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Spatial channel pairing based coherent combining for relay networks*

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Abstract: In this paper, spatial channel pairing (SCP) is introduced to coherent combining at the relay in relay networks. Closed-form solution to optimal coherent combining is derived. Given coherent combining, the approximate SCP solution is presented. Finally, an alternating iterative structure is developed. Simulation results and analysis show that, given the symbol error rate and data rate, the proposed alternating iterative structure achieves signal-to-noise ratio gains over existing schemes in maximum ratio combining (MRC) plus matched filter, MRC plus antenna selection, and distributed space-time block coding due to the use of SCP and iterative structure.

Key words: Spatial channel pairing, Coherent combining, Alternating iterative structure, Symbol error rate, Distributed space-time block coding
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1 Introduction

Distributed space-time block coding (DSTBC), maximum ratio combining (MRC), and their combination, have been proposed to exploit cooperative diversity in relay networks (Chang and Hua, 2003; Laneman and Wornell, 2003; Nabar *et al.*, 2004; Fang *et al.*, 2006; Jing and Hassibi, 2006; Jing, 2013; Nasir *et al.*, 2013). Data transmission from the source node to the destination node via relay stations (RSs) requires two time slots. Jing and Hassibi (2006) proposed the DSTBC for multi-relay networks to achieve cooperative diversity. To improve the performance of DSTBC, MRC receive beamforming was used at an RS in the first time slot while DSTBC was adopted in the second time slot; hence, substantial signal-to-noise ratio (SNR) gain was achieved by the MRC-DSTBC (Jing, 2010). Li *et al.* (2009) proposed three cooperative schemes for two-way relay networks. Lee *et al.* (2008) designed an iterative algorithm to maximize the sum-rate, but did not present any closed-form solution.

Hammerstrom and Wittneben (2006) introduced the concept of subcarrier pairing. The subcarrier pairing based resource allocation scheme

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for amplify-and-forward (AF) multi-relay orthogonal frequency division multiplexing (OFDM) systems was investigated in Dang *et al.* (2010) and Li *et al.* (2013). To avoid interference, each subcarrier pairing was assigned to all RSs, over a specific subcarrier, and the destination received signals transmitted from all the relays (Li *et al.*, 2013). Hottinen and Heikkinen (2007) and Li *et al.* (2009) proved that the sorted-SNR subcarrier pairing scheme was optimal for both AF and DF (decoding-and-forward) relaying in the same setup through a different approach. In Li *et al.* (2009), a joint optimization scheme for power allocation (PA) and subcarrier pairing was proposed to maximize the end-to-end transmission rate under a total power constraint. The studies mentioned above focus on one-way relay systems. For the case of two-way relaying, in Liu and Tao (2012), the joint optimization of channel and relay assignment for the maximum total throughput was formulated as a combinatorial optimization problem, which includes subcarrier pairing, subcarrier allocation, and relay selection. Chang and Dong (2013) investigated the design of subcarrier pairing at an RS to maximize the sum-rate of the system and proposed an iterative optimization method. The spatial channel pairing that maximizes the sum-rate was designed for narrow-band and wide-band multi-pair two-way networks with a block diagonalization (BD) beamforming scheme at an RS to substantially improve the sum-rate performance (Shu *et al.*, 2014a; 2014b; Wang *et al.*, 2015).

In this paper, we consider a one-way relay scenario with each user being single-antenna. We introduce spatial channel paring (SCP) to a coherent combining (CC) scheme at an RS to improve the performance of symbol error rate (SER) by exploiting the SCP gain. The closed-form expression for the optimal CC (OCC) is derived given SCP, whereas the approximate analytical solution is given for a fixed CC. Following this, we design an alternating iterative structure (AIS) between SCP and OCC. Simulation results are also presented to evaluate the performance and validate our scheme. Unlike the SCP in Shu *et al.* (2014b) and Wang *et al.* (2015; 2016), here our major aim is to exploit the SCP gain to substantially improve the reliability of information transmission/exchange in relay networks. Although we consider only the one-way case, the proposed scheme can be extended to two-way networks with each user being single-antenna or multi-relay networks. In the multi-relay scenario, full cooperation among RSs is required to complete our proposed method.

Our main contributions are as follows. The optimization problem of maximizing the SNR over SCP and OCC is formulated and established. However, the problem is an NP-hard problem. To address this, we reduce the joint problem to two individual subproblems. For a given SCP, the optimal closed-form expression of OCC is derived in a novel way. Fixing the OCC, we present a sub-optimal closed-form SCP method by approximation techniques. Then an AIS is introduced between them to further optimize the system performance. Simulation results show the benefits of our method over existing DSTBC and coherent combining approaches due to the use of both SCP and OCC. In other words, the proposed AIS harvests not only the OCC gain but also the SCP gain.

Notations: throughout the paper, matrices, vectors, and scalars are denoted by letters of bold upper case, bold lower case, and lower case, respectively. Let '$\otimes$' denote the Kronecker product of two matrices. Let $(\cdot)^*$, $(\cdot)^{\mathrm{H}}$, $(\cdot)^{\mathrm{T}}$, and $\mathrm{tr}(\cdot)$ denote the matrix conjugate, conjugate transpose, transpose, and trace, respectively. Let $\|\cdot\|_2$ denote the Frobenius norm, and the inequality symbol '$\succeq$' denote the generalized component-wise inequality between vectors. The matrix $\boldsymbol{I}_n$ denotes an $n \times n$ identity matrix.

2 System model

We consider a wireless relay system composed of one source S, one destination D, and one relay R (Fig. 1). Both S and D have only one antenna, while the relay R is equipped with M antennas. Assume that there is no direct link between S and D due to the poor quality of the channel. Let h_m represent the narrow-band channel fading coefficient from S to the mth ($m = 1, 2, \ldots, M$) antenna of R, g_m the channel from the mth antenna of R to D. All the channels in the system are complex and are assumed to be independent and identically distributed (i.i.d.) Rayleigh fading with variance one.

A transmission process is composed of two time slots. In the first time slot, source S transmits a symbol x_S to R with the power constraint $E\{x_S x_S^*\} = 1$. Then the received signal at the mth antenna of R can

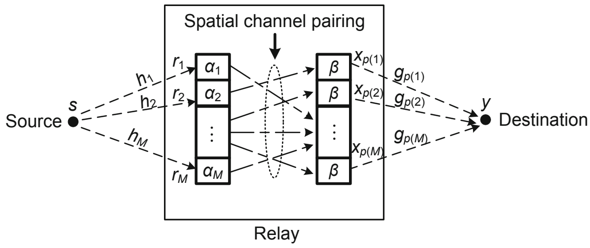

Fig. 1 Diagram block of a relay network

be given by

$$y_{R,m} = \sqrt{P_S} h_m x_S + n_{R,m}, \tag{1}$$

where P_S is the transmission power at source S and $n_{R,m}$ denotes the complex additive white Gaussian noise (AWGN) at the mth antenna of R with zero mean and variance σ_R^2.

In the second time slot, the AF relaying strategy is adopted and an SCP scheme is introduced. The received signal $y_{R,m}$ is then amplified and transmitted towards the destination D via the $p(m)$th antenna of R. Here, we have $p(m) \in \boldsymbol{p}$, and $\boldsymbol{p}$ is a permutation vector of $\{1,\ 2,\ \ldots,\ M\}$. For example, if $p(1)=2$, then the signal received by the 1st antenna of R will be transmitted via the 2nd antenna of R. Thereby the downlink channel g_2 is paired with the uplink channel h_1. For simplicity, the permutation vector $\boldsymbol{p}$ is called SCP below.

Then the signal transmitted at the $p(m)$th antenna of R can be expressed as

$$x_{R,p(m)} = \beta\alpha_m y_{R,m} = \beta\alpha_m \left(\sqrt{P_S} h_m x_S + n_{R,m}\right), \tag{2}$$

where β is the power normalization factor at the relay and α_m is the CC coefficient. In the following, we will explain β and α_m in detail.

Assume the total power constraint at the relay is P_R. Then α_m and β are subject to the following two power constraints:

$$\begin{cases} \beta^2\left(P_S \sum\limits_{m=1}^{M} |\alpha_m h_m|^2 + \sigma_R^2\right) = P_R, \\ \sum\limits_{m=1}^{M} |\alpha_m|^2 = 1. \end{cases} \tag{3}$$

Thus, β has to satisfy

$$\beta = \sqrt{\frac{P_R}{\sum\limits_{m=1}^{M} |\alpha_m h_m|^2 P_S + \sigma_R^2}}. \tag{4}$$

At the destination D, the received symbol y_D can be written as

$$\begin{aligned} y_D &= \sum_{m=1}^{M} g_{p(m)} x_{R,p(m)} + n_D \\ &= \beta\sqrt{P_S} \sum_{m=1}^{M} g_{p(m)} \alpha_m h_m x_S \\ &\quad + \beta \sum_{m=1}^{M} g_{p(m)} \alpha_m n_{R,m} + n_D, \end{aligned} \tag{5}$$

where n_D is the complex AWGN with zero mean and variance σ_D^2 at the destination.

We further write $g_{p(m)}$, h_m, and α_m as $g_{p(m)} = |g_{p(m)}| \exp(\mathrm{j}\theta_{g_{p(m)}})$, $h_m = |h_m| \exp(\mathrm{j}\theta_{h_m})$, and $\alpha_m = |\alpha_m| \exp(\mathrm{j}\theta_{\alpha_m})$, where $\theta_{g_{p(m)}}$, θ_{h_m}, and θ_{α_m} are the phases of $g_{p(m)}$, h_m, and α_m, respectively. In the design of α_m, we set $\theta_{\alpha_m} = -\theta_{g_{p(m)}} - \theta_{h_m}$ to cancel the channel phases. To simplify the derivations, we define the following weight vector:

$$\boldsymbol{w} \triangleq \Big[|\alpha_1|,\ |\alpha_2|,\ \ldots,\ |\alpha_M|\Big]^{\mathrm{T}}. \tag{6}$$

In the following, we will enhance the system performance by optimizing the permutation vector $\boldsymbol{p}$ and the weight vector $\boldsymbol{w}$.

3 Problem formulation

Based on Eq. (5), the SNR at the destination can be written as

$$\gamma(\boldsymbol{w},\boldsymbol{p}) = \frac{\left(\sum\limits_{m=1}^{M} |\alpha_m g_{p(m)} h_m|\right)^2 P_S}{\sum\limits_{m=1}^{M} |\alpha_m g_{p(m)}|^2 \sigma_R^2 + \beta^{-2}\sigma_D^2}. \tag{7}$$

By substituting β in Eq. (4) into Eq. (7), we have

$$\begin{aligned} &\gamma(\boldsymbol{w},\boldsymbol{p}) \\ &= \frac{\left(\sum\limits_{m=1}^{M} |\alpha_m g_{p(m)} h_m|\right)^2 P_S}{\sum\limits_{m=1}^{M}\left(|\alpha_m g_{p(m)}|^2\sigma_R^2 + |\alpha_m h_m|^2 \dfrac{P_S\sigma_D^2}{P_R}\right) + \dfrac{\sigma_R^2\sigma_D^2}{P_R}} \\ &= \frac{\left(\sum\limits_{m=1}^{M} |\alpha_m g_{p(m)} h_m|\right)^2 \dfrac{P_S P_R}{\sigma_R^2\sigma_D^2}}{\sum\limits_{m=1}^{M}\left(|\alpha_m g_{p(m)}|^2 \dfrac{P_R}{\sigma_D^2} + |\alpha_m h_m|^2 \dfrac{P_S}{\sigma_R^2}\right) + 1}. \end{aligned} \tag{8}$$

Define $\boldsymbol{A_p} \triangleq \boldsymbol{t_p t_p}^{\mathrm{T}}$ with

$$\boldsymbol{t_p} = \sqrt{\frac{P_S P_R}{\sigma_R^2 \sigma_D^2}} \Big[|g_{p(1)} h_1|,\ |g_{p(2)} h_2|,\ \ldots,\ |g_{p(M)} h_M| \Big]^{\mathrm{T}}, \tag{9}$$

and define

$$\begin{aligned}\boldsymbol{B_p} \triangleq & \frac{P_R}{\sigma_D^2} \mathrm{diag}(|g_{p(1)}|^2,\ |g_{p(2)}|^2,\ \ldots,\ |g_{p(M)}|^2) \\ & + \frac{P_S}{\sigma_R^2} \mathrm{diag}(|h_1|^2,\ |h_2|^2,\ \ldots,\ |h_M|^2) + \boldsymbol{I}_M.\end{aligned} \tag{10}$$

We can rewrite Eq. (7) as

$$\gamma(\boldsymbol{w}, \boldsymbol{p}) = \frac{\boldsymbol{w}^{\mathrm{T}} \boldsymbol{A_p w}}{\boldsymbol{w}^{\mathrm{T}} \boldsymbol{B_p w}}. \tag{11}$$

Since $\gamma(\boldsymbol{w}, \boldsymbol{p})$ is a function of $\boldsymbol{w}$ and $\boldsymbol{p}$, we can optimize these two vectors to maximize the SNR, i.e.,

$$\begin{aligned}& \max_{\boldsymbol{w},\, \boldsymbol{p}} \gamma(\boldsymbol{w}, \boldsymbol{p}) \\ & \text{subject to } \boldsymbol{p} \in S_{\boldsymbol{p}},\ \|\boldsymbol{w}\|_2 = 1,\ \boldsymbol{w} \succeq \boldsymbol{0},\end{aligned} \tag{12}$$

where $S_{\boldsymbol{p}}$ is the set of all possible permutations of $\{1,\ 2,\ \ldots,\ M\}$.

From the definition of function $\gamma(\boldsymbol{w}, \boldsymbol{p})$, it is evident that scaling $\boldsymbol{w}$ by a positive factor does not affect the value of the objective function $\gamma(\boldsymbol{w}, \boldsymbol{p})$ in the above optimization. Thus, the above optimization problem can be converted to

$$\begin{aligned}& \max_{\boldsymbol{w},\, \boldsymbol{p}} \gamma(\boldsymbol{w}, \boldsymbol{p}) \\ & \text{subject to } \boldsymbol{p} \in S_{\boldsymbol{p}},\ \boldsymbol{w} \succeq \boldsymbol{0},\end{aligned} \tag{13}$$

which is a hybrid nonlinear optimization. Generally, the optimization has no closed-form solution.

4 Proposed iterative structure between OCC and SCP

To solve the problem (13), we propose a novel iterative optimization method. This iterative structure is composed of three steps. In the first step, $\boldsymbol{p}$ is chosen to be $[1,\ 2,\ \ldots,\ M]$, and $\boldsymbol{w}$ is set to $[1/\sqrt{M},\ 1/\sqrt{M},\ \ldots,\ 1/\sqrt{M}]^{\mathrm{T}}$ or computed by the following expression:

$$\boldsymbol{w} = \frac{\boldsymbol{B_p}^{-1} \boldsymbol{t_p}}{\|\boldsymbol{B_p}^{-1} \boldsymbol{t_p}\|_2}, \tag{14}$$

which will be derived in Section 4.2. Given the known weighted coefficient vector $\boldsymbol{w}$, the optimal SCP vector $\boldsymbol{p}$ is solved by the following optimization problem:

$$\begin{aligned}& \max_{\boldsymbol{p}} \gamma(\text{fixed } \boldsymbol{w},\ \boldsymbol{p}) \\ & \text{subject to } \boldsymbol{p} \in S_{\boldsymbol{p}},\end{aligned} \tag{15}$$

which is a binary integer optimization problem. An exhaustive search among the permutation sets of $\boldsymbol{p}$ can achieve the optimal permutation for a given $\boldsymbol{w}$ and implies a high level of computation: exponential complexity. Thus, we will present an approximate analytical low-complexity implementation for the above optimization problem in Section 4.1.

In the second step, given the optimal $\boldsymbol{p}$ in the first step, we optimize the weighted coefficient vector $\boldsymbol{w}$:

$$\begin{aligned}& \max_{\boldsymbol{w}} \gamma(\boldsymbol{w}, \text{fixed } \boldsymbol{p}) \\ & \text{subject to } ||\boldsymbol{w}||_2 = 1,\ \boldsymbol{w} \succeq \boldsymbol{0},\end{aligned} \tag{16}$$

whose closed-form solution will be derived in Section 4.2.

In the last step, we introduce an iterative structure between the above two steps.

4.1 Optimization of $\boldsymbol{p}$ given $\boldsymbol{w}$

For the purpose of simplifying the optimization in Eq. (15), let us first define $|h'_m| = |\alpha_m||h_m|$ and form a new virtual uplink channel $\boldsymbol{h}' = [h'_1,\ h'_2,\ \ldots,\ h'_M]^{\mathrm{T}}$. Substituting $|h'_m|$ in the objective function (15) yields the following simple form:

$$\gamma(\boldsymbol{w}, \boldsymbol{p}) = \frac{\boldsymbol{w}^{\mathrm{T}} \boldsymbol{A_p w}}{\boldsymbol{w}^{\mathrm{T}} \boldsymbol{B_p w}} = \frac{\left(\sum\limits_{m=1}^{M} |g_{p(m)}||h'_m|\right)^2}{C}, \tag{17}$$

regardless of the impact of the coefficients α_m of CC on the denominator of $\gamma(\boldsymbol{w}, \boldsymbol{p})$ with

$$C = \frac{\sum\limits_{m=1}^{M} |\alpha_m g_{p(m)}|^2 \sigma_R^2 + \beta^{-2} \sigma_D^2}{P_S}, \tag{18}$$

which can be viewed as a constant in order to simplify the objective function $\gamma(\boldsymbol{w}, \boldsymbol{p})$ of the optimization problem (15). For medium- and large-scale scenarios, the simplification approximately holds. Actually, by simulation, we find the simplification also holds even in the small-scale case.

Based on the above approximation, the optimization problem (15) is converted to

$$\max_{\boldsymbol{p}} \left(\sum_{m=1}^{M} \left| g_{p(m)} \right|^2 \left| h'_m \right|^2 \right)$$
$$\text{subject to } \boldsymbol{p} \in S_{\boldsymbol{p}}. \tag{19}$$

In terms of the rearrangement inequality (Graham *et al.*, 1994)

$$\sum_{k=1}^{n} a_k b_k \geq \sum_{k=1}^{n} a_k b_{p(k)} \geq \sum_{k=1}^{n} a_k b_{n-k+1} \tag{20}$$

for $0 \leq a_1 \leq a_2 \leq \ldots \leq a_n$ and $0 \leq b_1 \leq b_2 \leq \ldots \leq b_n$, where $\boldsymbol{p}$ is any permutation of set $\{1,\ 2,\ \ldots,\ n\}$, we have

$$\sum_{m=1}^{M} |g^2_{f^{-1}w(m)}||h'^2_m| \geq \sum_{m=1}^{M} |g^2_{p(m)}||h'^2_m| \tag{21}$$

for any $\boldsymbol{p}$, where $\{f(1),\ f(2),\ \ldots,\ f(M)\}$ is the permutation of $\{1,\ 2,\ \ldots,\ M\}$ such that $|h'^2_{f(1)}| \geq |h'^2_{f(2)}| \geq \ldots \geq |h'^2_{f(M)}|$, and $\{w(1),\ w(2),\ \ldots,\ w(M)\}$ is also the permutation of $\{1,\ 2,\ \ldots,\ M\}$ such that $|g^2_{w(1)}| \geq |g^2_{w(2)}| \geq \ldots \geq |g^2_{w(M)}|$. In other words, $\boldsymbol{p} = \boldsymbol{f}^{-1}\boldsymbol{w}$ is the closed-form solution to the optimization problem (19) and is called the approximate closed-form solution to the optimization problem (15) when $\boldsymbol{h'}$, $\boldsymbol{g}$, and β are given.

4.2 Optimization of $\boldsymbol{w}$ given $\boldsymbol{p}$

In this subsection, we derive the analytical solution to the optimization problem (16) when SCP is fixed. Let us first define

$$\widetilde{\boldsymbol{w}} = \boldsymbol{B}_{\boldsymbol{p}}^{1/2}\boldsymbol{w} \tag{22}$$

and

$$\widetilde{\boldsymbol{t}}_{\boldsymbol{p}} = \boldsymbol{B}_{\boldsymbol{p}}^{-1/2}\boldsymbol{t}_{\boldsymbol{p}}. \tag{23}$$

Then $\gamma(\boldsymbol{w}, \boldsymbol{p})$ is simplified as

$$\begin{aligned}\gamma(\boldsymbol{w}, \boldsymbol{p}) &= \gamma(\widetilde{\boldsymbol{w}}, \boldsymbol{p}) = \frac{\widetilde{\boldsymbol{w}}^{\mathrm{T}} \boldsymbol{B}_{\boldsymbol{p}}^{-1/2} \boldsymbol{A}_{\boldsymbol{p}} \boldsymbol{B}_{\boldsymbol{p}}^{-1/2} \widetilde{\boldsymbol{w}}}{\widetilde{\boldsymbol{w}}^{\mathrm{T}} \widetilde{\boldsymbol{w}}} \\ &= \frac{\widetilde{\boldsymbol{w}}^{\mathrm{T}} \left(\boldsymbol{B}_{\boldsymbol{p}}^{-1/2} \boldsymbol{t}_{\boldsymbol{p}} \right) \left(\boldsymbol{B}_{\boldsymbol{p}}^{-1/2} \boldsymbol{t}_{\boldsymbol{p}} \right)^{\mathrm{T}} \widetilde{\boldsymbol{w}}}{\widetilde{\boldsymbol{w}}^{\mathrm{T}} \widetilde{\boldsymbol{w}}} = \frac{\left(\widetilde{\boldsymbol{w}}^{\mathrm{T}} \widetilde{\boldsymbol{t}}_{\boldsymbol{p}} \right)^2}{\widetilde{\boldsymbol{w}}^{\mathrm{T}} \widetilde{\boldsymbol{w}}},\end{aligned} \tag{24}$$

whose numerator is rewritten as

$$\widetilde{\boldsymbol{w}}^{\mathrm{T}} \widetilde{\boldsymbol{t}}_{\boldsymbol{p}} = \|\widetilde{\boldsymbol{w}}\|_2 \|\widetilde{\boldsymbol{t}}_{\boldsymbol{p}}\|_2 \cos\theta, \tag{25}$$

where θ is the angle between two real M-dimensional vectors $\widetilde{\boldsymbol{w}}$ and $\widetilde{\boldsymbol{t}}_{\boldsymbol{p}}$. Substituting Eq. (25) into Eq. (24) yields

$$\gamma(\widetilde{\boldsymbol{w}}, \boldsymbol{p}) = \|\widetilde{\boldsymbol{t}}_{\boldsymbol{p}}\|_2^2 \cos^2\theta. \tag{26}$$

Maximizing the above expression means $\cos^2\theta = 1$, i.e.,

$$\widetilde{\boldsymbol{w}} = \eta\, \widetilde{\boldsymbol{t}}_{\boldsymbol{p}}, \tag{27}$$

where η is the scaling factor to guarantee $\|\widetilde{\boldsymbol{w}}\|_2 = 1$. Considering Eq. (23) and the above solution, we have

$$\boldsymbol{w}_{\boldsymbol{p}} = \frac{\boldsymbol{B}_{\boldsymbol{p}}^{-1} \boldsymbol{t}_{\boldsymbol{p}}}{\|\boldsymbol{B}_{\boldsymbol{p}}^{-1} \boldsymbol{t}_{\boldsymbol{p}}\|_2}, \tag{28}$$

which is the unique closed-form solution to the optimization problem (16), called OCC, with the normalized power

$$\beta_{\boldsymbol{p}} = \frac{\sqrt{P_R}}{\sqrt{P_S \sum\limits_{m=1}^{M} |w_{p(m)}|^2 |h_m|^2 + \sigma_R^2}}, \tag{29}$$

at R. This completes the derivation of the OCC given SCP.

4.3 Proposed iterative structure

This subsection focuses on the scenario where ideal channel state information (CSI) is available at R. Here, we design an AIS between OCC and SCP, which can further improve the SER performance in relay networks. The simple concept diagram block is depicted in Fig. 2 and the detailed implementation process is given in Algorithm 1.

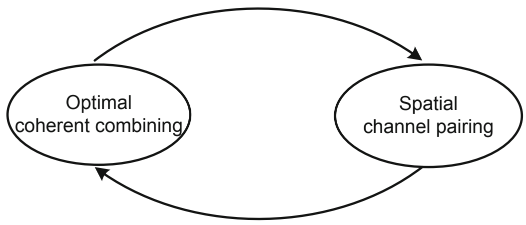

Fig. 2 Proposed alternating iterative structure between optimal coherent combining and spatial channel pairing

In Algorithm 1, ε represents the predefined small termination threshold.

Algorithm 1 Proposed alternating iterative structure between optimal coherent combining and spatial channel pairing

Input: P_S, P_R, σ_R^2, σ_D^2, β, $k=1$, $\gamma(\boldsymbol{p}^1, \boldsymbol{w}^1)=0$, and $\boldsymbol{w}^k=[1/\sqrt{M},\ 1/\sqrt{M},\ \ldots,\ 1/\sqrt{M}]^{\mathrm{T}}$.
Output: $\boldsymbol{p}^k$, $\boldsymbol{w}^k$, and β^k.
1: **Repeat**
2: Use Eq. (15) to find the optimal $\boldsymbol{p}^k$ provided that $\boldsymbol{w}$ in Eq. (28) is taken to be $\boldsymbol{w}^k$.
3: Compute the optimal $\boldsymbol{w}^k$ by using Eq. (28) provided that $\boldsymbol{p}$ in Eq. (21) is taken to be $\boldsymbol{p}^k$.
4: Compute β^k using Eq. (4).
5: $k=k+1$.
6: **Until** $|\ \gamma(\boldsymbol{p}^{k+1}, \boldsymbol{w}^{k+1}) - \gamma(\boldsymbol{p}^k, \boldsymbol{w}^k)\ | < \varepsilon$

5 Simulation results and discussion

In what follows, the performance of the proposed SCP-based CC is evaluated and compared to those of existing schemes. The baseband system parameters in our simulation are set as follows: R is equipped with $M=4$ antennas, and both destination and source nodes have one antenna. Channels corresponding to different users are assumed to be independently Rayleigh block-fading. The average SNRs at R and node D are defined as $\mathrm{SNR}_R = P_S/\sigma_R^2$ and $\mathrm{SNR}_D = P_R/\sigma_D^2$, respectively.

Below, a scheme called MRC plus antenna selection (AS, MRC plus AS) is used as one of references. In this scheme, the MRC is adopted to combine the received M-branch signals in the first slot at the relay. In the second time slot, via the AF-strategy, the coherent combined signal is transmitted through the best branch of the downlink M branches to the destination.

To evaluate the convergence of the proposed AIS, its curves of SER versus the number of iterations are demonstrated for three different SNRs ($\mathrm{SNR}_R = \mathrm{SNR}_D = 10$, 15, and 20 dB) with 16-ary quadrature amplitude modulation (16-QAM). From Fig. 3, it is clear that the SER curves converge to the corresponding error ceil by using only two or three iterations. Thus, the proposed iterative structure has rapid convergence. We also find that the convergence speed of the proposed method decreases with the increase of SNR.

Fig. 4 demonstrates the curves of SER of the proposed AIS versus the number of iterations for three distinct SNRs ($\mathrm{SNR}_D = 10$, 15, and 20 dB) with 16-QAM given $\mathrm{SNR}_R = 15$ dB. From Fig. 4, similar to Fig. 3, it is clear that the SER curves converge to the corresponding error ceil in only two or three iterations. Thus, the proposed iterative structure converges fast.

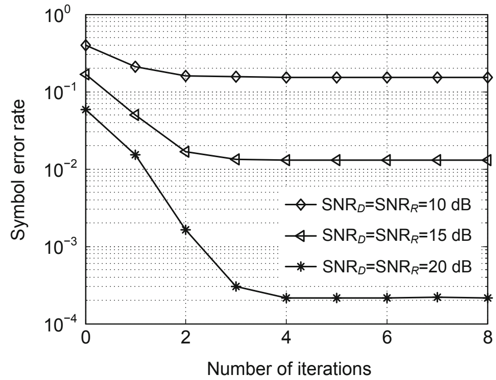

Fig. 3 Curves of the symbol error rate versus the number of iterations for the proposed AIS with 16-QAM (SNR_D=SNR_R)

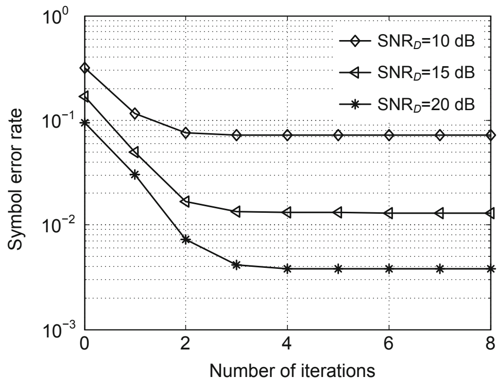

Fig. 4 Curves of the symbol error rate versus the number of iterations for the proposed AIS with 16-QAM (SNR_R=15 dB)

To see the impact of SCP on SER, Fig. 5 illustrates the curves of SER versus the average SNR of R for MRC plus MF (an abbreviation of maximum ratio combining plus matched filter (Li *et al.*, 2009)), MRC plus AS, the proposed AIS between SCP and OCC, and DSTBC (Jing, 2013), under the condition that the average SNR of relay R is equal to the average SNR of destination D. It can be seen that the proposed AIS between SCP and OCC shows a substantial improvement in SER over existing MRC plus MF and MRC plus AS due to the SCP gain. For example, for a fixed SER=10^{-3}, the proposed AIS achieves about 2.5, 2, and 6 dB SNR gains over

MRC plus MF, MRC plus AS, and DSTBC, respectively. It is also noted that DSTBC does not need CSI whereas the remaining three combining schemes require that both downlink and uplink CSIs be available at the RS.

Fig. 6 illustrates the curves of SER versus the average SNR of node D for MRC plus MF, MRC plus AS, the proposed AIS, and DSTBC when the average SNR of relay R is fixed at 20 dB. Evidently, the same performance trend is obtained as shown in Fig. 5. However, all schemes have error floors due to a fixed average SNR of R. Due to SCP, the proposed AIS attains around 6, 2, and 12 dB SNR gains over MRC plus MF, MRC plus AS, and DSTBC, respectively, for a given SER=10^{-3}.

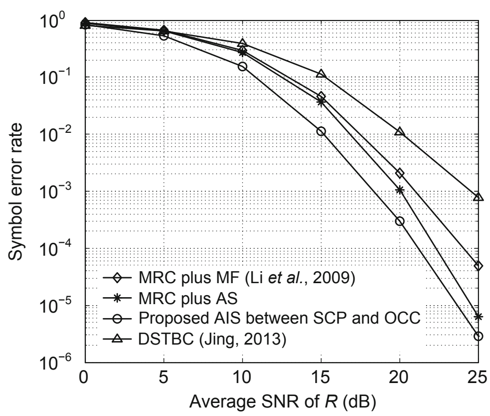

Fig. 5 Curves of the symbol error rate versus the average SNR$_R$ with 16-QAM (SNR$_D$=SNR$_R$)

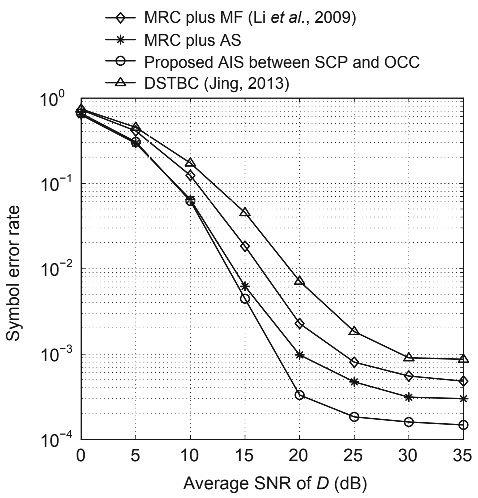

Fig. 6 Curves of the symbol error rate versus the average SNR$_D$ with 16-QAM (SNR$_R$=20 dB)

Fig. 7 illustrates the rate performance comparison among MRC plus MF, MRC plus AS, and the proposed AIS under SNR$_D$ = SNR$_R$. Evidently, the same performance trend is obtained as shown in Figs. 5 and 6. Given a rate of 3 bits/(s·Hz), the proposed AIS shows at least a 5-dB SNR improvement compared to MRC plus MF and MRC plus AS. Thus, the gain is also attractive due to SCP.

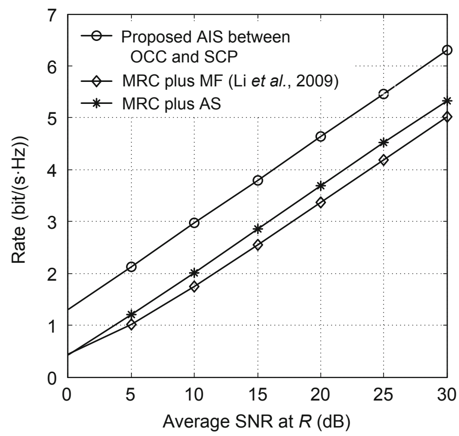

Fig. 7 Rate performance comparison (SNR$_D$=SNR$_R$)

6 Conclusions

We have proposed an AIS between SCP and OCC for relay networks. Based on our simulation and analysis, the proposed AIS performs much better than existing schemes (MRC plus MF, MRC plus AS, and DSTBC) in both SER and rate senses because of the use of SCP and the iterative structure. In summary, the SNR gain provided by SCP is rather attractive with a reasonable complexity. Therefore, the proposed AIS can be applied to future wireless communications like 5G.

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