Energy-efficient Power Allocation Scheme for Multi-relay Cooperative Communications

Yinlong Xu[1, 2], Zhiquan Bai[1], Bing Wang[1], Peng Gong[3,*], and Kyungsup Kwak[4]

[1]School of Information Science and Engineering, Shandong University, China
[2]Key Lab. of Higher Education of Sichuan Province for Enterprise Informationlization and Internet of Things, Sichuan University of Science and Engineering, China
[3]National Key Laboratory of Mechatronic Engineering and Control, Beijing Institute of Technology, China
[4]Graduate School of Information Technology and Telecommunications, INHA

[*]Corresponding author: penggong@bit.edu.cn

Abstract—**For the increasing cost of energy and infrastructures of wireless communication systems, energy-efficient communication technologies become an important concern for the standardization authorities and cellular operators. In this paper, we propose an energy-efficient relay selection and power allocation strategy subject to a total power constraint. The proposed scheme first selects the transmission mode according to the energy efficiency of the different transmission link. Then, we analyze the energy efficiency of the proposed system and present the optimal number of the relay nodes and the best power distribution factors in broadcasting phase and the cooperative transmission phase. Closed-form expressions of the energy efficiency of the proposed scheme are derived. Simulation results show that the proposed scheme achieves good energy efficiency in both low and high signal-to-noise ratio region.**

Keywords—Energy Efficient; Cooperative Communication; Green Communication; Outage Probability; Power Allocation .

I. INTRODUCTION

With the rapid development of telecommunication industry, modern communication systems consume more and more energy. Energy efficiency in cellular networks is an important concern for the standardization authorities and cellular operators. Verizon has set its own energy-consumption standard (TEEER) and established an associated measurement process for new telecommunication-related equipment. The requirement of energy efficiency in communication systems will become increasingly strict.

Cooperative communication technology allows single antenna users to exploit the other users' antennas and generates a virtual multiple-input multiple-output (MIMO) system without additional investment. The research on energy efficiency of cooperative communication system can reduce the energy consumption and satisfy the requirements of user quality of service (QoS). Recently, various energy efficient schemes in wireless communications have been proposed. Hasan presented a brief survey of the methods to improve the power efficiency of cellular networks [1]. The author discussed how the cooperative concepts can be made more energy efficient at the system level. The energy-efficient precoding scheme has been investigated in [2] considering that the terminals are equipped with multiple antennas. Opportunistic decode-and-forward (ODF) switches the transmission mode between the direct transmission (DT) and relaying depending on the achievable rate [3]. The results obtained in the paper proved that the proposed dynamic cooperation scheme improves the overall performance compared to the non-cooperative or the fixed type cooperative strategies. Osama in [4] presented an opportunistic energy-efficient (OEE) relay selection cooperative scheme which uses the energy efficiency metric to select the best relay or resort to the direct transmission.

In this paper, we follow the recent trend towards cooperative communication systems that support the green vision of the next-generation wireless networks [5]. The relay selection and power allocation strategies are investigated under energy efficiency principle. We first select the transmission mode between the DT and relaying based on the energy efficiency of the transmission link. Then, the energy efficiency principle is applied in the random distributed multi-relay DF cooperative system. Different relay selection and power allocation strategies are presented in low and high signal to noise ratio (SNR) regions. Simulation results show that the proposed scheme can achieve good system energy efficiency both in low and high SNR regions.

The rest of this paper is organized as follows. In Section II, the cooperative protocol considering the energy efficiency and channel model are introduced. The energy efficiency of the system and the corresponding power allocation strategy are derived in Section III. In section IV, simulation results about the BER performance and energy efficiency of the system are provided with comparison to the conventional cooperative system. Finally, the conclusions are drawn in section V.

II. COOPERATIVE SYSTEM MODEL

In this paper, we consider a cooperative network with N relay nodes distributed randomly within a two-dimensional circle centered with the source node as shown in Figure 1. The link among the terminals are modeled as independent, quasi static Rayleigh fading channels, where the channel will be considered as constant during the transmission of one block, but will varies from block to block. Let h_{ij} denotes the instantaneous channel power gain (the square of the amplitude of the instantaneous channel gain) between terminal i and terminal j. It is assumed that the channel power gains h_i (for i=1,.., N) are independent exponential random variables. Let m_i denotes the mean of h_i and we assume that m_i (for i=1,…,N) is known by all the relays. Without loss of generality, the noise at the receiver is zero-mean Gaussian with unit variance.

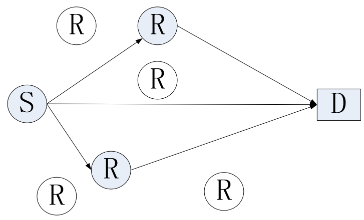

Figure 1. Two-stage transmission in cooperative communication

The cooperative scheme selects to operate either in the DT mode or DF mode. In the DT mode, the source uses the whole transmission time for sending the data to destination. The signal received at the destination can be denoted as y_{DT} [6],

$$y_{DT} = \sqrt{P_S} h_{sd} x_s + n_d , \quad . \quad (1)$$

where h_{sd} is the channel coefficient of the S-D link. x_s is the transmitted signal from the source S with average unit energy. n_d is the complex Gaussian random variable with zero mean and variance N_0. P_S is the transmission power of the source.

In DF cooperative mode, the transmission from the source to the destination consists of two phases, namely the broadcasting and relaying phases. In the first phase, the source broadcasts the data and all the relays operate in the listening mode. In the second phase, the relays satisfying the energy efficiency threshold will decode the received signals, and then synchronously retransmit the obtained signals to the destination. The destination node will combine the signals received in the two phases by maximal ration combining (MRC) technique [7] and coherent detection. The signal received at the relays can be written as,

$$y_{sr} = \sqrt{P_S} h_{sr} x_s + n_r \quad (2)$$

$$y_d = \sum_{i=1}^{n} \sqrt{P_i} h_{id} x_r + n_i \quad (3)$$

where h_{sr} and h_{rd} are the channel coefficients of the S-R and R-D links, respectively. x_r is the signal sent by the relay based on its detection of x_s and P_i is the transmission power at the relay i. The noise components n_r is also assumed to be independently and identically distributed (i.i.d.) complex Gaussian random variable. n_r and n_i are the complex Gaussian random variables with zero mean and variance N_0.

The instantaneous SNRs of the S-D, S-R and R-D links can be expressed respectively as $\gamma_{sd} = |h_{sd}|^2 P_s / N_0$, $\gamma_{sr} = |h_{sr}|^2 P_s / N_0$, and $\gamma_{id} = |h_{id}|^2 P_i / N_0$.

Therefore, the correspondingly average SNRs are equal to $\overline{\gamma_{sd}} = E\left(|h_{sd}|^2\right) P_s / N_0$, $\overline{\gamma_{sr}} = E\left(|h_{sr}|^2\right) P_s / N_0$, and $\overline{\gamma_{id}} = E\left(|h_{id}|^2\right) P_i / N_0$.

where E(.) denotes the expectation statistical average operator. All the channel coefficients here follow Rayleigh fading distribution. The probability density function (PDF) of $\gamma_i \left(i \in \{sd, sr, rd\}\right)$ can be written as,

$$f_{\gamma_i}(\gamma) = \frac{1}{\overline{\gamma_i}} e^{-\frac{\gamma}{\overline{\gamma_i}}}, \text{ for } \quad \gamma \geq 0 \quad (4)$$

We can readily obtain that

$$P\left(\gamma_i > a\right) = \exp\left(-a / \overline{\gamma_i}\right). \quad (5)$$

III. Energy-Efficient Cooperative Communication

A. Relay selection based on energy efficiency

In this section, we analyze the energy-efficiency metric denoted as the ratio between the end-to-end capacity and the transmitted energy consumption. The relays participating in cooperative transmission are selected based on this energy efficiency metric. The energy efficiency of the DT mode can be expressed as [8],

$$EE_0 = \frac{C_{SD}}{P_{DT}} . \quad (6)$$

The energy efficiency of the DF mode can be expressed as

$$EE_m = \frac{C_m}{P_{DF}} \quad (7)$$

where the P_{DT} and P_{DF} are the power consumed by the DT mode and DF mode, respectively. C_{SD} and C_m are the channel capacity of the DT case and cooperative case, which can be shown as,

$$C_{SD} = B \log_2 (1 + \frac{P_S}{N_0} |h_{sd}|^2) \quad (8)$$

$$C_m = \frac{1}{2} B \min \left\{ \log_2 (1 + \frac{P_S}{N_0} |h_{sr}|^2), \log_2 (1 + \frac{P_r}{N_0} |h_{rd}|^2) \right\} \quad . \quad (9)$$

We take the energy efficiency of the DT case as the baseline. Then, the relays can be separated into two groups. 1) The relays whose energy efficiency is larger than that of the DT mode. 2) The other relays that do not meet the energy efficiency requirement. All the relays in the first case are chose in available relay set. $P(EE_0 > EE_m)$ denotes the probability of the energy efficiency of the DT mode larger than that of the DF mode. This probability will be different from system to system. Here, we use Monte Carlo simulation to compute the probability.

B. Power Allocation under Energy Efficient Principle

In this subsection, we aim to present the power allocation scheme of multi-relay cooperative system under energy efficiency principle. We first consider a simple multi-hop (MH) protocol [3] where the time slot is divided into two equal slots. As mentioned before, we can have the partial CSI at the source and the relay. If the first relay group is empty, the source will transmit the data to the destination directly and the relay will keep silent in the second time slot. When the first group is not empty, the selected relays will decode the message and retransmit the message to the destination. In this case, the destination will only receive the message from the relays. In the second condition, both the number of the relays participating in the transmission and the p_{opt} used at the relay will be determined by the following procedure.

In fact, since the mutual information in the Rayleigh fading channel is a random variable and varies from block to block, it is not possible to guarantee that it is above a certain threshold with 100%. A suitable performance metric for this slow-fading channel [9] is the probability of an outage for a given transmission rate targeted at R. Additionally, we set that $\delta \in (0,1]$ and $(1-\delta) \in [0,1)$ denote the fractions of the total end-to-end transmission power P allocated at the source and the relay, respectively.

Then, we define the energy efficiency of our system as follows,

$$\Gamma = \frac{R\left((1-P_{DT}(outage)) * P(EE_{DT} > EE_{DF})\right)}{P} + \frac{R(1-P_{DF}(outage)) * P(EE_{DT} \le EE_{DF})}{P} \quad (10)$$

where P_{DT}(outage) and P_{DF}(outage) are the system outage probability in DT mode and DF mode, respectively. R is the transmission rate of the system. P is the energy consumed in the entire transmission process.

The energy efficiency Γ can be divided into two parts Γ_1 and Γ_2. Γ_1 is energy efficiency of the system in DT mode and Γ_2 is energy efficiency of the system in DF mode.

1) *Energy efficiency in DT mode*:

For Rayleigh fading, $\left(|h_{sd}|^2\right)$ is exponentially distributed with parameter σ_{SD}^{-2}. The outage probability in DT mode can be expressed as follow [10],

$$P_{DT}(outage) = 1 - \exp\left(-\frac{(2^R-1)N_0}{\delta P_s \sigma_{SD}^2}\right) . \quad (11)$$

Then, the energy efficiency in DT mode can be shown as

$$\Gamma_1 = \frac{R\left(\exp(-\frac{(2^R-1)N_0}{\delta P_s \sigma_{SD}^2}) * P(EE_{DT} > EE_{DF})\right)}{P} . \quad (12)$$

It can be found that the function $\exp(-\frac{(2^R-1)N_0}{\delta P_s \sigma_{SD}^2})$ is sigmoidal and therefore Γ_1 is quasi-concave w.r.t. [11]. The first order derivative of Γ_1 is,

$$\frac{\partial \Gamma_1}{\partial P} = \frac{RP(EE_{DT} > EE_{DF})\left(\frac{(2^R-1)N_0}{\delta \sigma_{SD}^2 P} - 1\right)}{P^2} . \quad (13)$$

Γ_1 is maximized in the unique point where

$$p^* = \frac{(2^R-1)N_0}{\delta \sigma_{SD}^2} . \quad (14)$$

The optimal power can be rewritten as

$$p_{opt} = \min\left\{\frac{(2^R-1)N_0}{\delta \sigma_{SD}^2}, p\right\} . \quad (15)$$

2) *Energy efficiency in DF mode*

The outage probability in DF mode can be expressed as follows [10],

$$P_{DF} = \Pr(\frac{1}{2}\min\left\{\sum_{i=1}^{n}\log_2(1+\frac{P_s}{N_0}|h_{si}|^2), \log_2(1+\sum_{i=1}^{n}\frac{p_i}{N_0}|h_{id}|^2)\right\} < R) . \quad (16)$$

Then, the energy efficiency in DT mode can be shown as

$$\Gamma_2 = \frac{R\sum_{m=1}^{n} C_n^m p_1^m (1-p_1)^{n-m} \exp(-\frac{(2^{2R}-1)N_0 m}{\delta P \sigma_{sr}^2})}{P} \times (\sum_{i=1}^{m}|h_{id}|^2 \ge \frac{(2^{2R}-1)N_0 m}{(1-\delta)P}) . \quad (17)$$

Since the entries of $|h_{id}|^2$ are exponential distribution, the sum $\sum_{i=1}^{m}|h_{id}|^2$ is Erlang distributed random variable, which implies that

$$\Gamma_2 = \frac{R\sum_{m=1}^{n} C_n^m p_1^m (1-p_1)^{n-m} \exp(-\frac{(2^{2R}-1)N_0 m}{\delta P \sigma_{sr}^2})}{P} \times \left(\exp(-\frac{(2^{2R}-1)mN_0}{\sigma_{rd}^2(1-\delta)P})\sum_{k=0}^{m-1}\frac{1}{k!}\left[\frac{(2^{2R}-1)mN_0}{\sigma_{rd}^2(1-\delta)P}\right]^k\right) \quad (18)$$

We take the first order derivative of Γ_2 and p_{opt} is the unique positive solution of the following equation (in P):

$$\frac{A}{B}\frac{z^n}{(n-1)!} - \sum_{k=0}^{n-1}\left[1+(1-\frac{A}{B})k\right]\frac{z^k}{k!} = 0 \quad (19)$$

where $A = \frac{1}{\delta \sigma_{sr}^2} + \frac{1}{(1-\delta)\sigma_{rd}^2}$, $B = \frac{1}{(1-\delta)\sigma_{rd}^2}$,

$d = (2^{2R}-1)mN_0$, $z = B\frac{d}{P}$.

Substituting the result of (12) and (18) into (10), we can get the optimal number of the relays participating in the transmission and the p_{opt} used at the relay.

IV. Numerical Results

In this section, we present the simulation results that illustrate our analytical results and demonstrate the energy efficiency and BER performance of the proposed scheme.

First, we use Monte Carlo simulation to compute the probability when the energy efficiency of the DT mode is above that of the DF mode. The system parameters used for the 2.5GHz radio from [12] is summarized in Table Ⅰ.

TABLE I. Simulation Parameters

P_{cr}=112mW	P_{ct}=98mW	α=1.88
N_f=10dB	N_0=-171dBm/Hz	B=10kHz
κ=3.5	d_0=1m	λ=0.12

We consider the cooperative network with N relay nodes distributed random over two-dimensional circle area. To examine the effect of the relay's location on the system performance, we choose three kinds of relay configurations: a. the source node is set as the center; b. the intermediate node is set as the center; c. the destination node is set as the center. For a given node configuration, the different relay distributions are generated for 10^4 runs. The energy efficiency of the DT mode and the energy efficiency of the DF mode are calculated using the equations (6) and (7).

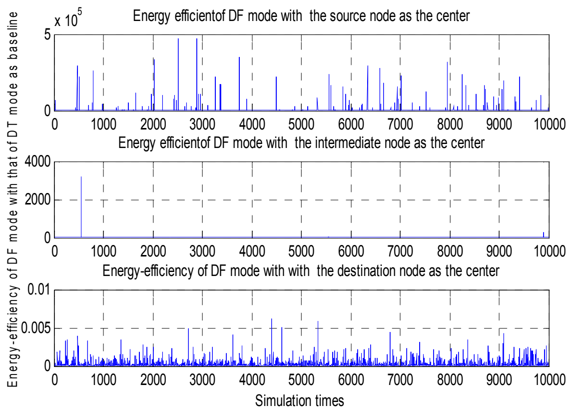

Figure 2. The energy efficiency of the DF mode in different relay configurations

Fig.2 reveals the energy efficiency of the DT mode and the energy efficiency of the DF mode. We can find that when the relays distribute randomly when the destination node is set as the center, the probability of energy efficiency of the DF mode above that of DT mode is highest, but the amplitude of the energy efficiency is small. When the source node is set as the center, both the probability and amplitude of the energy efficiency are good, which keep the balance between the complexity and performance of the system.

Then, we present the energy efficiency and BER performance of the proposed scheme .The mean channel power gains between terminals are assumed to follow the path loss model. We set $E\left(|h_{sd}|^2\right)=d_{sd}^{-\alpha}$, $E\left(|h_{sr}|^2\right)=d_{sr}^{-\alpha}$, and $E\left(|h_{rd}|^2\right)=d_{rd}^{-\alpha}$ to capture the effect of the path loss on system, where d_{ij} is the distance between node i and j, $\alpha\in[3,5]$ is the path loss factor. The total number of the relay is set to 3.

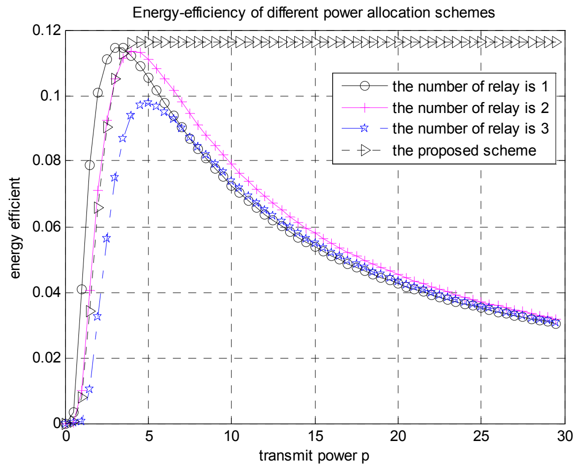

Figure 3. The energy efficiency in different power allocation schemes

The simulation about the energy efficiency of the system in different power allocation schemes is present in Figure 3. We can see that the simulation and analytical results match well. When the transmit power is above the threshold, which are calculated by (15) and (19), the energy efficiency of the system will decrease sharply. This verifies that using all the available power is not optimal in the sense of system energy-efficiency. The proposed scheme is calculated with equation (10). Because the distribution of the relay is random, the energy efficiency of the proposed scheme approaches the curve in the figure with probability.

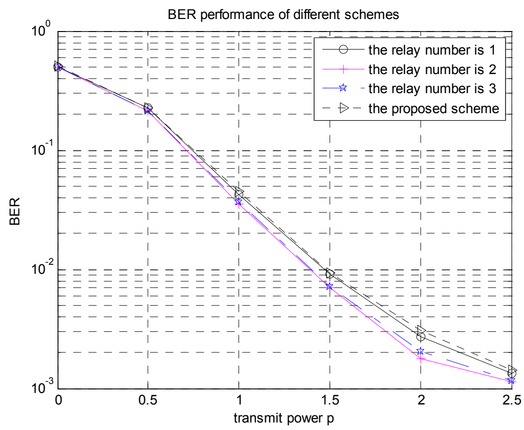

Figure 4. The BER performance of different power allocation schemes

Figure 4 illustrates the BER performance of different relaying schemes, such as the proposed scheme, the scheme where the relay number is set as 1 with energy efficient control, the scheme where the relay number is set as 2 with energy efficient control, and the scheme where the relay number is set as 3 with energy efficient control. We can see that the BER performance of the schemes with energy efficient control will tend to remain unchanged when the transmit power is above certain threshold. The propose scheme achieves a little lower performance because the energy efficiency gained comes at the price of the system performance.

For the energy efficient control scheme, which addresses the long performance of mobile users, we can use financial incentives [13] for the users require high quality of service, as well as a corresponding fee for the users require lower quality but high energy efficient service.

V. CONCLUSIONS

In this paper, we propose an energy efficient relay selection and power allocation strategy subject to a total power constraint. The proposed scheme uses energy efficiency metric for the relay selection. The optimal number of the relay nodes and the best power distribution factor are provided in the two phase transmissions. The analysis and simulation results show that the proposed scheme can achieve good energy efficiency both in low and high SNR regions. But, the improvement of the energy efficiency comes at the price of the system performance. When the error probability is decreased to a certain extent, the BER performance of the system will tend to keep unchanged. The design of the target energy efficiency of the system is important to secure the QoS of the users.

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Yinlong Xu was born in Henan province in 1988. He joined the wide-band wireless communication research lab of Shandong University, Jinan, China, in 2011. His research interests include cooperative communication.

Zhiquan Bai received his BS degree from Inner Mongolia University, Huhehot, China, in 2000, MS degree from Shandong University, Jinan, China, in 2003, and PhD degree with honor from INHA University under the Grant of Korean Government IT Scholarship, Korea, in 2007. From 2007 to 2008, he was a post-doctor in UWB Wireless Communications Research Center, INHA University, Korea. After that, he has been an associate professor in the School of Information Science and Engineering, Shandong University, China. He is a member of the IEEE. His current research fields include cooperative communication and MIMO system, cognitive radio, ultra wideband technologies and advanced channel coding and modulation.

Bing Wang was born in Shandong province in 1986. He became a MS student majored in Communications and Information Systems in School of Information Science and Engineering, Shandong University, Jinan, China from 2011. His major research field is spectrum sensing in cognitive radio systems.

Peng Gong received the BS degree in Mechatronical Engineering from Beijing Institute of Technology, Beijing, China, in 2004, and the MS and Ph.D. degrees from the Inha University, Korea, in 2006 and 2010, respectively. In July 2010, he joined the School of Mechatronical Engineering, Beijing Institute of Technology, China. His research interests include link/system level performance evaluation and radio resource management in wireless systems, information security, and the next generation wireless systems such as 3GPP LTE, UWB, MIMO, Cognitive radio etc.

Kyungsup Kwak received his BS degree from Inha University, Incheon, Korea, in 1977; MS degree from the University of Southern California in 1981; and PhD degree from the University of California at San Diego in 1988. From 1988 to 1989, he was a member of Hughes Network Systems, San Diego, California. From 1989 to 1990, he was with the IBM Network Analysis Center, North Carolina. Since then, he has been with the School of Information and Communication, Inha University, Korea, as a professor. He is the director of UWB Wireless Communications Research Center in Inha University and Inha Fellow Professor (IFP). His research interests include multiple access communication systems, mobile communication systems, UWB radio systems, and ad hoc networks, as well as high-performance wireless Internet.