Cochannel Interference Suppression in the Single Antenna Amplify-and-Forward Relay Networks

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Abstract
We consider an amplify-and-forward relay system with a source node (S), a relay node (R), and a destination node (D) with an arbitrary number of cochannel interferers at the relay. Each node is equipped with a single antenna and operates under the frequency selective circumstance. For such a system, we propose a system scheme to suppress the relay cochannel interference (CCI) at both the relay and the destination, where the relay performs noise selective nulling in the training block to make the relay training sequence avoid suffering from the thermal noise and CCIs at R, and the destination combines the data blocks from the S→R→D link and the S→D link. Simulation results show that the proposed system scheme achieves better channel estimation and symbol detection performance than the original one.
Key words: COCHANNEL INTEFERENCE SUPPRESSION, NOISE NULLING, DIVERSITY COMBINING, AMPLIFY-AND-FORWARD, RELAY NETWORKS

1. Introduction

The multi-user environment of cooperative communication brings the diversity gain and the cochannel interference (CCI) at the same time. Although the amplify-and-forward protocol has been well investigated, most of the existing works only consider the condition without CCI [1-3], and this assume does not accord with the practical scenarios of cooperative communication. In [4], the authors analyze the performance of AF relay with CCIs. In [5], the authors further study the problem when CCIs present at both the relay and the destination. CCIs could limit the diversity gain of systems and induce severe performance degradation [6].

To cope with CCI, the CCI suppressing capabilities of multi-antenna relays performing equal-gain combining (EGC), maximal ration combining (MRC) and optimum combining (OC) are analyzed in [7], and an estimate-amplify-and-forward (EAF) protocol is proposed based on the conventional AF (CAF) protocol in [8]. In EAF scheme, the CCI and thermal noise present at both relay and destination, and the relay is assumed to have the channel state information (CSI) of the channel. With the pilots sent by the source node, the relay can estimate the second order statistics of the channels between the interferences and the relay, and then performs OC to suppress the CCIs. However, the cochannel suppression schemes based on EGC, MRC or OC, only fit to cope with the relay equipped with multi-antenna. The cochannel suppression problem in single antenna systems has not been considered. To suppress the CCIs in single antenna AF relay systems, a new system scheme is proposed here. The scheme is developed on the superimposed training system proposed in [9], and can be applied in the system where the $\mathsf{S} \to \mathsf{D}$ link exists. In the scheme, both the relay and the destination answer for the CCI suppression. The relay performs noise nulling selectively on the frequency pins that will accommodate the relay training sequence, which prevents the relay training from suffering CCIs and the thermal noise at R and improves the channel estimation performance. The terms *relay noise* and *relay noise power* indicate the CCIs and the thermal noise at R, and their power, respectively. We refer this relay protocol as noise selective nulling AF (NSN AF). The destination node uses the *empty* frequency pins (the frequency pins do not accommodate any training sequences) to estimate the *relay noise power*, and combines the date blocks from the $\mathsf{S} \to \mathsf{R} \to \mathsf{D}$ link and the $\mathsf{S} \to \mathsf{D}$ to suppress the *relay noise*. We refer this system scheme as NSN AF relay system scheme.

Notation: Superscripts *H*, * and *T* denote the complex conjugate transpose, complex conjugation, transpose, respectively. $\mathbf{1}_{N\times 1}$ and $\mathbf{0}_{N\times 1}$ represent the $N\times 1$ vector of all ones and zeros, respectively. The $N\times N$ DFT matrix and $N\times N$ identity matrix are denoted by $\mathbf{F}$ and $\mathbf{I}$, respectively, and $\mathbf{F}_{N\times L}$ denotes the first *L* columns of $\mathbf{F}$. $|\cdot|$ denotes the absolute value and $[\mathbf{A}]_{ij}$ denotes the element in the *i*th row and the *j*th column of A, $\tilde{\mathbf{x}} = \mathbf{F}\mathbf{x}$.

2. NSN AF Relay System Model

The system model is shown in figure 1, which includes three single antenna node operating in half-duplex mode: the source node S, the relay node R and the destination node D. N_{I} cochannel interferences with arbitrary power exist at R. The CCI at D is not within the scope of this paper.

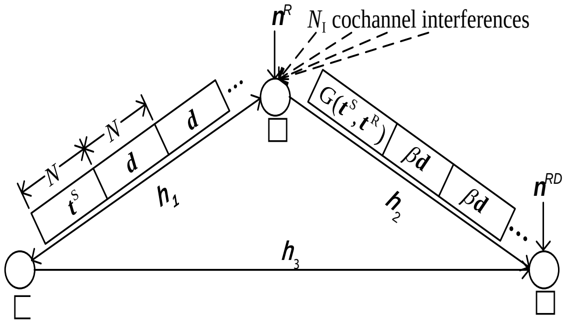

Figure 1. Three-node one-way relay networks

The system has three useful channel, they are the channel between S and R ($\mathsf{S} \to \mathsf{R}$), the channel between R and D ($\mathsf{R} \to \mathsf{D}$), and the channel between S and D ($\mathsf{S} \to \mathsf{D}$). The channel response of them are $\mathbf{h}_1 = [h_{1,0}, h_{1,1}, \ldots h_{1,L_1-1}]^T$, $\mathbf{h}_2 = [h_{2,0}, h_{2,1}, \ldots h_{2,L_2-1}]^T$, and $\mathbf{h}_3 = [h_{3,0}, h_{3,1}, \ldots h_{3,L_3-1}]^T$, respectively. Besides, there are N_{I} channel between cochannel interference and the relay with channel response $\mathbf{h}_i^{\mathrm{I}} = [h_{i,0}^{\mathrm{I}}, h_{i,1}^{\mathrm{I}}, \ldots h_{i,L_i^{\mathrm{I}}-1}^{\mathrm{I}}]^T$, $i = 1, 2, ..., N_{\mathrm{I}}$, respectively. The system operates over a frequency-selective channel. All channels as well as their taps are independent with each other, besides, all taps are assumed as zeros-mean circularly symmetric complex Gaussian random variables. We also assume perfect synchronization between S, R and D, and the cyclic prefix inserted in the system is long enough.

2.1 Signal Transmission Model

2.1.1 Signal Transmission Model in Channel

First we build a model of CCI. Let $s_i(n)$ represents the symbol form *i*th interference at time index n, $i = 0, 1, ..., N_{\mathrm{I}} - 1$, $E[|s_i(n)|^2] = P_i$ [8]. Let $\mathbf{v}_{\mathrm{int},t} = [v_{\mathrm{int}}(0), v_{\mathrm{int}}(1), ..., v_{\mathrm{int}}(N-1)]^H$ denotes the CCI received by the relay with training block, which can be calculated as

$$\mathbf{v}_{\mathrm{int},t}=\sum_{i=0}^{N_I-1}e^{\mathrm{j}\varphi_i}\underbrace{\begin{bmatrix} h_i^{\mathrm{I}}(L_i^{\mathrm{I}}-1) & h_i^{\mathrm{I}}(L_i^{\mathrm{I}}-2) & \cdots & h_i^{\mathrm{I}}(1) & h_i^{\mathrm{I}}(0) & 0 & \cdots & \cdots & 0\\ 0 & h_i^{\mathrm{I}}(L_i^{\mathrm{I}}-1) & \cdots & h_i^{\mathrm{I}}(2) & h_i^{\mathrm{I}}(1) & h_i^{\mathrm{I}}(0) & 0 & \cdots & 0\\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots\\ 0 & \cdots & \cdots & 0 & \cdots & 0 & h_i^{\mathrm{I}}(L_i^{\mathrm{I}}-1) & \cdots & h_i^{\mathrm{I}}(0)\end{bmatrix}}_{\mathbf{H}_i^{\mathrm{I}}}\begin{bmatrix} s_i(-L_i^{\mathrm{I}}+1)\\ s_i(-L_i^{\mathrm{I}}+2)\\ \vdots\\ s_i(-1)\\ s_i(0)\\ s_i(1)\\ s_i(2)\\ \vdots\\ s_i(N-1)\end{bmatrix}, \quad (1)$$

where $e^{\mathrm{j}\varphi_i}$ represents the stochastic phase shift caused by the asynchronies between the interferences and the relay, and each φ_i is drawn independently from a uniform distribution over $[0,2\pi]$ [10]. The CCI received by the relay with data block $\mathbf{v}_{\mathrm{int},d}$ can be calculated in the same way.

The construction method of $\mathbf{t}^{\mathrm{S}}$ and $\mathbf{t}^{\mathrm{R}}$ is not within the scope of this paper, we only offer a pair of sequence as an example. First, we calculate a sequence with $c(k)=\exp(j2\pi k^2/(2M)),\ k=0,1,...M-1$, and put $N/M-1$ zeros after each $c(k)$, obtaining the sequence $\mathbf{b}=[c(0),\underbrace{0,0,....,}_{N/M-1}c(1),\underbrace{0,0,...,}_{N/M-1}c(15),\underbrace{0,0,...0}_{N/M-1}]^T$. Let $\mathbf{t}^{\mathrm{S}}=\mathbf{Fb}$. Perform cyclic shift on $\mathbf{b}$ to get the sequence $\mathbf{b}_1=[0,c(0),\underbrace{0,0,....,}_{N/M-1}c(1),\underbrace{0,0,...,}_{N/M-1}c(15),\underbrace{0,0,...0}_{N/M-2}]^T$. Let $\mathbf{t}^{\mathrm{R}}=\mathbf{Fb}_1$. The $\mathbf{t}^{\mathrm{S}}$ and $\mathbf{t}^{\mathrm{R}}$ offered here are suitable for the system satisfying $L_1+L_2\le M$. Both sequences occupy M frequency pins only.

Let $\mathbf{H}_1$ to be a column-wise circulant matrix with the first column as $[\mathbf{h}_1^T,\mathbf{0}_{1\times(N-L_1)}]^T$, where $\mathbf{0}_{p\times q}$ represents a $p\times q$ matrix of all zeros. With (1), the training block received by relay can be written as

$$\mathbf{r}_t=\mathbf{H}_1\mathbf{t}^{\mathrm{S}}+\mathbf{v}_{\mathrm{int},t}+\mathbf{n}_t^{\mathrm{R}}, \quad (2)$$

where $\mathbf{n}_t^{\mathrm{R}}$ represents an $N\times 1$ white Gaussian noise vector added on training block at R, with variance σ_n^2 on each entries.

Let K_{R} denote the set of all indices of nonzero entries in $\mathbf{b}_1$. To suppress the *relay noise* at R, define an $N\times N$ diagonal matrix $\tilde{\mathbf{J}}$, which diagonal entries are zeros except $[\tilde{\mathbf{J}}]_{kk}=1,\ k\in\mathsf{K}_{\mathrm{R}}$. The operations of relay before amplifying is shown in figure 2 and (3).

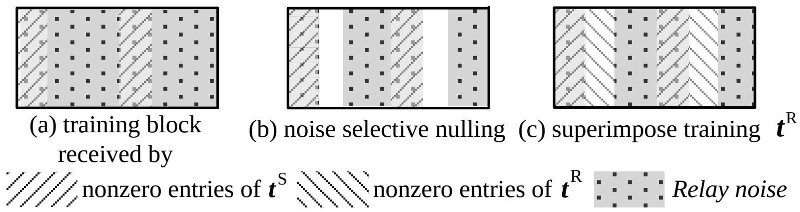

Figure 2. Operation on the training block at the NN AF relay

$$G(\mathbf{t}^{\mathrm{S}},\mathbf{t}^{\mathrm{R}})=\sqrt{\alpha}\beta\mathbf{J}\mathbf{r}_t+\sqrt{1-\alpha}\beta\mathbf{t}^{\mathrm{R}}, \quad (3)$$

where $\mathbf{J}=\mathbf{F}^H\tilde{\mathbf{J}}\mathbf{F}$, α controls the power allocation between $\mathbf{t}^{\mathrm{S}}$ and $\mathbf{t}^{\mathrm{R}}$, and β is the amplification factor. The relay suppresses part of *relay noise* that occupy the same frequency pins with $\tilde{\mathbf{t}}^{\mathrm{R}}$ and leaves the noise on *empty* frequency pins for *relay noise power* estimation at D. This relay protocol is referred as noise selective nulling AF (NSN AF).

Let $\mathbf{H}_2$ denote the column-wise circulant matrix with the first column $[\mathbf{h}_2^T,\mathbf{0}_{1\times(N-L_2)}]^T$. With (2) and (3), the training block received by D can be expressed as

$$\mathbf{y}_t=\sqrt{\alpha}\beta\mathbf{H}_2\mathbf{J}\mathbf{H}_1\mathbf{t}^{\mathrm{S}}+\sqrt{1-\alpha}\beta\mathbf{H}_2\mathbf{t}^{\mathrm{R}}+\sqrt{\alpha}\beta\mathbf{H}_2\mathbf{J}(\mathbf{v}_{\mathrm{int},t}+\mathbf{n}_t^{\mathrm{R}})+\mathbf{n}_t^{\mathrm{RD}}, \quad (4)$$

where $\mathbf{n}_t^{\mathrm{RD}}$ denotes the noise added on the training block from the $\mathsf{R}\to\mathsf{D}$ link at D, with variance σ_n^2 on each entries. Similarly, the data block received by D can be expressed as

$$\mathbf{y}_d=\mathbf{H}_2\mathbf{H}_1\mathbf{d}+\mathbf{H}_2(\mathbf{v}_{\mathrm{int},d}+\mathbf{n}_d^{\mathrm{R}})+\mathbf{n}_d^{\mathrm{RD}}, \quad (5)$$

where $\mathbf{n}_d^{\mathrm{RD}}$ denotes the noise added on the data block from the $\mathsf{R}\to\mathsf{D}$ link at D, with variance σ_n^2 on each entries.

2.1.2 Signal Transmission Model in

Channel

Let $\mathbf{H}_3$ denote the column-wise circulant matrix with the first column as $[\mathbf{h}_3^T, \mathbf{0}_{1\times(N-L_3)}]^T$, then the training block from the $\mathsf{S}\to\mathsf{D}$ link received by D can be written as

$$\mathbf{x}_t = \mathbf{H}_3\mathbf{t}^{\mathrm{S}} + \mathbf{n}_t^{\mathrm{SD}}, \quad (6)$$

whereas the data block from the $\mathsf{S}\to\mathsf{D}$ link received by D can be written as

$$\mathbf{x}_d = \mathbf{H}_3\mathbf{d} + \mathbf{n}_d^{\mathrm{SD}}, \quad (7)$$

where $\mathbf{n}_t^{\mathrm{SD}}$ and $\mathbf{n}_d^{\mathrm{SD}}$ denote the noise added on training block and data block from the $\mathsf{S}\to\mathsf{D}$ link, respectively, with variance σ_n^2 on each entries.

2.2 LS Channel Estimation

2.2.1 Estimating of $\mathsf{S}\to\mathsf{R}\to\mathsf{D}$ link

Define $\mathsf{H}_i = \mathbf{F}_N^H\mathbf{H}_i\mathbf{F}_N = \mathrm{diag}\{H_i(0), H_i(1), \cdots, H_i(N-1)\}$, $i = 1,2$, where $H_i(k)$ represents the kth element of the frequency-domain channel responses. The frequency-domain expression of (4) is

$$\tilde{\mathbf{y}}_t = \sqrt{\alpha}\tilde{\mathbf{J}}\mathsf{H}_1\mathsf{H}_2\tilde{\mathbf{t}}^{\mathrm{S}} + \sqrt{1-\alpha}\mathsf{H}_2\tilde{\mathbf{t}}^{\mathrm{R}} + \sqrt{\alpha}\tilde{\mathbf{J}}\mathsf{H}_2(\tilde{\mathbf{v}}_{\mathrm{int},t} + \tilde{\mathbf{n}}_t^{\mathrm{R}}) + \tilde{\mathbf{n}}_t^{\mathrm{RD}}, \quad (8)$$

We extract the nonzero entries of $\tilde{\mathbf{t}}^{\mathrm{S}}$ from (8) and get

$$\tilde{y}_t(k) = \sqrt{1-\alpha}\mathrm{H}_1(k)\mathrm{H}_2(k)\tilde{t}^{\mathrm{S}}(k) + \sqrt{1-\alpha}\mathrm{H}_2(k)(v_{\mathrm{int},t}(k) + n_t^{\mathrm{R}}(k)) + n_t^{\mathrm{RD}}(k), \; k \in \mathsf{K}_{\mathrm{S}}, \quad (9)$$

where K_{S} represents the set of indices to nonzero entries in $\tilde{\mathbf{t}}^{\mathrm{S}}$. We extract the nonzero entries of $\tilde{\mathbf{t}}^{\mathrm{R}}$ from (8) and get

$$\tilde{y}_t(k) = \sqrt{\alpha}H_2(k)\tilde{t}^{\mathrm{R}}(k) + n_t^{\mathrm{RD}}(k), \;\; k \in \mathsf{K}_{\mathrm{R}}. \quad (10)$$

With (9) and (10), the frequency responses estimation of $\mathsf{S}\to\mathsf{R}\to\mathsf{D}$ and $\mathsf{R}\to\mathsf{D}$ at the nonzero frequency pins of $\tilde{\mathbf{t}}^{\mathrm{S}}$ and $\tilde{\mathbf{t}}^{\mathrm{R}}$ can be estimated via LS estimation. We apply IDFT deconvolution to obtain the time-domain channel responses estimation $\hat{\mathbf{h}}_1$ and $\hat{\mathbf{h}}_2$. The entire channel frequency-domain estimates $\hat{\mathsf{H}}_i = \mathrm{diag}\{\hat{H}_i(0), \hat{H}_i(1), \cdots, \hat{H}_i(N-1)\}$, $i = 1,2$, can be obtained by DFT transform by padded $N - L_i$ zeros to $\hat{\mathbf{h}}_1$ and $\hat{\mathbf{h}}_2$, respectively.

2.2.2 Estimating of $\mathsf{S}\to\mathsf{D}$ link

Let $\Phi_{L_3}[\mathbf{t}^{\mathrm{S}}]$ denote the $N\times L_3$ column-wise circulant matrix with the first column as $\mathbf{t}^{\mathrm{S}}$, and the time-domain LS estimate of $\mathsf{S}\to\mathsf{D}$ channel $\hat{\mathbf{h}}_3$ can be expressed as

$$\hat{\mathbf{h}}_3 = \Phi_{L_3}^{-1}[\mathbf{t}^{\mathrm{S}}]\mathbf{x}_t. \quad (11)$$

The entire channel frequency-domain estimate $\hat{\mathsf{H}}_3 = \mathrm{diag}\{\hat{H}_3(0), \hat{H}_3(1), \cdots, \hat{H}_3(N-1)\}$, can be obtained by DFT transform by padded $N - L_i$ zeros to $\hat{\mathbf{h}}_3$.

2.3 Estimation of the *Relay Noise Power*

The CCI signals arrive at R through frequency-selective channel, which implies that the both $\mathbf{v}_{\mathrm{int},t}$ and $\mathbf{v}_{\mathrm{int},d}$ are correlate at time-domain and frequency-domain. However, analysis to the correlation of CCI is hard under the condition that neither the interference signal nor the interference CSI is available. We adopt the suboptimum assumption that the CCI is white Gaussian noise to simplify the problem.

We put the indices of the *empty* frequency pins in $\mathbf{x}_t$ into the $(N-2M)\times 1$ vector $I_{\tilde{\mathbf{v}}^{\mathrm{D}}}$ orderly, and define $\tilde{\mathbf{v}}^{\mathrm{D}}$ as

$$\tilde{\mathbf{v}}^{\mathrm{D}} = \tilde{\mathbf{y}}_t(I_{\tilde{\mathbf{v}}^{\mathrm{D}}}, 1). \quad (12)$$

We estimate the *relay noise value* in *empty* frequency pins at R with zeros-forcing equalization, the equalization coefficients are calculated with

$$G_{\mathrm{RD}}(k) = \frac{1}{\sqrt{1-\alpha}\,\hat{H}_2(k)}. \quad (13)$$

Let K_n denote the set of entries to $I_{\tilde{\mathbf{v}}^{\mathrm{D}}}$, and then the estimate of *relay noise* can be expressed as

$$\breve{\mathbf{v}}^R(k) = G_{\mathrm{RD}}^*(k)\tilde{\mathbf{v}}^{\mathrm{D}}(k), \;\; k \in \mathsf{K}_n. \quad (14)$$

Let the mean of $\left|\breve{\mathbf{v}}^R(k)\right|^2$ as the estimation of *relay noise power*, which can be expressed as

$$\hat{\alpha}_{\mathrm{R}}^2 = \frac{1}{N-2M}\sum_{i=1}^{N-2M} |\,\breve{\mathbf{v}}^{\mathrm{R}}(I_{\tilde{\mathbf{v}}^{\mathrm{D}}}(i), 1)\,|^2 . \quad (15)$$

2.4 Diversity Combing and Symbol Detection

Once the frequency-domain channel responses of $\mathsf{S}\to\mathsf{D}, \mathsf{S}\to\mathsf{R}\to\mathsf{D}, \mathsf{R}\to\mathsf{D}$ are available, the received data blocks from both $\mathsf{S}\to\mathsf{R}\to\mathsf{D}$ and $\mathsf{S}\to\mathsf{D}$ links can be combined to achieve spatial diversity. We use frequency-domain equalization with a one-tap equalizer and perform the minimum mean square (MMSE) criterion on each subcarrier. We define $\mathbf{d}(k) = [\tilde{x}_d(k), \tilde{y}_d(k)]^T$, $k = 0,1,\ldots,N-1$, where $\tilde{x}_d(k)$ and $\tilde{y}_d(k)$ are the kth elements of $\tilde{\mathbf{x}}_d$ and $\tilde{\mathbf{y}}_d$, respectively. The MMSE coefficients are given by

$$\begin{aligned}\mathbf{c}(k) &= E[\mathbf{d}(k)\mathbf{d}^H(k)]^{-1}E[\mathbf{d}(k)\tilde{d}^*(k)] \\ &= [\mathbf{u}(k)\mathbf{u}^H(k) + \mathbf{N}(k)]^{-1}\mathbf{u}(k),\end{aligned} \quad (16)$$

Where $\mathbf{u}(k) = [\hat{H}_3(k), \hat{H}_1(k)\hat{H}_2(k)]^T$, $\mathbf{N}(k) = \mathrm{diag}\{\sigma_{SD}^2(k), \sigma_{SRD}^2(k)\}$, and $\sigma_{SD}^2(k) = \sigma_n^2$, $\sigma_{SRD}^2(k) = \alpha_{\mathrm{R}}^2\,|\,\mathsf{H}_2(k)|^2 + \sigma_n^2$ are the noise variances for $\mathsf{S}\to\mathsf{D}$ link and $\mathsf{S}\to\mathsf{R}\to\mathsf{D}$ link, respectively.

α_R^2 is replaced by $\hat{\alpha}_R^2$ in practice.

The output of the diversity combing is

$$\breve{d}(k) = \mathbf{c}^H(k)\mathbf{d}(k) = c_1^*(k)\tilde{x}_d(k) + c_2^*(k)\tilde{y}_d(k),\ k = 1, 2, \ldots, N. \quad (17)$$

3. Simulation Results

In this section, signal to noise ratio (SNR) means the power ratio between the symbols sent by S and the thermal noise, signal to interference ratio (SIR) means the power ratio between the symbols sent by S and that of the CCI interferences. We set $N_I = 1$, $N = 256$, $L_1 = 4$, $L_2 = 4$, $L_3 = 6$, $L_1^I = 5$, $M = 16$. The definition of normalized Mean Square Error (NMSE) is identical with that in [9].

Figure 3 depicts the improvement on channel estimation performance made by NSN AF relay. In figure 2, the term CAF means the conventional superimposed AF relay proposed in [9]. The SNR of each link is set to 25 dB and 30 dB respectively, whereas the SIR changes from 0 dB to 30 dB.

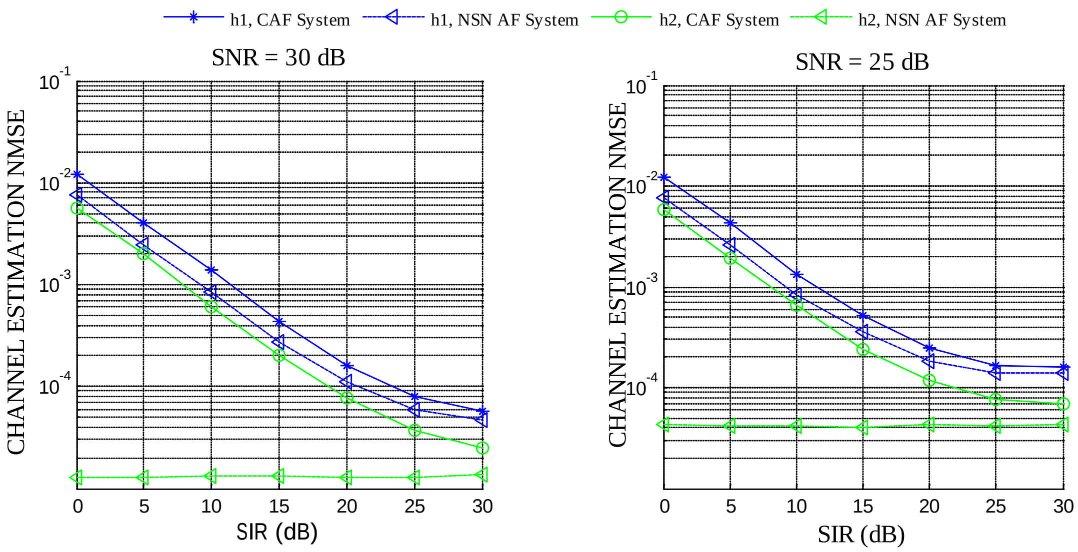

Figure 3. Channel Estimation NMSE vs. SIR

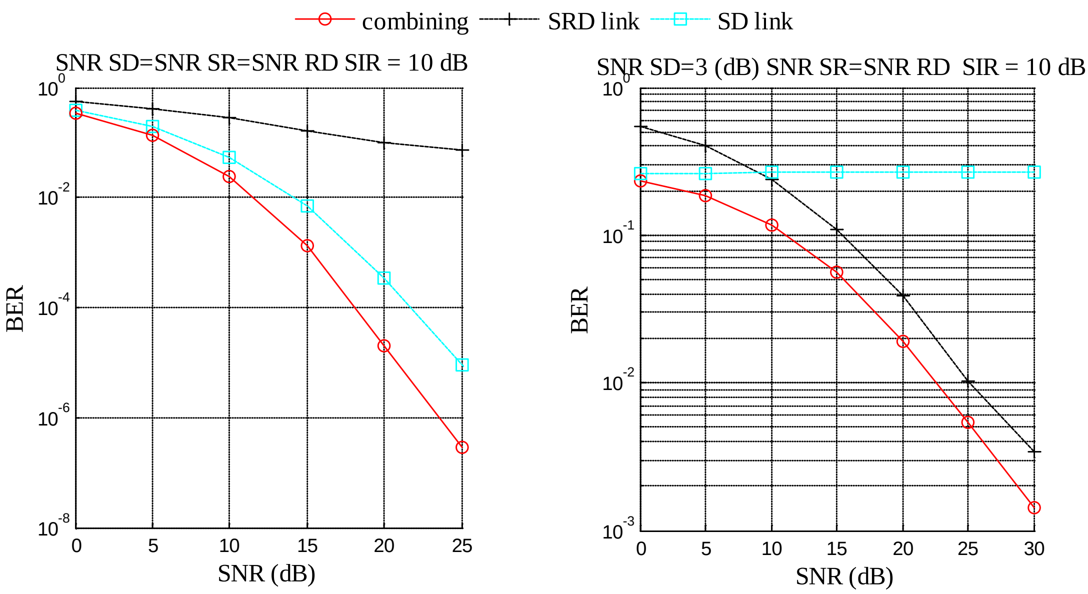

Figure 4. BER vs. SNR

Figure 4 depicts the improvement on BER performance made by combining. We consider two different situation here, one is that each link has the same SNR, the other is that the SNR of $S \to D$ link is set to 3 dB whereas the SNR of $S \to R$ and $R \to D$ change from 0 to 30 dB synchronous. We can see that even the $S \to D$ link has poor SNR compared with the $S \to R \to D$ link, the improvement on BER performance is still remarkable when the CCI exists.

4. Conclusions

We considered an amplify-and-forward relay system with an arbitrary number of CCIs at the relay. Each node is equipped with a single antenna. For such a system, we propose a system scheme to suppress the relay CCIs at both the relay and the destination, where the relay performs NSN AF protocol on the training block to make the relay training sequence avoid suffering from the CCIs, and the destination combines the data blocks from the $S \rightarrow R \rightarrow D$ link and the $S \rightarrow D$ link to further suppress the interferences. Simulation results show that the proposed system scheme achieves better channel estimation and symbol detection performance than the original one.

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