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Spatial channel pairing-based maximum ratio combining algorithm for cooperative relay networks

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Abstract: To improve the reliable performance of information transmission in cooperative relay networks, the scheme of the max-rate spatial channel pairing (SCP) based on maximum ratio combining (MRC) is proposed. The scheme includes three steps: channel phase cancellation, MRC, and SCP. Eventually, the solution of the scheme is modeled as convex optimization. The objective function of the optimization problem is to maximize the transmission rate and the optimization variable is the strategy of pairing between the uplink spatial sub-channels of each user and the corresponding downlink spatial ones. The theorem of the arrangement inequalities is adopted to obtain the approximate closed-form solution of the optimal pairing for this convex optimization. Simulation results demonstrate that compared to the existing distributed space-time block coding and coherent combined schemes without SCP, the proposed max-rate SCP plus MRC algorithm achieves appreciable improvements in symbol error rate in medium and high signal-to-noise ratio regimes. The achievable performance gain is due to the use of max-rate SCP.

Key words: relay; maximum ratio combining; coherent combining; spatial channel pairing; distributed space-time block coding

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The schemes of distributed space-time block coding (DSTBC) and coherent combining (CC) are two main ways to achieve cooperative diversity gain in relay networks[1-7]. Several combined and DSTBC schemes have been developed for relay networks in Refs. [1 - 5]. In Ref. [2], DSTBC for relay networks is designed to exploit cooperative diversity. In Ref. [3], the combination of maximum ratio combining (MRC) and DSTBC at relay station (RS) is proposed to make an improvement in symbol error-rate (SER). In Ref. [5], three CC schemes are proposed for two-way relay networks. The best CC scheme among the three CC schemes in Ref. [5], called CC scheme Ⅰ, is chosen for performance reference in the simulation section. In Refs. [8 - 14], subcarrier pairing and resource allocation are investigated in relay networks. In Ref. [15], the authors proposed a high-performance beamformer for multi-pair two-way relay networks with the amplify-and-forward relaying strategy. An optimal spatial channel pairing (SCP) based on the maximum sum-rate is proposed for multi-pair two-way relay network when block diagonalization based beamforming is adopted at RS in Ref. [16]. Due to the use of optimal SCP, the sum-rate of network is clearly improved. Following those works, the main contributions of this paper are as follows: we present a general SCP-based CC model for one-way relay networks and propose a joint scheme of max-rate SCP and MRC to further improve the SER performance of such networks.

1 System Model

A typical relay network consists of one source node A, one destination node B and one RS, as shown in Fig. 1. The RS has M antennas, while nodes A and B have only

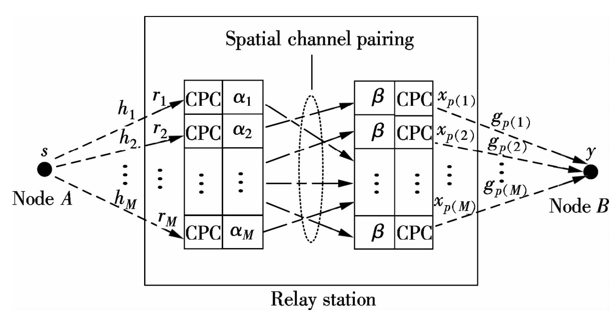

Fig. 1 A relay system model with spatial channel pairing and channel phase cancellation (CPC)

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one antenna and the relay network operates in half-duplex mode. The channel gains from node A to the m-th antenna of the RS and from the m-th antenna of RS to node B are denoted as h_m and g_m, respectively. In the half-duplex mode, data transmission from source node to destination node via RS spans two time slots.

In the first time slot, node A transmits data symbols to RS and the average transmit power of node A is P_A. Then, the symbols received by the m-th antenna of RS is given by

$$r_m = h_m s + n_{\mathrm{RS},m} \tag{1}$$

where h_m denotes the narrow-band channel gain from node A to the m-th antenna of RS; s represents the symbol transmited by node A; and $n_{\mathrm{RS},m}$ is the corresponding complex additive white Gaussian noise (AWGN) at the m-th antenna of RS with zero mean and variance σ_{RS}^2. Using the amplify-and-forward relaying strategy, r_m experiences two-way channel phase cancellation, amplifying, and permuting, and is transmitted towards node B by using the $p(m)$ antenna of RS in the second time slot, where $\{p(1), p(2), \ldots, p(M)\}$ is an arbitrary permutation of $\{1, 2, \ldots, M\}$ and can be viewed as a spatial channel paring or one-to-one mapping/function between uplink and downlink spatial channels. The final transmit signal from the antenna $p(m)$ at RS is expressed as

$$\begin{aligned} x_{p(m)} = {} & \exp(-\mathrm{j}\theta_{g_{p(m)}})\beta\alpha_m \exp(-\mathrm{j}\theta_{h_m}) r_m = \\ & \exp(-\mathrm{j}\theta_{g_{p(m)}})\beta\alpha_m \| h_m \| s + \\ & \exp(-\mathrm{j}\theta_{g_{p(m)}})\beta\alpha_m \exp(-\mathrm{j}\theta_{h_m}) n_{\mathrm{RS},m} \end{aligned} \tag{2}$$

where θ_{h_m} and $\theta_{g_{p(m)}}$ are the phases of complex channel gains h_m and $g_{p(m)}$, respectively; $\alpha_m \geqslant 0$ for all $m \in S_M$; and α_m and β are designed to satisfy the following transmit power constraint of RS:

$$\beta^2 \left[\sum_{m=1}^{M} \| \alpha_m h_m \|^2 P_A + \sigma_{\mathrm{RS}}^2 \sum_{m=1}^{M} \| \alpha_m \|^2 \right] = P_{\mathrm{RS}} \tag{3}$$

where P_{RS} is the total transmit power constraint at RS and $\| \cdot \|$ stands for the 2-norm or absolute value of a complex or real number. Eq. (3) specifies the value of β as

$$\beta = \sqrt{\frac{P_{\mathrm{RS}}}{\sum_{m=1}^{M} \| \alpha_m h_m \|^2 P_A + \sigma_{\mathrm{RS}}^2 \sum_{m=1}^{M} \| \alpha_m \|^2}} \tag{4}$$

Finally, the final received signal at node B is

$$\begin{aligned} y = {} & \left(\beta \sum_{m=1}^{M} \alpha_m \| g_{p(m)} h_m \| \right) s + \\ & \beta \sum_{m=1}^{M} \| g_{p(m)} \| \alpha_m \exp(-\mathrm{j}\theta_{h_m}) n_{\mathrm{RS},m} + n_B \end{aligned} \tag{5}$$

Note that the two complex exponential terms $\exp(-\mathrm{j}\theta_{g_{p(m)}})$ and $\exp(-\mathrm{j}\theta_{h_m})$ on the right-hand side of Eq. (2) are to cancel channel phases of two time slots and guarantee that all delayed fading versions of useful data symbols s are constructively combined at node B as shown in Eq. (5).

2 Max-Rate Spatial Channel Pairing based MRC Algorithm

In this section, the combination of the MRC and max-rate based SCP, which is named max-rate SCP plus MRC for short hereinafter, is proposed by using the maximum-rate criterion with the known parameters h, g and α. Then an approximate closed-form solution of the scheme is presented. To implement MRC[3,5], $\boldsymbol{\alpha}$ is set to be

$$\begin{aligned} \boldsymbol{\alpha} = {} & \{\alpha_1, \alpha_2, \cdots, \alpha_M\}^{\mathrm{T}} = \\ & \{ \| g_{p(1)} h_1 \|, \| g_{p(2)} h_2 \|, \cdots, \| g_{p(M)} h_M \| \}^{\mathrm{T}} \end{aligned} \tag{6}$$

Substituting Eq. (6) into Eq. (5) yields

$$\begin{aligned} y = {} & \left(\beta \sum_{m=1}^{M} \| g_{p(m)} h_m \|^2 \right) s + \\ & \beta \sum_{m=1}^{M} \| g_{p(m)}^2 h_m \| \exp(-\mathrm{j}\theta_{h_m}) n_{\mathrm{RS},m} + n_B \end{aligned} \tag{7}$$

$$\beta = \sqrt{\frac{P_{\mathrm{RS}}}{\sum_{m=1}^{M} \| g_{p(m)} h_m^2 \|^2 P_A + \sigma_{\mathrm{RS}}^2 \sum_{m=1}^{M} \| g_{p(m)} h_m \|^2}} \tag{8}$$

Based on Eq. (7), the receive signal-to-noise ratio (SNR) is given by

$$\begin{aligned} \mathrm{SNR}(p) = {} & \frac{P_A \beta^2 \left(\sum_{m=1}^{M} \| g_{p(m)} \|^2 \| h_m \|^2 \right)^2}{\beta^2 \sigma_{\mathrm{RS}}^2 \sum_{m=1}^{M} \| g_{p(m)}^4 h_m^2 \| + \sigma_B^2} = \\ & P_A P_{\mathrm{RS}} \left(\sum_{m=1}^{M} \| g_{p(m)} \|^2 \| h_m \|^2 \right)^2 \\ & \left\{ \sum_{m=1}^{M} \| g_{p(m)}^2 h_m^2 \| (P_{\mathrm{RS}} \sigma_{\mathrm{RS}}^2 \| g_{p(m)}^2 \| + \right. \\ & \left. \sigma_B^2 P_A \| h_m^2 \| + \sigma_B^2 \sigma_{\mathrm{RS}}^2) \right\}^{-1} \end{aligned} \tag{9}$$

which forms the following max-rate SCP:

$$\max_p \frac{1}{2} \log_2 (1 + \mathrm{SNR}(p)) \qquad \text{s.t. } p \in S_p \tag{10}$$

where S_p is a set of all permutations of $\{1, 2, \cdots, M\}$. Clearly, the optimization problem as shown in Eq. (10) is a binary combination optimization and can be solved by exhaustive search. Exhaustive search will require an exponential complexity $O(M!)$. To develop a low-complexity approximate solution to Eq. (10), the effect of the permutation p on the denominator of Eq. (9) is omitted, and the optimization problem as shown in Eq. (10) can be simplified as

$$\max_p \frac{1}{2} \log_2 \left\{ 1 + \frac{\left(\sum_{m=1}^{M} \| g_{p(m)} \|^2 \| h_m \|^2 \right)^2}{C} \right\}$$

$$\text{s.t. } p \in S_p \tag{11}$$

where

$$C = \left\{ P_A P_{\mathrm{RS}} \sum_{m=1}^{M} \| g_{p(m)}^2 h_m^2 \| (P_{\mathrm{RS}} \sigma_{\mathrm{RS}}^2 \| g_{p(m)}^2 \| + \sigma_B^2 P_A \| h_m^2 \| + \sigma_B^2 \sigma_{\mathrm{RS}}^2) \right\}^{-1} \tag{12}$$

is approximately viewed as a constant independent of $\{1, 2, \cdots, M\}$, then the optimization problem of Eq. (11) is transformed to

$$\max_p \left(\sum_{m=1}^{M} \| g_{p(m)} \|^2 \| h_m \|^2 \right) \qquad \text{s.t. } p \in S_p \tag{13}$$

In terms of the rearrangement inequality[17],

$$\sum_{k=1}^{n} a_k b_k \geqslant \sum_{k=1}^{n} a_k b_{p(k)} \geqslant \sum_{k=1}^{n} a_k b_{n-k+1} \tag{14}$$

for $0 \leqslant a_1 \leqslant \cdots \leqslant a_n$ and $0 \leqslant b_1 \leqslant \cdots \leqslant b_n$, where p is any permutation of set $0 \leqslant b_1 \leqslant \cdots \leqslant b_n$, thus

$$\sum_{m=1}^{M} \| g_{f^{-1}(w(m))}^2 \| \| h_m^2 \| \geqslant \sum_{m=1}^{M} \| g_{p(m)}^2 \| \| h_m^2 \| \tag{15}$$

where $\{w(1), w(2), \cdots, w(M)\}$ and $\{f(1), f(2), \cdots, f(M)\}$ are the permutations of $\{1, 2, \cdots, M\}$, with $g_{w(1)} \geqslant g_{w(2)} \geqslant \cdots \geqslant g_{w(M)}$ and $h_{f(1)} \geqslant h_{f(2)} \geqslant \cdots \geqslant h_{f(M)}$, respectively, and $f^{-1}(\cdot)$ is the inverse function or mapping of the permutation $f(\cdot)$. The composition function $f^{-1}(w)$ is the closed-form solution to the optimization problem Eq. (13) and called the approximate closed-form solution to the optimization problem Eq. (10) given the known parameters h, g and α.

3 Numerical Results and Discussion

The proposed max-rate SCP plus MRC algorithm and DSTBC and CC schemes are evaluated and compared in the following numerical simulation.

In the simulation scenario, RS employs four antennas ($M = 4$), while the source node and destination node each has one antenna. Channels corresponding to different nodes are assumed to be independently Rayleigh block-fading. The average receive SNRs at RS and destination node B are defined as $\mathrm{SNR}_{\mathrm{RS}} = P_A / \sigma_{\mathrm{RS}}^2$ and $\mathrm{SNR}_B = P_{\mathrm{RS}} / (M \sigma_B^2)$, respectively. In order to guarantee the proposed combined and reference schemes have the same spectrum efficiency, a full-rate quasi-orthogonal STBC with 4 by 4 code word in Ref. [18] is used.

Fig. 2(a) illustrates the curves of SER vs. average SNR of RS for exhaustive search and approximate closed-form solutions of the proposed max-rate SCP plus the MRC algorithm. From Fig. 2(a), it is clear that the approximate closed-form version achieves the same SER performance as the exhaustive search one. Fig. 2(b) demonstrates the curves of rate vs. the average SNR of RS for exhaustive search and approximate closed-form solutions of the proposed max-rate SCP plus the MRC algorithm. The rate evolution trend is identical to the SER one as indicated in Fig. 2(b). This further proves the equivalence between the approximate closed-form of this method and exhaustive search solutions.

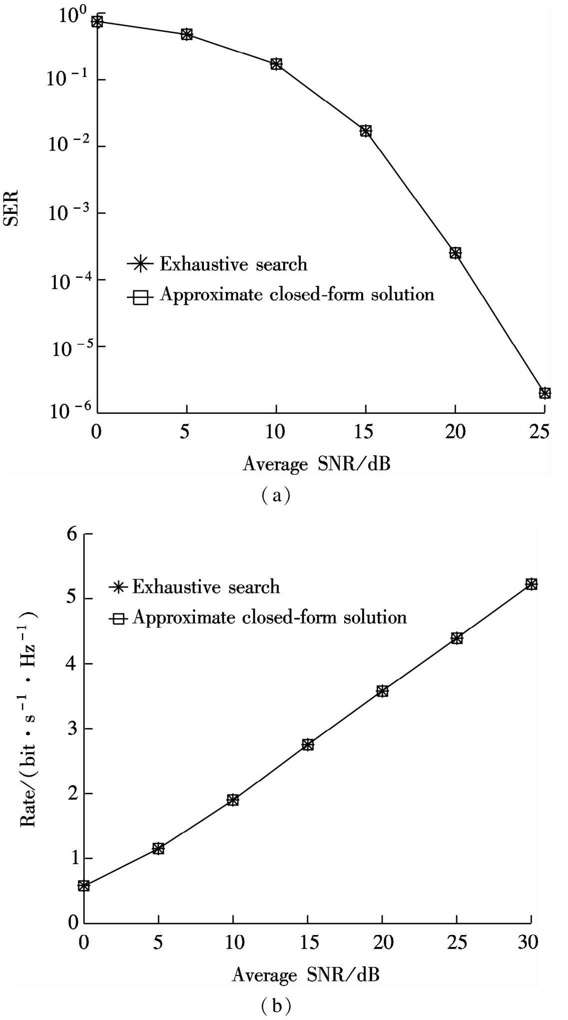

Fig. 2 Curves of SER and rate vs. average SNR of RS under the conditions of the modulation type of 16 QAM and the average SNR of RS equal to that of node B. (a) SER vs. average SNR; (b) Rate vs. average SNR

Fig. 3(a) illustrates the curves of SER as a function of the average SNR of RS for the CC scheme Ⅰ in Ref. [5], MRC-DSTBC in Ref. [3], and the proposed max-rate SCP plus MRC algorithm. From Fig. 3(a), it is evident that the proposed max-rate SCP plus MRC algorithm performs much better than the CC scheme Ⅰ in Ref. [5] and MRC plus DSTBC. For example, it achieves appreciable (about 3 and 7 dB) SNR gains over the CC scheme Ⅰ in Ref. [5] and MRC-DSTBC in Ref. [3] at SER = 10^{-3}, respectively. Fig. 3(b) demonstrates the curves of rate as a function of the average SNR of RS for the proposed max-rate SCP plus MRC algorithm and the CC scheme Ⅰ in Ref. [5]. The rate of the proposed max-mate SCP plus MRC is slightly greater than that of the CC scheme Ⅰ without SCP in Ref. [5]. In summary, due to the use of the max-rate SCP, both the SER and sum-rate performances of the proposed max-rate SCP plus MRC algorithm are improved compared to those of the existing CC and DSTBC schemes without SCP.

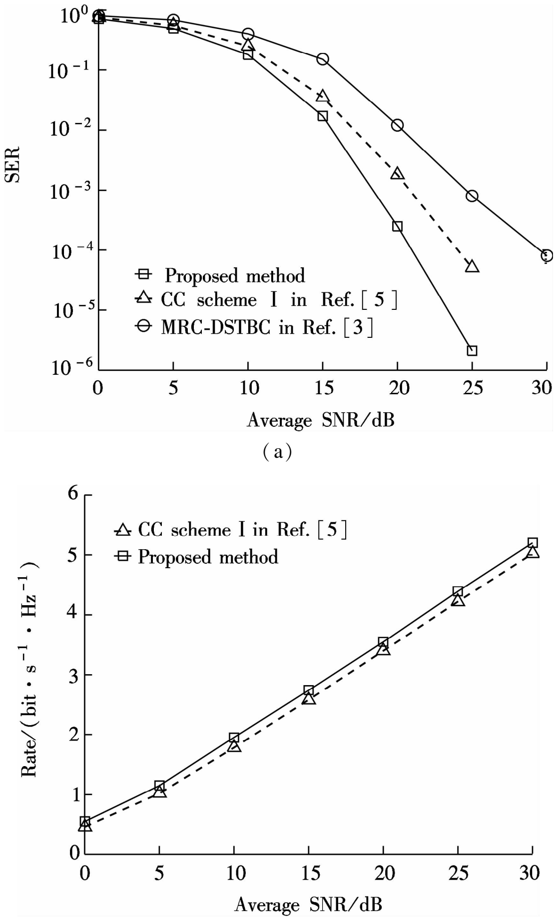

Fig. 3 Performance comparisons among different schemes under the conditions of the modulation type of 16 QAM and the average SNR of RS equal to that of node *B*. (a) SER vs. average SNR; (b) Rate vs. average SNR

4 Conclusion

In this paper, the max-rate SCP plus MRC algorithm is proposed and investigated for relay networks. Based on the analysis and simulation, the proposed max-rate SCP plus MRC algorithm performs better than existing DSTBC and CC schemes without SCP. Although the proposed max-rate SCP plus MRC algorithm is specifically designed for one-way relay networks, it can be applied to two-way relay networks with the same structure as indicated in Fig. 1 with minor revision due to the self-interference cancelation ability of the two-way relay networks.

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中继协作网络中基于空间信道配对的最大比合并算法

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摘要:为了提高中继协作网络中信息传输的可靠性,提出了基于最大比合并的速率最大化空间信道配对的方案. 该方案包括3个步骤:信道相位消除、最大比合并和空间信道配对. 将该方案建模为凸优化问题,优化的目标函数是最大化传输速率,优化变量为每个用户上行链路的空间子信道与其相应的下行链路的空间子信道的配对策略. 采用排序不等式定理推导并获得了该优化问题的最优空间信道配对解的近似闭合表达式. 仿真结果表明,相比于已有的分布式空时分组码和相干合并的方法,所提出的基于空间信道配对的最大比合并算法的符号误码率性能在中、高信噪比区间获得了明显的提高,此性能的提高归功于所提方法充分利用了空间信道配对增益.

关键词:中继;最大比合并;相干合并;空间信道配对;分布式空时分组码

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