Performance Evaluation of Distributed STBC in Wireless Relay Networks With Imperfect CSI

Wael Jaafar  
École Polytechnique de Montréal  
Department of Electrical Engineering  
Montreal, Quebec

Wessam Ajib  
Université du Québec à Montréal  
Department of Computer Science  
Montreal, Quebec

David Haccoun  
École Polytechnique de Montréal  
Department of Electrical Engineering  
Montreal, Quebec

Abstract—It has been shown that cooperative communication techniques have a great potential to increase the diversity in wireless relay networks and hence improve the Bit Error Rate (BER). When exploiting many users as relay nodes, a multi-antenna network called virtual-MIMO (Multiple Input Multiple Output) is set up. This special technique helps to solve the problem of transmission error occurrences when sending information through a low quality radio channel. Consequently, the transmission gets a better reliability and higher transmission rate.

In this work, we focus on the distributed Space-Time-Block-Coding (STBC) with Amplify-and-Forward (AF) and Decode-and-Forward (DF) relays, for various network configurations and channel knowledge conditions. We investigate and evaluate the performance - in term of BER - of a cooperative communication system using multiple relays equipped with multiple antennas when STBC coding is employed at the relays with AF (or DF) relaying. Also, we examine the behavior of these cooperative communication techniques when the Channel State Information (CSI) available at the receivers is imperfect.

I. INTRODUCTION

The new concept of multiple-input-multiple-output (MIMO) [1]-[3] systems is widely accepted as one of the most interesting advances at the physical layer of wireless systems. In a MIMO system, the signals are mapped to multiple antennas in a manner to obtain a spatial multiplexing gain and improve the transmission rate or obtain a diversity gain by means of Space-Time-Coding (STC), and thus improve the communication reliability. However, these gains are obtained at the cost of multiple RF front ends at the source and destination nodes whereas the size of mobile handsets cannot always allow the deployment of multiple antennas. In order to exploit the potential of MIMO technology on small-size wireless equipments, cooperative communication has become an attractive technique to extract MIMO gains by creating a virtual distributed MIMO systems. In cooperative communication [4], distributed nodes act jointly to transmit the data through the radio medium.

A growing interest on cooperative communication had led to the development of many transmission techniques. The authors of [5] proposed a variety of low-complexity cooperative protocols for a pair of relays network. They investigated the outage behavior of these protocols underlining the power and bandwidth costs associated. In [6], the authors implemented the rate-1/2 orthogonal STBC (Alamouti Code) in wireless relay networks. Their simulation results have shown that the diversity factor is around $R=2$, for very large values of $R$, where $R$ is the transmission rate. In [7], the authors proposed new designs of distributed STBC (DSTBC) from Orthogonal and Quasi-Orthogonal designs for wireless relay networks. They showed that such designs implemented on AF relays achieve higher diversity than selection DF with multiple relays. The diversity theoretical analysis for the DSTBC when the relays exploit the AF transmission technique has been detailed in [8]. The authors of [9] demonstrated that the performance of DSTBC in wireless relay networks still achieves performance improvement in correlated fading channels.

In this paper, we investigate the performance of a cooperative communication system based on multiple relays. All the relays are equipped with multiple antennas and exploit Distributed Space-Time-Block-Coding with AF or DF relaying technique. We consider different network configurations with different number of antennas at the relays and different number of relays in each configuration. We, then, study the effect of imperfect CSI at the receivers on the cooperative communication system reliability. We consider distinctively imperfect CSI available at the relays and imperfect CSI available at the destination node.

The rest of the paper is organized as follows. In the next section, we detail the considered system model. Section III presents our model analysis of the DSTBC multiple relays with multiple antennas cooperative communication when AF or DF relaying technique is employed. In section IV, we adapt the model for the case where imperfect CSI is available at the receivers. Section V presents and interprets the simulation results. Finally, a general conclusion closes the paper.

II. SYSTEM MODEL

A. Network Model

We assume a network composed of one single-antenna source node, $K$ relay nodes and one destination node with $L_d$ antennas. The $k^{th}$ relay has $M_k$ antennas ($k = 1, \ldots, K$). The total number of antennas of all relays is $L = \sum_{k=1}^{K} M_k$. We assume $L_d \geq L$. The relays do not provide additional traffic and the nodes are assumed “half-duplex”.

A cooperative communication is executed during two equal transmission phases. During the first phase, called “Broadcast Phase”, the source sends $T$ unprotected symbols over $T$ time periods. The relays amplify or decode (depending on the
transmission technique) the received symbols and enter into the second phase. In the “Relay phase”, the relays transmit simultaneously the received symbols using a STBC. We assume perfect synchronization between the relays. In our model, the network requires at least one relay as we assume that the direct link source-destination is always corrupted. Examples of network configurations are presented in table I.

### Table I

<table>
<thead>
<tr>
<th>Network Configuration</th>
<th>Number of relays</th>
<th>Number of antennas at each relay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Config. 1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Config. 2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Config. 3</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

**B. Channel Model**

We assume stationary terminals and quasi-static channel conditions for the entire transmission period. We assume flat fading Rayleigh wireless channels with independent identically distributed (i.i.d.) zero mean complex Gaussian distributed random variables, circularly symmetric with unit variance.

We assume the channel is unknown at the transmitters. In AF, the destination has CSI of all the channels. Whereas, in DF, the destination has CSI of the relays-destination channels only and each relay has the CSI of its source-relay channel.

The transmit power should be the same over the two phases in order to maximize the expected receive SNR [8]. Accordingly, we consider the same transmit power (denoted \( \eta \)) during the broadcast and the relay phases. We also assume that the transmit power of each relay is proportional to its number of antennas and thus the transmit power of the \( k \)th relay is \( \eta M_k/L \). Since Orthogonal or Quasi-Orthogonal STBC (OSTBC or QOSTBC) is used, we assume that each relay knows the code matrices to be applied during the relay phase.

During the broadcast phase, the matrix of signals received at the \( k \)th relay, \( R^k \) (whose size is \( M_k \times T \)), can be given by:

\[
R^k = \sqrt{\eta T} h^s,k s + N^s,k, \quad k = 1, \ldots, K
\]

where \( h^s,k \) is a \( M_k \times 1 \) vector of the source-\( k \)th relay channel coefficients, \( s \) is a \( 1 \times T \) vector of the transmitted symbols and \( N^s,k \) is the \( M_k \times T \) matrix of an additive white gaussian noise (AWGN) with zero mean and covariance matrix \( E\{N^s,k \} = N_0 I_{M_k} \) (the notation \( E\{\cdot\} \) denotes the expectation and \( I_{M_k} \) denotes the \( M_k \times M_k \) identity matrix). We denote \( A^i, A^*, A \) and \( ||A||_F \), the transpose, the conjugate transpose, the conjugate and the Frobenius norm of a complex matrix \( A \), respectively. We have: \( s = [s_1 \ldots s_T]' \),

\[
h^s,k = \begin{bmatrix} h^s,k_1 \\ \vdots \\ h^s,k_{M_k} \end{bmatrix}, \quad N^s,k = \begin{bmatrix} n^s,k_1 \\ \vdots \\ n^s,k_{M_k} \end{bmatrix} \quad \text{and} \quad R^k = \begin{bmatrix} r^k_1 \\ \vdots \\ r^k_{M_k} \end{bmatrix}
\]

The vector \( r^k_i \) (\( k = 1, \ldots, K, i = 1, \ldots, M_k \)) contains the received symbols at the \( i \)th antenna of the \( k \)th relay, and it can be expressed as follows,

\[
r^k_i = \sqrt{\eta T} h^s,k_i s + n^s,k_i.
\]

The next section details the model analysis of the relay phase for AF and DF relaying techniques.

**III. ANALYSIS OF DSTBC MULTIPLE ANTENNAS COOPERATIVE NETWORK MODEL**

**A. Amplify-and-Forward Relaying**

In the relay phase, the \( M_k \times T \) matrix of signals sent by the \( k \)th relay is given by:

\[
X^k = \begin{bmatrix} x^k_1 \\ \vdots \\ x^k_{M_k} \end{bmatrix} \quad \text{with} \quad x^k_i = \sqrt{\eta/L} \left( r^k_i A^k_i + r^k_i B^k_i \right),
\]

where \( A^k_i \) and \( B^k_i \), of dimensions \( T \times T \), are the STBC matrices associated to the \( i \)th antenna of the \( k \)th relay, \( \forall i = 1, \ldots, M_k \) and \( k = 1, \ldots, K \). Combining (2) and (3), we obtain:

\[
x^k_i = \sqrt{\eta/L} \left( h^s,k_i s^k A^k_i + h^s,k_i s^k B^k_i \right) + \sqrt{\eta/L} \left( n^s,k_i A^k_i + n^s,k_i B^k_i \right).
\]

Since we are assuming OSTBC or QOSTBC, we have two possible cases. The first one is \( A^k_i = 0 \) and \( B^k_i = 0 \) (i.e., the \( i \)th column of the code’s matrix of the \( k \)th relay has only conjugate symbols \( s_i, \ldots, s_T \)). The second case consists of \( A^k_i \neq 0 \) and \( B^k_i = 0 \) (i.e., the \( i \)th column of the code’s matrix of the \( k \)th relay has only symbols \( s_i, \ldots, s_T \)). We define:

1st case: \( \hat{x}^k = A^k_i \hat{s}^k \), \( \hat{s}^k = h^s,k_i s^k \), \( \hat{n}^s,k = n^s,k \), \( s = \hat{s}^k \)

2nd case: \( \hat{x}^k = A^k_i \hat{s}^k \), \( \hat{s}^k = h^s,k_i s^k \), \( \hat{n}^s,k = n^s,k \), \( s = \hat{s}^k \)

Combining (4) and (5), \( x^k_i \) can be expressed as:

\[
x^k_i = \sqrt{\eta^2 T/L} h^s,k_i s^k \hat{x}^k + \sqrt{\eta/L} \hat{n}^s,k \hat{x}^k.
\]

The received \( L_d \times T \) matrix of signals at the destination is

\[
D = \begin{bmatrix} d_1 \\ \vdots \\ d_{L_d} \end{bmatrix}
\]

with \( d_i = \sum_{k=1}^K d^k_i \),

\[
d^k_i = h^{l,d,k}_i x^k + n^{l,d,k}_i,
\]

where \( h^{l,d,k}_i \) is the received vector of signals at the \( i \)th antenna of the destination and \( d^k_i \) is the vector of signals coming from the \( k \)th relay and received at the \( i \)th antenna. It is given by:

\[
d^k_i = h^{l,d,k}_i x^k + n^{l,d,k}_i,
\]

where \( h^{l,d,k}_i \) is the \( l \)th row \((l = 1, \ldots, L_d)\) of the \( L_d \times M_k \) matrix of the \( k \)th relay-destination channel coefficients (denoted \( H^{l,d,k} \)) and where \( n^{l,d,k}_i \) is the \( l \)th row \((l = 1, \ldots, L_d)\) of \( N^{l,d,k} \), the \( L_d \times T \) matrix containing the AWGN of the \( k \)th relay-destination channel. The matrix \( N^{l,d,k} \) has zero mean elements and a covariance matrix \( E\{N^{l,d,k} \} = N_1 I_{L_d} \).

Substituting (6) in (8), \( d^k_i \) becomes:

\[
d^k_i = \sqrt{\eta^2 T/L} h^s,k + n^k_i,
\]
where
\[
S^k = \begin{bmatrix}
s_1^{(k), A_1} \\
\vdots \\
s_M^k \\
n_M^k \end{bmatrix}, \quad \mathbf{h}_i^k = \begin{bmatrix}
h_{1,1}^k & \cdots & h_{1,M_{k}^k}^k \\
\vdots \\
h_{M_{k}^k} & \cdots & h_{M_{k}^k, M_{k}^k} \\
\end{bmatrix},
\]
and \( n_k^l = n_k^{l,d} + \sqrt{\frac{\eta T}{L}} h_i^k + n_k^{l,s} \).

According to (7) and (9), \( d_l \) can be written as:
\[
d_l = \frac{\eta L}{\eta + 1} \mathbf{h}_l S_{eq} + n_l,
\]
where
\[
S_{eq} = \begin{bmatrix}
s_1^k \\
\vdots \\
s_K^k \end{bmatrix}, \quad \mathbf{h}_l = \begin{bmatrix}
h_1^l \\
\vdots \\
h_{L_d}^l \\
\end{bmatrix}, \quad \text{and} \quad n_l = \begin{bmatrix}
n_1^k \\
\vdots \\
n_{L_d}^k \end{bmatrix}.
\]

At the destination, we assume a maximum likelihood detection delivering \( \hat{s} \) (the \( 1 \times T \) vector of estimated symbols):
\[
\hat{s} = \arg \min_{\hat{s}} \left\| D - \frac{\eta L}{\eta + 1} \mathbf{H} S_{eq} \right\|_F,
\]
where \( S \) is the set of all possible transmitted vectors of symbols in the broadcast phase.

### B. Decode-and-Forward Relaying

Since relay \( k \) has the CSI of source-\( k \)th relay channel, it decodes the transmitted symbols by performing a maximum likelihood, delivering the \( 1 \times T \) vector \( s^{k,DF}_l \) as follows:
\[
\hat{s}^{k,DF}_l = \arg \min_{\hat{s}} \left\| \mathbf{D} - \frac{\eta L}{\eta + 1} \mathbf{H} S_{eq} + \mathbf{N} \right\|_F,
\]
where
\[
\mathbf{D} = \sqrt{\frac{\eta L}{\eta + 1}} \mathbf{H} S_{eq} + \mathbf{N}.
\]

The received \( L_d \times T \) matrix of signals (\( \mathbf{D}^{DF} \)) at the destination is defined by (similar to (7) and (8)):
\[
\mathbf{D}^{DF} = \begin{bmatrix}
d_1^{DF} \\
\vdots \\
d_{K}^{DF} \end{bmatrix}, \quad \text{where} \quad d_i^{DF} = \sum_{k=1}^{K} d_i^{k,DF},
\]
and \( d_i^{k,DF} = h_i^{k,d} \mathbf{x}_i^k + n_i^k \).

Using (13), \( d_i^{k,DF} \) becomes:
\[
d_i^{k,DF} = \frac{\eta L}{\eta + 1} h_i^k \mathbf{x}_i^k + n_i^k,
\]
where
\[
S_{eq}^{DF} = \begin{bmatrix}
\mathbf{s}_1^{DF} \\
\vdots \\
\mathbf{s}_K^{DF} \\
\end{bmatrix}, \quad \mathbf{h}_i^{DF} = \begin{bmatrix}
h_1^{k,d} \\
\vdots \\
h_{M_{k}^k}^{k,d} \end{bmatrix}, \quad \text{and} \quad n_l^{DF} = \sum_{k=1}^{K} n_l^k.
\]

Finally, the received signals at the destination is given by:
\[
\mathbf{D}^{DF} = \sqrt{\frac{\eta L}{\eta + 1}} \mathbf{H}^{DF} S_{eq} + \mathbf{N} \quad \text{with} \quad \mathbf{H}^{DF} = \begin{bmatrix}
\mathbf{h}_1^{DF} \\
\vdots \\
\mathbf{h}_{L_d}^{DF} \end{bmatrix}.
\]

The destination performs maximum likelihood detection and the detected symbols at the destination \( \mathbf{s}^{DF} \) are:
\[
\mathbf{s}^{DF} = \arg \min_{\mathbf{s} \in S} \left\| \mathbf{D}^{DF} - \frac{\eta L}{\eta + 1} \mathbf{H}^{DF} S_{eq} \right\|_F.
\]

### IV. Model Analysis With Imperfect CSI at the Receivers

In this section, we adapt the analysis of Section III to a new assumption. We consider imperfect CSI [11] at the receivers, which allows us to show the impact of channel knowledge errors on the performances of DSTBC wireless relay network.

#### A. Amplify-and-Forward Relaying

In sections II and III, we assumed that the destination has knowledge of the source-relays and relays-destination channels. Since the knowledge can be imperfect, then the estimated channels at the destination can be given by:
\[
\begin{cases}
\mathbf{z}_i^{k,s} = \mathbf{h}_i^{s,k} + \Delta \mathbf{h}_i^{s,k}, & \forall k = 1, \ldots, K, \\
\mathbf{h}_i^{k,d} = \mathbf{H}_i^{k,d} + \Delta \mathbf{H}_i^{k,d}
\end{cases},
\]
where \( \Delta \mathbf{h}_i^{s,k} \) and \( \Delta \mathbf{H}_i^{k,d} \) are matrices of the error estimation on the source-\( k \)th relay, and the \( k \)th relay-destination channels respectively, \( k = 1, \ldots, K \). \( \Delta \mathbf{h}_i^{s,k} \) and \( \Delta \mathbf{H}_i^{k,d} \) are composed of i.i.d. zero mean complex Gaussian distributed coefficients, circularly symmetric with variances \( \sigma_i^{s,k} \) and \( \sigma_i^{k,d} \) respectively. If \( \Delta \mathbf{h}_i^{s,k} \) and \( \Delta \mathbf{H}_i^{k,d} \) are null, then perfect CSI is considered.
B. Decode-and-Forward Relaying

In DF relaying, the model of the source-$k^{th}$ relay channel estimate at the $k^{th}$ relay is expressed by: $h_{s,k} = h_{s,k} + \Delta h_{s,k}$, where $\Delta h_{s,k}$ is a $M_k \times 1$ vector of i.i.d. zero mean complex Gaussian distributed random variables, circularly symmetric with variance $\sigma_s k^2$ and represents the error on the channel estimation. The estimated vector of symbols at the $k^{th}$ relay is given by:

$$\hat{s}_{k,DF} = \arg \min_{\hat{s} \in \mathbb{C}^4} \| R^k \sqrt{\eta_T} \hat{s} \|_F,$$

(19)

The destination node has knowledge of the $k^{th}$ relay-destination channel, $\forall k = 1, \ldots, K$, modelled as $H_{k,d}$ in (17).

V. SIMULATION RESULTS

In this section, we present the BER performance using Monte-Carlo simulations of DSTBC with AF or DF relaying techniques. Without loss of generality, we choose the structure of QOSTBC with $T = L = 4$ that offers a data rate of $1/2$ symbol/time periods (4 symbols/channel realization). The code matrices at the relays are then:

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix}, \quad A_2 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix}, \quad A_3 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix}, \quad A_4 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix},$$

$$B_1 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix}, \quad B_3 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix}, \quad B_4 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix}.$$

$A_i$ and $B_i (\forall i = 1, \ldots, 4)$ will be associated with the networks according to the network configuration. The structure of the quasi-orthogonal code at the destination is:

$$\begin{bmatrix} s_1 & -s_2^* & -s_3^* & s_4 \\ s_2 & s_1^* & -s_4^* & -s_3 \\ s_3 & -s_2^* & s_1^* & -s_4 \\ s_4 & s_3^* & s_2^* & s_1 \end{bmatrix}.$$

(20)

This is the transpose of the original proposed QOSTBC [10]. The original form is obtained by $s = [s_1 \ s_2^* - s_3^* \ s_4]^T$. Figures 1 and 2 present the BERs of AF and DF relaying techniques respectively for different network configurations. We assume perfect CSI at the receivers and BPSK modulated symbols. Fig.1 shows that the BERs of all network configurations are the same for AF relaying. This is expected since the cooperation is exploited in a distributed fashion, where no communication is needed between the relays. Thus, the diversity $d$ achieved has its maximal value, $d = 4$. This result agrees with the theoretical result in [8], where diversity in relay networks is defined by $d = \min(L_s, L_d)\ L$, where $L_s, L_d$ and $L$ are the number of antennas at the source, the destination and the sum of the antennas of all relays, respectively. In Fig.2 (with DF relaying), we notice substantial difference in BER performances between the configurations. In fact, the BER is better when the configuration converges to a MIMO relay. The diversity of the system is directed by the diversity at the broadcast phase since the relays decode the received information. Therefore, config. 1, 2 and 3 achieve diversities 4, 2 and 1 respectively.

Figures 3 and 4 show the BER results using AF relaying with config.3 and imperfect CSI. In Fig.3, we choose $\sigma_{k,d}^2 = 0.01$. The BER increases rapidly when $\sigma_{s,k}^2$ increases. The degradation is severe when the error exceeds 10%. This result agrees with the rule cited in [11] that states that the channel estimation error should be $10dB$ below the additive noise power for an accurate channel estimation. Accordingly, when $\sigma_{s,k}^2 \leq 10\%$, BER drops slightly. At $BER=10^{-4}$, the SNR degradation is less than $0.5dB$ when $\sigma_{s,k}^2$ jumps from 1% to 10%. This is a very interesting result since AF helps to reduce the error on the overall system as it leaves the decoding task to the destination. Fig.4 presents the BER performance for $\sigma_{s,k}^2 = 0.01$. When $\sigma_{s,k}^2 \leq 15\%$, the BERs are almost the same. It means the channel estimation error at the relay phase has less impact on the transmission reliability than the broadcast phase. This can be explained by the use of AF and the additive protection gained from the QOSTBC design on the relay phase. We notice that the error tolerated at the relay (broadcast) phase is 15% (10%) thanks to the increased reliability of the code at the relay phase.

Figures 5 and 6 consider DF relaying, config.3 and imperfect CSI. In Fig.5, we choose $\sigma_{k,d}^2 = 0.01$. The BER performance degrades when $\sigma_{s,k}^2$ increases. For $\sigma_{s,k}^2 \leq 0.1$,
the degradation is insignificant at low SNR due to the decoding capability of the relays. Then, it increases very fast at high SNR. In fact, the channel estimation errors provide more often erroneous estimated symbols at the relays at high SNR. However, for $\sigma^2 > 0.1$, the BER becomes excessively high. In Fig.6, we have $\sigma^2 = 0.01$. We found that for $\sigma^2 \leq 0.15$, the BERs are almost the same. $\sigma^2$ has a little impact on the BER. This is due to the QOSTBC use during the relay phase to increase reliability. However, when $\sigma^2 > 0.15$, the BER degrades severely. At BER=$10^{-2}$, the degradation is 1.3dB (3.5dB) between the $\sigma^2 = 0.1$ curve and the $\sigma^2 = 0.3$ ($\sigma^2 = 0.5$) curve.

VI. CONCLUSION

In this paper, we investigated and evaluated the performance of using multiple relays with multiple antennas in wireless networks employing Space-Time-Block-Coding with Amplify-and-Forward and Decode-and-Forward relaying techniques. We evaluated the BER performances of the system for different network configurations (different number of relays and different number of antennas per relay) for both perfect and imperfect CSI at the receivers. We showed that the AF relaying resists slightly better to imperfect CSI than DF relaying. In addition, it gives better network configuration flexibility since it is designed in a distributed fashion.

Fig. 3. BER vs. SNR for QOSTBC AF Relays, Config.3, $\sigma^2 = 0.01$

Fig. 4. BER vs. SNR for QOSTBC AF Relays, Config.3, $\sigma^2 = 0.01$

Fig. 5. BER vs. SNR for QOSTBC DF Relays, Config.3, $\sigma^2 = 0.01$

Fig. 6. BER vs. SNR for QOSTBC AF Relays, Config.3, $\sigma^2 = 0.01$

REFERENCES