Energy-Aware Hybrid Cooperative Relaying with Asymmetric Traffic

Jian Chen, Lu Lv, Wenjin Geng, and Yonghong Kuo

In this paper, we study an asymmetric two-way relaying network where two source nodes intend to exchange information with the help of multiple relay nodes. A hybrid time-division broadcast relaying scheme with joint relay selection (RS) and power allocation (PA) is proposed to realize energy-efficient transmission. Our scheme is based on the asymmetric level of the two source nodes' target signal-to-noise ratio indexes to minimize the total power consumed by the relay nodes. An optimization model with joint RS and PA is studied here to guarantee hybrid relaying transmissions. Next, with the aid of our proposed intelligent optimization algorithm, which combines a genetic algorithm and a simulated annealing algorithm, the formulated optimization model can be effectively solved. Theoretical analyses and numerical results verify that our proposed hybrid relaying scheme can substantially reduce the total power consumption of relays under a traffic asymmetric scenario; meanwhile, the proposed intelligent optimization algorithm can eventually converge to a better solution.

Keywords: Hybrid relaying strategy, asymmetric traffic, energy consumption, relay selection, power allocation, intelligent optimization algorithm, PA, RS.

I. Introduction

Cooperative communication networks, where relays are allowed to collaborate with each other to assist with a transmission from a source to a destination, promise significant performance gains in overall throughput and energy saving [1]–[3]. This has made relays an attractive option for use in cellular, ad hoc, and wireless sensor networks [4]. To recover the spectral efficiency loss induced by the half-duplex constraint in a conventional relay transmission, a two-way relaying protocol has been proposed — one that has aroused considerable efforts by the research community to improve spectral efficiency (see [5]–[12]).

With the explosive growth of high data rate applications, more and more energy is being consumed in wireless networks to assure quality of service (QoS) [13]–[14]. Therefore, reducing such energy consumption has attracted increasing attention in light of the background of limited energy resources and environmentally friendly transmission behaviors. As a highly energy-efficient operation, joint relay selection (RS) and power allocation (PA) has been investigated for two-way relaying in the literature, ranging from single RS [15]–[17] to multi-RS [18]–[21]. In [15], taking the energy consumption and residual energy state of candidate relay nodes into consideration, an optimal distributed joint RS and PA scheme for wireless multi-hop cooperative relay networks was proposed to increase an achievable date rate and prolong the average network lifetime. The authors of [16] studied the transmit power consumption for a two-way relay channel at required end-to-end rates and proposed an efficient joint RS and PA scheme to minimize the total transmit power. Furthermore, an energy-efficient cooperative multi-relaying scheme in [18] was proposed so as to reduce the energy

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Jian Chen (corresponding author, jianchen@mail.xidian.edu.cn), Lu Lv (lulv@stu.xidian.edu.cn), Wenjin Geng (wenjingeng@gmail.com), and Yonghong Kuo (yhkuo@mail.xidian.edu.cn) are with the School of Telecommunications Engineering, Xidian University, Xi'an, China.

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consumption with a simple RS criterion. In [19], the authors investigated an adaptive cooperative scheme with joint multi-RS and power optimization by using the least possible number of relays with optimal power distribution to minimize the energy consumption. In [20], a multi-RS scheme for two-way relaying was studied through the use of a heuristic approach to solve an optimization problem, and the results showed that multi-RS significantly outperformed single-RS in sum rate enhancement and energy consumption reduction.

The aforementioned works all concentrate on bidirectional symmetric traffic. However, traffic flows are always asymmetric in reality.

With the rapid development of wireless communications, the number of high data rate services supported by mobile terminals is sharply increasing [22]–[25]. Although located in the same relaying network, the QoS provisions of these mobile terminals may be various, indicating that heterogeneous QoS requirements should be considered under an energy-constraint scenario so as to decrease the energy consumption of relays [26]–[27]. For sufficient utilization of relay networks that have a limited energy resource, it is of great necessity to design an appropriate relay transmission strategy with joint RS and PA under an asymmetric traffic environment; this would help to minimize the energy consumption of the relay networks.

In this work, we focus on a two-way amplify-and-forward (AF) relaying network with asymmetric traffic, where two source nodes wish to exchange information with the help of multiple relay nodes. A novel hybrid transmission strategy inspired by the time-division broadcast (TDBC) protocol [28] is proposed to satisfy the heterogeneous QoS requirements from both source nodes in a green manner. At first, taking various QoS provisions into consideration, an energy-aware hybrid cooperative relaying strategy is proposed according to the signal-to-noise ratios (SNRs) of the two source nodes, by which the transmission mode and corresponding transmission direction of a relay node can be determined. Meanwhile, the reliability of the information exchange can be guaranteed through the coordination between source and relay nodes. After this, a joint RS and PA scheme to minimize the power consumption of relay networks, in view of energy utilization, is presented, whereby a nonlinear combinational optimization model is derived. Based on the formulated model, an intelligent optimization algorithm is proposed to efficiently solve the combinational optimization by combining a genetic algorithm (GA) and a simulated annealing (SA) algorithm; thus, a local optimum can be prevented and the proposed algorithm's convergence speed and search efficiency can be raised. Numerical results demonstrate that our proposed hybrid strategy is preferable for heterogeneous QoS requirements of mobile terminals and achieves significant energy saving; it is shown that the proposed intelligent optimization algorithm can eventually converge to a better solution.

The remainder of this paper is organized as follows. Section II gives the system model and proposed hybrid cooperative relaying strategy. In Section III, an optimization framework with joint RS and PA is formulated, followed by an intelligent optimization algorithm. Extensive simulations and discussions are presented in Section IV. Finally, Section V concludes the paper.

II. System Model

We study a wireless network consisting of two source nodes (SNs) and N relay nodes (RNs), where S_1 and S_2 denote the two SNs and $\mathbf{R} = \{R_1, R_2, \dots, R_N\}$ represents the RNs. Both SNs intend to exchange information via the participating RNs using a TDBC protocol. We consider a quasi-static fading channel, for which the fading coefficients are constant within one transmission block but change independently from one block to another. The channel gains of S_1 to S_2, S_1 to R_n, and S_2 to R_n are expressed as h_0, h_{1n}, and h_{2n}, respectively. In particular, the channel gains are assumed to be reciprocal; that is, $h_{1n} = h_{n1}$, $h_{2n} = h_{n2}$ [11]. Note that the two-way relaying network is able to collect perfect channel state information (CSI) by applying training signals and both SNs transmit data with constraint power P_{s1} and P_{s2}, respectively. Furthermore, independent and identically distributed (i.i.d.) additive white Gaussian noise (AWGN) at terminals S_1, S_2, and R_n is denoted by $n_1 \sim CN(0, N_0)$, $n_2 \sim CN(0, N_0)$, and $n_R^{(1)}, n_R^{(2)} \sim CN(0, N_0)$, respectively.

To depict the level of the QoS asymmetry, we model the traffic pattern using the two SNs' target SNR thresholds, Γ_{th1} and Γ_{th2}, which is a widely used metric to indicate a specific traffic in practice [10]–[12]. If only the bidirectional relaying is to be allowed to perform information exchange between the source terminals, then the transmit power of RNs should be regulated in accordance with the SN that owns the higher SNR threshold, thus resulting in significant energy waste. In this regard, to coordinate the transmission of RNs and also reduce power consumption, an energy-aware hybrid cooperative relaying strategy is proposed. More specifically, during each information exchange process, the transmission mode for each relay, either unidirectional or bidirectional, can be dynamically designated so that various target SNR thresholds are guaranteed. In this way, the whole cooperative system adaptively adjusts to the asymmetric QoS environment. In what follows, we consider two types of TDBC relaying scenarios; that is, with asymmetric SNR thresholds and with identical SNR thresholds.

1. Hybrid Relaying with Asymmetric SNR Thresholds

In the case where $\Gamma_{\text{th1}} \neq \Gamma_{\text{th2}}$, the transmission mode for each relay is adaptively designated as unidirectional or bidirectional. To facilitate the subsequent discussions, we let both $o_{1n} \in \{0, 1\}$ and $o_{2n} \in \{0, 1\}$ denote a unidirectional transmission indicator, and we use $t_n \in \{0, 1\}$ to denote a bidirectional transmission indicator. For instance, if R_n acts as a bidirectional relay, then $t_n = 1$; otherwise, $t_n = 0$. If R_n is selected for unidirectional relaying with the information flow from S_1 to S_2, then we have $o_{1n} = 1$; otherwise $o_{1n} = 0$. Additionally, o_{2n} has the same rationale with o_{1n}. Obviously, during an information exchange process, the following condition should be satisfied: $t_n + o_{1n} + o_{2n} \le 1,\ \forall n \in \{1, \dots, N\}$.

As illustrated by Fig. 1, the two-way TDBC relaying scenario considered in this paper consists of three successive time slots. During time slot 1, S_1 (S_2) broadcasts a signal, x_1 (x_2), to the candidate RNs and its destination, then S_2 (S_1) and R_n receive an AWGN-corrupted superposition of the transmitted signal; that is,

$$y_{1,S_2} = \sqrt{P_{S_1}}\, h_0 x_1 + n_{S_2}, \tag{1}$$

$$y_{1,R_n} = \sqrt{P_{S_1}}\, h_{1n} x_1 + n_{R_n}^{(1)}, \tag{2}$$

where y_{1,S_2} and y_{1,R_n} denote the received signals at S_2 and R_n, respectively.

In time slot 2, the RNs serving as unidirectional relays remain silent; S_2 (S_1) broadcasts the signal x_2 (x_1) to bidirectional RNs. The received signals at S_1 (S_2) and R_n are given by

$$y_{2,S_1} = \sqrt{P_{S_2}}\, h_0 x_2 + n_{S_1}, \tag{3}$$

$$y_{2,R_n} = \sqrt{P_{S_2}}\, h_{2n} x_2 + n_{R_n}^{(2)}, \tag{4}$$

respectively. In time slot 3, unidirectional relays are activated again and amplify the signals received from the intended terminal to both users. Meanwhile, bidirectional relays combine the previous two slots' messages and forward them to S_1 and S_2; the received signals are shown by

$$\begin{aligned} y_{3,S_1} = \sum_{n=1}^{N} \Big[& t_n \beta_{t_n} h_{1n} \left(y_{1,R_n} + y_{2,R_n} \right) \\ & + h_{1n} \left(o_{1n} \beta_{o_{1n}} y_{1,R_n} + o_{2n} \beta_{o_{2n}} y_{2,R_n} \right) \Big] + n_{S_1}, \end{aligned} \tag{5}$$

$$\begin{aligned} y_{3,S_2} = \sum_{n=1}^{N} \Big[& t_n \beta_{t_n} h_{2n} \left(y_{1,R_n} + y_{2,R_n} \right) \\ & + h_{2n} \left(o_{1n} \beta_{o_{1n}} y_{1,R_n} + o_{2n} \beta_{o_{2n}} y_{2,R_n} \right) \Big] + n_{S_2}, \end{aligned} \tag{6}$$

where β_{t_n}, $\beta_{o_{1n}}$, and $\beta_{o_{2n}}$ are normalization factors. Let us denote P_n as the transmit power of R_n, then the normalization factors can be arrived at and are given as follows:

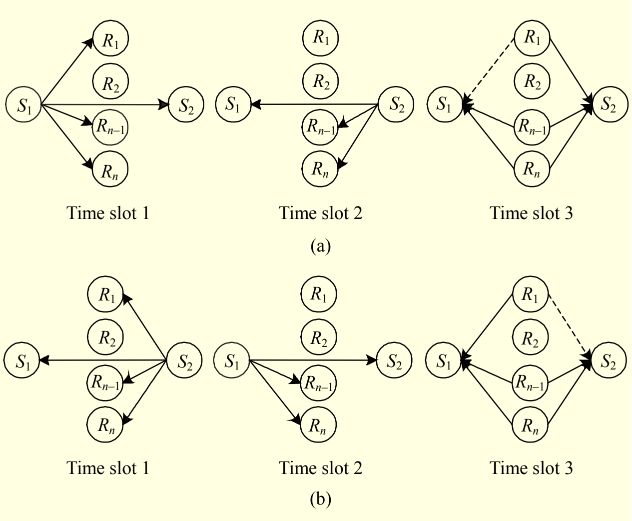

Fig. 1. Hybrid relaying strategy with asymmetric SNR thresholds: (a) $\Gamma_{\text{th1}} < \Gamma_{\text{th2}}$ and (b) $\Gamma_{\text{th1}} > \Gamma_{\text{th2}}$.

$$\beta_{t_n} = \sqrt{P_n \Big/ \left(P_{S_1} |h_{1n}|^2 + P_{S_2} |h_{2n}|^2 + 2N_0 \right)}, \tag{7}$$

$$\beta_{o_{1n}} = \sqrt{P_n \Big/ \left(P_{S_1} |h_{1n}|^2 + N_0 \right)}, \tag{8}$$

$$\beta_{o_{2n}} = \sqrt{P_n \Big/ \left(P_{S_2} |h_{2n}|^2 + N_0 \right)}. \tag{9}$$

Since both S_1 and S_2 know their own transmitted signals and the overall CSI, then the two source terminals can implement self-interference cancellation and obtain y_{S_1} and y_{S_2} [5], respectively, which are expressed as follows:

$$\begin{aligned} y_{S_1} = \sum_{n=1}^{N} \Big[& \left(t_n \beta_{t_n} + o_{2n} \beta_{o_{2n}} \right) h_{1n} h_{2n} \sqrt{P_{S_2}}\, x_2 + h_{1n} n_{R_n}^{(1)} \\ & \times \left(t_n \beta_{t_n} + o_{1n} \beta_{o_{1n}} \right) + h_{1n} n_{R_n}^{(2)} \left(t_n \beta_{t_n} + o_{2n} \beta_{o_{2n}} \right) \Big] + n_{S_1}, \end{aligned} \tag{10}$$

$$\begin{aligned} y_{S_2} = \sum_{n=1}^{N} \Big[& h_{1n} h_{2n} \sqrt{P_{S_1}}\, x_1 \left(t_n \beta_{t_n} + o_{2n} \beta_{o_{2n}} \right) \\ & + h_{2n} n_{R_n}^{(1)} \left(t_n \beta_{t_n} + o_{1n} \beta_{o_{1n}} \right) + h_{2n} n_{R_n}^{(2)} \left(t_n \beta_{t_n} + o_{2n} \beta_{o_{2n}} \right) \Big] \\ & + n_{S_2}. \end{aligned} \tag{11}$$

Therefore, by using a maximum ratio combining, the end-to-end SNRs for the SNs after a transmission comprising three successive time slots can be derived as

$$\Gamma_{S_1}=\frac{P_{S_2}g_0}{N_0}+\frac{P_{S_2}}{N_0}\times\frac{\left[\sum_{n=1}^{N}\left(t_n\beta_{t_n}+o_{2n}\beta_{o_{2n}}\right)\left|h_{1n}h_{2n}\right|\right]^2}{\sum_{n=1}^{N}\left(2t_n\beta_{t_n}^2+o_{1n}\beta_{o_{1n}}^2+o_{2n}\beta_{o_{2n}}^2\right)\times g_{1n}+1},\tag{12}$$

$$\Gamma_{S_2}=\frac{P_{S_1}g_0}{N_0}+\frac{P_{S_1}}{N_0}\times\frac{\left[\sum_{n=1}^{N}\left(t_n\beta_{t_n}+o_{1n}\beta_{o_{1n}}\right)\left|h_{1n}h_{2n}\right|\right]^2}{\sum_{n=1}^{N}\left(2t_n\beta_{t_n}^2+o_{1n}\beta_{o_{1n}}^2+o_{2n}\beta_{o_{2n}}^2\right)\times g_{2n}+1},\tag{13}$$

where $g_0=\left|h_0\right|^2$, $g_{1n}=\left|h_{1n}\right|^2$, and $g_{2n}=\left|h_{2n}\right|^2$.

It should be noted that (12) and (13) are the generalized SNR expressions with asymmetric QoS requirements. For a further discussion, when $\Gamma_{\text{th1}}<\Gamma_{\text{th2}}$, as depicted in Fig. 1(a), we have $o_{2n}=0,\ \forall n\in\{1,\dots,N\}$ in (13), because in this case, the unidirectional relays are selected to assist the information flow from S_1 to S_2 so as to satisfy the higher target SNR threshold of S_2. Applying the same rationale, we have $o_{1n}=0$, $\forall n\in\{1,\dots,N\}$ in (12) when $\Gamma_{\text{th1}}>\Gamma_{\text{th2}}$, as shown in Fig. 1(b).

2. Special Case with Identical SNR Thresholds

Under the assumption that the two SNs have symmetric traffic requirements (that is, $\Gamma_{\text{th1}}=\Gamma_{\text{th2}}$), the proposed hybrid cooperative relaying strategy degenerates into the conventional TDBC scheme. In this special case, only bidirectional RNs are used to realize information exchange while satisfying the identical SNR thresholds, so $o_{1n}=o_{2n}=0$ holds for all the RNs, as illustrated in Fig. 2. Therefore, the end-to-end SNRs for S_1 and S_2 can be simplified as

$$\Gamma_{S_1}^{\text{conv}}=\frac{P_{S_2}g_0}{N_0}+\frac{P_{S_2}}{N_0}\cdot\frac{\left(\sum_{n=1}^{N}t_n\beta_{t_n}\left|h_{1n}h_{2n}\right|\right)^2}{\sum_{n=1}^{N}2t_n\beta_{t_n}^2g_{1n}+1},\tag{14}$$

$$\Gamma_{S_2}^{\text{conv}}=\frac{P_{S_1}g_0}{N_0}+\frac{P_{S_1}}{N_0}\cdot\frac{\left(\sum_{n=1}^{N}t_n\beta_{t_n}\left|h_{1n}h_{2n}\right|\right)^2}{\sum_{n=1}^{N}2t_n\beta_{t_n}^2g_{2n}+1}.\tag{15}$$

In the following sections, we shall consider an efficient joint multiple RS and PA scheme to realize the energy-aware hybrid cooperative relaying strategy, and thus to achieve significant energy saving of the relay networks. It is worth noting that the proposed joint scheme is based on a centralized approach with assumed complete CSI. This assumption involves some timely and accurate channel estimation and feedback techniques, which are beyond the scope of this paper.

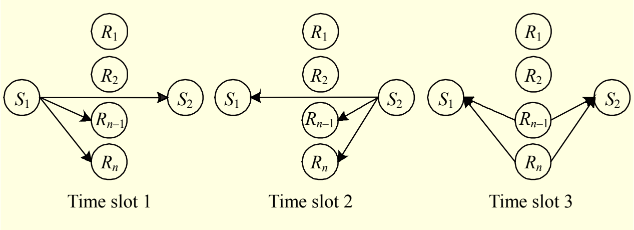

Fig. 2. Hybrid relaying strategy with identical SNR thresholds.

III. Problem Formulation and Intelligent Optimization Algorithm

This paper investigates a resource allocation problem for multi-user two-way relay networks under asymmetric QoS constraints. Considering the proposed hybrid strategy, our objective is not only to appropriately designate a transmission mode for selected RNs but also to optimally allocate available transmit power so as to minimize the sum energy consumption of a relay network. To this end, an optimization framework with a joint RS and PA scheme is formulated. After that, a penalty function–based GA-SA optimization algorithm is presented to effectively solve the above problem.

1. Optimization Framework of Joint Multiple RS and PA

According to (12) and (13), the optimization framework of the hybrid relaying strategy with joint multiple RS and PA can be mathematically formulated as

$$\begin{aligned}
\min\ & \sum_{n=1}^{N}\left(t_n+o_{1n}+o_{2n}\right)\cdot P_n\\
\text{s.t. } & \Gamma_{S_1}\geq\Gamma_{\text{th}1},\\
& \Gamma_{S_2}\geq\Gamma_{\text{th}2},\\
& 0\leq P_n\leq P_{\max,n} \qquad \forall n=1,2,\dots,N,\\
& t_n+o_{1n}+o_{2n}\leq 1 \qquad \forall n=1,2,\dots,N,
\end{aligned}\tag{16}$$

where $P_{\max,n}$ is the maximum transmit power of R_n. Note that a relay is defined to be selected if it is allocated with transmit power; that is, $t_n+o_{1n}+o_{2n}=1$. In particular, the cases $o_{1n}=0$ and $o_{2n}=0$ correspond to $\Gamma_{\text{th1}}>\Gamma_{\text{th2}}$ and $\Gamma_{\text{th1}}<\Gamma_{\text{th2}}$, respectively, as mentioned previously. This indicates a certain hybrid transmission process with QoS asymmetry; for example, the unidirectional information flow is from S_2 to S_1 or from S_1 to S_2. Additionally, when the SNR thresholds are identical, only the bidirectional relays are used and we have $o_{1n} = o_{2n} = 0$. Then, the joint optimization can be decomposed into a simplified conventional form.

It can be seen from (16) that the obtained optimization problem is a mixed integer nonlinear programming problem, which is known to be NP-complete. Therefore, it is difficult to derive a closed-form solution from using only the traditional iterative method. In the following, a penalty function–based intelligent optimization algorithm combing GA and SA is presented to find an optimal solution: $G^* = \{t_n^*, o_{1n}^*, o_{2n}^*, p_n^*\}$.

2. Penalty Function–Based Intelligent Optimization Algorithm

Since t_n, o_{1n}, and o_{2n} involved in (16) are all binary variables, the optimal solution cannot be directly derived by using the gradient search–based traditional iterative algorithm [27]. Due to the global stochastic search characteristic of the GA [29], each binary variable is usually encoded as a fixed-length binary string; thus, the discrete variables can be effectively solved. Moreover, by introducing the penalty function to the objective function in (16), the nonlinear combinatorial optimization problem can be transformed into a linear combinatorial optimization problem, from which the solution is always in the feasible region and the convergence speed can be accelerated. Nevertheless, the GA may enter a local optimum prematurely during the iterative process; thus, it is necessary to force the search iterations of GA to escape from the local optimum by combining GA with the SA algorithm [30]. In this regard, based on the penalty function, a GA-SA optimization algorithm is presented. The process of this intelligent algorithm is described as follows:

1) Initialize the iteration loop $t = 0$ and encode the power value based on the binary mechanism shown in Fig. 3. Generate initial population with the size of S_{ini}.

2) Adopt the single-point crossover method to generate offspring $c(t)$ by adjusting the crossover probability $P_c(t)$ dynamically; abide by the rule of single point mutation to generate offspring $m(t)$ by adjusting the mutation probability $P_m(t)$.

3) Decode the population $p(t)$, $c(t)$, and $m(t)$; calculate the fitness: $F(G,R)=\left(f(G)+\sum_{i=1}^{M}R_i\left|g_i'(G)\right|^2\right)^{-1}$, where $f(G)$ is the objective function defined in (16), M is the number of constraint conditions, R_i is the penalty factor, and $g'_i(G)$ is the reconstructed value derived from the first three constraints with global reference.

4) Select the next generation $p(t+1)$ from $p(t)$, $c(t)$, and $m(t)$ by using the roulette wheel method; output the local solution $\bar{G}$ and the corresponding fitness value $F\left(\bar{G},R\right)$, then execute step 5.

5) Initialize the temperature T of the SA algorithm and the iteration number $k = 0$, then execute step 6.

6) Add perturbation ΔG to the local solution $\bar{G}$ by randomly changing the transmission mode and the power value of RNs; derive the new fitness value $F\left(\bar{G}+\Delta G,R\right)$, if $\Delta F = F\left(\bar{G}+\Delta G,R\right)-F\left(\bar{G},R\right)\geq 0$ holds, accept the new solution, or accept the new solution with a probability of $\exp(\Delta F/T)\geq$ random(0, 1); otherwise, add new perturbation again.

7) Judge the convergence criteria of SA: if it satisfies, output the global solution G^*; otherwise, execute step 8.

8) Set $k = k + 1$. If $k \leq L$ holds, where L denotes the maximal perturbation times, then return to step 6; otherwise, return to step 5.

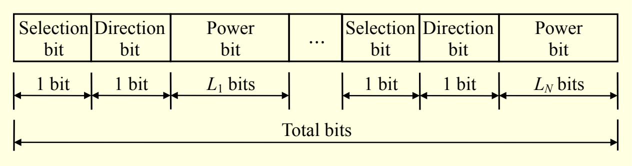

Fig. 3. Bidirectional encoding mechanism of GA.

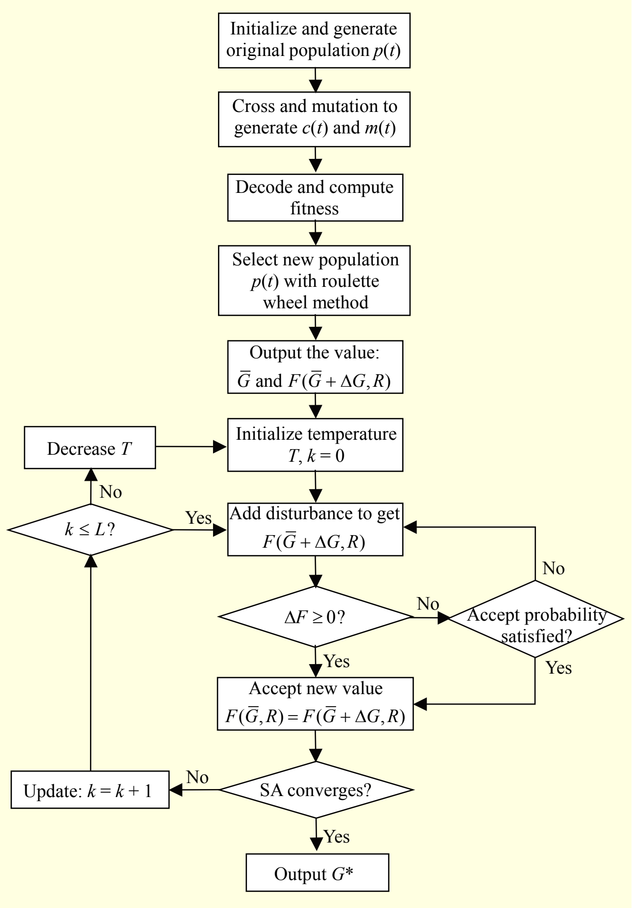

Fig. 4. Flowchart of intelligent optimization algorithm.

The flowchart of the penalty function–based intelligent optimization algorithm is shown in Fig. 4.

IV. Numerical Evaluation

In this section, numerical results and extensive discussions are presented to validate both the energy saving of the hybrid relaying strategy and the intelligent optimization algorithm. We assume that *N* RNs are randomly collocated in a circular area that has an origin at (50, 0) and a radius of 10 m. The bandwidth is set to be 20 kHz, and the power spectral density of the AWGN is set to be –174 dBm/Hz. The path loss model can be expressed as $h = A \cdot d^{-\alpha}$, where *A* denotes the path loss factor and *d* denotes the distance between the two SNs. Other simulation parameters are shown in Table 1. For a fair comparison, we also assume that the same optimization model among the cooperative strategies is adopted.

Figure 5 depicts the total power consumption with varying SNR threshold of S_2 from 5 dB to 10 dB; the SNR threshold of S_1 is fixed at 5 dB. As can be perceived, our proposed hybrid strategy outperforms the other two strategies in all cases; that is, less power is consumed while promising the two SNs' QoS demands. This energy saving is due to the application of the hybrid relaying transmission mode; the transmission modes of participating RNs can be dynamically configured to satisfy the two SNs' requirements in an energy-efficient manner. Whereas for the other two schemes, the QoS asymmetry is ignored and all the selected RNs determine their power based on the higher SNR threshold, thus resulting in significant energy waste. It can also be observed that in the low SNR threshold region, the hybrid strategy still maintains a superior performance over the conventional TDBC with a direct link in overall power consumption, thus validating the foregoing analysis. However, this performance gap is small when the two SNR threshold values are very close. In particular, when the two SNR threshold values are identical, the performance of the proposed strategy is the same as that of the conventional TDBC with a direct link, since only bidirectional relays are used in this situation.

However, the performance disparities become larger with an increase of S_2's SNR threshold. The reason is that the proposed hybrid strategy can appropriately adjust the transmission modes of the selected unidirectional and bidirectional RNs. Thus, considerable power is saved in terms of the various QoS requirements.

Table 1. List of simulation parameters.

Parameters	Values
Constant *A* of path loss factor	0.097
Constant *α* of path loss exponent	3
Distance *d* between SNs	100 m
Transmit power P_{S_1} of S_1	20 μW
Transmit power P_{S_2} of S_2	20 μW
Maximum transmit power of each R_n	20 μW

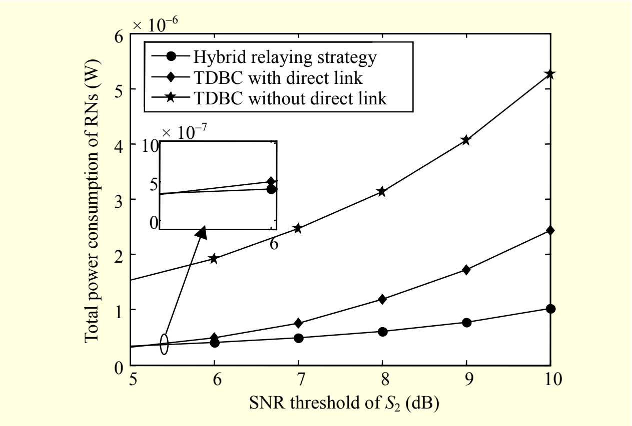

Fig. 5. Performance of total power consumption vs. SNR threshold of S_2 for $\Gamma_{\text{th1}} = 5$ dB.

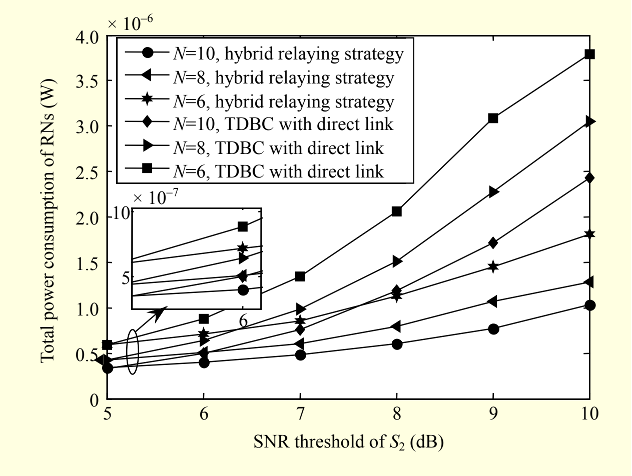

Fig. 6. Performance of total power consumption as SNR threshold of S_2 varies for different numbers of RNs when $\Gamma_{\text{th1}} = 5$ dB.

In Fig. 6, we compare the performance of the total power consumption in both the hybrid relaying and the conventional TDBC relaying situations, with respect to the SNR threshold of S_2 and the number of relays. It is clearly shown that the overall power consumption grows with the increased SNR threshold of S_2, due to the fact that more power is needed to promise the high traffic demands of the SNs. After careful inspection, we note that the proposed hybrid strategy consumes less power compared with the conventional TDBC strategy in the minor asymmetric SNR region, but the performance difference

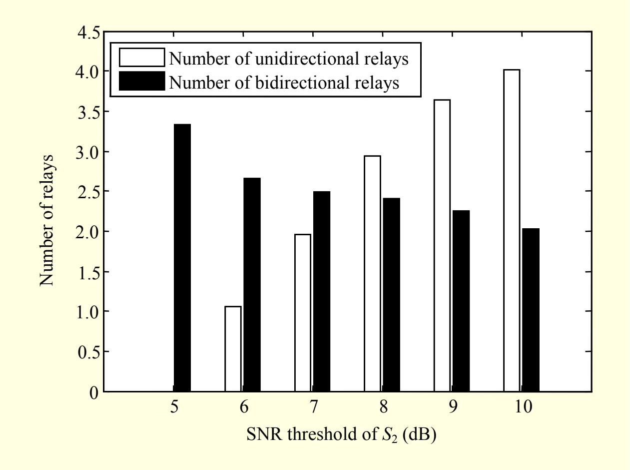

Fig. 7. Average number of unidirectional and bidirectional relays as SNR threshold of S_2 varies.

between the two strategies is small, as expected. Furthermore, this difference becomes unapparent as the number of RNs increases since the degrees of freedom associated with RS is enhanced. In addition, the total power consumption decreases with the increased number of relays in all situations. Furthermore, for all three cases, the performance gap between the hybrid relaying strategy and the conventional TDBC with a direct link becomes more noticeable when enlarging the SNR threshold of S_2, which implies the superiority of the hybrid relaying strategy in energy saving. Therefore, our proposed hybrid cooperative relaying strategy is preferable for energy constraint services.

Figure 7 shows a histogram plot of the average number of selected unidirectional and bidirectional relays when the SNR threshold of S_1 is fixed at 5 dB. At first glance, with the increased disparity of the SNR thresholds, the total number of selected relays grows accordingly for the sake of guaranteeing the asymmetric QoS requirements. It can also be seen that in the presence of symmetric traffic demands of SNs, only the bidirectional relays are chosen to realize information exchange, as expected. However, with an increase of the SNR threshold of S_2, the number of unidirectional relays dramatically increases, as seen for $\Gamma_{\text{th}2} = 6$ dB to 10 dB. Interestingly, in this situation, the number of bidirectional relays slightly decreases. The reason for this is that a rapid growth of unidirectional relays inevitably results in a reduction of bidirectional relays, because the change of the total number of participating relays is relatively small.

The convergence performance of the proposed mixed optimization algorithm is investigated in two different cases and exhibited in Figs. 8 and 9, respectively. In Fig. 8, various relay numbers are considered. Note that the proposed algorithm takes merely less than 20 iteration steps to converge to a stable solution with $N = 6$. However, 40 iterations are needed when $N = 10$. This can be explained by the fact that, since a binary encoding method is adopted in our proposed algorithm, a larger relay number corresponds to an enormous initial population size; thus, the algorithm requires a longer time to converge. In addition, the total power consumption of RNs decreases with the growing relay number, as expected.

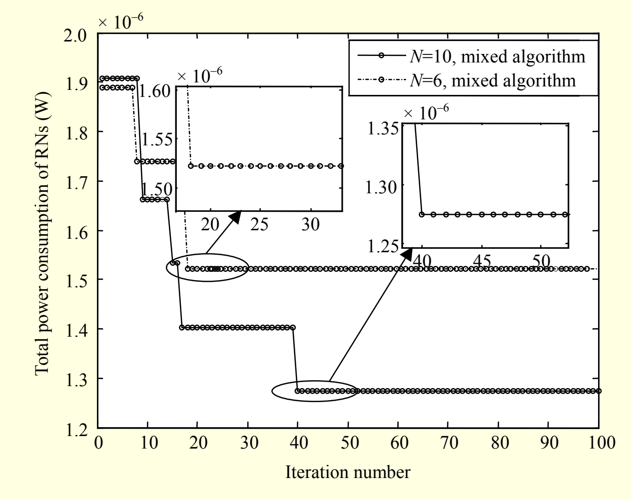

Fig. 8. Convergence performance of mixed algorithm with various relay numbers.

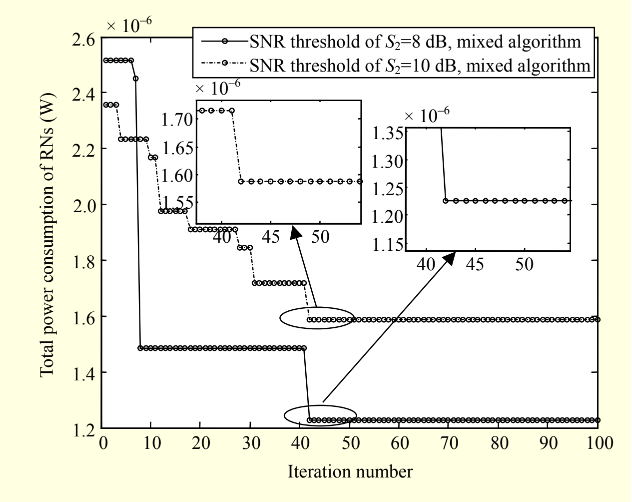

Fig. 9. Convergence performance of mixed algorithm with various SNR thresholds of S_2.

In Fig. 9, different SNR thresholds of S_2 are analyzed. After careful inspection, we note that the proposed algorithm takes approximately 40 iterations to reach a stable solution in both cases. This indicates that the convergence performance of the mixed algorithm is barely affected by the value of S_2's target SNR threshold. Additionally, a higher SNR value of S_2 leads to more power consumption of RNs, as previously mentioned. Therefore, the results confirm that the proposed strategy is

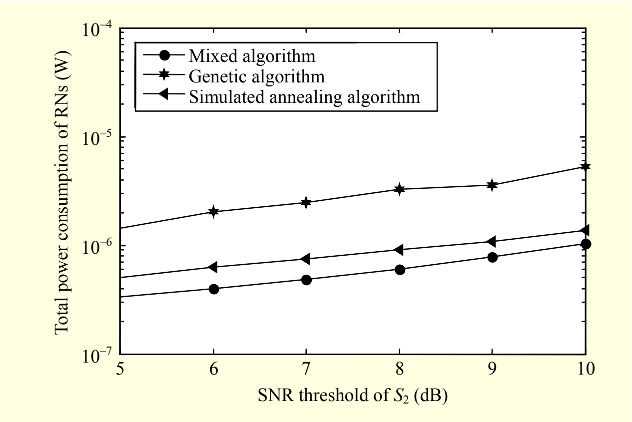

Fig. 10. Comparison among three optimization algorithms.

applicable to a practical system, where resource allocation should be accomplished in a timely manner and the values of the number of relays and SNR thresholds of SNs are determined by system requirement.

Figure 10 unveils the superiority of the proposed mixed optimization algorithm in energy saving with respect to the varying SNR threshold of S_2, while the SNR threshold of S_1 is assumed to be 5 dB. It is shown that under the asymmetric QoS circumstances, the overall power consumption of the GA-SA optimization algorithm is lower than its GA or SA counterparts, indicating that a better solution is achieved. The reason is that the idea of combining a GA with SA takes full advantage of the fact that a GA explores the whole model space and SA converges rapidly. Consequently, the local optimum is prevented and lower power consumption as well as higher search efficiency is readily obtained.

The total power consumption of the GA algorithm is always high, because the GA may tap into a local optimum prematurely during the iterative process. Moreover, the overall power consumed by the three optimization algorithms increases with an increase of the asymmetric QoS requirements, as previously mentioned in Fig. 6.

V. Conclusion

In this paper, our investigations focused on the AF-TDBC protocol. Contrary to that of current research activities, our main purpose was to examine the impact of traffic asymmetry on network energy consumption. Under the assumption that a network's traffic knowledge (for instance, information about two SNs' target SNR thresholds) was available, an energy-efficient hybrid cooperative relaying strategy was proposed, followed by an optimization framework with joint RS and PA. Based on this framework, an intelligent optimization algorithm combining GA with SA was designed to maximally enhance the search efficiency. Therefore, a local optimum was avoided, and the limitation of the traditional iterative algorithm based on gradient search was compensated. Finally, numerical results demonstrated that significant energy savings were achieved in an asymmetric QoS environment and the proposed intelligent optimization algorithm converged to a better solution.

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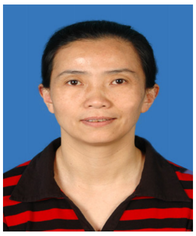
Jian Chen received his BS degree in electronic technology and physics from the School of Electronic and Information Engineering, Xi'an Jiaotong University, China, in 1989; his MS degree in optical engineering from Xi'an Institute of Optics and Precision Mechanics of Chinese Academy of Science, China, in 1992; and his PhD degree in communication and information systems from Xidian University, China, in 2005. From 2007 to 2008, he was a visiting scholar at the University of Manchester, UK. Since 1992, he has been with the School of Telecommunications Engineering, Xidian University, Xi'an, China, where he is now a professor. His main research interests include cognitive radio, multimedia communications, and wireless sensor networks.

Lu Lv received his BS degree in telecommunications engineering from the School of Vocational and Technical, Hebei Normal University, Shijiazhuang, China, in 2013. He is currently working towards his PhD degree in communication and information systems at the School of Telecommunications Engineering, Xidian University, Xi'an, China. His current research interests include cooperative communications, cognitive radio, and physical layer security.

Wenjin Geng received her BS degree in information and computing science from the School of Mathematics and Physics, North China Electric Power University, Baoding, China, in 2011 and her MS degree in communication and information systems from the School of Telecommunications Engineering, Xidian University, Xi'an, China, in 2014. Her main research interests include resource allocation in wireless networks.



Yonghong Kuo received her BS and MS degrees in biomedical science and electronic engineering from the School of Electronic and Information Engineering, Xi'an Jiaotong University, China, in 1989 and 1992, respectively, and her PhD degree in biomedical science and electronic engineering from Peking Union Medical University, Beijing, China, in 1998. Since 1998, she has been with the School of Telecommunications Engineering, Xidian University, Xi'an, China, where she is now a professor. Her main research interests include signal processing, cognitive radio, and wireless sensor networks.