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Link selection based on switching between full-duplex and half-duplex modes

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Multiple-input multiple-output systems can achieve a full sum rate (SR) via full duplex (FD). However, its performance is degraded by self-interference (SI) that occurs between the transmitter and receiver at the same node and thus is constrained by error floors. Conversely, half duplex (HD) can avoid the SI albeit at lower spectral efficiency, and the slope of its error curve is determined by the diversity order. In this study, a link selection scheme based on switching between FD and HD is examined as a simple method to improve the bit error rate (BER) performance of FD systems. In the proposed link selection algorithm, either FD or HD is selected based on the received minimum distance and signal-to-interference plus noise ratio. Simulation results indicate that the proposed hybrid FD/HD switching system offers significant BER performance improvement when compared with that of the conventional FD and FD based on only the received minimum distance under the same fixed SR. Under relatively sufficient SI cancellation, it is demonstrated to outperform the HD with a diversity advantage in low and medium signal-to-noise ratio region.

KEYWORDS
full duplex (FD), half duplex (HD), joint transmit and receive antenna selection, maximum likelihood (ML) receiver, X-duplex (XD)

1 | INTRODUCTION

Full-duplex (FD) two-way communication is a promising technique for doubling the spectral efficiency of conventional half-duplex (HD) systems via simultaneously performing both signal transmission and reception on the same frequency at the same time slot at a communication node [1,2]. In contrast to conventional HD communication, self-interference (SI) occurs between the transmitter and receiver at the same communication node. Recent studies revealed that SI generated in FD radios can be significantly reduced via passive and active approaches [1–4]. In [5], an FD WiFi-ready design is implemented such that the SI is limited to an extremely minimum level. The aforementioned SI suppression techniques enabled the practical feasibility of FD radios for 5G [6]. In multiple-input multiple-output (MIMO) FD systems, joint transmit and receive antenna selection is considered to obtain better system performance [7,8]. However, residual SI still exits and affects the FD system performance. When the residual SI is relatively high, its symbol error rate (SER) performance is highly constrained by the error floors.

Specifically, the FD communication mode can achieve higher spectral efficiency than HD mode while HD outperforms FD in the high SI situation. Hence, the MIMO system performance can be improved if it is possible to exploit advantages of both the transmission modes. Thus, an effective method to enhance the system performance corresponds to a communication mode selection between FD and HD [9–13]. A hybrid FD/HD switching scheme (called X-duplex) in [9–11] is proposed for the relay system. In

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[12], an X-duplex (XD) radio with two bidirectional transmission modes is examined. Results indicate that its average sum rate (SR) exceeds those of the pure HD and FD modes via maximizing the instantaneous SR. Reference [13] indicates that a dynamic hybrid FD/HD transmission mode can be employed for resource scheduling in LTE scenarios on the unlicensed band including the 5G ultra dense network.

In this study, link selection schemes based on dynamic switching between FD and HD are applied to improve the FD system performance including error floors while maintaining the transmit data rate summed at both communication nodes. In a manner different from a previous study in [12] where each node consists of a shared antenna and the instantaneous SR is adopted for a mode selection criterion, the proposed scheme is equipped with two separated antennas at both communication nodes. Thus, it is assumed for the purposes of simplicity that each node exhibits a transmit (TX) radio frequency (RF) chain, a receive (RX) RF chain, and two antennas. In the FD mode, an antenna is defined as a TX antenna while the other antenna is used as an RX antenna. With respect to switching between FD and HD, we consider two selection criteria including received minimum distance and minimum maximum pair-wise error probability (PEP). It is noted that the mode selection criteria used in [9–13] did not consider the different minimum distances in different signal constellations of FD and HD modes. In the switching algorithm, the FD mode requires a TX-RX antenna pair (TRAP) selection based on maximum SR or minimum maximum SER while the HD mode uses a maximum channel gain selection. Simulations demonstrate that the proposed XD systems employing the minimum maximum PEP-based link selection exhibits a better bit error rate (BER) performance when compared to pure FD and HD modes under a fixed data rate. Additionally, the study examines effects of different SI cancellation factors on the BER performance of the XD systems by using the proposed link selection algorithm.

2 | SYSTEM MODEL

As shown in Figure 1A and 1B, we consider an XD communication system that consists of two nodes, n_A and n_B. They can either transmit or receive the signals on the same frequency band simultaneously. As mentioned in the Introduction section, each node is equipped with a TX RF, an RX RF chain, and two separated antennas. The connections between the TX/RX RF chains and the antennas are adaptable based on the instantaneous channel conditions between the two nodes, minimum Euclidean distance of the transmitted signal constellation, signal to noise ratio (SNR) in HD mode, and signal-to-interference-plus-noise ratio (SINR) in FD mode. In this study, a communication system with a link (HD mode) or two links (FD mode) can be adaptively selected among 12 possible communication patterns, as shown in Figure 1A and 1B.

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 $p = 1, 2, \ldots, 12$. It is noted

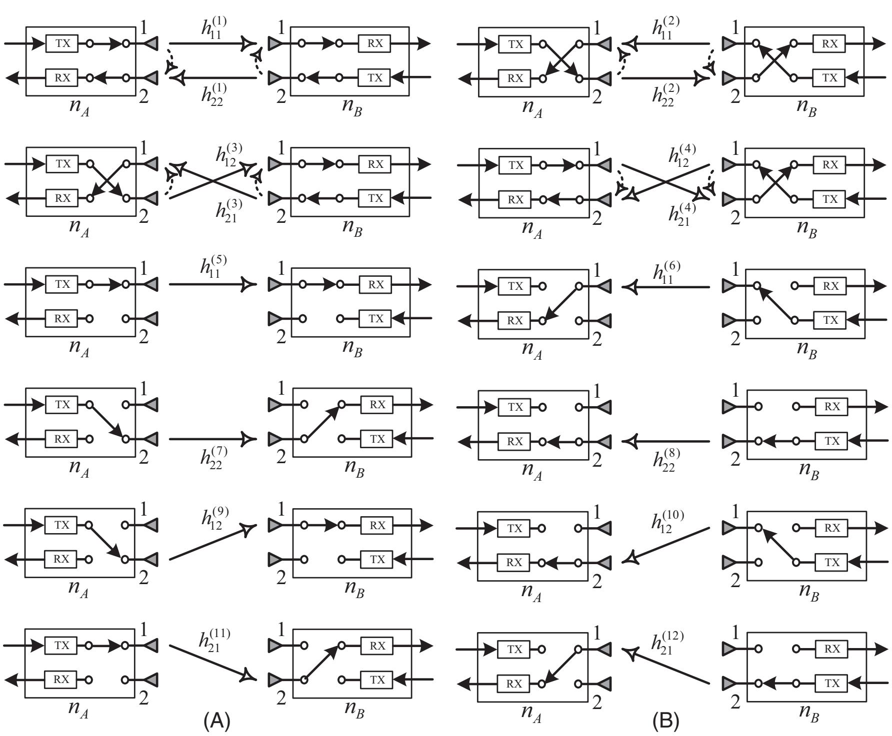

FIGURE 1 (A) Odd patterns in switching-based link selection for the XD model and (B) even patterns in switching-based link selection for the XD model

that odd patterns {1, 3, 5, 7, 9, 11} in Figure 1A and even patterns {2, 4, 6, 8, 10, 12} in Figure 1B denote the same channel gain, respectively. It is assumed that $h_{ij}^{(p)}$ exhibits an independent and identically distributed (i.i.d.) circular complex Gaussian distribution with zero-mean and unit-variance (ie, $h_{ij}^{(p)} \sim CN(0, 1)$) and follows the nonselective independent block fading. We assume that the channel reciprocity is valid and the channel side information is available at both nodes. At the beginning of each time slot, a link pattern selection module used in each node can estimate all the possible communication link patterns. The proposed XD system can be either bidirectional (FD with patterns from pattern 1 to 4) or one-directional (HD with patterns from 5 to 12) by link adaptation. Thus, it is considered as an extended model to cover HD and FD systems. When the XD system is operated in a bidirectional FD mode, SI cancellation techniques should be employed [2–4]. The residual SI can be modeled as Gausssian noise [14].

We define the channel coefficients of pattern (p) connected from node n_B to node n_A and from n_A to n_B as $h_{AB}^{(p)}$ and $h_{BA}^{(p)}$. Specifically, $h_{AB}^{(p)}$ and $h_{BA}^{(p)}$ represent an element of sets of $\left\{h_{22}^{(1)}, h_{11}^{(2)}, h_{21}^{(3)}, h_{12}^{(4)}, h_{11}^{(6)}, h_{22}^{(8)}, h_{12}^{(10)}, h_{21}^{(12)}\right\}$ and $\left\{h_{11}^{(1)}, h_{22}^{(2)}, h_{12}^{(3)}, h_{21}^{(4)}, h_{11}^{(5)}, h_{22}^{(7)}, h_{12}^{(9)}, h_{21}^{(11)}\right\}$, respectively. Subsequently, the signal received at the RX antenna at nodes n_A and n_B is given as follows, 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 $x_B^{(p)}$ denote the transmitted signal with unit power from nodes n_A and n_B defined by signal constellations $X_A^{(p)}$ and $X_B^{(p)}$, respectively, as used at pattern (p). Specifically, P_s denotes the transmit power at each node and η denotes an SI cancellation factor. Additionally, $w_A^{(p)}$ and $w_B^{(p)}$ denote the residual SI at nodes n_A and n_B, respectively. They correspond to complex Gaussian random variables with zero-mean and unit-variance. Furthermore, $n_A^{(p)}$ and $n_B^{(p)}$ denote additive white Gaussian random variables with zero-mean and unit-variance at nodes n_A and n_B, respectively.

3 | LINK ADAPTATION BASED ON SWITCHING BETWEEN FD AND HD

First, we briefly introduce two selection criteria as presented in [7] to determine a TRAP in FD systems. Switching between FD and HD can be considered as a simple approach to improve the error performance of the FD systems. In order to select a link pattern which offers better BER performance of XD systems relative to conventional FD systems under an identical fixed SR, the first switching algorithm exploits minimum Euclidean distance between the received signal constellations. Subsequently, the second switching-based link adaptation algorithm is based on the SNR of the HD mode and SINR of the FD mode in addition to instantaneous channel conditions between the two nodes and minimum Euclidean distance of the transmitted signal constellations.

3.1 | TRAP selection in FD

A selection criterion is based on the maximum bidirectional SR (max-SR) of two nodes and is given as follows:

$$q^*_{\text{max-SR}} = \underset{q \in \{1,2,3,4\}}{\arg\max} \left\{ R_A^{(q)} + R_B^{(q)} \right\} \tag{3}$$

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

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

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

Subsequently, the max-SR approach is re-expressed as follows:

$$q^*_{\text{max-SR}} = \underset{q \in \{1,2,3,4\}}{\arg\max} \left\{ \left(1 + \frac{P_s}{\eta P_s + 1} \left| h_{BA}^{(q)} \right|^2 \right) \left(1 + \frac{P_s}{\eta P_s + 1} \left| h_{AB}^{(q)} \right|^2 \right) \right\}. \tag{6}$$

The other selection criteria relies on the minimum maximum SER [7] and is expressed as follows:

$$q^*_{\text{min-max-SER}} = \underset{q \in \{1,2,3,4\}}{\arg\min} \left\{ \max \left(\text{SER}_B^{(q)}, \text{SER}_A^{(q)} \right) \right\}. \tag{7}$$

The instantaneous error performance is affected by the node with the worst SINR, and thus, the selected link is equivalently obtained as follows [7]:

$$q^*_{\text{min-max-SER}} = \underset{q \in \{1,2,3,4\}}{\arg\max} \left\{ \min \left(\left| h_{BA}^{(q)} \right|^2, \left| h_{AB}^{(q)} \right|^2 \right) \right\}. \tag{8}$$

It is noted that four possible patterns exist for TRAP selection in FD systems. A selection criterion determines a TRAP among the set of all available four candidate subsets of TRAPs. However, patterns {1, 3} and patterns {2, 4} are assumed to exhibit identical instantaneous SINR at each node. For the purpose of simplicity, only patterns 1 and 3 are considered in the FD systems.

3.2 | Minimum distance-based switching between FD and HD

It is widely known that the error performance of a MIMO ML system is affected by the minimum Euclidean distance between the received signal constellations. Thus, we expect that the received minimum distance can be exploited as a criterion for switching between FD and HD modes, and this consists of two steps. The first step of the switching algorithm computes the received minimum distance of the FD mode while the second step calculates the received minimum distance of the HD mode.

In the FD step of the switching algorithm, a TRAP corresponding to the pattern (q^*_{FD}), $q^*_{\mathrm{FD}} \in \{1, 3\}$, is first selected based on a criterion among two criteria introduced in Section 3.1. Subsequently, a mode selection criterion based on the received minimum distance for switching between FD and HD is derived as follows. In the FD mode, ML detection is performed at each RX antenna of nodes n_A and n_B as follows:

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

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

where X_B and X_A denote the sets of M_B and M_A possible transmit symbols, respectively. We combine (9) and (10), and they are re-expressed as follows:

$$\hat{\mathbf{x}}^{(q^*_{\mathrm{FD}})} = \arg\min_{\mathbf{x}^{(q^*_{\mathrm{FD}})} \in \mathbf{X}} \left\| \mathbf{y}^{(q^*_{\mathrm{FD}})} - \mathbf{H}_d^{(q^*_{\mathrm{FD}})} \mathbf{x}^{(q^*_{\mathrm{FD}})} \right\|^2 \tag{11}$$

where $\mathbf{X}$ denotes the set of all $M_A M_B$ possible symbol vectors, $\mathbf{y}^{(q^*_{\mathrm{FD}})} = \left[y_A^{(q^*_{\mathrm{FD}})} \; y_B^{(q^*_{\mathrm{FD}})} \right]^{\mathrm{T}}$, $\mathbf{H}_d^{(q^*_{\mathrm{FD}})} = \mathrm{diag}\left\{ h_{AB}^{(q^*_{\mathrm{FD}})}, h_{BA}^{(q^*_{\mathrm{FD}})} \right\}$, and $\mathbf{x}^{(q^*_{\mathrm{FD}})} = \left[x_B^{(q^*_{\mathrm{FD}})} \; x_A^{(q^*_{\mathrm{FD}})} \right]^{\mathrm{T}}$.

The received minimum distance $d_{\mathrm{FD,\,min}}$ in FD mode is defined as follows:

$$d_{\mathrm{FD,min}} = \min_{\mathbf{x}_m^{(q^*_{\mathrm{FD}})}, \mathbf{x}_n^{(q^*_{\mathrm{FD}})} \in \mathbf{X}, \mathbf{x}_m^{(q^*_{\mathrm{FD}})} \neq \mathbf{x}_n^{(q^*_{\mathrm{FD}})}} \left\| \mathbf{H}_d^{(q^*_{\mathrm{FD}})} \left(\mathbf{x}_m^{(q^*_{\mathrm{FD}})} - \mathbf{x}_n^{(q^*_{\mathrm{FD}})} \right) \right\|, \tag{12}$$

where (12) is reformulated as follows:

$$d_{\mathrm{FD,min}} = \min_{\bar{\mathbf{e}}_{mn}^{(q^*_{\mathrm{FD}})} \in \bar{E}} \left\| \mathbf{H}_d^{(q^*_{\mathrm{FD}})} \mathbf{D}^{(q^*_{\mathrm{FD}})} \bar{\mathbf{e}}_{mn}^{(q^*_{\mathrm{FD}})} \right\|, \tag{13}$$

where $\mathbf{D}^{(q^*_{\mathrm{FD}})} = \mathrm{diag}\left\{ d_B^{(q^*_{\mathrm{FD}})}, d_A^{(q^*_{\mathrm{FD}})} \right\}$ and $\bar{\mathbf{e}}_{mn}^{(q^*_{\mathrm{FD}})} = \left[\bar{e}_{mn,B}^{(q^*_{\mathrm{FD}})} \quad \bar{e}_{mn,A}^{(q^*_{\mathrm{FD}})} \right]^{\mathrm{T}}$. Specifically, $d_A^{(q^*_{\mathrm{FD}})}$ and $d_B^{(q^*_{\mathrm{FD}})}$ denote the minimum distances in signal constellations corresponding to the modulation levels employed in nodes n_A and n_B, respectively, in the pattern (q^*_{FD}), and $\bar{e}_{mn,A}^{(q^*_{\mathrm{FD}})}$ and $\bar{e}_{mn,B}^{(q^*_{\mathrm{FD}})}$ denote the normalized error factors of $\left(x_{m,A}^{(q^*_{\mathrm{FD}})} - x_{n,A}^{(q^*_{\mathrm{FD}})} \right)$ and $\left(x_{m,B}^{(q^*_{\mathrm{FD}})} - x_{n,B}^{(q^*_{\mathrm{FD}})} \right)$, respectively, by $d_A^{(q^*_{\mathrm{FD}})}$ and $d_B^{(q^*_{\mathrm{FD}})}$. Additionally, $\bar{E}$ denotes the set of the normalized error vectors. The received minimum distance of (13) is lower bounded by the minimum distance in signal constellation. Subsequently, the squared received minimum distance of FD mode is given as follows:

$$\begin{aligned} d^2_{\mathrm{FD,\,min}} &\geq \lambda_{\min}\left(\mathbf{H}_d^{(q^*_{\mathrm{FD}})} \mathbf{D}^{(q^*_{\mathrm{FD}})} \right) \min_{\bar{\mathbf{e}}_{mn}^{(q^*_{\mathrm{FD}})} \in \bar{E}} \left| \bar{\mathbf{e}}_{mn}^{(q^*_{\mathrm{FD}})} \right|^2 \\ &= \min_{q^*_{\mathrm{FD}} \in \{1,3\}} \left(\left| h_{BA}^{(q^*_{\mathrm{FD}})} d_B^{(q^*_{\mathrm{FD}})} \right|^2, \left| h_{AB}^{(q^*_{\mathrm{FD}})} d_A^{(q^*_{\mathrm{FD}})} \right|^2 \right) \end{aligned} \tag{14}$$

where $\lambda_{\min}\left(\mathbf{H}_d^{(q^*_{\mathrm{FD}})} \mathbf{D}^{(q^*_{\mathrm{FD}})} \right)$ denotes a minimum singular value of the matrix $\mathbf{H}_d^{(q^*_{\mathrm{FD}})} \mathbf{D}^{(q^*_{\mathrm{FD}})}$. It is noted that $\lambda_{\min}\left(\mathbf{H}_d^{(q^*_{\mathrm{FD}})} \mathbf{D}^{(q^*_{\mathrm{FD}})} \right) = \min\left(\left| h_{AB}^{(q^*_{\mathrm{FD}})} d_B^{(q^*_{\mathrm{FD}})} \right|^2, \left| h_{BA}^{(q^*_{\mathrm{FD}})} d_A^{(q^*_{\mathrm{FD}})} \right|^2 \right)$ with $d_B^{(q^*_{\mathrm{FD}})} = d_A^{(q^*_{\mathrm{FD}})} = d_{\mathrm{FD},s}$ and $\min_{\bar{\mathbf{e}}_{mn}^{(q^*_{\mathrm{FD}})} \in \bar{E}} \left\| \bar{\mathbf{e}}_{mn}^{(q^*_{\mathrm{FD}})} \right\|^2 = 1$. Thus, it is assumed in the study that the FD mode uses the same signal constellation in both the nodes.

In the HD mode, a maximum channel gain (max-Gain) criterion for joint transmit and receive antenna selection is given as $h_{BA}^{(q^*_{\mathrm{FD}})} = \max\left\{ \left| h_{11}^{(5)} \right|^2, \left| h_{22}^{(7)} \right|^2, \left| h_{12}^{(9)} \right|^2, \left| h_{21}^{(11)} \right|^2 \right\}$. Hence, the selected pattern in the HD mode is given as follows:

$$\begin{aligned} &\text{Selected Pattern } \left(q^*_{\mathrm{HD}} \right) \\ &= \arg\max_{q_{\mathrm{HD}} \in \{5,7,9,11\}} \left\{ \left| h_{11}^{(5)} \right|^2, \left| h_{22}^{(7)} \right|^2, \left| h_{12}^{(9)} \right|^2, \left| h_{21}^{(11)} \right|^2 \right\}. \end{aligned} \tag{15}$$

The squared received minimum distance of an HD ML system with the selected pattern $\left(q^*_{\mathrm{HD}} \right)$ is then defined as follows:

$$d^2_{\mathrm{HD}} = \left| h_{BA}^{(q^*_{\mathrm{HD}})} d_{\mathrm{HD},s} \right|^2 \tag{16}$$

where $d_{\mathrm{HD},s}$ denotes the minimum distance in signal constellation employed in the HD mode. It is noted that patterns {5, 7, 9, 11} and patterns {6, 8, 10, 12} are assumed to exhibit identical instantaneous SNR at each node. For the purpose of simplicity, only patterns 5, 7, 9, and 11 are considered in the HD systems.

Thus, the mode selection criterion for switching between FD and HD based on the received minimum distance in an XD MIMO ML system with a fixed total transmission bit rate is proposed as follows:

$$\text{Selected Mode} = \arg\max\left\{\min_{q^*_{\text{FD}}\in\{1,3\}}\left(\left|h_{AB}^{(q^*_{\text{FD}})}\right|^2 d^2_{\text{FD},s},\ \left|h_{BA}^{(q^*_{\text{FD}})}\right|^2 d^2_{\text{FD},s}\right), d^2_{\text{HD},s}\right\}. \quad (17)$$

In this study, three cases, namely, no-transmission, 8-QAM, and 64-QAM, are assumed for each transmission. For example, under 6 bits/transmission ($R=6$), two combinations of aforementioned modulation orders are considered. In the example, the set of two cases are given as $\mathbf{M}_{\text{all}}=\{[64,1],[8,8]\}$, where each subset consists of modulation orders of nodes n_A and n_B, respectively, and 1 means no-transmission. Here, $\mathbf{M}_{\text{all}}$ corresponds to the set $\boldsymbol{\Gamma}_{\text{all}}=\{[d_{\text{HD},s},0],[d_{\text{FD},s},D_{\text{FD},s}]\}=\left\{[2/\sqrt{42},0],[2/\sqrt{6},2/\sqrt{6}]\right\}$. It is noted that if the transmission set is given as $\mathbf{M}_{\text{subset},2}=\{[8,8]\}$, then the XD system can only be operated as an FD system wherein the XD system is operated as an HD system for $\mathbf{M}_{\text{subset},1}=\{[64,1]\}$.

3.3 | Minimum maximum PEP-based switching between FD and HD

The minimum distance-based switching method between FD and HD presented in Section 3.2 does not reflect a major difference between FD and HD, which comes from the residual SI in the FD mode. Thus, the received SINR values of FD and HD evidently differ when it is not possible to obtain the perfect SI cancellation in the FD mode. When compared to the minimum distance-based switching approach, in order to further improve the BER performance of XD systems, a selection criterion for switching between FD and HD modes is employed as follows:

$$\text{Selected Mode} = \arg\min\left\{\max\left(\text{PEP}_{\text{FD}}^{(q^*_{\text{FD}})}\right), \text{PEP}_{\text{HD}}^{(q^*_{\text{HD}})}\right\} \quad (18)$$

where $\text{PEP}_{\text{FD}}^{(q^*_{\text{FD}})}$ and $\text{PEP}_{\text{HD}}^{(q^*_{\text{FD}})}$ of the ML system with the FD and HD modes, respectively, are expressed as follows:

$$\text{PEP}_{\text{FD}}^{(q^*_{\text{FD}})}\left(\mathbf{H}_d^{(q^*_{\text{FD}})}\right) \approx \alpha\cdot Q\left(\sqrt{\frac{P_s}{\eta P_s+1} d^2_{\text{FD, min}}\left(\mathbf{H}_d^{(q^*_{\text{FD}})}\right)}\right), \quad (19)$$

$$\text{PEP}_{\text{HD}}^{(q^*_{\text{HD}})}\left(h_{BA}^{(q^*_{\text{HD}})}\right) \approx \beta\cdot Q\left(\sqrt{P_s\, d^2_{\text{HD}}\left(h_{BA}^{(q^*_{\text{HD}})}\right)}\right). \quad (20)$$

Specifically, α and β denote the average number of the nearest neighbor vectors.

Even if all the nodes can use the different symbol constellation, we do not consider α and β while developing a simple switching criterion. Thus, the selection criterion of (18) can be combined with only the SINR and SNR values that are included in the Q functions corresponding to (19) and (20), respectively. Subsequently, the switching criterion of the above (18) is approximately redefined as follows:

$$\begin{cases} \text{FD mode if } \frac{P_s}{\eta P_s+1} d^2_{\text{FD, min}}\left(\mathbf{H}_d^{(q^*_{\text{FD}})}\right) > P_s\, d^2_{\text{HD}}\left(h_{AB}^{(q^*_{\text{HD}})}\right), \\ \text{HD mode if not}. \end{cases} \quad (21)$$

Thus, the expression in (21) is re-expressed as follows:

$$\begin{cases} \text{FD mode if } \text{SINR}_{\text{FD}} d^2_{\text{FD, min}} > \text{SNR}_{\text{HD}} d^2_{\text{HD}}, \\ \text{HD mode if not}. \end{cases} \quad (22)$$

where $d^2_{\text{FD, min}}=\min\left(\left|h_{AB}^{(q^*_{\text{FD}})}\right|^2, \left|h_{BA}^{(q^*_{\text{FD}})}\right|^2\right) d^2_{\text{FD},s}$ and $d^2_{\text{HD}}=\left|h_{BA}^{(q^*_{\text{HD}})}\right|^2 d^2_{\text{HD},s}$.

It is noted that the switching criterion of (22) is based on the SINR, SNR, channel conditions, and minimum distance. The channel state information (CSIs) of SINR, SNR, and channel coefficient are obtained via pilot symbols-based estimation [1,15]. In the study, the CSIs are assumed to be perfectly known at both nodes. When compared with the previous minimum distance-based switching method, the additional CSIs for the minimum maximum PEP-based switching algorithm correspond to the SINR in the FD mode and SNR in the HD mode. For example, given $\mathbf{M}_{\text{all}}=\{[64,1],[8,8]\}$, the summary of the minimum maximum PEP-based switching algorithm to select a communication mode is described in Table 1. In the algorithm, $n=1$ and $n=2$, are associated with $\mathbf{M}_{\text{subset},1}=\{[64,1]\}$ and $\mathbf{M}_{\text{subset},2}=\{[8,8]\}$, respectively, where HD mode is operated in one of the patterns $\{5,7,9,11\}$, and FD mode corresponds to one of the patterns $\{1,3\}$. An input δ indicates a TRAP selection parameter in FD mode, where $\delta=1$ and $\delta=2$ correspond to the max-SR criterion of (6) and min-max-SER criterion in (8), respectively.

4 | SIMULATION RESULTS

The performance of the proposed XD systems with two separated antennas at both communication nodes over the HD and

TABLE 1 Minimum maximum PEP-based switching algorithm

Inputs: $\delta, h_{11}, h_{22}, h_{12}, h_{21}, d_{\mathrm{HD},s}, d_{\mathrm{FD},s}, \mathrm{SNR}_{\mathrm{HD}}, \mathrm{SINR}_{\mathrm{FD}}$

for $n = 1:2$

  if $n == 1$

    $\left|h_{BA}^{(q_{\mathrm{HD}}^{*})}\right|^2 = \max\left\{\left|h_{11}^{(5)}\right|^2, \left|h_{22}^{(7)}\right|^2, \left|h_{12}^{(9)}\right|^2, \left|h_{21}^{(11)}\right|^2\right.$

    $d_{\mathrm{HD}}^2 = \left|h_{BA}^{(q_{\mathrm{HD}}^{*})}\right|^2 d_{\mathrm{HD},s}^2$

    $\gamma_{\mathrm{HD}} = \mathrm{SNR}_{\mathrm{HD}} d_{\mathrm{HD}}^2$

  else

    if $\delta == 1$

      $\zeta_1 = (1 + \mathrm{SINR}_{\mathrm{FD}})^2 \left|h_{11}^{(1)}\right|^2 \left|h_{22}^{(1)}\right|^2$

      $\zeta_2 = (1 + \mathrm{SINR}_{\mathrm{FD}})^2 \left|h_{12}^{(3)}\right|^2 \left|h_{21}^{(3)}\right|^2$

    elseif $\delta == 2$

      $\zeta_1 = \min\left(\left|h_{11}^{(1)}\right|^2, \left|h_{22}^{(1)}\right|^2\right)$

      $\zeta_2 = \min\left(\left|h_{12}^{(3)}\right|^2, \left|h_{21}^{(3)}\right|^2\right)$

    end

    if $\zeta_1 > \zeta_2$

      $h_{BA}^{(q_{\mathrm{FD}}^{*})} = h_{11}^{(1)}, \ h_{AB}^{(q_{\mathrm{FD}}^{*})} = h_{22}^{(1)}$

    else

      $h_{BA}^{(q_{\mathrm{FD}}^{*})} = h_{12}^{(3)}, \ h_{AB}^{(q_{\mathrm{FD}}^{*})} = h_{21}^{(3)}$

    end

    $d_{\mathrm{FD,min}}^2 = \min\left(\left|h_{BA}^{(q_{\mathrm{FD}}^{*})}\right|^2, \left|h_{AB}^{(q_{\mathrm{FD}}^{*})}\right|^2\right) d_{\mathrm{FD},s}^2$

    $\gamma_{\mathrm{FD}} = \mathrm{SINR}_{\mathrm{FD}} d_{\mathrm{FD,min}}^2$

  end

  if $\gamma_{\mathrm{HD}} < \gamma_{\mathrm{FD}}$

    Selected mode = FD mode

  else

    Selected mode = HD mode

  end

end

Outputs: $h_{BA}^{(q_{\mathrm{HD}}^{*})}, h_{AB}^{(q_{\mathrm{FD}}^{*})}, h_{BA}^{(q_{\mathrm{FD}}^{*})}$, Selected mode

FD systems is evaluated via Monte Carlo simulations. The simulation setup is based on the fixed data rate corresponding to 6 bits/transmission ($R = 6$), which is a data rate at a transmit node in HD mode and an SR at both nodes in the FD mode over frequency-flat block Rayleigh fading channels. The SNR is defined by the ratio of the symbol energy to the noise power spectral density. With respect to the BER performance comparison, the following eight MIMO ML systems are considered.

a. HD system with $\mathbf{M}_{\text{subset},1} = \{[64, 1]\}$ and a randomly selected channel coefficient (termed as HD-random)
b. HD system with $\mathbf{M}_{\text{subset},1} = \{[64, 1]\}$ and a channel coefficient selected under the max-Gain criterion (termed as HD-maxGain)
c. FD system with $\mathbf{M}_{\text{subset},2} = \{[8, 8]\}$ and a TRAP selected by the max-SR criterion (termed as FD-maxSR)
d. FD system with $\mathbf{M}_{\text{subset},2} = \{[8, 8]\}$ and a TRAP selected by the min-max-SER criterion [7] (termed as FD-minmaxSER)
e. XD system with $\mathbf{M}_{\text{all}} = \{[64, 1], [8, 8]\}$ and minimum distance-based switching criterion where the FD mode employs the max-SR criterion for a TRAP selection and HD mode uses the max-Gain criterion (termed as XD-maxSR-mdSwitch)
f. XD system with $\mathbf{M}_{\text{all}} = \{[64, 1], [8, 8]\}$ and minimum distance-based switching criterion where the FD mode employs the min-max-SER criterion for a TRAP selection and HD mode uses the max-Gain criterion (termed as XD-minmaxSER-mdSwitch)
g. XD system with $\mathbf{M}_{\text{all}} = \{[64, 1], [8, 8]\}$ and minimum maximum PEP-based switching criterion where the FD mode employs the max-SR criterion for a TRAP selection and HD mode uses the max-Gain criterion (termed as XD-maxSR-PEPSwitch)
h. XD system with $\mathbf{M}_{\text{all}} = \{[64, 1], [8, 8]\}$ and minimum maximum PEP-based switching criterion where the FD mode employs the min-max-SER criterion for a TRAP selection and HD mode uses the max-Gain criterion (termed as XD-minmaxSER-PEPSwitch)

It is noted that since an identical data rate corresponding to 6 bits/transmission is assumed for all MIMO ML systems, the summed BER results of two nodes in FD mode are computed as opposed to the average BER of both nodes. Table 2 lists simulation parameters to evaluate the proposed XD systems. It is noted that the simulations consider only patterns 5, 7, 9, and 11 for HD mode. Thus, at node n_A, an antenna is used for TX transmission and the other antenna is idle.

The comparison results for BER performance of eight MIMO systems under the assumption of perfect SI cancellation ($\eta = 0$) are shown in Figure 2. The BER curves of FD with min-max-SER and HD systems cross at approximately SNR = 25.5 dB. If a communication mode is employed for all channel realizations, then the FD mode is preferred for SNR < 25.5 dB while the HD mode is preferred for SNR ≥ 25.5 dB. It is also observed that four XD systems corresponding to (e), (f), (g), and (h) exhibit almost identical BER results. It is noted that when $\eta = 0$, the minimum maximum PEP-based switching and minimum distance-based switching are identical. They outperform the FD systems in (c) and (d) and also provide a better SNR gain of approximately 3 dB than the HD system utilizing a diversity

TABLE 2 Simulation Parameters

Transmission mode	FD		HD	
Node	n_A	n_B	n_A	n_B
2 antennas per node	1 TX 1 RX	1 RX 1 TX	1 TX 1 idle	1 RX 1 idle
Signal constellation	8-QAM	8-QAM	64-QAM	N/A
Minimum distance	$2/\sqrt{6}$	$2/\sqrt{6}$	$2/\sqrt{42}$	N/A

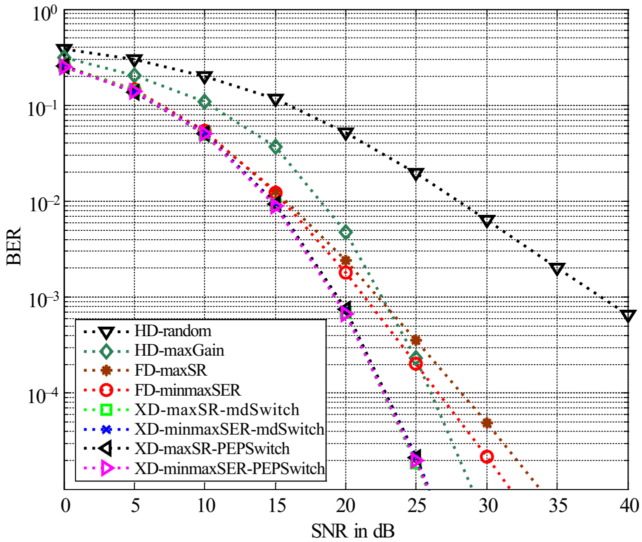

FIGURE 2 BER performance of the MIMO ML systems with perfect SI cancellation ($\eta = 0$) under a fixed SR corresponding to 6 bits/transmission

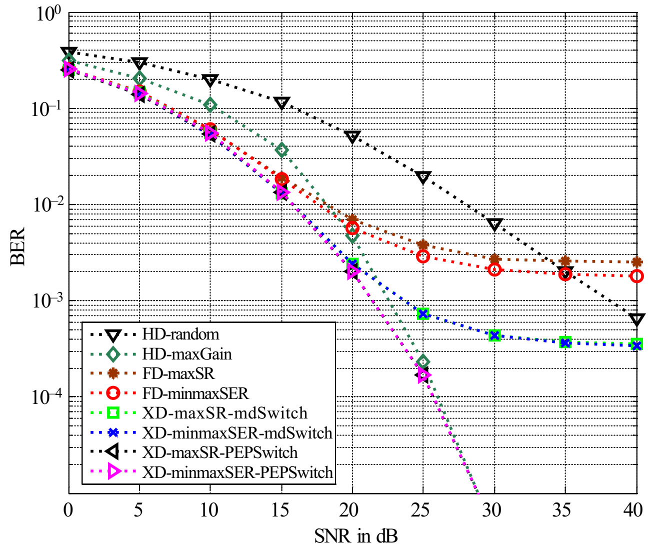

FIGURE 3 BER performance of the MIMO ML systems with $\eta = 0.01$ under a fixed SR corresponding to 6 bits/transmission

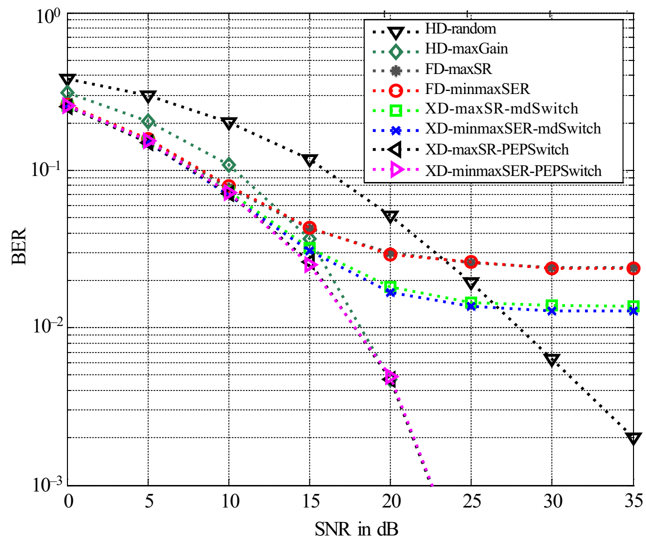

FIGURE 4 BER performance of the MIMO ML systems with $\eta = 0.05$ under a fixed SR corresponding to 6 bits/transmission

advantage based on the max-Gain criterion. Joint transmit and receive antenna selection using the max-Gain criterion leads to a significant enhancement in BER performance for the HD system, wherein error floor is absent due to no SI. The XD systems can be operated as a hybrid of FD and HD system where the best of HD mode or FD mode is selected for each channel realization due to the adaptive link selection based on switching between the FD and HD modes. In the perfect SI cancellation situation, the XD systems always offer optimal performance.

In Figures 3 and 4, the BER results under imperfect SI cancellation corresponding to $\eta = 0.01$ and $\eta = 0.05$, respectively, are illustrated. It is observed that when the residual SI exists, the BER curves for FD systems of (c) and (d) are constrained by error floors. Additionally, the XD systems for (e) and (f) with the minimum distance-based switching criterion still exhibit error floors even if they can improve the performance of the conventional FD systems. Under $\eta = 0.01$ and $\eta = 0.05$, the BER curves of FD system for (d) and HD system for (b) cross at approximately SNR = 19.5 dB and SNR = 13 dB, respectively. The former exhibits poorer performance relative to the latter at high SNR due to the presence of SI. If we were to select a communication mode for all channel realizations under $\eta = 0.01$, then FD mode and HD mode are preferred for SNR < 19.5 dB and SNR ≥ 19.5 dB, respectively. With respect to $\eta = 0.05$, FD mode is preferable for SNR < 13 dB. It is expected that the SNR bordering point between FD and HD systems decreases when the SI cancellation factor increases. Conversely, XD systems employing the minimum maximum PEP-based switching criterion eliminates error floors, and thus offers significantly better performance than the XD systems with the minimum distance-based switching criterion. In the XD systems, max-SR and min-max-SER criteria used for a TRAP selection in FD mode exhibit almost identical performance. Furthermore, the BER curves of XD systems for (g) and (h) under $\eta = 0.01$ and $\eta = 0.05$ encounter that of HD system for (b) at approximately SNR = 28 dB and SNR = 20 dB, respectively. The aforementioned SNR bordering points occur due to each residual SI level and can be approximately computed as SNR = 27.8 dB and SNR = 20.8 dB, respectively, from the inequality expression of $\left(P_s/(\eta P_s+1)\right) d^2_{\mathrm{FD,\,min}}\left(\mathbf{H}_d^{(q^*_{\mathrm{FD}})}\right) > P_s d^2_{\mathrm{HD}}\left(h_{AB}^{(q^*_{\mathrm{HD}})}\right)$ given in the switching criterion (21) with the assumption of channel coefficients with unit-variance. Thus, it is anticipated that the SNR bordering point between the XD system with minimum maximum PEP-based switching and the HD system with max-Gain selection decreases when the residual SI cancellation level increases. Given the same fixed data rate, the XD system using the minimum maximum PEP-based switching method offers lower BER results relative to that of the HD system with link selection based on max-Gain in low and medium SNR ranges (up to approximately 28 dB under $\eta = 0.01$ and approximately 20 dB for $\eta = 0.05$).

We examine the effects of different SI cancellation factors on the BER performance of the proposed XD-minmaxSER-PEPSwitch systems in (h). Figure 5 shows the BER results as a function of SI cancellation factor η given three different SNR values of 15 dB, 20 dB, and 25 dB. It is observed that when the value of SI cancellation factor increases, the BER performances are saturated and not degraded. This implies that the proposed XD systems that adopt the minimum maximum PEP-based switching do not experience an error floor. We use the simulation parameters given in Table 2 with the

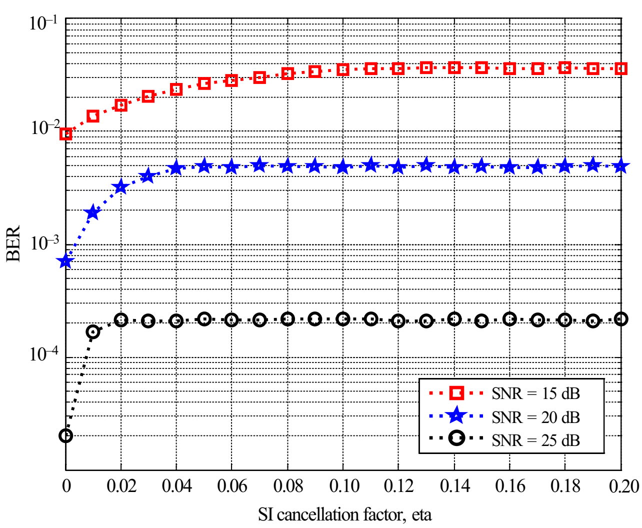

FIGURE 5 BER performance of XD-minmaxSER-PEPSwitch systems as a function of SI cancellation factor η under a fixed SR corresponding to 6 bits/transmission

assumption of channel coefficients with unit-variance, and the selection criterion in (21) is re-expressed as follows:

$$\begin{cases} \text{FD mode if } \eta\ \mathrm{SNR} < 6, \\ \text{HD mode if not .} \end{cases} \tag{23}$$

With respect to a sufficiently high level of η and the given SNR range, the inequality of $\eta\,\mathrm{SNR} > 6$ is satisfied. Subsequently, the proposed XD systems are operated in the HD mode and are thus free from the effects of error floor.

Additionally, when both communication nodes are equipped with multiple antennas and TX/RX RF chains, the problem of link selection in XD MIMO systems becomes complicated based on the number of antennas, number of TX/RX RF chains, and signal transmission format employed at multiple transmit antennas. Given the presence of multiple antennas at both nodes, increases in the number of transmit antennas used in FD mode increases SI. Although it is possible to employ passive and active suppression techniques as mentioned in [1–4] to cancel the SI, the residual SI factor can exceed that in the situation with two antennas. Therefore, an interesting future study for XD MIMO systems with many antennas and multiple TX/RX RF chains corresponds to optimal and efficient link selection issues combined with switching between FD and HD.

5 | CONCLUSION

The study presents a hybrid MIMO ML system that switches between FD mode and HD mode under a fixed SR. The first switching operation exploits only the received minimum distance. The second switching operation is based on the minimum maximum PEP criterion, where SINR in FD mode and SNR in HD mode are utilized in addition to the received minimum distance. Specifically, in FD mode, two methods including max-SR and min-max-SER are employed to select a TRAP. The results indicate that both switching criteria in XD systems significantly improve the FD systems and HD systems even under perfect SI cancellation. The proposed link selection algorithm based on the minimum maximum PEP for the XD systems obtains considerably higher BER performance than that of the XD systems using the minimum distance-based switching and previous FD systems [7]. Furthermore, it simultaneously outperforms the HD system in an SNR range approximately less than SNR = 28 dB for $\eta = 0.01$ and SNR = 20 dB for $\eta = 0.05$. Additionally, it is free from error floor.

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