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Cognitive with Two-Path MIMO System Relaying

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ABSTRACT

In this paper, a MIMO Cognitive Radio system using two-path relaying with amplify and forward protocol is investigated. The Cognitive Radio system, the primary user (PU) transmitter cooperates with the secondary user (SU) transmitter and receiver to send the PU data to the PU destination. All the nodes are equipped with multiple antennas. The investigated cognitive radio system is different from the conventional one in such a way, it uses the inter-relay interference (IRI) between the two relays to transmit SU data and minimize IRI effect on the PU destination. Two different techniques are used to detect the data in the destination which are Full Interference Cancellation and Zero Forcing techniques. Computer Simulations are used to evaluate the performance of the system. The performance is measured in terms of bit error rate. The effect of channel estimation error on the BER performance is also studied.

Keywords:
Cooperative communications, wireless communication, relaying system, amplify and forward, MIMO, cognitive radio.

1. Introduction

Two-path relaying architecture is considered as one of the techniques that help in improving the spectral efficiency, performance and reliability of cooperative networks. It has also shown a high and satisfactory performance in mitigating the interference that occurs in wireless systems such as the inter-relay interference (IRI) [1].

The spatial diversity is considered as the cornerstone of two path relaying architecture. It can be achieved in multiple input multiple output (MIMO) systems by sending the same information across multiple, independent fading channels to reduce the fading factor. When multiple copies of the same data are sent across independently fading channels, the amount of fade suffered by each copy will be different. This is done to guarantee that at-least one of the copies will suffer less fading compared to the rest of the copies. Thus, the chance of properly receiving the transmitted data correctly increases. Consequently, this improves the reliability of the entire system and most importantly reduces the co-channel interference significantly.

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The use of two path relaying has attracted much interest where the author in [2] used the two-path relay technique in order to send data from the source to the destination, with either amplify and forward (AF) or decode and forward (DF) as the relaying protocol. The author in [3] applied successive interference cancellation (IC) in two path relaying in order to mitigate the inter-relay interference. The IC is performed at the relay when the IRI is much stronger than the channel gain from the source to the relay. The author in [4] and [5] used the Dirty Paper Coding (DPC) technique which is based upon the interference pre-subtraction at the source in order to solve the inter-relay interference problem. The full knowledge of all channel state information (CSI) is a perquisite for the DPC which makes it really complex to apply in practice. Moreover, for the sake of avoiding spectrum scarcity, cognitive radio (CR) was employed a long time ago. Accordingly, the author in [6] applied cooperative relaying in CR systems, where a secondary user (SU) is used as a relay for the primary user (PU). This is done so that the (SU) can either amplify and forward (AF) or decode and forward (DF) the data sent from the (PU) in exchange of being allowed by the (PU) to accommodate a time slot where the (SU) can transmit its data in CR mode.

The paper investigates the MIMO cognitive radio system where the PU's transmitter cooperates with the SU's transmitter and receiver in order to send the PU's data to its destination. This is done in order for the SU to transmit its data and simultaneously minimize the IRI effect on the PU's data. The used detection techniques are the full interference cancellation (FIC) detection technique and zero forcing (ZF) detection technique [7]. The performance is measured in terms of the bit error rate for the two algorithms.

2. System Model

The employed system model is shown in Figure 1, and it consists of the transmitter of primary user's (PU Tx) as the source (S) while the destination (D) is the receiver of the primary user's (PU Rx) and an additional two relays ($\mathrm{R_Q}$,R_Z). $\mathrm{R_Q}$ is the receiver for the secondary user's (SU Rx) where it amplifies and forward the data it receives while R_Z functions as the transmitter of the secondary user's (SU Tx) that sends the secondary user's data as well as amplifying the data that it receives. The transmission of data across the system model is explained very abstractly and will be explained in details later during the description of detection techniques.

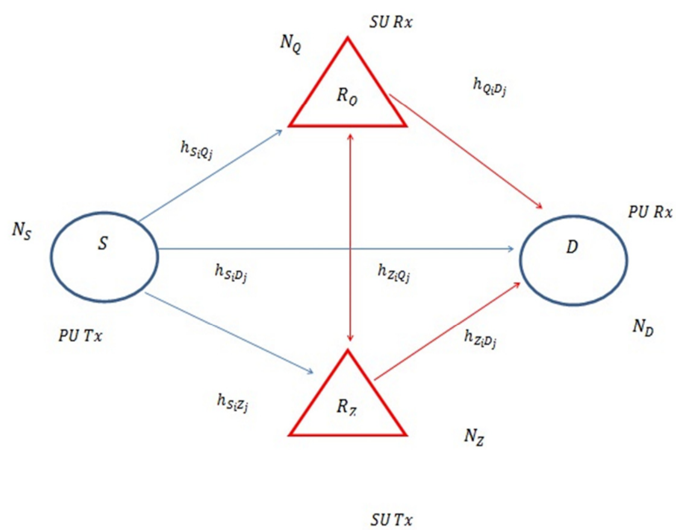

Fig. 1. System model

The source (S) transmits its data to the destination (D) through the direct link and to one of the relays, either R_Q or R_Z , per time slot. The relays transmit the received data from previous time slots between each other and to the destination as well. The number of antennas in the source, the destination and relays R_Q and R_Z varies from $1 \leq N \leq 5$. As shown in Figure 1, the received signal at relay R_Q from the source and relay R_Z is given by $\boldsymbol{Y_q}$:

$$\boldsymbol{Y_q(t) = s(t)H_{sq} + x(t)H_{zq} + w(t)} \tag{1}$$

Where $\boldsymbol{s(t)}$ is the transmitted signal from (S) and $\boldsymbol{x(t)}$ is the transmitted signal from the relay R_Z. The channel gains between S and R_Q is denoted by $\boldsymbol{H_{sq}}$ with an average channel gain of V_S^2. The channel gains between R_Z and R_Q is represented in the channel matrix that is denoted by $\boldsymbol{H_{zq}}$ with an average channel gain of V_r^2. $\boldsymbol{w(t)}$ is the AWGN experienced by the transmitted data with zero-mean and variance σ^2.

The received signal at destination from the source and relay R_Q is given by $\boldsymbol{Y_d}$:

$$\boldsymbol{Y_d(t) = s(t)H_{sd} + x(t)H_{zd} + w(t)} \tag{2}$$

The channel gains between S and D , R_Z and D are represented in the channel matrix that is denoted by $\boldsymbol{H_{sd}}$ and $\boldsymbol{H_{zd}}$ respectively with an average channel gain of V_S^2 and V_d^2. For notational simplicity, all the channels are assumed to be independent and identically distributed (i.i.d) flat Rayleigh fading channels. AF protocol is applied by both relays since it is less complex and more flexible in handling IRI than DF protocol [6].

3. Mathematical Formulation of MIMO Cognitive Radio System with Two Path Relaying

The cognitive radio technique that is used in two path relaying systems achieves spatial diversity as well as resolving the problem of spectrum underutilization when the primary user is not utilizing the spectrum and therefore the secondary user gets the opportunity to utilize it. In addition, cognitive radio overcomes the spectrum scarcity problem in which the primary user allows the secondary user to share the same bandwidth to send its data. In return the secondary user sends the primary user data at the same time [9-10].

As shown in figure 1, the S and D represent the PU network while R_Q and R_Z represent the SU network. R_Q and R_Z use amplify and forward technique in order to relay the data that is being sent by the PU. As a reward, the PU allows the SU to transmit their data simultaneously. The transmission is in the form of two PU symbols and one SU symbol along three time slots.

In the first time slot as per figure 2, PU transmitter transmits the subtraction of two successive modulated signals which are denoted by s_1 and s_2 directly to PU receiver with a total power of P_s over N antennas. The channels' gains experienced by these bits are denoted by $\boldsymbol{H_{sd}}$. At the same time, SU transmits its data b_1 to the destination of PU with power P_Z over N antennas. Similarly, the channels' gains experienced by these bits are denoted by $\boldsymbol{H_{zd}}$. The AWGN experienced during this time slot by all the transmitted bits is represented by $\boldsymbol{w_d^1}$ and $\boldsymbol{w_q^1}$, where the superscript (1) represents the first time slot.

The received signals for the first time slot at D and R_Q respectively given by:

$$\boldsymbol{y_D^1} = \sqrt{\frac{P_S}{2}}\, \boldsymbol{H_{sd}}\, (\boldsymbol{s_1} - \boldsymbol{s_2}) + \sqrt{P_Z}\, \boldsymbol{H_{zd}}\, \boldsymbol{b_1} + \boldsymbol{w_d^1} \tag{3}$$

$$\boldsymbol{y}_{\boldsymbol{Q}}^{\mathbf{1}} = \sqrt{\frac{P_S}{2}}\, \boldsymbol{H}_{\boldsymbol{sq}}\, (\boldsymbol{s}_{\mathbf{1}} - \boldsymbol{s}_{\mathbf{2}}) + \sqrt{P_Z}\, \boldsymbol{H}_{\boldsymbol{zq}}\, \boldsymbol{b}_{\mathbf{1}} + \boldsymbol{w}_{\boldsymbol{q}}^{\mathbf{1}} \tag{4}$$

where in general the channel matrix is given as:

$$\mathbf{H}_{xy} = \begin{bmatrix} h_{x_1y_1} & h_{x_1y_2} & .. & .. & .. & h_{x_1y_N} \\ h_{x_2y_1} & h_{x_2y_2} & .. & .. & .. & h_{x_2y_N} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ h_{x_Ny_1} & h_{x_Ny_2} & .. & .. & .. & h_{x_Ny_N} \end{bmatrix} \tag{5}$$

where $h_{x_1y_1}$ represents the channel gain from the transmitter to the receiver

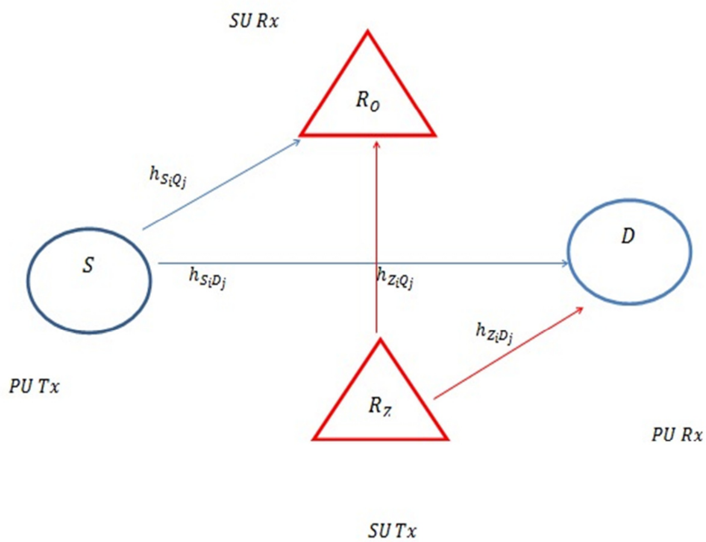

Fig. 2. First Time Slot Model

In the second time slot as per figure 3, PU transmitter transmits the second symbol S_2 with a total power of P_s to SU transmitter and PU receiver, while SU receiver transmits the previous received data to both R_Q and PU receiver after applying AF protocol. The noise vectors during this time slot are represented by $\boldsymbol{w}_{\boldsymbol{d}}^{\mathbf{2}}$ and $\boldsymbol{w}_{\boldsymbol{q}}^{\mathbf{2}}$**.** Assuming SU Rx retransmits the data with power P_{R_Q}, where the normalized amplification factor is defined as,

$$g_q^2 = \frac{P_Q}{E\left|\boldsymbol{y}_{\boldsymbol{Q}}^{\mathbf{1}}\right|^2} = \frac{P_Q}{V_S^2 P_S + V_R^2 P_Z + \sigma^2}. \tag{6}$$

The received signals at D and R_Z during the second time slot are given by:

$$\boldsymbol{y}_{\boldsymbol{D}}^{\mathbf{2}} = \sqrt{P_s}\, \boldsymbol{H}_{\boldsymbol{sd}}\, \boldsymbol{s}_{\mathbf{2}} + \boldsymbol{H}_{\boldsymbol{qd}}\, g_q \boldsymbol{y}_{\boldsymbol{Q}}^{\mathbf{1}} + \boldsymbol{w}_{\boldsymbol{d}}^{\mathbf{2}} \tag{7}$$

$$\boldsymbol{y_Z^2} = \sqrt{P_s}\,\boldsymbol{H_{sz}}\,\boldsymbol{s_2} + \boldsymbol{H_{qz}}\,g_q\,\boldsymbol{y_Q^1} + \boldsymbol{w_z^2} \tag{8}$$

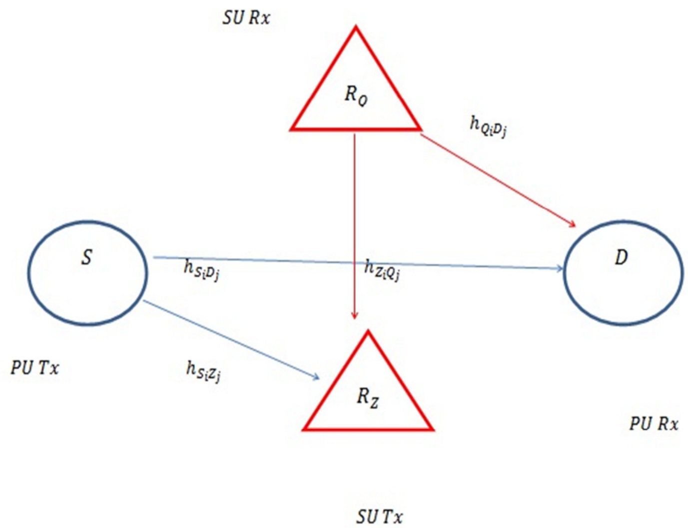

Fig. 3. Second Time Slot Model

During the third time slot as per figure 4, PU Tx is quiet while SU Tx transmits the received signal after removing the interfered SU data b_1 and adding a new fresh version of it but with negative sign, i.e. $-b_1$ with power P_Z.The received signals at D and R_Q during the third time slot are respectively given by:

$$\boldsymbol{y_D^3} = \boldsymbol{H_{zd}}\,g_z(\boldsymbol{y_Z^2} - \boldsymbol{b_{11}}) - \sqrt{P_Z}\boldsymbol{H_{zd}}\boldsymbol{b_1} + \boldsymbol{w_d^3} \tag{9}$$

$$\boldsymbol{y_Q^3} = \boldsymbol{H_{zq}}\,g_z\,(\boldsymbol{y_Z^2} - \boldsymbol{b_{11}}) - \sqrt{P_Z}\boldsymbol{H_{zq}}\boldsymbol{b_1} + \boldsymbol{w_q^3} \tag{10}$$

where $\boldsymbol{b_{11}}$ is the modified image of SU data ***b1*** such that:

$$\boldsymbol{b_{11}} = \boldsymbol{H_{qz}}\boldsymbol{H_{zq}}\boldsymbol{b_1}g_q \tag{11}$$

Assuming that $R_Z$retransmits the data with power P_{R_Z}, and then the normalized amplification factor is defined as

$$g_Z^2 = \frac{P_Z}{E|\boldsymbol{y_Z^2}|^2} = \frac{P_Z}{V_S^2P_S+V_R^2P_S+\sigma^2} \tag{12}$$

The above equations for the three time slots at the destination can be combined as follows:

$$\boldsymbol{y_D} = \boldsymbol{H_D}\boldsymbol{x_S} + \boldsymbol{w_D} \tag{13}$$

where

$$\boldsymbol{y_D} = [\boldsymbol{y_D^1}, \boldsymbol{y_D^2}, \boldsymbol{y_D^3}],\ \boldsymbol{x_S} = \left[\sqrt{P_S}\,\boldsymbol{S_1}, \sqrt{P_S}\boldsymbol{S_2}, \sqrt{P_B}\,\boldsymbol{b_1}\right]^T \tag{14}$$

$$\boldsymbol{H_D} = \begin{bmatrix} \sqrt{\frac{1}{2}}\boldsymbol{H_{sd}} & -\sqrt{\frac{1}{2}}\boldsymbol{H_{sd}} & \boldsymbol{H_{zd}} \\ \sqrt{\frac{1}{2}}\boldsymbol{H_{qd}}g_q\boldsymbol{H_{sq}} & \boldsymbol{H_{sd}} - \sqrt{\frac{1}{2}}\boldsymbol{H_{qd}}g_a\boldsymbol{H_{sq}} & \boldsymbol{H_{qd}}g_q\boldsymbol{H_{zq}} \\ \sqrt{\frac{1}{2}}\boldsymbol{H_{zd}}g_z\boldsymbol{H_{qz}}g_q\boldsymbol{H_{sq}} & \boldsymbol{H_{zd}}g_z\boldsymbol{H_{sz}} - \sqrt{\frac{1}{2}}\boldsymbol{H_{zd}}g_z\boldsymbol{H_{qz}}g_q\boldsymbol{H_{sq}} & -\boldsymbol{H_{zd}} \end{bmatrix} \tag{15}$$

The noise vector at the destination is given by:

$$\boldsymbol{w_D} = \begin{bmatrix} \boldsymbol{w_d^1} \\ \boldsymbol{w_d^2} + g_q\boldsymbol{H_{q_i d_j}}\boldsymbol{w_q^1} \\ \boldsymbol{w_d^3} + \boldsymbol{H_{z_i d_j}}\, g_z(\boldsymbol{w_z^2} + \boldsymbol{H_{q_i z_j}}\boldsymbol{g_q}\boldsymbol{w_q^1}) \end{bmatrix} \tag{16}$$

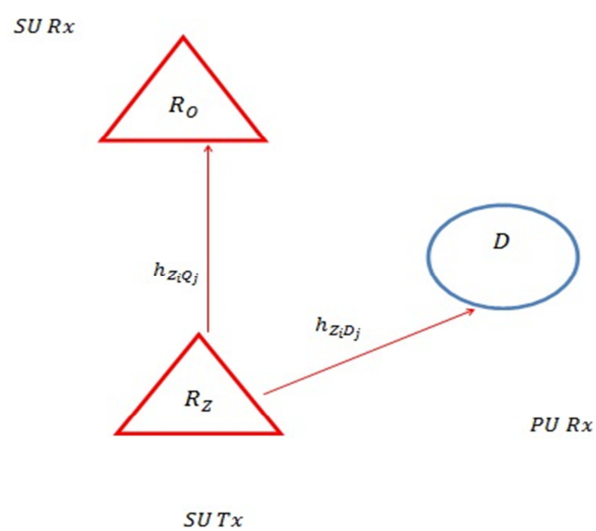

Fig. 4. Third Time Slot Model

4. Full- Interference Cancellation (FIC) for the Cognitive MIMO System

The FIC algorithm is considered as one of the efficient algorithm that can be used to cancel the inter-relay interference that occurs between the relays.

The performance of the implemented system may get enormously affected by the IRI especially in cases like simultaneous data transmission between the source and the relays. In FIC algorithm, S sends data to both D and SU receiver at the odd time slots and at the same time SU transmitter amplifies and sends the received data from S to D and SU receiver at the (n-1) slot. Moreover, since the relay receives data from both the source and the other relay; this forms the IRI between the relays which is transferred to the destination. The IRI is treated as noise since it alters the value of the transmitted bits and degrades the performance of the system. The removal of the IRI is done at the destination; however this can be done at the relays too. In FIC algorithm, the destination is able to remove the IRI factor since it is represented as a single iterative term in the received signal. Thus, the IRI cancellation will only require storing one previous received signal sample. The timeslots are divided as odd and even ones where the received signal at the destination is given by:

$$\boldsymbol{y_d(n) = H_{sd}x_s(n) + H_{zd}\, g_z\left(H_{sz} - H_{qz}H_{sd}H_{qd}^{-1}\right)x_S(n-1) + H_{sz}g_z H_{qz}H_{qd}^{-1}y_d(n-1) + w'(\mathrm{n})} \tag{17}$$

where

$$\boldsymbol{y_d(n-1) = H_{sd}x_s(n-1) + H_{zd}x_z(n-1) + w_d(n-1)} \tag{18}$$

This is the received signal at the destination in the previous time slot which is part of that third term that expresses the IRI which is transferred to the destination and the last term represents the noise. While for the $\boldsymbol{y_d(n)}$, the first term on the right hand side (R.H.S) of the equation represents the transmitted symbols from the source while the second term on R.H.S represents the transmitted symbols from the relays that were sent by the source at the previous timeslot. In addition, the channel matrices are represented by the general matrix in (3.5). The noise is given by

$$\boldsymbol{w'}(\mathbf{n}) = \boldsymbol{H_{zd}}\, g_z w_Z(n-1) - \boldsymbol{H_{sz}}g_z\boldsymbol{H_{qz}H_{qd}^{-1}}\, w_d(n-1) + \boldsymbol{w_d(n)} \tag{19}$$

where $w_d(n)$ and $w_z(n)$ are the Gaussian noise at the destination and R_Z respectively. Moreover, g_z is the amplification factor at R_Z and it is given by

$$g_z^2 = \frac{P_S}{v_S^2\, P_S + v_{qz}^2\, P_S + \sigma^2} \tag{20}$$

The IRI is removed by subtraction at the destination, where the received signal at the odd slot is given by:

$$\boldsymbol{y_d(n) = H_{sd}x_s(n) + H_{zd}\, g_z\left(H_{sz} - H_{qz}H_{sd}H_{qz}^{-1}\right)x_S(n-1) + w'(n)} \tag{21}$$

While the received signal at an even slot will be given as:

$$\boldsymbol{y_d(n) = H_{sd}x_s(n) + H_{qd}\, g_q\left(H_{sq} - H_{qz}H_{sd}H_{zd}^{-1}\right)x_S(n-1) + w'(n)} \tag{22}$$

g_q is the amplification factor at R_Q where it is represented as given

$$g_q^2 = \frac{P_S}{v_S^2\, P_S + v_{qz}^2\, P_S + \sigma^2} \tag{23}$$

Two techniques can be used for detection which is forward detection and backward detection. The description of both of them as follows:

A. Forward Detection

1- At n=1, we will let $\boldsymbol{y^f(1) = y_d(1)}$ and the forward data detection $\boldsymbol{x_s^f(1)}$ is the hard decision of $\boldsymbol{y^f(1)\, H_{sd}^{-1}}$

2- At n=2, the signal sample from the direct link can be separated as $\boldsymbol{y^f(2) = y_d(2) - H_{qd}\, g_q\left(H_{sq} - H_{qz}H_{sd}H_{zd}^{-1}\right)x_s^f(1)}$ and the data detection for $\boldsymbol{x_s^f(2)}$ is the hard decision of $\boldsymbol{y^f(2)\, H_{sd}^{-1}}$

3- Step number 2 is repeated for N signal samples

B. Backward Detection

1- At n=N+1 , let $\boldsymbol{y^b(N)} = \boldsymbol{y'_d(N+1)}$ with backward data detection $\boldsymbol{x_s^b(N)}$ is the hard decision of $\boldsymbol{y^b(N)}\left(\boldsymbol{H_{zd}}\, g_z\left(\boldsymbol{H_{sz}} - \boldsymbol{H_{qz}H_{sd}\,H_{qd}^{-1}}\right)\right)^{-1}$

2- Then back to n=N, the signal sample transmitted from the relay links can be separated from $\boldsymbol{y'_d(N)}$ as $\boldsymbol{y^b(N-1)} = \boldsymbol{y'_d(N)\,H_{sd}\,x_s^b(N)}$. The data detection $\boldsymbol{x_s^b(N-1)}$ is the hard decision of $\boldsymbol{y^b(N-1)H_{qd}}\, g_q\left(\boldsymbol{H_{sq}} - \boldsymbol{H_{qz}H_{sd}H_{zd}^{-1}}\right)^{-1}$

3- Step number 2 is repeated for N signal samples.

5. Zero-Forcing Algorithm (ZF) for MIMO System

The Zero-Forcing (ZF) algorithm is one of the most used detection techniques in MIMO systems since it is less complex in implementation and its performance is better compared to the FIC. In ZF, the MIMO channel at the destination is inverted in order to totally minimize the interference from the other transmitted signals assuming that the MIMO channel is known to the receiver. Moreover, at the destination linear signal detection is used in order to get the desired transmitted signal. Maximum Ratio Combining (MRC) is used at the destination where the interference signal from other antennas is minimized through a weight matrix.

Equalization method treats all transmitted signals as interferences except for the desired stream from the target transmit antenna. Therefore, interference signals from other transmit antennas are minimized or nullified in the course of detecting the desired signal from the target transmit antenna [10].

To facilitate the detection of desired signals from each antenna, the effect of the channel is inverted by a weight matrix where in our case the zero-forcing (ZF) technique nullifies the interference by the following weight matrix:

$$\boldsymbol{x} = \boldsymbol{H_D^{-1}y_D} \tag{24}$$

where $\boldsymbol{y_D}$ is given by (13) and $\boldsymbol{H_D}$ is given by (15)

6. Simulations and Results

In this section, numerical results are used to evaluate the performance of the detection algorithms with two path relaying architecture in a MIMO system considering a Rayleigh fading environment. The performance is measured in terms of the bit error rate (BER) versus signal to noise ratio (SNR). The results are obtained using MATLAB software for known channel parameters. The effect of channel estimation error is also investigated. The simulation parameters are as follows; the number of bits is N=10,000 the type of modulation is QPSK and the number of relays is two. Amplify and Forward relaying protocol is used. The performances of FIC and ZF are evaluated and compared.

Figure 5 shows BER performance of FIC algorithm for the MIMO Cognitive system. When the number of antennas increase overall system components denoted as N, e.g. $1 \leq N \leq 5$, this resulted in better detection of the data. A number of copies of the same data are transmitted but each copy got affected by noise differently. Therefore, this guarantees that at-least one of the copies is less affected by noise than the others. Therefore, the chance of properly receiving the transmitted data increases. It is also shown that, when the number of antennas equals 5, the improvement in BER isn't significant compared to the other cases. Therefore, using 4 antennas is sufficient to achieve adequate performance and on the other side, reduce the cost.

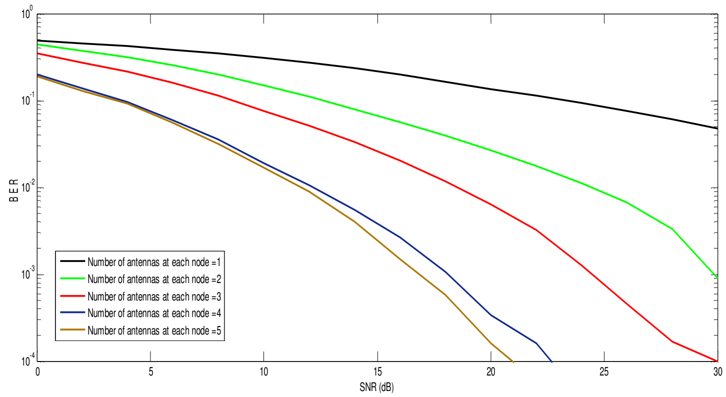

Fig. 1. BER performance of FIC with different number of antennas at the source, destination and both relays

Figure 6 shows the BER performance of the ZF algorithm in a MIMO system. Here, we assume equal number of antennas, denoted as N, where $1 \leq N \leq 5$, over all four system nodes of the system. The figure shows that as the number of antennas increases at source, destination and both relays, better BER performance is achieved. This is because the number of copies of the same data is received with different noise effect.

For comparison purposes, we include the maximum likelihood detection (MLD) algorithm which calculates the minimum Euclidian distance to detect the signal. In our case, the Euclidian distance is given by $||\boldsymbol{y_D} - \boldsymbol{H_D}\boldsymbol{x_s}||^2$where $\boldsymbol{y_D}$ is given by (13) and $\boldsymbol{H_D}$ is given by (15). It is noted that MLD is considered as the best performance in terms of minimizing the probability of error compared to the FIC and ZF. This is clear from Figure 7 which plots the BER performance of the three detection algorithm when three antennas is used. On the other hand, MLD is considered as the one with the most computational complexity. Moreover, ZF is practically simpler than the FIC in the implementation phase and it is more efficient also in terms of performance where the probability of error is minimized compared to the FIC.

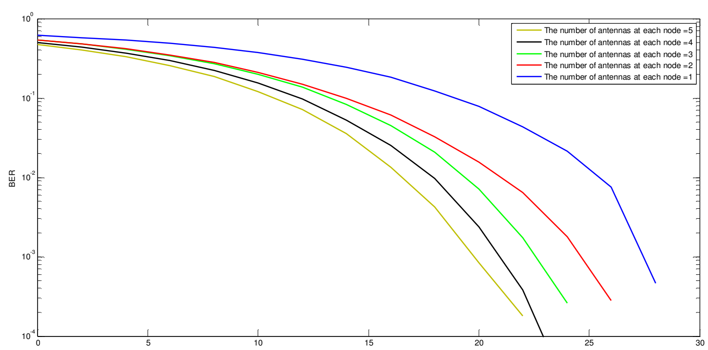

Fig. 2. BER performance of ZF with different number of antennas at the source, destination and both relays

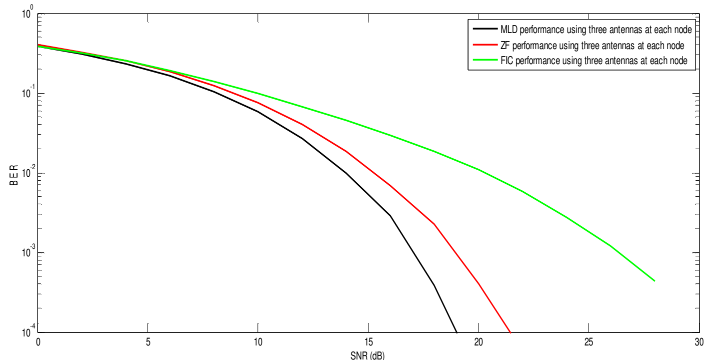

Fig. 3. BER performance of the FIC and ZF with three antennas in use at the source, destination and each relay

Finally, the effect of channel estimation error is investigated. In practice, most of the existing work assumes that the source and the destination can obtain the perfect Channel State Information (CSI) of the channel. However, such an assumption is not practical in wireless communication. If the channel state information is unknown to the receiver and channel estimation algorithms are used. Then the effect of channel estimation error can be represented as a random variable drawn from Gaussian distribution that can be modelled as: $\hat{h} = h + e$; where h is the channel gain from the source to the destination. While e denotes the channel estimation errors. For simplicity, let $[|e|^2] = \sigma_E^2$, a parameter which reflects the accuracy of channel estimation. Figure 8 shows a comparison between the performance of the FIC with variance of 0.2 and 0.4 compared with performance of the FIC without channel estimation error. Figure 9 shows a comparison between the performance of the ZF with variance of 0.2 and 0.4 compared with performance of the ZF without channel estimation error. It is concluded through the figures that the performance is much better without channel estimation error.

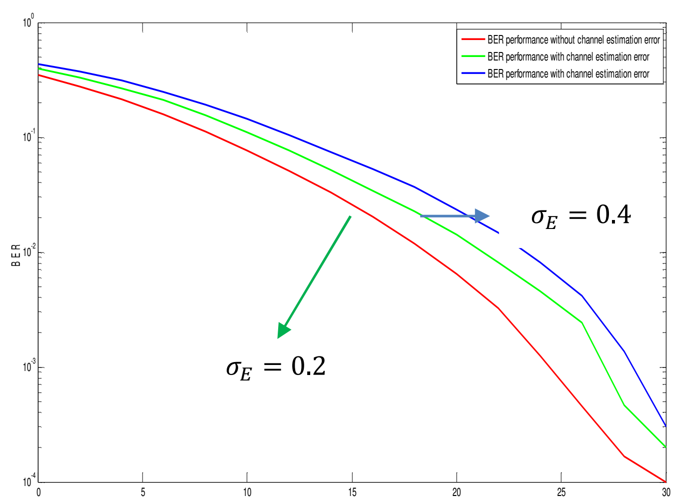

Fig. 4. Comparison in BER performance of FIC with channel estimation error and without channel estimation error

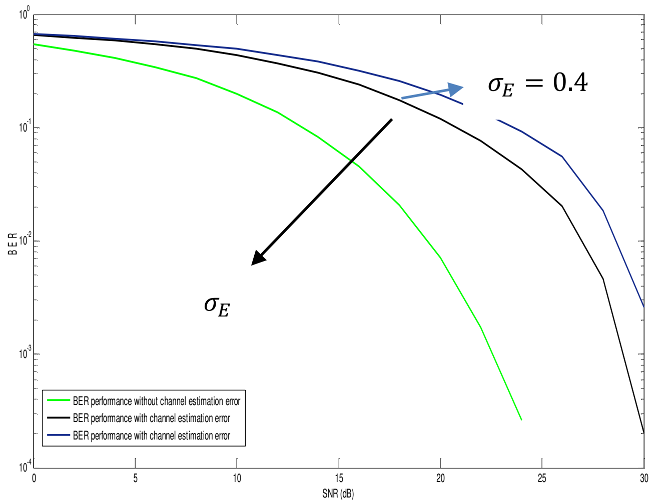

Fig. 5. Comparison in BER performance of ZF with channel estimation error and without channel estimation error

7. Conclusion

Two detection algorithms for cognitive radio employing two-path amplify and forward relaying has been implemented for MIMO cognitive radio system with AF two path relaying. These algorithms are ZF and FIC algorithms and are able to minimize the inter-relay interference on the primary user (PU) Rx as well as allowing the secondary user (SU) to cooperate with the primary user to send its data and in return the secondary user shares the available bandwidth. This achieves bandwidth efficiency since there is no need for additional bandwidth for the secondary user to transmit its data. The results show that ZF has better performance than FIC algorithm. Furthermore, when the number of antennas increases, the BER performance enhanced but if it increases to five, there is no much enhancement in the BER performance. Therefore, using four antennas in the MIMO system is sufficient since adding more antennas will be costly and does not add significant performance. Finally, the effect of channel estimation error has been investigated and it was concluded that the performance without channel estimation error is better than using channel estimation error.

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