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Dynamic Asymmetric Power Splitting Scheme for SWIPT Based Two-Way Multiplicative AF Relaying

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***Abstract*—Power splitting (PS) scheme design is one of the most important challenges in simultaneous wireless information and power transfer (SWIPT) based two-way multiplicative amplify-and-forward (AF) relay networks. In this letter, we propose a novel dynamic asymmetric PS (DAPS) scheme to minimize the system outage probability by exploiting the asymmetric instantaneous channel gains between the relay node and the destination nodes. As the formulated optimization problem is a non-convex problem and difficult to solve, we reformulate it as a fractional programming problem and propose a Dinkelbach-based iterative algorithm to obtain the optimal asymmetric PS ratios. Both the analytical and simulation results demonstrate that the proposed DAPS scheme with the same channel state information overhead can significantly reduce the system outage probability as compared with the existing static symmetric PS scheme.**

***Index Terms*—Dynamic asymmetric power splitting (DAPS), simultaneous wireless information and power transfer, two-way multiplicative amplify-and-forward relay, Dinkelbach-based iterative algorithm.**

I. Introduction

Simultaneous wireless information and power transfer (SWIPT) is an appealing solution to prolong the lifetime of energy-limited networks, e.g., nonorthogonal multiple access networks [1], heterogeneous networks [2], cognitive radio networks [3], two-way relay networks (TWRNs) [4], via decoding information and extracting power from radio frequency (RF) signals [5], [6]. Of particular interest is the combination of SWIPT and TWRNs.

To date, several studies on amplify-and-forward TWRNs (AF-TWRNs) with SWIPT have been reported [4], [7]–[11]. Chen *et al.* [4] and Shah *et al.* [7] investigated the power splitting (PS) and time switching (TS) schemes for two-step AF-TWRNs, respectively, and derived analytical expressions for the outage probability and throughput. In [8], a jointly optimized power allocation and relay selection scheme was proposed to minimize the outage probability. The authors designed an optimal PS scheme to maximize the energy efficiency in [9].

Since the circuitry design of three-step TWRNs is simpler than that of two-step TWRNs [10], increasing attention has been paid to three-step TWRNs with SWIPT. For three-step additive TWRNs with TS SWIPT, the authors in [11] designed three wireless power transfer policies and analyzed the corresponding performance. For three-step additive TWRNs with PS SWIPT, the outage probability and system throughput were derived in [10].

More recently, it was found that three-step multiplicative TWRNs are superior to three-step additive TWRNs in outage performance [12]. Shah *et al.* introduced a static symmetric PS (SSPS) scheme[1] for two-way multiplicative AF relay networks, where it was shown that the SSPS ratio depicts a trade-off between energy harvesting (EH) and information processing, and determines the system outage performance. Note that although in [13] the instantaneous CSI is required at the relay to dynamically adjust the power amplification gain[2], it is not used to determine the PS ratio. Moreover, the three-step multiplicative TWRNs are asymmetric due to the asymmetric instantaneous channel gains between the relay node and the destination nodes. Accordingly, a properly designed asymmetric PS scheme should be able to offer superior outage performance instead of the symmetric PS scheme.

In this letter, we propose a *dynamic asymmetric* PS (DAPS) scheme[3], which splits the received signal with adjustable PS ratio based on instantaneous CSI to minimize the system outage probability. As part of the DAPS scheme, we propose a Dinkelbach-based iterative algorithm to optimize the asymmetric PS ratios.

The main contributions are summarized as follows.

- We propose a novel DAPS scheme, where the asymmetric PS ratios between energy harvesting and information processing can be adaptively adjusted to minimize the system outage probability by exploiting the asymmetric instantaneous channel gains between the relay node and the destination nodes. Compared with the SSPS scheme,

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[1]The SSPS scheme does not dynamically adjust itself according to the instantaneous CSI between the relay and destination nodes, and the PS ratio ρ_A equals ρ_B.

[2]In other words, the variable-gain amplify-and-forward technology is employed at relay.

[3]Note that the proposed DAPS scheme can also be employed to other asymmetric three-step TWRNs with SWIPT, e.g, PS based three-step TWRNs with asymmetric traffic requirements [14], but this is beyond the scope of this paper.

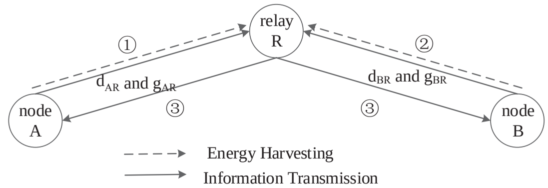

Fig. 1. System model of the three-step multiplicative AF-TWRN with SWIPT

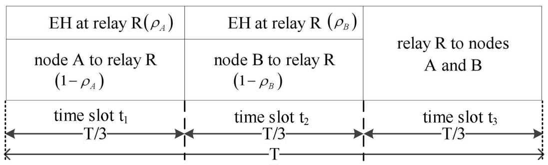

Fig. 2. Transmission time-block structure for the proposed DAPS scheme

the proposed DAPS scheme is more flexible, while no extra instantaneous CSI is required at the relay.

- We formulate an optimization problem to minimize the system outage probability by optimizing the asymmetric PS ratios, while guaranteeing that both destination nodes decode the information at the same time. As this optimization problem is difficult to solve, we reformulate it into a fractional programming problem and propose a Dinkelbach-based iterative algorithm to obtain the optimal solutions. Although the denominator of the fractional function to be maximized is non-convex, leading to the non-convexity of the subtraction function in each iteration, we obtain the closed-form solution for the subtraction function in each iteration, which greatly reduces the complexity of the proposed algorithm as compared with exhaustive search.

II. System model and Working Flow

We consider a three-step multiplicative AF-TWRN with SWIPT [13], as shown in Fig. 1. Two destination nodes *A* and *B* exchange information via an EH multiplicative AF relay node *R*. There is no direct link between *A* and *B*. The path loss model is given by $d_{iR}^{-\alpha}$ ($i = A$ or B), where d_{iR} is the i-R distance and α is the path loss exponent. Each link sees independent with frequency nonselective Rayleigh block fading. The complex channel coefficient between i and R is denoted by g_{iR}, with reciprocal transmitter and receiver. We assume that instantaneous CSI is only available at the relay through advanced channel estimation [15].

In the proposed DAPS scheme, the transmission time block structure for completing energy harvesting and information exchange is illustrated in Fig. 2 (T is the total transmission time block.). For analytical simplicity, we neglect the processing energy needed by the transmit/receive circuitry at the EH multiplicative AF relay [1], [10], [13].

At the first and the second time slot, *A* and *B* transmit their signal $x_A(t)$ and $x_B(t)$ to *R*, respectively. The received signal at *R* from node i ($i = A$ or B) can be expressed as

$$y_{iR}(t) = h_{iR}\sqrt{P_i}x_i(t) + w_i(t), \tag{1}$$

where $h_{iR} = \frac{g_{iR}}{\sqrt{d_{iR}^{\alpha}}}$ and $|h_{iR}|^2$ is the channel power gain; $x_i(t)$ denotes the normalized signal from i; P_i denotes the power of i, and $w_i(t)$ is the additive white Gaussian noise (AWGN) at i.

After receiving the signal transmitted from i, R splits it into two streams: $\sqrt{\rho_i}\left(h_{iR}\sqrt{P_i}x_i(t)+w_i(t)\right)$ and $\sqrt{1-\rho_i}\left(h_{iR}\sqrt{P_i}x_i(t)+w_i(t)\right)$ for energy harvesting and information processing, respectively, where ρ_i is the PS ratio. For example, $\rho_i = 1$ corresponds to fully energy harvesting. Thus, the total harvested energy at R is calculated as

$$E_{total} = \eta\frac{T}{3}\left(\rho_i P_i|h_{iR}|^2 + \rho_{\bar{i}}P_{\bar{i}}|h_{\bar{i}R}|^2\right), \tag{2}$$

where $\bar{i}$ denotes the index of the other destination node[4] and η is the energy conversion efficiency[5].

At the third slot, R multiplies the two received signals together, and broadcasts the multiplied signal to both *A* and *B* using the harvested energy E_{total}. The multiplied signal after amplification is written as

$$y_R = \sqrt{\frac{P_R}{\xi}}\left[h_{iR}\sqrt{(1-\rho_i)P_i}x_i + N_i\right]\left[h_{\bar{i}R}\sqrt{(1-\rho_{\bar{i}})P_{\bar{i}}}x_{\bar{i}} + N_{\bar{i}}\right], \tag{3}$$

where $P_R = \frac{E_{total}}{T/3}$ denotes the power of the EH relay node; $\frac{1}{\sqrt{\xi}} = \frac{1}{\sqrt{((1-\rho_i)|h_{iR}|^2P_i+\sigma_i^2)((1-\rho_{\bar{i}})|h_{\bar{i}R}|^2P_{\bar{i}}+\sigma_{\bar{i}}^2)}}$ is the power normalization factor; N_i with the variance σ_i^2 is the mixed AWGN, composed of the AWGN from both receiving antenna and RF-to-baseband conversion.

After receiving the amplified multiplicative signal $y_{R\ to\ i}$ from relay, the destination node performs a signal preprocessing before decoding signals, that is

$$y_i = x_i^* y_{R\ to\ i} = x_i^*(h_{iR}y_R + \hat{N}_i), \tag{4}$$

where $x_i^* = \frac{1}{x_i}$, and $\hat{N}_i$ with the variance $\hat{\sigma}_i^2$ is the mixed AWGN, composed of the AWGN from both receiving antenna and RF-to-baseband conversion.

Thus, the received signal y_i can be rewritten as

$$\begin{aligned} y_i =& \sqrt{\frac{P_R}{\xi}}\sqrt{(1-\rho_i)P_i}\sqrt{(1-\rho_{\bar{i}})P_{\bar{i}}}|h_{iR}|^2 h_{\bar{i}R}x_{\bar{i}} + x_i^*\hat{N}_i \\ &+ \sqrt{\frac{P_R}{\xi}}h_{iR}x_i^*N_iN_{\bar{i}} + \sqrt{\frac{(1-\rho_{\bar{i}})P_{\bar{i}}P_R}{\xi}}h_{iR}h_{\bar{i}R}x_i^*x_{\bar{i}}N_i \\ &+ \sqrt{\frac{(1-\rho_i)P_iP_R}{\xi}}|h_{iR}|^2N_{\bar{i}}. \end{aligned} \tag{5}$$

From (5), the end-to-end signal-to-noise ratio (SNR) of the link $\bar{i}\xrightarrow{R}i$ is given as

$$\gamma_i = \frac{j}{k+l+m+n}, \tag{6}$$

[4]If $i = A$, $\bar{i} = B$; if $i = B$, $\bar{i} = A$.

[5]In this work, since our main focus is on the novel DAPS scheme design, for analytical tractability, we consider the linear EH model [4], [7]–[11], [16]. In addition, the non-linear EH models [17], [18] can be decomposed into piecewise linear EH models, where each segment of the EH model is linear and results obtained based on linear EH models can be applied to each segment [18].

where

$$j = \eta P_S^3(\rho_i|h_{iR}|^2 + \rho_{\bar{i}}|h_{\bar{i}R}|^2)|h_{iR}|^4|h_{\bar{i}R}|^2(1-\rho_i)(1-\rho_{\bar{i}}),$$
$$k = \eta P_S^2(1-\rho_i)(\rho_i|h_{iR}|^2 + \rho_{\bar{i}}|h_{\bar{i}R}|^2)|h_{iR}|^4\sigma_{\bar{i}}^2,$$
$$l = \eta P_S^2(1-\rho_{\bar{i}})(\rho_i|h_{iR}|^2 + \rho_{\bar{i}}|h_{\bar{i}R}|^2)|h_{iR}|^2|h_{\bar{i}R}|^2\sigma_i^2,$$
$$m = \eta P_S(\rho_i|h_{iR}|^2 + \rho_{\bar{i}}|h_{\bar{i}R}|^2)|h_{iR}|^2\sigma_i^2\sigma_{\bar{i}}^2,$$
$$n = ((1-\rho_i)P_S|h_{iR}|^2 + \sigma_i^2)((1-\rho_{\bar{i}})P_S|h_{\bar{i}R}|^2 + \sigma_{\bar{i}}^2)\hat{\sigma}_i^2,$$
$$P_S = P_A = P_B.$$

III. Optimal DAPS Scheme Design

In this section, we first formulate an optimization problem to minimize the system outage probability by optimizing the asymmetric PS ratios. Then the optimization problem is reformulated as a fractional programming problem and a Dinkelbach-based iterative algorithm is proposed to obtain the optimal asymmetric PS ratios.

A. Optimization Problem Formulation

For a given target rate U, the system outage probability is defined as

$$P_{out} = \mathrm{Prob}\{(\gamma_{\mathrm{A}} < \gamma_{\mathrm{th}}) \cup (\gamma_{\mathrm{B}} < \gamma_{\mathrm{th}})\}, \tag{7}$$

where $\gamma_{th} = 2^U - 1$ [10], and γ_A and γ_B are detailed in (6).

It can be seen that P_{out} is limited by the weaker data stream with the lower end-to-end SNR in a two-way multiplicative AF relay network. Thus, we formulate the optimization problem as

$$\begin{aligned} &(\mathrm{P1}): && \max_{\rho_A,\rho_B} \min\{\gamma_A,\gamma_B\} \\ &\text{subject to} && 0 \le \rho_A, \rho_B \le 1. \end{aligned} \tag{8}$$

Proposition: (P1) is equivalent to (P2), given below[6]

$$(\mathrm{P2}): \quad \max_{\rho_A,\rho_B} \gamma_i \tag{9}$$

where for an arbitrary pair of (ρ_A, ρ_B)

$$\gamma_i = \begin{cases} \gamma_A, & \text{if } \gamma_A < \gamma_B \\ \gamma_B, & \text{if } \gamma_A \ge \gamma_B \end{cases}. \tag{10}$$

The proof is given in the Appendix. ■

B. Dinkelbach-based Iterative Algorithm

If γ_i is determined, then (P2) is a fractional programming problem. Thus, we can develop a Dinkelbach-based iterative algorithm to solve this problem, shown in Algorithm 1.

In Algorithm 1, q_i^*, s, $q_i^{(s)}$ and δ denote the maximum SNR, the iteration index, the γ_i at the s-th iteration, and the iteration termination condition, respectively.

In step 5 of Algorithm 1, $\tilde{\rho}_A^{(s)}$ and $\tilde{\rho}_B^{(s)}$ can be obtained by maximizing $G(q_i^{(s-1)}, \rho_A^{(s)}, \rho_B^{(s)})$, which is given by

$$\begin{aligned} G(q_i^{(s-1)}, \rho_A^{(s)}, \rho_B^{(s)}) = {} & m_1\rho_i + m_2\rho_{\bar{i}} + m_3\rho_i^2 + m_4\rho_i\rho_{\bar{i}} + m_5\rho_{\bar{i}}^2 \\ & + m_6\rho_i^2\rho_{\bar{i}} + m_7\rho_i\rho_{\bar{i}}^2 + m_8, \end{aligned} \tag{11}$$

[6]The feasible region of (P2) is as follows. The power splitting ratios ρ_A and ρ_B both take values in the range [0,1), but they cannot be 0 at the same time, otherwise both γ_A and γ_B equal zero and the achievable throughput is zero.

where

$$m_1 = r_1 + q_i^{(s-1)}\left(-r_3 - r_5 - r_7 + r_9 + r_{10}\right), m_6 = r_1,$$
$$m_2 = r_2 + q_i^{(s-1)}\left(-r_4 - r_6 - r_8 + r_9 + r_{11}\right), m_7 = r_2,$$
$$m_3 = -r_1 + q_i^{(s-1)}r_3, m_4 = -r_2 - r_1 + q_i^{(s-1)}\left(r_4 + r_5 - r_9\right),$$
$$m_5 = -r_2 + q_i^{(s-1)}r_6, m_8 = q_i^{(s-1)}\left(-r_9 - r_{10} - r_{11} - r_{12}\right).$$
$$r_1 = \eta P_S^3|h_{iR}|^6|h_{\bar{i}R}|^2, r_2 = \eta P_S^3|h_{iR}|^4|h_{\bar{i}R}|^4, r_3 = \eta P_S^2|h_{iR}|^6\sigma_{\bar{i}}^2,$$
$$r_4 = \eta P_S^2|h_{iR}|^4|h_{\bar{i}R}|^2\sigma_{\bar{i}}^2, r_5 = \eta P_S^2|h_{iR}|^4|h_{\bar{i}R}|^2\sigma_i^2,$$
$$r_6 = \eta P_S^2|h_{iR}|^2|h_{\bar{i}R}|^4\sigma_i^2, r_7 = \eta P_S|h_{iR}|^4\sigma_i^2\sigma_{\bar{i}}^2,$$
$$r_8 = \eta P_S|h_{iR}|^2|h_{\bar{i}R}|^2\sigma_i^2\sigma_{\bar{i}}^2, r_9 = P_S^2|h_{iR}|^2|h_{\bar{i}R}|^2\hat{\sigma}_i^2,$$
$$r_{10} = P_S|h_{iR}|^2\sigma_{\bar{i}}^2\hat{\sigma}_i^2, r_{11} = P_S|h_{\bar{i}R}|^2\sigma_i^2\hat{\sigma}_i^2, r_{12} = \sigma_i^2\sigma_{\bar{i}}^2\hat{\sigma}_i^2.$$

Algorithm 1 The Dinkelbach-based iterative algorithm

Input:
η, P_S and σ^2.
2: **Inputting**:
the instantaneous CSI, h_{AR} and h_{BR}.
3: **Initialization**:
the iteration index $s = 1$, $q_i^{(0)} = 0$.
4: **Optimization**:
5: for the given $q_i^{(s-1)}$, find $\tilde{\rho}_A^{(s)}$ and $\tilde{\rho}_B^{(s)}$ which maximize the subtraction function
$$F(q_i^{(s-1)}, \rho_A^{(s)}, \rho_B^{(s)}) = \max_{0 \le \rho_A^{(s)}, \rho_B^{(s)} \le 1} \{j - q_i^{(s-1)}(k+l+m+n)\};$$
6: obtain $\tilde{\rho}_A^{(s)}$ and $\tilde{\rho}_B^{(s)}$;
7: set $q_i^{(s)} = \tilde{j}/(\tilde{k} + \tilde{l} + \tilde{m} + \tilde{n})$, where $\tilde{j}$, $\tilde{k}$, $\tilde{l}$, $\tilde{m}$, $\tilde{n}$ are obtained by substituting $\tilde{\rho}_A^{(s)}$ and $\tilde{\rho}_B^{(s)}$ into j, k, l, m, n, respectively;
8: compare the value of $\left|F(q_i^{(s-1)}, \tilde{\rho}_A^{(s)}, \tilde{\rho}_B^{(s)})\right|$ with δ and set $s = s + 1$ if $\left|F(q_i^{(s-1)}, \tilde{\rho}_A^{(s)}, \tilde{\rho}_B^{(s)})\right| \ge \delta$;
9: repeat 5 to 8 until $\left|F(q_i^{(s-1)}, \tilde{\rho}_A^{(s)}, \tilde{\rho}_B^{(s)})\right| < \delta$;
10: obtain the optimal PS ratios $\vec{\rho}^* = \left(\tilde{\rho}_A^{(s)}, \tilde{\rho}_B^{(s)}\right)$, and the maximum SNR $q_i^* = q_i^{(s)}$.

According to the values of ρ_i and $\rho_{\bar{i}}$, (11) can be divided into three cases.

Case 1: If $\rho_i = 0$, then $G(q_i^{(s-1)}, \rho_A^{(s)}, \rho_B^{(s)}) = m_5\rho_{\bar{i}}^2 + m_2\rho_{\bar{i}} + m_8$, and the optimal $\rho_{\bar{i}}$ is given by $\rho_{\bar{i}} = -\frac{m_2}{2m_5}$.

Case 2: If $\rho_{\bar{i}} = 0$, then $G(q_i^{(s-1)}, \rho_A^{(s)}, \rho_B^{(s)}) = m_3\rho_i^2 + m_1\rho_i + m_8$, and the optimal ρ_i is given by $\rho_i = -\frac{m_1}{2m_3}$.

Case 3: If $\rho_i \ne 0$ and $\rho_{\bar{i}} \ne 0$, the partial derivatives of $G(q_i^{(s-1)}, \rho_A^{(s)}, \rho_B^{(s)})$ with respect to variables ρ_i and $\rho_{\bar{i}}$ can be separately obtained as

$$\begin{cases} m_1 + 2m_3\rho_i + m_4\rho_{\bar{i}} + 2m_6\rho_i\rho_{\bar{i}} + m_7\rho_{\bar{i}}^2 = 0 \\ m_2 + 2m_5\rho_{\bar{i}} + m_4\rho_i + 2m_7\rho_i\rho_{\bar{i}} + m_6\rho_i^2 = 0 \end{cases}. \tag{12}$$

Through some mathematical manipulation, (12) can be rewritten as the following quartic function

$$k_4\rho_{\bar{i}}^4 + k_3\rho_{\bar{i}}^3 + k_2\rho_{\bar{i}}^2 + k_1\rho_{\bar{i}}^1 + k_0 = 0, \tag{13}$$

where $k_4 = -3m_6m_7^2$, $k_3 = 8m_5m_6^2 - 4m_3m_7^2 - 4m_4m_6m_7$, $k_2 = 16m_3m_5m_6 - 6m_3m_4m_7 - 2m_1m_6m_7 + 4m_2m_6^2 - m_4^2m_6$, $k_1 = 8m_3^2m_5 - 4m_1m_3m_7 + 8m_2m_3m_6 - 2m_3m_4^2$, $k_0 = 4m_2m_3^2 - 2m_1m_3m_4 + m_1^2m_6$. Therefore, the

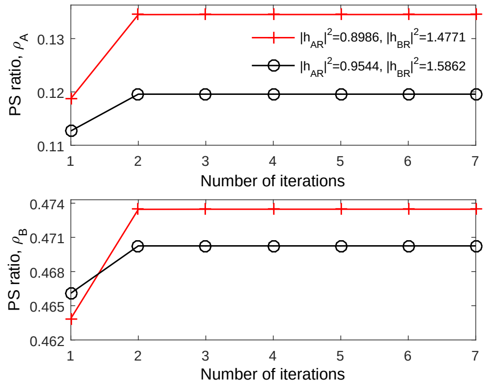

Fig. 3. PS ratios versus number of iterations with different channel gains

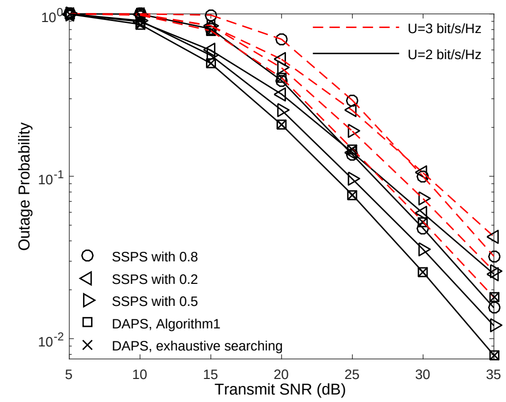

Fig. 4. Outage probability versus SNR for different U

closed-form real root(s) for quartic function (13) can be easily obtained [19].

For each of Cases 1-3, we have obtained closed-form expressions for ρ_i and $\rho_{\bar{i}}$. Among all the ρ_i and $\rho_{\bar{i}}$ obtained for the above three cases, the ρ_i and $\rho_{\bar{i}}$ that achieve the maximum value of $G(q^{s-1}, \rho_A^s, \rho_B^s)$ are selected as the optimal solution to the subtraction function[7], i.e., $\tilde{\rho}_A^{(s)}$ and $\tilde{\rho}_B^{(s)}$, respectively.

The convergence of the proposed algorithm can be proven following an approach similar to that in [20]: (i) We first prove that $F(q, \rho_A, \rho_B)$ is a strictly decreasing function in q. (ii) Based on (i) and the theorem that the maximum SNR q_i^* exists if and only if $\max\limits_{0\le\rho_A,\rho_B\le 1} \{j - q_i^*(k+l+m+n)\} = 0$ [21], we prove that as the number of iterations is large enough, q converges to the optimal q^*.

IV. Simulations

In this section, the proposed DAPS scheme is compared with the SSPS scheme [13] through simulation. The simulation parameters are set as follows: $d_{AR} = d_{BR} = 1$ m, $\alpha = 2.7$, $\eta = 1$, and $\delta = 10^{-1}$. We define $10\lg\frac{P_s}{\sigma^2}$ as the transmit SNR.

Fig. 3 plots the optimal PS ratios $\tilde{\rho}_A^{(s)}$ and $\tilde{\rho}_B^{(s)}$ versus the number of iterations for $U = 3$ bit/s/Hz. It can be seen that the proposed Dinkelbach-based iterative algorithm converges to the optimal asymmetric PS ratios after only two iterations. It also shows that the asymmetric instantaneous channel gains, $|h_{AR}|^2 < |h_{BR}|^2$, results in $\rho_A < \rho_B$. The reason is that the relay R can harvest more (or less) energy with a larger (or smaller) PS ratio from the destination node with a better (or worse) channel to R, which gives a trade-off between energy harvesting and information processing for the two destination nodes.

Fig. 4 compares the system outage probability of the SSPS scheme and the proposed DAPS scheme for different target rate U. We can see that the DAPS scheme is superior to the SSPS scheme in terms of outage performance, owing to the fact that the DAPS provides more flexibility and makes full use of the instantaneous CSI. Another observation is that the outage performance of DAPS with Algorithm 1 is almost the same as the DAPS scheme with the exhaustive searching method, indicating that Algorithm 1 obtains the optimal asymmetric PS ratios.

[7] If there exist more than one pair of ρ_i and $\rho_{\bar{i}}$ achieving the maximum value of $G(q^{s-1}, \rho_A^s, \rho_B^s)$, the pair of ρ_i and $\rho_{\bar{i}}$ with the smallest values are selected as the optimal solution to the subtraction function.

V. Conclusions

Considering the asymmetric instantaneous channel gains between the destination nodes and the relay, we have proposed a novel DAPS scheme with a Dinkelbach-based iterative algorithm to obtain the optimal asymmetric PS ratios. Simulations results have verified the quick convergence of the proposed iterative algorithm, and have shown the DAPS scheme achieves better outage performance with the same instantaneous CSI overhead by comparing the existing SSPS scheme.

Appendix

For ease of analysis, we ignore the antenna noise, and $\sigma_A^2 = \sigma_B^2 = \hat{\sigma}_A^2 = \hat{\sigma}_B^2 = \sigma^2$. Based on the feasible region of (P2), which can be found in the footnote of (9), the equivalence between P1 and P2 can be proven as follows.

Case I: If $|h_{AR}|^2 = |h_{BR}|^2$, then $\gamma_A = \gamma_B$ for an arbitrary pair of (ρ_A, ρ_B), i.e., (P1) and (P2) are equivalent.

Case II: If $|h_{AR}|^2 \neq |h_{BR}|^2$, by assuming $\gamma_A = \gamma_B$, we have

$$\begin{aligned}&|h_{AR}|^2\left[a|h_{BR}|^4(1-\rho_B)+b(1-\rho_A)+c\right]\\&=|h_{BR}|^2\left[a|h_{AR}|^4(1-\rho_A)+b(1-\rho_B)+c\right],\end{aligned}\tag{14}$$

where

$$\begin{aligned}&a=\eta P_S^2\sigma^2\left(\rho_A|h_{AR}|^2+\rho_B|h_{BR}|^2\right),\\&b=\eta P_S^2\sigma^2\left(\rho_A|h_{AR}|^2+\rho_B|h_{BR}|^2\right)|h_{AR}|^2|h_{BR}|^2,\\&c=\sigma^2\left((1-\rho_A)P_S|h_{AR}|^2+\sigma^2\right)\left((1-\rho_B)P_S|h_{BR}|^2+\sigma^2\right).\end{aligned}$$

Through some mathematical manipulation, we rewrite (14) as

$$\begin{aligned}\rho_{\bar{i}}&=\frac{P_S^2\sigma^2|h_{iR}|^2|h_{\bar{i}R}|^2(1-\rho_i)+P_S\sigma^4\left[(1-\rho_i)|h_{iR}|^2+|h_{\bar{i}R}|^2\right]+\sigma^6}{P_S^2\sigma^2|h_{iR}|^2|h_{\bar{i}R}|^2(1-\rho_i)+P_S\sigma^4|h_{\bar{i}R}|^2}\\&=1+\frac{P_S\sigma^4(1-\rho_i)|h_{iR}|^2+\sigma^6}{P_S^2\sigma^2|h_{iR}|^2|h_{\bar{i}R}|^2(1-\rho_i)+P_S\sigma^4|h_{\bar{i}R}|^2},\end{aligned}\tag{15}$$

where if $i = A$, $\bar{i} = B$; if $i = B$, $\bar{i} = A$. it can be seen from (15) that $\rho_{\bar{i}} > 1$ when $\rho_i \in [0, 1)$, which indicates that the assumption $\gamma_A = \gamma_B$ does not hold in this case. Thus, if $\gamma_A \neq \gamma_B$ holds, $\gamma_A = \gamma_B$, i.e., the proposition holds. ■

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