Energy Efficient Transmission for DF MIMO Relay Systems with Antenna Selection

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***Abstract*—This paper investigates the maximization of energy efficiency (EE) in decode-and-forward (DF) MIMO relaying systems with antenna selection. An iterative EE maximization algorithm is proposed to jointly select the active receive and transmit antennas at the relay, as well as optimize the transmission power of the source and relay. In particular, the antenna selection relies on a derived iterative property of EE, which guides us to select a pair of one receive and one transmit relay antennas that achieves the largest increment of EE under an initial transmission power. There is also a power adaptation for each iteration where we calculate the optimal transmission power and then set it as the initial one for the next iteration. In this process, the tool of fractional programming is used to find the maximum EE and the corresponding transmission power for each iteration. Simulation results show that the proposed algorithm achieves near-optimal performance at all the transmission distances. Moreover, it is capable of simultaneously improving EE and reducing the power consumption for transmission.**

***Index Terms*—MIMO relay, energy efficiency, antenna selection, power adaptation, decode-and-forward**

I. Introduction

Wireless relaying combined with the use of multiple antennas has become a key-factor in modern communications for its benefits of a large spectral efficiency and a large diversity gain [1], [2]. Meanwhile, with the rapid evolution of modern wireless communications, there is a radical increase in the energy consumption along with the escalation of greenhouse gas emission and electric bill [3]. It would be therefore urgent and important to design energy efficient MIMO relaying systems.

Antenna selection in which only a subset of available antennas are active for transmitting or receiving holds the promise of reducing the energy consumption when designing MIMO relay systems. However, to find the optimal subset of antennas that maximizes the throughput needs an exhaustive search, which is complexity prohibitive for practical use. Thus, there has been a variety of literatures devoted to finding low complexity algorithms for antenna selection in MIMO relay systems. In [4]–[6], the authors proposed fast antenna selection algorithms for MIMO relay systems, especially for the relay antenna selection since the relay node is often energy-limited. In previous works, the circuit power consumption of RF chains is not taken into account and the constraint is only the transmission power. The goal is that of finding an optimal subset of antennas to maximize the capacity. However, from [7] we know that a holistic power model which considers all the circuit power consumption should be adopted to quantify the energy efficiency (EE) of wireless networks. The EE of communication systems is usually defined as the ratio of rate to the overall power consumption, which includes both the transmission power and the circuit power consumption. Energy efficient resource allocation in amplify-and-forward (AF) MIMO relay systems with both perfect and statistical channel state information (CSI) are investigated in [8], where antenna selection is not considered. To the best of our knowledge, the EE maximization with antenna selection in DF MIMO relay systems has not been investigated in a systematic way.

In this paper, we try to maximize the EE in half-duplex DF MIMO relay systems with relay antenna selection when a holistic power model is considered. Specifically, our aim is to find the optimal subsets of active receive and transmit antennas of the relay as well as the optimal transmission power of the source and relay. Exhaustive search is complexity prohibitive, hence an iterative EE maximization algorithm relying on a joint iteration of active antennas and transmission power is proposed in this paper. We first derive an iterative equation for the EE in DF MIMO relay system with relay antenna selection under a holistic power model. Based on it, at each step we select one pair of receive and transmit antennas at the relay that achieves the largest increment of EE under the condition of given transmission power. Then a power adaptation is adopted where we calculate the optimal transmission power for the current step and set it as the initial transmission power for the next step. The optimal transmission power of the source and

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relay that maximizes EE for each step is obtained by using the tool of fractional programming. Simulation results show that near-optimal performance is achieved by the proposed algorithm. The EE with antenna selection is much better than that of conventional DF MIMO relay protocol.

II. System Model and Problem Formulation

A. System Model

Consider a two-hop MIMO relay system with one source, one relay and one destination. The source, relay and destination are equipped with N_s, N_r and N_d antennas, respectively. $\mathbf{H} \in \mathbb{C}^{N_r \times N_s}$ and $\mathbf{G} \in \mathbb{C}^{N_d \times N_r}$ denote the backward channel ($S \to R$) and the forward channel ($R \to D$) respectively. The selected subsets of active receive and transmit antennas at the relay are denoted by ω_r and ω_t, respectively. $L = |\omega_r| = |\omega_t|$[1] represents the number of active RF chains at the relay, where $|\cdot|$ denotes the cardinality of a set and $L \leq N_r$. Assume that all the channels are Rayleigh flat fading with average power varied with the path loss. The noise vectors at the relay and destination are Additive White Gaussian Noise (AWGN) with power of σ_r^2 and σ_d^2, respectively. Throughout this paper, assume all the nodes operate in half-duplex mode and hence the transmission time interval is divided into two time slots.

In the first time slot, the data at the source are multiplexed into N_s signal streams and transmitted to the relay. In the second time slot, the relay decodes the signal received from the antennas in the selected subset ω_r, multiplexes the signal into L streams and transmits the re-multiplexed signal to the destination from the antennas in the selected subset ω_t. According to [1], the capacity of our considered DF MIMO relay system is given by

$$C\left(P_s, P_r, \mathbf{H}_{\omega_r}, \mathbf{G}_{\omega_t}\right) = \frac{1}{2}\min\left(\log\left(\mathbf{I} + \frac{P_s}{N_s\sigma_r^2}\mathbf{H}_{\omega_r}^H\mathbf{H}_{\omega_r}\right), \log\left(\mathbf{I} + \frac{P_r}{L\sigma_d^2}\mathbf{G}_{\omega_t}\mathbf{G}_{\omega_t}^H\right)\right), \tag{1}$$

where $\mathbf{H}_{\omega_r}$ is the $L \times N_s$ subchannel matrix between the source and relay when the relay activates the receive antennas in ω_r, $\mathbf{G}_{\omega_t}$ is the $N_d \times L$ subchannel matrix between the relay and destination when the relay activates the transmit antennas in ω_t. P_s and P_r are the transmission power at the source and relay, respectively.

The overall power consumption of the system consists of two main parts: the power consumption for transmission, and the power consumption of RF chains and other circuit blocks P_c. The second term for our considered system is given by [10]

$$P_c = N_s P_{ct} + N_d P_{cr} + L(P_{cr,R} + P_{ct,R}) + P_{c0}, \tag{2}$$

where P_{ct} and $P_{ct,R}$ are the power consumed by each source and relay RF chain for transmission. P_{cr} and $P_{cr,R}$ are the power consumed by each destination and relay RF chain for reception. P_{c0} represents the power of frequency synthesizers and other units of circuits. Thus, the overall power consumption in the system can be expressed as

$$P = \frac{1}{\eta_s}P_s + \frac{1}{\eta_r}P_r + P_c, \tag{3}$$

where η_s and η_r are the drain efficiency of the power amplifier at the source and relay, respectively.

B. Problem Formulation

The main objective of this paper is to maximize the energy efficiency for DF MIMO relay systems with antenna selection adopted at the relay. According to the definition of energy efficiency in [7], the energy efficiency of our system under the holistic power model is given by

$$EE = \frac{C\left(P_s, P_r, \mathbf{H}_{\omega_r}, \mathbf{G}_{\omega_t}\right)}{\frac{1}{\eta_s}P_s + \frac{1}{\eta_r}P_r + N_s P_{ct} + N_d P_{cr} + |\omega_r| P_{c,R} + P_{c0}}, \tag{4}$$

where $P_{c,R} = P_{cr,R} + P_{ct,R}$. To maximize the energy efficiency defined in Eq. (4), a joint optimization over the transmission power and the active relay antennas is needed. Specifically, our aim is to solve the optimization problem given by

$$\begin{aligned} &\max_{(P_s, P_r, \omega_r, \omega_t)} \; EE \\ &s.t. \begin{cases} 1 \leq |\omega_r| = |\omega_t| \leq N_r \\ C\left(P_s, P_r, \mathbf{H}_{\omega_r}, \mathbf{G}_{\omega_t}\right) \geq C_{\min} \\ 0 < P_s \leq P_s^{\max}, 0 < P_r \leq P_r^{\max}. \end{cases} \end{aligned} \tag{5}$$

In problem (5), $C_{\min}$ is the minimum required rate. $P_s^{\max}$ and $P_r^{\max}$ are the maximum transmission power for the source and relay, respectively.

III. Optimization of the Energy Efficiency

In this section, an iterative EE maximization algorithm is proposed to address the problem above. The two main parts of the proposed algorithm, i.e., antenna selection and power adaptation, are elaborated in subsections A and B, respectively.

A. Antenna Selection under Given Transmission Power

The antenna selection process under given transmission power is based on the iterative property of the EE with relay antenna selection, which is stated in Theorem 1. The notations used in Theorem 1 are defined as follows.

For the given transmission power pair (P_s, P_r), the received SNRs at the relay and destination are denoted by $\gamma_r = \frac{P_s}{\sigma_r^2}$ and $\gamma_d = \frac{P_r}{\sigma_d^2}$, respectively. At each step, one receive antenna and one transmit antenna of the relay are selected and added into the subsets ω_r and ω_t, respectively. For convenience, we denote by $\mathbf{H}_n$ the subchannel matrix between the source and relay after n steps of selection. $\mathbf{G}_n$ represents the subchannel matrix between the relay and destination after n steps of selection. At the $(n+1)$th step, if the s_r^*th receive and s_t^*th transmit antenna of the relay are selected, the new $(n+1) \times N_s$ and $N_d \times (n+1)$ channel matrices are denoted by $\mathbf{H}_{n+1}$ and $\mathbf{G}_{n+1}$, respectively. $\mathbf{h}_s$ is a column vector which represents

[1]This is because each RF chain at the relay collects one receive and one transmit antenna [9]. Thus, once we activate one more RF chain, we actually activate a pair of receive and transmit antennas.

the conjugate transpose of the sth row of $\mathbf{H}$ and $\mathbf{g}_s$ is the sth column of $\mathbf{G}$. P_n stands for the overall power consumption for the nth step, i.e., the number of active receive and transmit relay antennas is n. According to Eq. (3), we have that $P_n = nP_{c,R}+\frac{1}{\eta_s}P_s+\frac{1}{\eta_r}P_r+N_sP_{ct}+N_dP_{cr}+P_{c0}$. To simplify the notations for EE in the derivation of Theorem 1, we have $EE_{(1,n)} = \frac{\log\left(\mathbf{I}+\frac{\gamma_r}{N_s}\mathbf{H}_n^H\mathbf{H}_n\right)}{P_n}$, $EE_{(2,n)} = \frac{\log\left(\mathbf{I}+\frac{\gamma_d}{n}\mathbf{G}_n\mathbf{G}_n^H\right)}{P_n}$ and $EE_{(n)} = \frac{1}{2}\min\left(EE_{(1,n)}, EE_{(2,n)}\right)$ based on Eq. (4).

***Theorem** 1:* With the antenna selection at the relay and given transmission power, the energy efficiency of the DF MIMO relay system under the holistic power model could be expressed by the following iterative equation.

$$EE_{(n+1)} = \frac{1}{2}\min\left(\Psi(n)EE_{(1,n)} + \Delta_{1,s,n},\right. \\ \left.\Psi(n)EE_{(2,n)} + D_n + \Delta_{2,s,n}\right), \tag{6}$$

where $\Psi(n)$, $\Delta_{1,s,n}$ are defined after Eq. (13) and D_n, $\Delta_{2,s,n}$ are defined after Eq. (18).

Proof: According to Eqs. (1) and (4), the energy efficiency for the $(n+1)$th step can be expressed by

$$EE_{(n+1)} = \frac{1}{2}\min\left(EE_{(1,n+1)}, EE_{(2,n+1)}\right), \tag{7}$$

where

$$EE_{(1,n+1)} = \frac{\log\left(\mathbf{I}+\frac{\gamma_r}{N_s}\mathbf{H}_{n+1}^H\mathbf{H}_{n+1}\right)}{P_{n+1}}, \tag{8}$$

$$EE_{(2,n+1)} = \frac{\log\left(\mathbf{I}+\frac{\gamma_d}{n+1}\mathbf{G}_{n+1}\mathbf{G}_{n+1}^H\right)}{P_{n+1}}. \tag{9}$$

Noting that

$$\mathbf{H}_{n+1}^H\mathbf{H}_{n+1} = \mathbf{H}_n^H\mathbf{H}_n + \mathbf{h}_s\mathbf{h}_s^H, \tag{10}$$

and applying the matrix determinant lemma to the numerator of Eq. (8), we can obtain that

$$\log\left(\mathbf{I}+\frac{\gamma_r}{N_s}\mathbf{H}_{n+1}^H\mathbf{H}_{n+1}\right) = \log\left(\mathbf{I}+\frac{\gamma_r}{N_s}\mathbf{H}_n^H\mathbf{H}_n\right) + \\ \log\left(1+\frac{\gamma_r}{N_s}\mathbf{h}_s^H\left(\mathbf{I}+\frac{\gamma_r}{N_s}\mathbf{H}_n^H\mathbf{H}_n\right)^{-1}\mathbf{h}_s\right). \tag{11}$$

Using the notations $\mathbf{T}_{1,n} = \left(\frac{N_s}{\gamma_r}\mathbf{I}+\mathbf{H}_n^H\mathbf{H}_n\right)^{-1}$ and $\delta_{1,s,n} = \mathbf{h}_s^H\mathbf{T}_{1,n}\mathbf{h}_s$, we can rewrite Eq. (11) as

$$\log\left(\mathbf{I}+\frac{\gamma_r}{N_s}\mathbf{H}_{n+1}^H\mathbf{H}_{n+1}\right) = \log\left(\mathbf{I}+\frac{\gamma_r}{N_s}\mathbf{H}_n^H\mathbf{H}_n\right) + \\ \log\left(1+\delta_{1,s,n}\right). \tag{12}$$

By combining Eqs. (8) and (12), we obtain the following iterative equation

$$EE_{(1,n+1)} = \Psi(n)EE_{(1,n)} + \Delta_{1,s,n}, \tag{13}$$

where $\Psi(n) = \frac{P_n}{P_{n+1}}$ and $\Delta_{1,s,n} = \frac{\log(1+\delta_{1,s,n})}{P_{n+1}}$.

We proceed to find the iterative equation of $EE_{(2,n+1)}$. Noting that

$$\mathbf{G}_{n+1}\mathbf{G}_{n+1}^H = \mathbf{G}_n\mathbf{G}_n^H + \mathbf{g}_s\mathbf{g}_s^H, \tag{14}$$

and applying the matrix determinant lemma to the numerator of Eq. (9), we have that

$$\log\left(\mathbf{I}+\frac{\gamma_d}{n+1}\mathbf{G}_{n+1}\mathbf{G}_{n+1}^H\right) = \log\left(\mathbf{I}+\frac{\gamma_d}{n+1}\mathbf{G}_n\mathbf{G}_n^H\right) + \\ \log\left(1+\frac{\gamma_d}{n+1}\mathbf{g}_s^H\left(\mathbf{I}+\frac{\gamma_d}{n+1}\mathbf{G}_n\mathbf{G}_n^H\right)^{-1}\mathbf{g}_s\right). \tag{15}$$

Using the notations $\mathbf{T}_{2,n} = \left(\frac{n+1}{\gamma_d}\mathbf{I}+\mathbf{G}_n\mathbf{G}_n^H\right)^{-1}$ and $\delta_{2,s,n} = \mathbf{g}_s^H\mathbf{T}_{2,n}\mathbf{g}_s$, we rewrite Eq. (15) as

$$\log\left(\mathbf{I}+\frac{\gamma_d}{n+1}\mathbf{G}_{n+1}\mathbf{G}_{n+1}^H\right) = \log\left(\mathbf{I}+\frac{\gamma_d}{n+1}\mathbf{G}_n\mathbf{G}_n^H\right) + \\ \log\left(1+\delta_{2,s,n}\right). \tag{16}$$

It's worth noting that the first term on the right-side of Eq. (16) can be expressed as the following equation by using the generalization of matrix determinant lemma

$$\log\left(\mathbf{I}+\frac{\gamma_d}{n+1}\mathbf{G}_n\mathbf{G}_n^H\right) = \log\left(\mathbf{I}+\frac{\gamma_d}{n}\mathbf{G}_n\mathbf{G}_n^H\right) + \\ \log\det\left(\mathbf{I}-\frac{\gamma_d}{n(n+1)}\mathbf{G}_n^H\left(\mathbf{I}+\frac{\gamma_d}{n}\mathbf{G}_n\mathbf{G}_n^H\right)^{-1}\mathbf{G}_n\right). \tag{17}$$

Thus, combining Eqs. (9), (16) and (17), we have the following iterative equation

$$EE_{(2,n+1)} = \Psi(n)EE_{(2,n)} + D_n + \Delta_{2,s,n}, \tag{18}$$

where $D_n = \frac{\log\det\left(\mathbf{I}-\frac{\gamma_d}{n(n+1)}\mathbf{G}_n^H\left(\mathbf{I}+\frac{\gamma_d}{n}\mathbf{G}_n\mathbf{G}_n^H\right)^{-1}\mathbf{G}_n\right)}{P_{n+1}}$ and $\Delta_{2,s,n} = \frac{\log(1+\delta_{2,s,n})}{P_{n+1}}$.

Finally, with Eqs. (7), (13) and (18), we can conclude that

$$EE_{(n+1)} = \frac{1}{2}\min\left(\Psi(n)EE_{(1,n)} + \Delta_{1,s,n},\right. \\ \left.\Psi(n)EE_{(2,n)} + D_n + \Delta_{2,s,n}\right). \tag{19}$$

■

Theorem 1 helps to decouple the effect of relay antenna selection in DF MIMO relay systems. In particular, the term D_n represents the impact of the circuit power consumption on the energy efficiency. The contribution to the energy efficiency of adding the sth receive or transmit antenna is captured by the term $\Delta_{\kappa,s,n}$, $\kappa = \{1, 2\}$. Therefore, it guides us to find a pair of receive and transmit antennas that brings the largest contribution to energy efficiency at each step. Moreover, since the term P_{n+1} is a constant for a given transmission power pair, the selection of the pair of receive and transmit antennas can be equivalent to the following problems

$$s_r^* = \arg\max_s\left(\log\left(1+\delta_{1,s,n}\right)\right), \tag{20}$$

$$s_t^* = \arg\max_s \left(\log\left(1 + \delta_{2,s,n}\right)\right). \tag{21}$$

Therefore, according to Eqs. (20) and (21), we add the s_r^*th receive antenna and s_t^*th transmit antenna into the subsets ω_r and ω_t respectively at each step.

B. Power Adaptation and the Proposed Algorithm

After the iteration of antennas and the update of the selected subsets of receive and transmit antennas, we are now in the position to calculate the optimal transmission power that maximizes the EE for the current antenna subsets. Since the numerator of EE is a concave function and the denominator is a convex function over (P_s, P_r), the maximization problem under certain antenna subsets is pseudo-concave. As shown in [11], this pseudo-concave problem can be efficiently solved by using the tool of fractional programming which is related to a parametric program. Based on this property, we adopt the Dinkelbach method in [11] to find the optimal transmission power pair (P_s^*, P_r^*) that maximizes the energy efficiency for each step. Then, we take this optimal value as the initial transmission power pair (P_s, P_r) for the next step. In the following iterations, we can always update (P_s, P_r) by the optimal pair (P_s^*, P_r^*) of the last iteration. It's worth pointing out that the antenna selection for the first step is independent with the transmission power as $\mathbf{T}_{1,n}$ and $\mathbf{T}_{2,n}$ are both identity matrices. Therefore, for the first iteration, we just select the antennas with the largest channel gains and then calculate the optimal transmission power pair using the Dinkelbach method. By using the proposed algorithm, the exponential calculations of the optimal EE is reduced to N_r only.

IV. Simulation Results

In this section, we provide simulation results to demonstrate the potential of the proposed algorithm. The EE is averaged over 2000 channel realizations. The values for P_{ct}, P_{cr}, $P_{c,R}$ and P_{c0} are 120mW, 85mW, 200mW and 30mW, respectively [10]. $P_s^{\max} = P_r^{\max} = 300$mW, $\eta_s = \eta_r = 0.38$, $C_{\min} = 0.5$(bits/s/Hz). The log-distance path loss model is adopted from [12] and its path loss exponent is 4. The noise factors among the nodes are the same and equal to $\sigma^2 = -174$dBm/Hz. $\alpha = d_{\mathrm{sr}}/d$ is the ratio of the distance between the source and relay d_{sr}, and the distance between the source and destination d. $N_s = N_r = N_d = 4$.

Figure 1 compares the performance of the proposed algorithm and the exhaustive search for different transmission distances between the source and destination for $\alpha = 0.5$. It is easy to find that near-optimal performance can be achieved by the proposed algorithm for all the distances[2]. Moreover, we can see that the EE gain over conventional protocol is remarkable. Thus antenna selection could not only reduce the complexity of RF chains, but could also improve the energy efficiency significantly. Figure 2 illustrates the total transmission power consumption when achieving the optimum

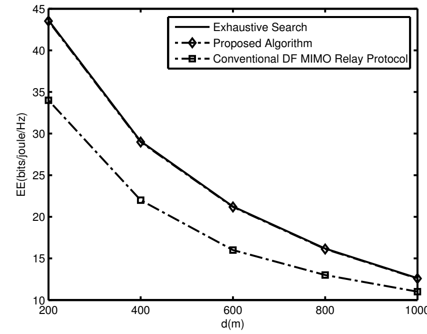

Fig. 1. Energy efficiency VS. the transmission distance d with $\alpha = 0.5$

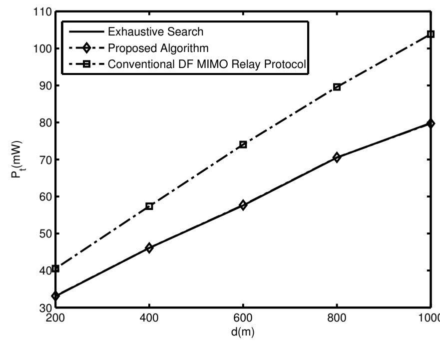

Fig. 2. The optimal total transmission power VS. the transmission distance d

EE as a function of the transmission distance, i.e., $P_t = P_s^* + P_r^*$. It can be seen that much more power is consumed for transmission when there is no antenna selection. The gap increases significantly upon increasing of the transmission distance. This fact shows that antenna selection could not only improve the energy efficiency, but could also reduce the transmission power.

V. Conclusion

In this paper, we investigated the EE maximization with relay antenna selection in DF MIMO relay systems. An iterative algorithm was proposed to jointly select the best antenna subsets at the relay, as well as optimize the transmission power. The proposed algorithm was based on the derived iterative property of EE and the transmission power adaptation, in which the tool of fractional programming was adopted. Simulation results demonstrated that the proposed algorithm enjoys a low complexity and achieves near-optimal performance. Moreover, it is capable of improving the EE, whilst reducing power consumption for transmission, therefore helps to guide the design of future energy efficient wireless relaying systems.

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