Self-Interference Aided Channel Estimation in Two-Way Relaying Systems

Jian Zhao, Marc Kuhn and Armin Wittneben
Communication Technology Laboratory, ETH Zurich
CH-8092 Zurich, Switzerland
Email: {zhao, kuhn, wittneben}@nari.ee.ethz.ch

Gerhard Bauch
DoCoMo Euro-Labs
D-80687 Munich, Germany
Email: bauch@docomolab-euro.com

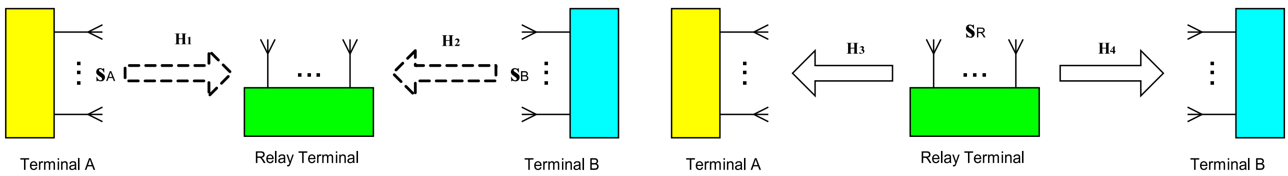
***Abstract*—In this paper, we propose a novel channel estimation scheme for the broadcast phase of the newly invented two-way relaying technique. Instead of using pilot sequences, we exploit the *self-interference*, which contains the data known at the receivers, to get a first estimate of the channel. Then a decision-directed iterative estimation process is started to improve the accuracy of the channel estimates. We consider a block fading channel model. The simulation results show that the proposed scheme has similar performance as pilot-aided channel estimation schemes in our simulation environment. Since pilot sequences are no longer needed in our proposed scheme, higher spectrum efficiency is achieved without performance loss.**

I. INTRODUCTION

Recently, a spectral efficient relaying technique called *two-way relaying* has been proposed in [1] and [2]. This relaying technique considers the scenario that two half-duplex wireless terminals exchange data via another half-duplex wireless relay. Here, *half-duplex* means that the terminals cannot transmit and receive signals at the same time using the same frequency channel due to the coupling between the transmit and receive circuits. The two-way relaying technique consists of two phases: the multiple access (MAC) phase and the broadcast (BRC) phase. In the MAC phase, the two terminals transmit their data simultaneously to the relay; the relay decodes and retransmits the combined data signals in the BRC phase. The back-propagated signal part containing the known data from the receiving terminal itself is called *self-interference (SI)*, which can be canceled before decoding. The two phases are separated in time (TDD) or in frequency (FDD). Compared to traditional relaying techniques, the two-way relaying technique achieves bidirectional communication between the two terminals in two channel uses instead of four.

We consider the problem of channel estimation in a two-way relaying system with multiple antennas, focusing on the BRC phase. As we know, multiple-input multiple-output (MIMO) systems require accurate channel knowledge at least at the receiver side in order to make correct decoding. However, accurate channel estimation in MIMO systems is generally difficult. Traditional channel estimation schemes transmit orthogonal pilot sequences on different transmit antennas before sending data. The received signal is correlated with the pilot sequences at the receiver. Based on the received signal and the knowledge of the pilot sequences, the channel matrices can be calculated. Such schemes waste system resources especially when the number of transmit antennas is large. In [3], the authors compared the linear least squares (LS) and minimum mean square error (MMSE) estimation algorithms and investigated the optimal choice of pilot signals. They showed that transmitting orthogonal pilot sequences from different antennas is optimal for the LS algorithm, which is widely used in current MIMO systems. Unlike conventional methods where pilots are time-multiplexed with data symbols, a pilot-embedding method was proposed in [4] and [5], where low-power orthogonal pilot sequences are transmitted concurrently with the data. Such schemes trade transmit power for higher spectrum efficiency. An iterative vector channel estimation scheme was proposed and analyzed in [6]. All those channel estimation schemes rely on an initial estimate of the MIMO channel based on the transmission of pilot sequences.

In this paper, we propose an SI aided channel estimation scheme for two-way relaying systems, where we use SI instead of pilot sequences to estimate the channel in the BRC phase. For the moment, we leave aside the channel estimation problem in the MAC phase, where the channel knowledge at the relay can be obtained from traditional schemes or the feedback from the terminals. We consider a two-way decode-and-forward (DF) relaying system as discussed in [1], which uses the *superposition coding scheme* at the relay, i.e., it re-encodes the decoded data symbols from the two terminals separately, adds them up and retransmits them in the BRC phase. We exploit the fact that the data in the SI is known at the corresponding receiver. Such *a priori* knowledge can be used for channel estimation. At the receiver side, we first use a linear MMSE estimator to get an initial estimate of the channel based on the SI. Then we start a decision-directed iterative estimation process to improve the accuracy of the channel estimates. We consider a block fading channel model, where the channel remains constant for a certain number of time slots. Simulation results show that we can achieve similar performance as pilot-aided channel estimation schemes in our simulation environment. The channel estimation in the proposed scheme is completely accomplished by the SI, and the pilot sequences are no longer required to be transmitted from the relay. Thus, our proposed channel estimation scheme can save system resources without losing performance. To the best of our knowledge, this is the first scheme that *utilizes* the SI instead of simply *canceling* it out.



(a) MAC phase (b) BRC phase

Fig. 1. MIMO two-way DF relaying system

The paper is organized as follows: The system model is shown in Section II. The details of the proposed *SI aided channel estimation scheme* is discussed in Section III, where the receiver first estimates the channel using the knowledge of the SI and then starts the decision-directed iterative channel estimation process. Comprehensive simulation results are presented in Section IV, where we show that the proposed scheme can achieve similar performance as the pilot-aided scheme in a block fading channel. After that, conclusions are drawn in Section V.

Notation We use bold uppercase letters to denote matrices and bold lowercase letters to denote vectors. $\mathbf{I}_N$ is an $N \times N$ identity matrix. $\mathcal{CN}(0, \mathbf{K})$ denotes a circularly symmetric complex normal zero mean random vector with covariance matrix $\mathbf{K}$. Furthermore, $\mathrm{E}[\cdot]$, $\mathrm{tr}(\cdot)$ and $(\cdot)^H$ denote the expectation, the trace and the conjugate transpose, respectively.

II. System Model

We consider a relaying system where two wireless terminals A and B exchange data via a half-duplex relay terminal. We assume that there is no direct connection between terminal A and B (for example, due to shadowing or too large distance between them). The number of antennas at terminal A, the relay and terminal B are denoted as N_A, N_R and N_B, respectively.

As shown in Fig. 1, the data of terminal A and B are exchanged in two phases when the two-way relaying technique is applied. The two phases can be separated in time or in frequency. In the MAC phase as shown in Fig. 1(a), terminal A and B transmit simultaneously to the relay. The modulated (e.g., QAM) data symbol vectors transmitted at terminal A and B are $\mathbf{s}_\mathsf{A} \in \mathbb{C}^{N_\mathsf{A} \times 1}$ and $\mathbf{s}_\mathsf{B} \in \mathbb{C}^{N_\mathsf{B} \times 1}$, respectively. They are also subject to the transmit power constraints, i.e., $\mathrm{E}(\mathbf{s}_\mathsf{A}^H \mathbf{s}_\mathsf{A}) = P_\mathsf{A}$ and $\mathrm{E}(\mathbf{s}_\mathsf{B}^H \mathbf{s}_\mathsf{B}) = P_\mathsf{B}$. The received signal $\mathbf{y}_\mathsf{R}$ at the relay can be expressed as

$$\mathbf{y}_\mathsf{R} = \mathbf{H}_1 \mathbf{s}_\mathsf{A} + \mathbf{H}_2 \mathbf{s}_\mathsf{B} + \mathbf{n}_\mathsf{R} \tag{1}$$

where $\mathbf{H}_1 \in \mathbb{C}^{N_\mathsf{R} \times N_\mathsf{A}}$ and $\mathbf{H}_2 \in \mathbb{C}^{N_\mathsf{R} \times N_\mathsf{B}}$ are the channel matrices from terminal A and B to the relay, respectively. The additive noise vector at the relay is $\mathbf{n}_\mathsf{R} \in \mathbb{C}^{N_\mathsf{R} \times 1}$, where $\mathbf{n}_\mathsf{R} \sim \mathcal{CN}(0, \sigma^2 \mathbf{I}_{N_\mathsf{R}})$. This is a multiple access scenario. The receiver structure for decoding the data contained in $\mathbf{s}_\mathsf{A}$ and $\mathbf{s}_\mathsf{B}$ in this scenario can be found in e.g., [7].

The BRC phase is shown in Fig. 1(b). The data decoded from $\mathbf{s}_\mathsf{A}$ and $\mathbf{s}_\mathsf{B}$ are remodulated by the relay into symbol vectors $\hat{\mathbf{s}}_\mathsf{A} \in \mathbb{C}^{N_\mathsf{R} \times 1}$ and $\hat{\mathbf{s}}_\mathsf{B} \in \mathbb{C}^{N_\mathsf{R} \times 1}$, respectively. The modulation scheme and the power allocation of $\hat{\mathbf{s}}_\mathsf{A}$ and $\hat{\mathbf{s}}_\mathsf{B}$ used at the relay are known to both terminal A and B. The relay then adds the two symbol vectors together and retransmits the sum vector $\mathbf{s}_\mathsf{R} \in \mathbb{C}^{N_\mathsf{R} \times 1}$:

$$\mathbf{s}_\mathsf{R} = \hat{\mathbf{s}}_\mathsf{A} + \hat{\mathbf{s}}_\mathsf{B}. \tag{2}$$

In order to satisfy the power constraint, we require $\mathrm{E}\{\mathbf{s}_\mathsf{R}^H \mathbf{s}_\mathsf{R}\} = \mathrm{E}\{\hat{\mathbf{s}}_\mathsf{A}^H \hat{\mathbf{s}}_\mathsf{A}\} + \mathrm{E}\{\hat{\mathbf{s}}_\mathsf{B}^H \hat{\mathbf{s}}_\mathsf{B}\} = P_\mathsf{R}$.

$\mathbf{s}_\mathsf{R}$ contains both the data from terminal A and B, i.e., part of the data transmitted at the relay are already known to the receivers of the two terminals. The received signal part that contains the known data is called *self-interference (SI)* for the specific receiver. For example, the signal received at terminal A can be written as

$$\begin{aligned} \mathbf{y}_\mathsf{A} &= \mathbf{H}_3 \mathbf{s}_\mathsf{R} + \mathbf{n}_\mathsf{A} & (3) \\ &= \underbrace{\mathbf{H}_3 \hat{\mathbf{s}}_\mathsf{A}}_{\text{SI for terminal A}} + \mathbf{H}_3 \hat{\mathbf{s}}_\mathsf{B} + \mathbf{n}_\mathsf{A}. & (4) \end{aligned}$$

Similarly, the signal received at terminal B in the BRC phase can be written as

$$\begin{aligned} \mathbf{y}_\mathsf{B} &= \mathbf{H}_4 \mathbf{s}_\mathsf{R} + \mathbf{n}_\mathsf{B} & (5) \\ &= \mathbf{H}_4 \hat{\mathbf{s}}_\mathsf{A} + \underbrace{\mathbf{H}_4 \hat{\mathbf{s}}_\mathsf{B}}_{\text{SI for terminal B}} + \mathbf{n}_\mathsf{B} & (6) \end{aligned}$$

where $\mathbf{H}_3 \in \mathbb{C}^{N_\mathsf{A} \times N_\mathsf{R}}$ and $\mathbf{H}_4 \in \mathbb{C}^{N_\mathsf{B} \times N_\mathsf{R}}$ denote the channel matrices from the relay to terminal A and B, respectively. $\mathbf{n}_\mathsf{A} \in \mathbb{C}^{N_\mathsf{A} \times 1}$ and $\mathbf{n}_\mathsf{B} \in \mathbb{C}^{N_\mathsf{B} \times 1}$ are the additive noise vectors at terminal A and B, where $\mathbf{n}_\mathsf{A} \sim \mathcal{CN}(0, \sigma_\mathsf{A}^2 \mathbf{I}_{N_\mathsf{A}})$ and $\mathbf{n}_\mathsf{B} \sim \mathcal{CN}(0, \sigma_\mathsf{B}^2 \mathbf{I}_{N_\mathsf{B}})$.

The SI is "harmless" because it contains the data that are supposed to be known to the receivers. If the decoding at the relay in the MAC phase is prefect, the data contained in $\hat{\mathbf{s}}_\mathsf{A}$ and $\hat{\mathbf{s}}_\mathsf{B}$ are the same as the corresponding data in $\mathbf{s}_\mathsf{A}$ and $\mathbf{s}_\mathsf{B}$. That is, $\hat{\mathbf{s}}_\mathsf{A}$ and $\hat{\mathbf{s}}_\mathsf{B}$ are also perfectly known to terminal A and B, respectively. Furthermore, if the receivers of terminal A and B also know the channel matrix $\mathbf{H}_3$ and $\mathbf{H}_4$, the corresponding receiver can perfectly cancel its SI before decoding. The remaining part only contains the data transmitted from the other side. Of course, in a real system some interference will remain even after cancelation due to the decoding errors at the relay in the MAC phase or due to the inaccuracy of the channel knowledge.

The decoding performance at the receivers in the BRC phase is highly dependent on the accuracy of the channel knowledge. Traditional channel estimation schemes use orthogonal pilot sequences to estimate the channel or ask the relay to feedback the channel knowledge, which wastes system resources. On the other hand, we can observe that the SI also contains the information about the channel. In the following, we consider how to exploit the SI to estimate the BRC phase channel $\mathbf{H}_4$ at the receiver of terminal B. Same discussions also apply to the receiver of terminal A.

III. SI Aided Channel Estimation

We consider a flat fading channel in a low-mobility environment. This corresponds to one subcarrier in an orthogonal frequency division multiplexing (OFDM) transmission system. We assume the channel matrix $\mathbf{H}_4$ remains constant during the transmission period of L symbol vectors, where L is the *coherence interval* and $L \geq N_{\mathsf{R}}$. The channel changes independently from one transmission period to another. Each BRC phase consists of a number of such transmission periods. We denote the transmitted symbol vectors from the relay during one transmission period as $\mathbf{s}_{\mathsf{R},1}, \cdots, \mathbf{s}_{\mathsf{R},L}$. So the corresponding $N_{\mathsf{B}} \times L$ received signal matrix $\mathbf{Y}_{\mathsf{B}} = [\mathbf{y}_{\mathsf{B},1}, \cdots, \mathbf{y}_{\mathsf{B},L}]$ at terminal B can be expressed as

$$\mathbf{Y}_{\mathsf{B}} = \mathbf{H}_4 \mathbf{S}_{\mathsf{R}} + \mathbf{N}_{\mathsf{B}} \quad (7)$$

$$= \mathbf{H}_4 (\hat{\mathbf{S}}_{\mathsf{A}} + \hat{\mathbf{S}}_{\mathsf{B}}) + \mathbf{N}_{\mathsf{B}} \quad (8)$$

where $\mathbf{S}_{\mathsf{R}} = [\mathbf{s}_{\mathsf{R},1}, \cdots, \mathbf{s}_{\mathsf{R},L}]$, $\hat{\mathbf{S}}_{\mathsf{A}} = [\hat{\mathbf{s}}_{\mathsf{A},1}, \cdots, \hat{\mathbf{s}}_{\mathsf{A},L}]$ and $\hat{\mathbf{S}}_{\mathsf{B}} = [\hat{\mathbf{s}}_{\mathsf{B},1}, \cdots, \hat{\mathbf{s}}_{\mathsf{B},L}]$ are the $N_{\mathsf{R}} \times L$ transmitted symbol matrices and $\mathbf{N}_{\mathsf{B}} = [\mathbf{n}_{\mathsf{B},1}, \cdots, \mathbf{n}_{\mathsf{B},L}]$ is the $N_{\mathsf{B}} \times L$ matrix of additive noise. Furthermore, we denote the binary data sequences sent by terminal A and B in the MAC phase as $\mathbf{d}_{\mathsf{A}}$ and $\mathbf{d}_{\mathsf{B}}$, respectively. The corresponding binary data sequences decoded at the relay are denoted as $\hat{\mathbf{d}}_{\mathsf{A}}$ and $\hat{\mathbf{d}}_{\mathsf{B}}$.

A. Linear MMSE Channel Estimation Using SI

Based on the received signal $\mathbf{Y}_{\mathsf{B}}$, we can construct a linear estimator $\mathbf{G}$ and get the channel estimate

$$\mathbf{H}_{4,\text{linear}} = \mathbf{Y}_{\mathsf{B}} \mathbf{G} \quad (9)$$

where $\mathbf{G} \in \mathbb{C}^{L \times N_{\mathsf{R}}}$. An MMSE channel estimator $\mathbf{G}_{\text{m}}$ is a linear estimator that minimizes the mean square error (MSE) $\mathcal{E}$ of the channel estimates. In our case, the MSE can be expressed as

$$\mathcal{E} = \mathrm{E}\left\{\|\mathbf{H}_4 - \mathbf{Y}_{\mathsf{B}}\mathbf{G}\|_F^2\right\} \quad (10)$$

$$= \mathrm{tr}\{\mathbf{R}_{\mathbf{H}}\} - \mathrm{tr}\{\mathbf{R}_{\mathbf{H}}\mathbf{S}_{\mathsf{R}}\mathbf{G}\} - \mathrm{tr}\{\mathbf{G}^H \mathbf{S}_{\mathsf{R}}^H \mathbf{R}_{\mathbf{H}}\} + \mathrm{tr}\{\mathbf{G}^H(\mathbf{S}_{\mathsf{R}}^H \mathbf{R}_{\mathbf{H}} \mathbf{S}_{\mathsf{R}} + \sigma_{\mathsf{B}}^2 N_{\mathsf{B}} \mathbf{I}_L)\mathbf{G}\} \quad (11)$$

where $\mathbf{R}_{\mathbf{H}} = \mathrm{E}[\mathbf{H}_4^H \mathbf{H}_4]$.

The optimum solution is $\mathbf{G}_{\text{m}} = \arg\min_{\mathbf{G}} \mathcal{E}$, and it can be calculated by $\partial\mathcal{E}/\partial\mathbf{G} = 0$. Thus we have [3]

$$\mathbf{G}_{\text{m}} = (\mathbf{S}_{\mathsf{R}}^H \mathbf{R}_{\mathbf{H}} \mathbf{S}_{\mathsf{R}} + \sigma_{\mathsf{B}}^2 N_{\mathsf{B}} \mathbf{I}_L)^{-1} \mathbf{S}_{\mathsf{R}}^H \mathbf{R}_{\mathbf{H}}. \quad (12)$$

Hence, if $\mathbf{S}_{\mathsf{R}}$ is known at the receiver, the MMSE estimate of $\mathbf{H}_4$ can be written as

$$\mathbf{H}_{4,\text{MMSE}} = \mathbf{Y}_{\mathsf{B}} (\mathbf{S}_{\mathsf{R}}^H \mathbf{R}_{\mathbf{H}} \mathbf{S}_{\mathsf{R}} + \sigma_{\mathsf{B}}^2 N_{\mathsf{B}} \mathbf{I}_L)^{-1} \mathbf{S}_{\mathsf{R}}^H \mathbf{R}_{\mathbf{H}}. \quad (13)$$

In a two-way relaying system, the matrix $\mathbf{S}_{\mathsf{R}}$ is not completely known at terminal B before decoding. It can be seen from (8) that the terminal B receiver does not know the data in $\hat{\mathbf{S}}_{\mathsf{A}}$ before decoding. However, following the same procedure as (12), we can still get a suboptimum linear MMSE estimator [8] of $\mathbf{H}_4$ by just using $\mathbf{S}_{\mathsf{B}} = [\mathbf{s}_{\mathsf{B},1}, \cdots, \mathbf{s}_{\mathsf{B},L}]$ and the statistical knowledge of the channel and data, i.e.,

$$\hat{\mathbf{H}}_{4,\text{MMSE}} = \mathbf{Y}_{\mathsf{B}} (\mathbf{S}_{\mathsf{B}}^H \mathbf{R}_{\mathbf{H}} \mathbf{S}_{\mathsf{B}} + \mathbf{R}_{\mathbf{S}_{\mathsf{A}}\mathbf{H}} + \sigma_{\mathsf{B}}^2 N_{\mathsf{B}} \mathbf{I}_L)^{-1} \mathbf{S}_{\mathsf{B}}^H \mathbf{R}_{\mathbf{H}} \quad (14)$$

where $\mathbf{R}_{\mathbf{S}_{\mathsf{A}}\mathbf{H}} = \mathrm{E}[\hat{\mathbf{S}}_{\mathsf{A}}^H \mathbf{H}_4^H \mathbf{H}_4 \hat{\mathbf{S}}_{\mathsf{A}}]$. Note $\mathbf{S}_{\mathsf{B}}$ is constructed at terminal B using the same modulation scheme as $\hat{\mathbf{S}}_{\mathsf{B}}$, but using the data $\mathbf{d}_{\mathsf{B}}$. There may be errors in $\hat{\mathbf{d}}_{\mathsf{B}}$ depending on the decoding performance at the relay in the MAC phase.

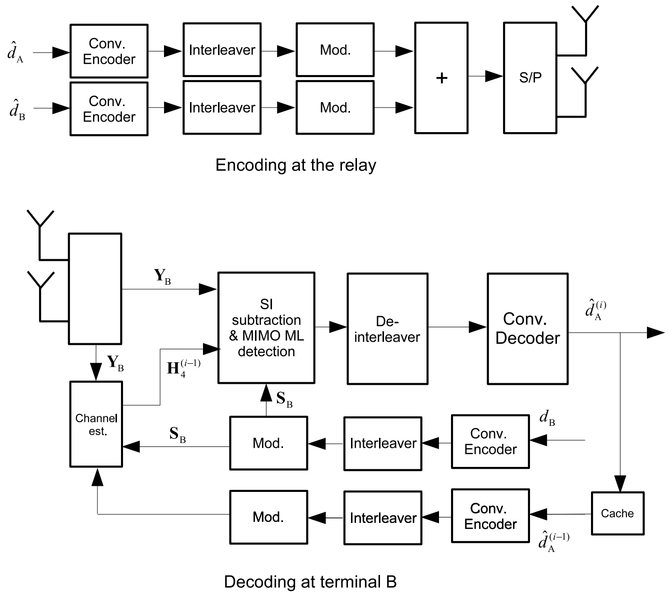


Fig. 2. Decision-directed channel estimation

B. Decision-Directed Iterative Channel Estimation

In general, the channel estimates obtained from (14) have bad accuracy. The same problem occurs even if $\hat{\mathbf{S}}_{\mathsf{B}}$ is made of orthogonal pilot sequences and is perfectly known to terminal B [4]. This is because the data signal $\hat{\mathbf{S}}_{\mathsf{A}}$, as well as noise, interferes the estimation result. In order to improve the accuracy of the estimated channel, a decision-directed approach has to be adapted, where channel estimation and data detection are performed jointly and iteratively. Furthermore, the performance of this approach can be greatly improved if error-correcting codes are applied. Fig. 2 shows an example of how convolutional codes can be integrated into the channel estimation and data detection process in the system. Its structure is simple yet the performance is good. At the relay side, the decoded data $\hat{\mathbf{d}}_{\mathsf{A}}$ and $\hat{\mathbf{d}}_{\mathsf{B}}$ are re-encoded by convolutional encoders, interleaved, modulated using e.g. QAM or PSK modulators and added up together. No pilot sequences are transmitted by the relay in the BRC phase.

At the receiver side of terminal B, the decision-directed iterative channel estimator works as follows:

1) The initial estimate of $\mathbf{H}_4$ is obtained by the known data from the SI according to (14) and we denote the estimate as $\mathbf{H}_4^{(1)}$;

2) In the ith iteration ($i \geq 2$), we subtract the SI using the previous channel estimate $\mathbf{H}_4^{(i-1)}$, i.e.,

$$\mathbf{Y}_\mathsf{B} - \mathbf{H}_4^{(i-1)}\mathbf{S}_\mathsf{B} = \mathbf{H}_4\hat{\mathbf{S}}_\mathsf{A} + \left(\mathbf{H}_4 - \mathbf{H}_4^{(i-1)}\right)\hat{\mathbf{S}}_\mathsf{B} + \tilde{\mathbf{N}}_\mathsf{B}$$
$$= \mathbf{H}_4^{(i-1)}\hat{\mathbf{S}}_\mathsf{A} + \left(\mathbf{H}_4 - \mathbf{H}_4^{(i-1)}\right)\hat{\mathbf{S}}_\mathsf{R} + \tilde{\mathbf{N}}_\mathsf{B}.$$

There may be difference between $\mathbf{S}_\mathsf{B}$ and $\hat{\mathbf{S}}_\mathsf{B}$ due to the decoding errors at the relay, and such interference terms are merged into $\tilde{\mathbf{N}}_\mathsf{B}$ in the above equations. The data contained in $\hat{\mathbf{S}}_\mathsf{A}$ are demapped from $\mathbf{Y}_\mathsf{B} - \mathbf{H}_4^{(i-1)}\mathbf{S}_\mathsf{B}$ using $\mathbf{H}_4^{(i-1)}$, where $\left(\mathbf{H}_4 - \mathbf{H}_4^{(i-1)}\right)\hat{\mathbf{S}}_\mathsf{R} + \tilde{\mathbf{N}}_\mathsf{B}$ is treated as noise. The demapped data from terminal A are deinterleaved and decoded by the convolutional decoder. The decoded data may still contain errors due to the channel estimation errors and noise.

3) The decoded data from terminal A are re-encoded using the convolutional encoder, interleaved and remodulated. It is denoted as $\mathbf{S}_\mathsf{A}^{(i)}$ and is added up with $\mathbf{S}_\mathsf{B}$, i.e.,

$$\mathbf{S}_\mathsf{R}^{(i)} = \mathbf{S}_\mathsf{A}^{(i)} + \mathbf{S}_\mathsf{B} \quad (15)$$

where $\mathbf{S}_\mathsf{R}^{(i)}$ represents the ith estimation of $\mathbf{S}_\mathsf{R}$. The ith channel estimate $\mathbf{H}_4^{(i)}$ can be calculated according to (13), i.e.,

$$\mathbf{H}_4^{(i)} = \mathbf{Y}_\mathsf{B}\left((\mathbf{S}_\mathsf{R}^{(i)})^H\mathbf{R}_\mathbf{H}\mathbf{S}_\mathsf{R}^{(i)} + \sigma_\mathsf{B}^2 N_\mathsf{B}\mathbf{I}_L\right)^{-1}(\mathbf{S}_\mathsf{R}^{(i)})^H\mathbf{R}_\mathbf{H}.$$

4) Go to step 2) and do iterative channel estimation. The algorithm stops after a certain number of iterations or when the decoded BER does not further improve.

Since the convolutional codes correct some errors in the decoded data of terminal A and provide a better estimation of $\mathbf{S}_\mathsf{R}$ in each iteration, the estimate of $\mathbf{H}_4$ improves with $\mathbf{S}_\mathsf{R}$; a better estimate of $\mathbf{H}_4$ also leads to less errors in the data detection in the next iteration.

IV. Simulation Results

In this section, we show the performance of the proposed SI aided channel estimation scheme. In particular, we compare the performance of our proposed scheme with the traditional pilot-aided channel estimation scheme. Without loss of generality, the pilots are placed at the beginning of each transmission period. The simulation setup is a two-way DF relaying system using the superposition coding scheme as discussed in Section II. The performance measures are the MSE of the estimated channel and the bit error rate (BER) of the decoded data.

A. MSE Performance of Initial Channel Estimation

We consider a two-way DF relaying system, where $N_\mathsf{A} = N_\mathsf{B} = N_\mathsf{R} = 2$. The relay uses 4QAM modulation and allocates equal power to transmit the data of terminal A and B in the BRC phase. The channel remains constant for each transmission period of L time slots, and varies independently between different transmission periods. $\mathbf{H}_4$ is assumed to be Rayleigh fading, i.e., in each channel realization, every entry of $\mathbf{H}_4$ is an i.i.d. $\mathcal{CN}(0,1)$ random variable. When pilot-aided channel estimation schemes are applied, orthogonal pilot sequences of length N_R are transmitted at each transmit antenna of the relay, which corresponds to the minimum length pilot sequences [3]. In the following, the MSE $\bar{\mathcal{E}}$ of the estimated channel is normalized, i.e, $\bar{\mathcal{E}} = \|\mathbf{H}_4 - \hat{\mathbf{H}}_4\|_F^2/(N_\mathsf{R}N_\mathsf{B})$, where $\hat{\mathbf{H}}_4$ denotes the estimated channel. The signal to noise ratio (SNR) at the receiver of terminal B is defined as $\mathrm{SNR} = P_\mathsf{R}/\sigma_\mathsf{B}^2$, which is the x-axis of the following figures.

Fig. 3 compares the MSE of the SI aided and pilot-aided channel estimation schemes in the BRC phase. In order to evaluate the proposed scheme, we assume the relay perfectly decodes what it receives in the MAC phase. No error-correcting codes or iterative decision-directed approaches are used in Fig. 3. In addition, we consider a *genie-aided* case, where we assume the genie at the receiver of terminal B knows perfectly what is transmitted at the relay, i.e., it knows exactly $\mathbf{S}_\mathsf{R}$ and uses (13) to estimate the channel. The MSE of this genie-aided channel estimation serves as a lower bound for the decision-directed channel estimation schemes. Fig. 3(a) shows how the channel estimation MSE $\bar{\mathcal{E}}$ changes with SNR when $L = 32$. Compared with the pilot-aided scheme, the SI aided scheme has lower MSE when $\mathrm{SNR} \leq 12$dB. The MSE for the SI aided scheme does not decrease further as SNR increases because the estimation error comes not only from the noise but also from the unknown data in the received signal.

Fig. 3(b) shows how the channel estimation MSE $\bar{\mathcal{E}}$ changes with L when SNR is fixed to 10dB. It is interesting to observe that the MSE of the SI aided and the genie-aided schemes both decreases linearly with the coherence interval L for the fixed SNR if L is plotted in logarithmic scale.

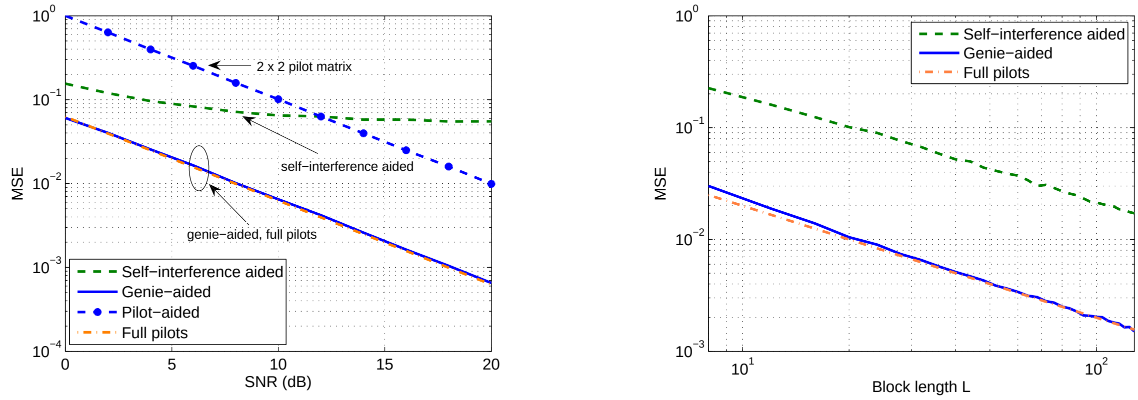
B. Decision-Directed Iterative Channel Estimation (Perfect Relay Decoding)

The channel estimation performance can be greatly improved if the decision-directed approach and error-correcting codes are applied. In our simulations, we use a rate 1/2 convolutional encoder with constraint length of 9 bits at the transmitter side. Such code is also used in the Universal Mobile Telecommunications System (UMTS) standard [9]. MIMO maximum-likelihood (ML) demappers and Viterbi decoders are applied at the receiver side of terminal B. We use random interleavers in the simulations. Each interleaver has the length of 6400 bits. The simulation parameters are summarized in Table I.

TABLE I
CONVOLUTIONAL ENCODER AND DECODER PARAMETERS

rate	1/2
constraint length	9 bits
generator polynomial	(561, 753)
traceback length	45
interleaver type	random
interleaver length	6400

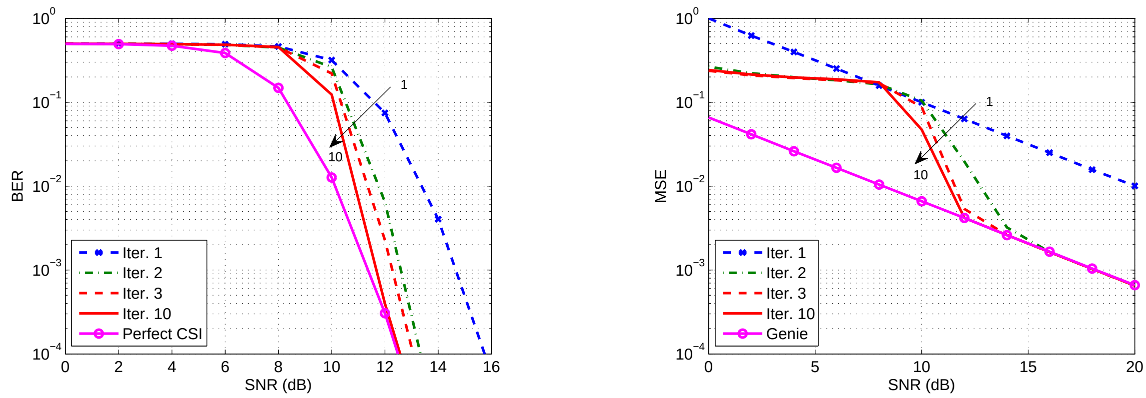
We consider an OFDM system with 64 subcarriers, where 50 subcarriers in each OFDM symbol are used to transmit data (including pilots). Each subcarrier corresponds to an i.i.d. Rayleigh fading channel, where the channel remains constant for $L = 32$ time slots. Again, we assume the relay perfectly



(a) Coherence interval $L = 32$

(b) SNR = 10dB

Fig. 3. MSE of channel estimation, $N_{\mathsf{A}} = N_{\mathsf{R}} = N_{\mathsf{B}} = 2$, block fading channel. In the curve "full pilots", orthogonal pilot sequences are transmitted in the whole transmission period to estimate the channel.



(a) BER

(b) MSE

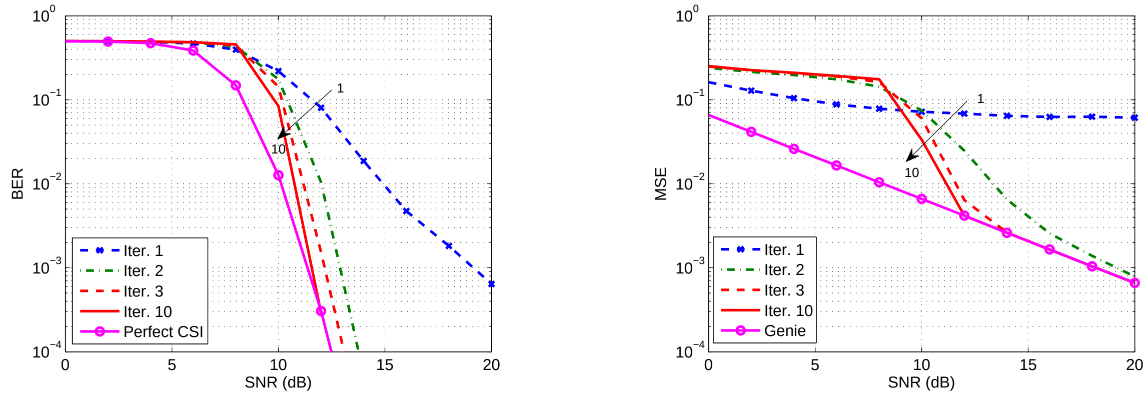
Fig. 4. Pilot-aided iterative channel estimation (assuming the decoding at the relay to be perfect in the MAC phase), channel remains constant for $L = 32$ time slots. $N_{\mathsf{A}} = N_{\mathsf{R}} = N_{\mathsf{B}} = 2$. The length of pilot sequences is N_{R}. The number in the figures denotes the number of iterations.

decodes what it receives in the MAC phase. Fig. 4 shows the BER and MSE performance when we use pilot sequences of length 2 at each subcarrier to estimate the channel. This wastes $1/16$ of the bandwidth. Longer pilot sequences can obtain better estimates of the channel, but at the price of more system resources. On the other hand, we can see in Fig. 4 that our short pilots can also get a good estimate of the channel when the decision-directed approach discussed in Section III-B is applied. In Fig. 5, we estimate the channel using the SI. Its performance is quite similar to Fig. 4. When the SNR is above 12dB, its BER performance after 10 iterations is identical to the BER when perfect CSI (channel state information) is available. In Fig. 5(b), we observe that the gap between our scheme and the "genie" bound is less than 1dB after three iterations when SNR is above 12dB. We conclude that the SI aided channel estimation requires less system resources but can still lead to similar performance as the traditional pilot-aided channel estimation scheme.

C. SI Aided Channel Estimation in Two-Way Relaying Systems

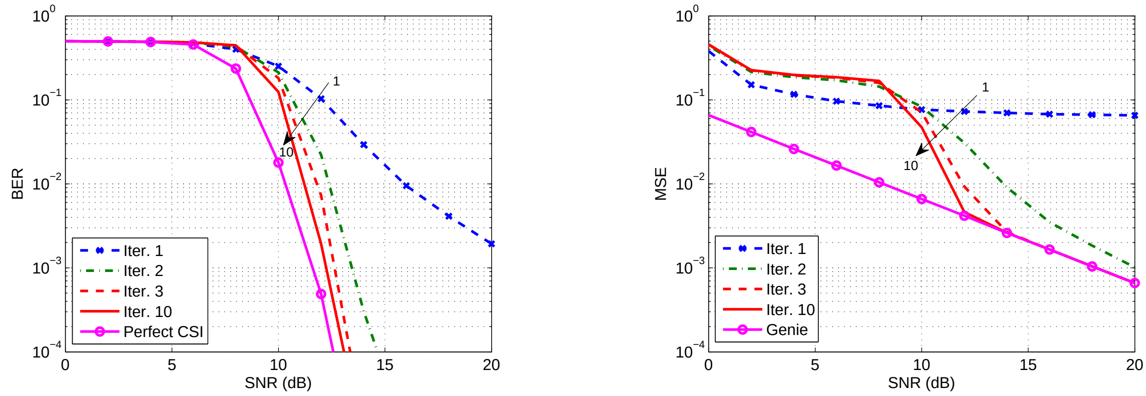
In the previous subsection, we assumed that the relay perfectly decodes the received data in the MAC phase, i.e. the SI is perfectly known at the receivers. However, in a real system, the decoding error in the MAC phase has to be considered.

In Fig. 6, we show the BER and MSE performance when both MAC and BRC phases are considered in the simulations. We assume the distance between terminal A and the relay is fixed, and the received SNR from terminal A at the relay is $P_{\mathsf{A}}/\sigma^2 = 20$dB. The channel between the relay and terminal A is a Ricean fading channel, where the K-factor of the line-of-sight (LOS) component is $K = 10$dB. This can be considered as a cellular relaying scenario, where terminal A and B represent respectively the base station and the mobile station, and the relay is placed in a position with good connection to the base station. Now we still assume the channel between the relay and terminal B remains constant for 32 time slots. To increase receive diversity, four antennas are deployed at the relay for receiving signals in the MAC phase, but only two of them are used to transmit in the BRC phase. Other simulation parameters are the same as the previous subsection. Comparing Fig. 6(a) with Fig. 5(a), we observe that the BER performance of SI aided channel estimation slightly degrades when the decoding errors in the MAC phase are present. However, the



(a) BER (b) MSE

Fig. 5. SI aided iterative channel estimation (assuming the decoding at the relay to be perfect in the MAC phase), channel remains constant for $L = 32$ time slots. The number in the figures denotes the number of iterations.



(a) BER (b) MSE

Fig. 6. SI aided iterative channel estimation in a two-way relaying system (representing a cellular relaying system), channel remains constant for $L = 32$ time slots. The number in the figures denotes the number of iterations.

gap between the proposed scheme and the perfect CSI case is less than 1dB when $\text{BER} = 10^{-3}$. Comparing Fig. 6(b) with Fig. 5(b), we can also see that the decoding errors at the relay in the MAC phase have a strong impact on the BRC phase channel estimation only in the low SNR regime (when the decoding at the relay is bad), and their impact in the high SNR regime is small.

V. Conclusions

We proposed a SI aided channel estimation scheme for two-way relaying systems. Instead of using pilot sequences, which wastes systems resources, we exploited the SI that is inherent in the two-way relaying system to estimate the channel. Simulation results showed that the proposed scheme can achieve similar performance as the traditional pilot-aided channel estimation scheme in our simulation environment. Alternatively, SI can be used together with pilot sequences to improve the performance of pilot-aided channel estimation schemes. To the best of our knowledge, this is the first scheme that *utilizes* SI for channel estimation. Due to space constraints, we only considered block-fading channel in this paper. Further results, e.g., on continuously time-varying channel, will be included in future publications.

References

[1] B. Rankov and A. Wittneben, "Spectral efficient protocols for half-duplex fading relay channels," *IEEE J. Select. Areas Commun.*, vol. 25, pp. 379–389, Feb. 2007.

[2] P. Larsson, N. Johansson, and K.-E. Sunell, "Coded bidirectional relaying," in *Proc. IEEE Veh. Tech. Conf.*, vol. 2, (Melbourne, Australia), pp. 851–855, May 7–10, 2006.

[3] M. Biguesh and A. B. Gershman, "Training-based MIMO channel estimation: A study of estimator tradeoffs and optimal training signals," *IEEE Trans. Signal Processing*, vol. 54, pp. 884–893, Mar. 2006.

[4] C. K. Ho, B. Farhang-Boroujeny, and F. Chin, "Added pilot semi-blind channel estimation scheme for OFDM in fading channels," in *Proc. IEEE Global Comm. Conf. (GLOBECOM)*, vol. 5, (San Antonio, TX), pp. 3075–3079, Nov. 25–29, 2001.

[5] H. Zhu, B. Farhang-Boroujeny, and C. Schlegel, "Pilot embedding for joint channel estimation and data detection in MIMO communication systems," *IEEE Commun. Lett.*, vol. 7, pp. 30–32, Jan. 2003.

[6] S.-M. Tseng, "Iterative vector channel estimation/MAP/PIC for CDMA systems in time-selective correlated multipath fading channels," *IEEE Trans. Commun.*, vol. 54, pp. 614–618, Apr. 2006.

[7] S. Verdú, *Multiuser Detection*. Cambridge University Press, Aug. 1998.

[8] S. M. Kay, *Fundamentals of Statistical Signal Processing, Volume I: Estimation Theory*. Prentice Hall PTR, 1993.

[9] ETSI, "Universal mobile telecommunications system (UMTS); multiplexing and channel coding (TDD)," Tech. Rep. 3GPP TS 25.222 version 4.2.0, Dec. 2001.