

Spectrum-Power Trading for Energy-Efficient Device-Centric Overlaying Communications

Qingqing Wu[†], Feng Wang[†], Derrick Wing Kwan Ng[‡], and Wen Chen[†]

[†]Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, China

[‡]School of Electrical Engineering and Telecommunications, The University of New South Wales, Australia

Emails: {wu.qq, zhongjiezh, wenchen}@sjtu.edu.cn, w.k.ng@unsw.edu.au

Abstract—In this paper, we propose device-to-device (D2D) overlaying communications with spectrum-power trading where D2D users (DUs) consume transmit power to relay the data of cell-edge cellular users (CUs) for uplink transmission in exchange for bandwidth from CUs for D2D communications. The proposed spectrum-power trading aims at exploiting individual disparities from both the spectrum and the power perspectives. Our goal is to maximize the weighted sum EE (WSEE) of DUs via a joint D2D relay selection, bandwidth allocation, and power allocation while guaranteeing the quality of service of each CU. We show that for a given D2D relay selection, the objective function of the WSEE maximization problem in a fractional form can be transformed into a subtractive-form that is more tractable based on the fractional programming theory. To perform D2D relay selection, we first reveal an important property, which connects the WSEE with both the *system-centric* EE and the *fairness-centric* EE. Based on this insight, the D2D relay selection problem is cast into a minimum weighted bipartite matching problem that can be solved efficiently with optimality. Simulation results demonstrate the effectiveness of the proposed scheme and algorithm.

I. INTRODUCTION

Cooperative transmission has been recognized as a key technology to provide high data rate and ubiquitous communication links for cellular users (CUs) [1]. For instance, with the help of a relay node, energy consumption can be significantly reduced for cell-edge users. In contrast to fixed relaying stations that are at the high cost of large infrastructure and operating expense, mobile user relaying is expected to be a flexible and efficient solution [2]. Furthermore, it is anticipated that the number of mobile devices, including smartphones and tablets, around the world will surpass 50 billion with 1 million connections per kilometer square by 2020 [3], [4]. With such a massive amount of devices and connections, great mobile relaying opportunities can be dynamically exploited for uplink communications. However, wireless terminals acting as relays will consume certain amount of power, which is very crucial for battery-capacity limited devices. Thus, how to motivate mobile users to serve as relays becomes a critical problem.

Meanwhile, device-to-device (D2D) communication has been recently envisioned as a promising technology to unlock the potential of 5G networks. Basically, two different lines of research for D2D communications can be identified depending on the spectrum sharing strategy between DUs and CUs, i.e., underlaying and overlaying [1]. The first line of research is

This paper is supported by NSFC 61671294, by Shanghai ST Key Project 16JC1402900, by Guangxi NSFC 2015GXNSFDA139037, by National Major Project 2017ZX03001002-005, by National 863 project 2015AA01A710. Derrick Wing Kwan Ng is supported under Australian Research Council's Discovery Early Career Researcher Award funding scheme (DE170100137).

D2D underlaying communications, where D2D communications reuse the spectrum of CUs directly causing interference to CUs [5], [6]. The second line of research is D2D overlaying communications, where D2D communications occupy dedicated spectrum resources that should have been assigned to CUs [2], [7]. Nevertheless, in both underlaying and overlaying cases, the quality of service (QoS) of CUs will be degraded obviously if DUs are allowed freely to utilize the spectrum resources of CUs.

In this paper, we propose a novel spectrum-power trading strategy to address the aforementioned two issues. Specifically, DUs help to relay the messages of CUs for uplink transmission in exchange for bandwidth from CUs for D2D communications. It is known that when the circuit power consumption for signal processing is comparable with the transmit power consumption, the energy efficiency (EE) optimization in this case differs significantly with conventional spectral efficiency (SE) optimization [8]–[12]. Our goal is to maximize the *weighted sum EE* (WSEE) of DUs via joint D2D relay selection, bandwidth allocation, and power allocation while guaranteeing the minimum data rate requirements of CUs. Since the optimization problem is highly non-convex, we aim at a suboptimal algorithm with a low computational complexity. Specifically, given the D2D relay selection solution, the joint bandwidth and power allocation problem with a fractional-form objective function is transformed into an equivalent optimization problem with a subtractive-form objective function that can be efficiently solved. To perform D2D relay selection, we first characterize an intrinsic property of the WSEE that has not been found in the literature, i.e., the WSEE is bounded below by the *system-centric* EE and the *fairness-centric* EE. Based on this insight, the D2D relay selection problem can be simplified to a relay power minimization problem that can be solved efficiently.

II. SYSTEM MODEL

A. Spectrum-Power Trading Model between DUs and CUs

As depicted in Fig. 1, we consider a wireless communication network which consists of multiple D2D pairs and CUs. We assume that the CUs are far away from the BS and require DUs to serve as relays in order to reduce their power consumption. To motivate some DUs to serve as relays, the CUs allow the DUs who serve as relays to utilize some of their available bandwidth for D2D communications. Thus, for DUs, the bandwidth obtained from the CUs can be regarded as a compensation of the power consumption for relaying. The set of D2D transmitters of D2D pairs is denoted as \mathcal{K} with $|\mathcal{K}| = K$ and the set of CUs is denoted as \mathcal{N} with $|\mathcal{N}| = N$, where $|\cdot|$

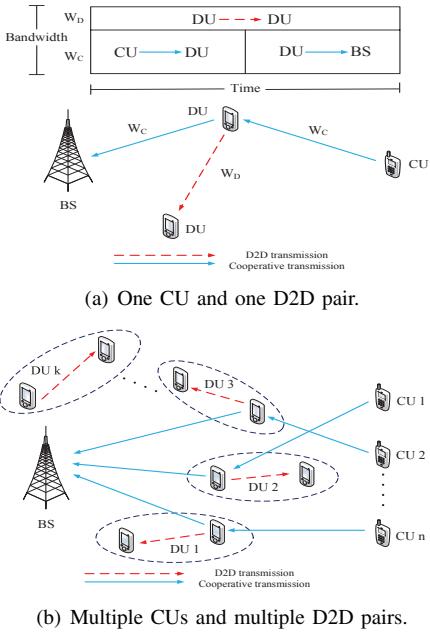


Fig. 1. The spectrum-power trading model between CUs and DUs.

indicates the cardinality of a set. Without loss of generality, we assume that CU n , $\forall n \in \mathcal{N}$, has been assigned a licensed band with a bandwidth denoted by W_{CU}^n . The licensed band of each CU is orthogonal to each other to avoid co-channel interference [6]. Since each D2D receiver only play a receiving role in the proposed model, the terms “D2D transmitter” and “DU” are used interchangeably with a slight abuse of terminology.

The channels of D2D communications and cooperative communications are assumed to experience quasi-static block fading [6]. For cooperative communications, we assume that the amplify-and-forward (AF) scheme is performed when a D2D transmitter acts as a half-duplex relay due to lower hardware complexity rather than the decode-and-forward (DF) strategy and is more suitable for mobile terminals. Each time slot is divided into two orthogonal phases with equal lengths for transmission from a CU to a DU and that from the DU to the BS. We also assume that D2D transmitter k , $\forall k \in \mathcal{K}$, experiences frequency flat fading on CU n 's band W_{CU}^n , $\forall n \in \mathcal{N}$, but may experience frequency selective fading across different CUs. In addition, CU n , $\forall n \in \mathcal{N}$, also experiences frequency flat fading on its own licensed band W_{CU}^n . Note that the results in this paper can also be extended to the more general case when the bandwidth of each CU is modeled by multiple orthogonal subcarriers. The channel state information (CSI) of all users is assumed to be perfectly known for resource allocation. We also assume that each CU is relayed by only one D2D transmitter since it has been shown that a single relay can achieve the full diversity gain [6], [13]. In addition, due to the limited battery capacity, each DU can relay at most one CU [6]. Without loss of generality, we assume the number of CUs is no larger than that of D2D transmitters, i.e., $K \geq N$. For the case of $K < N$, some CUs can be scheduled to transmit in the subsequent time slots according to different admission control policies [5].

B. DUs of Public-Interest and Power Consumption Model

In this paper, we assume each DU is willing to share its obtained bandwidth with other DUs and it is called the DUs of

public-interest. For example, when a DU is selected as a relay for a CU but it has less or no data packets to transmit, it is generous for this DU to share its obtained bandwidth from the CU with other DUs. Meanwhile, if some DU has large amount of data packets to transmit while only low power is left in the battery, then the bandwidth obtained by other DUs can be shared and utilized to help this DU to finish its transmission task. Under this strategy, the dynamics of the battery levels and transmission tasks of multiple users can also be exploited on top of the conventional channel diversity. In practice, DUs that have relayed more CUs can be prioritized by assigning higher weights when they have their own data packets to transmit.

For D2D communications, the channel power gain between D2D transmitter k and its intended D2D receiver on the bandwidth of CU n is denoted as $g_{k,n}$. The corresponding transmit power and bandwidth that are allocated for D2D transmitter k are denoted as $p_{k,n}$ and $b_{k,n}$, respectively. Hence, the achievable data rate of D2D pair k on the bandwidth of CU n can be expressed as

$$r_{k,n} = b_{k,n} \log_2 \left(1 + \frac{p_{k,n} g_{k,n}}{b_{k,n} N_0} \right), \quad (1)$$

where N_0 is the spectral density of the additive white Gaussian noise. Then, the total data rate of D2D pair k is given by

$$R_k = \sum_{n=1}^N r_{k,n} = \sum_{n=1}^N b_{k,n} \log_2 \left(1 + \frac{p_{k,n} g_{k,n}}{b_{k,n} N_0} \right). \quad (2)$$

For cooperative communications, the channel power gain between CU n and D2D transmitter k as well as D2D transmitter k and the BS are denoted as $h_{k,n}^{s,r}$ and $h_{k,n}^{r,d}$, respectively. The corresponding bandwidth used for the cooperative communication of CU n through D2D transmitter k is denoted as $w_{k,n}$. In order to study the potential saved power for CUs, we assume that each CU transmits with a fixed *transmit power density*, denoted as \hat{p}_n , which is in general a practical spectral power mask assumption. In addition, the power allocated by D2D transmitter k for relaying CU n is denoted as $q_{k,n}$. Hence, the achievable data rate of CU n under the AF strategy can be expressed as [13]

$$\begin{aligned} R_n^{\text{CU}} &= \sum_{k=1}^K x_{k,n} R_{k,n} \\ &= \sum_{k=1}^K \frac{x_{k,n} w_{k,n}}{2} \log_2 (1 + \text{SNR}(q_{k,n}, w_{k,n})), \end{aligned} \quad (3)$$

where $R_{k,n}$ is the corresponding link data rate and $\text{SNR}(q_{k,n}, w_{k,n}) = \frac{\hat{p}_n h_{k,n}^{s,r} q_{k,n} h_{k,n}^{r,d}}{N_0 (\hat{p}_n h_{k,n}^{s,r} w_{k,n} + q_{k,n} h_{k,n}^{r,d} + N_0 w_{k,n})}$. $x_{k,n}$ is the D2D relay selection indicator defined as

$$x_{k,n} = \begin{cases} 1, & \text{if DU } k \text{ is selected for relaying CU } n, \\ 0, & \text{otherwise.} \end{cases} \quad (4)$$

Remark 1: If D2D transmitter k obtains more bandwidth for itself in the spectrum-power trading, then less bandwidth, $w_{k,n}$, is left for cooperative relaying. Subsequently, the actual transmit power of CU n , i.e., $p_n = \hat{p}_n w_{k,n}$, will decrease and more

Note that bandwidth variable, $w_{k,n}$, is involved in the expression since we also consider bandwidth allocation for resource allocation.

power is thus saved for CU n . This suggests that the transmit power saved for CUs can be directly reflected by the amount of the bandwidth that DUs have obtained in the spectrum-power trading.

In order to evaluate the EE of each D2D transmitter, we also need to model its power consumption under the context of the spectrum-power trading. It has been shown in [6] that the overall power consumption of a transmitter mainly consists of two parts: the dynamic power consumed in the power amplifier (PA) for transmission and the static power consumed for circuits. Thus, for D2D transmitter k , the dynamic power consumption is modeled as a linear function of the transmit power, which includes not only the transmit power consumption for its own information but also that for relaying, i.e.,

$$P_{t,k} = \sum_{n=1}^N \frac{p_{k,n}}{\xi_k} + \sum_{n=1}^N x_{k,n} \frac{q_{k,n}}{2\xi_k}, \quad (5)$$

where $\xi_k \in (0, 1]$ is a constant that accounts for the PA efficiency of D2D transmitter k . The static power consumption for circuits of D2D transmitter k is denoted as $P_{c,k}$, which is caused by filters, frequency synthesizer, analog-to-digital converters, etc. Therefore, the overall power consumption of D2D transmitter k can be expressed as

$$P_k = P_{t,k} + P_{c,k} = \sum_{n=1}^N \frac{p_{k,n}}{\xi_k} + \sum_{n=1}^N x_{k,n} \frac{q_{k,n}}{2\xi_k} + P_{c,k}. \quad (6)$$

III. ENERGY-EFFICIENT SPECTRUM-POWER TRADING

In this paper, we aim at maximizing the WSEE of DUs, which is defined as

$$\text{EE}_{\text{sum}} = \sum_{k=1}^K \theta_k \frac{R_k}{P_k}, \quad (7)$$

where the constant weights, $\theta_k \geq 0$, $\forall k$, are provided by upper layers capturing different priorities of different DUs and $\text{EE}_k = \frac{R_k}{P_k}$. The WSEE maximization approach is quite useful for heterogeneous user EE requirements since these predefined weights provides more degrees of freedom for customizing the performance of different DUs. Specifically, the WSEE maximization problem can be formulated as

$$\begin{aligned} & \underset{\{(p_{k,n}), \{q_{k,n}\}, \{b_{k,n}\}, \{w_{k,n}\}, \{x_{k,n}\}, \{R_k\}, \{P_k\}}}{\text{maximize}} \sum_{k=1}^K \theta_k \text{EE}_k \\ \text{s.t. } & \text{C1: } \sum_{n=1}^N p_{k,n} + \sum_{n=1}^N x_{k,n} \frac{q_{k,n}}{2} \leq P_{\text{DU}}^k, \quad \forall k \in \mathcal{K}, \\ & \text{C2: } \sum_{k=1}^K b_{k,n} + \sum_{k=1}^K x_{k,n} w_{k,n} \leq W_{\text{CU}}^n, \quad \forall n \in \mathcal{N}, \\ & \text{C3: } \sum_{k=1}^K x_{k,n} R_{k,n} \geq R_{\text{CU}}^n, \quad \forall n \in \mathcal{N}, \\ & \text{C4: } \sum_{k=1}^K x_{k,n} = 1, \quad \forall n \in \mathcal{N}, \quad \text{C5: } \sum_{k=1}^N x_{k,n} \leq 1, \quad \forall k \in \mathcal{K}, \\ & \text{C6: } x_{k,n} \in \{0, 1\}, \quad \forall k \in \mathcal{K}, n \in \mathcal{N}, \\ & \text{C7: } p_{k,n} \geq 0, \quad q_{n,k} \geq 0, \quad \forall n \in \mathcal{N}, k \in \mathcal{K}, \\ & \text{C8: } b_{k,n} \geq 0, \quad w_{k,n} \geq 0, \quad \forall n \in \mathcal{N}, k \in \mathcal{K}. \end{aligned} \quad (8)$$

In problem (8), C1 constrains the maximum transmit power of the D2D transmitter to P_{DU}^k . Constraint C2 guarantees that the bandwidth allocated to DUs and CU n does not exceed CU n 's available bandwidth, W_{CU}^n . In C3, R_{CU}^n denotes the minimum required data rate of CU n . C4, C5, and C6 indicate that the message from each CU can only be relayed by one D2D transmitter and each D2D transmitter only relays the messages of at most one CU. In this case, even if some DUs do not relay any messages from CUs, they can still access the bandwidth due to the public-interest protocol adopted by the DUs. C6–C8 are the feasible and boundary constraints of the optimization variables.

Note that problem (8) is neither convex nor quasi-convex due to the sum-of-ratios objective function, the products of optimization variables in constraints C1–C3, and the binary optimization variables, $x_{k,n}$, $\forall k, n$. In general, an exhaustive search for all possible cases to obtain a globally optimal solution would require an exponential computational complexity which is prohibitive in practice. Thus, in the following, we aim to develop a low computational complexity and effective method to obtain a suboptimal solution for problem (8) via exploiting the special structure of the problem itself. Specifically, we first study joint bandwidth and transmit power allocation for a given D2D relay selection by exploiting the sum-of-ratios structure of the objective function. Then, we propose a computationally efficient scheme for D2D relay selection by exploiting the lower bound of the objective function.

A. Joint Bandwidth and Power Allocation

1) *Problem Transformation:* For a given D2D relay selection set, the following theorem states the equivalence of an optimization problem with a sum-of-ratios objective function and a parameterized problem with a subtractive-form objective function [14].

Theorem 1: If $S^* = \{p_{k,n}^*, q_{k,n}^*, b_{k,n}^*, w_{k,n}^*\}$ is the optimal solution to problem (8), then there exist $\alpha^* = (\alpha_1, \dots, \alpha_K)$ and $\beta^* = (\beta_1, \dots, \beta_K)$ such that S^* is the optimal solution to the following problem with $\alpha = \alpha^*$ and $\beta = \beta^*$:

$$\underset{S \in \mathcal{F}}{\text{maximize}} \sum_{k=1}^K \alpha_k (\theta_k R_k - \beta_k P_k), \quad (9)$$

where S is a set of the optimization variables in problem (8) and \mathcal{F} is the corresponding feasible set. Furthermore, S^* satisfies the following system of equations for $\alpha = \alpha^*$ and $\beta = \beta^*$,

$$\alpha_k P_k - 1 = 0, \quad k \in \mathcal{K}, \quad (10)$$

$$\beta_k P_k - \theta_k R_k = 0, \quad k \in \mathcal{K}. \quad (11)$$

Theorem 1 suggests that for the sum-of-ratios maximization problem (8), there exists an equivalent parameterized maximization problem with an objective function in a subtractive form, i.e., problem (9), with some additional given parameters. Therefore, in the sequel, we first solve problem (9) for given (α, β) and then develop an efficient approach to update (α, β) until (10) and (11) are both satisfied.

2) *Equivalent Optimization Problem:* By applying the above transformation to (8), we obtain the following optimization

problem for a given (α, β) in each iteration

$$\begin{aligned} & \underset{\{p_{k,n}\}, \{q_{k,n}\}, \{w_{k,n}\}, \{b_{k,n}\}}{\text{maximize}} \sum_{k=1}^K \alpha_k \left(\theta_k \sum_{n=1}^N b_{k,n} \log_2 \left(1 + \frac{p_{k,n} g_{k,n}}{b_{k,n} N_0} \right) \right. \\ & \quad \left. - \beta_k \left(\sum_{n=1}^N \frac{p_{k,n}}{\xi_k} + \sum_{n=1}^N x_{k,n} \frac{q_{k,n}}{2\xi_k} + P_{c,k} \right) \right) \\ & \text{s.t. C1, C2, C3, C7, C8.} \end{aligned} \quad (12)$$

As can be observed, the transformed problem (12) is more tractable than the original problem in (8). To characterize the property of problem (12), we provide the following lemma. Due to space limitation, all the proofs have been put in the journal version of this paper.

Lemma 1: Problem (12) is a concave maximization problem.

With Lemma 1, the optimal solution of problem (12) can be obtained by exploiting the Karush-Kuhn-Tucker (KKT) conditions that leads to a computationally efficient algorithm. Denote λ_k and μ_n as the non-negative Lagrange multipliers associated with constraints C1 and C3, respectively. Note that C2, C7, and C8 will be absorbed into the optimal solution in the following.

Theorem 2: Given λ_k and μ_n , $\forall k, n$, the optimal power allocation of maximizing the Lagrangian function, \mathcal{L} , is given by

$$p_{k,n} = b_{k,n} \left[\frac{\alpha_k \theta_k \xi_k}{(\alpha_k \beta_k + \lambda_k \xi_k) \ln 2} - \frac{N_0}{g_{k,n}} \right]^+, \forall k \in \mathcal{K}, n \in \mathcal{N}, \quad (13)$$

$$q_{k,n} = \begin{cases} w_{k,n} \tilde{q}_{k,n}, & x_{k,n} = 1, \\ 0, & \text{otherwise, } \forall k \in \mathcal{K}, n \in \mathcal{N}, \end{cases} \quad (14)$$

where $[x]^+ \triangleq \max\{x, 0\}$ and $\tilde{q}_{k,n}$ is given by

$$\tilde{q}_{k,n} = \left[\frac{\sqrt{A_{k,n} - m_{k,n} d_k (a_{k,n} + 2c_{k,n})}}{2(a_{k,n} + c_{k,n}) c_{k,n} d_k} \right]^+, \quad (15)$$

where $A_{k,n} \triangleq a_{k,n} m_{k,n} d_k (a_{k,n} m_{k,n} d_k + 4(a_{k,n} + c_{k,n}) c_{k,n} \mu_n)$, $a_{k,n} \triangleq \hat{p}_n h_{k,n}^{s,r} h_{k,n}^{r,d}$, $m_{k,n} \triangleq \hat{p}_n h_{k,n}^{s,r} + N_0$, $c_{k,n} \triangleq h_{k,n}^{r,d}$, and $d_k \triangleq (\lambda_k + \frac{\alpha_k \beta_k}{\xi_k})$. Moreover, the optimal bandwidth allocation $b_{k,n}$ and $w_{k,n}$, $\forall k, n$, is given by solving the following linear programming problem,

$$\begin{aligned} & \underset{\{b_{k,n}\}, \{w_{k,n}\}}{\text{maximize}} \sum_{k=1}^K \sum_{n=1}^N b_{k,n} \left(\alpha_k w_k \log_2 \left(1 + \tilde{p}_{k,n} \frac{g_{k,n}}{N_0} \right) \right. \\ & \quad \left. - \frac{\alpha_k \beta_k}{\xi_k} \tilde{p}_{k,n} - \lambda_k \tilde{p}_{k,n} \right) \\ & \quad + \sum_{k=1}^K \sum_{n=1}^N x_{k,n} w_{k,n} \left(\frac{\mu_n}{2} \log_2 (1 + SNR(\tilde{q}_{k,n})) \right. \\ & \quad \left. - \frac{\alpha_k \beta_k}{2\xi_k} \tilde{q}_{k,n} - \lambda_k \frac{\tilde{q}_{k,n}}{2} \right) \\ & \quad + \sum_{k=1}^K \lambda_k P_{DU}^k - \sum_{k=1}^K \alpha_k \beta_k P_{c,k} - \sum_{n=1}^N \mu_n R_{CU}^n \\ & \text{s.t. C2: } \sum_{k=1}^K b_{k,n} + \sum_{k=1}^K x_{k,n} w_{k,n} \leq W_{CU}^n, \forall n \in \mathcal{N}, \\ & \quad \text{C8: } b_{k,n} \geq 0, w_{k,n} \geq 0, \forall n \in \mathcal{N}, k \in \mathcal{K}, \end{aligned} \quad (16)$$

where $\tilde{p}_{k,n} \triangleq \left[\frac{\alpha_k \theta_k \xi_k}{(\alpha_k \beta_k + \lambda_k \xi_k) \ln 2} - \frac{N_0}{g_{k,n}} \right]^+, \forall k, n$.

Algorithm 1 Energy-Efficient Resource Allocation

- 1: Initialize the maximum tolerance ϵ ;
 - 2: repeat
 - 3: Initialize α and β , and set the iteration index $\ell = 0$;
 - 4: repeat
 - 5: Obtain w_k , $p_{k,k'}$, and p_n from (13)-(16);
 - 6: Update dual variables λ_k and μ_n ;
 - 7: until λ_k and μ_n converge;
 - 8: Compute R_k and P_k from (2) and (6);
 - 9: Update α and β ;
 - 10: $\ell = \ell + 1$;
 - 11: until $\sum_{k=1}^K (|\alpha_k P_k - 1| + |\beta_k P_k - \theta_k R_k|) \leq \epsilon$.
-

Since problem (16) is a linear programming problem with respect to $b_{k,n}$ and $w_{k,n}$, $\forall k, n$, the optimal solution can always be found at the vertices of the feasible region. As such, standard linear optimization algorithms, such as the simplex method [15], can be employed to obtain the optimal solution efficiently. With the obtained bandwidth and power allocation from (13)-(16), the optimal Lagrange multipliers can be efficiently found by the subgradient based algorithms, e.g. the ellipsoid method. The details of the proposed resource allocation are summarized in Algorithm 1.

B. D2D Relay Selection

As mentioned, obtaining the optimal solution of the D2D relay selection may require an exhaustive search among all the possible cases, which is not computationally efficient and introduces prohibitively long delay in practice. Thus, we aim at designing a low computational complexity scheme. Now, we first characterize an important property of the objective function of problem (8) to shed light on the design of D2D relay selection.

Theorem 3: The WSEE, EE_{sum} , is bounded below by the *system-centric EE* and the *fairness-centric EE*, i.e.,

$$\begin{aligned} EE_{\text{sum}} &= \sum_{k=1}^K \theta_k \frac{R_k}{P_k} = \sum_{k=1}^K \frac{\theta_k R_k}{\sum_{n=1}^N \left(\frac{p_{k,n}}{\xi_k} + x_{k,n} \frac{q_{k,n}}{2\xi_k} \right) + P_{c,k}} \\ &\geq \max \left\{ \underbrace{\frac{\sum_{k=1}^K \theta_k R_k}{\sum_{k=1}^K P_k}}_{\text{System-centric EE}}, \underbrace{\frac{K^2 \sqrt{\prod_{k=1}^K \theta_k R_k}}{\sum_{k=1}^K P_k}}_{\text{Fairness-centric EE}} \right\}. \end{aligned} \quad (17)$$

Furthermore, the WSEE equals the *system-centric EE* when only one DU occupies all the bandwidth obtained from CUs and other DUs do not occupy any bandwidth and merely act as relays. In contrast, the WSEE equals the *fairness-centric EE* when all the DUs achieve the same user EE.

Remark 2: The key insight of Theorem 3 is that the WSEE is closely related to the *system-centric EE* and the *fairness-centric EE*, which paves the way for us to analyze the WSEE via studying these two alternatives. In particular, the bound is tight in both extreme unfairness and fairness cases. Furthermore, it is interesting to note that the *system-centric EE* and the *fairness-centric EE* share a symmetric mathematical structure: the numerators are related directly to the arithmetic mean and geometric mean of the weighted DU data rates, respectively,

TABLE I
SIMULATION PARAMETERS

Parameters	Descriptions
Maximum transmit power of each DU, P_{DU}^k	23 dBm
Fixed transmit power density of each CU, \hat{p}_n	5×10^{-8} W/Hz [1]
Licensed bandwidth of each CU, W_{CU}^n	2 MHz [1]
Static circuit power of each device, $P_{c,k}$	[20 – 250] mW [6]
Power spectral density of thermal noise, N_0	-174 dBm/Hz
PA efficiency of each DU, ξ_k	0.38
Path loss model for cellular links	$(128.1 + 37.6 \log_{10} d)$
Path loss model for D2D links	$(148 + 40 \log_{10} d)$
Lognormal Shadowing	8 dB
Penetration loss	20 dB
Fading distribution	Rayleigh fading

while both the denominators are the same system power consumption. To the best of our knowledge, this relationship has never been revealed and exploited in existing works on EE optimization.

As observed in (17), D2D relay selection variables, $x_{k,n}$, $\forall k, n$, are only involved in the denominator of either the *system-centric EE* or the *fairness-centric EE*. Thus, we only need to determine the D2D relay selection with the objective of minimizing the system power consumption. Specifically, if DU k is selected for relaying CU n , the minimum relaying transmit power consumption of DU k can be expressed as

$$q_{k,n}^{\min} = \frac{(\hat{p}_n h_{k,n}^{s,r} + N_0) N_0 W_{CU}^n \left(2^{\frac{2R_{CU}^n}{W_{CU}^n}} - 1 \right)}{\hat{p}_n h_{k,n}^{s,r} h_{k,n}^{r,d} - N_0 h_{k,n}^{r,d} \left(2^{\frac{2R_{CU}^n}{W_{CU}^n}} - 1 \right)}. \quad (18)$$

Motivated by Theorem 3, a suboptimal solution of the D2D relay selection can be obtained by solving the following problem

$$\begin{aligned} & \underset{\{x_{k,n}\}}{\text{minimize}} \quad \sum_{k=1}^K \sum_{n=1}^N x_{k,n} \frac{q_{k,n}^{\min}}{\xi_k} \\ & \text{s.t.} \quad \text{C4, C5, C6.} \end{aligned} \quad (19)$$

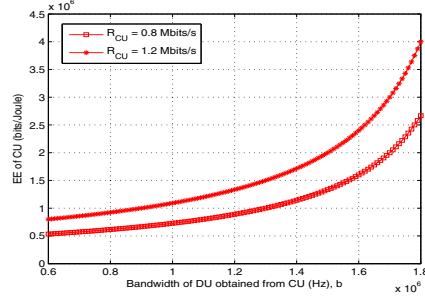
It is worth noting that problem (19) is a minimum weighted bipartite matching problem and thus can be efficiently solved by the Hungarian method [16] with global optimality.

First, the complexity of the Hungarian method solving D2D relay selection problem (19) is $\mathcal{O}(K^3)$. Second, the complexity for obtaining bandwidth and power allocation linearly increases with KN . Third, since there are $2K$ Lagrange multipliers, the complexity of the ellipsoid method is $\mathcal{O}(K^2)$ [15]. Finally, the complexity for updating α and β is independent of K . Therefore, the proposed algorithm enjoys a polynomial time computational complexity.

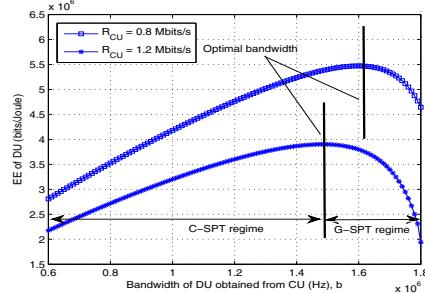
IV. NUMERICAL RESULTS

Unless specified otherwise, the parameters are set as those listed in Table I. Without loss of generality, we assume that all CUs have identical parameters, i.e., W_{CU}^n and R_{CU}^n . In addition, all DUs have the same maximum transmit power, $P_{\max} = P_{DU}^k$, and PA efficiency, ξ_k . The EE of the CU can be calculated as follows, $\widehat{\text{EE}}_n = \frac{R_{CU}^n}{\sum_{k=1}^K x_{k,n} (W_{CU}^n - b_{k,n}) \hat{p}_n + P_{c,n}} = \frac{R_{CU}^n}{\sum_{k=1}^K x_{k,n} w_{k,n} \hat{p}_n + P_{c,n}}$, $\forall n$, where $P_{c,n}$ denotes the circuit power of the CU and is assumed the same as that of the DU unless specified otherwise.

In Fig. 2, we provide an example to illustrate the effectiveness of the proposed spectrum-power trading. A network of a D2D



(a) EE of the CU versus the bandwidth obtained from the CU.

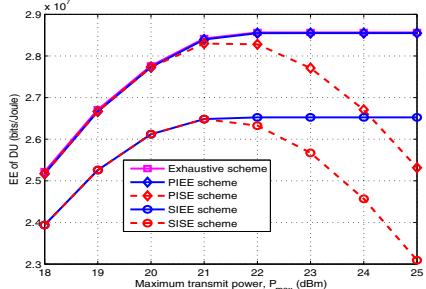


(b) EE of the DU versus the bandwidth obtained from the CU.

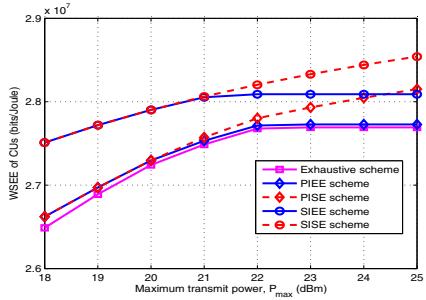
Fig. 2. Effect of the bandwidth obtained from a CU on EEs of both the DU and the CU.

pair and a CU is considered where the D2D channel distance is set as 30 m and the distances of CU-DU and DU-BS are set as 200 m and 300 m, respectively. Specifically, we plot the EEs of the CU and DU in Fig. 2 (a) and (b), respectively, with the x-axis denoting the bandwidth used for D2D communications, which is obtained from the CU in the spectrum-power trading. In this single D2D pair and single CU case, the user indexes and the relay selection variables are dropped for convenience and the EE of the CU is calculated as $\widehat{\text{EE}} = \frac{R_{CU}}{(W_{CU} - b)\hat{p} + P_c} = \frac{R_{CU}}{w\hat{p} + P_c}$.

As can be observed from Fig. 2 (a), the EE of the CU increases monotonically with the increase of traded bandwidth. This is because if a larger bandwidth is obtained by the DU, then less bandwidth is left for cooperative transmission with the CU, which results in lower transmit power for the CU and its EE is thereby improved, given its fixed transmit power density. In contrast, from Fig. 2 (b), we observe that the EE of DU first increases and then decreases with the obtained bandwidth from CU. This can be explained as follows. With small amount of obtained bandwidth, e.g. $b \in [0.6, 1.4]$ MHz, the data rate of DU almost increases linearly with an increasing of obtained bandwidth since the SNR of the D2D link is relatively high. In addition, as much more bandwidth is reserved for cooperative communication, only lesser transmit power is required at the DU for relaying data from the CU. Therefore, the increase of the DU's data rate dominates the EE of the DU in this regime and thus its EE increases gradually when the obtained bandwidth is less than the optimal required bandwidth, which can be regarded as a *conservative spectrum-power trading regime* (C-SPT regime). However, as the obtained bandwidth becomes larger than the optimal bandwidth for D2D communication, e.g. $b > 1.48$ MHz for $R_{CU}^n = 1.2$ Mbit/s, more and more transmit power has to be consumed at the DU for cooperative communication in order to fulfill the minimum



(a) EE of the DU versus the maximum transmit power of the DU.



(b) EE of the CU versus the maximum transmit power of the DU.

Fig. 3. EEs of DU and CU versus the maximum transmit power of the DU.

data rate requirement of the CU. In addition, the increased data rate of the DU also becomes saturated with an increasing obtained bandwidth. Therefore, the exponential increase of transmit power consumption dominates the EE of the DU in this regime and its EE decreases more rapidly when the obtained bandwidth is larger than the optimal bandwidth, which can be regarded as a *greedy spectrum-power trading regime* (G-SPT regime).

In Fig. 3, we consider a cellular network with a radius of 500 m. Five CUs are uniformly distributed within the distances of [400 500] m away from the BS. For the purpose of relaying, five D2D transmitters are uniformly distributed within the distances of [100 300] m away from the BS and the distances of D2D links are uniformly distributed among [40 150] m. Without loss of generality, the weights of all DUs and CUs are set as unity. In particular, we compare the achieved system EE of the following schemes: 1) Exhaustive search; 2) PIEE scheme: the proposed algorithm in Section III; 3) PISE scheme: the conventional SE maximization [2]; 4) SIEE scheme: WSEE maximization with no bandwidth sharing; 5) SISE scheme: the conventional SE maximization with no bandwidth sharing. From Fig. 3, it is observed that the PIEE scheme provides a close-to-optimal performance as the exhaustive search based scheme, which validates the effectiveness of exploiting the relationship between the WSEE and the *system-centric EE* and the *fairness-centric EE*. In addition, we observe in Fig. 3 (a) that the WSEE achieved by the PIEE scheme or the SIEE scheme first increases and then approaches a constant value, while that achieved by both the PISE scheme or the SISE scheme first increases and then decreases, with increasing maximum transmit power. This in essence attributes to the fundamental tradeoff between the SE and EE where SE maximization always greedily purses high data rates by exhausting all the available transmit power, while WSEE maximization strikes a good balance between pursuing high data rates and reducing the power consumption.

Correspondingly, in Fig. 3 (b), the EE of CUs achieved by the PISE scheme and SISE scheme monotonically increases while EE achieved by the PIEE scheme and SIEE scheme first increases and then remains constant, with increasing maximum transmit power of DUs. This is due to the fact that SE maximization enforces DUs to utilize more bandwidth of CUs than EE maximization, which thereby leads to more energy savings for CUs.

V. CONCLUSIONS

In this paper, D2D relay selection and bandwidth and power allocation have been jointly optimized to enhance the WSEE of DUs under the proposed spectrum-power trading strategy. We have also unveiled that the WSEE has an intrinsic relationship with the system-centric EE and fairness-centric EE, which sheds lights on new ways to address the WSEE maximization problem by using these two alternatives. Simulation results have shown that the proposed suboptimal algorithm obtains close-to-optimal performance and also demonstrated the performance gains achieved by the proposed spectrum-power trading scheme for both DUs and CUs.

REFERENCES

- [1] Y. Cao, T. Jiang, and C. Wang, "Cooperative device-to-device communications in cellular networks," *IEEE Wireless Commun. Mag.*, vol. 22, no. 3, pp. 124–129, Jun. 2015.
- [2] Y. Pei and Y.-C. Liang, "Resource allocation for device-to-device communications overlaying two-way cellular networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3611–3621, Jul. 2013.
- [3] S. Zhang, Q. Wu, S. Xu, and G. Li, "Fundamental green tradeoffs: Progresses, challenges, and impacts on 5G networks," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 33–56, First Quarter 2017.
- [4] Q. Wu, G. Y. Li, W. Chen, D. W. K. Ng, and R. Schober, "An overview of sustainable green 5G networks," *IEEE Wireless Commun. Mag.*, 2017, [Online] Available: <https://arxiv.org/abs/1609.09773>.
- [5] D. Feng, L. Lu, Y. Yuan-Wu, G. Y. Li, G. Feng, and S. Li, "Device-to-device communications underlying cellular networks," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3541–3551, Aug. 2013.
- [6] T. D. Hoang, L. B. Le, and T. Le-Ngoc, "Dual decomposition method for energy-efficient resource allocation in D2D communications underlying cellular networks," in *Proc. IEEE GLOBECOM*, 2015, pp. 1–6.
- [7] X. Lin, J. G. Andrews, and A. Ghosh, "Spectrum sharing for device-to-device communication in cellular networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 12, pp. 6727–6740, Dec. 2014.
- [8] Q. Wu, M. Tao, D. W. K. Ng, W. Chen, and R. Schober, "Energy-efficient resource allocation for wireless powered communication networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 3, pp. 2312–2327, Mar. 2016.
- [9] Q. Wu, W. Chen, M. Tao, J. Li, H. Tang, and J. Wu, "Resource allocation for joint transmitter and receiver energy efficiency maximization in downlink OFDMA systems," *IEEE Trans. Commun.*, vol. 63, no. 2, pp. 416–430, Feb. 2015.
- [10] Q. Wu, M. Tao, and W. Chen, "Joint Tx/Rx energy-efficient scheduling in multi-radio wireless networks: A divide-and-conquer approach," *IEEE Trans. Wireless Commun.*, vol. 15, no. 4, pp. 2727 – 2740, Apr. 2016.
- [11] D. W. K. Ng, E. S. Lo, and R. Schober, "Wireless information and power transfer: Energy efficiency optimization in OFDMA systems," *IEEE Trans. Wireless Commun.*, vol. 12, no. 12, pp. 6352–6370, Dec. 2013.
- [12] Q. Wu, G. Y. Li, W. Chen, and D. W. K. Ng, "Energy-efficient small cell with spectrum-power trading," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 12, pp. 3394–3408, Dec. 2016.
- [13] Y. Zhao, R. Adve, and T. J. Lim, "Improving amplify-and-forward relay networks: optimal power allocation versus selection," *IEEE Trans. Wireless Commun.*, vol. 6, no. 8, pp. 3114–3123, Aug. 2007.
- [14] R. Ramamonjison and V. K. Bhargava, "Energy efficiency maximization framework in cognitive downlink two-tier networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 3, pp. 1468–1479, Mar. 2015.
- [15] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.
- [16] H. W. Kuhn, "The hungarian method for the assignment problem," *Naval research logistics quarterly*, vol. 2, no. 1-2, pp. 83–97, 1955.