Outage Analysis and Optimization for Four-Phase Two-Way Transmission with Energy Harvesting Relay

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Abstract

This paper investigates the outage performance and optimization for the four-phase two-way transmission network with an energy harvesting (EH) relay. To enable the simultaneous information processing and energy harvesting at the relay, we firstly propose a power splitting-based two-way relaying protocol (PSTWR). Then, we discuss its outage performance theoretically and derive an explicit expression for the system outage probability. In order to find the optimal system configuration parameters such as the optimal power splitting ratio and the optimal transmit power redistribution factor, we formulate an outage-minimized optimization problem. As the problem is difficult to solve, we design a genetic algorithm (GA) based algorithm for it. Besides, we also investigate the effects of the power splitting ratio, the power redistribution factor at the relay, and the source to relay distance on the system outage performance. Finally, extensive simulation results are provided to demonstrate the accuracy of the analytical results and the effectiveness of the GA-based algorithm. Moreover, it is also shown that, the relay position greatly affects the system performance, where relatively worse outage performance is achieved when the EH relay is placed in the middle of the two sources.

Keywords: Energy harvesting, decode and forward, two-way relay network, outage probability, GA-based optimization

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1. Introduction

Prolonging the lifetime of a wireless network with fixed energy-supplying devices has become a critical issue [1-11]. Generally, those fixed energy- supplying such as batteries has limited service life. To solve this problem, one solution is to replace or recharge batteries, but it may cost a lot and usually inconvenient, particularly for devices deployed in dangerous environment or embedded in structures. Another way is using the energy harvesting (EH) technology which allows devices to collect energy from the surrounding environment.

Recently, EH has attracted extensive attention and has been considered as a promising approach to realize green communications [1-11]. Conventional EH sources such as solar, wind, vibration, thermoelectric effects or other physical phenomena (see [1-4]), rely on external energy sources that are not components of communication networks. However, these EH techniques require the deployment of peripheral equipment to take advantage of external energy sources. Most recently, a new operation of EH which collects energy from ambient radio-frequency (RF) signals has been proposed, which is based on the fact that RF signals can carry energy and information at the same time [5].

For wireless EH from RF signals, a few works can be found in the literature [5-11]. The idea of simultaneous wireless information and energy transfer (SWIET) was first proposed in [5], where the performance tradeoff between the energy and information rate was investigated. However, the receivers in [5] were assumed to be ideal and able to detect data and extract energy from the wireless signal at the same time. Later, this assumption was proved to be hard to realize in practical systems [6], where the authors proposed a practically realizable receiver architecture design, in which EH and signal detection could be operated in time switching or power splitting patterns, and this architecture has been widely used for various wireless systems [6-11]. Among these works, some of them focused on point-to-point communications (see e.g., [7-8]), while the others considered the relaying systems with SWIET (see e.g., [9-11]). Specifically, in [9], the outage and throughput performances were developed for the one-way transmission model composed of one source-destination pair and an amplify-and-forward (AF) EH relay. In [10], different power allocation strategies were investigated for the scenario where multiple source-destination pairs communicated via the help of a common EH relay. In [11], the outage probability and diversity gain were studied for different EH relaying strategies, where the spatial randomness of the relay locations was first taken into consideration.

As is known, the two-way relay system is a widely model which has been deeply investigated in recent years [12-17]. However, to the best of our knowledge, only a few works investigated the two-way relay system with EH technology [16-17]. Among these works, only one of them considered the SWIET in a two-way relay system with an EH relay node [17]. Specifically, in [17], the outage probability and the ergodic capacity for the two-way relay network were analyzed, where AF relaying protocol was considered.

In this paper, we also focus on SWIET for the two-way relay network with an EH relay node. We consider a scenario where two sources with sufficient energy supply want to exchange their information with the help of an energy-constrained relay. Due to the deep fading over their direct link or the shadowing of the barrier, the direct link between the two sources is unavailable. Compared with previous work, some differences of our work are deserved to be stressed as follows. Firstly, the decode-and-forward (DF) relaying protocol is adopted in our work rather than AF considered in [17], because the DF protocol can ensure better link reliability by blocking noise propagation to the subsequent stages in a multi-hop communication scenario, and the DF analysis is more complicated due to the decoding and re-encoding operation of the relay. Secondly, in [11], the authors investigated the one-way DF relaying transmission with direct link, where the impact of relay's random locations was first studied. But, in this paper, we focus on the two-way DF relaying transmission. We assume that the relay is located on the line between the two sources, and for such a system, we aim to optimize the system configuration parameters to minimize the system outage probability.

Note that, in the two-way relay system, there are several different transmission strategies. For example, four-phase transmission, three-phase transmission with digital network coding (NC), and two-phase transmission with physical NC. Although applying NC can improve the system spectral efficiency and capacity, four-phase two-way relaying is relatively simpler than two-phase NC and three-phase NC. Because in three-phase NC, dynamic data buffer management is required at the relay, and in two-phase NC, strict synchronization control is necessary at the relay, which make them much more complicated than four-phase two-way relaying to be deployed. Thus, many works still investigated the four-phase two-way relay transmission model because of its wide existence in current wireless communication systems and its easy implementation in practical systems [12][14]. As the first paper investigating the SWIET in two-way relay transmission, we focus on the practically realizable four-phase transmission in this paper. Our main contributions can be summarized as follows:

- We propose a power splitting-based two-way relaying protocol (PSTWR) to enable the simultaneous information processing and energy harvesting for DF two-way relay networks.
- We theoretically discuss the outage performance of the proposed PSTWR and then derive an explicit expression for its outage probability.
- In order to achieve the minimal outage performance of the system, we formulate an outage-minimal optimization problem to seek for the optimal power splitting ratio and the optimal transmit power redistribution factor. As the problem is difficult to solve, we present a genetic algorithm (GA) based algorithm for it.
- We investigate the effects of various system parameters, such as power splitting ratio, transmit power redistribution factor, and source to relay distances on the

system outage performance. Then, we present a large number of numerical results, which demonstrate our analytical results and the effectiveness of the proposed GA-based algorithm.

The rest of the paper is organized as follows. In Section 2, we present the system model and the proposed PSTWR protocol. In Section 3, we describe the process of two-way transmission and analysis the system outage performance. In Section 4, an optimization algorithm is proposed to find the optimal system parameters to achieve the minimum system outage probability. In Section 5, we provide numerical results. Finally, the conclusion is followed in Section 6.

2. System Model

2.1 Assumptions and Notations

Consider a two-way wireless relay network which has two sources (namely, u_1 and u_2 respectively) and an EH relay R. The two sources want to exchange their information with each other via the relay through orthogonal channels such as different time slots or non-overlapping frequency bands. In this paper, we assume that each node transmits in different time slots. Let f_1, g_1, f_2, g_2 denote the channel gain of u_1 to R channel, u_2 to R channel, R to u_1 channel and R to u_2 channel respectively. All the channel coefficients are assumed to be independent complex circular symmetric Gaussian random variables, following a Rayleigh distribution. The distance from u_1 to R and from u_2 to R are denoted as d_1 and d_2, respectively.

In this paper, the sources transfer both information and energy to R through its own transmitted RF signals simultaneously. The delivered energy can be obtained by R from the recipients, and used for the following communications. We assume that the energy constrained relay recharges its battery only by using the energy of its observations from u_1 and u_2, and the battery of the relay is assumed to be sufficiently large, so no energy overflow is required to be considered. The harvested energy from u_1 and u_2 is exhausted to relay the information for the two users in the following phases. We also assume that R employs the DF relaying strategy and operates in a half-duplex mode. All the nodes are equipped with a single antenna. Based on these, we shall describe the proposed PSTWR protocol in the following subsection.

2.2 Proposed PSTWR Protocol

Fig. 1 illustrates the transmission process and the architecture of the relay receiver in the PSTWR protocol. Let P_{u_1} and P_{u_2} denote the power of the received signal from u_1 and u_2 respectively, and T denotes the total time period of each round of two-way transmission. By adopting the equal time division strategy, T is equally divided into four phases, thus each phase lasts for a time duration of $T/4$. During the first phase, u_1 transmits its information to R, in which $(1-\alpha)P_{u_1}$ part of power is used for the information transmission from u_1 to relay, and the other part of power αP_{u_1} is used for energy harvesting, where $0 \le \alpha \le 1$ denotes the power splitting ratio. During the second phase, similar to phase 1, u_2 transmits its information to R, among which $(1-\alpha)P_{u_2}$ part is used for the information transmission from u_2 to relay, and the other part αP_{u_2} is used for energy harvesting. After the first two phases, R has already harvested $\alpha(P_{u_1}+P_{u_2})$ power from u_1 and u_2. Then, in the third phase, R decodes and re-encodes the signal it received, and uses $\theta(\alpha P_{u_1}+\alpha P_{u_2})$ part of the harvested energy for the information transmission from R to u_1. In the fourth phase, similar to phase 3, the remaining energy $(1-\theta)(\alpha P_{u_1}+\alpha P_{u_2})$ is used for the information transmission from R to u_2. For convenience, we assume the same α for u_1 and u_2, and the analysis of the system outage performance can be easily extended to different α for u_1 and u_2.

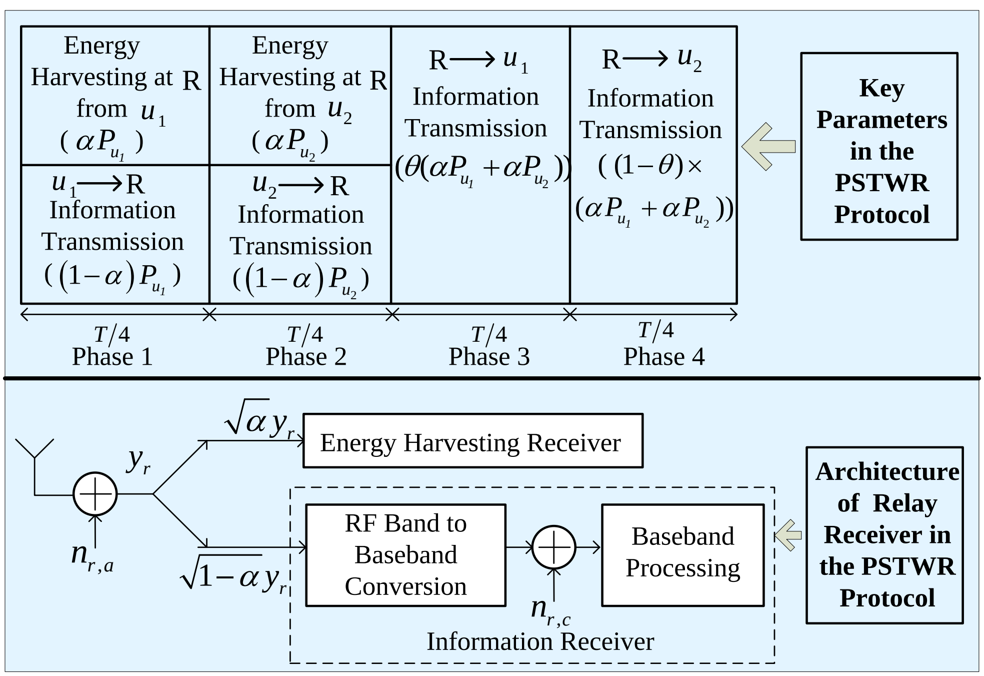


Fig. 1. PSTWR protocol and architecture of relay receiver.

Fig. 1 also describes the architecture of the relay receiver in the PSTWR protocol. As is shown, the received signal y_r at the relay antenna is split by the power splitter in $\alpha:1-\alpha$ proportion, in which $\sqrt{\alpha}y_r$ part of power is sent to the EH receiver, and the remaining part $\sqrt{1-\alpha}y_r$ is input into the information receiver. Note that y_r is corrupted by two noises, where $n_{r,a}$ is introduced by the receiving antenna which is modeled as a narrowband Gaussian noise, and $n_{r,c}$ is the sampled additive noise due to the RF band to baseband signal conversion. The details of the EH receiver and the information receiver can be found in [6].

3. Outage Probability Analysis

In this section, we shall first describe the process of the two-way transmission, and then analysis the explicit expression for the system outage probability.

As illustrated in **Fig. 1**, u_i ($i=1,2$) transmits its information to the relay during the i-th phase, and at the end of the i-th phase, after the processing of the relay receiver, the sampled baseband signal at the relay is given as follows

$$y_{r,i} = \frac{1}{\sqrt{d_i^m}}\sqrt{(1-\alpha)P_i}h_i s_i + \sqrt{(1-\alpha)}n_{r,a_i} + n_{r,c_i}, \tag{1}$$

where $0 \le \alpha \le 1$ denotes the power splitting ratio, P_i is the transmit power of u_i, m denotes the path loss exponent, s_i denotes the sampled and normalized information signal from u_i. h_i denotes the channel from u_i to R, and $h_i = f_1$ for $i=1$ and $h_i = g_1$ for $i=2$. n_{r,a_i} and n_{r,c_i} denote the baseband additive white Gaussian noise (AWGN) with variance σ^2_{r,a_i} due to the relay's receiving antenna and the sampled AWGN with variance σ^2_{r,c_i} due to the conversion from RF band signal to baseband signal, respectively.

The energy that R harvests from u_i is given by

$$E_{H,i} = \frac{\eta\alpha P_i |h_i|^2}{d_i^m}(T/4), \tag{2}$$

where $0 < \eta \le 1$ is used to describe energy conversion efficiency. So, the relay's transmit power harvested from u_i is given by

$$P_{r,i} = \frac{E_{H,i}}{T/4} = \frac{\eta\alpha P_i |h_i|^2}{d_i^m}. \tag{3}$$

The data rate from u_i at R is given by

$$R_{r,i} = \frac{1}{4}\log(1 + \frac{(1-\alpha)P_i |h_i|^2}{d_i^m \sigma^2_{r,i}}). \tag{4}$$

Defining $n_{r,i} = \sqrt{(1-\alpha)}n_{r,a_i} + n_{r,c_i}$ as the overall AWGN at the relay in the first two phases, so $\sigma^2_{r,i} = (1-\alpha)\sigma^2_{r,a_i} + \sigma^2_{r,c_i}$.

After the first two phases, the relay has already harvested $P_{r,1} + P_{r,2}$ transmit power from u_1 and u_2 in total. Then, R decodes and re-encodes the received signals and redistributes the harvested power in $\theta : 1-\theta$ portion, such that $\theta(P_{r,1} + P_{r,2})$ part is used for the information transmission to u_1 in the third phase, and the remaining part $(1-\theta)(P_{r,1}+P_{r,2})$ is for the information relaying to u_2 in the fourth phase.

Therefore, at the end of the k -th phase ($k=3,4$), the sampled received signal at u_i ($i=1,2$) is given by

$$y_{u,i}=\frac{1}{\sqrt{d_i^m}}\sqrt{\theta^*(P_{r,1}+P_{r,2})}h_k s_j+n_{u,a_i}+n_{u,c_i}\,, \quad (5)$$

where $j=1,2$ and $j\neq i$, $k=3$ for $i=1$ and $k=4$ for $i=2$, respectively. $\theta^*=\theta$ for $i=1$ and $\theta^*=1-\theta$ for $i=2$, respectively, $0\le\theta\le1$ is the transmit power redistribution factor, n_{u,a_i} and n_{u,c_i} are the baseband AWGN with variance σ^2_{u,a_i} and the sampled AWGN with variance σ^2_{u,c_i} at u_i, respectively. h_k denotes the channel from the relay to u_i, and $h_k=f_2$ for $k=3$ and $h_k=g_2$ for $k=4$. The date rate at u_i is given by

$$R_{u,i}=\frac{1}{4}\log(1+\frac{\theta^*(P_{r,1}+P_{r,2})|h_k|^2}{d_i^m\sigma^2_{u,i}})\,. \quad (6)$$

Defining $n_{u,i}=n_{u,a_i}+n_{c,a_i}$ as the overall AWGN at u_i, we have that $\sigma^2_{u,i}=\sigma^2_{u,a_i}+\sigma^2_{u,c_i}$.

In traditional one-way relay network, an outage occurs if either link's rate of two hops falls below the targeted rate R_0. Comparatively, the two-way relay network has two communication tasks which refer to four transmission links. Any link failure over the four links may result in system outage. So, the outage probability P_{out} for the four phase two-way relay transmission can be calculated as

$$P_{out}=1-\Pr[R_{r,1}\ge R_0,R_{u,2}\ge R_0]\cdot\Pr[R_{r,2}\ge R_0,R_{u,1}\ge R_0]\,. \quad (7)$$

Theorem 1: *Given a target transmission rate R_0, the outage probability for the two-way relay network with an EH relay is given by (8) in the next page, where* $a=(1-\theta)\alpha\eta P_1 d_1^{-m}$, $c=\theta\alpha\eta P_1 d_1^{-m}$, $b=(1-\theta)\alpha\eta P_2 d_2^{-m}$, $d=\theta\alpha\eta P_2 d_2^{-m}$, $c_0=ud_2^m\sigma^2_{u,2}$, $d_0=ud_1^m\sigma^2_{u,1}$, $a_0=ud_1^m\sigma^2_{r,1}(1-\alpha)^{-1}P_1^{-1}$, $b_0=ud_2^m\sigma^2_{r,2}(1-\alpha)^{-1}P_2^{-1}$, $e_0=e^{-\lambda_{f1}a_0-\lambda_{g1}b_0}$, $u=2^{4R_0}-1$, λ_{f_1} , λ_{f_2} , λ_{g_1} *and* λ_{g_2} *are the mean value of the exponential random variables* $|f_1|^2$ $|f_2|^2$ $|g_1|^2$ *and* $|g_2|^2$, *respectively.* $K_1(\cdot)$ *and* $K_2(\cdot)$ *denote the first-order and second-order modified Bessel function of the second kind respectively*.

Proof*:* See the appendix.

Since the exact expression of P_{out} is complicated, we derive its approximation expression at high SNR in the following corollary.

Corollary 1*: The outage probability in (8) can be approximated by (9) at high SNR as follows*

$$P_{out}=\begin{cases}1-\dfrac{\lambda_{f_1}\lambda_{g_1}e_0}{(c\lambda_{g_1}-d\lambda_{f_1})}\left(\dfrac{c}{\lambda_{f_1}}-\dfrac{d}{\sqrt{\lambda_{f_1}\lambda_{g_1}}}\right), & a\lambda_{g_1}\neq b\lambda_{f_1},\ c\lambda_{g_1}\neq d\lambda_{f_1}\\ 1-\dfrac{\lambda_{f_1}d_0e_0d}{\lambda_{g_1}c_0c}, & a\lambda_{g_1}\neq b\lambda_{f_1},\ c\lambda_{g_1}= d\lambda_{f_1}\\ 1-\dfrac{\lambda_{f_1}^2e_0b}{(c\lambda_{g_1}-d\lambda_{f_1})a}\cdot\left(\dfrac{c}{\lambda_{f_1}}-\dfrac{d}{\sqrt{\lambda_{f_1}\lambda_{g_1}}}\right), & a\lambda_{g_1}= b\lambda_{f_1},\ c\lambda_{g_1}\neq d\lambda_{f_1}\\ 1-\dfrac{\lambda_{f_1}^2d_0e_0bd}{\lambda_{g_1}^2c_0ac}, & a\lambda_{g_1}= b\lambda_{f_1},\ c\lambda_{g_1}= d\lambda_{f_1}\end{cases} \tag{9}$$

***Proof**:* For $0<x\le\sqrt{\nu+1}$ **,** the modified Bessel function of the second kind has the approximate expression [21] as follows

$$K_\nu\left(x\right)\approx\frac{\Gamma\left(\nu\right)}{2}\left(\frac{2}{x}\right)^\nu,\qquad \nu>0, \tag{10}$$

where $\Gamma\left(\nu\right)$ denotes the Gamma function. At high SNR, a, b, c and d contained in the denominators of the variables in $K_1\left(\cdot\right)$ and $K_2\left(\cdot\right)$ are relatively high, which makes the variables in $K_1\left(\cdot\right)$ and $K_2\left(\cdot\right)$ in (8) are very close to zero. So the approximation in (10) can be used. Substituting $K_1\left(x\right)=1/x$ and $K_2\left(x\right)=2/x^2$ into (8), the approximation expression of P_{out} at high SNR can be obtained.

***Remark 1**: With the system outage probability obtained in (8), the system spectral efficiency of the proposed PSTWR protocol for such a two-way relay network can be given by*

$$S=\frac{(1-P_{out})R_0}{B}\cdot\frac{T/4\times2}{T}=\frac{(1-P_{out})R_0}{2B}, \tag{11}$$

where B denotes the system bandwidth, and the coefficient $1/2$ is due to the fact that four equal phases are used to transmit two new signals.

$$P_{out}=\begin{cases}1-\dfrac{4\lambda_{f_1}^2\lambda_{g_1}^2e_0}{(a\lambda_{g_1}-b\lambda_{f_1})(c\lambda_{g_1}-d\lambda_{f_1})}\left(\sqrt{\dfrac{c_0a\lambda_{g_2}}{\lambda_{f_1}}}K_1\left(2\sqrt{\dfrac{c_0\lambda_{g_2}\lambda_{f_1}}{a}}\right)-\sqrt{\dfrac{c_0b\lambda_{g_2}}{\lambda_{g_1}}}K_1\left(2\sqrt{\dfrac{c_0\lambda_{g_2}\lambda_{g_1}}{b}}\right)\right) & \\ \quad\times\left(\sqrt{\dfrac{d_0c\lambda_{f_2}}{\lambda_{f_1}}}K_1\left(2\sqrt{\dfrac{d_0\lambda_{f_2}\lambda_{f_1}}{c}}\right)-\sqrt{\dfrac{d_0d\lambda_{f_2}}{\lambda_{f_1}}}K_1\left(2\sqrt{\dfrac{d_0\lambda_{f_2}\lambda_{g_1}}{d}}\right)\right), & a\lambda_{g_1}\neq b\lambda_{f_1},\ c\lambda_{g_1}\neq d\lambda_{f_1}\\ 1-\dfrac{4\lambda_{f_1}^2\lambda_{f_2}\lambda_{g_1}d_0e_0}{(a\lambda_{g_1}-b\lambda_{f_1})c}\left(\sqrt{\dfrac{c_0a\lambda_{g_2}}{\lambda_{f_1}}}K_1\left(2\sqrt{\dfrac{c_0\lambda_{g_2}\lambda_{f_1}}{a}}\right)-\sqrt{\dfrac{c_0b\lambda_{g_2}}{\lambda_{g_1}}}K_1\left(2\sqrt{\dfrac{c_0\lambda_{g_2}\lambda_{g_1}}{b}}\right)\right)K_2\left(2\sqrt{\dfrac{c_0\lambda_{g_1}\lambda_{f_2}}{d}}\right), & a\lambda_{g_1}\neq b\lambda_{f_1},\ c\lambda_{g_1}= d\lambda_{f_1}\\ 1-\dfrac{4\lambda_{f_1}^2\lambda_{g_1}\lambda_{g_2}c_0e_0}{(c\lambda_{g_1}-d\lambda_{f_1})a}K_2\left(2\sqrt{\dfrac{c_0\lambda_{g_1}\lambda_{g_2}}{b}}\right)\left(\sqrt{\dfrac{d_0c\lambda_{f_2}}{\lambda_{f_1}}}K_1\left(2\sqrt{\dfrac{d_0\lambda_{f_2}\lambda_{f_1}}{c}}\right)-\sqrt{\dfrac{d_0d\lambda_{f_2}}{\lambda_{f_1}}}K_1\left(2\sqrt{\dfrac{d_0\lambda_{f_2}\lambda_{g_1}}{d}}\right)\right), & a\lambda_{g_1}= b\lambda_{f_1},\ c\lambda_{g_1}\neq d\lambda_{f_1}\\ 1-\dfrac{4\lambda_{f_1}^2\lambda_{f_2}\lambda_{g_2}c_0d_0e_0}{ac}K_2\left(2\sqrt{\dfrac{c_0\lambda_{g_1}\lambda_{g_2}}{b}}\right)K_2\left(2\sqrt{\dfrac{c_0\lambda_{g_1}\lambda_{f_2}}{d}}\right), & a\lambda_{g_1}= b\lambda_{f_1},\ c\lambda_{g_1}= d\lambda_{f_1}\end{cases} \tag{8}$$

4. Outage-Minimal System Design

4.1 Optimization Problem Formulation

In a practical system with specific parameters, that is, channels distribution and source-relay distance, it is desirable to obtain the optimal configuration pair of α and θ to achieve the minimum system outage probability. The system optimization problem can be formulated as follows:

$$\begin{aligned} &\min_{\alpha,\theta} \ P_{out} \\ &\text{s.t.} \quad 0 \le \alpha \le 1,\ 0 \le \theta \le 1,\ d_1 > 0,\ d_2 > 0 \end{aligned} \tag{12}$$

Because of the Bessel functions involved in the analytical expressions of P_{out} shown in (8), it is difficult to obtain an analytic solution of α and θ. To solve this problem, in the following subsection, we shall design a genetic algorithm (GA) based optimization algorithm to obtain the optimal solution of α and θ to achieve the optimal outage performance.

4.2 GA-Based Algorithm

Genetic algorithm is a global random search and optimization method which imitates the natural evolution mechanism. It is a general optimization algorithm which can be applied to most of the function optimization problems and has been widely used to a lot of optimization applications [18].

GA starts with the generation of a random population, which is a group of chromosomes. Each chromosome has a fitness which is evaluated against the objective function. According to the survivor selection criterion based on survival of the fittest, chromosomes with better fitness will survive for evolution while chromosomes with less fitness will be discarded. The evolution includes three operations: mate selection, crossover and mutation. Mate selection selects chromosome mates with better fitness from the survivors to create new offspring. Crossover is then executed over the selected chromosome mates to reproduce new offspring. Crossover is a process of gene recombination which can transfer partial genes from parents to offspring. Mutation is implemented to alter partial genes of offspring, which can avoid converging into local optimal solution fast. That is to say, new genes are generated after mutation, which leads to searching solutions in distinct area of solution space. The evolution process repeats until the termination conditions are satisfied. In this work, α and θ can be regarded as genes respectively, and the combination of α and θ compose a chromosome. Objective function in (12) is used to calculate each chromosome's fitness. $Q_{\min}(t)$ denotes the optimal solution of the t-th generation, and δ is the predefined precision of GA. Main steps of the GA-based optimization algorithm are as follows:

GA-based Optimization Algorithm	
Step 1	*Population initialization*: K_{ini} chromosomes are randomly generated as the initial population of the t-th $(t=0)$ generation.
Step 2	*Fitness evaluation*: each chromosome's fitness is evaluated by objective function in (12). If $\left|Q_{\min}(t)-Q_{\min}(t-1)\right|<\delta$, algorithm ends; Otherwise, go to **Step 3**;
Step 3	*Survivor selection*: $K_{\text{sel}}=\varepsilon\cdot K_{\text{ini}}$ chromosomes with best fitness survive while the others with less fitness are eliminated to make room for new offspring, where $\varepsilon\in(0,1)$ is the selection rate to survival;
Step 4	*Mate selection*: Two mates are selected from the K_{sel} survival chromosomes to produce new offspring by adopting Roulette wheel selection;
Step 5	*Crossover*: Single-point crossover is applied to produce two offspring from two selected mates. Sufficient offspring are produced until the number of survivors and offspring is equal to K_{ini}.
Step 6	*Mutation*: A probability μ is used to decide whether a gene is mutated or not. Gene mutation leads to the production of a new group of α and θ. After mutation, $t=t+1$, and return to **Step 2**.

The computational complexity of the proposed GA-based algorithm depends on the number of iterations N_{ite} in GA, the number of chromosomes K_{ini} in each iteration, and the complexity in evaluating the fitness value in (8), which has the computational complexity of $O(1)$. Therefore, the total complexity of our proposed method is $O(N_{\text{ite}}\cdot K_{\text{ini}})$. To the best of our knowledge, the convergence of GA for the case of finite iteration number is still an open problem [19]. So in this paper, instead of giving theoretical analysis, we shall investigate the convergence of GA-based optimization algorithm by simulations in Section 5.

5. Numerical Results

In this section, we provide some numerical results to verify our theoretical analysis on the system outage probability and the effectiveness of the proposed GA-based algorithm. Besides, we also discuss the effects of various system parameters including power splitting ratio α, transmit power redistribution factor θ, and source-relay distance: d_1 and d_2 on the system outage performance by simulations.

Unless specifically stated, we set $R_0=1$ bit/sec/Hz, $\eta=1$, $P_1=P_2=1$ Watt, $B=1$ Hz, and $m=2.7$ (which corresponds to urban cellular network). All the mean values of the exponential random variables $|f_1|^2$, $|f_2|^2$, $|g_1|^2$ and $|g_2|^2$ are set to be 1. For simplicity, we assume that $\sigma_a^2=\sigma_{r,a_1}^2=\sigma_{r,a_2}^2=\sigma_{u,a_1}^2=\sigma_{u,a_2}^2$, and $\sigma_c^2=\sigma_{r,c_1}^2=\sigma_{r,c_2}^2=\sigma_{u,c_1}^2=\sigma_{u,c_2}^2$. And in GA, $K_{\text{ini}}=100$, $\varepsilon=0.5$, $\mu=0.05$ and $\delta=10^{-5}$.

5.1 Verification of the Analytical Outage Probability

In this subsection, simulation results are obtained through the Monte Carlo simulation using (7) to justify our analytical expression for the system outage probability in (8). The antenna noise variance σ_a^2 and the conversion noise variance σ_c^2 are set to be 10^{-5}, and θ is set to be 0.5[1].

From **Fig. 2**, it can be seen that, the analytical and the simulation results match well for all α ($0 \le \alpha \le 1$), this verifies the analytical expression for P_{out} presented in *Theorem 1*.

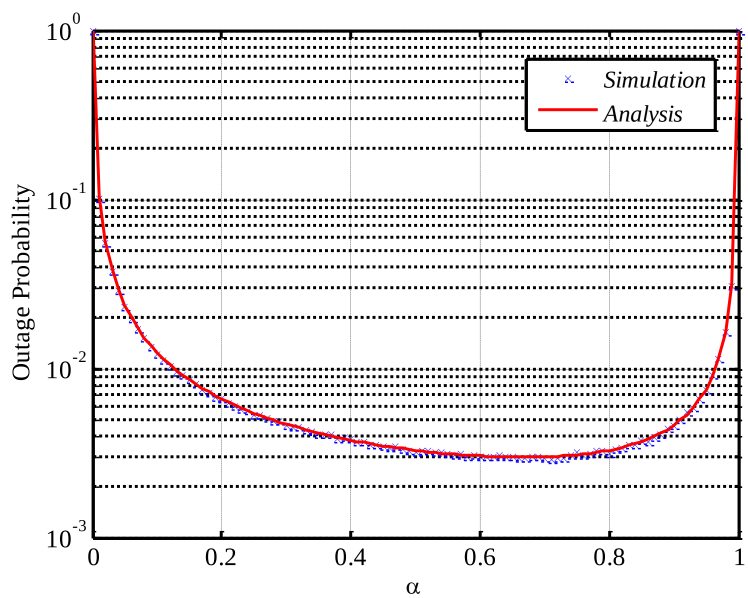


Fig. 2. Outage probability: numerical vs simulation.

5.2 Effect of α and θ on System Outage Probability

Fig. 3 (a) plots the optimal system outage probability for different α. The optimal outage probability means that, for each particular α, we calculate all the possible outage probabilities obtained against different θ, and choose the lowest outage probability as the optimal one. It can be observed that, no matter what value of θ is, the optimal outage probability decreases as α increases from 0 to the optimal value ($\alpha = 0.67$), and start increasing as α increases from the optimal value. The reason is that, the relay obtains less transmit power ($P_{r,1} + P_{r,2}$) from energy harvesting for smaller α than the optimal α, which incurs more outages in phases 3 and 4. On the other hand, when α gets higher, the relay may obtain more transmit power than the

[1] The effect of θ on system outage probability will be shown in subsection 5.2.

optimal value. Thus, less power is left for the users to transmit their own information to the relay. Consequently, poor signal strength is observed at the relay, which makes the relay hard to decode the signal correctly and results in higher outage probability.

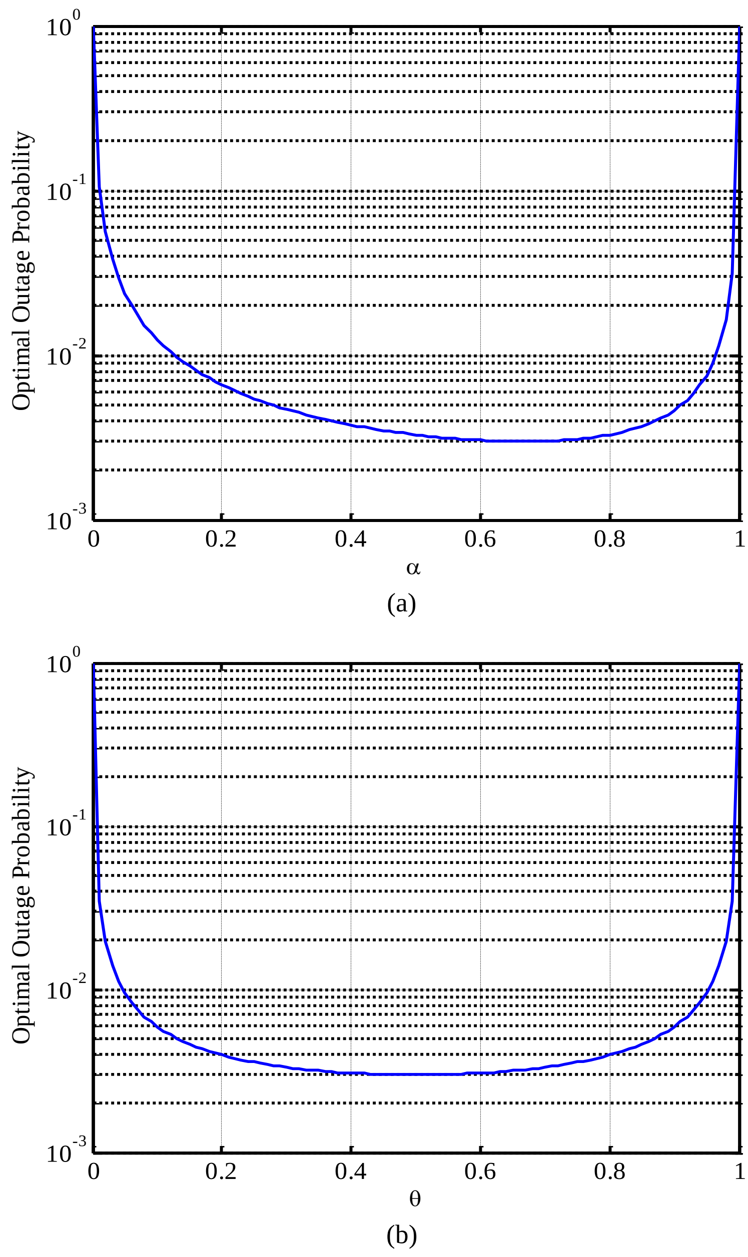


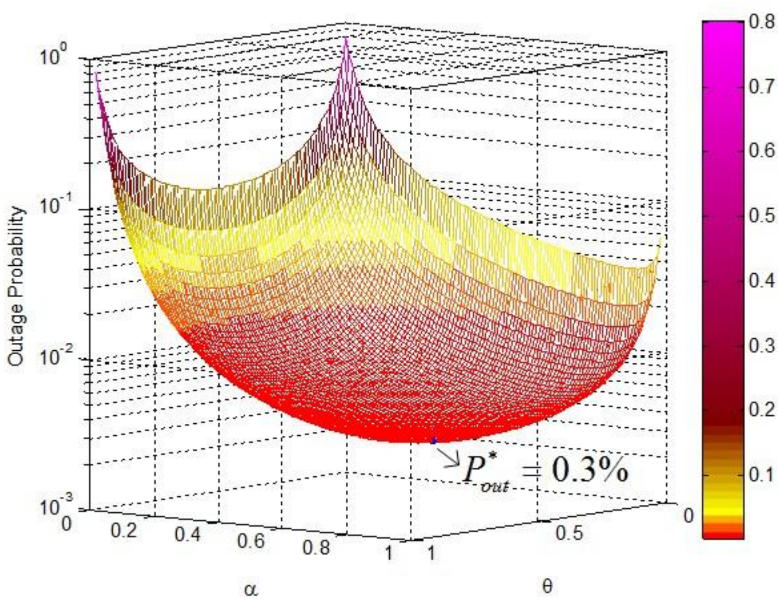
Fig. 3. (a) Optimal system outage probability for different α (b) optimal system outage probability for different θ.

Fig. 3 (b) plots the optimal system outage probability for different θ. Similarly, the optimal outage probability means that, for each particular θ, we calculate all the possible outage probabilities obtained against different α, and choose the lowest outage probability as the optimal one. It can be observed that, no matter what value of α is, the optimal outage probability is achieved when $\theta = 0.5$. This is due to the fact that, when the system is symmetric (where $P_1 = P_2$, $d_1 = d_2$ and independent identically distributed channels f_i and g_i, $i = 1, 2$), the optimal transmit power redistribution strategy is to equally distribute the relay power to the two users.

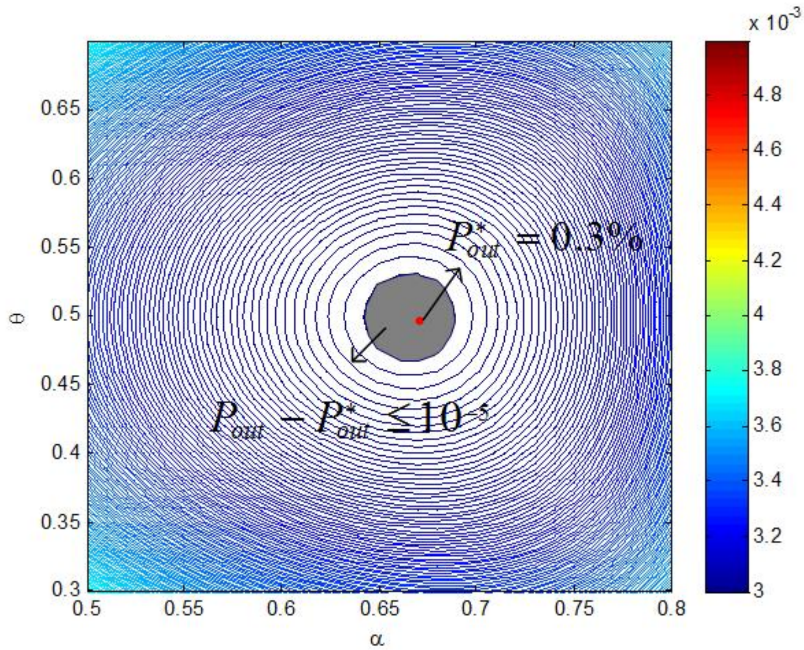
5.3 Optimal Region of α and θ for Optimal Outage Probability

Let P^*_{out} denote the minimal system outage probability. It is assumed that if $P_{out} - P^*_{out} \leq 10^{-5}$, $P_{out} \approx P^*_{out}$. With this assumption, the corresponding α and θ of P_{out} can be considered as the α^* and θ^*.

Fig. 4 (a) shows the outage probability versus α and θ, where it shows that $P^*_{out} = 0.3\%$. **Fig. 4 (b)** plots the optimal region of α and θ, and all the pairs of α and θ within the gray area lead to $P_{out} - P^*_{out} \leq 10^{-5}$. It shows that the optimal region is $\mathbf{P}_{out} = \{P_{out}(\alpha, \beta): \alpha \in [0.64, 0.70], \beta \in [0.45, 0.54]\}$. The $\mathbf{P}_{out}$ may guide us to select a proper α and θ pair to obtain the optimal outage probability.



(a)



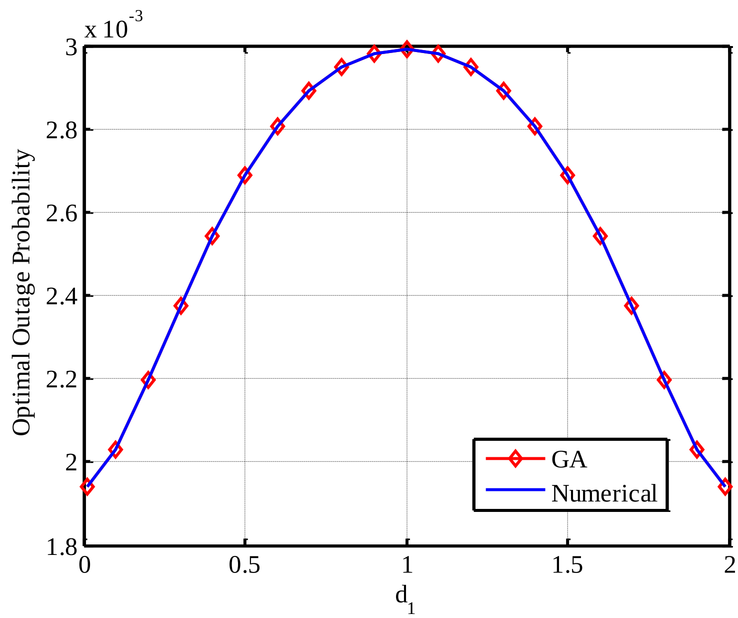
(b)

Fig. 4. (a) 3-dimensional graph for system outage probability (b) optimal region of α and θ for optimal outage probability.

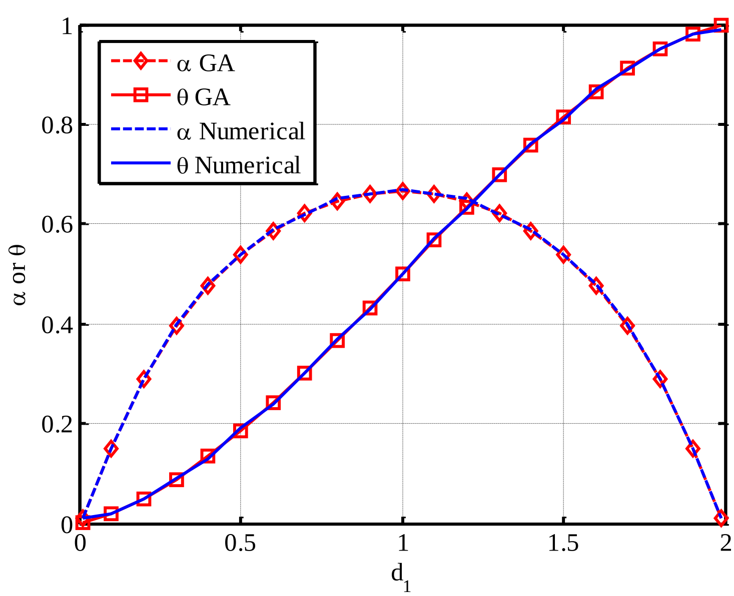
5.4 Effect of Relay Location on System Outage Probability

To investigate the influence of the relay location on the system outage probability, the distance from relay to u_2 is set to be $d_2 = 2 - d_1$. **Fig. 5 (a)** plots the optimal system outage probability for different d_1. It can be observed that the optimal outage probability increases as d_1 increases, and achieve its maximum when $d_1 = d_2 = 1$, i.e., the relay is deployed in the middle of the two sources. It is noteworthy that the system outage probability is different from the traditional case where EH is not considered at the relay and the minimal outage probability is achieved when the relay is deployed in the middle of the two sources.

Fig. 5 (b) plots the optimal α and θ versus d_1. It can be observed that θ increases as d_1 increases, which can be easily understood: more harvested energy should be allocated to u_1 in order to combat the growing path loss. As for α, it increases as d_1 increases, and achieve its maximum when $d_1 = 1$, and later, it starts decreasing as d_1 increases. We also



(a)



(b)

Fig. 5. (a) Optimal system outage probability for different d_1 (b) optimal α and θ vs d_1.

note that when $d_1 = d_2 = 1$, $\theta = 0.5$ and $\alpha = 0.67$, which corresponds to our previous analysis of **Fig. 3**.

5.5 System Spectral Efficiency of the Proposed PSTWR Protocol

To explore more system performance limit for such a two-way relay network with an EH relay, we also plot the system spectral efficiency of the proposed PSTWR protocol in this subsection. **Fig. 6 (a)** plots the system spectral efficiency for different d_1 and **Fig. 6 (b)** shows the effects of two sources' transmit power P_1 and P_2 on the system spectral efficiency, where we set $P_1 = 1$, and let P_2 vary from 0.5 to 1.5. It can be seen that, as P_2 / P_1 increases, the system spectral efficiency also increases, which is due to the fact that, the system outage probability decreases as P_2 / P_1 increases.

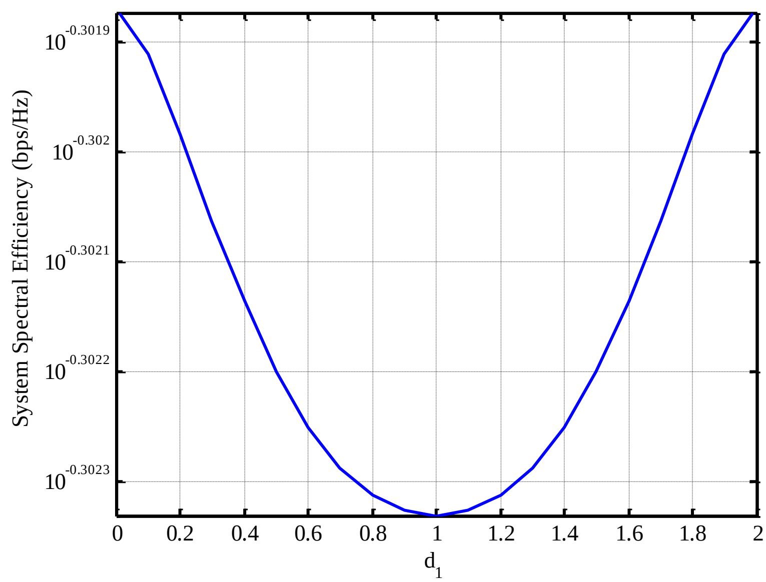
5.6 Convergence Behavior of the Proposed GA-Based Algorithm

For an arbitrary two-way relay system with given parameters, the proposed GA-based optimization algorithm can be used to obtain the optimal α and θ to achieve the optimal outage performance. **Fig. 7** illustrates the convergence behavior of the proposed GA-based algorithm. It can be seen that the algorithm converges fast, and the predefined precision is achieved within 20 runs.

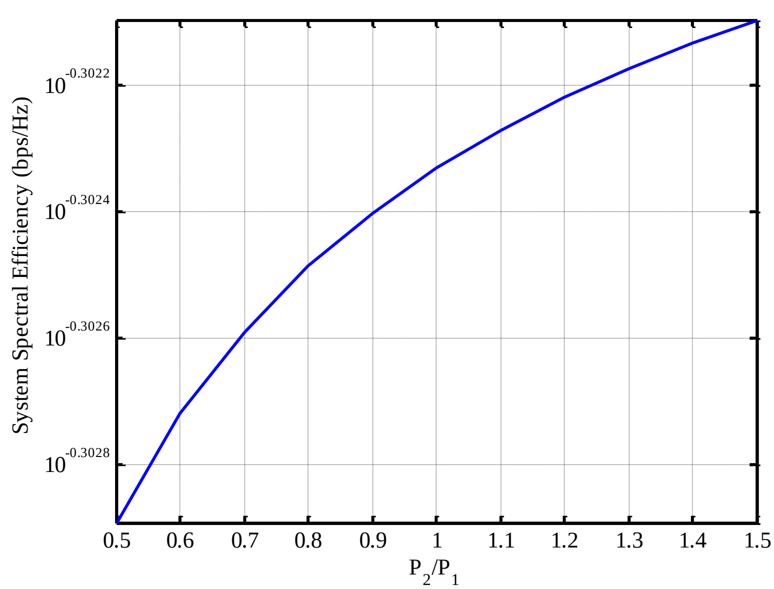
6. Conclusion

In this paper, a two-way transmission network with an EH relay was considered. By adopting the power splitting receiver architecture, we proposed a PSTWR protocol to enable the simultaneous information processing and energy harvesting at the relay for the two-way transmission. Then, the explicit expression for the system outage probability was presented, based on which, we discussed the effects of various system parameters on the system outage performance. Additionally, a GA-based algorithm was proposed to find the optimal pair of system parameters to achieve the minimal outage probability. Extensive numerical results demonstrated the accuracy of the analytical results and revealed that the GA-based algorithm is effective and converges fast.

For future work, we intend to extend the performance analysis of SWIET to the model of two-way relay network with network coding technology employed, and investigate the performance gain brought by the combination of network coding and energy harvesting.



(a)



(b)

Fig. 6. (a) System spectral efficiency for different d_1 (b) for different P_2 / P_1.

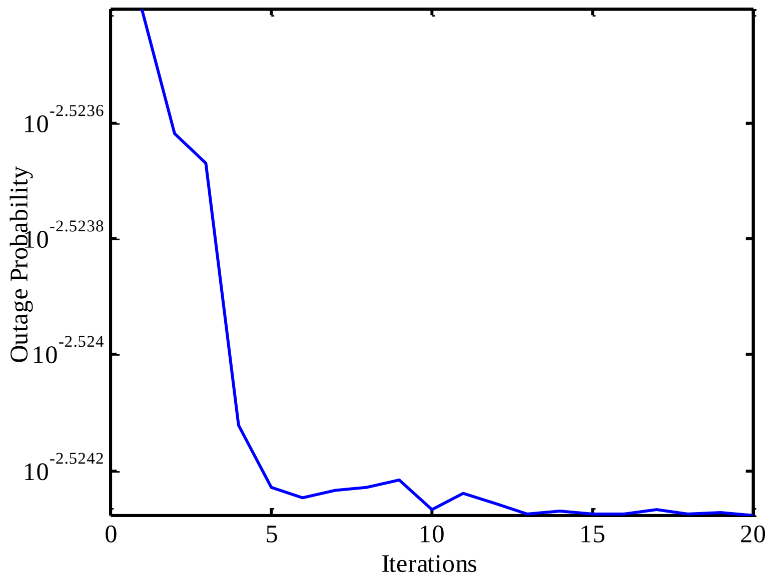


Fig. 7. Convergence behavior of the GA-based algorithm

Appendix

This appendix derives the P_{out} in (8) of *Theorem 1*.

Proof: As all the channels are independent, P_{out} can be rewritten as:

$$P_{out} = 1 - \Pr[R_{r,1} \geq R_0] \cdot \Pr[R_{u,2} \geq R_0] \cdot \Pr[R_{r,2} \geq R_0] \cdot \Pr[R_{u,1} \geq R_0] \tag{A.1}$$

Substituting (3), (4), and (6) into (A.1), we have that

$$P_{out} = 1 - \Pr[|f_1|^2 \geq a_0]\Pr[|g_2|^2 \geq \frac{c_0}{a|f_1|^2 + b|g_1|^2}]\Pr[|g_1|^2 \geq b_0]\Pr[|f_2|^2 \geq \frac{d_0}{c|f_1|^2 + d|g_1|^2}] \tag{A.2}$$

where, $a = (1-\theta)\alpha\eta P_1 d_1^{-m}$, $b = (1-\theta)\alpha\eta P_2 d_2^{-m}$, $c = \theta\alpha\eta P_1 d_1^{-m}$, $d = \theta\alpha\eta P_2 d_2^{-m}$, $a_0 = u d_1^m \sigma_{r,1}^2 / (1-\alpha)P_1$, $b_0 = u d_2^m \sigma_{r,2}^2 / (1-\alpha)P_2$, $c_0 = u d_2^m \sigma_{u,2}^2$, $d_0 = u d_1^m \sigma_{u,1}^2$, $u = 2^{4R_0} - 1$.

Since $|f_1|^2$ and $|g_1|^2$ are exponential random variables with mean λ_{f_1} and λ_{g_1}, respectively, we can obtain that

$$\Pr[R_{r,1} \geq R_0] = e^{-\lambda_{f_1} a_0} \tag{A.3}$$

$$\Pr[R_{r,2} \geq R_0] = e^{-\lambda_{g_1} b_0} \tag{A.4}$$

On setting $z = a|f_1|^2 + b|g_1|^2$, we can write the probability density function (PDF) of z as

$$f_z(z)=\begin{cases}\dfrac{\lambda_{f_1}\lambda_{g_1}}{a\lambda_{g_1}-b\lambda_{f_1}}\left(e^{-\frac{\lambda_{f_1}}{a}z}-e^{-\frac{\lambda_{g_1}}{b}z}\right), & a\lambda_{g_1}\neq b\lambda_{f_1}\\ \dfrac{\lambda_{f_1}\lambda_{g_1}}{ab}e^{-\frac{\lambda_{g_1}}{b}z}\cdot z, & a\lambda_{g_1}=b\lambda_{f_1}\end{cases} \tag{A.5}$$

Thus,

$$\begin{aligned}\Pr\left[|g_2|^2\geq\frac{c_0}{a|f_1|^2+b|g_1|^2}\right]&=\int_0^\infty e^{-\frac{\lambda_{g_2}c_0}{z}}\cdot f_z(z)dz\\ &=\begin{cases}\dfrac{2\lambda_{f_1}\lambda_{g_1}}{a\lambda_{g_1}-b\lambda_{f_1}}\left(\sqrt{\dfrac{c_0a\lambda_{g_2}}{\lambda_{f_1}}}K_1\left(2\sqrt{\dfrac{c_0\lambda_{g_2}\lambda_{f_1}}{a}}\right)-\sqrt{\dfrac{c_0b\lambda_{g_2}}{\lambda_{g_1}}}K_1\left(2\sqrt{\dfrac{c_0\lambda_{g_2}\lambda_{g_1}}{b}}\right)\right), & a\lambda_{g_1}\neq b\lambda_{f_1}\\ \dfrac{2\lambda_{f_1}\lambda_{g_2}c_0}{a}K_2\left(2\sqrt{\dfrac{c_0\lambda_{g_1}\lambda_{g_2}}{b}}\right), & a\lambda_{g_1}=b\lambda_{f_1}\end{cases}\end{aligned} \tag{A.6}$$

where $K_1(\cdot)$ and $K_2(\cdot)$ denote the *first-order and second-order modified Bessel function of the second kind* respectively, and the last equality is obtained by applying the formula, $\int_0^\infty \exp(-\frac{\beta}{4x}-\gamma x)dx=\sqrt{\frac{\beta}{\gamma}}K_1\left(\sqrt{\beta\gamma}\right)$ and $\int_0^\infty x\cdot\exp(-\beta x-\frac{\gamma}{x})dx=\frac{2\gamma}{\beta}K_2\left(2\sqrt{\beta\gamma}\right)$ [20].

Taking steps similar to above, we can arrive at

$$\Pr\left[|f_2|^2\geq\frac{d_0}{c|f_1|^2+d|g_1|^2}\right]=\begin{cases}\dfrac{2\lambda_{f_1}\lambda_{g_1}}{c\lambda_{g_1}-d\lambda_{f_1}}\left(\sqrt{\dfrac{d_0c\lambda_{f_2}}{\lambda_{f_1}}}K_1\left(2\sqrt{\dfrac{d_0\lambda_{f_2}\lambda_{f_1}}{c}}\right)-\sqrt{\dfrac{d_0d\lambda_{f_2}}{\lambda_{g_1}}}K_1\left(2\sqrt{\dfrac{d_0\lambda_{f_2}\lambda_{g_1}}{d}}\right)\right), & c\lambda_{g_1}\neq d\lambda_{f_1}\\ \dfrac{2\lambda_{f_1}\lambda_{g_2}d_0}{c}K_2\left(2\sqrt{\dfrac{d_0\lambda_{f_2}\lambda_{g_1}}{d}}\right), & c\lambda_{g_1}=d\lambda_{f_1}\end{cases} \tag{A.7}$$

Substituting (A.3), (A.4), (A.6) and (A.7) into (A.2), we can obtain (8). This ends the proof for *Theorem 1*.

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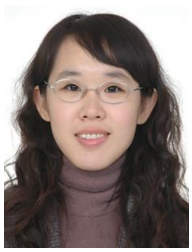

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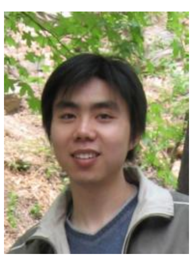

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