2011 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS) December 7-9, 2011

Loop-Interference Suppression Strategies Using Antenna Selection in Full-Duplex MIMO Relays

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***Abstract*—Loop-interference (LI) from relay transmission to reception reduces the channel capacity and makes the relay system unstable in full-duplex (FD) multi-input multi-output (MIMO) relay systems. conventional schemes to suppress LI still have drawbacks: 1) incur a dispensable signal-to-noise ratio (SNR) loss in low SNR regions; 2) increase the system complexity due to the requirement of weighting matrices; and 3) make insufficient practical sense due to varying signal-to-interference ratios (SIRs). In this paper, we propose a new LI suppression scheme using transmit antenna selection in order to solve the above problems. Simulation results show that the proposed scheme outperforms a conventional scheme, especially in low SNR and high SIR regions, even though the proposed scheme has a lower complexity.**

I. Introduction

Multi-input multi-output (MIMO) relay systems are a promising technique for the next-generation of wireless communication systems as MIMO relay systems provide a wide coverage area, high spectral efficiency, and increased system capacity [1]. Recently full-duplex (FD) mode relaying systems have gained much attention and have been intensively studied, as these systems use the same time and channel from the relay station to the destination, without duplex loss. Unfortunately, however, FD relay systems incur loop-interference (LI) due to signal leakage between transmission and reception at the relay station. LI deteriorates the channel capacity, which can even fall below that of half-duplex relay systems; In addition, LI makes the relay system unstable and even results in the oscillation of relay systems [2].

In FD single-input single-output (SISO) relay systems, LI has been known to cause significant problems. In general, LI is suppressed by estimating the LI channel and then subtracting it from that of the SISO relay system [3]. However, this time domain approach is not appropriate for LI suppression in practical MIMO relay systems due to its high computational complexity. For this reason, some spatial domain solutions have been recently proposed for LI suppression in MIMO relay systems, including the zero forcing (ZF) scheme [4], minimum mean square error (MMSE) scheme [5], and their variants [6,7] being conventionally applied to suppress LI in FD-MIMO relay systems. From a practical point of view, however, conventional schemes such as ZF and MMSE still have several drawbacks. For instance, conventional schemes suppress LI without considering the power of LI; also, conventional schemes increase the system complexity by using two weighting matrices. To resolve these problems, a new LI suppression scheme is needed. Generally, a well-known transmit antenna selection scheme is used to obtain a high diversity gain, as reported in [8-11]. In this paper, we propose a method to suppress LI using the transmit antenna selection schemes in FD-MIMO relay systems. Our simulation results then confirm that the proposed scheme improves the bit error probability (BER) performance in comparison to conventional schemes in low signal-to-noise ratio (SNR) and high signal-to-interference ratio (SIR) regions. Finally, we present the scheme for making low-complexity cost-effective relay systems.

The remainder of this paper is organized as follows. We start with a discussion of the FD-MIMO relay system and channel in the presence of LI and noise in Section II. In Section III, We then present and discuss conventional LI suppression system models and schemes such as ZF and MMSE. Next, we highlight the proposed transmit antenna selection scheme in Section IV. In Section V, we evaluate results of the BER performance for our proposed scheme through simulations, and then conclude the paper in Section VI.

The notation used in this paper is defined as follows, where all matrices and vectors are in boldface: $(\cdot)^{-1}$ is the inverse operation; $(\cdot)^H$ denotes the conjugate transpose operation; $\mathrm{tr}\{\cdot\}$ denotes the matrix trace; $\det(\cdot)$ is the determinant; and $\mathrm{E}\{\cdot\}$ refers to the expectation operation.

II. System and Channel Model

In this section, we describe the FD-MIMO relay system and channel model with LI and noise similar to that in [4-7]. As shown in Fig. 1, we consider a two-hop multi-antenna system in which a communication from a source (e.g., base station) to relay station and from a relay station to destination (e.g., mobile) takes place; We assume here that the power of transmission from the source to destination is too weak for reliable communication. The source has M_s transmit antennas and the relay station has N_t transmit and N_r receive antennas. In addition, the destination has M_d receive antennas. In order to satisfy the conditions for a spatial multiplexing (SM) system, M_s should be less than or equal to N_t and N_r ($M_s < N_t, N_r$). Here, we denote $\mathbf{x}$[i] as the source transmitted signal vector ($M_s \times 1$) at time instant i, $\mathbf{r}$[i] as the relay received signal vector ($N_r \times 1$), $\mathbf{t}$[i] as the decoded relay signal

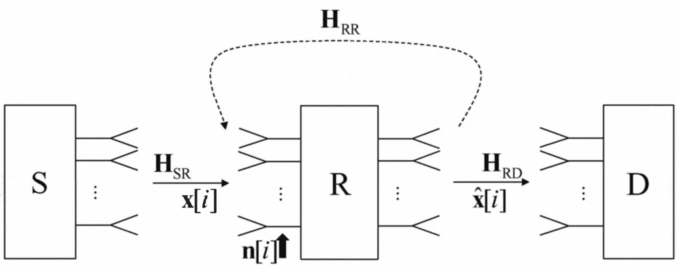

Fig. 1. FD-MIMO relay system model with LI and Gaussian noise

vector ($M \times 1$), and [i] as the relay transmitted vector ($N_t \times 1$). $\mathbf{H}_{\mathrm{SR}}$ has a source to relay channel matrix ($N_r \times M_s$) and $\mathbf{H}_{\mathrm{RR}}$ has an LI channel matrix ($N_r \times N_t$). Let us then consider the case in which the number of receive and transmit antennas are same in the relay system ($N_r = N_t$). Other conditions for this system include slowly varying flat Rayleigh fading channels ($\mathbf{H}_{\mathrm{SR}}$, $\mathbf{H}_{\mathrm{RR}}$, $\mathbf{H}_{\mathrm{RD}}$) and constant fading coefficients during frame transmissions, such as quasi-static fading. Here, **n**[i] is an additive white Gaussian noise vector ($N_r \times 1$). For two-hop relay systems, the relay receives a combination of the signal transmitted from the source, the LI signal, and a receiver noise signal. The received relay signal can be express as:

$$\mathbf{r}[i] = \mathbf{H}_{\mathrm{SR}}\mathbf{x}[i] + \mathbf{H}_{\mathrm{RR}}\hat{\mathbf{x}}[i] + \mathbf{n}[i], \tag{1}$$

where the transmitted relay signal vector $\hat{\mathbf{x}}$[i] can be presented using the received signal **r**[i] and an arbitrary relay protocol function $R(\cdot)$. The previous received signal **r**[i-1] from the source generates transmitted data at the relay $\hat{\mathbf{x}}$[i]=R(**r**[i-1]). This transmitted signal enters through the LI channel as a received signal in the relay station. In this paper, we specificaly focus on the decoded and forward (DF) relay protocol.

The relay needs to attain the channel state information (CSI) of $\mathbf{H}_{\mathrm{RR}}$ in order to suppress the LI. The CSI can be obtained by using the training sequence; When the training sequence is sent to the destination, this signal can then be retransmitted to the relay. Through this process, we can precisely identify the LI channel (i.e., with no estimation error) [6]. In addition, we suppose that the characteristics of the LI channel $\mathbf{H}_{\mathrm{RR}}$ have a low rank. This rank is because if the distance of the reflected LI is increased, $\mathbf{H}_{\mathrm{RR}}$ becomes a rank deficient channel in practical relay systems [4]. Through this feature of the LI channel $\mathbf{H}_{\mathrm{RR}}$, LI suppression schemes are more effective in FD-MIMO relay systems.

III. Conventional LI Suppression Schemes

In this section, we introduce conventional LI suppression schemes that take advantage of estimation techniques by using ZF and MMSE estimation filters. Using these conventional schemes, we can generate the weighting matrices **A** and **B** [4, 5]. The received signal vector **r**[i] is:

$$\mathbf{r}[i] = \mathbf{A}\mathbf{H}_{\mathrm{SR}}\mathbf{x}[i] + \mathbf{A}\mathbf{H}_{\mathrm{RR}}\mathbf{B}\mathbf{t}[i] + \mathbf{A}\mathbf{n}[i]. \tag{2}$$

Ultimately, we express the goal of the conventional scheme,

$$\mathbf{A}\mathbf{H}_{\mathrm{RR}}\mathbf{B}\mathbf{t}[i] + \mathbf{A}\mathbf{n}[i] \to 0. \tag{3}$$

ZF Scheme: The n rank matrix, $\mathbf{H}_{\mathrm{RR}}$ has a null space of $N - n$ dimensions. With the ZF scheme, **A** and **B** can project the LI signal into the null space of $\mathbf{H}_{\mathrm{RR}}$ ($\mathbf{A}\mathbf{H}_{\mathrm{RR}}\mathbf{B}\mathbf{t}[i] \to 0$). **A** and **B** can be attained by the singular value decomposition (SVD) of $\mathbf{H}_{\mathrm{RR}}$, as shown in [4,5].

MMSE Scheme: The goal of the MMSE scheme is to determine which **A** and **B** can minimize the error between the source transmitted signal $\mathbf{H}_{\mathrm{SR}}\mathbf{x}[i]$ and received relay signal $\mathbf{r}[i]$. first, the mean square error (MSE) can be expressed as follows:

$$\mathbf{MSE} = \mathrm{E}\{(\mathbf{H}_{\mathrm{SR}}\mathbf{x}[i] - \mathbf{r}[i])(\mathbf{H}_{\mathrm{SR}}\mathbf{x}[i] - \mathbf{r}[i])^H\}. \tag{4}$$

Then, we find A and B using conditions of the minimize MSE, i.e., $\arg(\frac{\partial}{\partial \mathbf{A}}\mathrm{tr}\{\mathbf{MSE}\} = 0), \arg(\frac{\partial}{\partial \mathbf{B}}\mathrm{tr}\{\mathbf{MSE}\} = 0)$.

$$\mathbf{A} = \mathbf{H}_{\mathrm{SR}}\mathbf{R}_{\mathbf{x}}\mathbf{H}_{\mathrm{SR}}^H(\mathbf{H}_{\mathrm{SR}}\mathbf{R}_{\mathbf{x}}\mathbf{H}_{\mathrm{SR}}^H + \mathbf{H}_{\mathrm{RR}}\mathbf{R}_{\mathbf{t}}\mathbf{H}_{\mathrm{RR}}^H + \mathbf{R}_{\mathbf{n}})^{-1}. \tag{5}$$

where the signal and noise covariance matrices are given by $\mathbf{R}_{\mathbf{x}} = \mathrm{E}\{\mathbf{x}\mathbf{x}^H\}$, $\mathbf{R}_{\mathbf{t}} = \mathrm{E}\{\mathbf{t}\mathbf{t}^H\}$, and $\mathbf{R}_{\mathbf{n}} = \mathrm{E}\{\mathbf{n}\mathbf{n}^H\}$. Note that the result of the weighting matrix **B** using the minimized condition is the same as for the ZF scheme.

The MMSE scheme is different from ZF such that the MMSE scheme can suppress not only the LI signal, but also additive Gaussian noise ($\mathbf{A}\mathbf{H}_{\mathrm{RR}}\mathbf{B}\mathbf{t}[i] + \mathbf{A}\mathbf{n}[i] \to 0$) [5]. Therefore, the BER performance of the MMSE scheme for LI suppression is better than for the ZF scheme.

IV. Proposed LI Suppression Scheme

In this section, we introduce a new LI suppression scheme using transmit antenna selection (Fig. 2). First, we provide the motivation for this work, which is followed by a discussion of the LI suppression system and then present the transmit antenna selection criterion.

A. Motivation

Conventional schemes based on estimation filter techniques commonly incur a dispensable SNR loss in low SNR regions, as shown in the numerical results of [5]. In addition, the weighting matrices **A** and **B** increase the system complexity for LI suppression as the matrices depend on the LI channel, which changes frequently with time. Finally, these conventional schemes are insufficient for varying SIRs, since they just suppress the LI signal to close to zero using the characteristics of the LI channel without consideration of the varying SIRs. In order to resolve the above problems, we propose an LI suppression scheme based on transmit antenna selection.

B. Proposed Scheme Based on Transmit Antenna Selection

As shown in Fig. 2, we apply the proposed scheme to suppress the LI signal in the relay transmit weighting matrix **B**. Specifically, we select substandard subset antennas instead of the best subset antennas, as in [8-11]. In addition, in order to reduce the dispensable SNR loss and to simplify the LI suppression system, we eliminate the weighting matrix **A** from the conventional schemes. As such, the received relay signal becomes:

$$\mathbf{r}[i] = \mathbf{H}_{\mathrm{SR}}\mathbf{x}[i] + \mathbf{H}_{\mathrm{P}}\mathbf{t}[i] + \mathbf{n}[i], \tag{6}$$

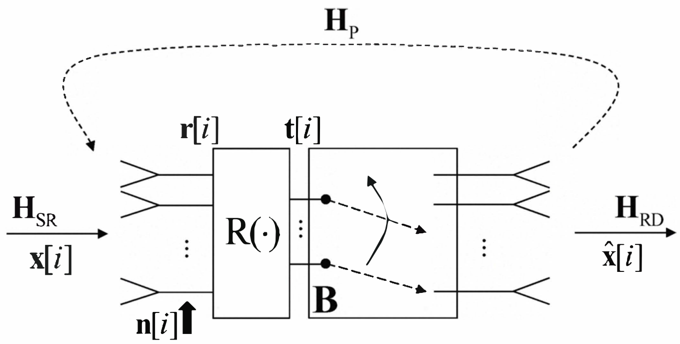

Fig. 2. Proposed LI suppression system model using transmit antenna selection.

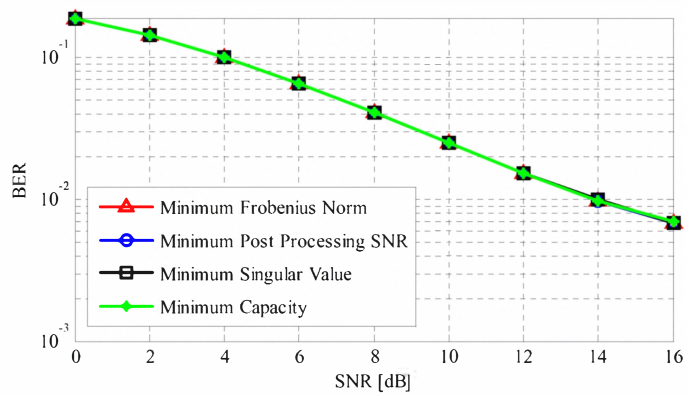

Fig. 3. BER performance comparison of an SM-MIMO link for four kinds of antenna selection criteria.

where $\mathbf{H}_{\mathrm{P}}$ denotes the selected LI channel matrix using the proposed scheme with $N_r \times N_k$ dimensions. Here, N_k presents the number of selection antenna among the number of relay transmit antennas N_t. Eventually, there are a total of $\binom{N_k}{N_t}$ possible selections of relay transmit antennas. In other words, according to the acceptance condition of the SM-MIMO system, the number of selected relay transmit antennas is less than or equal to the number of relay receive antennas ($N_k \leq N_r$).

Analytically, we can express the effective $\mathrm{SNR_k}$ for each stream $k = 1, 2, ..., M_t$ with ZF detection as follows:

$$\mathrm{SNR}_k^{(\mathrm{ZF})} = \frac{E_s}{N_k N_0 [\mathbf{H}_{\mathrm{P}}^H \mathbf{H}_{\mathrm{P}}]_{kk}^{-1}}, \tag{7}$$

where E_s is the total relay transmitted signal energy and N_0 is the variance of complex Gaussian noise. Finally, the goal of the proposed scheme is to choose the subset of transmit antennas that minimizes the effective $\mathrm{SNR_k}$.

C. Antenna Selection Criterion

In this section, we discuss the four kinds of transmit antenna selection criteria required to suppress the LI signal.

1) Minimum Frobenius Norm Selection: Among the Frobenius norm of all possible selected LI channel matrices, $\mathbf{H}_{\mathrm{P}}$, we choose the smallest Frobenius norm of $\mathbf{H}_{\mathrm{P}}$ for selecting the transmit antennas.

2) Minimum Post Processing SNR: We compute the post-processing SNR of each N_k multiplexed stream. As the BER performance mainly depends on the minimum SNR of each multi-stream, we select the subset of transmit antennas with the minimum SNR_{min}; $\min_k e_k^H [\mathbf{H}_{\mathrm{P}}^H \mathbf{H}_{\mathrm{P}}]^{-1} e_k$, where e_k is the k^{th} column of $\mathbf{I}_{N_k}$.

3) Minimum Singular Value: We compute the singular value of $\mathbf{H}_{\mathrm{P}}$. Then, we select the largest singular value in each $\mathbf{H}_{\mathrm{P}}$. Finally, we choose corresponding antennas with the minimum singular value among $\mathbf{H}_{\mathrm{P}}$.

4) Minimum Capacity: To select the transmit antennas, we first compute the capacity of the LI channel matrix $\mathbf{H}_{\mathrm{P}}$. We then choose the smallest capacity $\mathbf{H}_{\mathrm{P}}$ ($minimum\ C_P = \log\det(\mathbf{I}_{N_k} + E_s/N_k N_0 \mathbf{H}_{\mathrm{P}}^H \mathbf{H}_{\mathrm{P}})$).

Now, let us consider the computational complexity of the four kinds of criteria. One way to quantify the complexity of the matrix computation is to count the number of required flops. Computing the Frobenius norm $\|\mathbf{H}_{\mathrm{P}}\|_F^2$ requires $O(N_k^2)$ flops. However, other matrix operations such as the inverse, SVD, and determinant of $\mathbf{H}_{\mathrm{P}}$ require $O(N_k^3)$ flops [12]. As a result, we chose the Frobenius norm selection criterion as it has the lowest computational complexity.

V. Simulation Results

In this section, we present the BER performance of the proposed scheme and then compare it with a conventional scheme through Monte Carlo simulations.

A. Simulation Parameters

The signal transmitted from the source to the relay station is modulated into 4QAM and used a linear detection method such as ZF. We assume that the source transmitted signals can be perfectly decoded via the relay protocol $R(\cdot)$. Since we used the DF relay protocol and two source transmitting antennas, the two pre-coded multi-stream signals are transmitted from the relay station to the destination, i.e., $M_s = 2$, $N_r = 3$, and $M_d = 2$. Here, SIR defines the LI power before applying the LI suppression schemes, and the rank of the LI channel $\mathbf{H}_{\mathrm{RR}}$ is assumed to be 1. Finally, the BER performance of the FD-MIMO relay system is measured by averaging over 100,000 transmission periods.

B. BER Performance Using Four Transmit Antenna Selection Criteria

Fig. 3 shows the BER performance comparison of four transmit antenna selection criteria at the 13dB SIR with $N_k = 2$ and $N_t = 3$. Generally, the minimum-post processing SNR selection scheme is seen to provide the best BER performance among the transmit antenna selection criteria [8,9]. However, for the degenerate rank case (i.e., rank=1), the result of the BER performance is almost the same. Therefore, it is reasonable to choose the minimum Frobenius norm-based transmit antenna selection scheme in order to reduce the complexity in practical systems, such as in [10,11].

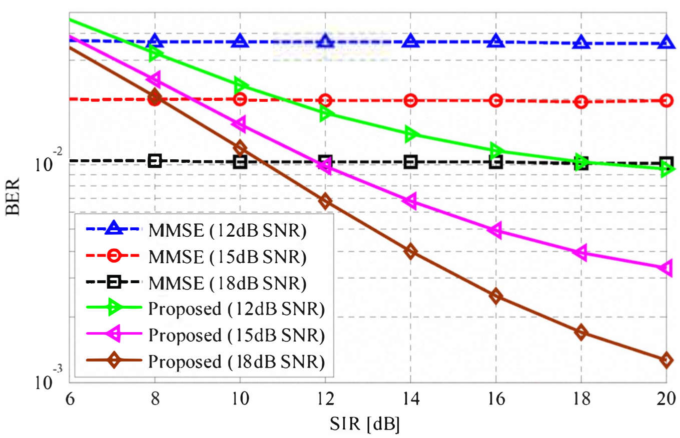

Fig. 4. BER performance for SM-MIMO link to compare MMSE and proposed schemes according to increasing SIR.

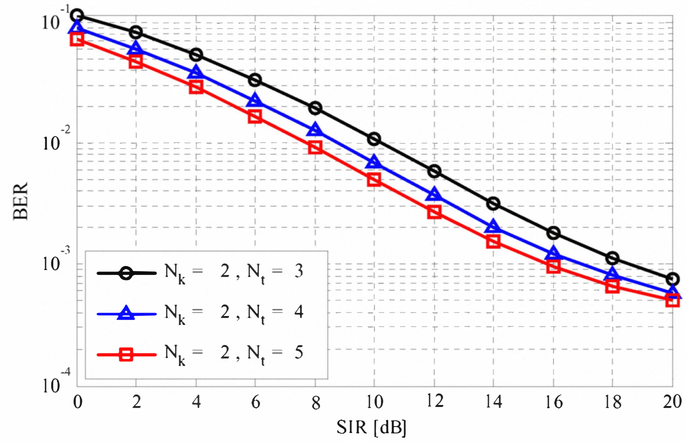

Fig. 5. BER performance of SM-MIMO link with transmit antenna selection with respect to increasing the number of relay transmit antennas.

C. BER Performance Comparison of Proposed and MMSE Schemes

Fig. 4 compares the BER performance of the proposed and MMSE schemes when the SNR is 12dB, 15dB, and 18dB with $N_k = 2$ and $N_t = 3$. As the SIR increases, it can be observed that the BER performance of the proposed scheme also improves; in contrast, the BER performance of the conventional scheme (MMSE) does not change due to suppression of LI regardless of the SIR. Based on these results, the MMSE scheme is insufficient for use in practical systems, as the BER performance of proposed scheme is better than the MMSE scheme for both low SNR and high SIR regions.

D. BER Performance of Proposed Scheme with Increasing Number of Transmit Antennas

Fig. 5 shows the BER performance of the proposed scheme in terms of an increasing number of relay transmit antennas at 20dB SNR with $N_k = 2$ and $N_t \in \{3, 4, 5\}$. At the BER value of 10^{-3}, the proposed scheme with $N_t = 4$ gives an SNR gain of about 1.5dB SIR and $N_t = 5$ gives an SNR gain of about 2.5dB SIR compared to that of $N_t = 3$. From the above results, we can conclude that increasing the number of relay transmit antennas improves the BER performance. In addition, this method should reduce the cost-effective problem in practical systems as we fixed the two multi-streams using two RF-chains and just increased the number of transmit antennas.

VI. Conclusion

Although full-duplex (FD)-MIMO relay systems provide advantages such as increased spectral efficiency and capacity, they also incur loop-interference (LI) due to signal leakage from the transmit signal to the receive signal; Thus, LI has an adverse affect on MIMO relay systems, such as reducing the channel capacity. To resolve this problem, an LI suppression scheme was developed using a transmit antenna selection process. In comparison to conventional schemes, the proposed scheme shows better BER performance, especially in low SNR and high SIR regions. Furthermore, the proposed scheme has low complexity and thus is helpful for realizing cost-effective relay systems.

Acknowledgment

This work was supported by a grant (UD1000211D) from the basic research program of the Agency for Defense Development (ADD), Korea.

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