A Low Complexity Energy Efficiency Maximization Method for Multiuser Amplify-and-Forward MIMO Relay Systems With a Holistic Power Model

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***Abstract*—In this letter, we investigate the energy efficiency (EE) maximization problem in multiuser amplify-and-forward (AF) MIMO relay systems with a holistic power model. A low complexity EE maximization method is proposed to jointly select the active antennas and the user, as well as optimize the transmission power of the user and relay. More specifically, the active antennas at the relay are selected by a norm-based scheme. We also propose a low complexity iteration scheme based on fractional programming, which can efficiently solve the pseudo-concave problem, in order to select the user and optimize the transmission power. Simulation results show that the proposed low complexity method enjoys a probability of 99% to hit the optimal EE obtained by exhaustive search. Moreover, it has an average gain of 42% in the EE over the conventional AF MIMO relay protocol.**

***Index Terms*—Energy efficiency, user selection, antenna selection, amplify-and-forward, MIMO relay.**

I. INTRODUCTION

WIRELESS relaying is an extensively studied technique to increase the reliability, data rate and coverage for communication systems. In this context, the amplify-and-forward (AF) approach is widely used due to its advantage of a low complexity design of relays. Meanwhile, the use of multiple antennas has become a key-factor in modern communications for its benefit of a larger diversity and a higher spectrum efficiency.

The fact that the nodes in mobile networks are often under a limited power supply has garnered a great deal of interest on the aspect of energy efficient transmission in AF MIMO relay systems. Most existing literatures on the efficient use of energy try to maximize the rate or to minimize the total power under a QoS constraint [1], [2]. However, the results of these schemes cannot guarantee to be global energy efficient when the EE (energy efficiency) is adopted as the performance metric, which is defined as the ratio of rate to the total power. To the best of our knowledge, the first paper that investigates the maximization of EE in MIMO relay systems is [3]. The authors proposed a suboptimal algorithm based on fractional programming and alternative optimization for the single-user scenario where the numbers of active antennas among nodes are fixed. More recently, multiuser MIMO relay systems attract much attention in future communication systems such as 5G. However, adopting multiple antennas will consume more circuit power. In this case, antenna selection at the relay in which only a subset of available antennas are active for transmitting and receiving is a good choice to reduce the power consumption without incurring much performance loss.

Motivated by this background, we investigate the EE maximization for a multiuser AF MIMO relay system with a holistic power model in this letter, where a joint selection of the active antennas and the user, as well as the optimization of transmission power is considered. Exhaustive search is the only optimal method which is yet complexity prohibitive. To avoid this problem, a low complexity EE maximization method is proposed. It consists of two main parts. First, the active antennas at the relay are selected by a norm-based scheme. Then, the user selection and transmission power optimization are handled by an iterative process, in each iteration fractional programming is introduced to solve the pseudo-concave EE maximization problem. Simulation results show that near-optimal performance is achieved. The EE with user and antenna selection is much better than that of conventional AF MIMO relay protocol.

II. SYSTEM MODEL

Consider a multiuser AF MIMO relay communication system. There are N_s users each of which is equipped with only one antenna due to its size and cost constraints. In each timeslot, only one user is scheduled to transmit its own information to the base station (BS) with the aid of a multi-antenna relay. In particular, N_r and N_d antennas are equipped at the relay and BS, respectively. The selected active receive and transmit antenna subsets at the relay are denoted by ω_r and ω_t, respectively. We assume $L = |\omega_r| = |\omega_t|$, 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. Moreover, all the nodes operate in half-duplex mode and hence we have two phases for transmission.

In the first phase, the received signal at the relay is modeled as

$$\mathbf{y}_1 = \mathbf{h}_1(i, \omega_r)s + \mathbf{n}_1, \tag{1}$$

where s is the transmitted scalar symbol with an average power P_s. $\mathbf{h}_1(i, \omega_r)$ represents the channel gains between the ith user and the corresponding subset of receive antennas ω_r at the relay. $\mathbf{n}_1$ is the $L \times 1$ AWGN (Additive White Gaussian Noise) vector with variance $\sigma_1^2\mathbf{I}_L$. At the BS, the received signal during the first phase is

$$\mathbf{y}_0 = \mathbf{h}_0(i)s + \mathbf{n}_0, \tag{2}$$

where $\mathbf{h}_0(i)$ stands for the channel gains between the ith user and the BS. $\mathbf{n}_0$ is the $N_d \times 1$ AWGN vector with variance $\sigma_0^2\mathbf{I}_{N_d}$.

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The signal received at the BS during the second phase is presented by

$$\mathbf{y}_2 = \mathbf{H}_2(\omega_t)\mathbf{G}\mathbf{h}_1(i,\omega_r)s + \mathbf{H}_2(\omega_t)\mathbf{G}\mathbf{n}_1 + \mathbf{n}_2, \quad (3)$$

where $\mathbf{G}$ is the AF matrix of the relay, and $\mathbf{H}_2(\omega_t)$ denotes the $N_d \times L$ subchannel matrix. $\mathbf{n}_2$ is the $N_d \times 1$ AWGN vector with variance $\sigma_2^2\mathbf{I}_{N_d}$. The average power for transmission used by the relay is P_r, which could be obtained by

$$\mathrm{tr}\left\{\sigma_1^2\mathbf{G}\mathbf{G}^H + P_s\mathbf{G}\mathbf{h}_1(i,\omega_r)\left(\mathbf{h}_1(i,\omega_r)\right)^H\mathbf{G}^H\right\} = P_r, \quad (4)$$

where $\mathrm{tr}\{\cdot\}$ represents the trace of a matrix.

After the two phases, the BS now has two received signals containing s. We could rewrite it in the standard way as follows

$$\mathbf{y} = \mathbf{h}s + \mathbf{n}, \quad (5)$$

where $\mathbf{y} = \begin{bmatrix}\mathbf{y}_0\\ \mathbf{y}_2\end{bmatrix}$, $\mathbf{h} = \begin{bmatrix}\mathbf{h}_0(i)\\ \mathbf{H}_2(\omega_t)\mathbf{G}\mathbf{h}_1(i,\omega_r)\end{bmatrix}$, and $\mathbf{n} = \begin{bmatrix}\mathbf{n}_0\\ \mathbf{H}_2(\omega_t)\mathbf{G}\mathbf{n}_1 + \mathbf{n}_2\end{bmatrix}$. The optimal and information preserving receiving filter is the Wiener filter. In this case, the achievable rate is given by

$$R = \frac{1}{2}\log_2\left(1 + P_s\mathbf{h}^H\mathbf{K}_n^{-1}\mathbf{h}\right), \quad (6)$$

where $\mathbf{K}_n$ is the covariance matrix of the noise vector $\mathbf{n}$. The factor 1/2 comes from the fact that the signal s is transmitted in two phases.

The holistic energy consumption is the energy consumed for transmission plus the energy consumption of RF chains, which can be expressed as

$$\begin{aligned} E &= \frac{T}{2}\left(\frac{1}{\eta_{pa,u}}P_s + P_{ct} + L\cdot P_{cr,AF} + N_d\cdot P_{cr}\right) \\ &\quad + \frac{T}{2}\left(\frac{1}{\eta_{pa,r}}P_r + L\cdot P_{ct,AF} + N_d\cdot P_{cr}\right) \\ &= \frac{T}{2}\left(\frac{1}{\eta_{pa,u}}P_s + \frac{1}{\eta_{pa,r}}P_r + L\cdot P_{AF} + P_c\right), \end{aligned} \quad (7)$$

where T is the two phases transmission time, $\eta_{pa,u}$ and $\eta_{pa,r}$ are the drain efficiency of the power amplifiers at the user and relay, $P_c = P_{ct} + 2N_d\cdot P_{cr}$, $P_{AF} = P_{cr,AF} + P_{ct,AF}$. P_{ct} and $P_{ct,AF}$ are the power consumed by each user and relay RF chain for transmission. P_{cr} and $P_{cr,AF}$ are the power consumed by each BS and relay RF chain for reception, respectively [4], [5].

III. Energy Efficiency Maximization

In this section, we first formulate the optimization problem. Then, a low complexity joint user and antenna selection for EE maximization algorithm (J-SEEM) is proposed. Finally, the special scenario when the direct link is weak is considered.

A. Problem Formulation

From [6], the optimal relay matrix that maximizes the capacity in Eq. (6) is as follows

$$\mathbf{G} = \upsilon\mathbf{v}_2(1)\left(\mathbf{h}_1(i,\omega_r)\right)^H, \quad (8)$$

where υ is a scaling factor to satisfy the power constraint on the relay. $\mathbf{v}_2(1)$ is the right singular vector corresponding to the largest singular value of $\mathbf{H}_2(\omega_t)$. By substituting Eqs. (8) and (4) into Eq. (6), we obtain the achievable rate given by

$$R = \frac{1}{2}\log_2\left(1 + P_s\beta_0(i) + \frac{P_s\beta_1(i,\omega_r)\cdot P_r\beta_2(\omega_t)}{1 + P_s\beta_1(i,\omega_r) + P_r\beta_2(\omega_t)}\right), \quad (9)$$

where $\beta_0(i) = |\mathbf{h}_0(i)|^2/\sigma_0^2$, $\beta_1(i,\omega_r) = |\mathbf{h}_1(i,\omega_r)|^2/\sigma_1^2$ and $\beta_2(\omega_t) = \lambda_{\max}/\sigma_2^2 \cdot \lambda_{\max}$ is the square of the largest singular value of $\mathbf{H}_2(\omega_t)$.

As a result, the EE of our system is given by [3]

$$EE = \frac{T\cdot R}{E} = \frac{\log_2\left(1 + P_s\beta_0(i) + \frac{P_s\beta_1(i,\omega_r)\cdot P_r\beta_2(\omega_t)}{1 + P_s\beta_1(i,\omega_r) + P_r\beta_2(\omega_t)}\right)}{\frac{1}{\eta_{pa,u}}P_s + \frac{1}{\eta_{pa,r}}P_r + |\omega_r|\cdot P_{AF} + P_c} \quad (10)$$

in which the equivalent received SNR $= P_s\beta_0(i) + ((P_s\beta_1(i,\omega_r)\cdot P_r\beta_2(\omega_t))/(1 + P_s\beta_1(i,\omega_r) + P_r\beta_2(\omega_t)))$. To maximize EE in Eq. (10), we should jointly select the active antennas at the relay and the user, as well as optimize the transmission power. Specifically, our aim is to solve the optimization problem given by

$$\begin{aligned} &\max_{(P_s,P_r,i,\omega_r,\omega_t)} EE \\ &\text{s.t.} \begin{cases} \text{SNR} \geq \gamma \\ 1 \leq |\omega_r| = |\omega_t| \leq N_r \\ 0 < P_s \leq P_s^{\max}, 0 \leq P_r \leq P_r^{\max}. \end{cases} \end{aligned} \quad (11)$$

In problem (11), γ is the minimum required SNR at the receiver. $P_s^{\max}$ and $P_r^{\max}$ are the maximum transmission power for the user and the relay, respectively.

B. J-SEEM Algorithm

In this subsection, we propose an efficient joint user and antenna selection algorithm (J-SEEM) to address the problem (11). This algorithm consists of two main parts. First, a fast selection scheme for the active antenna subsets at the relay is proposed based on Lemma 1. Next, the user selection and transmission power optimization are tackled by an iterative process based on Theorem 1. In particular, the tool of fractional programming is adopted to find the maximum EE for each iteration based on Propositions 1 and 2.

Lemma 1: For a fixed L, if $\tilde{R} > R$ for any (P_s, P_r) in the feasible region, then $\tilde{EE}^* > EE^*$, in which $\tilde{EE}^*$ and EE^* are the maximum EE for each case, respectively.

Proof: Denote the optimal transmission power that achieves the EE^* by (P_s^*, P_r^*), which is also feasible for $\tilde{EE}$. Since $\tilde{R} > R$ for any (P_s, P_r) in the feasible region and the circuit power consumption is the same for a fixed L, $\tilde{EE}(P_s^*, P_r^*) > EE(P_s^*, P_r^*) = EE^*$. Noting that the $\tilde{EE}^* \geq \tilde{EE}(P_s^*, P_r^*)$, we can conclude $\tilde{EE}^* > EE^*$. ■

It can be easily seen that the achievable rate R is an increasing function of $\beta_0(i)$, $\beta_1(i,\omega_r)$ and $\beta_2(\omega_t)$ when the transmission power of the user and relay are fixed. From Lemma 1, we know the optimal selection for a fixed L is to maximize these three parameters as possible. For $\beta_2(\omega_t)$, the optimal subset of antennas ω_t^* should lead to the largest $\lambda_{\max}$, which is upper bounded by $\|\mathbf{H}_2(\omega_t)\|_F$. Therefore, we can order the relay antennas by their channel gains and select the L antennas with the largest gains as the selected ω_t^*, which is independent of the selection of i and ω_r. Clearly, the norm-based scheme can guarantee the optimal ω_r^* for each user i.

Note that the user selection cannot guarantee that both $\beta_0(i)$ and $\beta_1(i,\omega_r^*)$ achieve respective maximum value at the same time. The following theorem provides the user selection criterion based on the trade-off between $\beta_0(i)$ and $\beta_1(i,\omega_r^*)$.

Theorem 1: In high SNR regimes for a fixed L, if $\tilde{\beta_0}+(1/(1+\varepsilon)^2)\tilde{\beta_1}>\beta_0+(1/(1+\varepsilon)^2)\beta_1$, then $\tilde{EE}(\tilde{\beta_0},\tilde{\beta_1},\beta_2,P_s,P_r)>EE(\beta_0,\beta_1,\beta_2,P_s,P_r)$, in which $\varepsilon=\tilde{\beta_1}P_s/\beta_2P_r$.

Proof: The proof falls naturally into three cases. 1) Both $\tilde{\beta_0}$ and $\tilde{\beta_1}$ are larger. In this case, $\tilde{EE}>EE$ for any feasible (P_s,P_r). 2) $\tilde{\beta_0}>\beta_0$ and $\tilde{\beta_1}<\beta_1$. In this case, if $\tilde{\beta_0}+(1/(1+\varepsilon)^2)\tilde{\beta_1}>\beta_0+(1/(1+\varepsilon)^2)\beta_1$, we have

$$\frac{\tilde{\beta_0}-\beta_0}{\beta_1-\tilde{\beta_1}}>\left(\frac{\beta_2P_r}{\beta_2P_r+\tilde{\beta_1}P_s}\right)^2. \quad (12)$$

In the high SNR regimes, the term on the right-side of Eq. (12) can be approximated by $\Delta=((1+\beta_2P_r)/(1+\beta_2P_r+\tilde{\beta_1}P_s))^2$, which satisfies the following inequality

$$\Delta>\frac{(1+\beta_2P_r)(\beta_2P_r)}{(1+\beta_2P_r+\tilde{\beta_1}P_s)(1+\beta_2P_r+\beta_1P_s)}. \quad (13)$$

According to Eqs. (12) and (13), we have

$$\frac{\tilde{\beta_0}-\beta_0}{\beta_1-\tilde{\beta_1}}>\frac{(1+\beta_2P_r)(\beta_2P_r)}{(1+\beta_2P_r+\tilde{\beta_1}P_s)(1+\beta_2P_r+\beta_1P_s)}. \quad (14)$$

Combining Eqs. (14) and (10), we can obtain the result $\tilde{EE}(\tilde{\beta_0},\tilde{\beta_1},\beta_2,P_s,P_r)>EE(\beta_0,\beta_1,\beta_2,P_s,P_r)$. 3) $\tilde{\beta_0}<\beta_0$ and $\tilde{\beta_1}>\beta_1$. In the same manner as the case two, we can arrive at the conclusion. Due to space limitation, we omit the detailed proof. ■

According to Theorem 1, the user selection can be captured by the following iterative process: 1) For an initial ε^*, find the optimal user of the current iteration according to Eq. (15).

$$i^*=\arg\max_i\left\{\beta_0(i)+\frac{1}{(1+\varepsilon^*)^2}\beta_1(i,\omega_r^*)\right\}, \quad (15)$$

where $\varepsilon^*=\beta_1(i^*,\omega_r^*)P_s^*/\beta_2(\omega_t^*)P_r^*$ changes iteratively with the selection of the user and its initial value is $\beta_1(1,\omega_r^*)/\beta_2(\omega_t^*)$. Here, ε^* is only concerned with the optimal user rather than two different users for fast practical implementations. Its validity has been verified by simulation results. P_s^* and P_r^* are the optimal transmission power for each iteration of the user selection. 2) Update ε^* and obtain the optimal user for this new iteration. 3) If the optimal user for this new iteration is the same as the one for the previous iteration, then stop and output the selected user and corresponding maximum EE. Otherwise we repeat 2).

In each iteration, the optimal transmission power P_s^* and P_r^* can be efficiently obtained by using the tool of fractional programming which is related to a parametric program as stated in [7].

Proposition 1: An optimization problem $\max\{(R(x)/P(x))|x\in S\}$ 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

$$\max\{R(x)-qP(x)|x\in S\}, \quad q\in R. \quad (16)$$

The maximum value can be achieved $q^*=R(x^*)/P(x^*)$ 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 [7].

Proposition 2: For each iteration of the user selection, the rate function R is concave over the transmission power (P_s,P_r) when the required SNR γ is high.

Proof: Denote the constant channel parameters for each iteration by β_0^*, β_1^* and β_2^*. When the received SNR is high, the first summand in the rate function of Eq. (9), i.e., 1 can be ignored. Thus the rate can be approximated by $R(P_s,P_r)=(1/2)\log_2(P_s\beta_0^*+((P_s\beta_1^*\cdot P_r\beta_2^*)/(1+P_s\beta_1^*+P_r\beta_2^*)))$. The Hessian matrix of $\tilde{R}=-R(P_s,P_r)$ is as follows

$$\nabla^2\tilde{R}=\begin{bmatrix}A & B\\ C & D\end{bmatrix}, \quad (17)$$

in which A and $AD-BC$ are shown by Eqs. (18) and (19), respectively, shown at the bottom of the page. It is easy to check that both A and $AD-BC$ are positive for all the transmission power in the feasible region, which is a convex set. Thus the Hessian matrix of $\tilde{R}$ is positive definite. Now we know that the function $\tilde{R}$ is convex. Then, we can conclude R is concave over the transmission power for high SNR regimes. ■

Since the denominator of EE in Eq. (10) is convex over (P_s,P_r), the maximization of EE for each iteration of user selection is a pseudo-concave problem when γ is high. It can be efficiently solved by the Dinkelbach method.

Based on discussions above, a J-SEEM algorithm is proposed to maximize the EE of the considered system. The main idea behind the algorithm relies on two key points. First, select the active antenna subsets at the relay according to the norm-based scheme. Second, find the optimal user and maximum EE based on the iterative process in Eq. (15), in which the Dinkelbach method is adopted. The details of the proposed algorithm are presented in Algorithm 1.

Algorithm 1 THE PROPOSED J-SEEM ALGORITHM

Step 1: Initialize all the channels, noise factors, and set $L=1$.
Step 2: For each user i select the optimal subset ω_t^* and ω_r^* using the norm-based scheme.
Step 3: Find the optimal user i^* and the corresponding maximum EE^* according to the iterative process in Eq. (15). EE$(L)=EE^*$
Step 4: Set $L=L+1$, if $L\leq N_r$, go to step 2; else stop.
Step 5: Choose the L with the largest EE(L) and the corresponding antenna subsets and transmission power.

$$A=\frac{1}{2\ln 2}\left(\frac{1}{P_s^2}-\frac{\beta_1^{*2}}{(1+\beta_1^*P_s+\beta_2^*P_r)^2}+\frac{\beta_1^{*2}\beta_0^{*2}}{(\beta_0^*+\beta_0^*\beta_1^*P_s+\beta_0^*\beta_2^*P_r+\beta_1^*\beta_2^*P_r)^2}\right) \quad (18)$$

$$AD-BC=\frac{2\beta_1^*\beta_2^{*2}\beta_0^*(1+\beta_1^*P_s)(1+\beta_1^*P_s+\beta_2^*P_r)+\beta_1^{*2}\beta_2^{*2}(1+2\beta_2^*P_r+2\beta_1^*(P_s+\beta_2^*P_sP_r))}{4\ln^2(2)P_s^2(1+\beta_1^*P_s+\beta_2^*P_r)^2(\beta_0^*+\beta_0^*\beta_1^*P_s+\beta_0^*\beta_2^*P_r+\beta_1^*\beta_2^*P_r)^2} \quad (19)$$

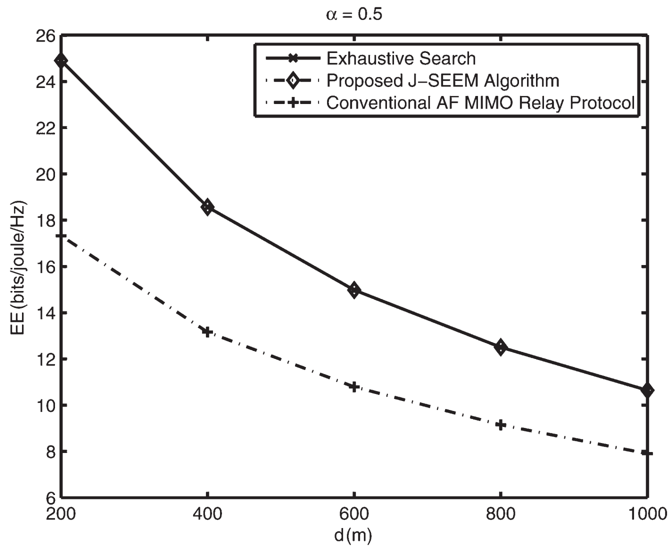

Fig. 1. Energy efficiency as a function of d with $\alpha = 0.5, n = 3, \gamma = 15$ dB.

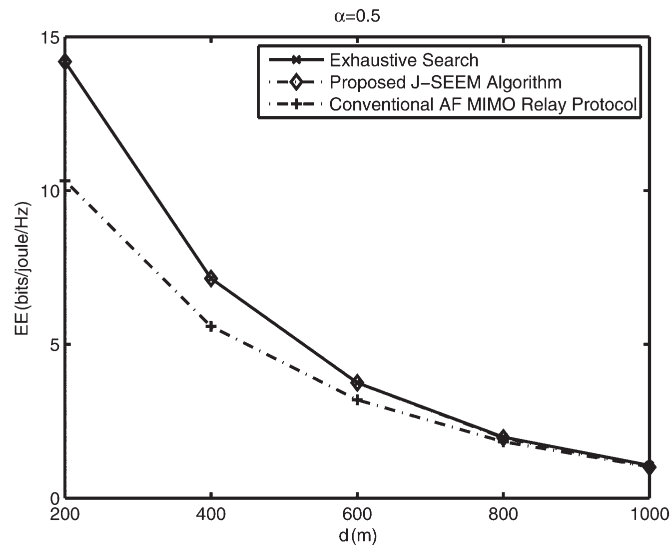

Fig. 2. Energy efficiency as a function of d with $\alpha = 0.5, n = 5, \gamma = 0$ dB.

C. Weak Direct Link Scenario

The complexity of Algorithm 1 can be further reduced when the direct link is relatively weak due to the large distance. In this case, $\beta_0(i)$ can be ignored and the optimal user is the one that simply leads to the largest $\beta_1(i, \omega_r^*)$, which is captured by the following problem

$$i^* = \arg\max_i \beta_1 \left(i, \omega_r^*\right). \tag{20}$$

In this context, there no longer exists the trade-off between $\beta_0(i)$ and $\beta_1(i, \omega_r^*)$. Thus, the iterative process in Eq. (15) is avoided and thus the Dinkelbach method is called only once. As a result, a further reduction of the computation complexity along with an improvement of performance can be obtained.

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. Simulation parameters are as follows [4], [5]. $P_{ct} = 120$ mW, $P_{cr} = 85$ mW, $P_{AF} = 80$ mW, $P_s^{\max} = P_r^{\max} = 500$ mW, $\eta_{pa,u} = 0.38$, $\eta_{pa,r} = 0.5$, $B = 10$ MHz. The noise factors among the nodes are the same and equal to $\sigma^2 = -174$ dBm/Hz. $\alpha = d_{\mathrm{ur}}/d$ is the ratio of the distance between the user and relay d_{ur}, and the distance between the user and BS d. n is the exponent of the log-distance path loss model. $N_s = N_r = N_d = 4$.

Fig. 1 shows the EE versus the distance d for $\alpha = 0.5, n = 3$, $\gamma = 15$ dB. It is easy to find that near-optimal performance can be achieved by the proposed algorithm in this relatively high SNR scenario. More specifically, the proposed algorithm achieves the optimal EE for 1980 out of the total 2000 channel realizations, i.e., a probability of 99% to hit the optimal value. As to the convergence, only one iteration is needed for the user selection process in 1947 out of 2000 channel realizations, and in the other 53 channel realizations there are only two iterations. Thus, there exists no channel realization in which our algorithm isn't convergent in our simulations. Moreover, it can be seen that an average gain of 42% over the conventional AF MIMO relay protocol is obtained in this case. It's worth pointing that our proposed algorithm gets a good performance in low SNR regimes too though our proofs rely on high SNR conditions. Fig. 2 shows the EE versus the distance d for $\alpha = 0.5$, $n = 5$, $\gamma = 0$ dB. In this low SNR scenario, our proposed algorithm could also achieve near-optimal performance though the performance gain over the conventional AF MIMO relay protocol decreases in this case.

V. Conclusion

This letter presented a low complexity EE maximization method (J-SEEM) for multiuser AF MIMO relay systems under a holistic power model. In particular, the active antennas at the relay are selected based on their norms. Meanwhile, the user selection and transmission power optimization are addressed by an iteration scheme, where the tool of fractional programming is used to solve the pseudo-concave EE maximization problem for each iteration. Simulation results show that the proposed algorithm enjoys a probability of 99% to achieve the optimal EE with low complexity. Moreover, it has an average gain of 42% in the EE over the conventional AF MIMO relay protocol.

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