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Link Adaptation for Full Duplex Systems

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Abstract

This paper presents a link adaptation scheme for adaptive full duplex (AFD) systems. The signal modulation levels and communication link patterns are adaptively selected according to the changing channel conditions. The link pattern selection process consists of two successive steps such as a transmit-receive antenna pair selection based on maximum sum rate or minimum maximum symbol error rate, and an adaptive modulation based on maximum minimum norm. In AFD systems, the antennas of both nodes are jointly determined with modulation levels depending on the channel conditions. An adaptive algorithm with relatively low complexity is also proposed to select the link parameters. Simulation results show that the proposed AFD system offers significant bit error rate (BER) performance improvement compared with conventional full duplex systems with perfect or imperfect self-interference cancellation under the same fixed sum rate.

Keywords: *Full duplex (FD), Adaptive Modulation (AM), Link Adaptation, Maximum Likelihood (ML) Receiver, Joint Transmit and Receive Antenna Selection*

1. Introduction

Full-duplex (FD) transmission has been considered as a promising technique for doubling the spectral efficiency of conventional half-duplex (HD) systems by simultaneously performing both signal transmission and reception on the same frequency at the same time slot at a communication node [1], [2]. Recent researches have shown that self-interference (SI) generated in FD radios can be significantly suppressed through passive and active approaches [1]-[4]. In Multiple-input multiple-output (MIMO) FD systems, joint transmit and receive antenna selection methods have been presented to obtain better system performance [5],[6]. However, the residual SI still exists and affects the FD system performance. When the residual SI is relatively high, its symbol error rate (SER) performance is constrained by the error floors.

In this work, an adaptive modulation technique is applied to improve the FD system performance including error floors while remaining the transmit data rate summed at both communication nodes. For

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different channel conditions, a transmit-receive antenna pair (TRAP) for bi-direction together with modulation orders of both nodes is jointly selected for FD radios to optimize the system performance. A simple link adaptation scheme based on the instantaneous channel information is developed for FD systems, called an adaptive full duplex (AFD) scheme. Thus, a link adaptation algorithm with relatively low complexity is proposed to yield the better BER performance under a fixed data rate.

2. System Model

Consider an AFD communication system where two nodes, n_A and n_B, can be set to either transmit or receive the signals on the same frequency band at the same time. For simplicity, each node is assumed to have two antennas and two RF chains. The connections between the transmit/receive (Tx/Rx) RF chains and the antennas are adaptable and can be determined depending on the minimum Euclidean distance and the channel conditions between two nodes. In this work, one communication system with two links (FD mode) is adaptively selected among four possible communication patterns, as described in Figure 1.

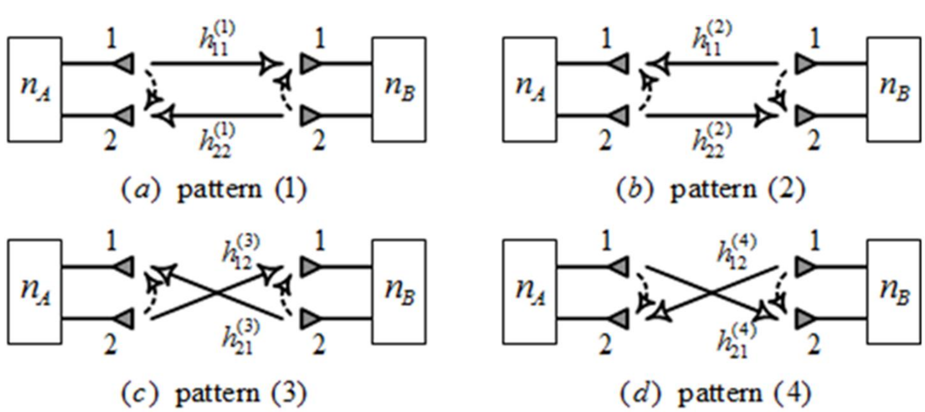

Figure 1. Adaptive modulation-based link selection for AFD model

The channel coefficient of link pattern (p) between the *j*-th antenna at node n_A and the *i*-th antenna at node n_B is denoted by $h_{ij}^{(p)}$, $i=1,2$, $j=1,2$, and $p=1,2,3,4$, which is shown in Figure 1. It is assumed that $h_{ij}^{(p)}$ has a complex Gaussian distribution with zero-mean and unit-variance and follows the non-selective independent block fading. It is assumed that the channel reciprocity is valid and the channel side information is available at both nodes. In the beginning of each time slot, an adaptive module used in each node can estimate all the possible communication link patterns. The proposed AFD system can be bi-directional FD with either patterns (1) or (2) by link adaptation. Since the patterns (1) and (2), respectively, can be regarded as the identical ones to patterns (3) and (4), the communication patterns (1) and (2) are only considered in this work. Here the patterns (1), (2), (3), and (4), respectively, correspond to (a), (b), (c), and (d) in Fig. 1. When the AFD system is operated in bi-directional FD mode, SI cancellation techniques should be employed [2]-[4]. The residual SI can be modeled as a Gaussian noise [7]. Let's define the channel coefficients of pattern (p) connected from node n_B to node n_A and from n_A to n_B, respectively, as

$h_{AB}^{(p)}$ and $h_{BA}^{(p)}$. Then, the signals, $y_A^{(p)}$ and $y_B^{(p)}$, received at the Rx antenna at nodes n_A and n_B are given by, respectively,

$$y_A^{(p)} = \sqrt{P_s}\, h_{AB}^{(p)} x_B^{(p)} + \sqrt{\eta P_s}\, w_A^{(p)} + n_A^{(p)} \tag{1}$$
$$y_B^{(p)} = \sqrt{P_s}\, h_{BA}^{(p)} x_A^{(p)} + \sqrt{\eta P_s}\, w_B^{(p)} + n_B^{(p)} \tag{2}$$

where $x_A^{(p)}$ and $x_B^{(p)}$, respectively, denote the transmitted signal with unit power from nodes n_A and n_B defined by signal constellations $X_A^{(p)}$ and $X_B^{(p)}$ used at pattern (p). P_s stands for the transmit power at each node and η indicates a SI cancellation factor. $w_A^{(p)}$ and $w_B^{(p)}$, respectively, represent the residual SI at nodes n_A and n_B. They are complex Gaussian random variables with zero-mean and unit-variance. $n_A^{(p)}$ and $n_B^{(p)}$, respectively, are additive white Gaussian random variables with zero-mean and variance N_0 at nodes n_A and n_B.

3. Link Pattern Selection

To select a link pattern which can provide the better BER performance of AFD systems than the conventional FD systems under an identical fixed sum rate, the proposed link adaptation procedure requires two steps. First one is to select a TRAP based on maximum sum rate or minimum maximum SER criteria. After TRAP selection, an adaptive modulation based on a maximum minimum norm or maximum minimum SINR criteria is performed to assign signal modulation levels for the selected TRAP.

3.1 Tx-Rx antenna pair selection

Two criteria employed in [5], which are given as (3) and (7) below, are employed to select a TRAP in the first step. One selection criterion is based on the maximum bidirectional sum rate (Max-SR) of two nodes, which is given as

$$q_{Max-SR}^{*} = \arg\max_{q\in\{1,2\}} \left\{ R_A^{(q)} + R_B^{(q)} \right\} \tag{3}$$

where $R_A^{(q)}$ and $R_B^{(q)}$ denote the rate of nodes n_A and n_B in link pattern (q), respectively, which can be expressed as

$$R_A^{(q)} = \log_2\left(1 + \frac{P_s}{\eta P_s + 1}\left|h_{BA}^{(q)}\right|^2\right) \tag{4}$$

$$R_B^{(q)} = \log_2\left(1 + \frac{P_s}{\eta P_s + 1}\left|h_{AB}^{(q)}\right|^2\right) \tag{5}$$

Then, the Max-SR approach can be rewritten as

$$q^{*}_{Max-SR} = \arg\max_{q\in\{1,2\}} \left\{ \left|h_{BA}^{(q)}\right|^2 + \left|h_{AB}^{(q)}\right|^2 \right\} \tag{6}$$

The other one relies on the minimum maximum SER [5] and can be given as

$$q^{*}_{Min-Max-SER} = \arg\min_{q\in\{1,2\}} \left\{ \max\left(SER_A^{(q)}, SER_B^{(q)} \right) \right\} \tag{7}$$

As the instantaneous error performance is influenced by the node with the worst SINR, the selected link can be equivalently obtained as

$$q^{*}_{Min-Max-SER} = \arg\max_{q\in\{1,2\}} \left\{ \min\left(\left|h_{BA}^{(q)}\right|^2, \left|h_{AB}^{(q)}\right|^2 \right) \right\} \tag{8}$$

Note that there exist two possible patterns for TRAP selection in FD mode. In other words, according to a selection criterion, the first step is to determine one TRAP among the set of all available two candidate subsets of TRAPs.

3.2 Adaptive modulation based on maximum minimum norm

In the first step of the proposed link adaptation, a TRAP corresponding to the pattern (q^*), $q^* \in \{1, 2\}$, is selected according to one criterion among two criteria introduced in section 3.1. Now we have a FD mode in which ML detection can be performed at each Rx antenna of nodes n_A and n_B as follows:

$$\hat{x}_B^{(q^*)} = \arg\min_{x_B^{(q^*)} \in X_B^{(q^*)}} \left\| y_A^{(q^*)} - h_{AB}^{(q^*)} x_B^{(q^*)} \right\|^2 \tag{9}$$

$$\hat{x}_A^{(q^*)} = \arg\min_{x_A^{(q^*)} \in X_A^{(q^*)}} \left\| y_B^{(q^*)} - h_{BA}^{(q^*)} x_A^{(q^*)} \right\|^2 \tag{10}$$

where $X_A^{(q^*)}$ and $X_B^{(q^*)}$, respectively, are the sets of M_A and M_B possible transmit symbols. Then, (9) and (10) can be combined as

$$\left[\hat{x}_A^{(q^*)}, \hat{x}_B^{(q^*)} \right] = \arg\min_{x_A^{(q^*)} \in X_A^{(q^*)},\, x_B^{(q^*)} \in X_B^{(q^*)}} \left\{ \left\| y_B^{(q^*)} - h_{BA}^{(q^*)} x_A^{(q^*)} \right\|^2 + \left\| y_A^{(q^*)} - h_{AB}^{(q^*)} x_B^{(q^*)} \right\|^2 \right\} \tag{11}$$

(11) can be re-expressed as

$$\hat{\mathbf{x}}^{(q^*)} = \arg\min_{\mathbf{x}^{(q^*)} \in \mathbf{X}^{(q^*)}} \left\| \mathbf{y}^{(q^*)} - \mathbf{H}_d^{(q^*)} \mathbf{x}^{(q^*)} \right\|^2 \tag{12}$$

where $\mathbf{X}^{(q^*)}$ is the set of all $M_A M_B$ possible symbol vectors and

$$\mathbf{y}^{(q^*)} = \begin{bmatrix} y_A^{(q^*)} & y_B^{(q^*)} \end{bmatrix}^T \tag{13}$$

$$\mathbf{H}_d^{(q^*)} = \begin{bmatrix} h_{AB}^{(q^*)} & 0 \\ 0 & h_{BA}^{(q^*)} \end{bmatrix} \tag{14}$$

$$\mathbf{x}^{(q^*)} = \begin{bmatrix} x_B^{(q^*)} & x_A^{(q^*)} \end{bmatrix}^T \tag{15}$$

The received minimum distance $d_{\min}$ can be defined as

$$d_{\min} = \min_{\mathbf{x}_m^{(q^*)}, \mathbf{x}_n^{(q^*)} \in \mathbf{X}^{(q^*)},\, \mathbf{x}_m^{(q^*)} \neq \mathbf{x}_n^{(q^*)}} \left\| \mathbf{H}_d^{(q^*)} \left(\mathbf{x}_m^{(q^*)} - \mathbf{x}_n^{(q^*)} \right) \right\| \tag{16}$$

(16) can be reformulated as

$$d_{\min} = \min_{\overline{\mathbf{e}}_{mn}^{(q^*)} \in \overline{E}^{(q^*)}} \left\| \mathbf{H}_d^{(q^*)} \mathbf{D}^{(q^*)} \overline{\mathbf{e}}_{mn}^{(q^*)} \right\| \tag{17}$$

where

$$\mathbf{D}^{(q^*)} = \begin{bmatrix} d_B^{(q^*)} & 0 \\ 0 & d_A^{(q^*)} \end{bmatrix} \tag{18}$$

$$\overline{\mathbf{e}}_{mn}^{(q^*)} = \begin{bmatrix} \overline{e}_{mn,B}^{(q^*)} & \overline{e}_{mn,A}^{(q^*)} \end{bmatrix}^T \tag{19}$$

Here $d_A^{(q^*)}$ and $d_B^{(q^*)}$, respectively, are the minimum distances in signal constellations corresponding to the modulation levels employed in nodes n_A and n_B in pattern (q^*). $\overline{e}_{mn,A}^{(q^*)}$ and $\overline{e}_{mn,B}^{(q^*)}$ are normalized error factors of $(x_{m,A}^{(q^*)} - x_{n,A}^{(q^*)})$ and $(x_{m,B}^{(q^*)} - x_{n,B}^{(q^*)})$, respectively, by $d_A^{(q^*)}$ and $d_B^{(q^*)}$. $\overline{E}^{(q^*)}$ is the set of normalized error vectors. The received minimum distance of (17) can be lower-bounded by the selected TRAP and minimum distance in signal constellation. Then the squared received minimum distance is given by

$$d_{\min}^2 = \min_{\overline{\mathbf{e}}_{mn}^{(q^*)} \in \overline{E}^{(q^*)}} \left\| \mathbf{H}_d^{(q^*)} \mathbf{D}^{(q^*)} \overline{\mathbf{e}}_{mn}^{(q^*)} \right\|^2 \geq \lambda_{\min}^2 \left(\mathbf{H}_d^{(q^*)} \mathbf{D}^{(q^*)} \right) \min_{\overline{\mathbf{e}}_{mn}^{(q^*)} \in \overline{E}^{(q^*)}} \left\| \overline{\mathbf{e}}_{mn}^{(q^*)} \right\|^2 = \min\left(\left| h_{BA}^{(q^*)} d_B^{(q^*)} \right|^2, \left| h_{AB}^{(q^*)} d_A^{(q^*)} \right|^2 \right) \tag{20}$$

where $\lambda_{\min}$ is a minimum singular value of the matrix $\mathbf{H}_d^{(q^*)} \mathbf{D}^{(q^*)}$. Note that $\min_{\overline{\mathbf{e}}_{mn}^{(q^*)} \in \overline{E}^{(q^*)}} \left\| \overline{\mathbf{e}}_{mn}^{(q^*)} \right\|^2 = 1$ and

$$\lambda_{\min}^2\left(\mathbf{H}_d^{(q^*)}\mathbf{D}^{(q^*)}\right)=\min\left(\left|h_{AB}^{(q^*)}d_B^{(q^*)}\right|^2,\left|h_{BA}^{(q^*)}d_A^{(q^*)}\right|^2\right).$$

Thus, the adaptive modulation approach for an AFD MIMO ML system with a fixed total transmission rate is proposed as follows

$$u^* = \underset{\left\{d_{u,A}^{(q^*)},d_{u,B}^{(q^*)}\right\}\in\mathbf{\Gamma}_{all}}{\arg\max}\left\{\min\left(\left|h_{BA}^{(q^*)}d_{u,B}^{(q^*)}\right|^2,\left|h_{AB}^{(q^*)}d_{u,A}^{(q^*)}\right|^2\right)\right\} \text{ subject to } r_A+r_B=R \quad (21)$$

where $\mathbf{\Gamma}_{all}\in\left\{d_{u,A}^{(q^*)},d_{u,B}^{(q^*)}\right\}$, $u=1,2,\cdots,U$, is a set of the minimum distances determined by a combination of signal modulation schemes and R is the total transmission bit rate of both nodes. Also, r_A and r_B, respectively, are the number of bits assigned to nodes n_A and n_B. In this paper, three cases, namely, 4-QAM, 8-QAM, and 16-QAM are assumed for each transmission. For example, under 6 bits/transmission ($R=6$), five combinations of aforementioned modulation orders are considered. In this example, the set of three cases ($U=3$) can be given as $\mathbf{M}_{all}=\{[16,4],[8,8],[4,16]\}$, where each subset consists of modulation orders of nodes n_A and n_B, respectively, and 1 means no-transmission. Here $\mathbf{M}_{all}$ corresponds to the set $\mathbf{\Gamma}_{all}=\left\{\left[2/\sqrt{10},2/\sqrt{2}\right],\left[2/\sqrt{6},2/\sqrt{6}\right],\left[2/\sqrt{2},2/\sqrt{10}\right]\right\}$.

Compared with computational complexity of the previous FD system with a TRAP selection presented in [5], the additional complexity of AFD systems comes from the evaluation of (21), which mainly depends on the number of signal modulation set considered. This increased complexity is relatively small. Note that the second step associated with the proposed link selection algorithm does not require a singular value decomposition (SVD) computation, which is a part of complexity-reduction. On the other hand, an adaptive modulation algorithm presented in [5] should perform SVD for the effective channel matrix reflecting the modulation level.

4. Simulation Results

In this section, the performances of the proposed AFD systems with 2 transmit antennas and 2 receive antennas are evaluated through Monte Carlo simulations under different channel conditions. The SNR is defined by the symbol energy to the noise power spectral density ratio, P_s/N_0. For the BER performance comparison, five MIMO systems obtained from the AFD scheme are considered under the identical fixed data rate of 6 bits/transmission, which is a sum rate at both nodes in FD mode.

(a) FD system with a randomly selected TRAP and equal rate
(b) FD system with a TRAP selected by the Min-Max-SER criterion and equal rate [5]
(c) FD system with a TRAP selected by the Max-SR criterion and equal rate [5]
(d) AFD system with a TRAP selected by the Min-Max-SER criterion and an adaptive modulation of (21)
(e) AFD system with a TRAP selected by the Max-SR criterion and an adaptive modulation of (21)

Note that the equal rate scheme of (b), (c), and (d) uses equal modulation of 8-QAM at both nodes. The adaptive rate scheme is based on the link pattern selection algorithm of (17) proposed in this work.

Figures 2 and 3 show the comparison for BER performance of various MIMO systems, where $\eta=0$ and $\eta=0.01$, respectively, is assumed for FD mode. Here $\eta=0$ represents perfect SI cancellation. Because the same data rate of 6 bits/transmission is assumed for all systems, the summed BER results of two nodes in FD mode are considered instead of the average BER of both nodes. From these figures, it can be seen that when the residual SI exists, the BER curves for all systems are constrained by error floors. When the AFD scheme is operated as FD modes (a), (b), and (c) with equal rate, a TRAP is determined by three selection methods such as random, Min-Max-SER, and Max-SR criteria. It is observed that the Min-Max-SER criterion improves much better BER performance including the error floor than the Max-SR. This is because the error performance in FD systems can be dominated by a link with the maximum SER among a TRAP. If an adaptive signal modulation approach of (21) is employed for FD systems, the link pattern selection algorithm proposed in section 3 outperforms the equal rate scheme using equal 8-QAM signal modulation per each node. In AFD mode as in FD mode, the Min-Max-SER criterion is shown to perform better than the Max-SR. Furthermore, it can be observed that the proposed AFD approach provides much better BER performance than the FD systems with both perfect and imperfect SI cancellation conditions.

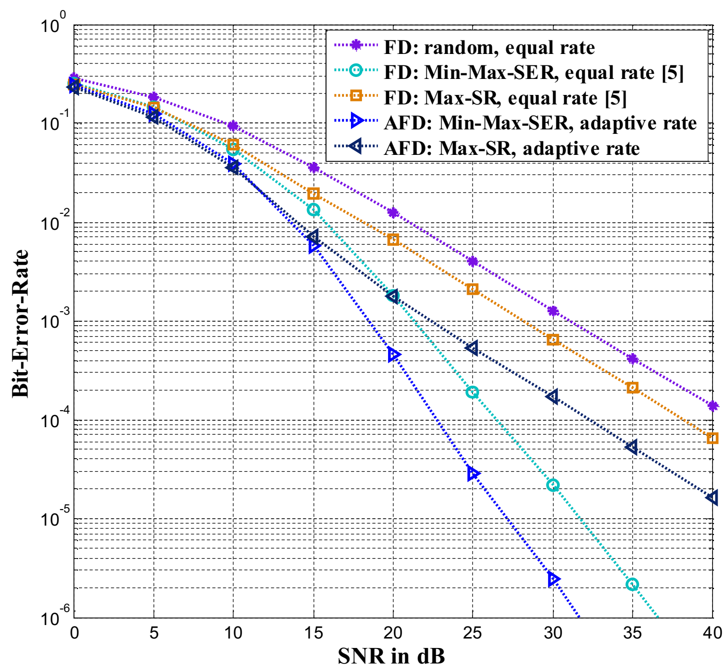

Figure 2. BER performance of the MIMO systems with perfect SI cancellation ($\eta = 0$) under a fixed sum rate of 6 bits/transmission

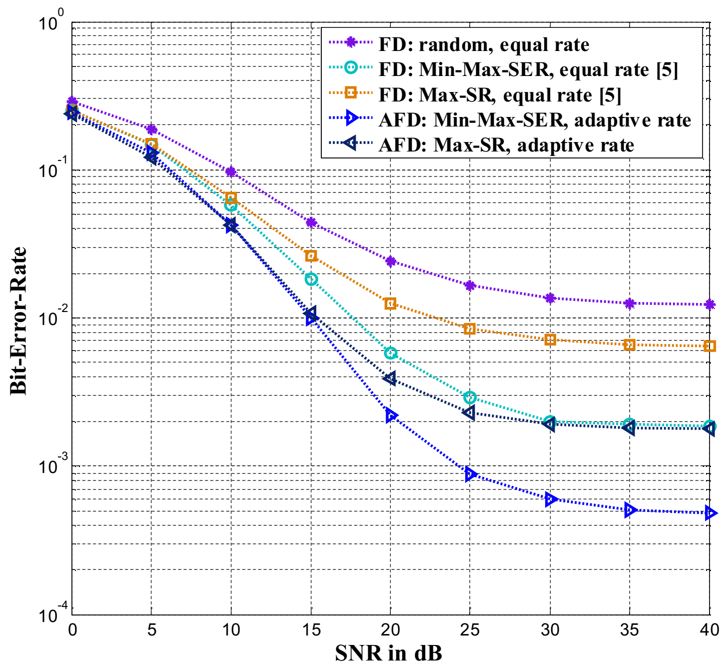

Figure 3. BER performance of the MIMO systems with $\eta = 0.01$ under a fixed sum rate of 6 bits/transmission

5. Conclusions

This paper presents a new adaptive MIMO scheme of FD systems. A link adaptation algorithm is also proposed to obtain better BER performance for AFD systems under a fixed sum rate. The proposed link selection method consists of two steps. The first one is a TRAP selection. Based on the selected TRAP, the second one is to adaptively and jointly determine signal modulation levels and link pattern using a maximum minimum norm criterion. The AFD system employing the Max-SR TRAP selection and adaptive modulation based on the maximum-minimum-norm outperforms the previous FD systems [5] and others in terms of BER minimization with small additional computational complexity. Thus the proposed AFD scheme outperforms the conventional FD with perfect or imperfect SI cancellation situations under the identical fixed sum rate.

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