A New Duplex without Loss of Data Rate and Utilizing Selection Diversity

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***Abstract*— This paper presents a new duplex approach which does not require guard resources suitable for indoor 2×2 MIMO environments. In the proposed duplex, two virtual channels in the spatial domain are generated by precoding and postcoding MIMO channels, not to use guard resources in either the time or frequency domain. In addition, this system can achieve selection diversity since the generation of virtual channels is not unique for the given channels information. We will show the generation of the virtual channel, and that the capacity and reliability of the communication links improves when the problem of the guard resource is addressed and selection diversity is utilized.**

I. Introduction

In two-way communication between two nodes, a protocol called duplex is required to generate two data transmission links. Frequency division duplex (FDD) and time division duplex (TDD) are the most straightforward and prevalent duplex schemes. Most commercial wireless communication systems, such as IS-95, have adopted FDD [1]. More recently, TDD has begun to see realization in mobile WiMax [2].

To prevent overlap between links, FDD and TDD adopt guard bands and guard times, respectively [3]. However, the drawback to this is that data transmission efficiency decreases with the use of guard resources, since a portion of the time and frequency resources can no longer be used for data transmission [3]. Such a problem can be alleviated if the two links are not divided in either time or frequency domain. Spatial domain can be one of such candidates, since only a signal processing technique, such as singular value decomposition (SVD), is needed to isolate two links orthogonally, as opposed to frequency or time domain, where each link uses the resources orthogonally by utilizing different time or frequency slots.

To isolate two data links in the spatial domain, each antenna of each node should be capable of transmitting and receiving data in the same band simultaneously [3]. In outdoor communication where the power gap between the transmitted and received signal is too huge with large distance, such an implementation is very difficult. Therefore, antenna or spatial resource is uncommon for duplex [4]. In indoor communication environment where the power gap between transmitted and received signal is relatively small, such an implementation can be more practical.

In this paper, we propose a new duplexing scheme in the spatial domain for 2×2 multiple-input multiple-output (MIMO) environments. The proposed duplexing mechanism generates two virtual channels to use the spatial resource for duplex, and they are each assigned to each link. Therefore, the the guard resource problem can be resolved. We investigate the generation of virtual channels and analyze the capacity and bit-error-rate (BER) performance of duplex by generating virtual channels.

II. System Model for Duplex in Spatial Domain

In this section, we analyze the system model for a duplexing scheme in the spatial domain for two-way communication between node a and node b. In this paper, we define $link_{\rm tr}$ as a data transmission link from node t to node r.

When spatial resource is used for duplexing, both $link_{\rm ab}$ and $link_{\rm ba}$ can use the same band for data transmission simultaneously. For that, however, each antenna at node a and b must be capable of transmitting and receiving signals in the same frequency band at the same time. Even though this is possible since the electromagnetic fields of the transmitted and received signals are independent of each other [5][6][7], e.g., single antenna continuous wave radar (CW radar) [6][7], the most significant problem is the interference caused by echo signals. Fig.1 shows the channel model for such a system. $\mathbf{H}_a$ and $\mathbf{H}$ denote a 2×2 echo channel at node a and the MIMO channel from node b to a, respectively. By the channel reciprocity [4], the MIMO channel from node a to b can be expressed as $\mathbf{H}^{\rm H}$. Then, the received signals at node a can be expressed as

$$\mathbf{y}_a = \mathbf{H}\mathbf{x}_b + \rho_a \mathbf{H}_a \mathbf{x}_a + \mathbf{w}_a, \tag{1}$$

This work is supported in part by the Ministry of Education and Human Resources Development (MOE), the Ministry of Commerce, Industry and Energy (MOCIE) and the Ministry of Labor (MOLAB) through the fostering project of the Lab of Excellency.

This work is also supported in part by Korea Science & Engineering Foundation through the NRL Program (Grant R0A-2007-000-20043-0).

978-1-4244-1645-5/08/$25.00

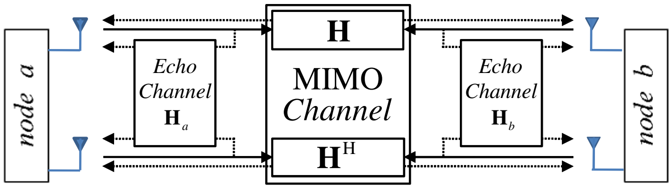

Fig. 1. Channel Model for a duplexing system in spatial domain. $\mathbf{H}$ represents the 2×2 MIMO channel matrix from node b to node a, and $\mathbf{H}_a$ and $\mathbf{H}_b$ represent a 2×2 echo channel matrices at node a and node b, respectively.

where $\mathbf{x}_a$, $\mathbf{y}_a$, $\mathbf{w}_a$, and ρ_a represent the 2×1 transmitted signal, received signal, AWGN vectors, and the power of the echo signals at node a, respectively. Since the power of the directly induced echo signal is dominant, we can consider $\mathbf{H}_a$ and $\mathbf{H}_b$ to have a very strong Line-Of-Sight (LOS) component.

Practically speaking, the power of the echo signal is much larger than the received powers of the desired signals. Therefore, a huge dynamic range is needed for the receiving filters. Thus, such systems in Fig.1 are improper for utilization in outdoor cellular systems which require 120-140dB isolation [8].

However, in an indoor communication environment [9], the problem of dynamic ranges can be alleviated since the power gap between the transmitted and received signal is not extremely large as in outdoor cellular systems. Moreover, if echo cancelers are used to eliminate the LOS component of the echo signals as in [8], the problem of dynamic ranges of receiving filters can further be alleviated. Before LOS component is eliminated, $\mathbf{H}_a$ and $\mathbf{H}_b$ can be considered as Ricean fading channels with high κ factor. After LOS component is eliminated, $\mathbf{H}_a$ and $\mathbf{H}_b$ can be regarded as Rayleigh fading channels. In this paper, we consider an indoor communication environment in which the duplexing scheme can be operated.

III. Virtual-Channel Division Duplex via Dual-Coding

This section investigates 2×2 virtual-channel division duplexing (VDD) for two-way communication between node a and node b. VDD uses spatial resources for duplexing, and both $link_{\mathrm{ab}}$ and $link_{\mathrm{ba}}$ share the same frequency band simultaneously. To use the spatial resource for duplexing, two virtual MIMO channels are generated by precoding and postcoding $\mathbf{H}$, and are assigned to $link_{\mathrm{ab}}$ and $link_{\mathrm{ba}}$, respectively. We introduce the designs of precoders and postcoders. Since the design procedures for the precoder and postcoder are equivalent at node a and node b, we only show the design process of node a and $link_{\mathrm{ba}}$ without loss of generality.

In precoding and postcoding processes, the interference from the echo signals and crosstalk between the received signals should be eliminated. For such purposes, we propose two-step precoding and two-step postcoding. We call the entire process of two-step precoding and two-step postcoding the *dual-coding* process. The first step in this dual-coding is echo signal cancellation and the second step is orthogonalization of the received signals. Fig.2 shows the dual-coding process. At node a, the overall precoder ($\mathbf{Q}_a$) and the overall postcoder ($\mathbf{P}_a$) are the multiplication of precoders and the multiplication of postcoders

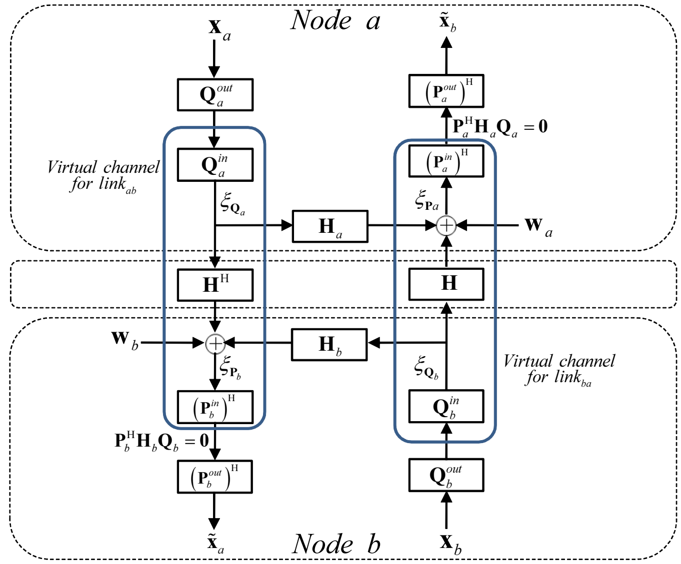

Fig. 2. Block diagram of dual-coding process. The full precoder and postcoder have the forms $\mathbf{Q}_i = \xi_{\mathbf{Q}_i}\mathbf{Q}_i^{in}\mathbf{Q}_i^{out}$ and $\mathbf{P}_i = \xi_{\mathbf{P}_i}\mathbf{P}_i^{in}\mathbf{P}_i^{out}$, respectively.

in each process, respectively. $\mathbf{Q}_a$ and $\mathbf{P}_a$ can be expressed as

$$\mathbf{Q}_a = \xi_{\mathbf{Q}_a}\mathbf{Q}_a^{in}\mathbf{Q}_a^{out} \text{ and } \mathbf{P}_a = \xi_{\mathbf{P}_a}\mathbf{P}_a^{in}\mathbf{P}_b^{out}, \tag{2}$$

where $\xi_{\mathbf{Q}_a}$ and $\xi_{\mathbf{P}_a}$ are power normalization factors which prevent the violation of transmit power constraint and noise enhancement. At node b, $\mathbf{Q}_b$ and $\mathbf{P}_b$ can be generated by the same processes.

In the first step of the dual-coding process (inner coding process) at node a, $\mathbf{H}_a$ is precoded by $\mathbf{Q}_a^{in}$ and postcoded by $\mathbf{P}_a^{in}$. To achieve the complete elimination of the echo signals, $\mathbf{Q}_a^{in}$ and $\mathbf{P}_a^{in}$ should be designed such that $\left(\mathbf{P}_a^{in}\right)^{\mathrm{H}}\mathbf{H}_a\mathbf{Q}_a^{in} = \mathbf{0}$, where $\mathbf{0}$ denotes a 2×2 zeros matrix. At the same time, on $link_{\mathrm{ba}}$, $\mathbf{H}$ is also precoded by $\mathbf{Q}_b^{in}$ and postcoded by $\mathbf{P}_a^{in}$. In this process, the virtual 2×2 MIMO channel for $link_{\mathrm{ba}}$ is generated. The virtual MIMO channel for $link_{\mathrm{ba}}$ can be expressed as

$$\mathbf{H}_{\mathrm{ba}} = \xi_{\mathbf{P}_a}\xi_{\mathbf{Q}_b}\left(\mathbf{P}_a^{in}\right)^{\mathrm{H}}\mathbf{H}\mathbf{Q}_b^{in}. \tag{3}$$

Meanwhile, in the second step (outer coding process), $\mathbf{H}_{\mathrm{ba}}$ is broken down into orthogonal substreams to eliminate the interference between the received signals caused by crosstalk among antennas. For this, as in SVD-based MIMO spatial multiplexing systems [1][4], $\mathbf{Q}_b^{out}$ and $\mathbf{P}_a^{out}$ are determined using SVD of $\mathbf{H}_{\mathrm{ba}} = \mathbf{U}_{\mathrm{ba}}\mathbf{\Sigma}_{\mathrm{ba}}\mathbf{V}_{\mathrm{ba}}^{\mathrm{H}}$ as

$$\mathbf{Q}_b^{\mathrm{out}} = \mathbf{V}_{\mathrm{ba}}, \quad \mathbf{P}_a^{\mathrm{out}} = \mathbf{U}_{\mathrm{ba}}, \tag{4}$$

where $\mathbf{U}_{\mathrm{ba}}$ and $\mathbf{V}_{\mathrm{ba}}$ are unitary matrices. $\mathbf{\Sigma}_{\mathrm{ba}}$ is a diagonal matrix whose diagonal entries are singular values of $\mathbf{H}_{\mathrm{ba}}$. Using (2)-(4), (1) can be modified as

$$\begin{aligned}\mathbf{P}_a^{\mathrm{H}}\mathbf{y}_a &= \mathbf{P}_a^{\mathrm{H}}\mathbf{H}\mathbf{Q}_b\mathbf{x}_b + \rho_a\mathbf{P}_a^{\mathrm{H}}\mathbf{H}_a\mathbf{Q}_a\mathbf{x}_a + \mathbf{P}_a^{\mathrm{H}}\mathbf{w}_a \\ &= \mathbf{\Sigma}_{\mathrm{ba}}\mathbf{x}_b + \xi_{\mathbf{P}_a}\left(\mathbf{P}_a^{in}\mathbf{U}_{\mathrm{ba}}\right)^{\mathrm{H}}\mathbf{w}_a,\end{aligned} \tag{5}$$

Let us assume that $\mathbf{P}_a^{\mathrm{H}} = \xi_{\mathbf{P}_a}\left(\mathbf{P}_a^{in}\mathbf{U}_{\mathrm{ba}}\right)^{\mathrm{H}}$ is designed such that it does not affect the average noise power.

The generations of the inner precoder and the postcoder in each step of dual-coding process are as follows:

A. Precoder and Postcoer in Inner Coding Process

In this process, the echo signals are eliminated using echo channel information. Because the antennas can transmit and receive signals in the same band simultaneously, the channel information of the echo channels can be obtained with the aid of the pilot signals operating in the time division multiplexing (TDM) method at node a and b.

In order to make $\left(\mathbf{P}_a^{in}\right)^{\mathrm{H}}\mathbf{H}_a\mathbf{Q}_a = \mathbf{0}$, the orthogonal properties of the unitary vectors are used, and $\mathbf{P}_a^{in}$ and $\mathbf{Q}_a^{in}$ can be designed as

$$\mathbf{P}_a^{in} = \left[\mathbf{u}_{a,i}\ \mathbf{u}_{a,i}\right],\ \mathbf{Q}_a^{in} = \left[\mathbf{v}_{a,j}\ \mathbf{v}_{a,j}\right],\ 1 \le i, j \le 2,\ i \ne j, \tag{6}$$

where $\mathbf{u}_{a,i}$ and $\mathbf{v}_{a,j}$ represent the ith and jth column vectors of $\mathbf{U}_a$ and $\mathbf{V}_a$, respectively. $\mathbf{U}_a$ and $\mathbf{V}_a$ are unitary matrices generated by SVD of $\mathbf{H}_a = \mathbf{U}_a\mathbf{\Sigma}_a\mathbf{V}_a^{\mathrm{H}}$. $\mathbf{U}_a$ and $\mathbf{V}_a$ always have two orthogonal column vectors whether $\mathbf{H}_a$ is Rayleigh fading channel or Ricean fading channel. Therefore, from (6), it can be inferred that determination of inner precoder and postcoder is not unique and has four cases.

B. Power Normalization Factors

Applying the precoders and the postcoders in (6), the SVD of the virtual channel on $link_{\mathrm{ba}}$ can be expressed as

$$\mathbf{H}_{\mathrm{ba}} = \begin{bmatrix} \pm\alpha & \mp\beta \\ \pm\alpha & \pm\beta \end{bmatrix} \begin{bmatrix} \chi & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \pm\gamma & \mp\delta \\ \pm\gamma & \pm\delta \end{bmatrix}^{\mathrm{H}}, \tag{7}$$

$$\chi = 2\xi_{\mathbf{P}_a}\xi_{\mathbf{Q}_b}\left|\mathbf{u}_{a,i}^{\mathrm{H}}\mathbf{H}\mathbf{v}_{b,j}\right| \tag{8}$$

where $|\alpha|^2 = |\beta|^2 = |\gamma|^2 = |\delta|^2 = \frac{1}{2}$. $\mathbf{u}_{a,i}$ and $\mathbf{v}_{b,j}$ represent $i\,th$ and $j\,th$ column vectors of $\mathbf{U}_a$ and $\mathbf{V}_b$, respectively. From (7), it is clear that the rank of $\mathbf{H}_{ba}$ is 1. Thus, only one stream can be used for data transmission on each link and $\mathbf{x}_b$ must have the form $\mathbf{x}_b = [x\ \ 0]^{\mathrm{T}}$, where x is an arbitrary constellation of a transmitted symbol. Using (3)-(4), $\mathbf{x}_b$ is encoded as

$$\mathbf{Q}_b^{in}\mathbf{V}_{\mathrm{ba}}\mathbf{x}_b = \begin{bmatrix} \pm 2x\gamma v_{b,j}(1) \\ \pm 2x\gamma v_{b,j}(2) \end{bmatrix}, \tag{9}$$

where $v_{b,j}(1)$ and $v_{b,j}(2)$ represent the 1st and 2nd elements of jth column vector of $\mathbf{V}_b$, respectively. Note that the power of the transmitted signal is doubled by the precoding processes, since $|\pm 2x\gamma v_{b,j}(1)|^2 + |\pm 2x\gamma v_{b,j}(2)|^2 = 2|x|^2$ by the properties of the unitary matrices.

Meanwhile, when the noise vector at node a is denoted as $\mathbf{w}_a = [w_a(1)\ \ w_a(2)]^{\mathrm{T}}$ where $\mathbf{E}\left[|w_i(1)|^2\right] = \mathbf{E}\left[|w_i(2)|^2\right] = \sigma^2$, the postcoded noise vector can be expressed as

$$\mathbf{U}_2^{\mathrm{H}}\left(\mathbf{P}_a^{in}\right)^{\mathrm{H}}\mathbf{w}_a = \begin{bmatrix} \zeta \\ 0 \end{bmatrix}, \tag{10}$$

where $\zeta = \pm 2\alpha^* u_{a,i}(1)w_a^*(1) \pm 2\alpha^* u_{a,i}^*(2)w_a(2)$. $u_{a,i}(1)$ and $u_{a,i}(2)$ represent the 1st and 2nd elements of the ith column vector of $\mathbf{U}_a$, respectively. By the properties of the unitary matrices, $\mathbf{E}\left[|\zeta|^2\right] = 2\sigma^2$, it also becomes clear that the noise is concentrated in one stream used for data transmission. A similar process occurs on $link_{\mathrm{ab}}$. Therefore, the power normalization factors can be determined as

$$\xi_{\mathbf{P}_a} = \xi_{\mathbf{Q}_b} = \xi_{\mathbf{P}_b} = \xi_{\mathbf{Q}_a} = \sqrt{1/2}. \tag{11}$$

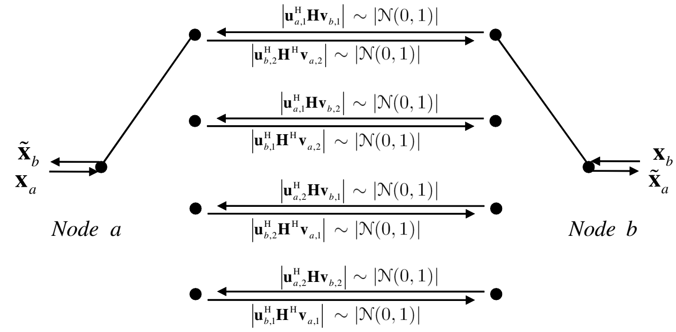

Fig. 3. Principle of selection diversity in VDD systems. In VDD systems, there are four combinations of virtual channels for given $\mathbf{H}$, $\mathbf{H}_a$, and $\mathbf{H}_b$. However, since each link can use only one path for data transmission. the best path can be selected for data transmission.

C. Selection Diversity in VDD System

From (8) and (11), the virtual channel on $link_{\mathrm{ba}}$ has a link whose gain is $\left|\mathbf{u}_{a,i}^{\mathrm{H}}\mathbf{H}\mathbf{v}_{b,j}\right|$. Since the Gaussianity of $\mathbf{H}$ remains after orthogonal transformations [1], it is inferred that $\mathbf{u}_{a,i}^{\mathrm{H}}\mathbf{H}\mathbf{v}_{b,j} \sim \mathcal{N}(0,1)$. Therefore, when $\mathbf{H}_{\mathrm{ba}}$ is generated by specific $\mathbf{u}_{a,i}$ and $\mathbf{v}_{b,j}$, $link_{\mathrm{ba}}$ is equivalent to SISO Rayleigh fading channel.

However, as mentioned above, there are four cases of selecting inner precoders and postcoders in 2×2 VDD systems. This means that it is possible to generate four virtual channels for the given $\mathbf{H}$, $\mathbf{H}_a$, and $\mathbf{H}_b$. Since only one path can be used for data transmission on each link, we should select only one of four candidates of virtual channels, and VDD can achieve selection diversity [13]. Such a selection diversity can be achieved because VDD system uses the information of $\mathbf{H}_a$ and $\mathbf{H}_b$ to generate the virtual channels, as opposed to FDD and TDD systems where information of $\mathbf{H}_a$ and $\mathbf{H}_b$ can not be used. Fig.3 shows the principle of selection diversity in VDD systems. In this paper, we select inner precoders and postcoders such that the sum capacity of $link_{\mathrm{ab}}$ and $link_{\mathrm{ba}}$ is maximized. It is easily seen that such a selection is equivalent to the selection such that $\lambda_{ab} \times \lambda_{ba}$ is maximized in high SNR.

IV. Resource Usage and Capacity of FDD, TDD, and VDD

In this section, we compare the usage of time, frequency, and spatial resource in FDD, TDD, and VDD systems in 2×2 flat-fading MIMO environment. It is assumed that FDD and TDD use SVD-based spatial multiplexing system [1]. To compare FDD, TDD, and VDD fairly, let us limit the amount of resource used to transmit data. We assume that the bandwidth W is limited, and each node can use limited energy E, N subcarriers in 2×2 MIMO environment. It is also assumed that the amounts of data on $link_{\mathrm{ab}}$ and $link_{ba}$ are equivalent, and the links are symmetric. When the number of carriers is generalized, the following relationships are satisfied:

$$\text{Symbol duration} = (\text{Subcarrier spacing})^{-1} \tag{12}$$

$$\text{Signal power} = E \times (\text{Symbol duration})^{-1}, \tag{13}$$

$$\text{Noise power} = N_0 \times (\text{Subcarrier spacing}), \tag{14}$$

where N_0 denotes the spectral density of white noise. For a single carrier system, $N = 1$.

In FDD systems, W is divided by two links and a portion of W is used for the guard band. Therefore, using (12),

$$W = W_{\text{ab}}^{\text{FDD}} + W_{\text{ba}}^{\text{FDD}} + \varepsilon W, \tag{15}$$

$$T^{\text{FDD}} = T_{\text{ab}}^{\text{FDD}} = T_{\text{ba}}^{\text{FDD}} = \frac{2N}{W(1-\varepsilon)}, \tag{16}$$

where ε denotes the ratio of the guard band to the entire bandwidth. $W_{\text{ab}}^{\text{FDD}}$ and $W_{\text{ba}}^{\text{FDD}}$ denote the bandwidth assigned to $link_{\text{ab}}$ and $link_{\text{ba}}$, respectively. $T_{\text{ab}}^{\text{FDD}}$ and $T_{\text{ba}}^{\text{FDD}}$ represent symbol durations on $link_{\text{ab}}$ and $link_{\text{ba}}$, respectively. Since two streams are generated by SVD of 2×2 MIMO channel, the energy E is shared by two streams.

On the other hand, in TDD systems, both links utilize the full bandwidth and the guard time is simply added to the symbol durations. Therefore,

$$W_{\text{ab}}^{\text{TDD}} = W_{\text{ba}}^{\text{TDD}} = W, \tag{17}$$

$$T^{\text{TDD}} = T_1^{\text{TDD}} + T_2^{\text{TDD}} + \tau T^{\text{TDD}}, \tag{18}$$

where $T_{\text{ab}}^{\text{TDD}} = T_{\text{ba}}^{\text{TDD}} = N/W$. T^{TDD} and τ denote the total amount of the time resource for both $link_{\text{ab}}$ and $link_{\text{ba}}$, and the ratio of the guard time to T^{TDD}, respectively. Equivalently to FDD, the energy E is shared by two streams.

In the case of VDD systems, since full bandwidth and full time is used for data transmission in both links,

$$W_{\text{ab}}^{\text{VDD}} = W_{\text{ba}}^{\text{VDD}} = W, \tag{19}$$

$$T^{\text{VDD}} = T_{\text{ab}}^{\text{VDD}} = T_{\text{ba}}^{\text{VDD}} = \frac{N}{W}. \tag{20}$$

From (7), it is observed that the virtual-channels of VDD have only one stream. Comparing (20) to (16) and (18), it can be inferred that each link of VDD can transmit more than twice the number of symbols compared to FDD and TDD, and each symbol of VDD can use energy $E/2$. Therefore, the energy $E/2$ is used in each stream for each symbol.

Using (12)-(20), link SNRs of FDD(η^{FDD}), TDD(η^{TDD}), and VDD(η^{VDD}) can be calculated as

$$\eta^{\text{FDD}} = \eta^{\text{TDD}} = \eta^{\text{VDD}} = \frac{E}{2N_0N}. \tag{21}$$

From (21), it is observed that the link SNRs of FDD and TDD system is not affected by the amount of the guard resource and link SNRs of three systems are equivalent. Then, the ergodic link capacity of each system on $link_{\text{ba}}$ can be expressed as [10]

$$C_{\text{ba}}^{\text{D}} = \mathbf{E}\left[\sum_{n=1}^{N}\sum_{k=1}^{r(\mathbf{H}_{\text{ba}})} \log_2\left(1 + \lambda_{ba,k}^2 \frac{E}{2N_0N}\right)\right], \tag{22}$$

where $\text{D} = \text{FDD, TDD, VDD}$. $\lambda_{ba,k}$ and $r(\mathbf{H}_{\text{ba}})$ represent the kth singular value and the rank of $\mathbf{H}_{\text{ba}}$, respectively. When $\text{D} = \text{FDD or TDD}$, $\mathbf{H}_{\text{ba}} = \mathbf{H}$.

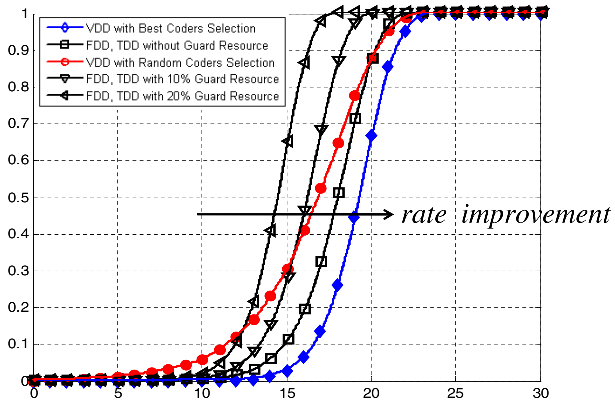

Fig. 4. CDF of data rate in FDD, TDD, and VDD systems when SNR=30dB. When only one realization of virtual channel is used among four candidates, the data rate of VDD is higher than those of FDD and TDD with the guard resource, but lower than FDD and TDD without the guard resource. However, when the precoders and postcoders are selected such that the sum capacity is maximized, the data rate of VDD outperforms those of ideal FDD and TDD.

V. Simulation Results

In this section, the capacity and BER performance of VDD are compared to those of FDD and TDD systems in 2×2 MIMO environment. We assume that $\mathbf{H}$ is ITU-R indoor office channel [9] and the distance between node a and b is $50m$, $N = 1$, and $\mathbf{H}_a$, $\mathbf{H}_b$ are Ricean fading channels with $\kappa = 10$.

Even though the same amount of resource is given, the amount of resource used on each link of each duplexing system is deferent. Especially, the amount of time resource is varied by using the guard resource even though the same amount of total bandwidth is given. Therefore, when comparing the capacity of FDD, TDD, and VDD systems, we use normalized mean link capacity, normalized by total amount of time and frequency resource. On $link_{\text{ba}}$, this is represented mathematically as

$$C_{norm}^{\text{D}} = \frac{W_{\text{ba}}^{\text{D}} T_{\text{ba}}^{\text{D}} C_{\text{ba}}^{\text{D}}}{W T^{\text{D}}} \quad bps/Hz, \tag{23}$$

where $\text{D} = \text{FDD}, \text{TDD}, \text{VDD}$. When the precoder and postcoder of VDD are selected so that the sum capacity of $link_{\text{ab}}$ and $link_{\text{ba}}$ is maximized, (23) is equivalent to

$$C_{norm}^{\text{VDD}} = \max_{\mathbf{P}_a^{in}, \mathbf{P}_b^{in}, \mathbf{Q}_a^{in}, \mathbf{Q}_b^{in}} \frac{C_{\text{ab}}^{\text{VDD}} + C_{\text{ba}}^{\text{VDD}}}{2} \quad bps/Hz, \tag{24}$$

since $link_{\text{ab}}$ and $link_{\text{ba}}$ are symmetric.

Fig.4 shows CDF of the data rate for FDD, TDD and VDD when SNR=30dB. When only one realization of virtual channels is used among four candidates, VDD is highly probable to have a higher data rate than FDD and TDD with the guard resource, but a lower data rate than FDD and TDD without the guard resource. However, when the precoder and postcoder are selected so that the sum capacity of two links is maximized, the data rate of VDD outperforms those of FDD and TDD even when the guard resource is not used. This is because the channel gain is improved by the selection diversity.

Fig.5 shows 10% outage capacity of ideal FDD, TDD systems, and VDD systems. With 10% outage capacity, the reliability and multiplexing gain of a communication system can be

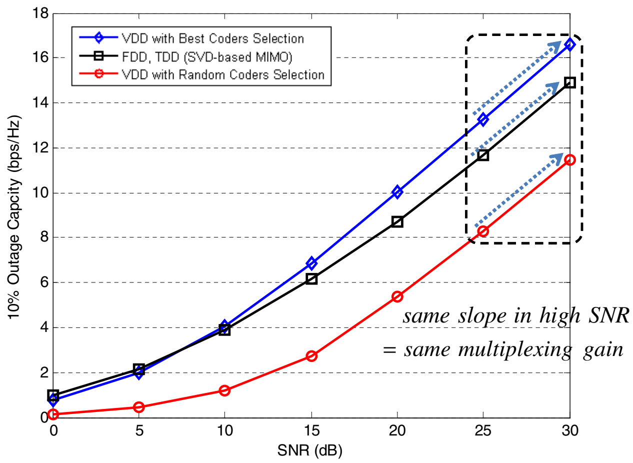

Fig. 5. 10% outage capacity of FDD, TDD, and VDD. When only one realization of virtual channel is used among four candidates, VDD support less reliable links than those of FDD and TDD. However, when the precoders and postcoders of VDD system are selected such that the sum capacity is maximized, VDD can support more reliable links than those of FDD and TDD. In high SNR, VDD can offer the same multiplexing gain as FDD and TDD.

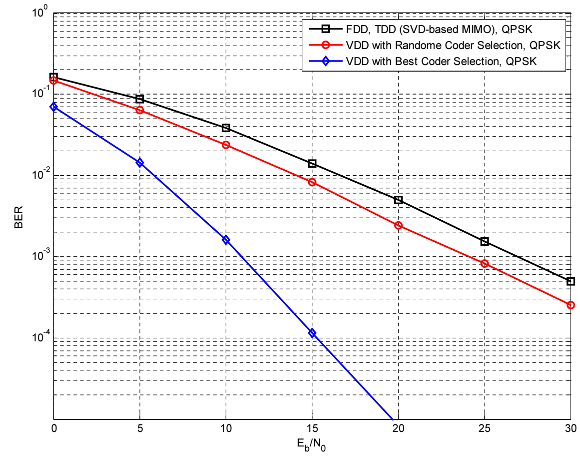

Fig. 6. BER of FDD, TDD, and VDD systems. When the precoders and postcoders of VDD system are selected such that the sum capacity is maximized, it is shown that selection diversity gain is achieved. However, when only one realization of virtual channel is used among four candidates, VDD system can not achieve selection diversity because only one realization of virtual channels is possible.

measured [4]. When the precoders and postcoders are selected so that the sum capacity of VDD is maximized, VDD can support more reliable communication links than FDD and TDD.

In high SNR, ideal FDD and TDD systems have a multiplexing gain of $M = 2$ [4]. Note that VDD has the same slope as ideal FDD and TDD regardless of precoder and postcoder selection. This means that VDD also achieves the same amount of multiplexing gains as ideal FDD and TDD, even though the spatial resource is used for duplexing, not for multiplexing. This is because VDD system achieves time multiplexing by using full bandwidth on both links and spatial resource for duplexing.

In Fig6, BER performance of FDD, TDD, and VDD systems is compared. Let us assume that FDD and TDD systems utilize SVD-based MIMO spatial multiplexing systems. When only one realization of a virtual channel is used among four candidates, VDD system is equivalent to SISO system with Rayleigh fading channel. In this case, as analyzed in [14], BER of VDD has the same diversity order as those of FDD and TDD, but achieves power gain. Meanwhile, when the precoders and postcoders of VDD system are selected in such a way that the sum capacity of two links is maximized, it is shown that the diversity order is increased to 2 due to the selection diversity. However, although four candidates of virtual channels are all generated from $\mathbf{H}$, $\mathbf{H}_a$, and $\mathbf{H}_b$, four paths are not independent. Therefore, VDD system can not achieve diversity order of 4 but 2, even though the degree-of-freedom of this system is 4.

VI. Conclusion

We proposed a new duplexing scheme, called virtual-channel division duplex, in a 2×2 MIMO system that uses spatial resources for duplexing. This system addresses the problem of data loss stemming from the guard resources by isolating two links in the spatial domain. Moreover, when generating the virtual channels, VDD can achieve selection diversity. By selection diversity, the capacity of VDD can be further improved and it can support more reliable communication links.

References

[1] D. Tse, P. Viswanath, "Fundamentals of Wireless Communication", *CAMBRIDGE*, 2005

[2] *IEEE 802.16e, Part 16, Amendent 2*, pp 317-650.

[3] *WINNER D2.5, v1.0*, pp 31, 2004

[4] A. Paulraj, R. Nabar, and D. Gore "Intorduction to Space-Time Wireless Communications",*Cambridge*, 2003.

[5] C. A. Balanis, "Antenna Theory: Analysis and Design", *Wiley*, 3rd Edition, 2005

[6] M. I. Skolnik, "Introduction to Radar Systems", *McGraw Hill*, 3rd Edition, 2000

[7] P. D. L. Beasley, "Solving the Problems of a Single Antenna Frequency Modulated CW Radar", *IEEE International Radar Conference*, pp. 391 - 395, 1990

[8] S. Chen, M.A. Beach, J.P. McGeehan, "Division-Free Duplex for Wireless Applications", *IEEE Electronics Letter*, vol. 34, No. 2, pp. 147 - 148, January, 1998

[9] Guidelines for the evaluation of radio transmission technologies for IMT-2000, Recommendation ITU-R M.1225, 1997.

[10] H. Bocskei, D. Gesbert, and A. Paulraj, "On the Capacity of OFDM-Based Spatial Multiplexing System", *IEEE Trans. on Communications*, vol. 50, no. 2, pp. 225-234, Feb. 2002.

[11] Harry L. Van Trees, "Optimum Array Processing: Part IV of Detection, Estimation, and Modulation Theory", *John Wiley and Sons, Inc.*, 2002

[12] M. Chiani, M. Z. Win, and A. Zanella, "On the Capacity of Spatially Correlated MIMO Ralyeigh-Fading Channels", *IEEE Trans. on Information Theory*, vol. 49, no. 10, pp. 2363-2371, Oct. 2003.

[13] Young Gil Kim and Sang Wu Kim, "Optimum Selection Diversity for BPSK Signals in Rayleigh Fading Channels", *IEEE Trans. on Communications*, vol. 49, no. 10, pp. 1715-1718, Oct. 2001.

[14] B. N. Getu and J. B. Andersen, "BER and Spectral Efficiency of a MIMO System", *IEEE The 5th International Symposium on Wireless Personal Multimedia Communications*, vol. 2, pp. 397-401, 27-30, Oct. 2002.