dd} is the channel gain between the users of the D2D pair. The total energy consumption E_d of the D2D pair can be given by $E_d = \tau_e p_d^r + \tau_i p_d + \tau_i p_d^c$.

Now we formulate the energy efficiency optimization problem for a NOMA-based cellular network with energy harvesting as

$$\max_{\boldsymbol{p}_c, p_d, \tau_e, \tau_i} \frac{R_d}{E_d} = \frac{\tau_i W \log_2\left(1 + \frac{p_d g_{dd}}{\sum_{k=1}^{K} p_k g_{kd} + \sigma^2}\right)}{\tau_e p_d^r + \tau_i p_d + \tau_i p_d^c} \tag{5a}$$

$$\text{s.t. } \tau_e, \tau_i \geq 0 \tag{5b}$$

$$\tau_e + \tau_i \leq T \tag{5c}$$

$$\mathrm{SINR}_k \geq \gamma_k, \quad \forall k \in \mathcal{K} \tag{5d}$$

$$0 \leq p_u \leq P_u^{\max}, \quad \forall u \in \mathcal{K} \cup \{d\} \tag{5e}$$

$$\tau_e p_u^r + \tau_i p_u + \tau_i p_u^c \leq \tau_e \eta P_0\, h_u, \ \forall u \in \mathcal{K} \cup \{d\}, \tag{5f}$$

where $\boldsymbol{p}_c = [p_1, p_2, \cdots, p_K]$, $P_u^{\max}$ is the maximal transmit power of user u, and γ_k is the minimum SINR of CU $k \in \mathcal{K}$.

III. Power Control and Time Allocation

Problem (5) is nonconvex due to the objective function (5a) and constraints (5f). To solve problem (5), the Dinkelbach method is applied to transform the fractional objective function into a subtractive function according to the following lemma.

Lemma 1: Solving problem (5) is equivalent to the problem given by $\psi(q) = 0$, where the function $\psi(q)$ is defined by

$$\psi(q) = \max_{\boldsymbol{p}_c, p_d, \tau_e, \tau_i} R_d - qE_d \tag{6a}$$

$$\text{s.t. } (5b) - (5f). \tag{6b}$$

Since Lemma 1 can be proved by using the same method in [8], the proof is omitted. Thus, our goal turns to find a q so that zero is the optimal value of problem (6). To solve nonconvex problem (6), we first provide the optimal and feasible conditions and then obtain the optimal solution.

A. Optimal and Feasible Conditions

To solve problem (5), we obtain the following lemmas about the optimal time utilization and power allocation.

Lemma 2: For problem (5), the maximum energy efficiency can always be achieved at $\tau_e + \tau_i = T$.

Proof: Suppose that $\{\boldsymbol{p}_c^*, p_d^*, \tau_e^*, \tau_i^*\}$ is the optimal solution of (5) with maximum energy efficiency EE^*, and satisfies $\tau_e^* + \tau_i^* < T$. Then, we construct a new solution $\{\boldsymbol{p}_c^*, p_d^*, \bar{\tau}_e, \bar{\tau}_i\}$, where $\bar{\tau}_e = \frac{\tau_e^* T}{\tau_e^* + \tau_i^*}$, $\bar{\tau}_i = \frac{\tau_i^* T}{\tau_e^* + \tau_i^*}$ such that $\bar{\tau}_e + \bar{\tau}_i = T$. With the new solution, constraints (5b)-(5f) are still satisfied and $\overline{EE} = EE^*$ can be verified where $\overline{EE}$ is the new energy efficiency. Therefore, the maximum energy efficiency can always be achieved at $\tau_e + \tau_i = T$. ■

In the following, we define $\tau = \tau_i$, and τ_e can be replaced by $T - \tau$ in problems (5) and (6).

Lemma 3: For any optimal solution to problem (5), constraints (5d) must hold with equality.

Proof: Assume that the optimal power of CUs is $\boldsymbol{p}_c^* = [p_1^*, \cdots, p_K^*]$, the optimal power of the D2D-Tx is p_d^* and $\mathrm{SINR}_k > \gamma_k$ is satisfied. With all the other powers of CUs and p_d^* fixed, we reduce the power p_k^* to $\bar{p}_k = p_k^* - \Delta$, $\Delta > 0$ such that $\mathrm{SINR}_k \geq \gamma_k$. With the new power $\bar{p}_k$, the objective function (5a) is increased with satisfying all constraints of (5), which contradicts that the solution is optimal. Note that there exists one unique solution satisfying (5d) with equality for all CUs since the coefficient matrix and the augmented matrix of corresponding linear equations are row full-rank. Besides, this unique solution is positive and component-wise minimum. ■

Setting constraints (5d) with equality, the optimal power of CUs can be expressed as

$$p_K^* = \frac{\gamma_K (p_d g_{dB} + \sigma^2)}{g_{KB}}, \tag{7}$$

$$p_k^* = \frac{\gamma_k (\sum_{j=k+1}^{K} p_j g_{jB} + p_d g_{dB} + \sigma^2)}{g_{kB}}, \ \forall k \in \mathcal{K} \setminus \{K\}. \tag{8}$$

To solve (8), we introduce

$$S_k = \sum_{j=k}^{K} p_j^* g_{jB}, \quad \forall k \in \mathcal{K}. \tag{9}$$

Plugging (9) into (8) yields

$$S_k = A_k S_{k+1} + B_k, \quad \forall k \in \mathcal{K} \setminus \{K\}, \tag{10}$$

where $A_k = \gamma_k + 1$, $B_k = \gamma_k (p_d g_{dB} + \sigma^2)$. We obtain $S_K = B_K$. Solving (10) with the recursion method, S_k is given by

$$S_k = \sum_{j=k}^{K} B_j \prod_{l=k}^{j-1} A_l, \quad \forall k \in \mathcal{K}, \tag{11}$$

where we define $\prod_{l=k}^{k-1} A_l = 1$. Hence, combining (9) and (11) yields

$$p_k^* = \frac{\sum_{j=k}^{K} B_j \prod_{l=k}^{j-1} A_l - \sum_{j=k+1}^{K} B_j \prod_{l=k+1}^{j-1} A_l}{g_{kB}} = C_k p_d + D_k, \tag{12}$$

where $C_k = (\gamma_k g_{dB} + \gamma_k g_{dB} \sum_{j=k+1}^{K} \gamma_j \prod_{l=k+1}^{j-1} (\gamma_l + 1))/g_{kB}$, and $D_k = (\gamma_k \sigma^2 + \gamma_k \sigma^2 \sum_{j=k+1}^{K} \gamma_j \prod_{l=k+1}^{j-1} (\gamma_l + 1))/g_{kB}$.

According to (12), constraints (5e) can be rewritten as

$$p_d \le P_d^*, \tag{13}$$

where $P_d^* = \min\{\min_{k\in\mathcal{K}}\{(P_k^{\max} - D_k)/C_k\}, P_d^{\max}\}$. Note that problem (5) is feasible only if P_d^* is non-negative, i.e., $P_k^{\max} \ge D_k, \forall k \in \mathcal{K}$.

Consequently, (6) can be simplified as

$$\begin{aligned}
\min_{\tau, p_d} \quad & -\tau W \log_2\left(\frac{Gp_d + F}{Ep_d + F}\right) \\
& \quad + q(\tau p_d + \tau(p_d^c - p_d^r) + Tp_d^r) && \text{(14a)}\\
\text{s.t. } & 0 \le \tau \le T && \text{(14b)}\\
& 0 \le p_d \le P_d^* && \text{(14c)}\\
& \tau p_d + \tau H_k \le I_k, \quad \forall k \in \mathcal{K} \cup \{0\}, && \text{(14d)}
\end{aligned}$$

where $E = \sum_{k=1}^{K} C_k g_{kd}$, $G = E + g_{dd}$, $F = \sum_{k=1}^{K} D_k g_{kd} + \sigma^2$, $H_0 = p_d^c - p_d^r + \eta P_0\ h_d$, $I_0 = \eta P_0\ Th_d - Tp_d^r$, $H_k = (D_k + p_k^c - p_k^r + \eta P_0\ h_k)/C_k$, and $I_k = (\eta P_0\ Th_k - Tp_k^r)/C_k, \forall k \in \mathcal{K}$.

Before solving problem (14), feasibility conditions are given by the following lemma.

Lemma 4: The optimization problem (14) is feasible if and only if $P_d^* \ge 0$ and $I_k \ge 0, \forall k \in \mathcal{K} \cup \{0\}$. Since Lemma 4 can be proved by the contradiction method, the proof is omitted.

B. Optimal Solution

To solve nonconvex problem (14), the optimal solution is obtained by analyzing the Karush-Kuhn-Tucker (KKT) conditions. Specifically, the Lagrangian function of (14) is

$$\begin{aligned}
&\mathcal{L}(\tau, p_d, \alpha_1, \alpha_2, \beta_1, \beta_2, \boldsymbol{\lambda}) \\
&= -\tau W \log_2\left(\frac{Gp_d + F}{Ep_d + F}\right) \\
&\quad + q(\tau p_d + \tau(p_d^c - p_d^r) + Tp_d^r) + \alpha_1(-\tau) + \alpha_2(\tau - T) \\
&\quad + \beta_1(-p_d) + \beta_2(p_d - P_d^*) + \sum_{k=0}^{K} \lambda_k(\tau p_d + \tau H_k - I_k), \quad (15)
\end{aligned}$$

where α_1, α_2, β_1, β_2, and $\boldsymbol{\lambda} = [\lambda_1, \lambda_2, \cdots, \lambda_K] \succeq \mathbf{0}$ are non-negative dual variables. All the locally optimal solutions should satisfy the KKT conditions of problem (14) as follows

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial \tau} &= -W \log_2\left(\frac{Gp_d + F}{Ep_d + F}\right) + q(p_d + p_d^c - p_d^r) \\
&\quad - \alpha_1 + \alpha_2 + \sum_{k=0}^{K} \lambda_k(p_d + H_k) = 0 && \text{(16a)}\\
\frac{\partial \mathcal{L}}{\partial p_d} &= \frac{\tau W}{\ln 2}\left(-\frac{G}{Gp_d + F} + \frac{E}{Ep_d + F}\right) + q\tau \\
&\quad - \beta_1 + \beta_2 + \sum_{k=0}^{K} \lambda_k \tau = 0 && \text{(16b)}
\end{aligned}$$

$$\alpha_1(-\tau) = \alpha_2(\tau - T) = \beta_1(-p_d) = \beta_2(p_d - P_d^*) = 0 \quad \text{(16c)}$$

$$\lambda_k(\tau p_d + \tau H_k - I_k) = 0, \quad \forall k \in \mathcal{K} \cup \{0\} \quad \text{(16d)}$$

$$(14b) - (14d), \alpha_1, \alpha_2, \beta_1, \beta_2, \lambda_k \ge 0, \quad \forall k \in \mathcal{K} \cup \{0\}. \quad \text{(16e)}$$

To obtain the globally optimal solution, we find all feasible solutions to KKT conditions (16) and pick the best one as the final result. It can be easily observed that $p_d = 0$ or $\tau = 0$ or $\tau = T$ are not optimal solutions to the problem, since the achievable throughput of the D2D pair is 0 in this case. According to constraints (14b) and (14c), the optimal solution to problem (14) falls into two cases: 1) $0 < \tau < T$, $0 < p_d < P_d^*$; 2) $0 < \tau < T$, $p_d = P_d^*$. We obtain all solutions that satisfy the KKT conditions in each individual case.

1) **Case** $0 < \tau < T$, $0 < p_d < P_d^*$

According to (14d), a feasible region of (τ, p_d) consists of $K + 1$ linear constraints. In the following, solutions (τ, p_d) that satisfy (14d) are classified into: a vertex point, a boundary point and an inner point.

a) If the solution is located in a vertex, at least two of the constraints in (14d) hold with equality. For finite K, we can traverse all couples of $K+1$ constraints to obtain the exact τ and p_d. Assume that the i-th constraint and the j-th constraint in (14d) hold with equality, the closed form of p_d and τ can be given by

$$\begin{cases}
p_d^* = \dfrac{I_j H_i - I_i H_j}{I_i - I_j} & \text{(17a)}\\[2ex]
\tau^* = \dfrac{I_i - I_j}{H_i - H_j}. & \text{(17b)}
\end{cases}$$

Considering (16e), we can check whether (17) is a feasible solution to problem (14).

b) If the solution is located in a boundary, we assume that the i-th constraint in (14d) is the only one that holds with equality. From (16c)-(16d), all dual variables, except λ_i, equal to zero. Then, (16) can be simplified as

$$\begin{cases}
\tau p_d + \tau H_i = I_i & \text{(18a)}\\
-W \log_2\left(\dfrac{Gp_d + F}{Ep_d + F}\right) + q(p_d + p_d^c - p_d^r) \\
\qquad + \lambda_i(p_d + H_i) = 0 & \text{(18b)}\\
\dfrac{\tau W}{\ln 2}\left(-\dfrac{G}{Gp_d + F} + \dfrac{E}{Ep_d + F}\right) + q\tau + \lambda_i \tau = 0. & \text{(18c)}
\end{cases}$$

Substituting (18c) into (18b) yields

$$f(p_d) - (p_d + H_i)f'(p_d) + M = 0, \tag{19}$$

where $f(p_d) = -W \log_2\left(\frac{Gp_d+F}{Ep_d+F}\right)$ and M is a constant defined by $q(p_d^c - p_d^r - H_i)$. Defining

$$g(p_d) = f(p_d) - (p_d + H_i)f'(p_d) + M, \tag{20}$$

we have $g'(p_d) = -(p_d + H_i)f''(p_d) < 0$ since $f''(p_d) > 0$. Hence, $g(p_d)$ is monotonically decreasing, which indicates that (19) has one unique solution. From (19), (20) and (18a), we can obtain

$$\begin{cases}
p_d^* = g^{-1}(0) & \text{(21a)}\\[1ex]
\tau^* = \dfrac{I_i}{H_i + g^{-1}(0)}, & \text{(21b)}
\end{cases}$$

where $g^{-1}(\cdot)$ is the inverse function of $g(\cdot)$. Whether (21) is a feasible solution should be checked.

c) If the solution is located inside the feasibility region, all dual variables are equal to zero. With $\beta_1 = \beta_2 = 0$ and $\boldsymbol{\lambda} = \mathbf{0}$, p_d can be uniquely obtained from (16b). Since (14a) is a linear function of τ with given p_d, the optimal τ always lies in the maximal or minimal point, which contradicts that the solution is located inside the feasibility region. Hence, the globally optimal solution dose not exist in this situation.

2) **Case** $0 < \tau < T$, $p_d = P_d^*$
With $p_d = P_d^*$, (14a) is a linear function of τ where the optimal solution must lie in the boundary of feasible region. In addition, (14c) can be transformed to $\tau \leq \frac{I_i}{P_d^*+H_i}$, where $i = \arg\min_{k\in\mathcal{K}\cup\{0\}}\left(\frac{I_k}{P_d^*+H_k}\right)$. Since τ is strictly positive, the optimal τ^* must satisfy $\tau^* = \frac{I_i}{P_d^*+H_i}$ if the objective function is monotonically decreasing, i.e., both $-W\log_2\left(\frac{GP_d^*+F}{EP_d^*+F}\right) + q(P_d^* + p_d^c - p_d^r) < 0$ and $0 < \frac{I_i}{P_d^*+H_i} < T$ are satisfied, the optimal solution is given by

$$\begin{cases} p_d^* = P_d^* & \text{(22a)} \\ \tau^* = \min\limits_{k\in\mathcal{K}\cup\{0\}}\left(\dfrac{I_k}{P_d^*+H_k}\right). & \text{(22b)} \end{cases}$$

Compare all locally optimal solutions from all cases, the one which minimizes the objective function of problem (14) is accepted as the globally optimal solution.

C. Algorithm and Complexity Analysis

The optimal NOMA-based power control and time allocation (NOMA-OPT) algorithm to solve problem (5) is presented in Algorithm 1. The major complexity lies in **Case** 1 in each iteration, where **Case** 1a involves a complexity of $\mathcal{O}(K^2)$ for traversing $K+1$ constraints, and **Case** 1b has a complexity of $\mathcal{O}(K\log_2(1/\epsilon))$ due to the bisection method with a tolerance of ϵ. Thus, the total complexity of the NOMA-OPT is $\mathcal{O}(LK^2 + LK\log_2(1/\epsilon))$, where L is the number of iterations.

Algorithm 1 NOMA-OPT

1: **Initialization** Set the maximum tolerance ε and $q = q_0$.
2: **repeat**
3: With fixed q, obtain the optimal (τ^*, p_d^*) of (14).
4: Set $q_{\text{pre}} = q$, $q = \left(\tau^* W\log_2\left(\frac{Gp_d^*+F}{Ep_d^*+F}\right)\right)/(\tau^* p_d^* + \tau^*(p_d^c - p_d^r) + Tp_d^r)$.
5: **until** $|q_{\text{pre}} - q| \leq \varepsilon$.
6: Output $p_d = p_d^*$, $\tau_i = \tau^*$, $\tau_e = T - \tau^*$, $p_k = C_k p_d^* + D_k, \forall k \in \mathcal{K}$.

IV. Simulation Results

There are three CUs randomly located within the network. The channel gains are modeled as $148.1 + 37.6\log_{10} D$ [9], where D is the distance measured in kilometers. The other main system parameters are given as $\eta = 0.9$, $T = 10$ s, $\sigma^2 = -174$ dBm/Hz, $W = 20$ KHz, $\varepsilon = 10^{-7}$, $P_u^{\max} = 50$ mW, $p_u^c = 10$ mW, $p_u^r = 5$ mW, $\forall u \in \mathcal{K}\cup\{d\}$, and $\gamma_k = \gamma_0, \forall k \in \mathcal{K}$.

Fig. 1 illustrates the convergence behavior of the proposed algorithm corresponding to different values of the maximum transmit power P_0 while setting $\gamma_0 = 9$. It can be seen from Fig. 1 that no more than four iterations are needed to approach the optimal solution.

We compare the NOMA-OPT with the following three schemes: TDMA-based power and time optimization in [5] where CUs occupy different time slots with the D2D pair underlaying whole information transmission time (labeled as 'TDMA-OPT'), optimal NOMA-based power control with fixed time allocation in [7] where the time is equally divided between two phases (labeled as 'NOMA-OPFT') and optimal

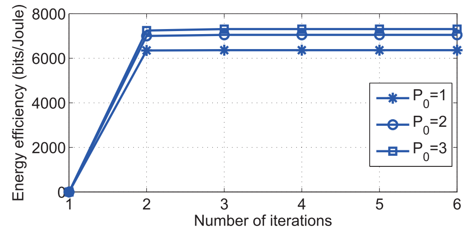

Fig. 1. Convergence behavior of Algorithm 1 with $\gamma_0 = 9$.

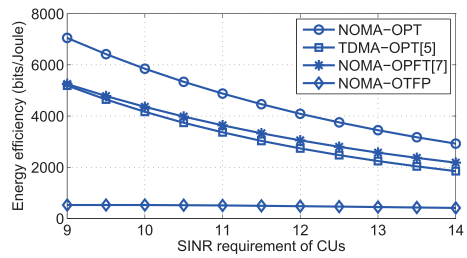

Fig. 2. Energy efficiency versus different γ_0 with $P_0 = 2$ W.

NOMA-based time allocation with maximum transmit power (labeled as 'NOMA-OTFP').

From Fig. 2, it can be observed that energy efficiency of each scheme decreases with the increased SINR requirement of CUs, since the power of the D2D-Tx is limited as SINR increases. Fig. 2 also illustrates that the proposed scheme is superior over NOMA-OPFT scheme and NOMA-OTFP scheme due to the joint optimization of time and power in our scheme. Furthermore, our scheme also outperforms TDMA-OPT scheme. The reason is that less time is utilized in energy harvesting in TDMA, which leads to low transmit power and low energy efficiency of the D2D pair.

V. Conclusion

This letter investigates power control and time allocation problem of a D2D underlaying NOMA-based cellular network with energy harvesting. The optimal energy efficiency of the D2D pair is achieved by solving the KKT conditions. Simulation results show that the proposed scheme yields larger energy efficiency than the existing representative schemes. The resource allocation of a multi-carrier network with multiple D2D pairs is left for future work.

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