A New Approach of MIMO-OFDM Two-Way Relay Networks for Optimal Design

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Abstract: In this paper, we study a training design problem for multiple-input multiple-output (MIMO) orthogonal frequency division multiplexing (OFDM) amplify-and-forward (AF) two way relay networks. Unlike the existing studies, we assume the spatially correlated fading and consider the non reciprocal channel condition, which is a more practical assumption but makes the training problem more challenging. The equivalent channels of bidirectional relaying links, which consist of self interfering channels and information-bearing channels, are estimated at each source node based on a linear minimum mean square error (LMMSE) approach. The total mean square error(MSE) of the channel estimation is minimized under the transmit power constraints at the source nodes and at the relay. To solve this problem, we first derive an optimal structure of the training signals, and then, convert the optimization problem into a tractable convex form, from which the optimal training scheme is designed efficiently. Furthermore, for a practical special case, the optimal training design is derived in semi-closed form, which provides useful insights. To reduce the required complexity, a low-complexity training scheme is also derived in closed-form. This scheme is shown to be asymptotically optimal in the high signal-to-noise ratio (SNR) regime and gives further insights into the optimal training. The performance of the proposed schemes is demonstrated through numerical simulations.

Keywords*:* Amplify-And-Forward Relay, Channel Estimation, MIMO-OFDM, Spatial Fading Correlation, Training Design, Twoway Relay.

I. INTRODUCTION

Two-way relay networks have gained a lot of research attention in recent years [1]–[3]. In the literature, there are several two-way relaying protocols including analog network coding and physical layer network coding, and their performance has been analyzed [2], [3]. Multiple-input multiple output(MIMO) technology utilizing multiple co-located antennas has outstanding capability to increase the throughput or improve the link reliability [4], [5]. Also, orthogonal frequency division multiplexing (OFDM) is a multi-carrier modulation scheme that has been adopted in many systems as a standard technique to combat the multi-path fading [6], [7].The combination of these two techniques, so called MIMOOFDM, is a key technology to achieve high data rate [6]. The MIMO-OFDM techniques can also be used in two-way relay networks to enhance the system performance further [8], [9].A key problem in the MIMO-OFDM relay system is to acquire accurate channel state information (CSI). For two-way relaying applications, obtaining accurate end-to-end bi-directional CSI is particularly important because two end source nodes should coherently detect the transmitted symbols and exactly cancel the self-interference. In practice, the CSI needs to be estimated by using training symbols. In this case, the accuracy of the channel estimation crucially depends on the design of training sequences. For narrowband two-way relay systems, the issue of training design has been well studied[10]–[12]. For the case of OFDM two-way relay networks, various methods for channel estimation and training design have been proposed [13]–[18]. Among those, the techniques of [13]–[15] are limited to the single-antenna scenario, and unfortunately, their extension to the multi-antenna scenario is not straightforward due to the presence of interference among transmit antennas. For MIMO-OFDM two-way relay systems, several training algorithms have been developed based on the expectation maximization approach [16] and the least squares(LS) approach [18], [17].The existing schemes [16]–[18], however, have several major limitations. Firstly, in [16]–[18], the channel estimation is not always accurate. The reason is that the training sequences are not optimally designed [16] and the received noise is enhanced [17], [18]. Since the training performance highly affects the subsequent data transmission performance, it is very important to improve the quality of the channel estimates in order to enhance the overall system performance. Secondly, the existing works [16]–[18] assumed spatially white MIMO channels; i.e., the individual channel gains from transmit antennas to receive antennas are independently faded.

This assumption might be reasonable in certain scenarios; for example, the downlink transmission from a base station with multiple antennas to a mobile terminal with single antenna, because the antennas at the base station can be placed sufficiently far apart. However, if the mobile terminal is equipped with multiple antennas, the channel in the system should be unavoidably spatially correlated due to limited size of the mobile device. Thus, in practical MIMO mobile systems, it should be more reasonable to assume the channels to be spatially correlated. Particularly, the spatially correlated channels can be frequently encountered in realistic two-way relaying scenarios, since the two end source nodes that intend to exchange their information are most likely to be mobile terminals [19]. Furthermore, the two-way relay systems are very susceptible to the spatial fading correlation, because if the fading is correlated at one of the nodes, then the overall channels of the end-to-end bidirectional links will eventually be correlated. For the above reasons, the training design problem for spatially correlated fading channels is a very important issue in practical MIMO two-way relay networks. Thirdly, all the schemes in [16]–[18] were developed under the assumption that the channels between the sources and the relay are reciprocal. Particularly, the symmetric property of the self-interfering channels was exploited as a key factor for channel training [16], [17]. Although the channel reciprocity usually holds in the time-division duplex (TDD) relaying scenario, it does not generally hold in the practical frequency division duplex (FDD) relaying scenario because the signal transmission and reception take place in different frequency bands [20]–[22]. In these applications, the approaches of[16] and [17] introduce a mismatch, leading to a significant performance degradation. Moreover, in [18], the same statistics of the first-hop and second-hop CSI were utilized for training design. However, this approach is not valid for nonreciprocal channels, because the first-hop and second-hop channels have different statistics in general. In order to address the channel estimation accuracy issue and to cope with a wide range of applications, it is very important to overcome the above limitations. However, the training problem for broadband MIMO-OFDM two-way relay systems is generally challenging to solve compared to those tackled in [10]–[12] for narrowband systems, for the following reasons. First, for the general OFDM two-way relaying scenario, the major challenge in the channel estimation arises from the frequency-selectivity and non-reciprocity of the fading channels. Second, the channel taps of the bidirectional links generally have different spatial fading correlations. In addition, the phase-shift effects in multi-carrier training symbols also need to be taken into consideration in the training design. To the best of our knowledge, the aforementioned issues have not been successfully addressed in the literature and have not been resolved yet.

Furthermore, for MIMO-OFDM two-way relay networks, the optimal training design still remains unknown under spatially correlated fading. These motivated our work. In this paper, we consider the training problem for MIMOOFDM two-way relay networks and resolve all of the issues related to the existing schemes [16]–[18]. To this end, we firstly develop a channel training method based on a linear minimum mean square error (LMMSE) criterion, which can capture the impact of the spatial fading correlation of the nonreciprocal channels. To improve the quality of the channel estimates, an optimal training design is presented by minimizing the total mean square error (MSE) under the transmit power constraints at the source nodes and at the relay. Overall, the technique developed in this paper is not restricted by the assumptions made in [16]–[18] and has a wider applicability. The contributions of this paper can be summarized as follows.

- We resolve the noise amplification issue by applying the LMMSE approach, leading to better performance than the existing methods even in spatially white environments.
- We design an optimal training for MIMO-OFDM two way relay networks considering the spatial fading correlation.
- We derive the optimal training structure that minimizes the total MSE of the LMMSE channel estimator as well as eliminates all the phase-shift interferences in bidirectional relaying links. It is shown that the existing training sequence designs in [17] and [18] are included in the proposed structure as special cases.
- Using the optimal structure, it is proved that the optimal training design problem is converted into a semi-definite programming (SDP), which is a standard convex form, and hence, is solvable efficiently with a polynomial time complexity. This is in sharp contrast to the originally formulated problem, which is too time-consuming to solve or is not solvable even numerically.
- We investigate an important practical scenario where the spatial characteristics of different channel taps are identical at each source node. In this special case, the optimal training is shown to have a specific structure that reduces the matrix-valued optimization problem to a simple power allocation problem, which is solvable with a lower-complexity.
- For the general case where the channels have different spatial characteristics, we propose a low-complexity training design in closed-form, which is proved to be asymptotically optimal in the high signal-to-noise ratio(SNR) regime.

In particular, it turns out that for the asymptotically high SNR case, the optimal training relies only on the eigen modes of the first-hop source-relay links, not those of the end-to-end bidirectional links. Such asymptotic analysis has not been done even for the case of narrowband MIMO two-way relay networks including[10]–[12]. Also, it turns out that for the case of spatially correlated channels, the existing training designs in [17]and [18] are suboptimal even in the high SNR regime. In addition to the above new aspects, new contributions in this paper as opposed to our previous work [12] are as follows:

- In the wideband OFDM two-way relaying scenario, we deal with more challenging channel training problem than[12] by addressing the frequency-selectivity issue.
- We derive more general theoretical results for the LMMSE-based training design than [12] by considering the more general scenario of the spatial fading correlation. The solution obtained in [12] is a special case of the proposed solution in this paper.
- We propose the asymptotically optimal training scheme in the high SNR case. This asymptotic scenario has never been studied in [12].
- We obtain new, interesting, and useful insights that were not observed in [12]. For example, unlike [12], the optimal training sequences turn out to have the nondiagonal structure. Also, in contrast to [12], we provide useful insights in the high SNR scenario.

II. SYSTEM MODEL AND CHANNEL ESTIMATION

A. MIMO-OFDM Two-Way Relay System

We consider a half-duplex MIMO-OFDM two-way relay system consisting of two source nodes, denoted by source 1and source 2, and a relay node. The ith source is equipped with Mi antennas for i= 1; 2, and the relay is equippedwithMrantennas.1 We adopt the amplify-and-forward (AF)relaying strategy due to its merits of simple operation and low complexity. The system model considered is applicable to bidirectional communication scenarios in various applications such as device-to-device/satellite/power-line communication systems and wireless sensor networks [23]–[26]. Also, in recent release of IMT-A standard, various cooperative relaying scenarios including the considered two-way relaying scheme have been incorporated in different network architectures and transmission modes for future standardization [27].There are K subcarriers and L + 1 channel taps in the communication links between the sources and the relay. The extension to the scenario with different number of channel taps is straightforward.

B. Training Procedure

The channel estimation process is conducted during two transmission phases: multiple access (MAC) phase and broadcast(BC) phase. In each phase, the transmission block consists of K OFDM training symbols. The training signal transmissions in the MAC and BC phases are shown in Fig. 1. The channel estimation task is assumed to be performed at each source node, not at the relay, as usually assumed in the AF relaying scenario [10]–[18]. The reasons for this assumption are as follows. First, it is practically difficult for the simplistic AF relay to estimate the CSI due to its hardware and processing limitations [29]. Second, even if the CSI estimation is possible, some amount of training should be taken at the relay to estimate the CSI. However, because the amount of training is limited in practice, the end-to end channel estimation performance may be degraded by the channel estimation at the relay. Also, the transmit power at the relay is not adapted because the first-hop CSI is unknown. Instead, the fixed amplifying gain is assumed to be used at the relay. The standard OFDM modulation and demodulation techniques are applied to each antenna and the cyclic prefix of length L is inserted per antenna transmission to avoid the interference between two adjacent symbol blocks. In the MAC phase, both source nodes transmit their training signals to the relay.

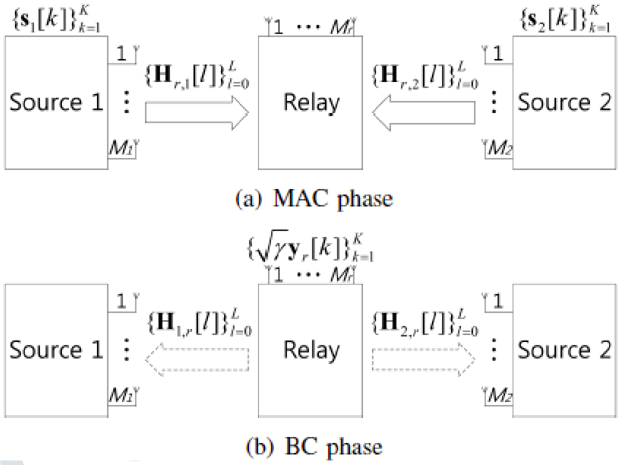

Fig.1. Training signal transmissions in MAC and BC phases.

III. SIMULATION RESULTS

Simulation results of this paper is as shown in bellow Figs.2 to 5.

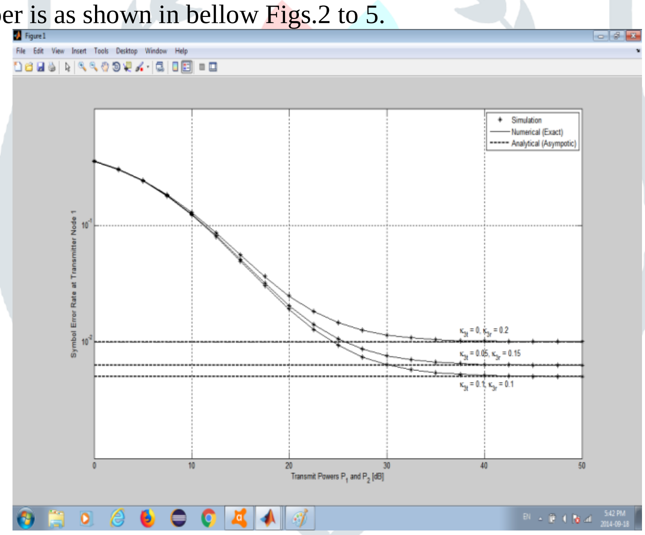

Fig.2. Simulation Results.

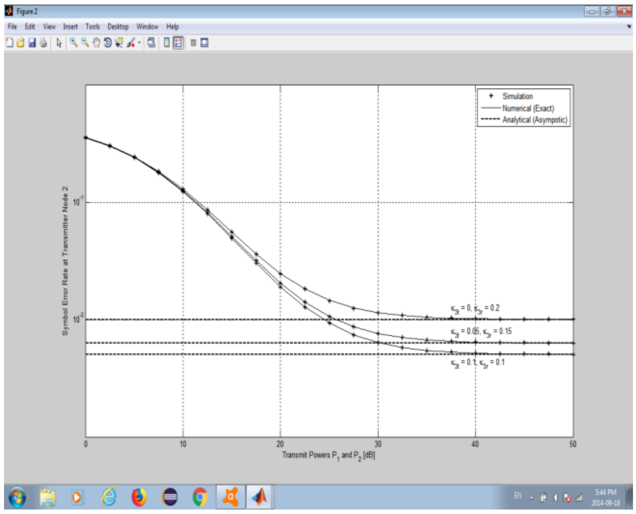

Fig.3. Simulation Results.

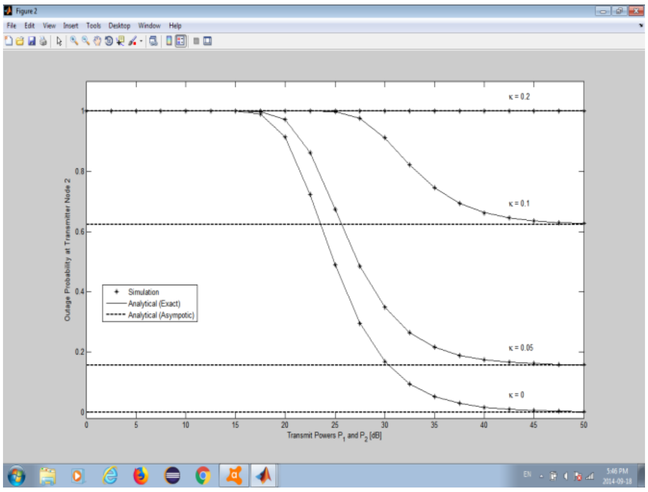

Fig.4. Simulation Results.

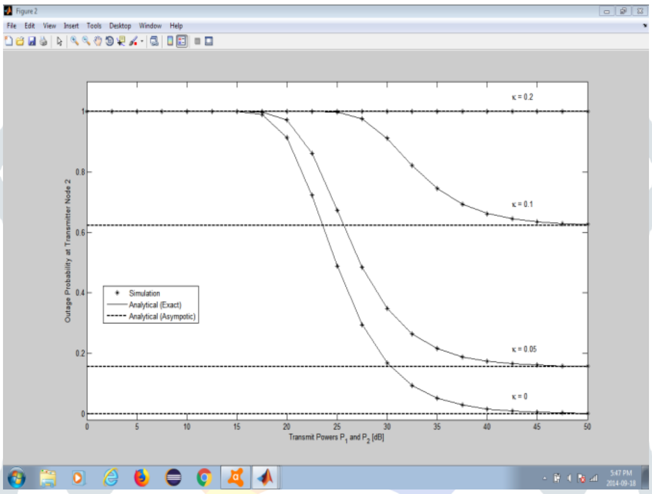

Fig.5. Simulation Results.

IV. CONCLUSION

In this paper, we studied the optimal training design for MIMO-OFDM AF two-way relay networks. Firstly, the LMMSE-based channel training technique was developed to obtain spatially correlated TDD/FDD channel estimates with an improved accuracy. Then the optimal training structure was derived in the sense of minimizing the total MSE, which was also shown to eliminate the phase-shift interferences among the training symbols. Using this structure, the optimal training design problem was recast as a tractable SDP form, from which we obtained the optimal solution with a polynomial time complexity. An important special scenario of identical spatial characteristics was also investigated, for which the optimal training was designed with a lower complexity. Finally, for ease of implementation while keeping the optimality, the low complexity solution was proposed in closed-form based on the upper bound. This solution was shown to be asymptotically optimal in the high SNR range and to be near-optimal even in the finite SNR range. Simulation results validated that under different relaying scenarios, the proposed schemes significantly outperformed the existing schemes in terms of the channel estimation. Also, numerical results revealed that the proposed methods were very useful for the applications requiring lower error rates and higher data rates due to the significantly enhanced BER and capacity performance.

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