# Energy-Efficient Distributed Relay Selection Based on Statistical Channel State Information

Haifang Jiang[1], Sihai Zhang[1,2], and Wuyang Zhou[1]

[1] Wireless Information Network Lab.,
Department of Electronic Engineering and Information Science,
University of Science and Technology of China, Hefei, Anhui, China, 230026
[2] Key Laboratory of Wireless Sensor Network & Communication,
Shanghai Institute of Microsystem and Information Technology,
Chinese Academy of Sciences865 Changning Road, Shanghai, China, 200050
`jhf@mail.ustc.edu.cn, {shzhang,wyzhou}@ustc.edu.cn`

**Abstract.** In this paper, distributed relay selection algorithms based on statistical Channel State Information (CSI) in amplify-and-forward mode are proposed, aiming to maximize energy efficiency. With the limited CSI, a tradeoff is made between the total power consumption and the target outage probability at the source. A forwarding threshold is obtained by minimizing the average transmission power. Each relay individually decides whether to participate in forwarding the source signals according to the forwarding threshold. Firstly, a Distributed Multiple Relay Selection (DMRS) algorithm is proposed, in which all candidate relays have the possibility of transmitting the source signals and the threshold is obtained by numerical search. Then a Distributed Single Relay Selection (DSRS) algorithm with low complexity is investigated under the assumption that only one relay forwards the signals. Simulation results indicate that the proposed algorithms provide significant performance gain in terms of energy efficiency over the existing AF-mode relay selection algorithms.

**Keywords:** Amplify-and-Forward(AF), statistical CSI, energy efficiency, distributed relay selection.

## 1 Introduction

Cooperative communication has drawn increasing research attention due to its ability to resist the impact of wireless fading channels. Compared to direct communication, cooperative communication has the potential of providing benefits of space diversity [1]. It has been widely accepted as an effective way to improving the energy efficiency in the energy-limited network, such as wireless sensor network and ad hoc network. Various cooperative schemes have been studied in the literature. Distributed Space-Time Coding (DSTC) for cooperative network is developed in [2]. “All Participate Forwarding” (APF) scheme is also proposed, where all relay nodes transmit the source signals to the destination. Several

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cooperative protocols are presented in [3], including fixed relaying, selection relaying and incremental relaying. These protocols allow relay nodes to operate in AF mode or Decode-and-Forward (DF) mode. Then their outage behaviors and diversity gains are also analyzed.

The performance of a wireless relay-assisted network can be improved by selecting relay nodes appropriately. Opportunistic Relay Selection (ORS) algorithm is proposed using a timer that is set inversely proportional to the channel gain [4,5]. It has been proved that the ORS algorithm is optimal in terms of outage behavior among all single-relay-forward algorithms. Y. Jing presents suboptimal multi-relay-forward algorithm with low complexity and full diversity obtained [6]. A new transmission protocol by combining AF mode and DF mode has even better outage behavior [7]. In this protocol, AF mode is adopted instead of direct link when the relay can't decode the source signals. These algorithms above all use equal power allocation, however, effective utilization of power can further improve the performance of the network. Power allocation about the APF algorithm and the ORS algorithm is analyzed to obtain lower outage probability [8,9].

Most of researches on relay selection focus on the outage behavior or symbol error rate analysis, however, energy efficiency is of great practical significance for the energy-limited network [10,11,12,13]. Distributed power allocation strategies are investigated in [10], attempting to minimizing the power consumption while providing a target outage probability. Energy-efficient single-relay-selection cooperative scheme is discussed for wireless sensor networks in [11,12], which jointly considers the MAC design and the physical layer power control. Based on a simple selective relay cooperative scheme, the tradeoff is analyzed between decreasing the energy cost of data transmission by using more relays and decreasing overhead for CSI acquisition by using less relays [13]. Nevertheless, the results are all obtained under the DF mode and the feedback overhead is often overwhelmed when the number of relay nodes becomes larger since the instantaneous CSI of the relay-destination links is needed.

In this paper, we propose distributed relay selection algorithms in AF mode, aiming to minimize the average total power consumption. Given the limited CSI, the source makes a tradeoff between the power consumption and the outage probability. Furthermore, the forwarding threshold and its own transmission power are obtained. The threshold decision mechanism is adopted and each relay individually decides on whether to forward the source signals according to the threshold. We first develop the upper bound of minimal power consumption (MPC-UB) with the assumption of perfect CSI. Then we propose the Distributed Multi-relay Mode (DMRM) algorithm based on statistical CSI. Finally, the Distributed Single-relay Mode (DSRM) algorithm with low computational complexity is studied. Our main contribution is developing distributed algorithms of high energy efficiency in AF mode by employing the threshold relaying criterion and the statistical CSI. These schemes reduce the amount of feedback overhead.

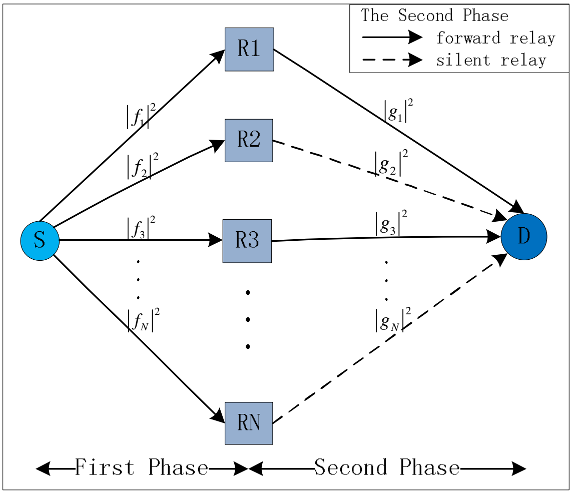

**Fig. 1.** Scheme Description

## 2 System Model

The system model of the relay-assisted network is illustrated in Fig. 1, including one source $S$, one destination $D$ and $N$ relay nodes $R_i (i = 1, 2, ...N)$. It is assumed that the source communicates with the destination only through AF-mode relay nodes because of deep fading in the direct link. All the nodes are equipped with one antenna and operate in half-duplex mode. The channels of source-relay links and relay-destination links all experience flat rayleigh fading and are independent of each other.

In the first phase, $S$ broadcasts signal $x$, the signal received at relay $R_i (i = 1, 2, ...N)$ is :

$$y_{ri} = \sqrt{P_s} f_i x + n_{ri} \tag{1}$$

where $P_s$ denotes the transmission power of the source. $f_i$ and $n_{ri}$ are respectively the channel coefficient and zero-mean Additive White Gaussian Noise (AWGN) with variance $N_0$ of the source-relay link for the $i$th relay node, $f_i \sim CN(0, \eta_i^2)$.

In the second phase, each relay individually checks the relaying criterion according to local CSI. If satisfy, the relay forwards the signal to the destination using orthogonal channel. Otherwise the relay keeps silence. The signal received from the $i$th relay at the destination is:

$$y_{di} = \sqrt{\frac{P_i}{P_s |f_i|^2 + N_0}} g_i x + n_{di} \tag{2}$$

where $P_i$ denotes the transmission power of $R_i$. $g_i$ is zero-mean complex Gaussian random variable, denoting the channel coefficient of the relay-destination link for the $i$th relay node, $g_i \sim CN(0, \sigma_i^2)$. $n_{di}$ is zero-mean AWGN of the relay-destination link with variance $N_0$. Maximal Ratio Combining (MRC) is applied on the signals. Thus the Signal-to-Noise Ratio ($SNR$) at the destination is:

$$SNR_D = \sum_{i \in A_R} \frac{P_s|f_i|^2 \cdot P_i|g_i|^2}{P_s|f_i|^2 + P_i|g_i|^2 + N_0} \cdot \frac{1}{N_0} \tag{3}$$

where $A_R$ is the set of forwarding relays.

# 3 Distributed Relay Selection Algorithm

## 3.1 Minimal Power Consumption with Perfect CSI

We assume that the source have completely instantaneous CSI, $f_i, g_i (i = 1, 2, ...N)$. Relay selection is made at the source. The source obtains its own transmission power, and then notices the relays in $A_R$. The problem can be expressed as:

$$\begin{aligned} &\min_{P_s, A_R} \; P_s + \sum_{i=1}^{N} P_i \\ &s.t. \;\; SNR_D \geq \mathit{\Gamma} \end{aligned} \tag{4}$$

where $\mathit{\Gamma}$ is defined as the target $SNR$. $SNR_D$ can be approximated under high $SNR$ range as follows:

$$SNR_D \approx \frac{P_s|f_i|^2 \cdot P_i|g_i|^2}{P_s|f_i|^2 + P_i|g_i|^2} \cdot \frac{1}{N_0} \tag{5}$$

The problem (4) is an multi-variable optimization problem and it is difficult to represent the solution with complete expressions. We assume that only one relay node participates in forwarding the signal, meanwhile others keep silence to save energy. It reduces the complexity of receiving at the destination. The problem (4) is simplified to a two-variable optimization problem which can be solved easily. The result of (4) with (5) is determined as:

$$A_R = \{i | \arg\min_i \frac{1}{|f_i|} + \frac{1}{|g_i|}\} \tag{6}$$

$$P_s = \frac{\mathit{\Gamma} N_0}{|f_i|^2}(1 + \frac{|f_i|}{|g_i|}) \tag{7}$$

$$P_i = \frac{\mathit{\Gamma} N_0}{|g_i|^2}(1 + \frac{|g_i|}{|f_i|}) \tag{8}$$

Obviously (6) (7) and (8) are the upper bound of minimal power consumption (MPC-UB) and it guarantees no outage in the network. However it is usually assumed that there is a centralized control entity gathering all instantaneous CSI in the network, which needs enormous feedback because of the time-varying characteristic of wireless channels. Thus it is impractical in implementation. In the follow, we devise effect distributed relay selection algorithms.

### 3.2 Distributed Multi-relay Model (DMRM) Algorithm

**Relaying Criterion and Problem Description.** In practice, the source generally acquire the instantaneous CSI of source-relay links easily, while only statistical CSI of relay-destination links, that is $f_i, \sigma_i^2 (i = 1, 2...N)$. The relay $R_i$ knows the local CSI relevant to itself, that is $f_i, g_i$. The channel capacity in AF mode is associated with both source-relay link and relay-destination link, thus the channel quality of both links should be taken into account in the relaying criterion. Based on a distributed mechanism with a forwarding threshold, each relay individually makes its decision on whether to forward the source signal. Therefore the relaying criterion is as follows: if $R_i (i = 1, 2...N)$ satisfies $\frac{1}{|f_i|^2} + \frac{1}{|g_i|^2} \leq \gamma$ where $\gamma$ is the forwarding threshold, $R_i$ forwards the signal using the transmission power as (8) at the second phase. Here we define the set of candidate relays from which the forwarding relays are selected as follows:

$$A_s = \{i|1/|f_i|^2 < \gamma\} \tag{9}$$

Maybe the outage event occurs when all relays keep silence because of the low threshold. So the target outage probability $\rho$ is introduced into the network. The research problem is that given $\mathit{\Gamma}$ and $\rho$, the source obtains the forwarding threshold $\gamma$ and its own transmission power by mean of minimizing the average total power consumption of the source and the candidate relays. The problem is described as:

$$\begin{aligned} \min_{\gamma} \quad & E[P_s] + \sum_{i \in A_s} E[P_i] \\ s.t.\ & Pr\{SNR_D \leq \mathit{\Gamma}\} \leq \rho \end{aligned} \tag{10}$$

**Forwarding Threshold $\gamma$.** For the sake of brevity, we set the result of arraying $|f_i|^2 (i = 1, 2...N)$ in ascending order as $|f_1|^2 \geq |f_2|^2 \geq ... \geq |f_N|^2$. Set $|A_s| = M$, and $\gamma_M$ is supposed to satisfy:

$$\begin{cases} \dfrac{1}{|f_M|^2} < \gamma_M < \dfrac{1}{|f_{M+1}|^2}, M = 1, 2...N-1 \\ \dfrac{1}{|f_N|^2} < \gamma_M, M = N \end{cases} \tag{11}$$

From the constraint condition in the problem (10) we obtain:

$$\begin{aligned} Pr\{SNR_D \leq \mathit{\Gamma}\} &= \prod_{i \in A_s} Pr\{\frac{1}{|f_i|^2} + \frac{1}{|g_i|^2} > \gamma_M\} \\ &= \prod_{i \in A_s} [1 - \exp(-\frac{1}{\sigma_i^2} \cdot \frac{1}{\gamma_M - 1/|f_i|^2})] \end{aligned} \tag{12}$$

It can be seen from (12) that the outage probability decreases with increment of $\sigma_i^2$ or $|f_i|^2$. Thus the inequality can be derived by calculation as follows:

$$Pr_l < Pr\{SNR_D \leq \mathit{\Gamma}\} < Pr_r \tag{13}$$

$$Pr_l = [1 - \exp(-\frac{1}{\max\limits_{i \in A_s} \sigma_i^2} \cdot \frac{1}{\gamma_M - 1/|f_i|^2})]^M \tag{14}$$

$$Pr_r = [1 - \exp(-\frac{1}{\min\limits_{i \in A_s} \sigma_i^2} \cdot \frac{1}{\gamma_M - 1/|f_M|^2})]^M \tag{15}$$

An appropriate threshold is of the utmost importance. When $\gamma$ increases, the number of relays satisfying the relaying criterion grows. It causes that the outage probability decreases at the destination, whereas the total power consumption increases, and vice versa. We need not only to ensure the target outage probability but also to consume the average total power as little as possible. The threshold decides the tradeoff between the power consumption and the outage behavior. Therefore we let (12) equal the target outage probability $\rho$. Considering the constraint condition (11), we obtain the range of $\gamma$:

$$\gamma_{\min M} < \gamma_M < \gamma_{\max M} \tag{16}$$

$$\gamma_{\min M} = \max(\frac{1}{|f_i|^2} - \frac{1}{\max\limits_{i \in A_s} \sigma_i^2 \cdot \ln(1 - \rho^{1/M})}, \frac{1}{|f_M|^2}) \tag{17}$$

$$\gamma_{\max M} = \begin{cases} \min(\frac{1}{|f_M|^2} - \frac{1}{\min\limits_{i \in A_s} \sigma_i^2 \cdot \ln(1 - \rho^{1/M})}, \frac{1}{|f_{M+1}|^2}), \\ \qquad\qquad\qquad\qquad M = 1, 2 ... N - 1 \\ \frac{1}{|f_M|^2} - \frac{1}{\min\limits_{i \in A_s} \sigma_i^2 \cdot \ln(1 - \rho^{1/M})}, M = N \end{cases} \tag{18}$$

$\gamma_M$ can be obtained by way of numerical search in the interval $[\gamma_{\min M}, \gamma_{\max M}]$. It deserves to be specially noted that if $\frac{1}{|f_1|^2} - \frac{1}{\max\limits_{i \in A_s} \sigma_i^2 \cdot \ln(1 - \rho^{1/M})} > \frac{1}{|f_M|^2}$ and $\frac{1}{|f_M|^2} - \frac{1}{\min\limits_{i \in A_s} \sigma_i^2 \cdot \ln(1 - \rho^{1/M})} < \frac{1}{|f_{M+1}|^2}$, it is certain that $\gamma_M$ has solution when $|A_s| = M$, or else $\gamma$ may have no solution. In the worst situation, $\gamma_M$ is unsolvable for all the cases $M = 1, 2, ... N$. Then $\gamma_M$ takes the value of $\gamma_{\max M}$ in order to increase the possibility of relay forwarding signals to avoid interrupt event.

**Transmission Power of Source.** When $|A_s| = M (M = 1, 2 ... N)$ and $\gamma_M$ has solution, we can obtain the average total power $E[P_{total}(M)]$. Set $Z = |g_i|^2$ and $X = |g_i|$, then the Probability Density Functions (PDF) of $Z$ and $X$ are respectively defined as:

$$f_Z(z) = \frac{1}{\sigma_i^2} \exp(-\frac{1}{\sigma_i^2} z) \tag{19}$$

$$f_X(x) = \frac{2x}{\sigma_i^2} \exp(-\frac{1}{\sigma_i^2} x^2) \tag{20}$$

For some relay $R_i$ in the $A_s$ which is selected as the reference in the transmission power of the source (7) , the average total power of the source and all the candidate relays is given as:

$$\begin{aligned} E[P_{total}(M)] &= E[P_s] + \sum_{j\in A_s} E[P_j] \\ &= \mathit{\Gamma} N_0 \cdot (\frac{1}{|f_i|^2} + 2\sqrt{\frac{\pi}{|f_i|^2\sigma_i^2}} Q(\sqrt{\frac{2\gamma_i'}{\sigma_i^2}})\ ) + C(\gamma_M) \end{aligned} \tag{21}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{+\infty}\exp{(-\frac{t^2}{2})}dt$ is complementary error function. $\gamma_i' = \dfrac{1}{\gamma - 1/|f_i|^2}$. $C(\gamma_M)$ is a constant:

$$\begin{aligned} C(\gamma) = \mathit{\Gamma} N_0 \cdot \sum_{j\in A_s} [-\frac{1}{\sigma_j^2} Ei(-\frac{\sqrt{\gamma_j'}}{\sigma_j^2}) \\ + 2\sqrt{\frac{\pi}{|f_j|^2\sigma_j^2}} Q(\sqrt{\frac{2\gamma_j'}{\sigma_j^2}})] \end{aligned} \tag{22}$$

where $Ei(x) = -\int_{-x}^{\infty} e^{-t}/t dt$ is the exponential integral function. Therefore we obtain with $|A_s| = M$:

$$\begin{aligned} i &= \arg_i\ \min\ \frac{1}{|f_i|^2} + 2\sqrt{\frac{\pi}{|f_i|^2\sigma_i^2}} Q(\sqrt{\frac{2\gamma_i'}{\sigma_i^2}}) \\ E[P_{total}(M)] &= \mathit{\Gamma} N_0 \cdot [\frac{1}{|f_i|^2} + 2\sqrt{\frac{\pi}{|f_i|^2\sigma_i^2}} Q(\sqrt{\frac{2\gamma_i'}{\sigma_i^2}})] + C(\gamma_M) \end{aligned} \tag{23}$$

Taking the minimum value among the $E[P_{total}(M)](M = 1, 2...N)$, we develop the solution to the problem (10) as follows:

$$\begin{aligned} M^* &= \arg_M\ \min\ E[P_{total}(M)] \\ \gamma^* &= \gamma_{M^*} \end{aligned} \tag{24}$$

As a consequence of the above, there is a tradeoff between the outage probability and the power consumption, which depends on the threshold $\gamma$. Besides, from the analysis above we can see that there is an interdependent relationship between $A_s$ and $\gamma$: on the one hand, obtaining $\gamma$ depends on $A_s$ ; on the other hand, $\gamma$ determines $A_s$ conversely. It leads to the difficulty in solving the problem. We first assume $|A_s| = M$, and then $\gamma$ can be obtained according to the constraint of $\rho$. Based on $\gamma$, the average total power values are developed. Finally we select the minimal value and further identify the transmission power of the source. The overview flowchart of DMRM algorithm is as Fig. 2.

### 3.3 Distributed Single-Relay Model (DSRM) Algorithm

The DMRM algorithm proposed to this point generally results in certain calculation in the threshold-solving procedure. In this section, we investigate the

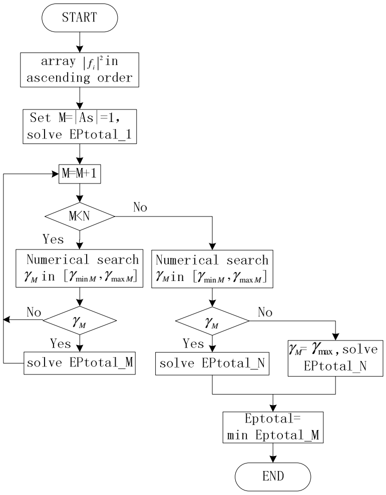

**Fig. 2.** DMRM algorithm flowchart

case where only one relay node is assumed to transmit, that is the average total power of the source and just this relay is considered by the source. The DSRM algorithm is motivated by limitations on the available CSI as well as ease of implementation. It is re-emphasized that the same channel information assumption in DMRM algorithm is adopted here. The problem is described as:

$$\begin{aligned} &\min_{i} \quad E[P_s] + E[P_i] \\ &s.t.\ Pr\{SNR_D \le \Gamma\} \le \rho \end{aligned} \tag{25}$$

where $SNR_D$ is as (5). According to the constraint condition about outage probability in (25), when the relay$i$ is selected we have:

$$\begin{aligned} Pr\{SNR_D \le \Gamma\} &= Pr\{\frac{1}{|f_i|^2} + \frac{1}{|g_i|^2} \ge \gamma_i\} \\ &= 1 - \exp(-\frac{1}{\sigma_i^2} \cdot \frac{1}{\gamma_i - 1/|f_i|^2}) = \rho \end{aligned} \tag{26}$$

Thus the threshold $\gamma_i$ should satisfy:

$$\gamma_i = \frac{1}{|f_i|^2} - \frac{1}{\sigma_i^2 \cdot \ln(1-\rho)} \tag{27}$$

Further we get $\gamma_i' = \frac{1}{\gamma_i - \frac{1}{|f_i|^2}} = \sigma_i^2 \cdot \ln(1-\rho)$. The average total power is:

$$E[P_{total}] = \Gamma N_0 \cdot [\frac{1}{|f_i|^2} + 4\sqrt{\frac{\pi}{|f_i|^2\sigma_i^2}} Q(\sqrt{-2\ln(1-\rho)} + \frac{C(\rho)}{\sigma_i^2})] \tag{28}$$

where $C(\rho) = \int_{-\ln(1-\rho)}^{+\infty} \frac{1}{x}\exp(-x)dx$. Thus we develop the solution to the problem (25) :

$$\begin{aligned} i &= \arg_i \min \frac{1}{|f_i|^2} + 4\sqrt{\frac{\pi}{|f_i|^2\sigma_i^2}}Q(\sqrt{-2\ln(1-\rho)}\,) + \frac{C(\rho)}{\sigma_i^2} \\ E[P_s] &= \Gamma N_0 \cdot [\frac{1}{|f_i|^2} + 2\sqrt{\frac{\pi}{|f_i|^2\sigma_i^2}}Q(\sqrt{-2\ln(1-\rho)}\,)] \end{aligned} \tag{29}$$

Observe that in (27), the task of finding the forwarding threshold can be substantially simplified compared to the DMRM algorithm. Thus the DSRM algorithm has significantly less computational complexity requirement. However we will see that there is a modest sacrifice in the performance of the DSRM algorithm.

## 4 Simulation Result

In this section, we show the simulation results of the performance of the algorithms proposed in this paper as well as other existing algorithms. The simulation scene is depicted as Fig. 1, where the coordinates of the source and the destination is (0, 0) and (0, 100) respectively. The relay nodes are normally distributed in vertical linearity. Set $\Gamma = 10dB$ as the target $SNR$. We adopt the channel model in [2] and the detail channel parameters are illustrated in Table 1.

**Table 1.** Channel Parameters

| **Parameters** | **Value** |
|---|---:|
| Antenna gain $G_t/G_r$ | 1 |
| Wavelength $\lambda$ | 1/3m |
| System loss factor $L$ | 1 |
| Constant $C$ | $G_tG_r\lambda^2/(4\pi)^2L$ |
| Path loss factor $\alpha$ | 3 |
| Channel gain of source-relay | $\eta_i^2 = C/d_{Si}^{\alpha}$ |
| Channel gain of relay-destination | $\sigma_i^2 = C/d_{iD}^{\alpha}$ |
| Variance of noise $N_0$ | $10^{-10}$ |

At first we make a comparison between the proposed algorithms and the existing algorithms to demonstrate the performance. In particular, we plot the average total power $E[P_{total}]$ versus the target outage probability $\rho$ in Fig. 3. Set $N = 4$ relay nodes in the network. The upper bound of the minimal power consumption (MPC-UB) is also given. Note that there is no outage in MPC-UB, because the source and the relay can satisfy the target SNR requirement by adjusting their transmission power. For a fair comparison, the definition of outage event for MPC-UB in [10] is introduced, that is an outage occurs when the total power is higher than a given power value. We observe that at the same outage probability, the average total power consumption of the DMRM algorithm is the least. The APF algorithm [2] has the most power consumption caused by additional relays. In the ORS algorithm [5], the relay with the minimal value $\frac{1}{|f_i|^2} + \frac{1}{|g_i|^2}$ is considered to decide the transmission power by the source. It is observed that the ORS algorithm is not optimal for energy efficiency problem. The DSRM algorithm makes sacrifices in performance for low computational complexity. However the DMRM algorithm has an additional power expenditure as the penalty of lack of complete CSI. The additional power expenditure decreases as $\rho$ increases, which reflects the tradeoff between the power consumption and the outage probability as discussed in Section III. As expected, the curve of DMRM approaches to, or even drops bellow the curve of MPC-UB in high $\rho$ range.

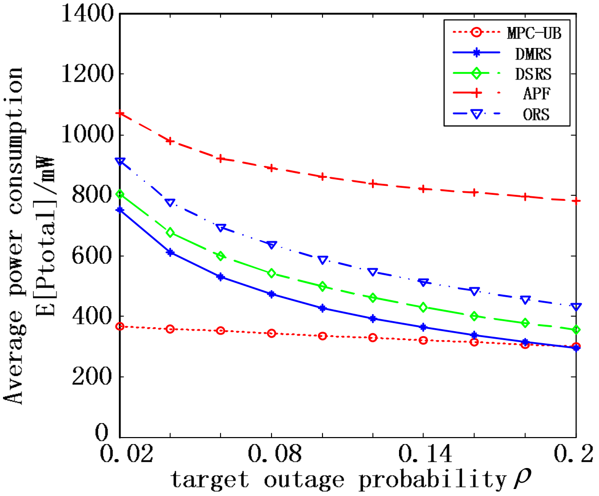

**Fig. 3.** $E[P_{total}]$ vs $\rho$ for different algorithms (N=4)

Then we investigate the effect of the number of relay nodes in performance in Fig. 4. Set $\rho = 0.1$ as the target outage probability. It is observed that as the number of relay nodes increases, the additional power expenditure of APF algorithm increases due to the fact that more relays which are supposed unnecessarily to forward signals waste power. It is suggested that more relay nodes may not be more energy-efficient. However, for other algorithms, the increment of relays means that the high space diversity order can be obtained. In other words, the possibility of good channel increases for each channel realization. Thus the average total power consumption decreases. Fig. 4 also remarks that the more relays there are in the relay-assistant network, the more power savings is obtained in DMRM algorithms compared to others.

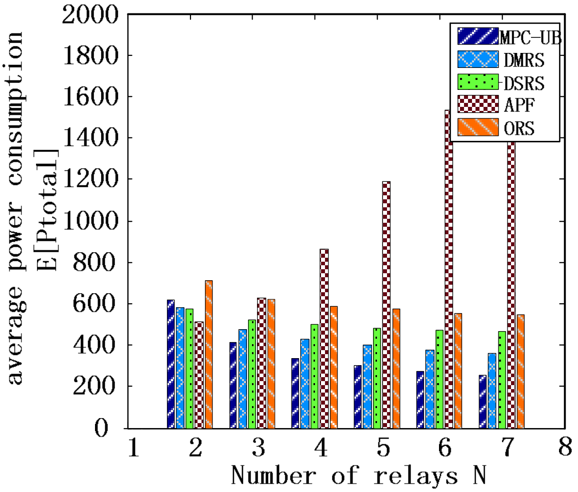

**Fig. 4.** $E[P_{total}]$ vs $N_{relay}$ for different algorithms ($\rho$=0.1)

## 5 Conclusion

In this paper, we propose two distributed algorithms for relay selection under statistical CSI in AF mode. The relay decision mechanism is adopted. In order to meet the target SNR and the target outage probability, the source makes a tradeoff between the power consumption and the outage probability. Furthermore, the forwarding threshold and its own transmission power are obtained. In the DMRM algorithm, all candidate relays have the possibility of transmitting the source signals. We obtain the threshold by numerical search and the average total power consumption of the DMRM algorithm is the least. In contrast, the low-complexity DSRM algorithm assumes that only one relay forwards the signals and consequently, has a modest sacrifice in performance. Simulation results indicate that compared to the APF and the ORS relay selection algorithms, the proposed algorithms have better performance in energy efficiency, which are more suitable for the energy-limited network.

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