Power Allocation Strategy for Soft-Decision-and-Forward Protocol with Alamouti Code Based on ML Decoding

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***Abstract*—In this paper, the power allocation strategy for the soft-decision-and-forward (SDF) protocol in the cooperative communication network with one source, one relay, and one destination, where each node has two transmit and receive antennas, is determined. For the slow-varying Rayleigh fading channel, the optimal power allocation ratio can be determined so as to minimize the average bit error rate. Due to the difficulty in deriving the optimal value analytically, an alternative strategy of maximizing the product signal-to-noise ratio (SNR) of direct and relay links, which we call the suboptimal power allocation, is considered. Through the numerical analysis, we show that the performance gap between the suboptimal and optimal power allocation strategies is negligible in the high SNR region.**

***Index Terms*—Cooperative relaying, harmonic mean, power allocation, product signal-to-noise ratio (SNR), soft-decision-and-forward (SDF).**

I. Introduction

In wireless communication systems, the useful signals are deteriorited by the fadings which leads to the performance degradation of the system. Using the cooperation between source and relays, their performance can be improved. In [1] and [2], Sendonaris, Erkip, and Aazhang proposed the cooperative diversity. Laneman and Wornell [3] applied the space-time coding [4] to the cooperative communication networks and derived the outage probability and diversity order. Yang, Song, No, and Shin [5] proposed the maximum-likelihood (ML) decoding for AF and soft-decision-and-forward (SDF) protocols with two antennas using Alamouti code [6]. From the numerical results, it has been shown that SDF protocol outperformed AF protocol under both the squaring method and ML decoding.

Due to the limited resources in wireless communication systems, the power allocation is a very important matter. Hasna and Alouini [7] worked on the power allocation problem for AF and DF protocols for dual-hop relaying system. In [8], the power allocation strategy for AF protocol has been developed so as to maximize the average SNR and minimize the outage probability, which is equivalent to maximization of the product of the direct link and relay link SNRs in the high SNR region. In [9], the authors derived the SER for the dual-hop wireless communication with AF relaying and investigated the optimal power allocation.

In this paper, for a slow-varying Rayleigh fading channel, the optimal and suboptimal power allocations are considered when the channel state informations (CSIs) are not fedback into the transmitter. The proposed power allocation strategy is to maximize the product SNR, which we call the suboptimal power allocation. In the high SNR region, it is shown that the performance using the suboptimal power allocation is approaching the performance of the optimal power allocation in the slow-varying Rayleigh fading channel.

Throughout this paper, the following notations are used. $\mathbb{E}[\cdot]$ denotes the expectation of a random variable. $X \sim \mathcal{CN}(0, \sigma^2)$ means that X is a complex normal random variable with zero mean and variance $\sigma^2/2$ in both real and imaginary parts, respectively. $(\cdot)^{\mathrm{T}}$, $(\cdot)^{\dagger}$, and $\|\cdot\|$ denote the transpose of a matrix, the conjugate transpose of a matrix, and the Frobenius norm of a matrix or a vector, respectively. $\mathbf{0}_n$ and $\mathbf{I}_n$ are the zero matrix and the identity matrix of size n, and bold-face uppercase and lowercase letters denote matrices and vectors, respectively. For a complex number, $|\cdot|$, $\Re\{\cdot\}$, and $(\cdot)^*$ represent the modulus, the real part, and the complex conjugate, respectively. S, R, and D are used to denote source, relay, and destination nodes, respectively.

II. Soft-Decision-and-Forward Protocol

In this section, the SDF protocol [5] in the cooperative communication network with two antennas shown in Fig. 1 is reviewed. First, let us define the notations used in this subsection. The conventional Alamouti code $\begin{bmatrix} a & b \\ -b^* & a^* \end{bmatrix}$ is denoted by $\mathbf{A}(a, b)$. For any 2×2 matrix $\mathbf{B} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}$, the 4×2 matrix $\mathbf{B}'$ and the vector $cv(\mathbf{B})$ are defined as $\mathbf{B}' = \begin{bmatrix} b_{11} & b_{21}^* & b_{12} & b_{22}^* \\ b_{21} & -b_{11}^* & b_{22} & -b_{12}^* \end{bmatrix}^{\mathrm{T}}$ and

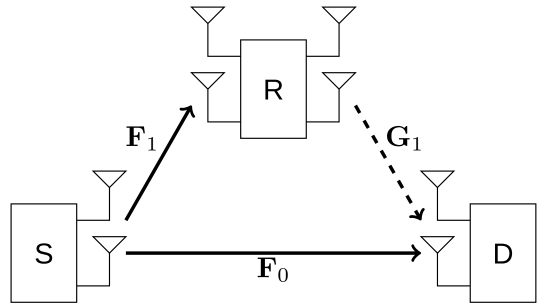

Fig. 1. Cooperative communication network composed of one source (S), one relay (R), and one destination (D) with two antennas at each node.

$cv\,(\mathbf{B}) = \begin{bmatrix} b_{11} & b_{21}^* & b_{12} & b_{22}^* \end{bmatrix}^{\mathrm{T}}$.

The name 'SDF' is originated from the notion that R obtains *soft-decision values* from the received signals from S, encodes them into Alamouti codes, and forwards them to D. The total transmit power P in the network is the sum of the transmit power P_1 at S and the transmit power P_2 at R. The channel gains of each link $\mathsf{S} \to \mathsf{D}$, $\mathsf{S} \to \mathsf{R}$, and $\mathsf{R} \to \mathsf{D}$ are Rayleigh-faded, i.e., $f_0^{ij} \sim \mathcal{CN}(0, \sigma_{\mathsf{SD}}^2)$, $f_1^{ij} \sim \mathcal{CN}(0, \sigma_{\mathsf{SR}}^2)$, and $g_1^{ij} \sim \mathcal{CN}(0, \sigma_{\mathsf{RD}}^2)$, where f_0^{ij}, f_1^{ij}, and g_1^{ij}, $1 \leq i, j \leq 2$, denote the path gains from the ith transmit antenna at S to the jth receive antenna at D, from the ith transmit antenna at S to the jth receive antenna at R, and from the ith transmit antenna at R to the jth receive antenna at D, respectively, and are the elements of the channel matrices $\mathbf{F}_0$, $\mathbf{F}_1$, and $\mathbf{G}_1$, respectively.

The transmission is composed of two phases. In the first phase, S transmits the signal using Alamouti code to R and D. Thus, the received signals at R and D are represented, respectively, as

$$\mathbf{Y}_{\mathsf{R}} = \sqrt{\frac{P_1}{2}}\mathbf{X}\mathbf{F}_1 + \mathbf{N}_{\mathsf{R}}$$
$$\mathbf{Y}_{\mathsf{D1}} = \sqrt{\frac{P_1}{2}}\mathbf{X}\mathbf{F}_0 + \mathbf{N}_{\mathsf{D1}}$$

where $\mathbf{X} = \mathbf{A}(x_1, x_2)$ is the transmit codeword at S in the first phase, $\mathbf{F}_0$ and $\mathbf{F}_1$ denote the channel matrices of $\mathsf{S} \to \mathsf{D}$ and $\mathsf{S} \to \mathsf{R}$, respectively, and $\mathbf{N}_{\mathsf{R}}$ and $\mathbf{N}_{\mathsf{D1}}$ are the 2×2 AWGN matrices with zero-mean and unit-variance entries. During the intermediate decoding at R, R obtains the soft-decision values from the received signals using maximal ratio combining as

$$\tilde{\mathbf{x}} \triangleq \begin{bmatrix} \tilde{x}_1 & \tilde{x}_2 \end{bmatrix}^{\mathrm{T}} = \lambda \mathbf{F}_1'^{\dagger} cv(\mathbf{Y}_{\mathsf{R}})$$

where

$$\begin{aligned} cv(\mathbf{Y}_{\mathsf{R}}) &= \begin{bmatrix} y_{11}^{(\mathsf{R})} & y_{21}^{(\mathsf{R})*} & y_{12}^{(\mathsf{R})} & y_{22}^{(\mathsf{R})*} \end{bmatrix}^{\mathrm{T}} \\ &= \sqrt{\frac{P_1}{2}}\mathbf{F}_1'\mathbf{x} + cv(\mathbf{N}_{\mathsf{R}}) \\ \lambda &= \sqrt{\frac{2}{\|\mathbf{F}_1\|^2(P_1\|\mathbf{F}_1\|^2 + 2)}} \end{aligned}$$

where $\mathbf{x} = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^{\mathrm{T}}$ is the transmitted signal vector at S. And then, R transmits the following codeword into D

$$\mathbf{X}_{\mathsf{R}} = \mathbf{A}(\tilde{x}_1, \tilde{x}_2) = \begin{bmatrix} \tilde{x}_1 & \tilde{x}_2 \\ -\tilde{x}_2^* & \tilde{x}_1^* \end{bmatrix}.$$

In the second phase, the received signal at D is expressed as

$$\mathbf{Y}_{\mathsf{D2}} = \sqrt{\frac{P_2}{2}}\mathbf{X}_{\mathsf{R}}\mathbf{G}_1 + \mathbf{N}_{\mathsf{D2}}$$

where $\mathbf{G}_1$ is the channel matrix of $\mathsf{R} \to \mathsf{D}$ and $\mathbf{N}_{\mathsf{D2}}$ denotes the 2×2 AWGN matrix with zero-mean and unit-variance entries. Converting the matrix form into the vector form gives the following alternative expression

$$\begin{aligned} cv(\mathbf{Y}_{\mathsf{D2}}) =& \frac{\sqrt{P_1P_2}}{2}\lambda\|\mathbf{F}_1\|^2\mathbf{G}_1'\mathbf{x} + \sqrt{\frac{P_2}{2}}\lambda\mathbf{G}_1'\mathbf{F}_1'^{\dagger} cv(\mathbf{N}_{\mathsf{R}}) \\ &+ cv(\mathbf{N}_{\mathsf{D2}}). \end{aligned}$$

The received signal at D during two phases can be rewritten as an equivalent vector model

$$\underbrace{\begin{bmatrix} cv(\mathbf{Y}_{\mathsf{D1}}) \\ cv(\mathbf{Y}_{\mathsf{D2}}) \end{bmatrix}}_{\mathbf{y}} = \underbrace{\sqrt{\frac{P_1}{2}}\begin{bmatrix} \mathbf{F}_0' \\ \sqrt{\frac{P_2}{2}}\lambda\|\mathbf{F}_1\|^2\mathbf{G}_1' \end{bmatrix}}_{\mathbf{H}}\mathbf{x} + \underbrace{\begin{bmatrix} cv(\mathbf{N}_{\mathsf{D1}}) \\ cv(\mathbf{N}_{\mathsf{D}}) \end{bmatrix}}_{\mathbf{n}} \tag{1}$$

where $cv(\mathbf{N}_{\mathsf{D}})$ means the equivalent noise at D in the vector form, which is given by

$$cv(\mathbf{N}_{\mathsf{D}}) = \sqrt{\frac{P_2}{2}}\lambda\mathbf{G}_1'\mathbf{F}_1'^{\dagger} cv(\mathbf{N}_{\mathsf{R}}) + cv(\mathbf{N}_{\mathsf{D2}}).$$

The ML decoding rule for the SDF protocol can be written as

$$\begin{aligned} \hat{\mathbf{x}} &= \arg\min_{\mathbf{x}}[(\mathbf{y} - \mathbf{H}\mathbf{x})^{\dagger}\mathcal{K}_{\mathbf{n}}^{-1}(\mathbf{y} - \mathbf{H}\mathbf{x})] \\ &= \arg\min_{\mathbf{x}}\left[\mathbf{x}^{\dagger}\mathbf{H}^{\dagger}\mathcal{K}_{\mathbf{n}}^{-1}\mathbf{H}\mathbf{x} - 2\Re\{\mathbf{y}^{\dagger}\mathcal{K}_{\mathbf{n}}^{-1}\mathbf{H}\mathbf{x}\}\right] \end{aligned}$$

where $\mathcal{K}_{\mathbf{n}} = \mathcal{E}\left[\mathbf{n}\mathbf{n}^{\dagger}\right] = \begin{bmatrix} \mathbf{I}_4 & \mathbf{0} \\ \mathbf{0} & \mathcal{K}_{cv(\mathbf{N}_{\mathsf{D}})} \end{bmatrix}$ with $\mathcal{K}_{cv(\mathbf{N}_{\mathsf{D}})} = \mathbf{I}_4 + P_2/(P_1\|\mathbf{F}_1\|^2+2)\cdot\mathbf{G}_1'\mathbf{G}_1'^{\dagger}$. The ML decoder for SDF protocol chooses $\hat{x}_i$ such that

$$\begin{aligned} \hat{x}_i =& \arg\min_{x_i}\left[\left(\frac{P_1}{2}\|\mathbf{F}_0\|^2 + \frac{P_1P_2\|\mathbf{F}_1\|^2\|\mathbf{G}_1\|^2}{2(P_1\|\mathbf{F}_1\|^2 + P_2\|\mathbf{G}_1\|^2 + 2)}\right)|x_i|^2 \right. \\ &\left. - 2\Re\{\eta_i x_i\}\right] \end{aligned}$$

where $\mathbf{y}^{\dagger}\mathcal{K}_{\mathbf{n}}^{-1}\mathbf{H} = \begin{bmatrix} \eta_1 & \eta_2 \end{bmatrix}$. Note that the ML decoder for SDF protocol using equal energy signals such as phase-shift keying (PSK) is simplified as

$$\hat{x}_i = \arg\max_{x_i}\Re\left\{\eta_i x_i\right\}.$$

TABLE I
THE OPTIMAL POWER ALLOCATION RATIOS (α°) IN DIFFERENT CHANNEL CONDITIONS.

$(\sigma^2_{\mathsf{SD}}, \sigma^2_{\mathsf{SR}}, \sigma^2_{\mathsf{RD}})$ \ P [dB]	0	2	4	6	8	10	12	14	$\alpha^{\star}$
(1,1,1)	0.979	0.928	0.880	0.835	0.790	0.749	0.711	0.686	0.6765
(1,1,4)	0.829	0.820	0.809	0.801	0.788	0.782	0.778	0.774	0.7688
(1,1,0.25)	1	1	1	1	1	1	0.880	0.773	0.5932
(1,4,1)	0.841	0.794	0.736	0.691	0.652	0.615	0.584	0.556	0.5932
(1,4,4)	0.651	0.645	0.637	0.630	0.624	0.620	0.614	0.613	0.6765

III. POWER ALLOCATION STRATEGY

In this section, end-to-end SNR for SDF cooperative network and PEP are expressed into the similar form to the AF relaying. However, it is hard to derive the closed-form expression for the PEP. Furthermore, it is very difficult to find the optimum power allocation in terms of minimizing the PEP. And thus, the suboptimum power allocation strategy is considered by using the maximization of product two SNRs such as direct link and relay link SNRs.

A. End-to-End SNR and PEP

Under the assumption of the ML decoding, the instantaneous end-to-end SNR, $\gamma_{\mathrm{eq}|\mathbf{H}}$, becomes the sum of two SNRs, i.e.,

$$\gamma_{\mathrm{eq}|\mathbf{H}} = \frac{P_1}{2}\|\mathbf{F}_0\|^2 + \frac{P_1 P_2 \|\mathbf{F}_1\|^2 \|\mathbf{G}_1\|^2}{2(P_1\|\mathbf{F}_1\|^2 + P_2\|\mathbf{G}_1\|^2 + 2)}.$$

This result is similar to the end-to-end SNR of the conventional AF relaying with a single antenna. Letting $\gamma_0 = P_1\|\mathbf{F}_0\|^2/2$, $\gamma_1 = P_1\|\mathbf{F}_1\|^2/2$, and $\gamma_2 = P_2\|\mathbf{G}_1\|^2/2$, the instantaneous end-to-end SNR can be rewritten as

$$\gamma_{\mathrm{eq}|\mathbf{H}} = \gamma_0 + \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1} \tag{2}$$

where $\gamma_0 \sim \mathcal{G}\left(4, \sigma^2_{\mathsf{SD}}P_1/2\right)$, $\gamma_1 \sim \mathcal{G}\left(4, \sigma^2_{\mathsf{SR}}P_1/2\right)$, and $\gamma_2 \sim \mathcal{G}\left(4, \sigma^2_{\mathsf{RD}}P_2/2\right)$, respectively. In the high SNR region, (2) can be approximated as

$$\gamma_{\mathrm{eq}|\mathbf{H}} \approx \gamma_0 + \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2}. \tag{3}$$

This is a reasonable approximation in the high SNR region since $\gamma_1, \gamma_2 \gg 1$. Thus, this approximation leads to almost the same performance in the high SNR region.

Using (1), the conditional PEP can be written as

$$\Pr(\mathbf{x}\to\hat{\mathbf{x}}|\mathbf{H}) = Q\left(\sqrt{\frac{1}{2}\left\|\mathcal{K}_{\mathbf{n}}^{-\frac{1}{2}}\mathbf{H}(\hat{\mathbf{x}}-\mathbf{x})\right\|^2}\right) \tag{4}$$

where $Q(x) = \int_x^{\infty} e^{-u^2/2}/\sqrt{2\pi}du$. Substitution of (3) instead of (2) into (4) leads to the following approximation as

$$\Pr(\mathbf{x}\to\hat{\mathbf{x}}|\mathbf{H}) \approx Q\left(\sqrt{\frac{1}{2}\left\{\gamma_0 + \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2}\right\}\delta^2_{\mathbf{x}}}\right) \tag{5}$$

where $\delta^2_{\mathbf{x}} = \|\hat{\mathbf{x}}-\mathbf{x}\|^2$. Now, we can approximate the PEP by averaging the conditional PEP in (5) over $\mathbf{H}$. It gives the average PEP for the OSDF protocol as

$$\Pr(\mathbf{x}\to\hat{\mathbf{x}}) \approx \mathbb{E}_{\mathbf{H}}\left[Q\left(\sqrt{\frac{1}{2}\left\{\gamma_0 + \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2}\right\}\delta^2_{\mathbf{x}}}\right)\right]. \tag{6}$$

Using the Craig's form of Q-function, (6) can be rewritten as the following approximate form

$$\Pr(\mathbf{x}\to\hat{\mathbf{x}}) \approx \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \mathcal{M}_{\gamma_0}\left(-\frac{\delta^2_{\mathbf{x}}}{2\sin^2\theta}\right) \times \mathcal{M}_{H(\gamma_1,\gamma_2)}\left(-\frac{\delta^2_{\mathbf{x}}}{4\sin^2\theta}\right)d\theta. \tag{7}$$

B. Proposed Power Allocation Strategy

In this section, the power allocation scheme for the SDF protocol is considered. The optimal power allocation ratio is selected so as to minimize the average PEP. But for the sake of tractability, we use the product of SNR [8] instead. In other words, the suboptimal power allocation is obtained by maximizing the product of two SNRs of the direct and relay links.

When CSI is not available at S, the optimal power allocation ratio, α°, can be chosen as the solution of the minimization problem of the PEP in (7) (or BER), i.e.,

$$\alpha^{\circ} = \arg\min_{0\le\alpha\le 1} \Pr(\mathbf{x}\to\hat{\mathbf{x}}). \tag{8}$$

Since it is difficult to find the global minimum analytically, the optimal power allocation ratios with respect to P and $(\sigma^2_{\mathsf{SD}}, \sigma^2_{\mathsf{SR}}, \sigma^2_{\mathsf{RD}})$ are listed in Table I through the numerical search.

Thus, when the CSI is not available at S, it is worthwhile to consider the alternative, namely, the suboptimal power allocation in the slow-varying Rayleigh fading channel. As one can see in [8], the outage probability of AF protocol with single antenna is approximated as the inverse of product SNR in the high SNR region. Similar to the work in [8], the power allocation is determined so as to maximize the product SNR. Using the result in [11] for harmonic mean of two gamma random variables, the average product of two SNRs of the direct and relay links at D is calculated as

$$\Pi(\gamma_{\mathrm{eq}}) \approx \mathbb{E}\left[\gamma_0\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2}\right] = \mathbb{E}\left[\gamma_0\right]\mathbb{E}\left[\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2}\right] = \frac{8}{9}\sigma^2_{\mathsf{SD}}P_1\frac{\Omega^5_{\min}}{\Omega^4_{\max}}{}_2F_1\left(9,5;10;1-\frac{\Omega_{\min}}{\Omega_{\max}}\right). \tag{9}$$

For example, we consider the symmetric channel, i.e., $\sigma^2_{\mathsf{SD}} = \sigma^2_{\mathsf{SR}} = \sigma^2_{\mathsf{RD}} = 1$. In this case, the suboptimal power allocation ratio is $\alpha > 0.5$. Letting $1 - (1-\alpha)/\alpha \triangleq x$, (9) can be rewritten as a function of x

$$\Pi(\gamma_{\text{eq}}) = \frac{4}{9}\frac{(1-x)^5}{(2-x)^2} P^2 {}_2F_1\left(9,5;10;x\right).$$

Then, the suboptimal power allocation is obtained as

$$\alpha^\star = \arg\max_{0\le\alpha\le 1} \Pi(\gamma_{\text{eq}}). \tag{10}$$

The resulting suboptimal power allocation ratio is $\alpha^\star = 0.6765$. We applied the similar approach to the asymmetric channels such as $\sigma^2_{\mathsf{RD}}/\sigma^2_{\mathsf{SR}} = 4$ and $\sigma^2_{\mathsf{RD}}/\sigma^2_{\mathsf{SR}} = 1/4$. The resulting suboptimal power allocation ratios are $\alpha^\star = 0.7688$ and $\alpha^\star = 0.5932$, respectively. As one can easily anticipate, we can observe that as the ratio $\sigma^2_{\mathsf{SR}}/\sigma^2_{\mathsf{RD}}$ becomes larger, the suboptimal power allocation ratio approaches to 0, and on the other hand, as the ratio $\sigma^2_{\mathsf{SR}}/\sigma^2_{\mathsf{RD}}$ becomes smaller, the suboptimal power allocation ratio approaches to 1.

IV. Numerical Results

It is assumed that the channel is Rayleigh-faded and frequency-flat quasi-static, i.e., the channel state does not change in one phase but varies independently from phase to phase. We only consider QPSK. For the sake of tractability, the channel conditions we considered are symmetric ($\sigma^2_{\mathsf{SD}} = \sigma^2_{\mathsf{SR}} = \sigma^2_{\mathsf{RD}}$) and asymmetric ($\sigma^2_{\mathsf{SR}} = 4\sigma^2_{\mathsf{RD}}$ and $4\sigma^2_{\mathsf{SR}} = \sigma^2_{\mathsf{RD}}$). For fair comparison, the total transmit power during two phases is set to P. A single relay cooperative communication network with two antennas at the transmitter and receiver is considered. First, the channel statistics are given as $\sigma^2_{\mathsf{SD}} = \sigma^2_{\mathsf{SR}} = 1$ and various values of σ^2_{RD}. Figs. 2, 3, and 4 plot the BER performance of the SDF protocol in the different channel conditions. Fig. 2 shows the BER of the SDF protocol in the symmetric channel, i.e., $\sigma^2_{\mathsf{RD}} = 1$. From the numerical result, we can conclude that the performance degradation under the suboptimal power allocation instead of the optimal power allocation is negligible. And the optimal power allocation has about 0.5 dB performance gain over the uniform power allocation.

Figs. 3 and 4 show the BERs for the asymmetric channel with $\sigma^2_{\mathsf{RD}} = 4$ and $\sigma^2_{\mathsf{RD}} = 0.25$, respectively. Fig. 3 shows that the performances of the optimal and suboptimal power allocations are almost the same, which comes from the increase of the received SNR in the $\mathsf{R} \to \mathsf{D}$ link. On the other hand, if $\mathsf{R} \to \mathsf{D}$ link is not good, the direct transmission ($\alpha = 1$) is optimal in the low SNR region. As the total transmit power increases, the cooperative communication network with SDF protocol outperforms the direct transmission. One can see from Fig. 4 that the performance gap between the optimal and suboptimal BERs becomes negligible as the total transmit power increases. This may imply that the maximization of the product SNR corresponds to the suboptimal power allocation.

Second, the channel statistics are given as $\sigma^2_{\mathsf{SD}} = 1$, $\sigma^2_{\mathsf{SR}} = 4$, and different σ^2_{RD}, i.e., better $\mathsf{S} \to \mathsf{R}$ link than $\mathsf{S} \to \mathsf{D}$ link is considered. Figs. 5 and 6 show the BERs for different power allocations for the case of $\sigma^2_{\mathsf{RD}} = 1$ and $\sigma^2_{\mathsf{RD}} = 4$. It is shown that the performance gap between the optimal and the suboptimal power allocation is very small. Clearly, the cooperative communication network with $\sigma^2_{\mathsf{SR}} = 4$ outperforms that with $\sigma^2_{\mathsf{SR}} = 1$.

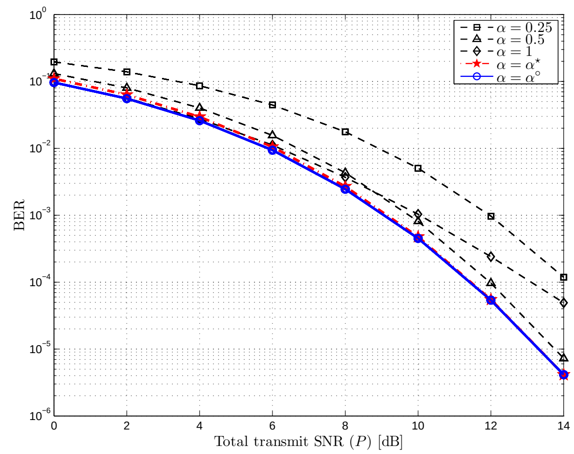

Fig. 2. Comparison of BERs of the SDF protocol with respect to different power allocation ratio $\alpha = 0.25,\ 0.5,\ 1,\ \alpha^\star$, and α° for QPSK in the symmetric Rayleigh fading channel ($\alpha^\star = 0.6765$ and α° in Table I).

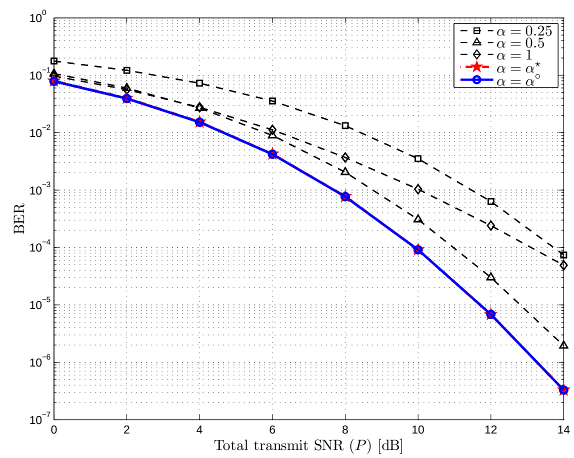

Fig. 3. Comparison of BERs of the SDF protocol with respect to different power allocation ratio $\alpha = 0.25,\ 0.5,\ 1,\ \alpha^\star$, and α° for QPSK in the asymmetric Rayleigh fading channel ($(\sigma^2_{\mathsf{SD}}, \sigma^2_{\mathsf{SR}}, \sigma^2_{\mathsf{RD}}) = (1,1,4)$, $\alpha^\star = 0.7688$, and α° in Table I).

V. Concluding Remarks

In this paper, we reviewed the SDF protocol with a single relay based on Alamouti code with two antennas at S, R, and D. The suboptimal power allocation strategy, obtained by maximizing the product SNR, for the slow-varying Rayleigh fading channel has been considered without feedback of the CSI. The numerical results show that the performance of SDF protocol with the suboptimal power allocation almost approaches to that with the optimal power allocation in the high SNR region. The performance analysis such as relay selection and power allocation strategy for the SDF cooperative communication

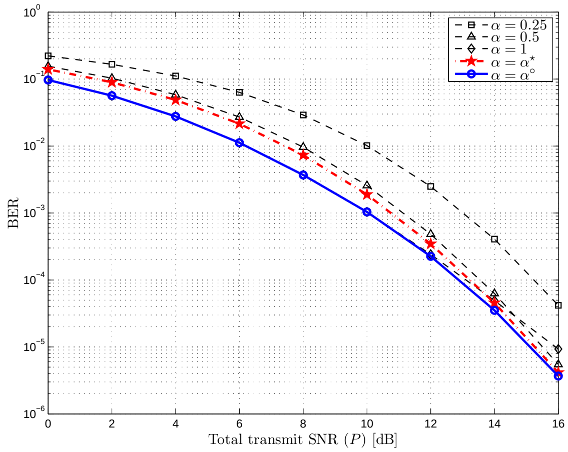

Fig. 4. Comparison of BERs of the SDF protocol with respect to different power allocation ratio $\alpha = 0.25,\ 0.5,\ 1,\ \alpha^\star$, and α° for QPSK in the asymmetric Rayleigh fading channel ($(\sigma^2_{\mathsf{SD}}, \sigma^2_{\mathsf{SR}}, \sigma^2_{\mathsf{RD}}) = (1, 1, 0.25)$, $\alpha^\star = 0.5932$, and α° in Table I).

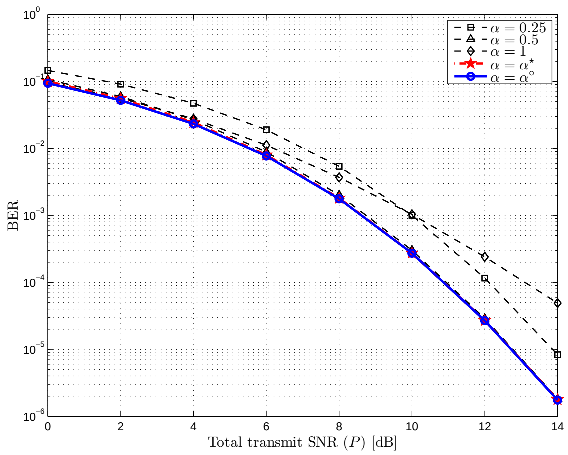

Fig. 5. Comparison of BERs of the SDF protocol with respect to different power allocation ratio $\alpha = 0.25,\ 0.5,\ 1,\ \alpha^\star$, and α° for QPSK in the asymmetric Rayleigh fading channel ($(\sigma^2_{\mathsf{SD}}, \sigma^2_{\mathsf{SR}}, \sigma^2_{\mathsf{RD}}) = (1, 4, 1)$, $\alpha^\star = 0.5932$, and α° in Table I).

network with multiple-relay remains as a future work.

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References

[1] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity—Part I: System description," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1938, Nov. 2003.

[2] ——, "User cooperation diversity—Part II: Implementation aspects and performance analysis," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1939–1948, Nov. 2003.

[3] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2003.

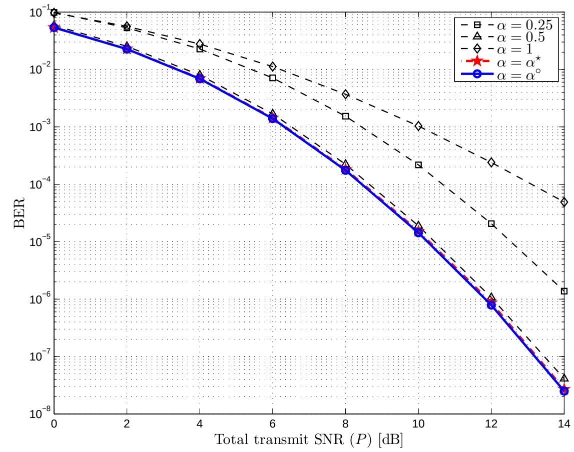

Fig. 6. Comparison of BERs of the SDF protocol with respect to different power allocation ratio $\alpha = 0.25,\ 0.5,\ 1,\ \alpha^\star_{\mathrm{a}}$, and $\alpha^\circ_{\mathrm{a}}$ for QPSK in the asymmetric Rayleigh fading channel ($(\sigma^2_{\mathsf{SD}}, \sigma^2_{\mathsf{SR}}, \sigma^2_{\mathsf{RD}}) = (1, 4, 4)$, $\alpha^\star = 0.6765$, and α° in Table I).

[4] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication: Performance analysis and code construction," *IEEE Trans. Inf. Theory*, vol. 44, no. 3, pp. 744–765, Mar. 1998.

[5] J.-D. Yang, K.-Y. Song, J.-S. No, and D.-J. Shin, "Soft-decision-and-forward protocol for cooperative communication networks based on Alamouti code," in *Proc. IEEE ISIT*, Seoul, Korea, 2009.

[6] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[7] M. O. Hasna and M.-S. Alouini, "Optimal power allocation for relayed transmissions over Rayleigh-fading channels," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 1999–2004, Nov. 2004.

[8] X. Deng and M. Haimovich, "Power allocation for cooperative relaying in wireless networks," *IEEE Commun. Lett.*, vol. 9, no. 11, pp. 994–996, Nov. 2005.

[9] Z. Fang, X. Bao, L. Li, and Z. Wang, "Performance analysis and power allocation for amplify-and-forward cooperative networks over Nakagami-m fading channels," *IEICE Trans. Commun.*, vol. E92-B, no. 3, pp. 1004–1012, Mar. 2009.

[10] H. Hui, S. Zhu, and G. LV, "Power allocation for amplify-and-forward opportunistic relaying systems," *IEICE Trans. Commun.* vol. E92-B, no. 11, pp. 3541–3545, Nov. 2009.

[11] Y. Han, S. H. Ting, C. K. Ho, and W. H. Chin, "Performance bounds for two-way amplify-and-forward relaying," *IEEE Trans. Wireless Commun.,* vol. 8, no. 1, pp. 432–439, Jan. 2009.

[12] M. O. Hasna and M.-S. Alouini, "Harmonic mean and end-to-end performance of transmission system with relays," *IEEE Trans. Commun.,* vol. 52, no. 1, pp. 130–135, Jan. 2004.

[13] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products,* 6th ed., Orlando, FL: Academic Press, 2002.

[14] R. U. Nabar, H. Bölcskei, and F. W. Kneubühler, "Fading relay channels: Performance limits and space-time signal design," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 6, pp. 1099–1109, Aug. 2004.