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Swarm Intelligence-based Power Allocation and Relay Selection Algorithm for wireless cooperative network

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Abstract

Cooperative communications can significantly improve the wireless transmission performance with the help of relay nodes. In cooperative communication networks, relay selection and power allocation are two key issues. In this paper, we propose a relay selection and power allocation scheme RS-PA-PSACO (Relay Selection-Power Allocation-Particle Swarm Ant Colony Optimization) based on PSACO (Particle Swarm Ant Colony Optimization) algorithm. This scheme can effectively reduce the computational complexity and select the optimal relay nodes. As one of the swarm intelligence algorithms, PSACO which combined both PSO (Particle Swarm Optimization) and ACO (Ant Colony Optimization) algorithms is effective to solve non-linear optimization problems through a fast global search at a low cost. The proposed RS-PA-PSACO algorithm can simultaneously obtain the optimal solutions of relay selection and power allocation to minimize the SER (Symbol Error Rate) with a fixed total power constraint both in AF (Amplify and Forward) and DF (Decode and Forward) modes. Simulation results show that the proposed scheme improves the system performance significantly both in reliability and power efficiency at a low complexity.

Keywords: Wireless cooperative communication, Power allocation, Relay selection, Swarm intelligence algorithms, PSACO

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1. Introduction

In recent years, MIMO(Multiple-Input Multiple-Output) systems have been widely used in wireless communication networks [1, 2]. The core concept of MIMO is to use multiple transmit antennas and receive antennas effectively to improve the spectrum efficiency and QoS (Quality of Service). However, mobile terminals are difficult to be equipped with multiple antennas because of size limitation at current radio wavelength. The cooperative communications use nearby nodes to relay information to achieve cooperative diversity in the transmit destination to generate a virtual MIMO system [3, 4, 5, 6]. Therefore, it has gained much attention as transmit strategies for future wireless networks.

In cooperative communication networks, relay selection and power allocation are two key issues, and a lot of methods for relay selection and power allocation have been presented. In AF cooperation, Reference [7] presented a convex optimal power allocation to maximize data rate and less-complex suboptimal power allocation. In a cognitive relay network comprising one source-destination pair and multiple relays in underlay, [8] proposed an AF relay selection and power allocation to the selected relays by searching space to maximize the SNR (Signal-to-Noise Ratio) at the secondary destination. In a dual-hop regenerative multi-relay system, an optimal relay selection scheme was proposed using secrecy outage in [9]. In [10], opportunistic FD relay selection scheme in underlay CR networks with DF relaying mode was proposed, and the closed-form expression of the outage probabilities of the proposed scheme was derived. For a 2-hop and 3-hop cooperative network, authors in [11] proposed a closed-form expression of probability of error over Rayleigh fading channel, and allocated the power for a AF relay in each hop. [12] proposed several relay selection strategies for cooperative Single-Carrier Frequency-Domain Equalization with the amplify and forward protocol. As can be seen, the objective in [7] and [8] focused on maximizing the data rate or SNR, which are related to the system capacity. And [9][10] focused on the outage probability of the proposed scheme. From another perspective, [11] aimed to reducing the probability of error, which ensured the system reliability. While in [12], error probability based selection criterion and mutual information based relay selection were both considered, which gave a thorough insight into relay selection. An AF single relay selection scheme was proposed in [13], in which both CSI (Channel State Information) and residual energy information were known in receiver. In [14], authors proposed three-partner selection strategies to balance the power distribution and transmission performance. Reference [15] presented a power allocation strategy for amplify-and-forward cooperative relaying networks in fading channels with the condition of the knowledge of the mean strengths of the channels. In DF cooperation, [16] proposed a power allocation based on partial CSI (Channel State Information) and PSO algorithms. In [17], authors proposed a cost model by contract theory to select relays of DF parallel cooperation. A power allocation scheme based on the particle swarm optimization algorithm in DF cooperation was proposed in [18], where the power was allocated only with the average channel state information at the transmitters. In [19], authors proposed a strategy to minimize the total transmit power in a DF multi-user, multi-relay cooperative uplink. The approaches in [13]-[19], however, were not designed specifically for different channel conditions and lacked the comprehensive insight into the solutions when the SNR values are quite different. In [20], a quantum particle swarm optimization (QPSO) based relay selection scheme was proposed, and the global optimal solution could be obtained. While, in [21], the combination of ACO and PSO algorithm was proposed. ACO algorithm can improve the optimization result of PSO algorithm, and the defects of ACO algorithm such as hard to converge can be made up by the high convergence of PSO algorithm, therefore, the scheme can obtain the optimal solution as well as better convergence speed.

In this paper, we propose a RS-PA-PSACO algorithm to obtain the best relay through finding optimal power allocation in cooperative network. PSACO algorithm combined both PSO [22] and ACO [23] algorithm. PSO is inspired by social behavior of bird flocking or fish schooling, while ACO imitates foraging behavior of real life ants. PSACO uses a simple pheromone-guided mechanism to improve the performance of PSO algorithm to find optimal power allocation strategy and obtain the best relay at the same time, and PSACO is simple for implementation. The main contributions of the paper can be summarized as follows:

(1) Dividing the optimization problem into two aspects for computational simplicity with different channel conditions:

1) Formulating the convex optimization problem for the relay selection and power allocation in cooperative communication system and obtaining the closed-form solution when the SNR is relatively high.

2) Proposing a RS-PA-PSACO algorithm for the relay selection and power allocation when the SNR value is relatively low. The scheme can not only obtain the best relay through finding optimal power allocation but also can effectively reduce the computational complexity of the optimization problem.

(2) Applying the swarm intelligence algorithms into the cooperative communication system, and analyzing the performance of the proposed algorithm through comparing with other power allocation schemes.

This proposed scheme are evaluated by simulations and compared with other power allocation schemes. The optimal solution could be obtained through RS-PA-PSACO algorithm with fast global search. The results indicate that when the SNR value is relatively low, the proposed scheme outperforms the equal power allocation scheme significantly with optimal relay selection.

The remainder of this paper is organized as follows. In section 2, the cooperative system model is introduced and the optimization problem is formulated. In section 3, we simplify the objective function and formulate the convex optimization problem when the SNR is relatively high, then obtain the closed-form solution. Section 4 addresses the issues to select the best relay and obtain optimal power allocation. The PSACO algorithm is presented in the same section. Simulation results and numerical analysis are presented in section 5, which is followed by the concluding remarks in section 6.

2. System Model

We choose 2-hop cooperation communications as an example in a cellular system shown in **Fig. 1**. A traditional wireless cooperative network contains source node, destination node and several relay nodes, as shown as in **Fig. 2**. S, D and R_n represent source node, destination node and the n-th (n=1, 2, …, N) relay node, respectively. We assume that the relay nodes are randomly distributed, and $h_{s,d}, h_{s,r_n}, h_{r_n,d}$ are the channel coefficients respectively from source node to destination node, source node to the n-th relay node and the n-th relay node to destination node. The cooperative communications in the system model shown in Fig. 2 includes two phases. In phase 1, the source node transmits its information to the n-th relay node and the destination node; in phase 2, the n-th relay node forwards the received signal to the destination node.

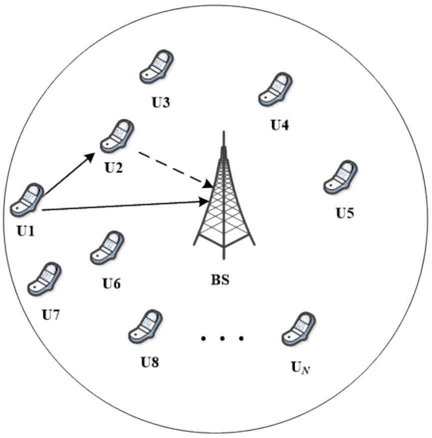

Fig. 1. Cooperative relay scenario in the cellular mobile network

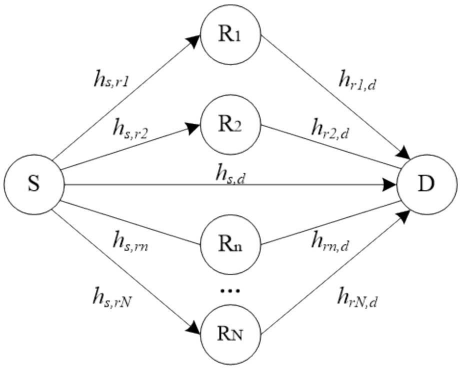

Fig. 2. Cooperative communication model

Each relay node could constitute a two-user cooperation model with source node and destination node as shown in **Fig. 3**. In this paper, we only consider 2-hop scenario.

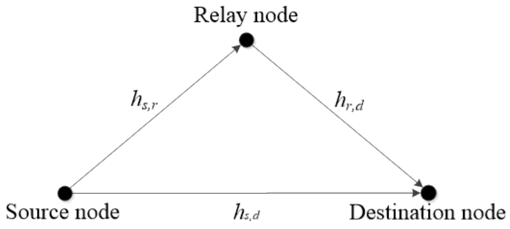

Fig. 3. Two-user cooperation model

In phase 1, the source node transmits its information to the n-th relay node and the destination node. The received signals y_{s,r_n} and $y_{s,d}$ at the n-th relay node and the destination node can be written as

$$y_{s,r_n} = \sqrt{P_s} h_{s,r_n} x + \eta_{s,r_n} \tag{1}$$

$$y_{s,d} = \sqrt{P_s} h_{s,d} x + \eta_{s,d} \tag{2}$$

In which P_s is the transmitted power at the source node, $h_{s,d}$ and h_{s,r_n} are the channel coefficients from the source node to the destination node and to the n-th relay node, respectively. They are modeled as zero-mean, complex Gaussian random variables with variances $\delta^2_{s,d}$ and δ^2_{s,r_n} . x is the transmitted information symbol. $\eta_{s,d}$ and η_{s,r_n} are AWGN (Additive White Gaussian Noise) between the source node and destination node, *n*-th relay node. They are modeled as zero-mean, complex Gaussian random variables with variances N_0 .

2.1 AF (Amplify and Forward) SER performance analysis

In phase 2, the *n*-th relay node amplifies the received signal and forwards it to the destination node with transmitted power P_{r_n} . The received signal at the destination node can be written as

$$y_{r_n,d} = \frac{\sqrt{P_{r_n}}}{\sqrt{P_s\,|h_{s,r_n}|^2 + N_0}}\, h_{r_n,d}\, y_{s,r_n} + \eta_{r_n,d} \tag{3}$$

in which $h_{r_n,d}$ is the channel coefficient between the relay node and the destination node, $\eta_{r_n,d}$ is an AWGN, also modeled as zero-mean, complex Gaussian random variables with variances N_0 .

The combined signal at the destination node by using MRC (Maximal Ratio Combining) can be written as [24]

$$y = a_s y_{s,d} + \sum_{n=1}^{N} a_n y_{r_n,d} \tag{4}$$

Where a_s and a_n are specified as

$$a_s = \frac{\sqrt{P_s}\, h^*_{s,d}}{N_0}, \quad a_n = \frac{\sqrt{\dfrac{P_s P_{r_n}}{P_s\,|h_{s,r_n}|^2 + N_0}}\, h^*_{s,r_n} h^*_{r_n,d}}{\left(\dfrac{P_{r_n}\,|h_{r_n,d}|^2}{P_s\,|h_{s,r_n}|^2 + N_0} + 1\right) N_0} \tag{5}$$

in which $h^*_{s,d}, h^*_{s,r_n}, h^*_{r_n,d}$ means the conjugate transpose of the $h_{s,d}, h_{s,r_n}, h_{r_n,d}$, respectively. We assume all the relay nodes attend to cooperate and the transmitted symbol x has average energy 1, so the instantaneous SNR of the MRC signal is

$$\gamma = \gamma_{s,d} + \sum_{n=1}^{N} \gamma_n \tag{6}$$

in which

$$\gamma_{s,d} = \frac{P_s\,|h_{s,d}|^2}{N_0}, \quad \gamma_n = \frac{1}{N_0} \frac{P_s P_{r_n}\,|h_{s,r_n}|^2 |h_{r_n,d}|^2}{P_s\,|h_{s,r_n}|^2 + P_{r_n}\,|h_{r_n,d}|^2 + N_0} \tag{7}$$

We assume either in AF or DF forward mode the channel coefficients $h_{s,d}, h_{s,r_n}$ and $h_{r_n,d}$ to be known at the receivers. The received signal from the source node in phase 1 and from the *n*-th relay node in phase 2 combined at the destination node by using MRC. In both forward modes, we consider the total transmitted power as

$$P_{sum} = P_s + \sum_{n=1}^{N} P_{r_n} \tag{8}$$

We need to note only in case of the relay node can decode the signal correctly that the Eq. (8) holds, otherwise the $\widetilde{P_{r_n}} = 0$.

The SER formulations for an uncoded system with M-QAM ($M = 2^k$ with k even) modulation [25], which are given by

$$\Psi_{QAM}(\gamma) = 4KQ(\sqrt{b_{QAM}\gamma}) - 4K^2Q^2(\sqrt{b_{QAM}\gamma}) \tag{9}$$

where $Q(u) = (1/\sqrt{2\pi})\int_u^\infty \exp(-t^2/2)dt$ is the Gaussian Q-function, γ is SNR, $K = 1-(1/\sqrt{M})$ and $b_{QAM} = 3/(M-1)$.

The upper bound of instantaneous SNR γ_n can be written as

$$\gamma_n \le \overline{\gamma_n} = \frac{1}{N_0}\frac{P_s P_{r_n}\left|h_{s,r_n}\right|^2\left|h_{r_n,d}\right|^2}{P_s\left|h_{s,r_n}\right|^2 + P_{r_n}\left|h_{r_n,d}\right|^2} \tag{10}$$

For a random variable Z, the MGF can be denoted as

$$M_Z(s) = \int_{-\infty}^{\infty}\exp(-sz)P_Z(z)dZ \tag{11}$$

If the SNR approximated as $\gamma \approx \gamma_1 + \sum_{n=1}^{N}\overline{\gamma_n}$, the SER of AF mode with M-QAM modulations can be given by Eq. (11) as follows

$$P_{QAM}^{AF} \approx \frac{4K}{\pi}\int_0^{\pi/2} M_{\gamma_1}(\frac{b_{QAM}}{2\sin^2\theta})\prod_{n=1}^{N} M_{\overline{\gamma_n}}(\frac{b_{QAM}}{2\sin^2\theta})d\theta - \frac{4K^2}{\pi}\int_0^{\pi/4} M_{\gamma_1}(\frac{b_{QAM}}{2\sin^2\theta})\prod_{n=1}^{N} M_{\overline{\gamma_n}}(\frac{b_{QAM}}{2\sin^2\theta})d\theta \tag{12}$$

in which $b_{QAM} = 3/(M-1)$, $K = 1-(1/\sqrt{M})$.

2.2 DF (Decode and Forward) SER performance analysis

In phase 2, if the *n*-th relay node could decode the transmitted symbol from the source node correctly, then the *n*-th relay forward the decoded symbol with power P_{r_n} to the destination node, otherwise the *n*-th relay node not send or remains idle. The received signal at the destination node can be written as

$$y_{r_n,d} = \sqrt{\widetilde{P_{r_n}}}\,h_{r_n,d}x + \eta_{r_n,d} \tag{13}$$

where $\widetilde{P_{r_n}} = P_{r_n}$ if the *n*-th relay node decodes the transmitted symbol correctly, otherwise $\widetilde{P_{r_n}} = 0$.

Since the derivation process in DF mode is similar to that in AF mode, we omit the unnecessary details in the derivation process of SER. Therefore, we obtain the SER of DF mode with M-QAM modulations as follows

$$P_{QAM}^{DF} = \sum_{i=0}^{2^N-1} F_2[(1+\frac{b_{QAM}P_s\delta_{s,d}^2}{N_0\sin^2\theta})\prod_{n=1}^{N}(1+\frac{b_{QAM}B_i(n)P_{r_n}\delta_{r_n,d}^2}{N_0\sin^2\theta})]\prod_{n=1}^{N}G_n(\widetilde{P_{r_n}}) \tag{14}$$

where

$$F_2(x(\theta)) = \frac{4K}{\pi}\int_0^{\pi/2}\frac{1}{x(\theta)}d\theta - \frac{4K^2}{\pi}\int_0^{\pi/4}\frac{1}{x(\theta)}d\theta \tag{15}$$

$$G_n(\widetilde{P_{r_n}}) = \begin{cases} F_1(1+\dfrac{b_{QAM}P_s\delta_{s,r_n}^2}{N_0\sin^2\theta}) & if\,\widetilde{P_{r_n}} = 0 \\ 1-F_1(1+\dfrac{b_{QAM}P_s\delta_{s,r_n}^2}{N_0\sin^2\theta}) & if\,\widetilde{P_{r_n}} = P_{r_n} \end{cases} \tag{16}$$

and $B_i(n) = \{0,1\}$, 0 and 1 respectively represents whether the *n*-th relay decodes the transmitted symbol correctly, and $b_{QAM} = 3/(M-1)$, $K = 1-(1/\sqrt{M})$ and γ is SNR.

2.3 System model

Under the transmit power constrained scenario, we assume that source node transmits with a fixed power P_s in phase 1; the rest power is shared by relay node in phase 2 so that minimum SER can be achieved. Therefore, the problem of allocating the available transmission power to minimize the SER can be expressed as

$$\begin{aligned} &\min \quad P_{SER}^{xF} \\ &\text{Subject to: } P_s + P_{r_n} = P_{sum} \end{aligned} \tag{17}$$

in which *xF*=AF or DF respectively in the corresponding model.

Observing Eq.(12) and Eq.(14), we find that to directly calculate the problem is complex. In order to obtain the solution of power allocation and the best relays, we treat the problems as two categories: high SNR and low SNR. With the relatively high SNR value, we simplify the expression and formulate them as convex problems and obtain the closed-form solutions; on the other hand, we propose a RS-PA-PSACO algorithm to solve the problems when SNR value is low. They are described in section 3and section 4 individually.

3. Convex optimization problem

3.1 Convex optimization problem in AF mode

If all the channel $h_{s,d}$, h_{s,r_n} and $h_{r_n,d}$ are available, i.e., $\delta_{s,d}^2 \neq 0$, $\delta_{s,r_n}^2 \neq 0$ and $\delta_{r_n,d}^2 \neq 0$, then when P_s / N_0 and P_{r_n} / N_0 are relatively high, the SER of AF mode with M-QAM modulation can be tightly approximated as [26]

$$P_{SER}^{AF} \approx \frac{BN_0^2}{b^2} \cdot \frac{1}{P_s \delta_{s,d}^2} \left(\frac{1}{P_s \delta_{s,r_n}^2} + \frac{1}{P_{r_n} \delta_{r_n,d}^2} \right) \tag{18}$$

where for M-QAM modulation, $b = b_{QAM} / 2 = 3/2(M-1)$ and

$$B = \frac{3(M-1)}{8M} + \frac{K^2}{\pi} \tag{19}$$

When we compare the computational complexity of Eq.(20) and Eq.(12), we can find that Eq.(12) involves integral calculation, and the Eq.(20) only involves addition and multiplication, it’s obvious that Eq.(20) has less computational complexity.

We consider the simplified expression as objective function. Therefore, the optimized problem can be expressed as

$$\begin{aligned} &\min \quad P_{SER}^{AF} \approx \frac{BN_0^2}{b^2} \cdot \frac{1}{P_s \delta_{s,d}^2} \left(\frac{1}{P_s \delta_{s,r_n}^2} + \frac{1}{P_{r_n} \delta_{r_n,d}^2} \right) \\ &\text{Subject to: } \quad P_s + P_{r_n} = P_{sum} \\ &\qquad\qquad P_s, P_{r_n} \geq 0 \end{aligned} \tag{20}$$

Now as we have formulated the constrained optimization problem,(20)is a convex optimization problem (proof in APPENDIX I). Therefore, We obtain its analytical solution by using Lagrange Method. The Lagrange cost function of this problem is defined as:

$$J = P_{SER}^{AF} + \lambda (P_s + P_{r_n} - P_{sum}) \tag{21}$$

$$J = \frac{BN_0^2}{b^2} \cdot \frac{1}{P_s \delta_{s,d}^2} \left(\frac{1}{P_s \delta_{s,r_n}^2} + \frac{1}{P_{r_n} \delta_{r_n,d}^2} \right) + \lambda (P_s + P_{r_n} - P_{sum}) \tag{22}$$

Now taking the partial derivatives of the Lagrange function J with respect to P_s, P_{r_n} and λ .Afterwards these derivatives will be equated to zero, like defined below

$$\frac{\partial J}{\partial P_s}=\frac{BN_0^2}{b^2}\left[\frac{-2P_s\cdot\delta_{s,d}^2\cdot\delta_{s,r_n}^2}{\left(P_s^2\cdot\delta_{s,d}^2\cdot\delta_{s,r_n}^2\right)^2}-\frac{P_{r_n}\cdot\delta_{s,d}^2\cdot\delta_{r_n,d}^2}{\left(P_s\cdot P_{r_n}\cdot\delta_{s,d}^2\cdot\delta_{r_n,d}^2\right)^2}\right]+\lambda=0 \tag{23}$$

$$\frac{\partial J}{\partial P_{r_n}}=\frac{BN_0^2}{b^2}\left(\frac{-1}{\delta_{s,d}^2\cdot\delta_{r_n,d}^2\cdot P_s\cdot P_{r_n}^2}\right)+\lambda=0 \tag{24}$$

$$\frac{\partial J}{\partial\lambda}=P_s+P_{r_n}-P_{sum}=0 \tag{25}$$

After some manipulations, we obtain a closed-form solution in AF mode :

$$P_S=\frac{\delta_{s,r_n}+\sqrt{A}}{3\delta_{s,r_n}+\sqrt{A}}P_{sum} \tag{26}$$

$$P_{r_n}=\frac{2\delta_{s,r_n}}{3\delta_{s,r_n}+\sqrt{A}}P_{sum} \tag{27}$$

Where, A=$\left(\delta_{s,r_n}^2+8\delta_{r_n,d}^2\right)$.

3.2 Convex optimization problem in DF mode

The SER of DF mode with M-QAM modulation can be upper bounded as [26]

$$P_{SER}^{DF}\le\frac{(M-1)N_0^2}{M^2}\cdot\frac{MbP_s\delta_{s,r_n}^2+(M-1)bP_{r_n}\delta_{r_n,d}^2+(2M-1)N_0}{(N_0+bP_s\delta_{s,d}^2)(N_0+bP_s\delta_{s,r_n}^2)(N_0+bP_{r_n}\delta_{r_n,d}^2)} \tag{28}$$

If all the channel $h_{s,d}$, h_{s,r_n} and $h_{r_n,d}$ are available, i.e., $\delta_{s,d}^2\ne0$, $\delta_{s,r_n}^2\ne0$ and $\delta_{r_n,d}^2\ne0$, the SER of DF mode with M-QAM modulation can be upper bounded as

$$P_{SER}^{DF}\le\frac{N_0^2}{b^2}\cdot\frac{1}{P_s\delta_{s,d}^2}\left(\frac{A^2}{P_s\delta_{s,r_n}^2}+\frac{B}{P_{r_n}\delta_{r_n,d}^2}\right) \tag{29}$$

where for M-QAM modulation, $b=b_{QAM}/2=3/2(M-1)$ and

$$A=\frac{M-1}{2M}+\frac{K^2}{\pi} \tag{30}$$

$$B=\frac{3(M-1)}{8M}+\frac{K^2}{\pi} \tag{31}$$

in which $K=1-(1/\sqrt{M})$.

It can be observed that Eq.(31) only involves addition and multiplication and has less computational complexity. Therefore, we consider the simplified expression as objective function and the optimized problem can be expressed as

$$\begin{aligned}&\min\ P_{SER}^{DF}\le\frac{N_0^2}{b^2}\cdot\frac{1}{P_s\delta_{s,d}^2}\left(\frac{A^2}{P_s\delta_{s,r_n}^2}+\frac{B}{P_{r_n}\delta_{r_n,d}^2}\right)\\&\text{Subject to:}\ \ P_s+P_{r_n}=P_{sum}\\&\qquad\qquad\quad P_s,P_{r_n}\ge0\end{aligned} \tag{32}$$

Just as the condition in the AF mode, it is also a convex optimization problem and we will use Lagrange Method to get a closed-form solution of this problem. The Lagrange cost function of this problem is defined as:

$$J = P_{SER}^{DF} + \lambda(P_s + P_{r_n} - P_{sum}) \tag{33}$$

$$J = \frac{N_0^2}{b^2} \cdot \frac{1}{P_s \delta_{s,d}^2} \left(\frac{A^2}{P_s \delta_{s,r_n}^2} + \frac{B}{P_{r_n} \delta_{r_n,d}^2} \right) + \lambda(P_s + P_{r_n} - P_{sum}) \tag{34}$$

Taking the partial derivatives of the Lagrange function J with respect to P_s, P_{r_n} and λ .Afterwards these derivatives will be equated to zero, like defined below

$$\frac{\partial J}{\partial P_s} = \frac{N_0^2}{b^2} \left(\frac{-2A^2}{\delta_{s,d}^2 \delta_{s,r_n}^2 P_s{}^3} + \frac{-B}{\delta_{s,d}^2 \delta_{r_n,d}^2 P_{r_n} P_s{}^2} \right) + \lambda = 0 \tag{35}$$

$$\frac{\partial J}{\partial P_{r_n}} = \frac{N_0^2}{b^2} \left(\frac{-B}{\delta_{s,d}^2 \delta_{r_n,d}^2 P_{r_n}{}^2 P_s} \right) + \lambda = 0 \tag{36}$$

$$\frac{\partial J}{\partial \lambda} = P_s + P_{r_n} - P_{sum} = 0 \tag{37}$$

After some manipulations, we obtain a closed-form solution in DF mode:

$$P_s = \frac{\sqrt{B}\delta_{s,r_n} + \sqrt{C}}{3\sqrt{B}\delta_{s,r_n} + \sqrt{C}} P_{sum} \tag{38}$$

$$P_{r_n} = \frac{2\sqrt{B}\delta_{s,r_n}}{3\sqrt{B}\delta_{s,r_n} + \sqrt{C}} P_{sum} \tag{39}$$

Where, $C = (B\delta_{s,r_n}^2 + 8A^2\delta_{r_n,d}^2)$.

In this section, we have obtained the closed-form solution both in AF mode and DF mode. Therefore, we can get the power allocation scheme of each potential relay node and their SERs. Through comparing their SERs, we obtain the optimal relay node with the minimum. SER. However, the above solution is under the assumption that the SNR is relatively high. When the condition is not satisfied, we cannot simplify the expression of SER directly. Therefore, we consider a optimal power allocation and relay selection algorithm to solve the optimization problem, which is illustrated in the followed section.

4. Optimal power allocation and relay selection algorithm

We propose RS-PA-PSACO algorithm which can simultaneously obtain the optimal solutions of relay selection and power allocation to minimize the SER with a fixed total power constraint. RS-PA-PSACO algorithm is based on PSACO algorithm [27] which can obtain the optimal P_s. PSO is an intelligent optimization algorithm based on simulating the social behavior of birds foraging. It starts from a set of random solutions which based on the objective function, and then find the optimal solution through iterations. The advantage of PSO is simple calculation, less parameters, fast convergence, and can also find the optimal solution without too much of the original information, while not required to be optimized function derivable and differentiable, and it is easy to implement simulation on a computer.

Particles update their velocities and positions as follows:

$$v_{t+1}^i = w_t v_t^i + c_1 r_1 (p_t^i - x_t^i) + c_2 r_2 (p_t^g - x_t^i) \tag{40}$$

$$x_{t+1}^i = x_t^i + v_{t+1}^i \tag{41}$$

in which x_t^i represents the current position of particle i in solution space and the iteration count is t, p_t^i is the best-found position of particle i up to iteration count t and represents the cognitive contribution to the velocity v_t^i. The range of v_t^i is $[-v_{\max}, v_{\max}]$, this is to control velocity v_t^i making particles not outside the search space excessively. p_t^g is the global best-found position among all particles in the swarm up to iteration count t and forms the social contribution to the velocity vector v_t^i; r_1 and r_2 are random numbers uniformly distributed in the interval (0, 1); c_1 and c_2 are the cognitive and social scaling parameters, respectively, usually ranges between 0 and 4, in order to balance the effect of population factors and individual factors on the algorithm, through a large number of previous studies, according to [27], generally considered $c_1 = c_2 = 2$ is the best. w_t is the particle inertia, which is reduced dynamically to decrease the search area in a gradual fashion. The variable w_t is updated as

$$w_t = (w_{\max} - w_{\min}) * \frac{(t_{\max} - t)}{t_{\max}} + w_{\min} \tag{42}$$

where $w_{\min}$ and $w_{\max}$ denote the minimum and maximum of w_t, respectively. $t_{\max}$ is the maximum iteration count and t is the current iteration count.

According to reference [28], the velocity and position are convergent only when the parameters meet $\begin{cases} -1 < w < 1 \\ 0 < c_1 r_1 + c_2 r_2 < 2w + 2 \end{cases}$, and their convergence rates vary with the value of w, c_1 and c_2. Reference [23] has analyzed the convergence performance.

PSACO is an algorithm that applies PSO for global optimization and ACO to update positions of particles to achieve the feasible solution rapidly. ACO helps PSO process not only to effectively perform global exploration for rapidly attaining the feasible solution space but also to effectively reach optimal or near optimal solution. There are two stages of PSACO algorithm. The first stage applies PSO, and ACO is implemented in the second stage. ACO works as a local search, and it applies pheromone-guided mechanism to refine the positions found by particles in the first stage. Each ant i generates a solution z_t^i around p_t^g the global best-found position among all particles in the swarm up to iteration count t as

$$z_t^i \sim N(p_t^g, \sigma) \tag{43}$$

which satisfies Gaussian distributions with mean p_t^g and standard deviation σ. At first, initially at $t = 1$ value of $\sigma = 1$ and is updated at the end of each iteration as $\sigma = \sigma \times d$, d is a parameter in $(0.25, 0.997)$ and if $\sigma < \sigma_{\min}$, then $\sigma = \sigma_{\min}$, $\sigma_{\min}$ is a parameter in $(10^{-4}, 10^{-2})$

The pseudo-code of PSACO algorithm is given in **Table 1**, in which P represents the number of particles in the population; $f(x_t^i)$ denotes the objective function value of particle i at position x, and $f_t^{best}(x_t^{best})$ represents the best function value in the population of solutions P at iteration count t.

Table 1. Particle swarm ant colony optimization algorithm

```
Initialize optimization
1.  Initialize constants for PSO and ACO processes, $P$, $t_{\max}$.
2.  Initialize randomly all particle positions $x_t^i$ and velocities $v_t^i$.
3.  Evaluate objective function value as $f(x_t^i)$.
4.  Assign best positions $p_t^i = x_t^i$ with $f(p_t^i) = f(x_t^i)$, $i = 1, ..., P$.
```

```
5.  Find $f_t^{best}(p_t^{best}) = \min\{f(p_t^1),..., f(p_t^i),..., f(p_t^P)\}$ and
    initialize $p_t^g = p_t^{best}$ and $f(p_t^g) = f^{best}(p_t^{best})$.
Perform optimization
while( $t \le t_{\max}$ )
    1. Update particle velocity $v_t^i$ and position $x_t^i$, according to Eq. (40) and Eq. (41) of all particles.
    2. Evaluate objective function value as $f(x_t^i)$.
    3. Generate $P$ solutions $z_t^i$ using Eq. (43).
    4. Evaluate objective function value as $f(z_t^i)$ and if $f(z_t^i) < f(x_t^i)$ then $f(x_t^i) = f(z_t^i)$ and $x_t^i = z_t^i$.
    5. Update particle best position if $f(p_t^i) > f(x_t^i)$ then $p_t^i = x_t^i$ with $f(p_t^i) = f(x_t^i)$.
    6. Find $f_t^{best}(p_t^{best}) = \min\{f(p_t^1),..., f(p_t^i),..., f(p_t^P)\}$;
       if $f(p_t^g) > f(p_t^{best})$ then $p_t^g = p_t^{best}$ and $f(p_t^g) = f^{best}(p_t^{best})$
    7. Increment iteration count $t = t + 1$.
end while
Report the best solution $p^g$ of the swarm with objective function value $f(p^g)$.
```

Based on the PSACO algorithm above, we propose a RS-PA-PSACO scheme to allocate power and select the optimal relay node. The potential relay nodes can be regarded as the particles. The potential relay nodes are randomly distributed initially. We treat Eq. (12) or Eq. (14) as objective function $f(x_t^i)$ in the PSACO algorithm, and we can get the optimal position of the particle, that is the power allocation coefficient. Then we put the coefficient into the objective function formula, and we can obtain SER of each potential relay respectively. Therefore, the best relay can be selected by comparing the SER performance.

5. Numerical results and analysis

In this simulation system model, as shown in **Fig. 4**, we assume there are five potential relay nodes randomly distributed in a circle with radius 0.5 and the center (0.5, 0). The source node and destination nodes are predetermined in (0, 0) and (1, 0), respectively. The unit in Fig. 4 is km.

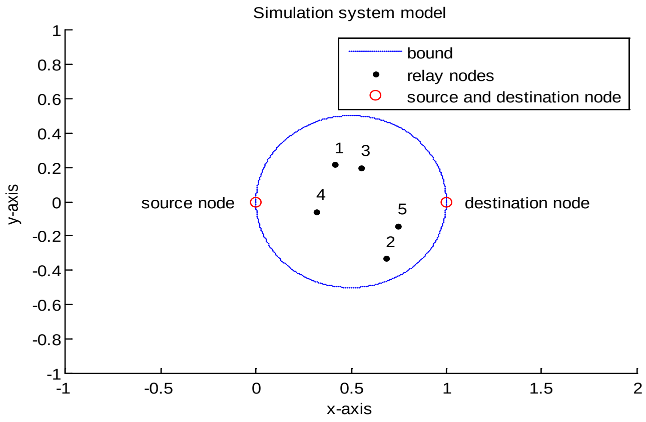

Fig. 4. Simulation system model

In the simulation, we consider channel coefficient variance $\delta_{sd}^2 = d_{sd}^{-2}$, $\delta_{sr}^2 = d_{sr}^{-2}$, $\delta_{rd}^2 = d_{rd}^{-2}$, respectively [29], in which d_{sd}, d_{sr}, d_{rd} means the distance between the source node and destination node, source node and relay node, relay node and destination node. Modulate mode is 16-QAM, and the Rayleigh fading and additive white Gaussian noise have been considered. The total power is set 1 and Monte-Carlo simulation time is 100. At the destination node, we combined source to destination and relay to destination signals by MRC. About the PSACO algorithm, we set the coefficients as follows, number of maximum iterations $t_{\max}$ is 30, particles number is 30, maximum velocity $v_{\max}$ is 0.075, $w_{\min}$, $w_{\max}$ are 0.4 and 0.7, constants $c_1 = c_2 = 2$, $\sigma = 1$, $\sigma_{\min} = 10^{-4}$ and $d = 0.25$ [22].

5.1 Performance comparison of different power allocation schemes

In order to prove the effectiveness of the proposed RS-PA-PSACO algorithm, we compare the SER performance of three different power allocation schemes in AF mode and DF mode respectively, as depicted in **Fig. 5** and **Fig. 6**.

We choose relay3 as a representative of all the relays because other relays' SER performance is similar. **Fig. 5** shows us the relay3's SER performance of three power allocation schemes in AF mode: direct transmission from source node to destination node (all the power allocated to the source node), equal power allocation, and power allocation based on RS-PA-PSACO algorithm. It can be observed that SER performance decreases as the SNR increases. We can also find that equal power allocation improves the SER performance than the direct transmission (Source Node to Destination Node, SD), and RS-PA-PSACO algorithm improves SER performance significantly than the other two schemes and can achieve 2.0-3.0dB gains than the equal power allocation scheme. In another word, RS-PA-PSACO scheme can improve the throughput performance at the same power cost, which means higher power efficiency.

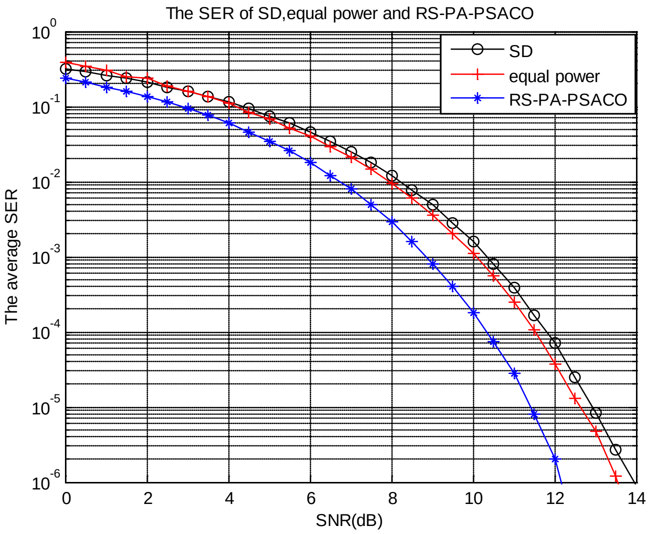

Fig. 5. SER of SD, equal power allocation and RS-PA-PSACO allocation (AF mode, relay3)

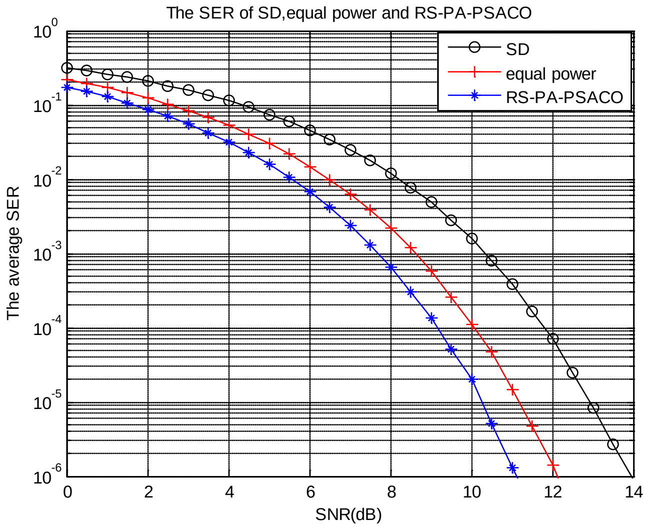

Fig. 6. SER of SD, equal power allocation and RS-PA-PSACO allocation (DF mode, relay3)

Fig. 6 shows us the relay3's SER performance of three power allocation schemes in DF mode, direct transmission (source node to destination node, SD), equal power allocation, power allocation based on RS-PA-PSACO algorithm. It can also be observed that SER performance decreases as the SNR increases. We can see that equal power allocation improves the SER performance than the direct transmission. RS-PA-PSACO algorithm improves SER performance significantly than above schemes and it can achieve 1.0-2.0dB gains.

5.2 Relay selection using RS-PA-PSACO algorithm

Through RS-PA-PSACO algorithm, we obtain the power allocation scheme and the SER performance of each potential relay node. By comparing the SER, we can get the best relay node.

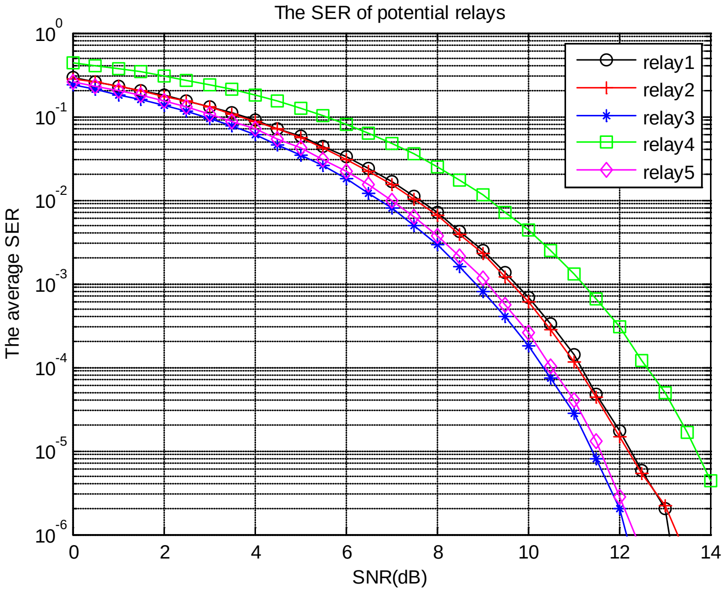

Fig. 7. SER of potential relays using RS-PA-PSACO (AF mode)

Fig. 7 compares SER performance of all the potential relays using RS-PA-PSACO algorithm in AF mode. It can be observed that relay3 gets the best SER performance over other relays, and relay4 has the worst SER performance, even worse than the direct transmission, because Rayleigh fading has a great influence on it. Therefore, relay3 has been selected as the best relay through RS-PA-PSACO algorithm to complete the cooperative communication.

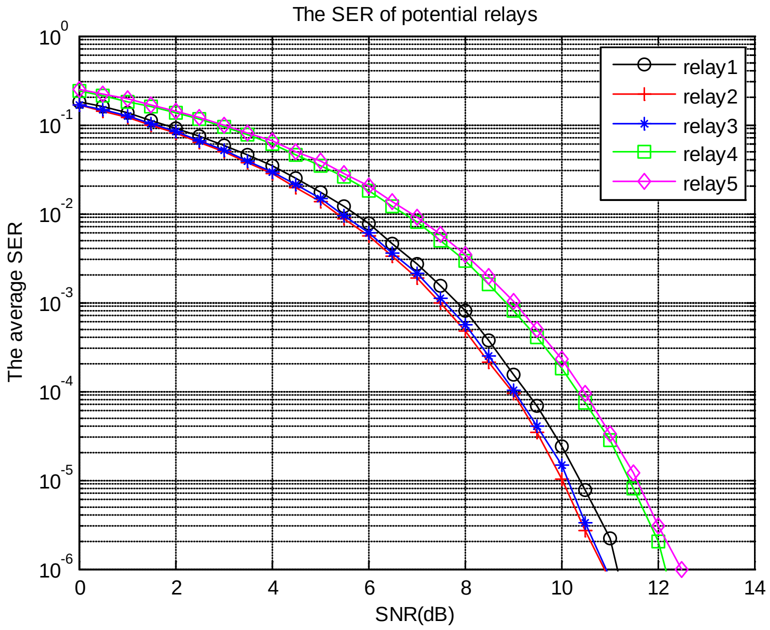

Fig. 8. SER of potential relays using RS-PA-PSACO (DF mode)

Fig. 8 compares SER performance of all the potential relays using RS-PA-PSACO algorithm in DF mode. It can also be observed that relay2 gets the best SER performance over other relays, and relay5 has the worst SER performance. Therefore, relay2 has been selected as the best relay through RS-PA-PSACO algorithm to complete the cooperative communication.

5.3 Performance comparison of the closed-form solution and RS-PA-PSACO algorithm

In section3, we have obtained the closed-form solution of the optimization problem both in AF and DF mode, as illustrated in Eq. (28) and Eq. (40), which are under the assume that SNR is relatively high. However, when the SNR value is relatively low, we can not obtain the closed-form solution directly. Therefore, we consider the expression without simplification in Eq. (12) and Eq. (16) as objective function in the PSACO algorithm, through which we can obtain the optimal solution of power allocation and relay selection. In this part, we tend to compare the SER performance of the closed-form solution and RS-PA-PSACO algorithm, which are under the assumption of relatively high SNR and low SNR respectively.

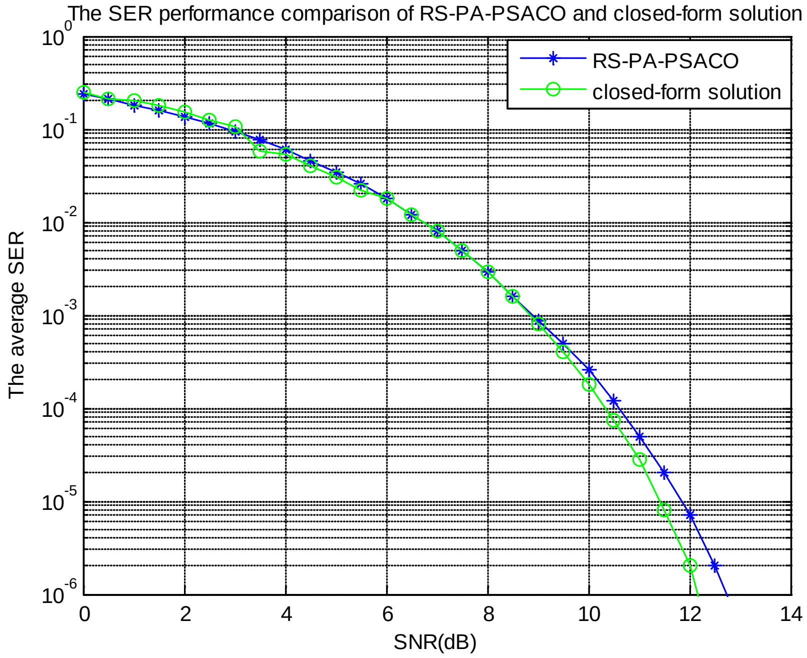

Fig. 9. SER of RS-PA-PSACO and closed-form solution (AF mode, relay3)

In **Fig. 9**, we have compared the SER performance of RS-PA-PSACO algorithm and the closed-form solution in AF mode. It can be observed that the average SER decreases as the SNR increases whatever scheme is adopted. When SNR is relatively low, the two schemes have almost the same SER performance and the RS-PA-PSACO scheme has a minor advantage over the closed-form solution. However, with the increase of SNR, the closed-form solution has a lower SER than the RS-PA-PSACO scheme, which indicates that the closed-form solution outperforms the RS-PA-PSACO scheme with relatively high SNR, because the closed-form solution is obtained under the assumption of relatively high SNR.

In **Fig. 10**, we have compared the SER performance of RS-PA-PSACO algorithm and the closed-form solution in DF mode. It can also be observed that the average SER decreases as the SNR increases whatever scheme is adopted. When SNR is relatively low, the two schemes have almost the same SER performance and the RS-PA-PSACO scheme has a minor advantage over the closed-form solution. However, with the increase of SNR, the closed-form solution has a lower SER than the RS-PA-PSACO scheme, which indicates that the closed-form solution outperforms the RS-PA-PSACO scheme with relatively high SNR, because the closed-form solution is obtained under the assumption of relatively high SNR.

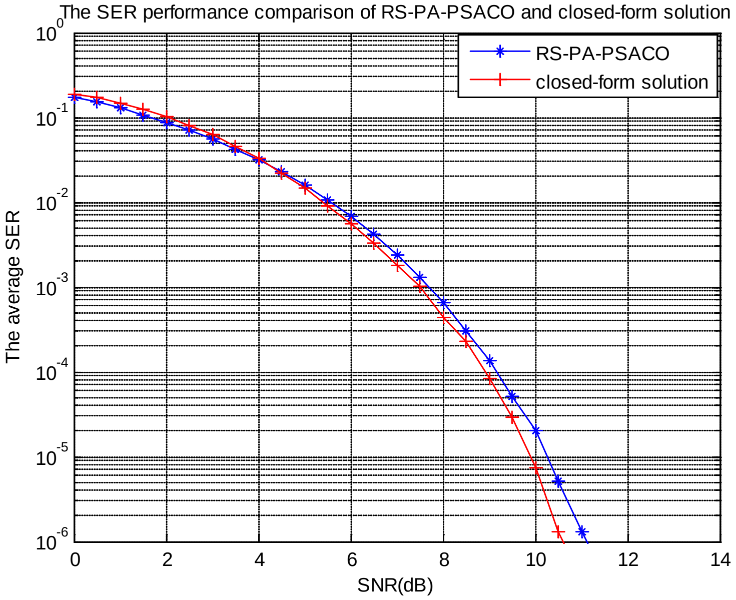

Fig. 10. SER of RS-PA-PSACO and closed-form solution (DF mode, relay3)

6. Conclusion

In this paper, we formulate the relay selection and power allocation problem in the wireless cooperative communication network. With relatively high SNR, we use simplified expression of SER formulation as objective function to reduce the calculating complexity and obtain the closed-form solution; on the other hand, we propose a scheme called RS-PA-PSACO based on a swarm intelligence algorithm PSACO to obtain the optimal power distribution coefficient and simultaneously select the best relay when the SNR value is low. Both schemes can minimize the SER subjected to a fixed total power constraint. Finally the simulation results show that the proposed RS-PA-PSACO algorithm is effective. It improves the system performance significantly both in reliability and power efficiency at a low complexity. Besides, by observing the performance comparison of the RS-PA-PSACO scheme and the closed-form solution, we have verified our previous conclusions: in order to minimize the SER subjected to a fixed total power constraint, we adopt the closed-form solution scheme when SNR is relatively high, and we consider the proposed RS-PA-PSACO algorithm when SNR value is low.

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APPENDIX I

The process of proving Eq. (20) to be a convex optimization problem.
Taking the partial derivatives of P_{SER}^{AF} with respect to P_s and P_{r_n} , we obtain the equations as follows

$$\frac{\partial P_{SER}^{AF}}{\partial P_s}=\frac{BN_0^2}{b^2}\cdot(\frac{-2}{\delta_{s,d}^2\delta_{s,r_n}^2P_s^{\ 3}}+\frac{-1}{\delta_{s,d}^2\delta_{r_n,d}^2P_{r_n}P_s^{\ 2}})$$

$$\frac{\partial P_{SER}^{AF}}{\partial P_{\mathrm{r_n}}}=\frac{BN_0^2}{b^2}\cdot(\frac{-1}{\delta_{s,d}^2\delta_{r_n,d}^2P_sP_{r_n}^{\ 2}})$$

Then taking the second differential , we obtain the following equations, and represent them with R、S and T.

$$\frac{\partial^2 P_{SER}^{AF}}{\partial P_s^{\ 2}}=\frac{BN_0^2}{b^2}\cdot(\frac{6}{\delta_{s,d}^2\delta_{s,r_n}^2P_s^{\ 4}}+\frac{2}{\delta_{s,d}^2\delta_{r_n,d}^2P_{r_n}P_s^{\ 3}})\text{ =R}$$

$$\frac{\partial^2 P_{SER}^{AF}}{\partial P_s\partial P_{r_n}}=\frac{BN_0^2}{b^2}\cdot(\frac{1}{\delta_{s,d}^2\delta_{r_n,d}^2P_s^{\ 2}P_{r_n}^{\ 2}})\text{ =S}$$

$$\frac{\partial^2 P_{SER}^{AF}}{\partial P_{r_n}^2}=\frac{BN_0^2}{b^2}\cdot(\frac{2}{\delta_{s,d}^2\delta_{r_n,d}^2P_sP_{r_n}^{\ 3}})\text{ =T}$$

Then we obtain this equation as follows

$$R\cdot T-S^2=\frac{B^2N_0^4}{b^4}\cdot(\frac{12\delta_{r_n,d}^2P_{r_n}+3\delta_{s,r_n}^2P_s}{\delta_{s,d}^4\delta_{s,r_n}^2\delta_{r_n,d}^4P_{r_n}^4P_s^5})$$

Note that P_s, P_{r_n} , B are positive, So, we can get R and $R\cdot T-S^2$ are both positive.
Therefore, P_{SER}^{AF} with respect to P_s and P_{r_n} is a concave function in the interval $(0,P_{sum})$, which proves that our problem is a convex optimization problem.

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