Research Article

Energy Efficient Design for Two-Way AF Relay Networks

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Conventional designs on two-way relay networks mainly focus on the spectral efficiency (SE) rather than energy efficiency (EE). In this paper, we consider a system where two source nodes communicate with each other via an amplify-and-forward (AF) relay node and study the power allocation schemes to maximize EE while ensuring a certain data rate. We propose an optimal energy-efficient power allocation algorithm based on iterative search technique. In addition, a closed-form suboptimal solution is derived with reduced complexity and negligible performance degradation. Numerical results show that the proposed schemes can achieve considerable EE improvement compared with conventional designs.

1. Introduction

The unprecedented growth of wireless networks has resulted in a rapid rise of energy consumption and led to an emerging trend of green radio [1]. Energy-efficient system design for green radio is earning considerable attention from both industry and academia for its positive impact on environment. The energy efficiency (EE) [2], which is widely defined as the system throughput per unit energy, has become one of the critical performance metrics for future communication systems.

In the green communication systems, several advanced wireless communication techniques, such as cooperative relay transmissions [3, 4] and small cells [5, 6], have been adopted to provide significant capacity improvements and reduce energy consumption. Compared with direct transmission, relay technique is essential to provide a more reliable transmission due to the smaller path loss attenuation of shorter hops. The two-way relay system was introduced in [7] for two source nodes which want to exchange information with each other via a relay.

Most previous works on two-way relay networks mainly focused on the relay selection or power allocation from the perspective of spectral efficiency (SE) [8, 9]. In [8], the smaller of the received signal-to-noise ratios (SNRs) of two

transceivers was maximized through joint relay selection and power allocation. Achievable data rate region for the two source nodes was obtained in [9], and considerable SE enhancement was achieved when compared with one-way relay network. However, the EE is a strictly decrease function of SE when only transmit power is considered [1]. After taking the circuit power used for electronic devices and signal processing into account, the relation between SE and EE is more complicated. This indicates that maximizing SE may not maximize EE in a practical two-way relay system.

Recently, some works have investigated energy related designs in two-way relay networks [10–15]. An efficient power allocation scheme to minimize the total transmit power consumption was presented in [10] for the machine-to-machine networks, where the source node communicated with its corresponding destination node via one or more relays. The authors in [12] proposed a transmission scheme to minimize the energy consumed per bit transmitted for both one-way and two-way relay networks by joint relay selection and power allocation. Reference [13] investigated a joint relay selection and power allocation scheme to minimize overall transmit power while ensuring a certain data rate. However, the circuit power was ignored in all of them. In a practical system, not only the transmit power but also the circuit power contributes to the total power consumption.

Therefore, minimizing the transmit power may not necessarily lead to a high EE [14]. In [15], after taking the realistic power consumption model into consideration, an analytical framework for the total energy consumption of AF multihop network while satisfying an average bit error rate requirement was developed. Based on this framework, the impact of the relay's location and energy resource allocation between the relay and the source were also evaluated. The EE of two-way and one-way relay systems was analyzed in [11] and the search technique was used to find the optimal solution which had high complexity and incurred additional energy.

In this paper, we propose an optimal energy-efficient power allocation algorithm for two-way relay networks while ensuring a certain throughput requirement. Using the results derived in [14], we first study the transmit power minimization problem for a fixed data rate, analyze the relation between SE and EE, and then apply this solution to formulate an equivalent optimization problem with one variable. To solve this problem, bisection search technique is used. However, the optimal power allocation with iterative search method has high computational complexity. In order to reduce the complexity, a closed-form solution of suboptimal power allocation algorithm is derived. The proposed algorithm not only eliminates the complexity of bisection search, but also can achieve near optimal EE capacity performance in two-way relay networks.

The rest of the paper is organized as follows. Section 2 introduces a two-way relay network model and formulates the corresponding power allocation problem. In Section 3, both the optimal and suboptimal power allocation schemes are proposed. Simulation results are given in Section 4. Section 5 concludes this paper.

2. System Model and Problem Formulation

2.1. System Model. Consider a relay network consisting of two source nodes $\mathbb{A}$ and $\mathbb{B}$ exchanging information with each other at the same transmission rate via a half-duplex AF relay $\mathbb{R}$. All the nodes are equipped with a single antenna. Assume that the signal is severely attenuated between two source nodes because of the high shadowing caused by obstacles or long distance, and thus the direct link transmission is not considered here.

The channels among three nodes are assumed as block fading channels and the perfect channel state information (CSI) is available at each node. Denote by h_{ar} and h_{br} the channel coefficients from source nodes $\mathbb{A}$ and $\mathbb{B}$ to relay node $\mathbb{R}$, respectively. To exchange information from both of two source nodes, $\mathbb{A}$ and $\mathbb{B}$ must transmit in two phases. In the multiple access phase, both of the two source nodes $\mathbb{A}$ and $\mathbb{B}$ simultaneously transmit their respective unit-energy symbols s_a and s_b to the relay node $\mathbb{R}$. Let P_a and P_b be the transmit power of source nodes $\mathbb{A}$ and $\mathbb{B}$, respectively. Thus the received signal can be expressed as

$$r = \sqrt{P_a} h_{ar} s_a + \sqrt{P_b} h_{br} s_b + z_r, \quad (1)$$

where z_r is the noise at relay node $\mathbb{R}$. All the noise terms in this paper are assumed to be independent Gaussian variables with zero mean and a variance of σ^2 .

In the broadcast phase, $\mathbb{R}$ transmits the received signal r to $\mathbb{A}$ and $\mathbb{B}$ with an amplification factor ξ . The received signals y_a and y_b at both of the two source nodes can be written as

$$\begin{aligned} y_a &= \xi h_{ar} r + z_a, \\ y_b &= \xi h_{br} r + z_b, \end{aligned} \quad (2)$$

$$\xi = \sqrt{\frac{P_r}{P_a |h_{ar}|^2 + P_b |h_{br}|^2 + \sigma^2}},$$

where z_i is the additive noise at the source node i ($i \in \{a, b\}$) and P_r is the transmit power of relay node $\mathbb{R}$. Since each source node receives a copy of its own transmitted signal as interference, the partner's message can be decoded after self-interference cancellation (SIC).

2.2. Problem Formulation. Define parameters $g_{ar} = |h_{ar}|^2/\sigma^2$ and $g_{br} = |h_{br}|^2/\sigma^2$ as the instantaneous channel gain-to-noise ratio (CNR); then the received SNR at two source nodes can be given as

$$\begin{aligned} \gamma_{ab} &= \frac{g_{ar} g_{br} P_a P_r}{g_{ar} P_a + g_{br} (P_b + P_r) + 1}, \\ \gamma_{ba} &= \frac{g_{ar} g_{br} P_b P_r}{g_{br} P_b + g_{ar} (P_a + P_r) + 1}. \end{aligned} \quad (3)$$

The instantaneous transmission data rate of nodes $\mathbb{A}$ to $\mathbb{B}$ can be obtained from the Shannon capacity formulae, which are, respectively,

$$\begin{aligned} R_{ab} &= \frac{1}{2} B \log_2 (1 + \gamma_{ab}), \\ R_{ba} &= \frac{1}{2} B \log_2 (1 + \gamma_{ba}), \end{aligned} \quad (4)$$

where B is the transmission bandwidth. Hence, the overall data rate can be driven as

$$R = R_{ab} + R_{ba}. \quad (5)$$

According to [16], the circuit power consumption P_c is incurred by signal processing and active electronic devices in the network, and it can be modeled as a linear function of transmission rate

$$P_c = P_s + \beta R, \quad (6)$$

where P_s is the static circuit power and β is the dynamic circuit power per unit data rate. Thus the total power consumption P_t is

$$P_t = \frac{\alpha (P_a + P_b + P_r)}{2} + P_c, \quad (7)$$

where α is a constant related to the efficiency of power amplifier.

In order to guarantee the quality of service (QoS), the transmission rate should be restricted by

$$R \geq \tilde{R}, \quad (8)$$

where $\tilde{R}$ is the minimum data rate requirement related to the type of traffic.

Since the total transmit power P_i at node i is limited, we have

$$P_i \leq \hat{P}_i, \quad i \in \{a, b, r\}, \quad (9)$$

where $\hat{P}_i$ is the maximum allowable transmit power.

The objective of this paper is to find the optimal power allocation of each node to maximize the EE of two-way relay network while ensuring a certain data rate. Hence, the optimization problem can be formulated as follows (P1):

$$P1 : \max_{P_i} \quad U = \frac{R}{P_t} \quad (10a)$$

$$\text{s.t.} \quad R_{ab} = R_{ba}, \quad (10b)$$

$$R \geq \tilde{R}, \quad (10c)$$

$$P_i \leq \hat{P}_i, \quad i \in \{a, b, r\}. \quad (10d)$$

We assume that $\tilde{R}$ can be achieved under constraint (10d). If not, the feasible solution of problem P1 does not exist. In this case, the scheduler may have to decrease $\tilde{R}$ to make the solution feasible.

3. Energy-Efficient Design

In this section, we aim to find the optimal transmit powers P_a^* , P_b^* , and P_r^* to maximize EE while satisfying a certain data rate. Before solving the problems (10a), (10b), (10c), and (10d), we introduce two auxiliary optimization problems below. Define the transmit power minimization (MinP) problem P2 under the required minimum data rate constraint as

$$P2 : \min_{P_i} \quad P_a + P_b + P_r \quad (11a)$$

$$\text{s.t.} \quad R_{ab} = R_{ba}, \quad (11b)$$

$$R \geq \tilde{R}. \quad (11c)$$

Using the similar approach in [14], we have the optimal solution to problem P2:

$$P_a = f_a(\check{\phi}) = \frac{\check{\phi}}{g_{ar}} + \check{\phi} \sqrt{\frac{2\check{\phi} + 1}{2\check{\phi}g_{ar}g_{br}}}, \quad (12a)$$

$$P_b = f_b(\check{\phi}) = \frac{\check{\phi}}{g_{br}} + \check{\phi} \sqrt{\frac{2\check{\phi} + 1}{2\check{\phi}g_{ar}g_{br}}}, \quad (12b)$$

$$P_r = f_r(\check{\phi}) = \check{\phi} \left(\frac{1}{g_{ar}} + \frac{1}{g_{br}} \right) + 2\check{\phi} \sqrt{\frac{2\check{\phi} + 1}{2\check{\phi}g_{ar}g_{br}}}, \quad (12c)$$

where $\check{\phi} = 2^{\tilde{R}/B} - 1$.

The other conventional optimization problem is data rate maximization (Max R) problem P3 subject to the total transmit power constraint. It can be described as follows

$$P3 : \max_{P_i} \quad R \quad (13a)$$

$$\text{s.t.} \quad R_{ab} = R_{ba}, \quad (13b)$$

$$P_i \leq \hat{P}_i, \quad i \in \{a, b, r\}. \quad (13c)$$

According to (12a), (12b), and (12c), it can be seen that both the overall data rate R and transmit power P_i at node i are the strictly increasing function of ϕ . Thus we can obtain the maximum achievable data rate $\hat{R}$

$$\hat{R} = B \log_2(1 + \hat{\phi}), \quad (14)$$

where $\hat{\phi} = \min_{i \in \{a, b, r\}} f_i^{-1}(\hat{P}_i)$ and $f_i^{-1}(\cdot)$ is the inverse function of $f_i(\cdot)$.

Since we assume that $\tilde{R}$ is achievable under the constraints (10b) and (10d), we have $\check{\phi} \leq \hat{\phi}$. The equivalent optimization problem of P1 can be reformulated as

$$P4 : \max_{\phi} \quad U(\phi) = \frac{R(\phi)}{\alpha \sum_{i \in \{a, b, r\}} (f_i(\phi)/2) + P_s + \beta R(\phi)} \quad (15a)$$

$$\text{s.t.} \quad \check{\phi} \leq \phi \leq \hat{\phi}, \quad (15b)$$

where $R(\phi) = B \log_2(1 + \phi)$.

According to [16], we can prove that the system EE $U(\phi)$ is a quasiconcave function of ϕ ($\phi > 0$).

3.1. Optimal Energy-Efficient Power Allocation. Since the EE U is a quasiconcave function of ϕ , an optimal solution $\tilde{\phi}$ that maximizes EE without any constraint always exists. Then $U(\phi)$ is an increasing function of ϕ when $0 \leq \phi \leq \tilde{\phi}$ and $U(\phi)$ is decreasing when $\phi \geq \tilde{\phi}$. The optimal solution ϕ^* for problem P4 is given as

$$\phi^* = \begin{cases} \hat{\phi}, & \check{\phi} \leq \hat{\phi} \leq \tilde{\phi} \\ \tilde{\phi}, & \check{\phi} \leq \tilde{\phi} \leq \hat{\phi} \\ \check{\phi}, & \check{\phi} \leq \check{\phi} \leq \hat{\phi} \end{cases} \quad (16)$$

It is noticeable that (16) is equivalent to

$$\phi^* = \min(\hat{\phi}, \max(\tilde{\phi}, \check{\phi})). \quad (17)$$

The remaining thing for problem P4 is to address ϕ^* and it can be solved by bisection search technique. Here we

Step 1. Initialization, $\phi_m = 0, \phi_l = 0, \phi_h = 0$.
 Step 2. Calculate $\check{\phi}$ and $\hat{\phi}$ according to (12a)–(12c) and (14). Set $\phi_l = \check{\phi}$ and $\phi_h = \hat{\phi}$.
 Step 3. Set $\phi_m = (\phi_l + \phi_h)/2$.
 Step 4. If its first derivative with respect to ϕ satisfies $(dU(\phi)/d\phi)|_{\phi=\phi_m} > 0$, then $\phi_l = \phi_m$, else $\phi_h = \phi_m$.
 Step 5. Repeat Step 3 until $\phi_h - \phi_l \leq \varepsilon$ where ε is a small positive constant to control the convergence accuracy.
 Step 6. Calculate the optimal solution $P_i^* = f_i(\phi_m), i = \{a, b, r\}$ according to (12a)–(12c).

ALGORITHM 1: Optimal power allocation (OPA) algorithm.

list the optimal power allocation method in Algorithm 1. In each iteration, the search region is divided into two parts. To update the search region, we should determine which part contains $\tilde{\phi}$ by calculating the first derivative of $U(\phi)$. Note that the sign of $dU(\phi)/d\phi$ can be determined by calculating the value of $U(\phi + \Delta\phi) - U(\phi)$, where $\Delta\phi$ is an infinitely small positive constant.

3.2. Suboptimal Energy-Efficient Power Allocation. Although the optimal power allocation solution is desirable, the cost to pay is the computational complexity in iterative search. It takes at most $\lceil \log_2((\hat{\phi} - \check{\phi})/\varepsilon) \rceil$ iterations to convergence which incurs additional energy consumption, where $\lceil x \rceil$ denotes the smallest integer not less than x . Thus, this straightforward approach is clearly not practical, and we need a low complexity approach to solve this problem.

Considering the following approximation for large ϕ :

$$\sqrt{2\phi(2\phi + 1)} \approx 2\phi + \frac{1}{2}, \quad (18)$$

then the EE of problem P4 can be written as

$$\begin{aligned} U(\phi) &= \frac{R(\phi)}{\alpha \sum_{i \in \{a, b, r\}} (f_i(\phi)/2) + P_s + \beta R(\phi)} \\ &\approx \frac{B \log_2(1 + \phi)}{\phi G_1 + G_2 + \beta B \log_2(1 + \phi)}, \end{aligned} \quad (19)$$

where $G_1 = \alpha((1/\sqrt{g_{ar}}) + (1/\sqrt{g_{br}}))^2$ and $G_2 = (\alpha/2\sqrt{g_{ar}g_{br}}) + P_s$. It can be easily proved that $\tilde{U}(\phi)$ is also a quasiconcave function of ϕ ; the unique solution $\tilde{\phi}$ for achieving the maximum $U(\phi)$ without any constraint always exists. Differentiating (19) with respect to ϕ and setting this derivative to zero, we can obtain

$$\frac{d\tilde{U}}{d\phi} = F \left(\frac{\phi + (G_2/G_1)}{1 + \phi} - \ln(1 + \phi) \right) = 0, \quad (20)$$

where

$$F = \frac{B}{G_1(\phi G_1 + G_2 + \beta B \log_2(1 + \phi))^2 \ln 2}. \quad (21)$$

Since F is a positive variable, equation (20) can be written as

$$\phi + \frac{G_2}{G_1} = (1 + \phi) \ln(1 + \phi). \quad (22)$$

FIGURE 1: System EE versus average CNR.

After some mathematical manipulation, we can find the root $\tilde{\phi}$ of (22), which is given as

$$\tilde{\phi} = \exp \left(W_0 \left(\frac{G_2}{G_1 e} - \frac{1}{e} \right) + 1 \right) - 1, \quad (23)$$

where $e \approx 2.7183$ is the base of the natural logarithm and $W_0(\cdot)$ denotes the real branch of the Lambert function [17]. Thus the suboptimal power allocation can be obtained by substituting $\tilde{\phi}$ into (17), (12a), (12b), and (12c). The suboptimal transmit power P_i^* at node i is

$$P_i^* = f_i(\phi^*), \quad i \in \{a, b, r\}. \quad (24)$$

4. Numerical Results

In this section, we provide simulations to evaluate the EEs of our proposed schemes and validate the previous analysis. The channel gains h_{ar} and h_{br} are assumed to be independent block Rayleigh fading with the same average CNR. Simulation parameters are set as follows: $B = 1$ kHz, $\hat{P}_a = \hat{P}_b = 5$ W, $\hat{P}_r = 10$ W, $P_s = 0.5$ W, $\alpha = 2$, $\hat{R} = 1$ kbps, and $\beta = 0.2$ W/kbps.

The system EE and corresponding data rate versus average CNR are evaluated in Figures 1 and 2 under different

FIGURE 2: System rate versus average CNR.

strategies. It can be seen that both EE and data rate increase with the average CNR. This is because the energy-efficient design tends to use less transmit power when CNR increases. Figure 1 shows that the proposed schemes outperform conventional schemes and the suboptimal scheme achieves near optimal performance. The performance gap between proposed schemes and conventional schemes becomes larger when CNR increases. In low CNR region, the transmit power dominates the total power consumption while in the high CNR region the circuit power does for the energy-efficient design. From Figure 2, it indicates that for specific channel realizations with bad quality, energy-efficient design may have to operate exactly at the maximum transmit power to meet the minimum rate requirement. It can be seen that the proposed schemes have lower SE than the MaxR scheme and can achieve higher EE with less power consumption at the cost of some SE loss when CNR is large enough. This indicates that our proposed schemes can achieve a better tradeoff between EE and SE.

5. Conclusion

In this paper, we studied the energy-efficient design of two-way networks under the constraints of transmit power and the minimum rate requirement. We proposed an optimal power allocation scheme based on iterative search method. In order to reduce the computational complexity, we also derived a closed-form solution for suboptimal algorithm that performs near the optimal scheme. Compared with traditional SE-oriented power allocation, the proposed schemes have significant improvement in terms of EE.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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