Joint Time Switching and Power Allocation for Secure Multicarrier Decode-and-Forward Relay Systems with Wireless Information and Power Transfer

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Abstract. Secure communication is critical in wireless networks due to the openness of the wireless transmission medium. In this paper, we study the secure communication in a multicarrier orthogonal frequency division multiplexing (OFDM) decode-and-forward (DF) relay network with an energy-constrained relay node which operates with a time-switching (TS) protocol. By jointly designing TS ratios of energy harvesting (EH) and information-decoding (ID) at the relay, TS ratio of signal forwarding from relay to destination and power allocation (PA) over all subcarriers at source and relay, we aim at maximizing the achievable secrecy rate of the DF relay network subject to a maximum transmit power constraint at source and an EH constraint at relay. The formulated optimization problem is a non-convex problem. We decouple it into a convex problem and a non-convex problem, where the non-convex problem can be solved by a constrained concave convex procedure (CCCP) based iterative algorithm to achieve a local optimum. Simulation results verify that our proposed joint TS and PA scheme achieves nearly global optimal resource allocation and outperforms the existing resource allocation scheme.

Keywords: Time switching (TS) · Power allocation (PA) · Energy harvesting (EH) · Relay networks · Secure communication

1 Introduction

Allowing battery operated wireless communication systems to harvest energy from radio signals, wireless information and energy transfer (WIET) is a

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promising energy harvesting (EH) technique to solve the energy scarcity problem in energy-constrained wireless networks [1–5]. In [2], a multiple-input-multiple-output (MIMO) system with WIET was studied and a power-splitting (PS) or time-switching (TS) EH scheme was proposed. By employing PS-based EH receiver at the relay, a decode-and-forward (DF) relay system with multiple source-destination pairs was studied in [3]. In [4], the authors aim for maximizing achievable rate of DF relay networks with WIET. It was shown that the proposed scheme is superior to the scheme with fixed time-switching ratios from the simulations. An EH relay network was investigated in [5]. With the aid of relay node, communication between sources and destinations can perform efficiently.

Secure communications had been investigated in [6,7]. The secure resource allocation in a multicarrier half-duplex relay system was studied in [6]. In [7], a full-duplex DF relay network was studied, whose objective is to maximize the achievable secrecy rate of the system. Unfortunately, there is still short of study on the secure communication in wireless relay systems with WIET.

In this paper, we investigate secure multicarrier communication in OFDM DF relay systems with WIET. As in [4], we assume that the EH relay will reallocate the energy amongst all the sub-channels. By jointly optimizing TS factors and power allocations on sub-channels, where the TS factors are consisted of energy harvesting, information-decoding at the relay node and signals transmitted to destination node, we aim to maximize the achievable secrecy rate subject to maximum transmit power constraint at source node and energy harvesting constraint at relay node. The formulated optimization problem is non-convex because both the objective function and the energy harvesting constraint at relay node are non-convex. By transforming the non-convex original problem into a solvable convex problem and a non-convex problem, the non-convex problem can be solved by a constrained concave convex procedure (CCCP) based iterative algorithm to achieve a local optimum. Simulation results show that our proposed joint TS ratios and PA allocation scheme can achieve nearly global optimal resource allocation and has a superior performance over the existing resource allocation scheme.

2 System Model and Problem Formulation

In Fig. 1, we consider a multicarrier DF relay system which contains a source node, a relay node, a legitimate destination node and a eavesdropper node. The relay node harvests energy from the source node [4,11]. The direct links between the source node and the two receivers are unavailable [11]. The reliable communication from source to destination is established by EH relay. At the eavesdropper node, it attempts to eavesdrop the signals which are transmitted from the EH relay to the destination [11].

In the network, we assume that the relay operates in time-division half-duplex mode. There is no inner energy supply at the relay node. So it will gather energy from the source node. In this paper, we adopt the time-switching protocol for

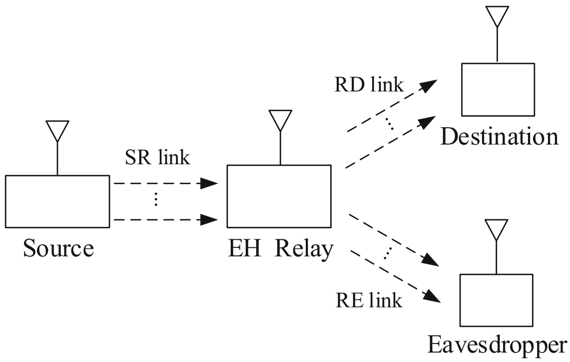

Fig. 1. The system model of multicarrier secure communications in the DF relay.

WIET. Each transmission block of time T is split into three parts with TS ratios. We denote them as α_1, α_2, and α_3, where $\alpha_1+\alpha_2+\alpha_3=1$. To be specific, $\alpha_1 T$, $\alpha_2 T$ and $\alpha_3 T$ are the continuance of the 1st phase, 2nd phase and the 3rd phase, respectively.

In this paper, the entire bandwidth is equally split into N orthogonal sub-channels. On the nth ($n \in \mathcal{N} = \{1, 2, \cdots, N\}$) sub-channel, we denote h_n^{SR}, h_n^{RD} and h_n^{RE} as the responses between SR link, RD link and the RE link, respectively. We assume that both the source node and the relay node can obtain the instantaneous channel state information of the entire system [11].

In the 1st phase, the relay harvests energy from the source node. It can be written as [4]

$$E = \alpha_1 T \tau \sum_{n=1}^{N} p_n^{S,1} \left|h_n^{SR}\right|^2 \tag{1}$$

where $p_n^{S,1}$ and τ denote the power transmitted from the source node on nth sub-channel for wireless energy transfer and energy conversion efficiency factor ($0 < \tau < 1$), respectively. For maximizing harvested energy at the EH relay node, transmitting power of the source node will be allocated to the sub-channel with the best channel gain [11]. Hence, (1) can be rewritten as $E = \alpha_1 T G$, where

$$G = \tau P_{stot} \left|h_k^{SR}\right|^2, \tag{2}$$

P_{stot} meams the maximum transmission power at the source node for WIET, and h_k^{SR} means kth sub-channel has best channel gain. In the 2nd phase, the source node transfers message to the relay node on all sub-channels. As in [4], at the relay node, it will decode the signals transmitted from the source node. Then, it will forward the decoded signals to the destination after reallocating them on sub-channels. Accordingly, the achievable secrecy rate is given by

$$R = \{\min[\sum_{n=1}^{N} \alpha_2 \log_2\left(1 + p_n^{S,2}\gamma_n^{SR}\right), \sum_{n=1}^{N} \alpha_3 \log_2\left(1 + p_n^{R}\gamma_n^{RD}\right)] - R^{'}\}^{+} \tag{3}$$

where $R^{'} = \sum_{n=1}^{N} \alpha_3 \log_2\left(1 + p_n^R \gamma_n^{RE}\right)$, $\{x\}^+$ denotes $\max\{x, 0\}$ for a real scaler x and $p_n^{S,2}$, p_n^R, $n \in \mathcal{N}$, denote the transmit power of source and relay over nth subcarrier for information transmission, respectively, $\gamma_n^{SR} = \frac{\left|h_n^{SR}\right|^2}{\sigma_R^2}$, $\gamma_n^{RD} = \frac{\left|h_n^{RD}\right|^2}{\sigma_D^2}$, and $\gamma_n^{RE} = \frac{\left|h_n^{RE}\right|^2}{\sigma_E^2}$. Here, σ_R^2, σ_D^2 and σ_E^2 denote the variances of additive Gaussian noises over each subcarrier at relay, legitimate destination and the eavesdropper, respectively. It is noted that in (3), it is assumed that the DF relay is only responsible for symbol-by-symbol decoding and forwarding as in [6]. The source rather than the relay encodes the secrete information into symbols. In the 3rd phase, the consumed energy for information transmission at relay should be less than or equal to the harvested energy in the first time slot, so it should satisfy,

$$\alpha_3 T \sum_{n=1}^{N} p_n^R \leq E. \tag{4}$$

In this paper, our objective is to maximize the achievable secrecy rate of the DF relay network subject to the power constraint at source and the EH constraint at relay. The optimization problem is formulated as

$$\max_{\{\alpha_1,\alpha_2,\alpha_3,p_n^{S,2}\geq 0,p_n^R\geq 0,n\in\mathcal{N}\}} \quad R \tag{5a}$$

$$\text{s.t.} \quad \sum_{n=1}^{N} p_n^{S,2} \leq P_{stot},\ \alpha_3 T \sum_{n=1}^{N} p_n^R \leq \alpha_1 T G, \tag{5b}$$

$$0 \leq \alpha_i \leq 1, i \in \{1,2,3\},\ \alpha_1 + \alpha_2 + \alpha_3 = 1. \tag{5c}$$

3 The Proposed Jiont TS and PA Scheme

The problem (5) is non-convex because the objective function and EH constraint at relay are both non-convex. In the following, we will make it tractable by decoupling the non-convex optimization problem into two subproblems.

It is noted that if $\gamma_n^{RD} \leq \gamma_n^{RE}$, we have $\min\left\{p_n^{S,2}\gamma_n^{SR}, p_n^R\gamma_n^{RD}\right\} \leq p_n^R\gamma_n^{RE}$. In this case, in order to achieve more achievable secrecy rate, we should not allocate any transmit power over the nth subcarrier. Let Ω be

$$\Omega = \left\{n | \gamma_n^{RD} > \gamma_n^{RE}, n \in \mathcal{N}\right\}. \tag{6}$$

The problem is recasted as follows

$$\max_{\{\alpha_1,\alpha_2,\alpha_3,p_n^{S,2}\geq 0,p_n^R\geq 0,n\in\Omega\}} \quad \hat{R} \tag{7a}$$

$$\text{s.t.} \quad \sum_{n\in\Omega} p_n^{S,2} \leq P_{stot},\ \alpha_3 T \sum_{n\in\Omega} p_n^R \leq \alpha_1 T G, \tag{7b}$$

$$0 \leq \alpha_i \leq 1, i \in \{1,2,3\},\ \alpha_1 + \alpha_2 + \alpha_3 = 1 \tag{7c}$$

where

$$\hat{R} = \left\{ \min\left[\sum_{n\in\Omega} \alpha_2 \log_2\left(1+p_n^{S,2}\gamma_n^{SR}\right), \sum_{n\in\Omega} \alpha_3 \log_2\left(1+p_n^{R}\gamma_n^{RD}\right) \right] - \sum_{n\in\Omega} \alpha_3 \log_2\left(1+p_n^{R}\gamma_n^{RE}\right) \right\}^+ . \tag{8}$$

Proposition 1. *The optimal solution* $\left(\alpha_1,\alpha_2,\alpha_3,p_n^{S,2},p_n^R\right)$, $n\in\Omega$, *to problem* (7) *should satisfy*

$$\sum_{n\in\Omega} \alpha_2 \log_2\left(1+p_n^{S,2}\gamma_n^{SR}\right) = \sum_{n\in\Omega} \alpha_3 \log_2\left(1+p_n^{R}\gamma_n^{RD}\right). \tag{9}$$

Proof. By using reduction to absurdity, we will demonstrate Proposition 1. Let the optimum solutions $\left(\alpha_1,\alpha_2,\alpha_3,p_n^{S,2},p_n^R\right)$ meet $\sum_{n\in\Omega} \alpha_2 \log_2\left(1+p_n^{S,2}\gamma_n^{SR}\right) \geq \sum_{n\in\Omega} \alpha_3 \log_2\left(1+p_n^{R}\gamma_n^{RD}\right)$. Thus, the achievable secrecy rate of DF relay networks is

$$\hat{R} = \sum_{n\in\Omega} \alpha_3 \log_2\left(\frac{1+p_n^R\gamma_n^{RD}}{1+p_n^R\gamma_n^{RE}}\right). \tag{10}$$

By decreasing α_2 and increasing α_1, α_3, which satisfies $\alpha_3 T\sum_{n\in\Omega} p_n^R \leq \alpha_1 TG$, the achievable secrecy rate of the networks $\hat{R}$ in (10) will increase. Consequently, it will contradict the previous setting that $\left(\alpha_1,\alpha_2,\alpha_3,p_n^{S,2},p_n^R\right)$ are the optimum solutions.

For another, let the optimum solutions $\left(\alpha_1,\alpha_2,\alpha_3,p_n^{S,2},p_n^R\right)$ meet inequality $\sum_{n\in\Omega} \alpha_2 \log_2\left(1+p_n^{S,2}\gamma_n^{SR}\right) \leq \sum_{n\in\Omega} \alpha_3 \log_2\left(1+p_n^{R}\gamma_n^{RD}\right)$. Thus, the achievable secrecy rate of DF relay networks is

$$\hat{R} = \sum_{n\in\Omega} \alpha_2 \log_2\left(1+p_n^{S,2}\gamma_n^{SR}\right) - \sum_{n\in\Omega} \alpha_3 \log_2\left(1+p_n^{R}\gamma_n^{RE}\right). \tag{11}$$

Based on inequality $\alpha_3 T\sum_{n\in\Omega} p_n^R \leq \alpha_1 TG$, by decreasing p_n^R, and holding α_3 constant, α_1 will decrease, too. With $\alpha_1+\alpha_2+\alpha_3=1$, α_2 will increase. So, the achievable secrecy rate of the networks $\hat{R}$ in (11) will increase, too. Consequently, it will contradict the previous setting that $\left(\alpha_1,\alpha_2,\alpha_3,p_n^{S,2},p_n^R\right)$ are the optimum solutions. □

From Proposition 1, the optimal α_2 and α_3 satisfy $\alpha_2=\lambda\alpha_3$, where

$$\lambda = \frac{\sum_{n\in\Omega} \log_2\left(1+p_n^R\gamma_n^{RD}\right)}{\sum_{n\in\Omega} \log_2\left(1+p_n^{S,2}\gamma_n^{SR}\right)}. \tag{12}$$

Furthermore, according to the EH constraint at relay $\alpha_3 T\sum_{n\in\Omega} p_n^R \leq \alpha_1 TG$ and $\alpha_1+\alpha_2+\alpha_3=1$, we obtain

$$\alpha_3 \leq \frac{G}{(1+\lambda)G+\sum_{n\in\Omega} p_n^R}. \tag{13}$$

According to Proposition 1, we equivalently transform the problem (7) into

$$\max_{\{\alpha_3, p_n^{S,2} \geq 0, p_n^R \geq 0, n \in \Omega\}} \quad \hat{R} = \sum_{n \in \Omega} \alpha_3 \log_2 \left(\frac{1 + p_n^R \gamma_n^{RD}}{1 + p_n^R \gamma_n^{RE}} \right) \tag{14a}$$

$$\text{s.t.} \quad \sum_{n \in \Omega} p_n^{S,2} \leq P_{stot}, (13), 0 \leq \alpha_3 \leq 1. \tag{14b}$$

From (14a), we can observe that achievable secrecy rate $\hat{R}$ increases with the increase of α_3. So, for the sake of getting the maximum, α_3 is

$$\alpha_3 = \frac{G}{(1+\lambda)\, G + \sum_{n \in \Omega} p_n^R}. \tag{15}$$

Substituting (12) and (15) into the objective function (14a), the optimization problem becomes

$$\max_{\{p_n^{S,2} \geq 0, p_n^R \geq 0, n \in \Omega\}} \frac{G \sum_{n \in \Omega} \log_2 \left(\frac{1 + p_n^R \gamma_n^{RD}}{1 + p_n^R \gamma_n^{RE}} \right)}{\left[1 + \frac{\sum_{n \in \Omega} \log_2 \left(1 + p_n^R \gamma_n^{RD}\right)}{\sum_{n \in \Omega} \log_2 \left(1 + p_n^{S,2} \gamma_n^{SR}\right)} \right] G + \sum_{n \in \Omega} p_n^R} \ \text{s.t.} \sum_{n \in \Omega} p_n^{S,2} \leq P_{stot}. \tag{16}$$

In order to solve the problem (16), we decompose this non-convex problem into two problems, i.e.,

$$\max_{\{p_n^{S,2} \geq 0, n \in \Omega\}} \sum_{n \in \Omega} \log_2 \left(1 + p_n^{S,2} \gamma_n^{SR}\right) \quad \text{s.t.} \quad \sum_{n \in \Omega} p_n^{S,2} \leq P_{stot} \tag{17}$$

and

$$\max_{\{p_n^R, n \in \Omega\}} \frac{G \sum_{n \in \Omega} \log_2 \left(\frac{1 + p_n^R \gamma_n^{RD}}{1 + p_n^R \gamma_n^{RE}} \right)}{\left[1 + \frac{\sum_{n \in \Omega} \log_2 \left(1 + p_n^R \gamma_n^{RD}\right)}{t^o} \right] G + \sum_{n \in \Omega} p_n^R} \quad \text{s.t.} \quad p_n^R \geq 0, n \in \Omega \tag{18}$$

where t^o denotes the optimal objective value of problem (17). For optimization problem (17), we can know that it is convex from [4,12]. And we express its closed-form solution as

$$p_n^{S,2} = \left(1/\nu - 1/\gamma_n^{SR}\right)^+, n \in \Omega \tag{19}$$

where ν is the lagrange multiplier introduced by $\sum_{n \in \Omega} p_n^{S,2} \leq P_{stot}$.

It is noted that the numerator of objective function (18) is concave respect to p_n^R and the denominator is neither convex nor concave respect to p_n^R. To our best of knowledge, the problem (18) has no globally optimal solution currently. Therefore, we develop a constrained concave convex procedure (CCCP) [9] based iterative algorithm to achieve the local optimum of the problem (18). Let

$$f\left(\mathbf{p^R}\right) = \sum_{n \in \Omega} \log_2 \left(1 + p_n^R \gamma_n^{RD}\right) \tag{20}$$

where $\mathbf{p^R} = \left(p_1^R, p_2^R \ldots, p_n^R\right), n \in \Omega$. The first-order Taylor expansion of (20) around $\tilde{\mathbf{p}}^{\mathbf{R}}$ is computed as [8]

$$\hat{f}\left(\mathbf{p^R}, \tilde{\mathbf{p}}^{\mathbf{R}}\right) = f\left(\tilde{\mathbf{p}}^{\mathbf{R}}\right) + \triangledown f\left(\tilde{\mathbf{p}}^{\mathbf{R}}\right)\left(\mathbf{p^R} - \tilde{\mathbf{p}}^{\mathbf{R}}\right) \tag{21}$$

where $\tilde{\mathbf{p}}^{\mathbf{R}} = \left(\tilde{p}_1^R, \tilde{p}_2^R \ldots, \tilde{p}_n^R\right), n \in \Omega$, and

$$\triangledown f\left(\tilde{\mathbf{p}}^{\mathbf{R}}\right) = \left(\frac{1}{\ln 2}\frac{\gamma_1^{RD}}{1+\tilde{p}_1^R\gamma_1^{RD}}, \frac{1}{\ln 2}\frac{\gamma_2^{RD}}{1+\tilde{p}_2^R\gamma_2^{RD}}, \ldots, \frac{1}{\ln 2}\frac{\gamma_n^{RD}}{1+\tilde{p}_n^R\gamma_n^{RD}}\right), n \in \Omega. \tag{22}$$

In the $(i+1)$th iteration of the proposed CCCP based iterative algorithm [10], we solve the following quasi-convex optimization problem

$$\max_{\{p_n^R, n\in\Omega\}} \quad \frac{G\sum_{n\in\Omega}\log_2\left(\frac{1+p_n^R\gamma_n^{RD}}{1+p_n^R\gamma_n^{RE}}\right)}{G + \frac{G}{t^o}\hat{f}\left(\mathbf{p^R}, \tilde{\mathbf{p}}^{\mathbf{R}(i)}\right) + \sum_{n\in\Omega} p_n^R} \quad \text{s.t.} \quad p_n^R \geq 0, n \in \Omega \tag{23}$$

where $\tilde{\mathbf{p}}^{\mathbf{R}^{(i)}}$ denotes the solution to the problem (23) at the ith iteration. Inversing the objective function of problem (23) and introducing a slack variable μ, the problem (23) is equivalently rewritten as

$$\min_{\{\mu\geq 0, p_n^R\geq 0, n\in\Omega\}} \mu \tag{24a}$$

$$\text{s.t.} \quad G + \frac{G}{t^o}\hat{f}\left(\mathbf{p^R}, \tilde{\mathbf{p}}^{\mathbf{R}^{(i)}}\right) + \sum_{n\in\Omega} p_n^R - \mu\left[G\sum_{n\in\Omega}\log_2\left(\frac{1+p_n^R\gamma_n^{RD}}{1+p_n^R\gamma_n^{RE}}\right)\right] \leq 0 \tag{24b}$$

then solve it by following Algorithm 1.

Algorithm 1 The Proposed CCCP Based Iterative Algorithm Using Bisection Search to Solve Problem (18)

1: **Initialization**: $\mu_L = 0$, $\mu_U = \mathrm{u}$, where u is large enough to problem (24), tolerance $\epsilon > 0$, $k = 0$;
2: **Repeat:** $\mu^{(k)} = \frac{1}{2}(\mu_L + \mu_U)$, and substitute $\mu^{(k)}$ into the subproblem (25);
3: **Initialization**: $i = 0$, $\tilde{\mathbf{p}}^{\mathbf{R}(0)}$;
4: **Repeat:** Solve subproblem (25):

$$\min_{\{p_n^R, n\in\Omega\}} G + \frac{G}{t^o}\hat{f}\left(\mathbf{p^R}, \tilde{\mathbf{p}}^{\mathbf{R}(i)}\right) + \sum_{n\in\Omega} p_n^R - \mu^{(k)}\left[G\sum_{n\in\Omega}\log_2\left(\frac{1+p_n^R\gamma_n^{RD}}{1+p_n^R\gamma_n^{RE}}\right)\right] \tag{25a}$$

$$\text{s.t.} \quad p_n^R \geq 0, n \in \Omega; \tag{25b}$$

5: $i = i + 1$, and update $\tilde{\mathbf{p}}^{\mathbf{R}(i)} = \mathbf{p}^{\mathbf{R}*}$, where $\mathbf{p}^{\mathbf{R}*}$ is the optimal solution of (25);
6: **Until:** Convergence;
7: **If** $U^* < 0$, where U^* is the optimal value of (25)
8: $\mu_U = \mu^{(k)}$;
9: **Else**
10: $\mu_L = \mu^{(k)}$;
11: **End**
12: $k = k + 1$;
13: **Until:** $\mu_U - \mu_L < \epsilon$.

4 Simulation Results

In this paper, we assume that the entire bandwidth is equally split into $N = 16$ sub-channels. On the nth ($n \in \mathcal{N} = \{1, 2, \cdots, N\}$) sub-channel, all the channel responses h_n^{SR}, h_n^{RD} and h_n^{RE} are independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean [4,11]. Their variances are d_{SR}^{-2}, d_{RD}^{-2} and d_{RE}^{-2}, respectively, through the use of a path loss model. d_{SR} means the distance between the source node and the relay node. d_{RD} means the distance between the relay node and the legitimate destination node and its value is 20 m. d_{RE} means the distance between the relay node and the eavesdropper node and its value is also 20m. To be specific, we make the following settings, $d_{SR} = \eta d_{RD}$ ($\eta = d_{SR}/d_{RD}$), $\sigma_R^2 = \sigma_D^2 = \sigma_E^2 = \sigma^2/N = 0.001$ mW, and $\tau = 0.9$.

In Fig. 2, we show the achievable secrecy rate comparison of our proposed joint time switching and power allocation scheme (denoted as "Proposed Joint TS and PA" in the legend), the scheme with two-dimensional search (denoted as "Two-Dimensional Search"), which can get the optimal solution of the original optimization problem with very high complexity, and the scheme with $\alpha_1 = \alpha_2 = \alpha_3 = 1/3$ and equal power allocation (denoted as "Equal TS and PA") versus η ($\eta = 10^{-1}$ to $\eta = 10^{1}$) with P_{stot} =100 mW. From the result of Fig. 2, we can see that the scheme proposed in this paper has a superior performance over the scheme with equal time switching factors and power allocation. We can also find that our proposed scheme is very close to the scheme with two-dimensional

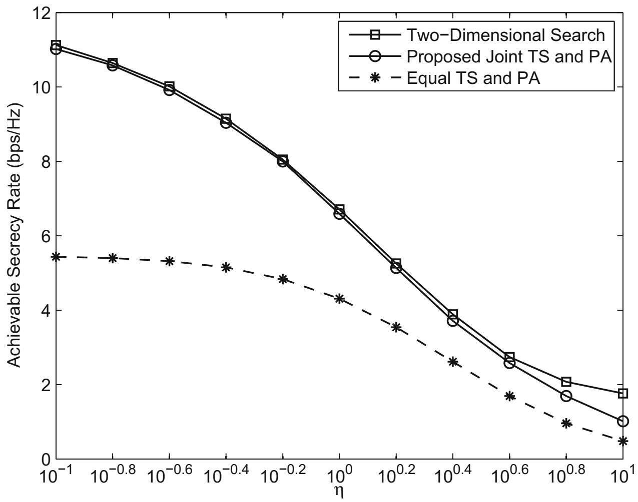

Fig. 2. Achievable secrecy rate versus η; performance comparison of our proposed joint time switching and power allocation scheme, the scheme with two-dimensional search and the scheme with equal time switching factors and power allocation for DF relay network where P_{stot} =100 mW and σ^2 =0.001 mW.

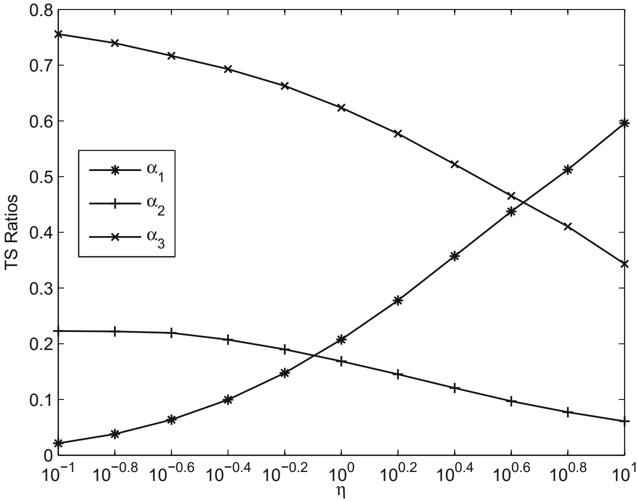

Fig. 3. Time switching factors versus η; obtained by our proposed joint time switching and power allocation scheme for the DF relay network where P_{stot} =100 mW and σ^2 =0.001 mW.

search when the distance between the SR and RD links is not large ($\eta < 10^{0.4}$). However, with the larger η, the our proposed scheme performs worse.

In Fig. 3, we show the time switching factors, i.e., α_1, α_2 and α_3 versus η ($\eta = 10^{-1}$ to $\eta = 10^1$). And they can be found by using the scheme proposed in this paper. From Fig. 3, it is found that both α_2 and α_3 decrease as η increases. On the contrary, α_1 increases with η. This is because in order to achieve more achievable secrecy rate, α_1 should be larger as η increases. Besides, the sum of α_1, α_2 and α_3 is 1.

5 Conclusions

In this paper, considering the DF scheme, we study the joint TS and PA for multicarrier secure communication with an energy harvesting relay. Simulation results have shown that our proposed joint TS and PA scheme achieves nearly global optimal resource allocation and has a superior performance over the existing resource allocation scheme.

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