An Iterative Algorithm for Joint Antenna Selection and Power Adaptation in Energy Efficient MIMO

Xingyu Zhou, *Student Member, IEEE,* Bo Bai, *Member, IEEE,* and Wei Chen, *Senior Member, IEEE*
E-mail: xy-zhou12@mails.tsinghua.edu.cn eebobai@tsinghua.edu.cn wchen@tsinghua.edu.cn
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

Abstract—**As the growth of wireless communications is accompanied by increased energy consumption, energy-efficient communication is becoming imperative. This paper will discuss the energy efficiency of MIMO systems with antenna selection. The optimal method for the maximization of energy efficiency is exhaustive search. To address the problem, an iterative algorithm which includes the transmit antenna selection and power adaptation is proposed. It is based on the iterative property of the energy efficiency, which is derived in this paper. This property guides us to select the antenna that achieves the largest energy efficiency increment at each step. There is also a power adaptation for each step where we calculate the optimal transmission power and then set it as the initial one for the next step. Moreover, one asymptotic property exists in the proposed algorithm, which states that the antenna selection and power adaptation can be decoupled in high and low SNR regimes. This fact reduces the complexity further and enables us to achieve the optimal performance with a greater probability. Simulation results show that the proposed algorithm achieves near-optimal performance in all the SNR regimes and has a remarkable gain over the no selection scheme in the energy efficiency and transmission power.**

I. INTRODUCTION

WITH the rapid evolution of wireless communications, there is a radical increase in the energy consumption which leads to the escalation of greenhouse gas emission and electric bill. Therefore, it is urgent and necessary to design wireless communication systems from the perspective of energy efficiency (bits per joule). MIMO (multiple-input-multiple-output) is an emerging technology that promises a significant increase in data rates and the reliability for communication systems [1], [2]. However, MIMO transmission is not always energy efficient than SISO when the energy consumption of all signal processing blocks in RF chains is taken into account [3]. Thus, it is crucial to find a practical and energy efficient method to extract the goodness of MIMO systems.

Antenna selection in which only a subset of available antennas is selected for transmission or reception has shown its great potential in reducing the power consumption yet incurring little performance loss. However, to find the optimal subset that maximizes the channel capacity or minimizes the bit error rate (BER) needs an exhaustive search, whose computation complexity will grow exponentially with the number of available antennas. There have been many literatures devoted to finding a low complexity capacity maximization method for antenna selection. The authors of [4], [5], [6] proposed efficient antenna selection algorithms that achieve the near-optimal performance with much less complexity. Conventional works on the antenna selection in MIMO mainly addressed the situation where the number of active antennas is given and fixed. Then they try to maximize the channel capacity for a given transmission power. However, from [7] we know that circuit power consumption (power consumption in RF chains) in MIMO systems should be taken into account to quantify the energy efficiency of wireless networks. Jiang and Cimini in [8] investigate to maximize the energy efficiency with antenna selection for single stream MIMO systems where the power consumption of RF chains is considered. However, the energy efficiency of multi-stream MIMO systems with antenna selection is more complicated where the received SNR of each data stream must be maximized, which has not been investigated in a systematic way.

In this paper, we try to maximize the energy efficiency of multi-stream MIMO systems with transmit antenna selection under a holistic power model. In this case, more active antennas consume more circuit power, thus it is needed to find the optimal active antennas and transmission power at the same time. An iterative equation for the energy efficiency of multi-stream MIMO systems with transmit antenna selection is first derived. Based on it, we can select one antenna that achieves the largest increment of the energy efficiency at each step under the condition of a given transmission power. Next, we calculate the optimal transmission power that achieves the maximum energy efficiency and set it as the initial one for the antenna selection of the next step. As a result, a joint iteration of the active antennas and the transmission power is adopted, which reduces the complexity significantly yet incurs little performance loss. Moveover, we prove that the transmission power has no impact on the selection of antennas in high and low SNR regimes. This fact helps to achieve the optimal energy efficiency with a greater probability. Simulation results

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show that the proposed algorithm achieves the near-optimal performance for all the SNR regimes. The energy efficiency of antenna selection is much better than that of no selection, which verifies that antenna selection could improve the energy efficiency significantly.

The rest of the paper is structured as follows: The system model and the problem formulation are given in Section II. In Section III, the iterative property of the energy efficiency is derived and then the efficient algorithm is developed. Finally, simulation results and conclusions are presented in Section IV and V, respectively.

II. System Model and Problem Formulation

A. System Model

Consider a point-to-point MIMO system equipped with N_t transmit and N_r receive antennas. We assume that the channel experiences a flat fading. The signal model for the considered MIMO system is given by

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}, \tag{1}$$

where $\mathbf{H}$ is the channel matrix and its $N_r \times N_t$ entries are i.i.d complex circular symmetric Gaussian random variables with zero-mean and unit variance. $\mathbf{n}$ is the additive white Gaussian noise vector, each of whose elements is circularly symmetric complex random variable with zero mean and variance N_0. $\mathbf{s}$ and $\mathbf{y}$ represent the transmitted and received signals, respectively. Moreover, we assume that the channel state information (CSI) is only perfectly known at the receiver. Therefore the instantaneous capacity of the signal model in Eq. (1) is given by [1]

$$C(P_t, \mathbf{H}) = \log\det(\mathbf{I}_{N_r} + \frac{P_t}{N_t N_0}\mathbf{H}\mathbf{H}^H), \tag{2}$$

where P_t is the transmission power.

In [9], the power consumption of RF chains and other circuits in MIMO is captured by

$$P_c = L_t \cdot P_{ct} + L_r \cdot P_{cr} + P_{c0}, \tag{3}$$

where L_t and L_r stand for the number of active transmit and receive RF chains, respectively. P_{ct} and P_{cr} are the power consumed by each transmit and receive RF chain. P_{c0} is the power of frequency synthesizers and other units of circuits. Thus, the overall power consumption of MIMO system can be obtained as

$$P = \frac{1}{\eta_{pa}} \cdot P_t + P_c, \tag{4}$$

where η_{pa} is the drain efficiency of the power amplifier.

B. Problem Formulation

The main task of this paper is to maximize the energy efficiency for multi-stream MIMO systems with transmit antenna selection. Specially, assume that all the N_r receive antennas are active and the available antennas at the transmitter is N_t. Ω is the subset of active transmit antennas and its cardinality $|\Omega|$ is L_t. According to [7], the energy efficiency of multi-stream MIMO under a holistic power model could be defined as

$$EE = \frac{C(P_t, \mathbf{H}_{(N_r,\Omega)})}{\frac{1}{\eta_{pa}} \cdot P_t + N_r \cdot P_{cr} + |\Omega| \cdot P_{ct} + P_{c0}}, \tag{5}$$

where $C(P_t, \mathbf{H}_{(N_r,\Omega)})$ corresponds to the capacity of the selected subchannel matrix under a given P_t. To maximize EE in Eq. (5), a joint optimization over the transmission power P_t and the active transmit antennas Ω is needed. Thus it can be formulated by an optimization problem which is defined as

$$\begin{aligned} (P_t^*, \Omega^*) &= \arg\max_{P_t,\Omega} EE \\ s.t.\ &: C(P_t^*, \mathbf{H}_{(N_r,\Omega^*)}) \geq R. \end{aligned} \tag{6}$$

R is the required minimal rate. Since the channel state information is only known at the receiver, the selection and optimal transmission power is calculated at the receiver and fedback to the transmitter through a noiseless feedback channel.

III. Optimization of the Energy Efficiency

A. Problem Analysis and Core Idea of the Proposed Algorithm

As the optimization problem in Eq. (6) is NP-hard, the optimal method to address it is the exhaustive search. That is for each combination of transmit antennas, it finds the optimal P_t^* that leads to the maximum energy efficiency. However, an exhaustive search requires $2^{N_t} - 1$ calculations of the optimal transmission power, which is obviously complexity prohibitive.

To solve the problem with a low complexity, we propose an iterative algorithm which adopts two iterations for each step: the iteration of the active antennas under a given transmission power and the iteration of the transmission power. What makes it feasible is the fact that a slight fluctuation in the transmission power has little influence in the optimality of antenna selection. It means that the optimal subset of active transmit antennas Ω^* keeps unchanged when the transmission power $P_t \in [P_t^* - \Delta, P_t^* + \Delta]$. Thus we can try to estimate and fix the optimal transmission power in advance.

However, even though we can fix a transmission power in advance, the antenna selection under a given transmission power is also NP-hard, which can only be solved by exhaustive search too. Fortunately, we find an iterative property for the energy efficiency of multi-stream MIMO systems with transmit antenna selection, which is stated in Theorem 1. Based on it, we can judiciously select one transmit antenna that achieves the largest increment of energy efficiency and add it into the subset at each step. After the selection of the current step, then we calculate the optimal transmission power P_t^* and set it as the initial P_t for the antenna selection of the next step. In the iteration process, there is a great probability of existing a Δ that let P_t fall into the interval $[P_t^* - \Delta, P_t^* + \Delta]$ in which the antenna selection keeps unchanged. Finally, we compare the energy efficiency of each step and choose the subset and the corresponding transmission power that achieves the largest energy efficiency as the solution. The flow diagram which is shown in Fig. 1 helps to demonstrate the core idea of the proposed algorithm.

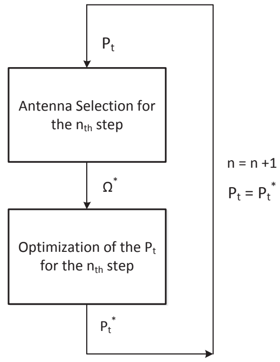

Fig. 1. The flow diagram of the proposed iterative algorithm

B. Antenna Selection under the Given Transmission Power

The antenna selection process under a given transmission power is based on the iterative property of the energy efficiency with antenna selection, which is stated in Theorem 1. The notations adopted in Theorem 1 are defined as follows. For a given P_t, the received SNR is $\gamma = \frac{P_t}{N_0}$. P_n stands for the overall power consumption when the number of active transmit antennas is n. According to Eq. (4), we have that $P_n = nP_{ct} + \frac{1}{\eta_{pa}}P_t + P_{c0} + N_r P_{cr}$. At each step, one transmit antenna is selected and added into the subset. We denote by $\mathbf{H}_n$ the subset of selected antennas after n steps of selection. At the $(n+1)$th step, if the s^*th column of $\mathbf{H}$ is selected, the new $N_r \times (n+1)$ channel matrix is denoted by $\mathbf{H}_{n+1}$. $\mathbf{h}_s$ is the column vector that represents the sth column of the channel matrix.

***Theorem** 1:* With the transmit antenna selection and a given transmission power, the energy efficiency of a multi-stream MIMO system under the holistic power model could be expressed by the following iterative equation.

$$EE(\mathbf{H}_{n+1}) = g(n)EE(\mathbf{H}_n) + D_n + \Delta_{s,n}, \tag{7}$$

where

$$g(n) = \frac{P_n}{P_{n+1}} \tag{8}$$

$$D_n = \frac{\alpha_n}{P_{n+1}} \tag{9}$$

$$\Delta_{s,n} = \frac{\delta_{s,n}}{P_{n+1}} \tag{10}$$

$$\alpha_n = \log\det(\mathbf{I}_n - \frac{\gamma}{n(n+1)}\mathbf{H}_n^H(\mathbf{I}_{N_r} + \frac{\gamma}{n}\mathbf{H}_n\mathbf{H}_n^H)^{-1}\mathbf{H}_n) \tag{11}$$

$$\delta_{s,n} = \log(1 + \mathbf{h}_s^H\mathbf{T}_n\mathbf{h}_s) \tag{12}$$

$$\mathbf{T}_n = (\mathbf{I}_{N_r}\frac{n+1}{\gamma} + \mathbf{H}_n\mathbf{H}_n^H)^{-1} \tag{13}$$

Proof: With the transmit antenna selection and a fixed transmission power P_t, the corresponding energy efficiency of the $(n+1)$th step can be obtained by

$$EE(\mathbf{H}_{n+1}) = \frac{C(\mathbf{H}_{n+1})}{P_{n+1}}, \tag{14}$$

where $P_{n+1} = (n+1)P_{ct} + \frac{1}{\eta_{pa}}P_t + P_{c0} + N_r P_{cr}$.

With Eq. (2), the capacity of the $(n+1)$th step for the transmit antenna selection is as follows

$$C(\mathbf{H}_{n+1}) = \log_2\det(\mathbf{I}_{N_r} + \frac{\gamma}{n+1}\mathbf{H}_{n+1}\mathbf{H}_{n+1}^H), \tag{15}$$

where γ is the SNR and equals $\frac{P_t}{N_0}$.

Observe that

$$\mathbf{H}_{n+1}\mathbf{H}_{n+1}^H = \mathbf{H}_n\mathbf{H}_n^H + \mathbf{h}_s\mathbf{h}_s^H \tag{16}$$

By applying the matrix determinant lemma to Eq. (15), we have that

$$\begin{aligned} C(\mathbf{H}_{n+1}) &= \log\det(\mathbf{I}_{N_r} + \frac{\gamma}{n+1}\mathbf{H}_n\mathbf{H}_n^H) \\ &+ \log(1 + \mathbf{h}_s^H(\mathbf{I}_{N_r}\frac{n+1}{\gamma} + \mathbf{H}_n\mathbf{H}_n^H)^{-1}\mathbf{h}_s) \end{aligned} \tag{17}$$

and the first item on the right-side of the equation (17) can be expressed as Eq. (18) by using the generalization of matrix determinant lemma

$$\begin{aligned} \log\det(\mathbf{I}_{N_r} + \frac{\gamma}{n+1}\mathbf{H}_n\mathbf{H}_n^H) &= C(\mathbf{H}_n) \\ + \log\det(\mathbf{I}_n - \frac{\gamma}{n(n+1)}&\mathbf{H}_n^H(\mathbf{I}_{N_r} + \frac{\gamma}{n}\mathbf{H}_n\mathbf{H}_n^H)^{-1}\mathbf{H}_n) \end{aligned} \tag{18}$$

We denote $\log\det(\mathbf{I}_n - \frac{\gamma}{n(n+1)}\mathbf{H}_n^H(\mathbf{I}_{N_r} + \frac{\gamma}{n}\mathbf{H}_n\mathbf{H}_n^H)^{-1}\mathbf{H}_n)$ by α_n. For the second item on the right-side of the equation (17), we denote $(\mathbf{I}_{N_r}\frac{n+1}{\gamma} + \mathbf{H}_n\mathbf{H}_n^H)^{-1}$ by $\mathbf{T}_n$. Thus, we have that

$$C(\mathbf{H}_{n+1}) = C(\mathbf{H}_n) + \alpha_n + \delta_{s,n}, \tag{19}$$

where $\delta_{s,n} = \log(1 + \mathbf{h}_s^H\mathbf{T}_n\mathbf{h}_s)$.

Apply $EE(\mathbf{H}_n) = \frac{C(\mathbf{H}_n)}{P_n}$ and Eq. (19) to Eq. (14), obtain that

$$EE(\mathbf{H}_{n+1}) = g(n)EE(\mathbf{H}_n) + D_n + \Delta_{s,n}, \tag{20}$$

where $g(n) = \frac{P_n}{P_{n+1}}$, $D_n = \frac{\alpha_n}{P_{n+1}}$ and $\Delta_{s,n} = \frac{\delta_{s,n}}{P_{n+1}}$. ■

From Theorem 1, it can be seen that the contribution to the energy efficiency of adding one more transmit antenna is depicted by the term $\Delta_{s,n}$. It motivates us to find the s^*th column that brings the largest contribution to the energy efficiency at each step. Moveover, since the P_n is a constant for a given transmission power at the nth step, the maximization of $\Delta_{s,n}$ is equivalent to the following problem.

$$s^* = \arg\max_s \delta_{s,n}. \tag{21}$$

C. Power Adaptation and the Proposed Algorithm

According to Eq. (21), we can select the transmit antenna that leads to the largest increment of energy efficiency at each step for a given P_t. After the selection of each step, we calculate the optimal transmission power that achieves the largest energy efficiency for the current subset of active antennas. Since the numerator of energy efficiency is a concave function and the denominator is a convex function of P_t, the energy efficiency is a pseudo-concave function of P_t. Thus the only optimum P_t^* is the one that leads the derivation of energy efficiency to be zero. For the first step of antenna selection,

Algorithm I
OPTIMIZATION ALGORITHM FOR ENERGY EFFICIENCY

Input: η_{pa}, P_{cr}, P_{ct}, P_{c0}, N_0, N_r, $\mathbf{H}$
Output: Ω^* P_t^*
Initial: $\Theta = \{1, 2 \dots N_t\}$, $\mathbf{H}_0 = \emptyset$
for $s = 1, \dots, N_t$
  $\Delta_s := \|\mathbf{H}(:, s)\|^2$
end
for $n = 1, \dots, N_t$
  $P_c = nP_{ct} + N_r P_{cr} + P_{c0}$
  $s^* := \arg\max_{s \in \Theta} \Delta_s$
  $\Theta := \Theta - \{s^*\}$
  $\mathbf{H}_n := [\mathbf{H}_{n-1}, \mathbf{H}(:, s^*)]$
  Calculate P_t^* by maximizing $h(P_t) = \frac{C(P_t, \mathbf{H}_n)}{\frac{1}{\eta_{pa}} \cdot P_t + P_c}$
  if $C(P_t^*, \mathbf{H}_{\Omega^*}) < R_{\min}$
    Update P_t^* that $C(P_t^*, \mathbf{H}_{\Omega^*}) = R_{\min}$
  $P_t(n) = P_t^*$
  $EE(n) = h(P_t^*)$
  $\gamma^* = \frac{P_t^*}{N_0}$
  $\mathbf{T}_n := (\mathbf{I}_{N_r} \frac{n+1}{\gamma^*} + \mathbf{H}_n \mathbf{H}_n^H)^{-1}$
  $\Delta_s := \mathbf{H}(:, s)^H \mathbf{T}_n \mathbf{H}(:, s)$, $s \in \Theta$
end
  $L = \text{find}(EE == \max(EE))$
Return $\Omega^* = \mathbf{H}_L$, $P_t^* = P_t(L)$

the proposed algorithm always chooses the transmit antenna with the largest norm as $\mathbf{T}_n$ is an identity matrix now. After the first selection, we can calculate the optimal P_t^* and take it as the initial P_t for the second selection. In the following steps, we can always update P_t by the P_t^* of the last step.

Based on Theorem 1 and the iteration of the transmission power, an iterative energy efficiency maximization algorithm is proposed. The fundamental idea of this algorithm has two key points: 1) judiciously select one transmit antenna which achieves the largest increment of energy efficiency for a given P_t at each step. 2) calculate the optimal transmission power P_t^* for the current subset of antennas and set it as the P_t for the next step. The details of the algorithm are presented in Algorithm I.

***Remark** 1:* The proposed algorithm enjoys a low complexity property compared to the exhaustive search. In the proposed algorithm, for each number of active antennas only one subset is chosen for the calculation of transmission power. As a result, the total number of calculations for the optimal transmission power is only N_t, which is far less than $2^{N_t} - 1$ in exhaustive search. Therefore, the proposed algorithm reduces the complexity significantly.

***Remark** 2:* The proposed algorithm could be easily extended to handle the energy efficiency with receive antenna selection. By using the method in this paper to derive the energy efficiency with receive antenna selection, we obtain a similar iterative equation. With a change of the term $\frac{n+1}{\gamma}$ by $\frac{N_t}{\gamma}$ and a transpose of the channel matrix in $\mathbf{T}_n$, an iterative energy efficiency maximization algorithm for the receive antenna selection is obtained.

D. Asymptotic Performance Analysis

For the maximization of the energy efficiency in high and low SNR regimes, the transmission power has no influence in the antenna selection, which is stated in Theorem 2. This fact helps us reduce the complexity in the iteration process and achieve the optimal performance with a greater probability.

***Theorem** 2:* For high and low SNR regimes, the antenna selection is independent with P_t.

Proof: The corresponding SNR here is $\gamma = \frac{P_t}{N_0}$ and thus we obtain

$$\begin{aligned} \mathbf{T}_n &= (\mathbf{I}_{N_r} \frac{n+1}{\gamma} + \mathbf{H}_n \mathbf{H}_n^H)^{-1} \\ &= \frac{\gamma}{n+1} (\mathbf{I}_{N_r} + \frac{\gamma}{n+1} \mathbf{H}_n \mathbf{H}_n^H)^{-1} \end{aligned} \tag{22}$$

By applying the matrix inverse lemma to the first equation of Eq. (22), we can get

$$\mathbf{T}_n = \mathbf{A}^{-1} - \frac{n+1}{\gamma} \mathbf{A}^{-1} (\mathbf{I}_{N_r} + \frac{n+1}{\gamma} \mathbf{A}^{-1})^{-1} \mathbf{A}^{-1}, \tag{23}$$

where $\mathbf{A} = \mathbf{H}_n \mathbf{H}_n^H$. Since $\lim_{\gamma \to \infty} \frac{n+1}{\gamma} = 0$, thus $\lim_{\gamma \to \infty} \mathbf{T}_n = (\mathbf{H}_n \mathbf{H}_n^H)^{-1}$. Therefore in high SNR regimes $\delta_{s,n} = \log(1 + \mathbf{h}_s^H \mathbf{T}_n \mathbf{h}_s) = \log(1 + \mathbf{h}_s^H (\mathbf{H}_n \mathbf{H}_n^H)^{-1} \mathbf{h}_s)$, which is independent with P_t.

Apply the matrix inverse lemma to $(\mathbf{I}_{N_r} + \frac{\gamma}{n+1} \mathbf{H}_n \mathbf{H}_n^H)^{-1}$, thus obtain

$$(\mathbf{I}_{N_r} + \frac{\gamma}{n+1} \mathbf{H}_n \mathbf{H}_n^H)^{-1} = \mathbf{I}_{N_r} - \frac{\gamma}{n+1} \mathbf{A} (\mathbf{I}_{N_r} + \frac{\gamma}{n+1} \mathbf{A})^{-1}, \tag{24}$$

where $\mathbf{A} = \mathbf{H}_n \mathbf{H}_n^H$. With $\gamma \to 0$, $\mathbf{T}_n$ tends to be an identity matrix. In this case, the column with the largest norm is always selected at each step regardless of the P_t for low SNR regimes. ■

IV. SIMULATION RESULTS

In this section, we provide simulation results to demonstrate the energy efficiency of multi-stream MIMO systems with transmit antenna selection. The results are averaged over 3000 channel realizations. The values for the parameters P_{ct}, P_{cr}, P_{c0} and η_{pa} are 120mW, 85mW, 30mW and 35%, which are adopted from [9]. d is the distance between the transmitter and receiver. The log-distance path loss model with an exponent of 4 is adopted as the large-scale path loss. N_t and N_r are both 8. R is 5 (bits/s/Hz).

First, we would like to show the energy efficiency as a function of d. Figure 2 compares the performance of the proposed algorithm and the exhaustive search for different transmission distances. It can be seen that near-optimal performance can be achieved by the proposed algorithm for all the distances. Moreover, we can see that the gain over the no selection scheme is remarkable. Thus antenna selection not only reduces the complexity of RF chains but also improves the energy efficiency significantly.

To have a more comprehensive understanding of the performance of the proposed algorithm in different SNR regimes, the

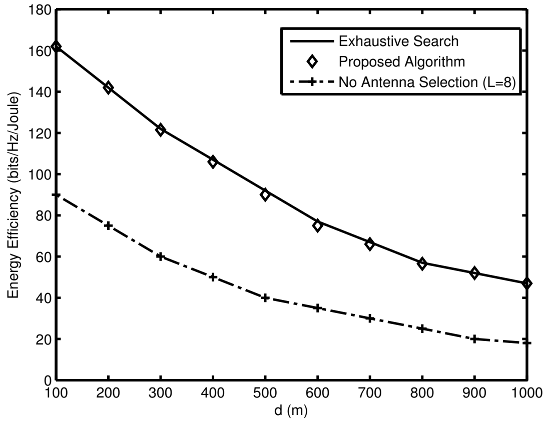

Fig. 2. Energy efficiency VS. the transmission distance d

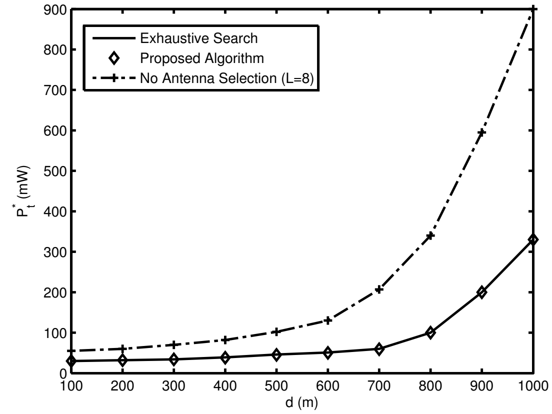

Fig. 4. The optimal transmission power P_t^* as a function of d

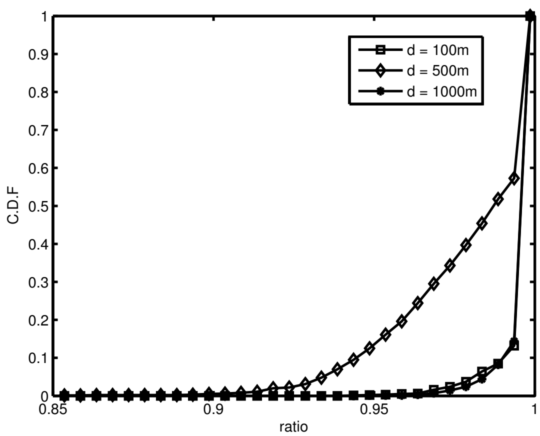

Fig. 3. CDF of the ratio between the energy efficiency of the proposed algorithm and exhaustive search

cumulative distribution function (CDF) of the ratio between the energy efficiency of the proposed algorithm and exhaustive search is plotted, as shown in Fig. 3. It can be seen that the performance of the proposed algorithm in near and far transmission distances is better than that in middle distance. There is a over 80 percent chance to achieve nearly the same energy efficiency of exhaustive search for the cases of $d = 100$m and $d = 1000$m. In these two cases, the received SNR is high and low, respectively. Thus the antenna selection is independent of the transmission power, which is proved in Theorem 2. As a result, the deviation of the transmission power has no impact on the antenna selection. In a word, it is more likely to succeed in obtaining the optimal subset of antennas in these cases.

Figure 4 illustrates the optimal transmission power P_t^* as a function of the transmission distance. It can be seen that much more power is consumed for the transmission when there is no antenna selection. The gap increases significantly with the transmission distance. On the other hand, we can see that the optimal transmission power with antenna selection is small and changes very slowly for most of the distances. This fact shows that antenna selection not only improves the energy efficiency but also reduces the transmission power.

V. Conclusion

We investigate the optimization of energy efficiency with the transmit antenna selection in MIMO systems where a holistic power model is taken into account. An iterative energy efficiency maximization algorithm is developed to avoid the computation complexity in exhaustive search. The proposed algorithm is based on the iterative property of energy efficiency which is derived in this paper. Based on it, a joint iteration of the active transmit antennas and the transmission power is adopted to solve the optimization problem efficiently. The proposed algorithm enjoys a low complexity and achieves the near-optimal performance in all the SNR regimes. Moreover, it can improve the energy efficiency and reduce the transmission power at the same time, which could help to guide the design of future energy efficient wireless communication systems.

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