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Minimization of Loop-Back Self Interference in Full-Duplex Relaying

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***Abstract---** Full duplex relaying is more spectrally efficient than the half-duplex relaying. Multi-hop communication is a promising technique to provide more extensive coverage area, high throughput, better performance and it consumes low transmit power. Loop-back self interference maybe occurred due to signal leakage from relay transmission to its own reception. Previous technique i.e.; time-domain cancellation tackle the problem that it does not exploit the spatial domain. e.g., low rank cannot be exploited to improve the performance. In order to overcome the drawback of time-domain cancellation, propose a Spatial suppression scheme i.e., Null-space projection which exploits the spatial domain and improves the performance.*

***Keywords---** full-duplex, interference cancellation, multiple-input multiple-output (MIMO) relay, minimum mean square error (MMSE), null-space projection, self-interference.*

I. INTRODUCTION

Relaying is used in wireless communication, relay nodes are using in relaying process. Relay node are receiving the information from source node while transmitting to destination node. Full-duplex relaying is more spectrally efficient than the half-duplex relaying. Multiple users can communicate each other by using MIMO. Multiple Input Multiple Output(MIMO) is one of several forms of smart antenna technology having usage of multiple antennas at both the transmitter and receiver to improve communication performance. During the full-duplex relaying process, the relay node receives its own transmitted data in feedback loop manner. loop-back self interference maybe occurred due to signal leakage from relay output to its input. In order to minimize the self interference, we propose methods in spatial domain: Null-space projection and beam selection. It overcomes the drawback of existing method: time domain cancellation tackle the problem that it is blindness to spatial domain. Spatial suppression schemes i.e., Null-space projection and beam selection can improve the performance.

II. BACKGROUND

Multi-hop communication is the promising technique to improve signal performance by using relaying process[5]. The relaying process is done by relay nodes between source and destination [8]. Full-duplex relaying is used in our method. Full-duplex relay nodes can transmit and receive the signals at a time. From information theory-oriented papers, e.g.,[4][5] and [8], study various full-duplex relaying schemes without considering the deleterious effect of the loop interference albeit otherwise presenting many seminal contributions. To improve the efficiency of resource usage in two-hop full duplex relay systems based on resource sharing and interference cancellation is used [3]. Need to improve the Capacity of MIMO wireless channel with full-duplex amplify-and-forward relay [1]. In order to reduce or control the self interference, the time domain cancellation is proposed [2]. We have to propose a new method in spatial domain [6] [7] which is the efficient and good technique than the time domain cancellation.

A. Nomenclature:

let $X^T, X^H, X^{-1}, X^+, rk\{X\}, tr\{X\}, and\ \|X\|_F = \sqrt{tr\{XX^H\}}$ denote the transpose, conjugate transpose, inverse, Moore-Penrose pseudo inverse, rank, trace, and Frobenius norm of matrix, respectively. The Euclidean norm of vector is given by $\|X\|_2 = \sqrt{X^H X}$ and $\binom{N}{N'}$, and is the binomial coefficient, i.e., the number of combinations to choose N elements from a set of elements. Respective column and row subset selection matrices of appropriate dimensions are represented by S and S^T which are binary matrices such that $\sum_i \{S\}_{i,j} = 1$;for all j and $\sum_i \{S\}_{i,j} \in \{0,1\}$;for all i. Identity and zero matrices of appropriate dimensions are I and 0, respectively. The expectation operator is denoted by $\varepsilon\{.\}$.

III. PREVIOUS WORK

Time-domain cancellation [2] is method which is used to minimize the loop-back self interference in full-duplex relaying. In each relay station in an SFN (single Frequency Network) for DTB (Digital Terrestrial Broadcasting), the loop interference is caused by the coupling from the transmitting antenna to receiving antenna. The interference must be reduced to an allowable level in order to avoid problems with distortion and oscillation.

A. Time-Domain Cancellation (TDC):

Cancellation is based on the reasonable presumption that the relay always knows its own transmitted signal at least approximately. If the relay can also determine the loop channel, the interference signal may be replicated and removed from the received signal. In practice, the relay may apply conventional analog pre cancellation to improve the feasibility of the digital mitigation techniques for lower dynamic range. However, the implementation of the

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electronics becomes expensive and difficult if the respective circuit is more sophisticated than a phase shifter that removes one (ideally the strongest) multipath component.The considered TDC scheme is a straightforward MIMO extension for earlier SISO schemes.

The relay contains a feedback loop with MIMO cancellation filter $C \in \mathbb{C}^{N_{rx} \times N_{tx}}$ $\hat{r} = r + C\tilde{t}$, where $\tilde{t} = \hat{t}$, $R_{\tilde{t}} = R_{\hat{t}}$, $\hat{H}_{SR} = H_{SR}$, and $\hat{H}_{RD} = H_{RD}$.

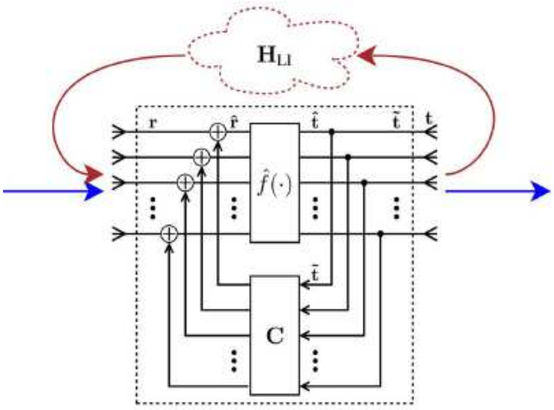

Fig.1: Time-domain loop interference cancellation

The equivalent receiver noise vector of the "interference-free" relay becomes

$$\hat{n}_R = \hat{H}_{LI}\hat{t} + H_{LI}\Delta\hat{t} + n_R$$

in which the residual loop interference channel is

$$\hat{H}_{LI} = H_{LI} + C = \hat{H}_{LI} + C + \Delta\hat{H}_{LI}$$

The MSE matrix of the relay input signal becomes

$$M = \varepsilon\{(H_{SR}\,x + n\_R - \hat{r})(H_{SR}x + n_R - \hat{r})^H\}$$
$$= (H_{LI} + C)R_{\hat{t}}(H_{LI} + C)^H + H_{LI}R_{\Delta\hat{t}}H_{LI}{}^H$$

The first term includes the channel estimation error and the second term arises due to the transmit signal noise. Cancellation can only minimize the known part of the first term by choosing $C = -\hat{H}_{LI}$ which results in $\hat{H}_{LI} = \Delta\hat{H}_{LI}$. Thereby, (12) yields the residual interference power as

$$P_l = tr\{M\} = tr\{\Delta\hat{H}_{LI}R_{\hat{t}}\hat{H}_{LI}^H\} + tr\{H_{LI}R_{\Delta\hat{t}}H_{LI}{}^H\}$$
$$= \varepsilon\{\|\Delta\hat{H}_{LI}\hat{t} + H_{LI}\Delta\hat{t}\|_2^2$$

The main drawback of TDC is its blindness to the spatial domain, e.g., low rank of H_{LI} is not expected to result in better isolation. Additionally, the scheme is sensitive to both channel estimation noise $\Delta\hat{H}_{LI}$ and transmit signal noise $\Delta\hat{t}$.In fact, TDC adds a new signal in the relay input which may actually lead to degraded isolation compared to pure natural isolation with high channel estimation noise. The advantage of time-domain cancellation is that it does not distort the desired signal or reduce the input and output dimensions of the relay, i.e., $\hat{N}_{rx} = N_{rx}$ and $\hat{N}_{tx} = N_{tx}$.

IV. PROPOSED METHOD

A. System model:

Let us consider the generic wireless multi-hop network illustrated in the upper left corner of Fig. 2. The network comprises nodes operating in both half-duplex and full-duplex modes and it is not restricted to any specific multi-hop routing protocol or multiple access strategy for the simultaneous transmissions [1]. We then focus on two-hop communication through any full-duplex relay (R) node from a set of source (S) nodes to a set of destination (D) nodes as illustrated in the lower right corner of Fig.3. The full-duplex relay receives and transmits simultaneously on the same frequency which necessitates to model explicitly the resulting loop interference (LI) signal. The sources and the destinations have in total N_S transmit and N_D receive antennas, respectively, and the relay is equipped with N_{rx} receive and N_{tx} transmit antennas. Before applying mitigation techniques the relay is likely implemented with spatially separated receive and transmit antenna arrays which constitutes natural isolation. However, the following results are also applicable in full-duplex relaying with a single antenna array]. Set $N_{rx} = N_{tx}$ in the special case.

B. Signal Model:

The signal model is built upon frequency-flat block-fading channels as in the majority of related papers. This implies that the system exploits Orthogonal Frequency Division Multiplexing (OFDM) for broadband transmission over multipath channels, and the signal model represents a single narrowband subcarrier.

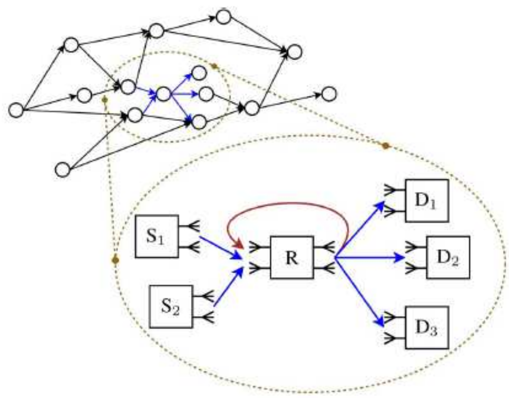

Fig.2: A wireless multi-hop network with FD Relays

For time instant i , let matrices , $H_{SR}[i] \in \mathbb{C}^{N_{rx} \times N_S}$, $H_{LI}[i] \in \mathbb{C}^{N_{rx} \times N_{tx}}$ and $H_{RD}[i] \in \mathbb{C}^{N_D \times N_{tx}}$ represent the respective MIMO channels from all sources to the relay, from the relay output to the relay input, and from the relay to all destinations.

The sources transmit the combined signal vector $x[i] \in \mathbb{C}^{N_S \times 1}$ and the relay transmits signal vector $t[i] \in \mathbb{C}^{N_{stx} \times 1}$ while it simultaneously receives signal vector $r[i] \in \mathbb{C}^{N_{rx} \times 1}$. The operation creates a feedback loop from the relay output to the relay input through channel $H_{LI}[i]$.

The relaying protocol is denoted by the generic function: $t[i] = f(r[i-\tau], r[i-(\tau+)], r[i-(\tau+1)], \ldots)$…….(1),which generates an output sample based on the sequence of input samples and causes integer processing delay $\tau > 0$. We focus on the mitigation of the loop interference and, thereby, keep the proposed schemes transparent and applicable with most of the readily available relaying protocols. In particular, omitting the delay causes severe causality problems in the practical implementation of relaying protocols: It is impossible to process a subcarrier and retransmit the OFDM symbol before the respective OFDM symbol is first completely received and demodulated. Furthermore, the loop signal may not be harmful at all with zero processing delay because the relay transmission only amplifies the same input signal. Finally, the respective received signals in the relay and in the destinations can be expressed as

$$r[i] = H_{SR}[i]x[i] + H_{LI}[i]t[i] + n_R[i],$$
$$y[i] = H_{RD}[i]t[i] + n_D[i] \ldots\ldots(2)$$

where $n_R[i] \in \mathbb{C}^{N_{rx}\times 1}$ and $n_D[i] \in \mathbb{C}^{N_D\times 1}$ are additive noise vectors in the relay and in the destinations, respectively. All signal and noise vectors have zero mean. Signal and noise covariance matrices are denoted by $R_x = \varepsilon\{x[i]x^H[i]\}$, $R_t = \varepsilon\{t[i]t^H[i]\}$. And $R_{nR} = \varepsilon\{n_R[i]n_R^H[i]\}$. For clarity, omit the time indices in the rest of the work.

C. Side Information for Mitigation Techniques:

Consider mitigation techniques [6] [7] that can be implemented transparently, i.e., using only information that the relay is expected to know by design or is able to measure by it. In other words, mitigation may exploit knowledge of only t, H_{LI} and H_{SR}. However, we assume that the available side information is degraded due to the following non-idealities which manifest themselves in the form of noise. In this paper, the noise is assumed to be completely unknown for the mitigation schemes while some additional information such as the covariance or norm bounds of the errors could facilitate a "robust" approach.

1) Channel Estimation Noise: The relay may exploit any off-the-shelf technique or one of the schemes developed specifically for full-duplex relays to obtain the respective estimates H_{LI} and H_{SR} of H_{LI} and H_{SR} . Model the practically non-ideal estimation process by defining estimation noises ΔH_{LI} and ΔH_{LI} such that the estimates differ from the true channel values:

$H_{LI} = H_{LI} + \Delta H_{LI}$ and $H_{SR} = H_{SR} + \Delta H_{SR} \ldots\ldots(3)$

All elements of ΔH_{LI} and ΔH_{SR} are assumed to be independent (both mutually and from the corresponding channels) circularly symmetric complex Gaussian random variables. The variance of the estimation noise is defined by relative estimation ϵ_H error such that

$$\varepsilon\{|\{\Delta\hat{H}_{LI}\}_{i,j}|^2\} = \epsilon_H^2\, \varepsilon\{|\{H_{LI}\}_{i,j}|^2\} \ldots\ldots(4)$$

for all i,j . Analogous relation holds between $\Delta\hat{H}_{SR}$ and H_{SR}.

2) Transmit Signal Noise: The relay knows perfectly the digital baseband signal $\tilde{t}$ generates, but the actual transmitted signal cannot be exactly known. This is because any practical implementation of conversion between baseband and radio frequency is prone to various distortion effects such as carrier frequency offset, oscillator phase noise, AD/DA conversion imperfections, I/Q imbalance, and power amplifier nonlinearity among others. Model the joint effect of all imperfections by introducing additive transmit distortion noise $\Delta\tilde{t}$ such that $t = t + \Delta\tilde{t}$.

Furthermore, we model all elements of $\Delta\tilde{t}$ with independent zero-mean random variables, and define their variance with relative distortion ϵ_t. The covariance matrix of the transmit noise becomes

$$R_{\Delta t} = \epsilon_t^2 \frac{tr\{R_{\tilde{t}}\}}{N_{tx}} I \ldots\ldots(5)$$

We assume that $\tilde{t}$ and $\Delta\tilde{t}$ are uncorrelated which implies that $R_t = R_{\tilde{t}} + R_{\Delta\tilde{t}}$ in which $R_{\tilde{t}} = \varepsilon\{\tilde{t}\tilde{t}^H\}$.

D. Novel Spatial Suppression Schemes:

To exploit the extra degrees of freedom offered by the spatial domain, propose method that the relay applies MIMO receive filter $G_{rx} \in \mathbb{C}^{\hat{N}_{rx}\times N_{rx}}$ and MIMO transmit filter $G_{tx} \in \mathbb{C}^{N_{tx}\times \hat{N}_{tx}}$ as illustrated in Fig 3. Now (2), (5), and (7) can be related as $\hat{r} = G_{rx}r$, $\tilde{t} = G_{tx}\hat{t}$, $R_{\tilde{t}} = G_{tx}\hat{t}G_{tx}^H$, $\hat{H}_{SR} = G_{rx}H_{SR}$, and $\hat{H}_{RD} = H_{RD}G_{tx}$.

Throughout the work, normalize filter gains to $\|G_{rx}\|_F^2 = N_{rx}$ and to $\|G_{tx}\|_F^2 = N_{tx}$ with all schemes.

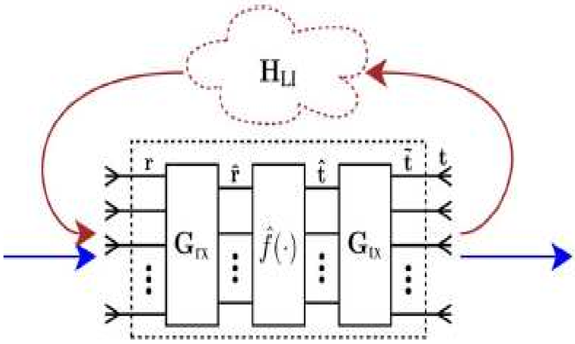

Fig.3: Spatial loop interference suppression

The equivalent receiver noise vector of the "interference-free" relay becomes

$$\hat{n}_R = \hat{H}_{LI}\tilde{t} + G_{rx}H_{LI}\Delta\tilde{t} + G_{rx}n_R \ldots\ldots(6)$$

in which the residual loop interference channel is

$$\hat{H}_{LI} = G_{rx}H_{LI}G_{tx} = G_{rx}\hat{H}_{LI}G_{tx} + G_{rx}\hat{H}_{LI}G_{tx} \ldots\ldots(7)$$

Based on (6), the residual interference power is given by

$$P_I = tr\{M\} = \varepsilon\{\|\hat{H}_{LI}\tilde{t} + G_{rx}H_{LI}\Delta\tilde{t}\|_2^2 \ldots\ldots(8)$$

Interference can be suppressed by designing G_{rx} and G_{tx} to minimize the first term and/or by designing only G_{rx} to minimize the second term that is due to transmit signal noise. Since (7) is a matrix equation, it needs to be first translated into a scalar value before formulating an optimization problem: In the fallowing paper, the Frobenius norm is adopted for this purpose while other metrics, rendering different optimization targets, are also available. On the other hand, (8) for spatial suppression is reduced to mere natural isolation when $G_{rx} = I$ and $G_{tx} = I$.

The implementation differs depending on the procedure:

- Independent design: One filter is designed without knowledge of the other filter which can be replaced by I.
- Separate design: One filter is designed given the other.
- Joint design: The filters are designed together.

of lower complexity, only global search gives the exact optimum in the general case. However, it is feasible because the number of antennas is in practice reasonably small.

1) Beam Selection (BS):

General (eigen) beam selection is based on the singular value decomposition (SVD) of $\hat{H}_{LI}$.

$$\hat{H}_{LI} = \hat{U}\hat{\Sigma}\hat{V}^H = [\hat{U}_{(1)}\ \hat{U}_{(0)}]\,\hat{\Sigma}\,[\hat{V}_{(1)}\ \hat{V}_{(0)}]^H.$$

in which sub matrices and $\hat{U}_{(0)}$ and $\hat{V}_{(0)}$ contain the basis vectors associated with zero singular values. By choosing beam selection matrices as

$$G_{rx} = \sqrt{\frac{N_{rx}}{\hat{N}_{rx}}} S_{rx}^T \hat{U}^H \text{ and } G_{tx} = \sqrt{\frac{N_{tx}}{\hat{N}_{tx}}} \hat{V} S_{tx}^T$$

the objective is transformed from (18) to $S_{BS} = \frac{N_{rx}}{\hat{N}_{rx}}\frac{N_{tx}}{\hat{N}_{tx}} \min\|S_{rx}^T\hat{H}_{LI}S_{tx}\|_F^2$.

As $\hat{U}^H\hat{U} = I$, $\hat{V}^H\hat{V} = I$ by definition. Filter design becomes conceptually similar to AS, but row and column selection is based on the effective diagonal channel $\hat{\Sigma}$instead of $\hat{H}_{LI}$.

a)Algorithm for optimal joint beam selection:

Design S_{rx}^T and S_{tx} to select $\hat{N}_{rx}$ rows and $\hat{N}_{tx}$ columns of Σ as follows

Step1: Select in total min $\{\hat{N}_{rx}+\hat{N}_{tx}\}$, max $\{\hat{N}_{rx}, \hat{N}_{tx}\}$ rows and columns such that all combinations pick only off-diagonal elements ofΣ. For this sub solution j_{BS}=0.

Step2: To satisfy objectivej_{BS}. Select the rest of the rows and columns such that the final selection matrices pick only the $\hat{N}_{rx}$+ $\hat{N}_{tx}$-max$\{\hat{N}_{rx}, \hat{N}_{tx}\}$ smallest singular values.

2) Null-Space Projection (NSP):

Next develop spatial suppression scheme that can eliminate all loop interference in the ideal case with perfect side information similarly to TDC. The phenomenon is desirable when the loop interference is dominating but AS or general BS does not offer sufficient attenuation.

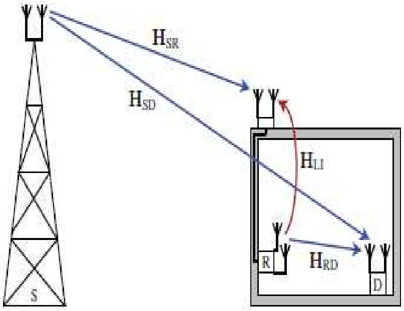

Fig.4: Two-hop full-duplex multi-antenna relay link

In null-space projection, G_{rx} and G_{tx} are selected such that the relay receives and transmits in different subspaces, i.e., transmit beams are projected to the null-space of the loop channel combined with the receive filter and vice versa. The condition can be stated for joint or separate filter design as

$$G_{rx}\hat{H}_{LI}G_{tx}=0\ldots\ldots (9).$$

To eliminate the known part of the first term in (8). Similarly, for suppressing the transmit signal noise, the condition becomes $G_{rx}\hat{H}_{LI} = 0$, partly eliminating the second term in (8).

One solution for joint NSP can be obtained with the optimal joint BS algorithm given in Table I, if , $\hat{N}_{rx}$, $\hat{N}_{tx}$ and rk$\{\hat{H}_{LI}\}$ are low enough w.r.t. N_{rx} *and* N_{tx}. Firstly, a total of max$\{N_{rx}, N_{tx}\}$ beams are selected in Step 1 corresponding to different singular values. Secondly, the last terms in (24) are zero if rk$\{ H_{LI} \}$< min$\{ N_{rx}, N_{tx} \}$. Thus, min$\{ N_{rx}, N_{tx} \} -$ rk$\{ \hat{H}_{LI} \}$ input and output beams may correspond to the same singular values after Step 2 and still , $S_{BS} = 0$ i.e. $S_{rx}^T\hat{H}_{LI}S_{tx}$=0, satisfying also the condition in (26). This proves that the BS algorithm results in null-space projection whenever

$$\hat{N}_{rx} + \hat{N}_{tx} + rk\{\hat{H}_{LI}\} \leq N_{rx} + N_{tx}\ldots\ldots (10).$$

The fallowing condition defines also the general existence of joint NSP, if G_{rx} *and* G_{tx} are additionally constrained to be of full rank. Even if H_{LI} is rank deficient, $\hat{H}_{LI}$ is of full rank in practice due to the estimation noise which also causes residual loop interference. Thereby, the condition in (10) can be alternatively evaluated using the anticipated value of $rk\{H_{LI}\}$based on prior information or by defining $rk\{\hat{H}_{LI}\}$ with a threshold below which the singular values are rounded to zero.

V. SIMULATION RESULTS

In this section, Fig.6 shows bit-error rate (BER) for a specific example setup with a decode-and-forward relay that uses linear zero-forcing detector for independent streams transmitted at different antennas. With proper self-interference mitigation or with large natural isolation, a full-duplex relay link achieves the same BER as its half-duplex counterpart, but offers significantly higher spectral efficiency by forwarding two symbols from the source to the destination within a time interval during which a half duplex relay forwards only one.

We see that interference mitigation manifests itself as a shift in the BER which is referred to as the *isolation improvement* obtained with signal processing w.r.t. natural isolation;

$$\Delta P_I = \frac{P_I|natural}{P_I|man - made}$$

Thus, we can evaluate the performance of the mitigation schemes by studying directly the statistics of $\boldsymbol{\Delta P_I}$ **:** Its cumulative distribution function $F_{\Delta P_I}(.)$ and the average isolation improvement $\varepsilon\{\Delta P_I\}$.

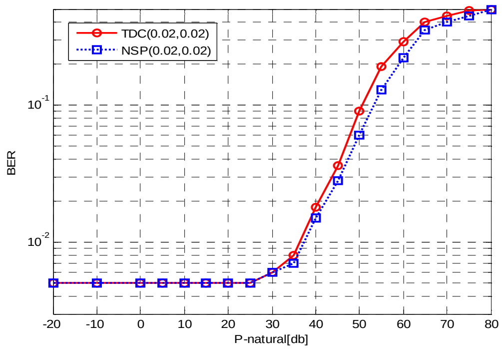

Fig.5: BER of quadrature phase-shift keying at a decode-and-forward relay with zero-forcing when $N_S = N_{rx} = \hat{N}_{rx} = \hat{N}_{tx} = 3$ and rk$\{ H_{LI} \}$=1 desired signal-to-noise ratio (SNR) is 25 dB. We choose $N_{rx} = 3$ for natural isolation and TDC, $N_{rx} = 4$ for beam selection that reduces to NSP.

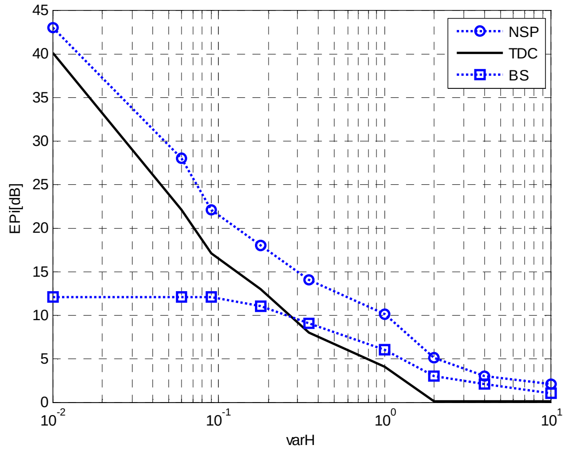

Fig.6: Average Isolation Improvement Vs Channel Estimation Noise

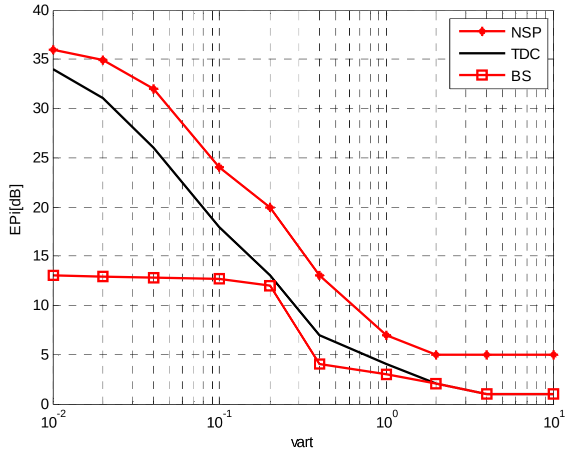

Fig.7: Average Isolation Improvement Vs Transmit Signal Noise

VI. CONCLUSION

Full-duplex MIMO relaying has large potential for spectrally efficient wireless transmission. In this paper, we concentrated on solving the main associated technical problem, i.e., the mitigation of relay self-interference. We extended the earlier SISO cancellation schemes for the MIMO relay case and proposed new solutions: null-space projection and beam selection that suppress the interference in the spatial domain. From above figures it can be noticed that when compared Time domain cancellation, proposed methods are better where it de noises proposed methods BER is lower than the Time domain cancellation. Signal distribution function is better in Null-space projection and beam selection when compared to time domain cancellation.

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