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MITIGATION OF SELF-INTERFERENCE IN BIDIRECTIONAL FULL-DUPLEX MIMO LINK USING MULTI ANTENNA TRANSCEIVER

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Abstract

Communication between two multi antenna full duplex transceivers using bidirectional MIMO links faces a major problem of self-interference of signals. Suppression in spatial domain and cancellation in time domain are the two methods that can be adopted to mitigate the self-interference. In suppression, self-interference is mitigated at the cost of spatial degrees of freedom unlike in cancellation where the signal responsible for self-interference is subtracted. The rate regions obtained by both the methods are compared and in case of suppression, the spatial multiplexing order is varied at each node and comparison between rate regions achieved by different stream configurations is made. The results characterize the significant difference in the rates achieved after implementing cancellation and suppression.

Keywords: Beam-forming, full-duplex bidirectional communication, Null Space Projection, suppression, cancellation.

1. Introduction

All wireless communication devices use single link for either transmission or reception but not both. In order to increase (almost double) the spectral efficiency and the capacity of the wireless communication systems, a single frequency can be used for both transmission and reception [1]. The major problem faced is the self-interference or loop interference which is caused by the interference of the signal received at the transceiver with the signal transmitted by the same transceiver.

The methods that can be adopted to mitigate this self-interference are suppression and cancellation. Suppression is a spatial domain scheme which

Nomenclatures

H_{ij}	Channel for transmission from terminal *i* to terminal *j*
n_j	Additive White Gaussian Noise added to the signal before being received at the terminal *j*
P_i	Maximum number of transmitting antennas at terminal *i*
$\hat{P}_i$	Number of antennas used for transmission at terminal *i*
Q_i	Maximum number of receiving antennas at terminal *i*
$\hat{Q}_i$	Number of antennas used for reception at terminal *i*
R_i	Receiving filter at terminal *i*
r_{ij}	Average Transmission rate from terminal *i* to terminal *j*, bit/s/Hz
S_{cj}	Column subset selection matrix
S_{rj}	Row subset selection matrix
T_i	Transmitting filter at terminal *i*
U_{jj}	Unitary matrix obtained by resolving the matrix of channel (H_{jj}) responsible for self-interference using SVD
V_{jj}	Unitary matrix obtained by resolving the matrix of channel (H_{jj}) responsible for self-interference using SVD

Greek Symbols

Γ	Signal-to-Noise ratio.

Abbreviations

iid	Independent and identically distributed
SNR	Signal-to-Noise ratio
SVD	Singular Value Decomposition

involves the trade-off between spatial degrees of freedom and self-interference. It is based on Null Space Projection [2] and uses multi antenna schemes like beam forming [3]. Cancellation on the other hand presumes that the signal causing interference is known and it is subtracted from the received signal. The transceivers at both the terminals are considered identical and the channels are reciprocal.

The major constraints in full duplex bidirectional communication are the uplink and downlink imbalance i.e., the unequal requested rates and time sharing for both the directions accordingly. The transceiver should be able to use a single frequency band for transmission and reception for the equal amount of time indicating the constraint of Temporal Symmetry. The system should be able to handle - asymmetry of traffic pattern i.e., the difference in the requested rates from the users and asymmetry of channel quality, i.e., the achieved transmission rates in both the directions. The achieved transmission rates may not be the same in both directions because of the difference in spatial multiplexing order at the two transceivers. Therefore, it is essential to observe rates in both directions at the same time making it a two dimensional analysis of rate regions.

To extend the analysis to large system limit where the number of antennas increases asymptotically to a large limit, replica method [4] – [9] is used in the evaluation of the average transmission rate [10]. Basing on the results obtained, the methods can be implemented for practical systems with not so large number of antennas.

2. System Model

Considering the bidirectional communication link shown in Fig.1, a single terminal acts as a transceiver. The signal received at a particular transceiver is interfered by the signal transmitted by the same transceiver creating self-interference or loop interference. For a terminal $i \in \{1, 2\}$ the total number of transmitting antennas is P_i and the total number of receiving antennas is Q_i [11].

The channel H_{ij} represents the propagation of signal from terminal i to terminal j where $i \neq j$ and. Information designated for terminal j is encoded in $x_i \in \mathbb{C}^{\hat{P}_i \times 1}$ at terminal i and passed through the channel $H_{ij} \in \mathbb{C}^{Q_j \times P_i}$ and decoded and recovered at terminal j $y_j \in \mathbb{C}^{\hat{Q}_j \times 1}$ indicating $\hat{P}_i$ and $\hat{Q}_j$ transmit and receive antennas respectively for spatial multiplexing. The maximum number of transmit antennas is P_i and the maximum number of receive antennas is Q_j for a feasible stream configuration ($\hat{P}_i$, $\hat{Q}_j$) where $i, j \in \{1,2\}$.

$$\hat{P}_i < P_i \text{ and } \hat{Q}_j < Q_j \tag{1}$$

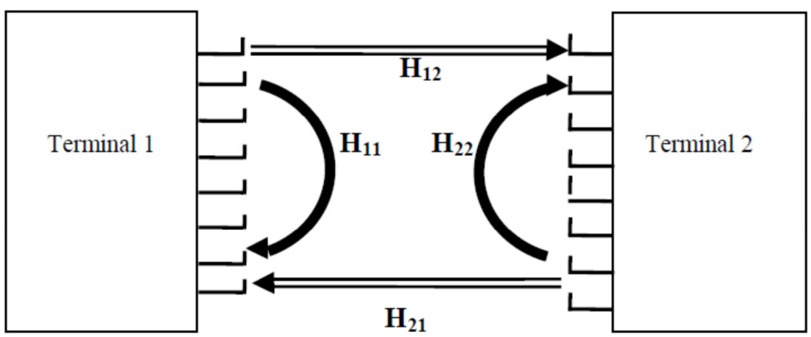

Fig. 1. Demonstration of Self Interference in bidirectional full duplex MIMO link.

Since, the link is full-duplex, the terminal j not only receives the encoded signal from terminal i but also receives its own transmitted signal designated for terminal i. The signal encoded as $x_j \in \mathbb{C}^{P_j \times 1}$ passes through the self-interference channel and is received with the receiving signal. In order to overcome this loop interference, the transceivers are equipped with linear transmit and receive filters, $T_i \in \mathbb{C}^{\hat{P}_i \times P_i}$ and $R_i \in \mathbb{C}^{\hat{Q}_i \times Q_i}$.

The signal received at terminal j is

$$y_j = R_j H_{ij} T_i x_i + R_j H_{jj} T_j x_j + R_j n_j \tag{2}$$

where $n_j \in \mathbb{C}^{Q_j \times 1}$ represents additive white Gaussian noise with unit variance per dimension i.e., $\varepsilon\{n_j n_j^H\}=\mathbf{I}$ [12]. Terminal j has knowledge of its receive side channels H_{ij} and H_{jj} but it is not necessary for terminal j to know its transmit side channel H_{ji}.

2.1. Suppression

Suppression is achieved by considering it as a form of null space projection. The filters T_j and R_j are chosen such that the term $R_j H_{jj} T_j = 0$ i.e., the self-interference component is removed. In addition to that, the filters must satisfy $T_j^H T_j = \mathbf{I}$ and $R_j R_j^H = \mathbf{I}$ in order to maintain the orthonormal subspaces.

The channel is transformed into a product of unitary orthonormal matrices using the SVD.

$$H_{jj}=U_{jj}\Sigma_{jj}V_{jj}^H \tag{3}$$

The filters can be realized as

$$T_j = \sqrt{P_j/\hat{P}_j}\; V_{jj}S_{cj} \tag{4}$$

$$R_j = \sqrt{Q_j/\hat{Q}_j}\; S_{rj}^T U_{jj}^H \tag{5}$$

Where S_{cj} and S_{rj} are column and row subset selection matrices respectively for which $S_{cj}^T S_{cj} = \mathbf{I}$ and $S_{rj} S_{rj}^T = \mathbf{I}$. Then, the term corresponding to the self-interference becomes

$$R_j H_{jj} T_j = R_j U_{jj}\Sigma_{jj}V_{jj}^H T_j = \sqrt{Q_j P_j/\hat{Q}_j \hat{P}_j}\; S_{rj}^T \Sigma_{jj} S_{cj} \tag{6}$$

The subset selection matrices should be chosen such that $S_{rj}^T \Sigma_{jj} S_{cj} = 0$ i.e., selection matrices should pick only the off diagonal elements of Σ_{jj} which are all zero in order to make $R_j H_{jj} T_j = 0$. The total number of transmitting and receiving antennas should be less than or equal to the maximum number of antennas present on a terminal.

$$P_j + Q_j = \max\{P_j, Q_j\} \tag{7}$$

Considering the Eqs. (1) and (7) together, the lower bounds can be

$$\max\{0, P_i - Q_i\} \le P_i \text{ and } \max\{0, Q_j - P_j\} \le Q_j \tag{8}$$

2.2. Cancellation

In cancellation, compromise in the spatial degrees of freedom is not required. All the antennas are used for transmission and reception i.e., $\hat{P}_i = P_i$ and $\hat{Q}_j = Q_j$. Assuming that a terminal is aware of its receive side channels and the signal transmitted from its own terminal, the interference signal is produced. Before the received signal is decoded, the signal produced at the terminal is subtracted from the received signal, i.e., the $R_jH_{jj}T_jx_j$ signal is subtracted from the received y_j signal. The transmitting and receiving filters used in order for the suppression of self-interference signals are not required. Therefore, $R_j = \mathbf{I}$ and $T_j = \mathbf{I}$.

3. Transmission Rates

After suppression or cancellation, the signal received will be

$$y_j = R_jH_{ij}T_ix_i + R_jn_j \tag{9}$$

The signal x_i is transmitted by $\hat{P}_i$ antennas with equal power. The transmit covariance matrix becomes

$$\{x_ix_i^{\mathrm{H}}\} = {}^{1}\!/\!_{\hat{P}_i}\,\mathbf{I} \tag{10}$$

Assuming that H_{ii}, $i \in \{1,2\}$ are uncorrelated with H_{ij}, $ij \in \{12, 21\}$, the filters T_i and R_j are chosen according to the channel state information of the channels responsible for self-interference. Since $\{n_jn_j^{\mathrm{H}}\}=\mathbf{I}$ and $R_jR_j^{\mathrm{H}}= \mathbf{I}$.

$$\{R_jn_j(R_jn_j)^{\mathrm{H}}\} = R_j\{n_jn_j^{\mathrm{H}}\}Rj^{\mathrm{H}} = \mathbf{I} \tag{11}$$

The average transmission rate [10] in either of the directions can be calculated as

$$r_{ij}= \varepsilon\{\log_2\{\det(\mathbf{I} + \frac{1}{\hat{P}_i} R_jH_{ij}T_j(R_jH_{ij}T_i)^{\mathrm{H}})\}\} \tag{12}$$

Instead of evaluating the Eq. (12), replica method [4]-[9] is applied in order to achieve the results in a large system limit. The elements of the channel H_{ij} are assumed to be independent and identically distributed (i.i.d) complex Gaussian variables with a variance Γ_{ij} which also denotes the signal-to-noise ratio (SNR). When the number antennas increases asymptotically to a large number, the average transmission rate converges to

$$\frac{r_{ij}}{\hat{P}_i} \simeq \log_2(1+\frac{Q_j}{P_i}.\frac{\Gamma_{ij}}{1+K})+\frac{Q_j}{P_i}(\log_2(1+K)-\frac{K}{1+K}\log_2(e)) \tag{13}$$

where K is a real positive solution to

$$\frac{r_{ij}}{K} = 1+\frac{\hat{Q}_j}{\hat{P}_i}.\frac{\Gamma_{ij}}{1+K} \tag{14}$$

By solving Eq. (14), the value of K is obtained as

$$K = [(1-\frac{Q_j}{P_i})\Gamma_{ij} -1] * [\sqrt{\frac{\Gamma_{ij}}{[(1-\frac{Q_j}{P_i})\Gamma_{ij} -1]^2}+\frac{1}{4}}+\frac{1}{2}] \tag{15}$$

From the equations obtained, it is observed that the transmission rate depends on the antenna ratio, i.e., one of the deciding factors is the antenna imbalance ratio. Rate also depends on the variance or the signal-to-noise ratio.

4. Numerical Results

The results are based on the assumptions that the SNR Γ is same in both the directions i.e., $\Gamma_{ij} = \Gamma_{ji} = \Gamma$. The maximum number of antennas at a terminal is 8, out of which maximum that can be used for transmission is 4. Figure 2 gives the transmission rates in a single direction for various stream configurations, i.e., varying the antenna ratio of transmitting and receiving sides. For a particular stream configuration (P_i, Q_j) in the direction *ij*, the stream configuration in the direction *ji* becomes $(P_i, Q_j) = (8 - Q_j, 9 - P_i)$. For convenience, $P_i = P_j = P$ and it is shown from Fig. 2 that the highest rate is achieved in the case of cancellation and the rate increases with the increase in spatial multiplexing order.

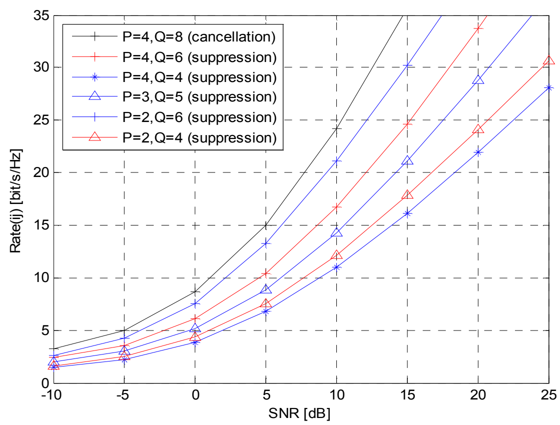

Fig. 2. Transmission Rates in terms of SNR (Γ) when P=4 and Q=8.

Figure 3 is the convex hull of the rate regions of different stream configurations. There are a total of 16 stream configurations and two typical stream configurations in which all the antennas are used for transmission and reception corresponding to the case of cancellation.

Since choosing the spatial multiplexing order for transmit side reveals the order for the receive side, the transmission rates in the two directions are indirectly coupled. Therefore, achieving higher transmission rate in one direction implies higher SNR in that direction and lower transmission rate and SNR in the other direction.

Figure 4 gives the achievable rate regions for different signal-to-noise ratio values for a particular stream configuration. As the SNR increases, rate also increases. Figure 5 shows the achievable rate regions for different stream configurations at a constant SNR value. The variation in the shape of the rate regions is observed with the variation in stream configuration.

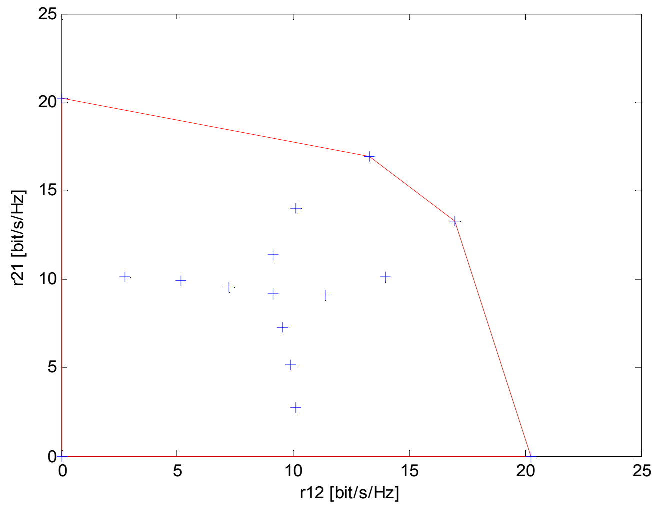

Fig. 3. Achievable rate regions when P = 4, Q = 8 and Γ = 8 dB.

From Figs. 4 and 5, it can be proved that the shape of the rate region is majorly dependent on the stream configuration rather than on the SNR. The rate is more in the direction in which spatial multiplexing order is high and correspondingly, a low rate is achieved in the opposite direction. The case where there is same number of antennas for transmitting and receiving is a difficult one to achieve and the case with more number of transmitting antennas than receiving antennas is preferred because of the better achieved rates.

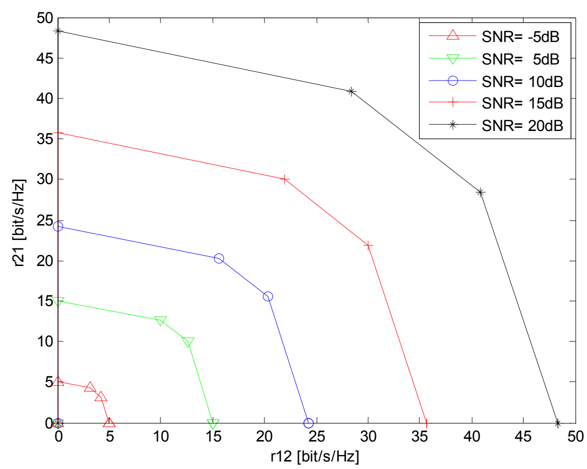

Fig. 4. Achievable rate regions when P=4, Q=8 and Γ ∈ {-5, 5, 10, 15, 20} dB.

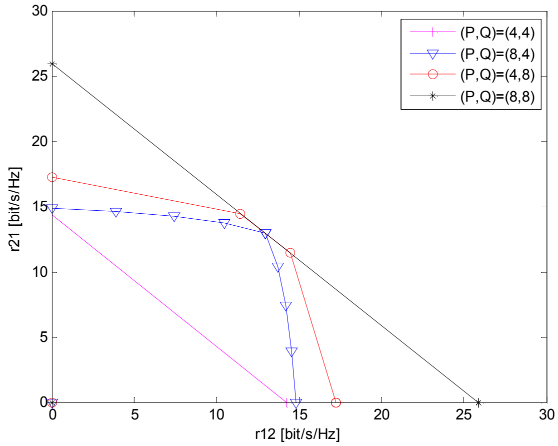

Fig. 5. Achievable rate regions at Γ=12 dB when (P,Q) ∈ {(4,4),(8,4),(4,8),(8,8)}.

Figure 6 shows that better rate regions can be achieved with the increase in spatial multiplexing order. As the number of antennas increases better rate regions can be achieved at a particular gain. This can be extended to the large system scenario with more number of antennas.

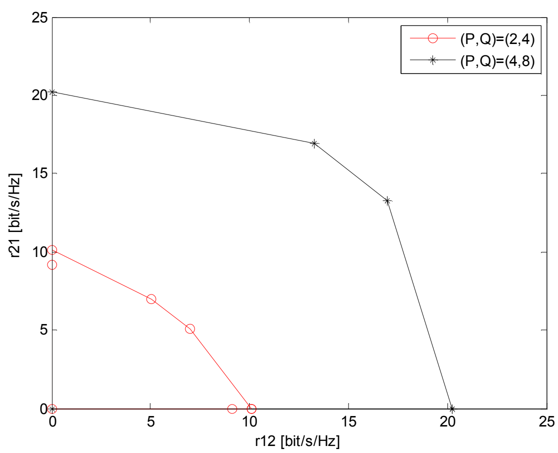

Fig. 6. Achievable rate regions at Γ=8 dB when (P, Q) ∈ {(2, 4), (4, 8)}.

5. Conclusion

This paper analyzes the methods- suppression where rate regions are achieved by varying spatial multiplexing order foregoing spatial degrees of freedom and cancellation where the self-interference signal is subtracted. It is proved from the simulation results that cancellation renders better achievable rate regions than suppression. By varying the stream configurations, considerable rate regions are obtained in the case of suppression and the case where there are more number of transmit antennas is preferred because of the better rates.

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