On Energy Efficiency Maximization of AF MIMO Relay Systems with Antenna Selection

(Invited Paper)

Xingyu Zhou*, *Student Member, IEEE,* Bo Bai* *Member, IEEE,* Wei Chen* *Senior Member, IEEE,* and Yuxing Han†
E-mail: xy-zhou12@mails.tsinghua.edu.cn eebobai@tsinghua.edu.cn wchen@tsinghua.edu.cn erica.yuxing.han@gmail.com
*State Key Laboratory on Microwave and Digital Communication
Tsinghua National Laboratory for Information Science and Technology (TNList)
Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
†Flora Production Inc., Santa Clara, CA 95054 US

***Abstract*—In this paper, we investigate the maximization of energy efficiency (EE) in amplify-and-forward (AF) MIMO relay systems combined with relay antenna selection. An iterative 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. Specifically, the antenna selection process is based on a derived iterative property of EE, which guides us to select a pair of receive and transmit relay antennas that achieves the largest increment of EE under an initial transmission power at each step. Then a power adaptation is adopted where we calculate the optimal transmission power using fractional programming and set it as the initial one for the next antenna selection. 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 transmission power.**

***Index Terms*—Energy efficiency, antenna selection, power adaptation, amplify-and-forward, MIMO relay**

I. Introduction

Wireless MIMO relaying is an extensively studied technique to increase the reliability, data rate and coverage for communication systems [1], [2]. In this context, the amplify-and-forward (AF) approach is widely used due to its advantage of a low complexity design of relays. Meanwhile, there is a radical increase in the energy consumption along with the rapid evolution of modern wireless communications [3]. Therefore, it becomes more and more important to design energy efficient AF MIMO relay systems.

The investigations on energy efficient AF MIMO relay systems concentrate upon two main aspects. The first one is the antenna selection (AS) technique, which selects a subset of active antennas for transmitting or receiving and thus holds the promise of reducing the energy consumption. However, an exhaustive search over all the possible subsets can hardly be adopted in practice due to its high computational expense. To avoid this problem, several literatures have focused on low complexity AS schemes for AF MIMO relay systems [4]–[6]. In these works, the circuit power consumption of RF chains is not considered and the constraint is only the transmission power. The goal is that of finding optimal antenna subsets to maximize the capacity. However, the results of these schemes cannot guarantee to be global energy efficient when the performance metric is chosen as energy efficiency (EE), which is defined as the ratio of rate to the total power. Therefore, another aspect of the studies on energy efficient MIMO relay is try to optimize the EE. In this case, a holistic power model which includes the circuit power as well as the transmission power should be adopted to comprehensively quantify the energy consumption in the system. The EE maximization in AF MIMO relay systems with both perfect and statistical channel state information (CSI) is investigated in the pioneer work [7], where antenna selection is not considered yet. To the best of our knowledge, the energy efficient design of AF MIMO relay systems considering the above-mentioned two aspects, i.e., the EE maximization with antenna selection, has not been investigated in a systematic way.

Motivated by this background, we investigate the EE maximization in AF MIMO relay systems combined with relay antenna selection under a holistic power model. Specifically, our task is to find the optimal number of active RF chains, the corresponding receive and transmit relay antenna subsets as well as the optimal transmission power of the source and relay. Exhaustive search for this NP-hard problem 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 AF MIMO relay system with relay antenna selection under the 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 for an initial transmission power. Then we update the transmission power by using the tool of fractional programming and set the

This paper is partially supported by the National Basic Research Program of China (973 Program 2013CB336600 and 2012CB316000), NSFC Excellent Young Investigator Award No. 61322111, NSFC under Grant No. 61401249, Chuanxin Funding, MoE new century talent program under No. NCET-12-0302, Beijing Nova Program No. Z121101002512051, Specialized Research Fund for the Doctoral Program of Higher Education (SRFDP) under Grant No. 20130002120001, National Science and Technology Key Project No. 2013ZX03003006-005 and 2013ZX03003004-002, and National innovative talents promotion program No. 2013RA2151.

new transmission power as the initial one for the next antenna selection. Simulation results show that our proposed scheme achieves near-optimal performance. The achievable EE with our scheme is much better than that of conventional AF MIMO relay protocol without antenna selection.

II. System Model and Problem Formulation

A. System Model

Consider a dual-hop AF MIMO relay system with one source, one relay and one destination. The source, relay and destination have N_s, N_r and N_d antennas, respectively. The direct link between the source and the destination is ignored due to the large distance. $\mathbf{H} \in \mathbb{C}^{N_r \times N_s}$ and $\mathbf{G} \in \mathbb{C}^{N_d \times N_r}$ represent the source-relay and relay-destination channels, respectively. Assume that all the channels are Rayleigh flat fading with average power varied with the path loss. Throughout this paper, assume the relay operates in half-duplex mode and hence the transmission time interval is divided into two time slots. The selected subsets of active receive and transmit antennas at the relay are denoted by ω_r and ω_t, respectively. In particular, if the number of active RF chains at the relay is L, then we have $\omega_r = \{r(1), r(2), \ldots, r(L)\}$ and $\omega_t = \{t(1), t(2), \ldots, t(L)\}$ where $r(l)$ and $t(l)$ stand for the indices for the lth selected receive and the lth selected transmit antenna, respectively. Note that the relay has two independent time slots for reception and transmission, and hence the selected receive subset is not necessarily the same as the transmit subset. The only constraint on the two selected subsets is that they have the same cardinality, i.e., $|\omega_r| = |\omega_t|$, which is equal to the number of active RF chains at the relay.

In the first time slot, the signal transmitted through the selected subchannel between the source and relay. During the second time slot, the relay amplifies the received signal and transmits it from the selected active transmit antennas to the destination. According to [1], [2], the achievable rate of our considered AF MIMO relay system is given by

$$R\left(P_s, P_r, \mathbf{H}_{\omega_r}, \mathbf{G}_{\omega_t}\right) = \frac{1}{2}\log_2 \frac{\left|\mathbf{I}_{N_d} + \alpha \mathbf{G}_{\omega_t}\mathbf{G}_{\omega_t}^H + \alpha\rho_1 \mathbf{F}\mathbf{F}^H\right|}{\left|\mathbf{I}_{N_d} + \alpha \mathbf{G}_{\omega_t}\mathbf{G}_{\omega_t}^H\right|}, \tag{1}$$

where $\mathbf{H}_{\omega_r}$ is the $|\omega_r| \times N_s$ subchannel matrix between the source and relay when the relay activates the receive antennas in ω_r, $\mathbf{G}_{\omega_t}$ is the $N_d \times |\omega_t|$ subchannel matrix between the relay and destination when the relay activates the transmit antennas in ω_t and $\mathbf{F} = \mathbf{G}_{\omega_t}\mathbf{H}_{\omega_r}$. $\alpha = \frac{P_r/N_0}{\rho_1 \mathrm{tr}\left(\mathbf{H}_{\omega_r}\mathbf{H}_{\omega_r}^H\right) + |\omega_r|}$ is the power coefficient satisfying the relay power constraint P_r, where $\rho_1 = P_s/(N_s N_0)$, P_s is the transmission power of the source and N_0 is the additive noise power.

The considered holistic power model in this paper 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 part in our considered system is given by [8]

$$P_c = N_s P_{ct} + N_d P_{cr} + |\omega_r|\left(P_{cr,R} + P_{ct,R}\right) + P_{c0}, \tag{2}$$

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 EE for AF MIMO relay systems with antenna selection adopted at the relay. According to the definition of EE in [3], the EE of our system under the holistic power model is given by

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

where $P_{c,R} = P_{cr,R} + P_{ct,R}$. To maximize the EE 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

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

In problem (5), $R_{\min}$ 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 avoid the computational expense of exhaustive search in problem (5). The main idea of this algorithm has two key points: 1) At each step, it judiciously selects a pair of receive and transmit relay antennas that achieves the largest increment of EE for a given transmission power pair. 2) Then it calculates the optimal transmission power pair for the current selected antenna subsets and set it as the initial transmission power pair for the next step. The two key points are respectively elaborated in subsections A and B.

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. For clarity, let us first define the notations used in Theorem 1.

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 the subchannel matrix between the source and relay, and the subchannel matrix between the relay and destination after n steps selection by $\mathbf{H}_n$ and $\mathbf{G}_n$, respectively. $\mathbf{\Phi}_n = \left|\mathbf{I}_{N_d} + \alpha_n \mathbf{G}_n \mathbf{G}_n^H\right|$ and

$\mathbf{\Theta}_n = \left|\mathbf{I}_{N_d} + \alpha_n \mathbf{G}_n \mathbf{G}_n^H + \beta_n \mathbf{F}_n \mathbf{F}_n^H\right|$ represent the denominator and numerator of Eq. (1) for the nth step, where $\alpha_n = \frac{P_r/N_0}{\rho_1 \mathrm{tr}\left(\mathbf{H}_n \mathbf{H}_n^H\right) + |\omega_r|}$ and $\beta_n = \alpha_n \rho_1$. P_n stands for the overall power consumption for the nth step, i.e., the number of active RF chains is n. According to Eq. (3), we have that $P_n = nP_{c,R} + \frac{1}{\eta_s}P_s + \frac{1}{\eta_r}P_r + N_s P_{ct} + N_d P_{cr} + P_{c0}$. At the $(n+1)$th step, if the l^*th receive and the s^*th transmit antenna of the relay are selected, i.e., $r(n+1) = l^*, t(n+1) = s^*$, 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. $\mathbf{h}_l$ is the transpose of the lth row of $\mathbf{H}$ and $\mathbf{g}_s$ is the sth column of $\mathbf{G}$.

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

$$EE_{(n+1)} = \Lambda(n) EE_{(n)} + D_{n+1} + \Delta_{(l,s),n+1}, \tag{6}$$

where $\Lambda(n)$, D_{n+1} and $\Delta_{(l,s),n+1}$ are defined after Eq. (23).

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

$$EE_{(n+1)} = \frac{R_{n+1}}{P_{n+1}}, \tag{7}$$

where $R_{n+1} = \frac{1}{2}\log_2 \frac{\mathbf{\Theta}_{n+1}}{\mathbf{\Phi}_{n+1}}$. Thus, in order to find the iteration equation of Eq (7), we have to find the respective iterations of $\mathbf{\Phi}_{n+1}$ and $\mathbf{\Theta}_{n+1}$ first. We begin with the term $\mathbf{\Phi}_{n+1} = \left|\mathbf{I}_{N_d} + \alpha_{n+1}\mathbf{G}_{n+1}\mathbf{G}_{n+1}^H\right|$. Noting that

$$\mathbf{G}_{n+1}\mathbf{G}_{n+1}^H = \mathbf{G}_n \mathbf{G}_n^H + \mathbf{g}_s \mathbf{g}_s^H, \tag{8}$$

and applying the matrix determinant lemma to $\mathbf{\Phi}_{n+1}$, we can obtain that

$$\mathbf{\Phi}_{n+1} = \left|\mathbf{I}_{N_d} + \alpha_{n+1}\mathbf{G}_n \mathbf{G}_n^H\right| \delta_{\phi,s,n+1}, \tag{9}$$

where

$$\delta_{\phi,s,n+1} = 1 + \alpha_{n+1}\mathbf{g}_s^H \mathbf{T}_{\phi,n}\mathbf{g}_s, \tag{10}$$

$$\mathbf{T}_{\phi,n} = \left(\mathbf{I}_{N_d} + \alpha_{n+1}\mathbf{G}_n \mathbf{G}_n^H\right)^{-1}. \tag{11}$$

It's worth pointing out that Eq. (9) can be further reduced by using the generalization of matrix determinant lemma.

$$\begin{aligned}\mathbf{\Phi}_{n+1} &= \left|\mathbf{I}_{N_d} + \alpha_n \mathbf{G}_n \mathbf{G}_n^H - \mu_n \mathbf{G}_n \mathbf{G}_n^H\right| \delta_{\phi,s,n+1} \\ &= \mathbf{\Phi}_n \delta_{\phi,1,n+1}\delta_{\phi,s,n+1},\end{aligned} \tag{12}$$

where

$$\mu_n = \alpha_n - \alpha_{n+1}, \tag{13}$$

$$\delta_{\Phi,1,n+1} = \left|\mathbf{I} - \mu_n \mathbf{G}_n^H \left(\mathbf{I}_{N_d} + \alpha_n \mathbf{G}_n \mathbf{G}_n^H\right)^{-1}\mathbf{G}_n\right|. \tag{14}$$

Now, we turn to find the iteration equation for the term $\mathbf{\Theta}_{n+1} = \left|\mathbf{I}_{N_d} + \alpha_{n+1}\mathbf{G}_{n+1}\mathbf{G}_{n+1}^H + \beta_n \mathbf{F}_{n+1}\mathbf{F}_{n+1}^H\right|$. By using the similar method in Eq. (8), we could rewrite $\mathbf{\Theta}_{n+1}$ as the following equation

$$\mathbf{\Theta}_{n+1} = \left|\mathbf{I}_{N_d} + \alpha_{n+1}\mathbf{G}_n \mathbf{G}_n^H + \beta_{n+1}\mathbf{F}_n \mathbf{F}_n^H + \mathbf{g}_s \mathbf{q}^H + \mathbf{q}\mathbf{g}_s^H\right|, \tag{15}$$

where $\mathbf{q} = \frac{\alpha_{n+1} + \beta_{n+1}\|\mathbf{h}_l\|^2}{2}\mathbf{g}_s + \beta_{n+1}\mathbf{F}_n \mathbf{h}_l^*$. We can simplify Eq. (15) with the rank-2 update property of determinant:

$$\mathbf{\Theta}_{n+1} = \left|\mathbf{I}_{N_d} + \alpha_{n+1}\mathbf{G}_n \mathbf{G}_n^H + \beta_{n+1}\mathbf{F}_n \mathbf{F}_n^H\right| \delta_{\theta,(l,s),n+1}, \tag{16}$$

where

$$\delta_{\theta,(l,s),n+1} = \left(1 + \mathbf{q}^H \mathbf{T}_{\theta,n}\mathbf{g}_s\right)^2 - \left(\mathbf{g}_s^H \mathbf{T}_{\theta,n}\mathbf{g}_s\right)\left(\mathbf{q}^H \mathbf{T}_{\theta,n}\mathbf{q}\right), \tag{17}$$

$$\mathbf{T}_{\theta,n} = \left(\mathbf{I}_{N_d} + \alpha_{n+1}\mathbf{G}_n \mathbf{G}_n^H + \beta_{n+1}\mathbf{F}_n \mathbf{F}_n^H\right)^{-1}. \tag{18}$$

We may now apply the generalization of matrix determinant lemma to Eq. (16) twice, i.e,. corresponding to $\mathbf{G}_n \mathbf{G}_n^H$ and $\mathbf{F}_n \mathbf{F}_n^H$ respectively, and thus obtain that

$$\mathbf{\Theta}_{n+1} = \mathbf{\Theta}_n \delta_{\theta,2,n+1}\delta_{\theta,1,n+1}\delta_{\theta,(l,s),n+1}, \tag{19}$$

where

$$\delta_{\theta,1,n+1} = |\mathbf{I} - \nu_n \mathbf{F}_n^H \left(\mathbf{I}_{N_d} + \alpha_{n+1}\mathbf{G}_n \mathbf{G}_n^H + \beta_n \mathbf{F}_n \mathbf{F}_n^H\right)^{-1}\mathbf{F}_n|, \tag{20}$$

$$\delta_{\theta,2,n+1} = |\mathbf{I} - \mu_n \mathbf{G}_n^H \left(\mathbf{I}_{N_d} + \alpha_n \mathbf{G}_n \mathbf{G}_n^H + \beta_n \mathbf{F}_n \mathbf{F}_n^H\right)^{-1}\mathbf{G}_n|, \tag{21}$$

$$\nu_n = \beta_n - \beta_{n+1}. \tag{22}$$

Having derived the two respective iterative equations for $\mathbf{\Phi}_{n+1}$ and $\mathbf{\Theta}_{n+1}$, we are able to show the iteration of EE. Combining Eqs (7), (12) and (19), we can conclude that

$$EE_{(n+1)} = \Lambda(n) EE_{(n)} + D_{n+1} + \Delta_{(l,s),n+1}, \tag{23}$$

where $\Lambda(n) = \frac{P_n}{P_{n+1}}$, $D_{n+1} = \frac{1}{2}\frac{\log \frac{\delta_{\theta,2,n+1}\delta_{\theta,1,n+1}}{\delta_{\phi,1,n+1}}}{P_{n+1}}$ and $\Delta_{(l,s),n+1} = \frac{1}{2}\frac{\log \frac{\delta_{\theta,(l,s),n+1}}{\delta_{\phi,s,n+1}}}{P_{n+1}}$.

■

Theorem 1 helps to decouple the effect of relay antenna selection in AF MIMO relay systems. In particular, the term D_{n+1} represents the impact of the circuit power consumption on the EE. The contribution to the EE of adding the lth receive and the sth transmit antenna at the $(n+1)$th step is captured by the term $\Delta_{(l,s),n+1}$. Therefore, it guides us to find a pair of receive and transmit antennas that brings the largest contribution to EE 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 problem

$$(r(n+1), t(n+1)) = \arg\max_{(l,s)} \frac{\delta_{\theta,(l,s),n+1}}{\delta_{\phi,s,n+1}}. \tag{24}$$

Thus, according to Eq (24), we add the $r(n+1)$th receive antenna and the $t(n+1)$th transmit antenna into the subsets ω_r and ω_t respectively at the $(n+1)$th step.

B. Power Adaptation and the Proposed Algorithm

After the update of the selected receive and transmit antenna subsets, we are now in the position to calculate the optimal transmission power that maximizes the EE for the current antenna subsets. It can be proved that the numerator of EE is a concave function and the denominator is a convex function

Algorithm I
OPTIMIZATION ALGORITHM FOR ENERGY EFFICIENCY

Step 1: Initialize all the channels, noise factors, and set $L = 1$.
Step 2: Select one pair of antennas at the relay (l^*, s^*) according to Eq (24), respectively.
Step 3: Update the selected subsets ω_r^* and ω_t^* and calculate the optimal transmission power pair (P_s^*, P_r^*) and maximum EE using the Dinkelbach method.
Step 4: Set the optimal transmission power pair (P_s^*, P_r^*) as the initial one for the next antenna selection.
Step 5: Set $L = L + 1$, if $L \leq N_r$, go to step 2; else stop.
Step 6: Choose the L with the largest EE and the corresponding antenna subsets and transmission power.

over (P_s, P_r) under the constraints of our problem. Thus the EE maximization problem under certain antenna subsets is pseudo-concave. As shown in Proposition 1, this pseudo-concave problem can be efficiently solved by using the tool of fractional programming which is related to a parametric program as stated in [9].

***Proposition** 1:* An optimization problem $\max\{\frac{R(x)}{P(x)}|x \in S\}$ is pseudo-concave when $R(x)$ is concave and $P(x)$ is convex for all $x \in S$. It can be related to the following parametric program

$$\max\{R(x) - qP(x)|x \in S\},\ q \in R. \tag{25}$$

The maximum value can be achieved $q^* = \frac{R(x^*)}{P(x^*)}$ if and only if q^* and x^* satisfy $F(q^*) = F(q^*, x^*) = \max\{R(x) - qP(x)|x \in S\} = 0$. The root of the $F(q)$ can be efficiently found by the Dinkelbach method [9].

Based on Proposition 1, the Dinkelbach method is employed to calculate the optimal transmission power pair (P_s^*, P_r^*) that maximizes the EE for each step. Then, this optimal power pair is set 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 because $\mathbf{T}_{\phi,n}$ and $\mathbf{T}_{\theta,n}$ are both identity matrices. Therefore, for the first iteration, the optimal pair of relay antennas can be selected regardless of the transmission power. According to Theorem 1 and the above-mentioned power adaptation process, an iterative EE maximization algorithm is proposed.[1] The details of the proposed algorithm are shown in Algorithm I.

IV. SIMULATION RESULTS

In this section, we provide simulation results to demonstrate the potential of the proposed algorithm. The EE is averaged over 3000 channel realizations. The values for P_{ct}, P_{cr}, $P_{c,R}$ and P_{c0} are 120mW, 85mW, 150mW and 30mW, respectively [8]. $P_s^{\max} = P_r^{\max} = 300$ mW, $\eta_s = 0.38$, $\eta_r = 0.5$, $R_{\min} =$ 0.5(bits/s/Hz). $n = 4$ is the exponent of the log-distance path loss model. The noise factors among the nodes are the same and equal to $N_0 = -174$ dBm/Hz. $\varepsilon = d_{\rm sr}/d$ is the ratio of the distance between the source and relay $d_{\rm sr}$, and the distance between the source and destination d. $N_s = N_r = N_d = 4$.

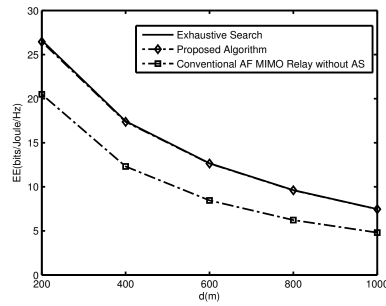

Fig. 1. Energy efficiency VS. the transmission distance d with $\varepsilon = 0.5$

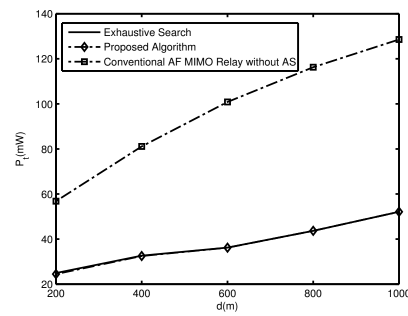

Fig. 2. The optimal total transmission power VS. the transmission distance d with $\varepsilon = 0.5$

Figure 1 demonstrates the performance of different algorithms as a function of the transmission distance between the source and destination d for $\varepsilon = 0.5$. It can be seen that near-optimal performance is achieved by the proposed algorithm for all the distances. Moreover, we can see that the EE gain over conventional protocol without AS is remarkable. Thus antenna selection could not only reduce the complexity of RF chains, but could also improve the EE significantly. Figure 2 illustrates the total transmission power consumption when achieving the optimum EE varies with the transmission distance, i.e., $P_t = P_s^* + P_r^*$. It shows that more energy is saved when our proposed scheme is adopted. The gap between our scheme and the conventional protocol increases significantly upon increasing of the transmission distance. This fact shows that antenna selection could not only improve the EE, but could also reduce the transmission power consumption.

V. CONCLUSION

An iterative algorithm was proposed to jointly select the best antenna subsets at the relay, as well as optimize the transmission power. The joint iteration of active antennas and transmission power constitute the core of the proposed algorithm. Simulation results demonstrated that the proposed algorithm enjoys a low complexity and achieves near-optimal performance.

[1]It is the fact that a slight fluctuation in the transmission power has little influence on the optimality of antenna selection makes our proposed algorithm feasible, which has been validated in our previous work [10]

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