Asymptotic Energy Efficiency Analysis for Noisy Relay Systems with Interference-Limited Destination

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***Abstract*—This paper analyzes the asymptotic energy efficiency performance in relay systems with the destination perturbed by the co-channel interference. The interference is caused by the time slot sharing in the relay-transmit phase. The closed-form expression for the energy per good-bit constrained by a certain bit error rate is derived. The energy consumption model does not only include the transmit and circuit energy, but also considers the energy required for retransmission. The retransmission probability depending on the link reliability is determined by the outage probability under the Rayleigh fading channel assumption. The numerical results analyze the impact of the interferer number on the system energy efficiency performance. How the energy consumption varies with the interference power distribution is presented. They also investigate the variation of the energy efficiency with the constellation size constrained by different bit error rates. Some interesting implications can be observed from the analysis.**

***Index Terms*—green communication; energy per good-bit; relay; co-channel interference.**

I. Introduction

Green information and communication technology (ICT) has drawn much attention in recent years. The dramatic expansion of wired and wireless networks incur the surge of energy consumption in the telecommunication and information community [1]. The increasing energy expenditure not only results in high operational expenditure (OPEX), but also leaves a significant environmental footprint [2]. The ICT industry contributes to 2% of the CO2 emission in the world each year. It is predicted that the percentage of the CO2 emission will reach 4% in 2020.

This emerging trend has triggered the focus shifting towards the energy-efficient network design in standardization bodies [3]-[5]. It also motivates the industry to initiate green action programs. The European Commission research project EARTH [6] aims at finding energy efficiency solutions for radio access networks. The topics range from near future component development to long term research about theoretical limits of different concepts. Meanwhile, the academia community carries out the energy efficiency oriented research [7]-[10].

The introduction of relay nodes (RN) between the base station (BS) and the nearby user equipment (UE) can reduce the transmission distance per hop and provide higher link reliability [11]. Thus the relay transmission is viewed as an enabling technique to reduce the overall energy consumption within the frame work of optimizing system capacity and maintaining user Quality of Service (QoS). On the other hand, the introduction of RN adds additional energy expenditure to the system. Therefore it is necessary to analyze the impact of RN on the energy efficiency performance of the whole network.

[12] derives the closed-form energy per good-bit (EPG) expressions for the state-of-the-art relaying protocols at high signal-to-noise ratio (SNR) regimes and compares their energy expenditure with practical implications observed. [13] analyzes the bit energy level achieved by different M-ary quadrature amplitude modulation (MQAM) schemes in the relay network. [14] analyzes how the whole system's power consumption and energy efficiency change with respect to different system parameters and configurations.

All the existing relay system models do not consider the impact of co-channel interference (CCI) on the system energy efficiency performance. But it is important to take into account this issue because the reuse of radio resources, e.g., time slots and frequency channels, can increase the spectral utilization at the cost of an increased interference. The established energy efficiency metric in the physical layer is merely bit-per-Joule without considering the possibility for retransmission due to the link degradation. Motivated by these considerations, this paper covers the gap for the energy efficiency analysis in relay systems with interference-limited destinations and link reliability involved as well.

The main contribution of this paper is as follows.

1) EPG is used as the energy efficiency metric to provide a comprehensive evaluation of the system energy consumption. Besides the transmit and circuit energy, the energy required for retransmission is also included, which is indicated by the link reliability and retransmission probability.

2) The closed-form expression for EPG with CCIs under the Rayleigh fading channel assumption constrained by the predefined bit error rate (BER) is derived. Both the maximum ratio combining (MRC) and non-MRC schemes are analyzed. CCI occurred at the destination is caused by the share of the relay-transmit time slot.

3) The numerical results analyze how the co-channel interference has the influence on the system energy efficiency

performance constrained by different BER requirements. The impact of the received interference power distribution on the energy efficiency performance is demonstrated. The variation of the energy per good-bit with the constellation size in the interference-limited network is also investigated. Some interesting observations with practical implications can be made from the analysis.

The rest of the paper is organized as follows. Section II describes the system and channel model we investigate. Section III formulates the energy consumption model. Section IV derives the EPG expressions for MRC and non-MRC schemes in the noisy relay system with CCIs at the destination. Section V analyzes the simulation results and their practical implications. Section VI concludes the paper finally.

II. System Model

We consider a dual-hop decode-and-forward (DF) relay system, where the signal from BS can be forwarded by a single RN to the UE. It is assumed that RNs work in the TDD half-duplex mode. The cooperative transmission consists of two phases as depicted in Fig. 1. In the relay-receive phase, BS broadcasts the signal to each UE and its assigned RN in separate time slots. Thus each RN is only perturbed by the noise. How to select the desired RN is beyond the scope of this paper. Then the received signals at RN and UE are represented respectively as

$$y_{\rm r} = \sqrt{P_{\rm s}} h_{\rm sr} x_{\rm s} + n_{\rm sr}, \qquad (1)$$

$$y_{\rm d} = \sqrt{P_{\rm s}} h_{\rm sd} x_{\rm s} + n_{\rm sd}, \qquad (2)$$

where $P_{\rm s}$ is the transmit power at BS. $x_{\rm s}$ is the transmit signal at BS with an average power of $E\left(|x_{\rm s}|^2\right) = 1$. $h_{\rm sr}$ is the channel state information (CSI) in the BS-RN link. $h_{\rm sd}$ is the CSI in the BS-UE link. n_{sr} and n_{sd} denote the additive white Gaussian noise (AWGN) in the BS-RN link and BS-UE link respectively with zero mean and variance N_0. It is noted that we focus on the derivation of EPG expressions for one specific UE, thus the user index is omitted.

Next in the relay-transmit phase, RN decodes and forwards what it received from BS to the corresponding UE simultaneously. Fig. 2 shows how the time slots are allocated among the two phases. Since all RNs transmit in the same time slot indicated by the dashed arrow in Fig. 1, each UE suffers from N CCIs denoted as $\{x_i\}_{i=1}^N$. Then the received signal at UE is modeled as

$$y_{\rm d} = \sqrt{P_{\rm r}} h_{\rm rd} x_{\rm s} + \sum_{i=1}^{N} \sqrt{P_i} h_i x_i + n_{\rm rd}, \qquad (3)$$

where $P_{\rm r}$ is the transmit power. $h_{\rm rd}$ is the CSI in the RN-UE link. $n_{\rm rd}$ is the additive white Gaussian noise in the RN-UE link with zero mean and variance N_0. $\{h_i\}_{i=1}^N$ denotes the channels from the interferers to the UE. The amplitudes of $h_{\rm sd}$, $h_{\rm sr}$, $h_{\rm rd}$ and h_i are assumed to be independent but not necessarily identically distributed Rayleigh fading channels

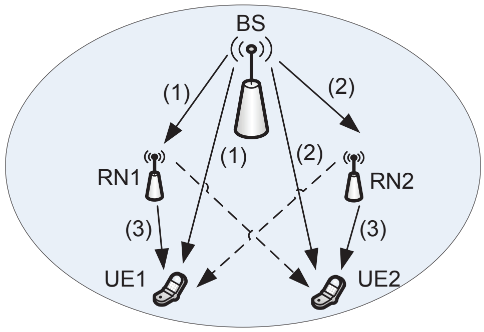

Fig. 1. Cooperative transmission scheme for 2 users. The number denotes the time slot index. The solid line is the useful signal. The dashed line is the interference signal.

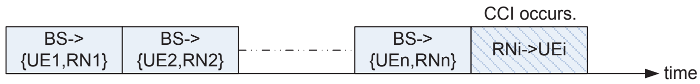

Fig. 2. Resource allocation for the cooperative transmission. The last time slot with the slashed background is the relay-transmit phase. RNs transmit to its assigned UE simultaneously in this time slot.

with $E\left(|h_{\rm sd}|^2\right) = \sigma_{\rm sd}^2$, $E\left(|h_{\rm sr}|^2\right) = \sigma_{\rm sr}^2$, $E\left(|h_{\rm rd}|^2\right) = \sigma_{\rm rd}^2$ and $E\left(|h_i|^2\right) = \sigma_i^2$.

III. Energy Consumption Model

We assume that BS transmits L bits to one specific UE. When the UE receives the signal successfully, it will send Acknowledge back. Otherwise, BS will retransmit the signal until the UE can receive it correctly. The number of retransmissions is a geometric random variable and has a mean of $\frac{1}{P_{\rm success}}$ [15]. Thus considering the link reliability and retransmission probability, the energy efficiency metric EPG is defined as

$$E = \frac{P_{\rm on} T_{\rm on} + P_{\rm tr} T_{\rm tr}}{L \cdot P_{\rm success}}. \qquad (4)$$

The definition indicates that the total energy consumed to transmit L bits consists of two parts. The first part $P_{\rm on} T_{\rm on}$ is the energy consumed in the transmit interval $T_{\rm on}$, where $P_{\rm on}$ includes the transmit power $P_{\rm t}$, the amplifier power $\alpha P_{\rm t}$, Transmit Electronic $P_{\rm ct}$ and Receive Electronic $P_{\rm cr}$ [16]. $P_{\rm tr} T_{\rm tr}$ is the energy consumed in the transient interval $T_{\rm tr}$, where $P_{\rm tr}$ is the transient power. Assuming the uncoded square MQAM is adopted, the amplifier efficiency is $\alpha = \frac{\xi}{\eta} - 1$ and $\xi = \frac{3\left(\sqrt{M}-1\right)}{\left(\sqrt{M}+1\right)}$. $P_{\rm success}$ is the system success probability.

IV. Energy Efficiency Analysis

The outage event occurs when the user's BER requirement is not satisfied. Thus the outage probability is defined as the probability that the received SNR at UE drops below a protection ratio $\gamma_{\rm th}$. For the uncoded square MQAM, the BER upper bound in the AWGN channel is derived as

$$P_b \le \frac{4Q\left(\sqrt{\frac{3b\gamma_b}{M-1}}\right)}{b}. \qquad (5)$$

where P_b is the required BER. b is the constellation size. $b = \log_2 M$. γ_b is the received SNR at UE. By approximating the bound as an equality, we derive the SNR threshold as

$$\gamma_{\rm th} = \frac{E_b}{N_0 T_b} = \gamma_b B \log_2 M. \tag{6}$$

where B is the bandwidth. Supposing that the symbol duration time $T_{\rm s} \approx \frac{1}{B}$, the transmit time is derived as

$$T_{\rm on} = \frac{L}{b} T_{\rm s} = \frac{L}{bB}. \tag{7}$$

A. DF RN without MRC

The system deployed with DF RN has 4 working states: 1) BS-UE link successful; 2) Both BS-UE link and BS-RN link in outage; 3) BS-UE link in outage, BS-RN link successful, but RN-UE link in outage; 4) BS-UE link in outage but BS-RN link and RN-UE link successful. Then the system average power consumption is

$$\begin{aligned} P_{\rm on1} &= \left(\left(1+\alpha\right) P_{\rm t} + P_{\rm ct} + 2P_{\rm cr}\right) p\left(\gamma_{\rm sd} \geq \gamma_{\rm th}\right) \\ &+ \left(\left(1+\alpha\right) P_{\rm t} + P_{\rm ct} + 2P_{\rm cr}\right) p\left(\gamma_{\rm sd} < \gamma_{\rm th}\right) p\left(\gamma_{\rm sr} < \gamma_{\rm th}\right) \\ &+ \left(2\left(1+\alpha\right) P_{\rm t} + 2P_{\rm ct} + 3P_{\rm cr}\right) p\left(\gamma_{\rm sd} < \gamma_{\rm th}\right) p\left(\gamma_{\rm sr} \geq \gamma_{\rm th}\right), \end{aligned} \tag{8}$$

where $\gamma_{\rm sd} = \frac{P_{\rm s}|h_{\rm sd}|^2}{N_0}$ is the SNR in the BS-UE link. $\gamma_{\rm sr} = \frac{P_{\rm s}|h_{\rm sr}|^2}{N_0}$ is the SNR in the BS-RN link. To facilitate our analysis it is supposed that BS and RN adopt the same energy consumption model. According to the system model that $|h_{\rm sd}|^2$ and $|h_{\rm sr}|^2$ obey exponential distribution with parameters $\sigma_{\rm sd}^2$ and $\sigma_{\rm sr}^2$ respectively, the cumulative density function (CDF) of $\gamma_{\rm sd}$ and $\gamma_{\rm sr}$ evaluated at $\gamma_{\rm th}$ can be calculated as

$$p\left(\gamma_{\rm sd} < \gamma_{\rm th}\right) = 1 - e^{-\frac{N_0}{P_{\rm s}\sigma_{\rm sd}^2}\gamma_{\rm th}}. \tag{9}$$

$$p\left(\gamma_{\rm sr} < \gamma_{\rm th}\right) = 1 - e^{-\frac{N_0}{P_{\rm s}\sigma_{\rm sr}^2}\gamma_{\rm th}}. \tag{10}$$

The system success probability in the non-MRC case is derived as

$$\begin{aligned} P_{\rm success1} &= p\left(\gamma_{\rm sd} \geq \gamma_{\rm th}\right) \\ &+ p\left(\gamma_{\rm sd} < \gamma_{\rm th}\right) p\left(\gamma_{\rm sr} \geq \gamma_{\rm th}\right) p\left(\gamma_{\rm rd} \geq \gamma_{\rm th}\right), \end{aligned} \tag{11}$$

where $\gamma_{\rm rd} = \frac{P_{\rm r}|h_{\rm rd}|^2}{\sum_{i=1}^{N} P_i |h_i|^2 + N_0}$ is the signal-to-interference-noise (SINR) ratio. Its CDF is formulated as [17]

$$p\left(\gamma_{\rm rd} \leq \gamma_{\rm th}\right) = 1 - \sum_{i=1}^{\alpha(\mathbf{R})} \sum_{j=1}^{\tau_i(\mathbf{R})} \chi_{i,j}\left(\mathbf{R}\right) \left(1 + \frac{R_{[i]}\gamma_{\rm th}}{P_{\rm r}\sigma_{\rm rd}^2}\right)^{-j}, \tag{12}$$

where $\mathbf{R} = diag\left(R_1, R_2, R_3, \cdots, R_N\right)$, $R_i \triangleq \sigma_i^2 P_i$. $\alpha\left(\mathbf{R}\right)$ represents the number of distinct diagonal elements of $\alpha\left(\mathbf{R}\right)$. $R_{[1]} > R_{[2]} > \cdots > R_{[\alpha[\mathbf{R}]]}$ are distinct diagonal elements in decreasing order. $\tau_i\left(\mathbf{R}\right)$ is the multiplicity of $R_{[i]}$. $\chi_{i,j}\left(\mathbf{R}\right)$ is the $(i,j)_{\rm th}$ characteristic coefficient of $\mathbf{R}$. Then the system EPG can be derives as

$$E1 = \frac{P_{\rm on1}T_{\rm on} + P_{\rm tr}T_{\rm tr}}{L \cdot P_{\rm success1}}. \tag{13}$$

B. DF RN with MRC

For the MRC case, it is assumed that UE knows the CSI in the BS-UE link and in the RN-UE link. UE combines the signals from RN and BS coherently to output the maximum equivalent SNR. That is $\gamma = \gamma_{\rm rd} + \gamma_{\rm sd}$. The system success probability in this case is given by

$$P_{\rm success2} = 1 - p\left(\gamma_{\rm sd} \leq \gamma_{\rm th}\right) p\left(\gamma_{\rm sd} + \gamma_{\rm rd} \leq \gamma_{\rm th}\right). \tag{14}$$

The system in the MRC scheme has the same 4 working states as that in the non-MRC case. Thus the system average power consumption in the MRC case is

$$P_{\rm on2} = P_{\rm on1}. \tag{15}$$

According to (12), the CDF of $\gamma_{\rm rd}$ conditioned on $\gamma_{\rm sd}$ is formulated as

$$\begin{aligned} & p\left(\gamma_{\rm rd} \leq \gamma_{\rm th}\right) = \\ & 1 - \sum_{i=1}^{\alpha(\mathbf{R})} \sum_{j=1}^{\tau_i(\mathbf{R})} \chi_{i,j}\left(\mathbf{R}\right) \left(1 + \frac{R_{[i]}\left(\gamma_{\rm th} - \gamma_{\rm sd}\right)}{P_r\sigma_{\rm rd}^2}\right)^{-j}. \end{aligned} \tag{16}$$

Then (16) is averaged over $\gamma_{\rm sd}$, the CDF of the equivalent SNR γ at UE can be derived as

$$\begin{aligned} & p\left(\gamma_{\rm sd} + \gamma_{\rm rd} \leq \gamma_{\rm th}\right) \\ & = \int_0^{\gamma_{\rm th}} p\left(\gamma_{\rm rd} \leq \gamma_{\rm th} - \gamma_{\rm sd} | \gamma_{\rm sd}\right) f\left(\gamma_{\rm sd}\right) d\gamma_{\rm sd}, \end{aligned} \tag{17}$$

where $f\left(\gamma_{\rm sd}\right) = \frac{N_0}{P_{\rm s}\sigma_{\rm sd}^2} e^{-\frac{N_0}{P_{\rm s}\sigma_{\rm sd}^2}\gamma_{\rm sd}}$ is the probability density function of $\gamma_{\rm sd}$. Then substituting (9), (16) and (17) into (14), the system success probability in the MRC case is derived. Similar to the non-MRC case, EPG for the MRC case can be calculated.

V. Numerical Analysis

In this section, we evaluate the energy efficiency performance in the relay system with the destination disturbed by the co-channel interference from other RNs. The energy consumption model established in Section III is utilized. The energy efficiency is measured by the closed-form expression for EPG derived in Section IV. It is expressed in decibel. The constellation size is $b \in \{2, 4, 6, 8\}$. The simulation parameters are listed in Table 1.

Fig. 3 shows how the system energy efficiency varies with the change of the interferer number. The energy efficiency performance with the number of interferer equal to 6, 8 and 10 is compared with no interferer case. The BER constraint is defined as 0.1. As predicted, the system is the most energy efficient when there is no interferer, which corresponds to the line with the marker diamond in Fig. 3. With the number of interferer increasing, more energy is consumed. When the number of interferer is 10, the system requires the maximum energy indicated by the line with the marker upper triangle in Fig. 3. The reason is that the link reliability is degraded as the number of interferer increases. More energy is consumed for retransmission. In our system model, CCI at UE is caused by the simultaneous transmission from multiple

RNs in the relay-transmit phase. While the introduction of RN in the network can extend the cell size, combat fading and improve the spectral efficiency, the influence of RN on other nodes in the network should be emphasized as well. It is necessary to properly design the number of RN in the practical deployment in order to strike a balance between the link reliability improvement for the served UE and the extra energy expenditure for other UEs who share resources in the network.

Fig. 4 investigates the impact of the received interference power distribution on the system energy efficiency performance constrained by a total received interference power. It is assumed that 6 co-channel interferers exist and the BER requirement is 0.01. The solid line with the marker square corresponds to the equal interference power distribution $\mathbf{R}_1 = [1, 1, 1, 1, 1, 1]\text{mW}$. The solid line with the marker diamond corresponds to the unequal interference power distribution $\mathbf{R}_2 = [0.5, 1, 2, 1.5, 0.75, 0.25]\text{mW}$. The solid line with the marker circle corresponds to the interference power distribution with only one effective interferer $\mathbf{R}_3 = [6, 0, 0, 0, 0, 0]\text{mW}$. Fig. 4 demonstrates that when the interference power is equally distributed, the system is the least energy efficient. The best scenario occurs when there is only one effective interferer. According to Theorem 2 in [17], the system outage probability P_{out} is Schur-concave with respect to $\mathbf{R}$. Thus $P_{\text{out}}(\mathbf{R}_1) > P_{\text{out}}(\mathbf{R}_2) > P_{\text{out}}(\mathbf{R}_3)$ because of $\mathbf{R}_1 < \mathbf{R}_2 < \mathbf{R}_3$. Fig. 4 reveals that the RN position has the impact on the energy expenditure in the network. The scenario that the received interference power is equally distributed should be avoided. RNs should be deployed according to the traffic density and distribution in the specific area. Alternatively, it is also feasible to optimize the transmit power for the energy efficiency improvement in the network in order to control the interference power to the minimum level.

Fig. 5 presents the impact of the constellation size on the system energy efficiency performance under different BER constraints with and without MRC. First, the simulation result shows that when the constellation size is either smaller or larger, the energy consumption is relatively higher. The optimal constellation size exists to achieve the minimum energy consumption. The reason is that the larger constellation size indicates more bits can be transmitted at a time. Then the transmit time is shorter, less transmit power is consumed. On the other hand, the outage probability increases for the larger constellation size and more retransmission energy is required.

Second, it is observed that with the BER increasing, the optimal constellation size to achieve the minimum energy consumption increases. For $P_b = 0.1$, the minimum EPG locates at $b = 4$ which is represented by the red line. For $P_b = 0.15$, the minimum EPG locates at $b = 4$ which is represented by the yellow line. But for $P_b = 0.3$, the minimum EPG locates at $b = 6$ which is represented by the blue line. This is because when the BER requirement becomes more tolerant, the threshold for retransmission becomes smaller and more bits can be transmitted at a time. Then the outage probability decreases and at the same time the transmit time is shorter for the larger constellation size.

Third, for a given BER, EPG in the dashed line is always smaller corresponding to the MRC scheme than that in the solid line corresponding to the non-MRC scheme. For the smaller BER, the energy efficiency difference between MRC and non-MRC is significant especially for the larger constellation size. It reveals that the system with MRC is more energy efficient than that without MRC especially for the larger constellation size. The MRC scheme can increase the link reliability and the transmit time can be saved further for the larger constellation size. Thus the receive diversity is robust against CCIs and can improve the system energy efficiency. However, with the BER requirement more tolerant, the energy efficiency discrepancy between MRC and non-MRC schemes is not obvious. In this case, non-MRC is a better choice because it is easily

TABLE I
SIMULATION PARAMETERS

$L = 20000\text{bits}$	$B = 20\text{kHz}$
$T_{\text{tr}} = 5\text{ms}$	$P_{\text{s}} = 10\text{mW}$
$P_{\text{r}} = 10\text{mW}$	$P_{\text{tr}} = 2\text{W}$
$N_0 = 10^{-9}$	$\eta = 0.35$
$P_{\text{ct}} = 1\text{mW}$	$P_{\text{cr}} = 0.8\text{mW}$

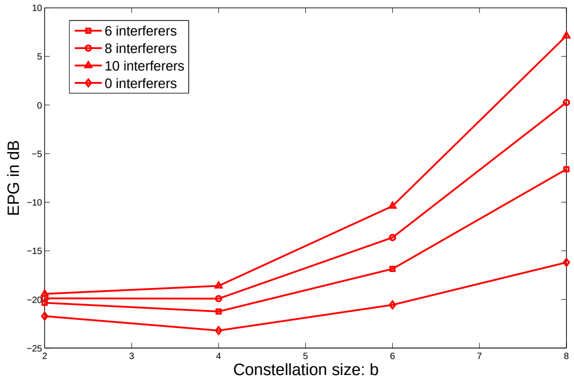

Fig. 3. The variation of EPG with the number of interferers.

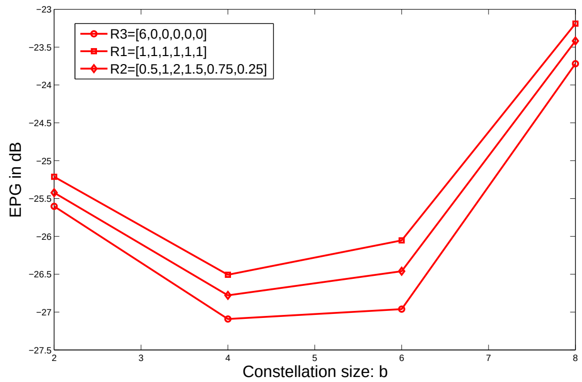

Fig. 4. The impact of the received interference power distribution on the system energy efficiency.

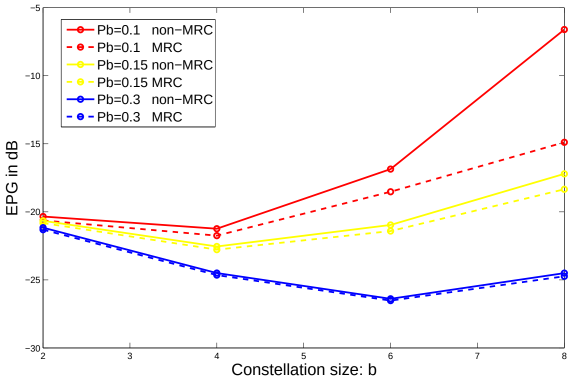

Fig. 5. The variation of EPG with the constellation size for MRC and non-MRC schemes constrained by different BER.

implemented.

VI. Conclusion

This paper analyzes the energy efficiency performance in the DF relay system with the destination perturbed by the co-channel interference with the simultaneously transmission from other RNs occurred in the relay-transmit phase. A more comprehensive energy consumption model is formulated. Besides the transmit and circuit energy, the energy required for the retransmission is also considered. The retransmission probability is determined by the system outage probability under the Rayleigh fading assumption constrained by users' BER requirements. The asymptotic closed-form expressions for the energy per good-bit with MRC and non-MRC schemes are derived. The simulation results present that the number of interferers and the interference power distribution have the impact on the system energy efficiency performance. Thus it is important to optimize the number, position and the transmit power of RNs to make the tradeoff between the link reliability and the extra energy consumption. The simulation results also demonstrate that the MRC scheme has the better energy efficiency performance than non-MRC especially for more tolerant BER requirement at the larger constellation size. The receive diversity is robust against CCIs and can improve the system energy efficiency performance. The optimal constellation size to minimize the energy per good-bit exists in the interference-limited network. The optimal constellation size varies with the BER requirement.

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