# Power Control for Achieving Energy-Efficient Multiuser Two-Way Balancing Relay Networks

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***Abstract*—Energy efficiency is a growing concern for the future wireless networks as energy consumption becomes a global environment problem. In this paper, an energy-efficient power control scheme is investigated for achieving the maximum energy efficiency in multiuser two-way balancing relay networks. We formulate the design problem as a ratio of the spectral efficiency over the entire energy consumption of the network under a total power constraint. An optimal power control scheme is proposed to iteratively improve the efficiency and finally reach the globally optimal solution. Compared with a heuristic scheme where the total available power is equally distributed among all nodes, the proposed scheme can dramatically improve not only the energy efficiency but also the spectral efficiency.**

## I. Introduction

Relay networks have received a lot of interest to improve the network performance by expanding the coverage and increasing the capacity. The relay networks operated in a half-duplex mode suffer from a loss of spectral efficiency by a factor of $1/2$. Unlike one-way relaying schemes, two-way relaying can help compensate the spectral efficiency loss by utilizing the radio resource in a more efficient manner. The energy consumption in wireless networks is swiftly increasing with the rapid growth of wireless applications [1],[2]. Thus, the design of energy-efficient relay networks becomes an challenging issue toward green communications [3],[4]. In addition to energy saving, energy-efficient communications can provide the benefit of reducing interference to other users as well as lessening the environmental impact.

The power consumption of wireless networks can be classified into two folds: dynamic and static. In general, the circuit power is static and independent of channel conditions, while the transmit power level is adapted to the instantaneous channel conditions. In this paper, we investigate a power control problem for multiuser two-way relay networks and intend to maximize the energy efficiency by considering both the static and dynamic power consumption.

Recently, the energy efficiency has become a paramount factor for designing multiuser two-way relay networks. Moreover, the available spectrum resource needs to be efficiently utilized for achieving an acceptable data rate. Consequently, there is a performance trade-off between the spectral efficiency and the energy efficiency. Energy-efficient wireless networks have addressed in several works [5]–[12]. In [5], interference management and resource allocation were investigated in designing an energy-efficient access network, while a network architecture in terms of antenna placement and macro-cell/micro-cell selection was optimized for minimizing the energy consumption [6]. The authors in [7] proposed opportunistic schemes to decide which subset of the relay nodes cooperates together in order to minimize the energy consumption. It was claimed in [10] that two-way relaying is not always energy-efficient when taking the self-interference and the receiver processing energy consumption into account. However, most of the previous works on energy efficiency were merely considered in single-user scenarios and focused on minimizing the energy consumption in the network. The optimal power control for maximizing the energy efficiency of multiuser two-way relay interference networks has not been addressed prior to our work.

In contrast to the aforementioned works, we emphasis on power control schemes for multiuser two-way relay networks in order to improve energy efficiency under a total power constraint, while balancing the rates of the forward and backward links. The multiuser two-way relay network consists of $N$ source-destination pairs and one relay node, each of which is equipped with a single antenna. The relay helps both the source and destination nodes in forwarding the signals to their corresponding pair nodes through an amplify-and-forward (AF) strategy [13]. The *bits-per-Joule-per-Hertz* is adopted as the performance metric for the network energy efficiency. With the considered design problem, an energy-efficient power control algorithm is proposed to iteratively enhance the energy efficiency and finally attain the globally optimal solution.

The remainder of this paper is organized as follows. The system model and problem formulation are introduced in Section II. The optimal power control for achieving the maximum energy efficiency is designed in Section III. Numerical results are presented in Section IV. Finally, conclusions are drawn in Section V.

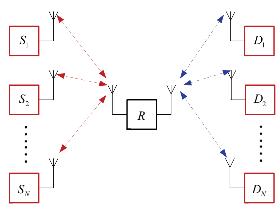


Fig. 1. A multiuser two-way relay network.

## II. System Model

### A. Transmission Model

Consider a half-duplex two-way multiuser relay network in Fig. 1, where $N$ source-destination ($S_i \longleftrightarrow D_i$, for $i = 1, \ldots, N$) pair nodes, each of which is equipped with a single antenna, exchange their information with the assistance of a single-antenna relay. The exchange of information symbols between the pair of nodes takes two time slots. In the first time slot, both $N$ source and $N$ destination nodes concurrently send their information to the relay, while the relay broadcasts the amplified signals in the second time slot.

Define $h_i$ as the channel gain between the $i^{th}$ source node to the relay node, and $g_j$ as the channel gain between the relay node to the $j^{th}$ destination node. Let $P_i$, $Q_j$ and $W_r$ denote the transmit power at the $i^{th}$ source node, the $j^{th}$ destination node and the relay node, respectively. Hence, the received signal $r$ at the relay in the first time slot can be written as

$$r = \sum_{i=1}^{N} \sqrt{P_i} h_i x_{s_i} + \sum_{j=1}^{N} \sqrt{Q_j} g_j x_{d_j} + z \,, \tag{1}$$

where $x_{s_i}$ and $x_{d_j}$ are the data symbols transmitted by the $i^{th}$ source and the $j^{th}$ destination nodes, respectively, $z$ represents the complex Gaussian noise at the relay node with zero mean and covariance $\sigma_z^2$. It is assumed that the power of the data symbol is normalized to one, i.e., $E\left[|x_{s_i}|^2\right] = E\left[|x_{d_i}|^2\right] = 1$ for all $i$. By multiplying the received signal $r$ with a normalized amplifying gain

$$\alpha = \sqrt{W_r / \left( \sum_{i=1}^{N} P_i |h_i|^2 + \sum_{j=1}^{N} Q_j |g_j|^2 + \sigma_z^2 \right)} \,, \tag{2}$$

the received signals at the $i^{th}$ source and the $j^{th}$ destination nodes in the second time slot are respectively given by

$$y_{s_i} = h_i \alpha r + v_{s_i} \,; \tag{3}$$

$$y_{d_j} = g_j \alpha r + v_{d_j} \,, \tag{4}$$

where $v_{s_i}$ and $v_{d_j}$ are the complex Gaussian noise at $i^{th}$ source and $j^{th}$ destination with zero mean and variance $\sigma_{v_{s_i}}^2$ and $\sigma_{v_{d_j}}^2$, respectively. By removing the self-interference from the received signals (3) and (4), the $i^{th}$ source and $j^{th}$ destination nodes can extract their intended signals, which are expressed in (5) and (6) at the top of the next page. Using (2), (5) and (6), the average signal-to-interference-plus-noise ratio for the $i^{th}$ source and the $j^{th}$ destination nodes can be written as

$$\Upsilon_{s_i}(\mathbf{P}, \mathbf{Q}, W_r) = \frac{W_r Q_i |h_i g_i|^2}{W_r I_{s_i} + \sigma_{v_i}^2 I_\alpha} \,; \tag{7}$$

$$\Upsilon_{d_j}(\mathbf{P}, \mathbf{Q}, W_r) = \frac{W_r P_j |g_j h_j|^2}{W_r I_{d_j} + \sigma_{v_j}^2 I_\alpha} \,, \tag{8}$$

where $\mathbf{P} = [P_1, \ldots, P_N]^T$, $\mathbf{Q} = [Q_1, \ldots, Q_N]^T$, $I_{s_i} = \sum_{j=1, j\neq i}^{N} Q_j |h_i g_j|^2 + \sum_{l=1, l\neq i}^{N} P_l |h_i h_l|^2 + |h_i|^2 \sigma_z^2$, $I_{d_j} = \sum_{i=1, i\neq j}^{N} P_i |g_j h_i|^2 + \sum_{k=1, k\neq j}^{N} Q_l |g_j g_l|^2 + |g_j|^2 \sigma_z^2$, and $I_\alpha = \left( \sum_{i=1}^{N} P_i |h_i|^2 + \sum_{j=1}^{N} Q_j |g_j|^2 + \sigma_z^2 \right)$. From the capacity formula, the achievable rates for the $i^{th}$ source and $j^{th}$ destination nodes are given as

$$R_{s_i}(\mathbf{P}, \mathbf{Q}, W_r) = \frac{1}{2} log_2 \left( 1 + \Upsilon_{s_i} \right) \,; \tag{9}$$

$$R_{d_j}(\mathbf{P}, \mathbf{Q}, W_r) = \frac{1}{2} log_2 \left( 1 + \Upsilon_{d_j} \right) \,, \tag{10}$$

where the rate is scaled by a factor of $1/2$ since two time slots are required for each data transmission.

### B. Energy Consumption Model

In addition to the transmit power consumption, the circuit power consumption needs to be taken into consideration [4]. In particular, the transmit power is exclusively adopted for data transmission in order to attain reliable communications, while the circuit power represents the total power consumption of the involved electronic devices. Furthermore, the transmit power is planned dynamically according to the instantaneous channel gains, but the circuit power usually remains static and is relatively independent of the channel conditions. Thus, the total required power in Watts for the relay network is given as

$$P_{Total} = \sum_{i=1}^{N} P_i + \sum_{j=1}^{N} Q_j + W_r + P_c \,, \tag{11}$$

where $P_c$ is the total circuit power dissipations of the nodes in the network.

### C. Problem Formulation

We define the energy efficiency for the multiuser two-way relay network as the sum rate per unit power [2]. By considering the rate balancing between the forward and the backward directions, the energy efficiency is defined as

$$\eta_{EE} = \frac{R(\mathbf{P}, \mathbf{Q}, W_r)}{P_{Total}} = \frac{\sum_{m=1}^{N} min\left( R_{s_m}, R_{d_m} \right)}{P_{Total}} \,. \tag{12}$$

Given the total power budget of the network $P_{max}$, the optimization problem for designing energy-efficient power control can be formulated as

$$\begin{aligned} \max_{\mathbf{P}, \mathbf{Q}, W_r} \quad & \frac{\sum_{m=1}^{N} min\left( R_{s_m}, R_{d_m} \right)}{\sum_{i=1}^{N} P_i + \sum_{j=1}^{N} Q_j + W_r + P_c} \\ s \cdot t \cdot \quad & \sum_{i=1}^{N} P_i + \sum_{j=1}^{N} Q_j + W_r + P_c \leqslant P_{max} \,. \end{aligned} \tag{13}$$

Through the epigraph form in [14], the optimization problem in (13) can be equivalently transformed as:

$$\begin{aligned} \max_{\mathbf{P}, \mathbf{Q}, W_r, \mathbf{t}} \quad & \frac{\sum_{i=1}^{N} t_m}{\sum_{i=1}^{N} P_i + \sum_{j=1}^{N} Q_j + W_r + P_c} \,, \\ s \cdot t \cdot \quad (C.1) \quad & \sum_{i=1}^{N} P_i + \sum_{j=1}^{N} Q_j + W_r + P_c \leqslant P_{max} \,; \\ (C.2) \quad & \frac{1}{2} log_2 \left( 1 + \Upsilon_{s_m} \right) \geq t_m \,; \\ (C.3) \quad & \frac{1}{2} log_2 \left( 1 + \Upsilon_{d_m} \right) \geq t_m \,, \end{aligned} \tag{14}$$

$$y_{s_i} = \underbrace{\sqrt{Q_i}\alpha h_i g_i x_{d_i}}_{\text{desired signal}} + \underbrace{\alpha \sum\nolimits_{j=1, j\neq i}^{N} \sqrt{Q_j} h_i g_j x_{d_j} + \alpha \sum\nolimits_{l=1, l\neq i}^{N} \sqrt{P_l} h_i h_l x_{s_l}}_{\text{interference}} + \underbrace{\alpha h_i z + v_{s_i}}_{\text{noise}} . \quad (5)$$

$$y_{d_j} = \underbrace{\sqrt{P_j}\alpha g_j h_j x_{s_j}}_{\text{desired signal}} + \underbrace{\alpha \sum\nolimits_{i=1, i\neq j}^{N} \sqrt{P_i} g_j h_i x_{s_i} + \alpha \sum\nolimits_{k=1, k\neq j}^{N} \sqrt{Q_k} g_j g_k x_{d_k}}_{\text{interference}} + \underbrace{\alpha g_j z + v_{d_j}}_{\text{noise}} . \quad (6)$$

where $\mathbf{t} = [t_1, \ldots, t_N]^T$.

## III. Optimal Power Control Algorithm

It can be observed from (14) that the optimization problem is not convex due to the non-convex constraints of (C.2) and (C.3). We make use of the following lower bound to replace the achievable rates $R_{s_i}$ and $R_{d_j}$, as follows [16]:

$$R_{s_i} = \frac{1}{2} log_2(1 + \Upsilon_{s_i}) \geq \frac{\rho_{s_i}}{2} log_2(\Upsilon_{s_i}) + \frac{\beta_{s_i}}{2} ; \quad (15)$$

$$R_{d_j} = \frac{1}{2} log_2(1 + \Upsilon_{d_j}) \geq \frac{\rho_{d_j}}{2} log_2(\Upsilon_{d_j}) + \frac{\beta_{d_j}}{2} , \quad (16)$$

where the coefficients $\rho_{s_i}$, $\beta_{s_i}$ $\rho_{d_j}$ and $\beta_{d_j}$ can be chosen as

$$\rho_{s_i} = \Upsilon_{s_i}/(1 + \Upsilon_{s_i}) ; \quad (17)$$

$$\beta_{s_i} = log_2(1 + \Upsilon_{s_i}) - \rho_{s_i} log_2(\Upsilon_{s_i}) ; \quad (18)$$

$$\rho_{d_j} = \Upsilon_{d_j}/(1 + \Upsilon_{d_j}) ; \quad (19)$$

$$\beta_{d_j} = log_2(1 + \Upsilon_{d_j}) - \rho_{d_j} log_2(\Upsilon_{d_j}) , \quad (20)$$

for any given $\Upsilon_{s_i}$ and $\Upsilon_{d_j}$. The bound (15) becomes tight with the equality at the point $\Upsilon_{s_i}$ when the constant $(\rho_{s_i}, \beta_{s_i})$ are selected as mentioned above, and the equality holds for $(\rho_{s_i}, \beta_{s_i}) = (1, 0)$ if $\Upsilon_{s_i}$ approaches infinity. Moreover, the tightness of the bound (16) is defined similarly. Using (15) and (16), the optimization problem (14) can be rewritten as

$$\max_{\mathbf{P}, \mathbf{Q}, W_r, \mathbf{t}} \quad \frac{\sum_{m=1}^{N} t_m}{\sum_{i=1}^{N} P_i + \sum_{j=1}^{N} Q_j + W_r + P_c} , \quad (21)$$

$$\begin{aligned} s \cdot t \cdot \quad & (C.1) \quad \sum_{i=1}^{N} P_i + \sum_{j=1}^{N} Q_j + W_r + P_c \leqslant P_{max} ; \\ & (C.2) \quad \frac{\rho_{s_m}}{2} log_2\Big(\Upsilon_{s_m}(\mathbf{P}, \mathbf{Q}, W_r)\Big) + \frac{\beta_{s_m}}{2} \geq t_m ; \\ & (C.3) \quad \frac{\rho_{d_m}}{2} log_2\Big(\Upsilon_{d_m}(\mathbf{P}, \mathbf{Q}, W_r)\Big) + \frac{\beta_{d_m}}{2} \geq t_m . \end{aligned}$$

By utilizing change of variables and letting $\bar{P}_i = log(P_i)$, $\bar{Q}_j = log(Q_j)$ and $\bar{W}_r = log(W_r)$, the optimization problem (21) can be equivalently transformed as

$$\max_{\bar{\mathbf{P}}, \bar{\mathbf{Q}}, \bar{W}_r, \mathbf{t}} \quad \frac{\sum_{m=1}^{N} t_m}{\sum_{i=1}^{N} e^{\bar{P}_i} + \sum_{j=1}^{N} e^{\bar{Q}_j} + e^{\bar{W}_r} + P_c} , \quad (22)$$

$$\begin{aligned} s \cdot t \cdot \quad & (C.1) \quad \sum_{i=1}^{N} e^{\bar{P}_i} + \sum_{j=1}^{N} e^{\bar{Q}_j} + e^{\bar{W}_r} + P_c \leqslant P_{max} ; \\ & (C.2) \quad \frac{\rho_{s_m}}{2} log_2\Big(\Upsilon_{s_m}(e^{\bar{\mathbf{P}}}, e^{\bar{\mathbf{Q}}}, e^{\bar{W}_r})\Big) + \frac{\beta_{s_m}}{2} \geq t_m ; \\ & (C.3) \quad \frac{\rho_{d_m}}{2} log_2\Big(\Upsilon_{d_m}(e^{\bar{\mathbf{P}}}, e^{\bar{\mathbf{Q}}}, e^{\bar{W}_r})\Big) + \frac{\beta_{d_m}}{2} \geq t_m , \end{aligned}$$

where $\bar{\mathbf{P}} = [\bar{P}_1, \ldots, \bar{P}_N]^T$ and $\bar{\mathbf{Q}} = [\bar{Q}_1, \ldots, \bar{Q}_N]^T$. Notice that the objective function in (22) is a concave-over-convex fractional function, and the considered problem can be efficiently solved by applying Dinkebach's method in an iterative fashion [17]. Denote the energy efficiency, $q$, with respect to a specific $(\bar{\mathbf{P}}, \bar{\mathbf{Q}}, \bar{W}_r, \mathbf{t})$ as

$$q = \frac{\sum_{m=1}^{N} t_m}{\sum_{i=1}^{N} e^{\bar{P}_i} + \sum_{j=1}^{N} e^{\bar{Q}_j} + e^{\bar{W}_r} + P_c} . \quad (23)$$

By introducing and updating the parameter $q$, the optimization problem (22) can be iteratively solved by [17]

$$\max_{\bar{\mathbf{P}}, \bar{\mathbf{Q}}, \bar{W}_r, \mathbf{t}} \sum_{m=1}^{N} t_m - q\Big(\sum_{i=1}^{N} e^{\bar{P}_i} + \sum_{j=1}^{N} e^{\bar{Q}_j} + e^{\bar{W}_r} + P_c\Big) ,$$

$$s \cdot t \cdot \quad (C.1), (C.2) \,\&\, (C.3) , \quad (24)$$

where the parameter $q$ is updated according to (23), and the maximum energy efficiency, $q^*$, of the network can be achieved when the following condition is satisfied:

$$\sum_{m=1}^{N} t_m^* = q^* \Big(\sum_{i=1}^{N} e^{\bar{P}_i^*} + \sum_{j=1}^{N} e^{\bar{Q}_j^*} + e^{\bar{W}_r^*} + P_c\Big) , \quad (25)$$

where $\bar{\mathbf{P}}^*$, $\bar{\mathbf{Q}}^*$ and $\bar{W}_r^*$ are the optimal solutions corresponding to $q^*$. For given $\rho_{s_m}$, $\beta_{s_m}$, $\rho_{d_m}$, $\beta_{d_m}$ and $q$, the optimization problem (24) is a typical concave maximization problem, and the optimal solution can be directly obtained using some convex optimization techniques [14]. The procedures of the proposed iterative algorithm is described in Table I. By following these procedures, it can be proved that the obtained solution can attain the maximum energy efficiency of the network in (13) [18]. The detailed proof is not presented here due to the space limitations.

## IV. Numerical Results

In this section, we evaluate the performance of the proposed optimal power control algorithm (optimal PC). The number of the source-destination pairs, $N$, is set to five. The static power in total is given by $P_c = 0.22$ Watts. The channel-to-noise power ratios (CNRs) for each link at the source ($\gamma_s$), relay ($\gamma_r$) and destination ($\gamma_d$) are all set to 15 dB. The maximum number of iterations, $L_{max}$, is set as 25. The optimization problem with an equal transmit power constraint (optimal EPC) is also included as a special case of (13). In addition, a heuristic power control (heuristic EPC) scheme where the maximum available transmit power $P_{max}$ is equally allocated to all the nodes is simulated for performance comparison.

TABLE I

AN ITERATIVE ENERGY-EFFICIENT POWER CONTROL ALGORITHM

**Input**:

$\bar{\mathbf{P}} \longleftarrow \bar{\mathbf{P}}^{(0)}, \bar{\mathbf{Q}} \longleftarrow \bar{\mathbf{Q}}^{(0)}, \bar{W}_r \longleftarrow \bar{W}_r^{(0)}$;

Set the maximum number of iterations $L_{max}$ and the tolerance $\delta$;

Calculate: $\Upsilon_{s_m}$ and $\Upsilon_{d_m}$ using (7) and (8) respectively.

Compute: **t**.

Initialize: $\rho_{s_m}^{(1)}, \beta_{s_m}^{(1)}, \rho_{d_m}^{(1)}, \beta_{d_m}^{(1)}, q^{(1)}$ using (17)-(20) and (23) respectively;

**Output**:

Maximum energy efficiency: $q^{opt}$;

Optimal power allocation scheme: $\left(\bar{\mathbf{P}}^{opt}, \bar{\mathbf{Q}}^{opt}, \bar{\mathbf{W}}^{opt}\right)$.

**Iterative Algorithm**:

1. **for** $l = 1 : L_{max}$
2. obtain $\left(\bar{\mathbf{P}}^{(l)}, \bar{\mathbf{Q}}^{(l)}, \bar{W}_r^{(l)}\right)$ using (24) for given $q^{(l)}, \rho_{s_m}^{(l)}, \beta_{s_m}^{(l)}, \rho_{d_m}^{(l)}, \beta_{d_m}^{(l)}$;
3. **if** $R\left(\bar{\mathbf{P}}^{(l)}, \bar{\mathbf{Q}}^{(l)}, \bar{W}_r^{(l)}\right) - q^{(l)} P_{Total}\left(\bar{\mathbf{P}}^{(l)}, \bar{\mathbf{Q}}^{(l)}, \bar{W}_r^{(l)}\right) \leq \delta$
4. $\left(\bar{\mathbf{P}}^{opt}, \bar{\mathbf{Q}}^{opt}, \bar{W}_r^{opt}\right) = \left(\bar{\mathbf{P}}^{(l)}, \bar{\mathbf{Q}}^{(l)}, \bar{W}_r^{(l)}\right)$, and $q^{opt} = q^{(l)}$; convergence=1; break;
5. **else**
6. update following parameters: $\rho_{s_m}^{(l)}, \beta_{s_m}^{(l)}, \rho_{d_m}^{(l)}, \beta_{d_m}^{(l)}, q^{(l)}$ using (17)-(20) and (23) respectively; convergence=0;
7. **end**
8. **end**
9. **if** convergence=0
10. $\left(\bar{\mathbf{P}}^{opt}, \bar{\mathbf{Q}}^{opt}, \bar{W}_r^{opt}\right) = \left(\bar{\mathbf{P}}^{(L_{max})}, \bar{\mathbf{Q}}^{(L_{max})}, \bar{W}_r^{(L_{max})}\right)$, and $q^{opt} = q^{(L_{max})}$.
11. **end**.

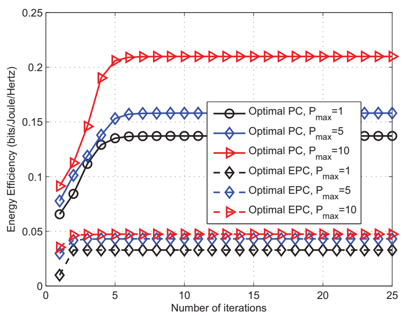


Fig. 2. Convergence of the proposed power allocation algorithm.

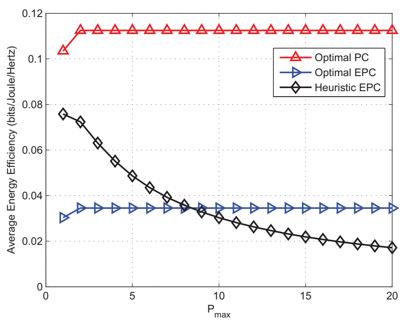


Fig. 3. Average energy efficiency versus $P_{max}$.

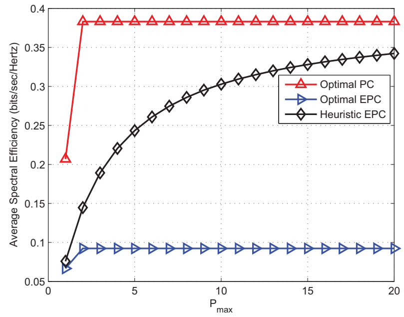


Fig. 4. Average spectral efficiency versus $P_{max}$.

The convergence behaviors of the optimal PC scheme and the optimal EPC scheme are demonstrated in Fig. 2, which only involves a single realization of Rayleigh fading channels. The maximum transmit power is set as one, five, and ten. It is shown that the proposed algorithm requires around six iterations for performance convergence. Due to the imposed equal transmit power constraint, the optimal EPC scheme can serve as the lower bound for the optimal PC scheme. Fig. 3 demonstrates the average energy efficiency of the proposed algorithm versus the maximum allowable transmit power $P_{max}$. We compare the performance among the proposed optimal PC, optimal EPC and heuristic EPC schemes. It can be found that the optimal PC scheme always outperforms the heuristic EPC and the optimal EPC schemes. Also, the heuristic EPC scheme exhibits better performance than the optimal EPC scheme at low power regimes, while its performance becomes worse than that of the optimal EPC at high power regimes for which $P_{max} \geq 8$. Fig. 4 plots the average spectral efficiency versus $P_{max}$. One can see that the optimal PC has superior performance than both the optimal EPC and the heuristic EPC schemes, while the gap between the optimal PC and the heuristic EPC schemes becomes small at high power regimes. When compared with the heuristic EPC scheme in Fig. 3 and Fig. 4, the optimal PC scheme can improve not only the energy efficiency but also the spectral efficiency.

## V. CONCLUSION

In this paper, we propose an energy-efficient power control scheme for multiuser two-way balancing relay networks. The energy efficiency balancing problem was transformed into a non-fractional problem and solved in an iterative fashion. Simulation results illustrate the convergence of the proposed algorithm. The proposed power control scheme can effectively improve not only the energy efficiency but also the spectral efficiency, as compared with the heuristic equal power allocation scheme.

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