Generalized Bidirectional Multi-pair Multi-antenna Wireless Network Coding

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***Abstract*— In this paper, we focus on increasing the throughput and diversity of network coded MIMO transmissions in bidirectional multi-pair wireless relay networks. All nodes have multi-antenna capability. Pairs of nodes want to exchange messages via a relay having multi-antenna and encoding/decoding capability. Nodes transmit their messages to the relay in the first (MAC) phase. The relay decodes all the messages and XORs them and broadcasts the XORed message in the second (BC) phase. We develop a generalized framework for bidirectional multi-pair multi-antenna wireless network coding, which models different MIMO transmission schemes including spatial multiplexing (V-BLAST), orthogonal STBC (OSTBC), and non-orthogonal STBC (NO-STBC) in a unified way. Enhanced throughputs are achieved by allowing all nodes to simultaneously transmit at their full rate. High diversity orders are achieved through the use of NO-STBCs, characterized by full rate and full transmit diversity. We evaluate and compare the performance of V-BLAST, OSTBC, and NO-STBC schemes in one-dimensional 1-pair linear network (one pair of nodes and a relay) and two-dimensional 2-pair 'cross' network (two pairs of nodes and a relay).**

Keywords *– Wireless network coding, relay networks, MIMO, V-BLAST, orthogonal and non-orthogonal STBC.*

I. INTRODUCTION

In recent years, wireless network coding has been widely popular in both academia and industry because of its wide applicability in wireless ad-hoc/mesh networks [1]. The use of relay as an intermediate node to facilitate the communication between two nodes willing to exchange messages but are out of each other's range has been a widely studied strategy. Half-duplex communication using two-phase protocols is common in such relay networks. In the first phase of the protocol (MAC phase), nodes send their messages to the relay. In the second phase (BC phase), the relay processes the received signal and broadcasts it to the nodes. Analog network coding adopts an amplify-and-forward (AF) approach to broadcast an analog version of the received signal [2]. Physical network coding (PNC) [3] employs estimate-and-forward relaying as apposed to AF relaying in ANC. Popular relaying strategies have been compress-and-forward/quantize-and-forward (CF/QF) [4], decode-and-forward [5], denoise-and-forward [6].

The advantages of the use of wireless network coding in conjunction with multi-antenna techniques [7],[8] in wireless networks has been widely recognized [9]-[14]. Enhanced throughputs and increased spatial diversity performance are potential benefits of combining MIMO with wireless network coding (MIMO-NC). We note that several of the above and other works on MIMO-NC consider specific MIMO encoding schemes. For example, the MIMO encoding used in [11] is orthogonal space-time block coding (OSTBC) [15]. In the MINEC (MIMO Network Coding) protocol in [5], spatial multiplexing is used in the MAC phase and Alamouti code is used in the BC phase, where nodes are equipped with one antenna each and relay has two antennas. However, a unified framework which allows us to consider different MIMO encoding schemes, including spatial multiplexing (V-BLAST), OSTBC, and non-orthogonal STBC (NO-STBC), in conjunction with wireless network coding is essential to compare the rate (throughput) and BER performance (diversity) achieved by different MIMO encoding/NC combinations.

In this paper, we develop a generalized framework that models wireless network coding with bit-wise XOR at the relay in conjunction with different MIMO encoding schemes at the nodes and the relay in a unified way. We assume that all nodes have multi-antenna capability. The communication scenario is such that multiple pairs of nodes want to exchange messages via a relay having multi-antenna and wireless XOR capability. In this bidirectional communication system, enhanced throughputs are achieved by allowing all nodes to simultaneously transmit at their full rate. High diversity orders are achieved through the use of NO-STBCs, characterized by full rate and full transmit diversity. We present a throughput and diversity comparison of V-BLAST, OSTBC, and NO-STBC[1] schemes in one-dimensional 1-pair linear network (one pair of nodes and a relay) and two-dimensional 2-pair 'cross' network (two pairs of nodes and a relay). In both networks NO-STBC scheme achieves higher throughput than OSTBC. Our simulation results show that, for the same throughput (in number of bits per channel use), NO-STBC scheme achieves better performance than V-BLAST.

II. GENERALIZED WIRELESS NETWORK CODING

We consider bidirectional wireless relay networks, where pairs of nodes want to communicate messages to each other via a relay. Nodes are out of communication range of each other, but are within the communication range of the relay. Example topologies include i) one-dimensional 1-pair linear network shown in Fig. $1(a)$, where one pair of nodes (S_1, S_2) exchange messages through relay R, and ii) two-dimensional 2-pair 'cross' network shown in Fig. $1(b)$, where two node pairs (S_1, S_2) and (S_3, S_4) exchange messages through relay R. Without loss of generality, we assume that all the nodes are homogeneous with n_S transmit/receive antennas each, and the relay has n_R transmit/receive antennas.

[1]We consider the full rate, full transmit diversity NO-STBCs in [16], constructed using n^2 data symbols; linear combinations of which are sent using n transmit antennas in n channel uses.

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Communication is half-duplex, where message exchange happens in two phases. In the first phase (MAC phase), all the nodes simultaneously transmit their messages using their respective n_S transmit antennas. The relay receives the sum signal from all the nodes using its n_R receive antennas and decodes the messages. The relay then XORs these decoded messages and broadcasts the XORed message to all nodes in the second phase (BC phase) using n_R transmit antennas. The nodes receive the XORed message using their respective n_S receive antennas and decode the XORed message, which is then used to 'network decode' the message meant for them. The transmit/receive signal models for the MAC and BC phases are developed below.

A. Tx/Rx Signal Model in MAC Phase

Let K denote the number of node pairs (i.e., $2K$ is the total number of nodes), where (S_{2k-1}, S_{2k}), $k = 1, 2, \cdots, K$, are the K node pairs. Let $\mathbf{M}_i$ denote the signal from node S_i, $i = 1, 2, \cdots, 2K$. $\mathbf{M}_i$ is a $n_S \times T_m$ matrix, where $T_m = t_m B_m$ is the total number of channel uses in the MAC phase, t_m is number of channel uses in one MIMO encoded block, and B_m is the number of MIMO encoded blocks in the MAC phase. t_m depends on the type of MIMO transmission scheme (spatial multiplexing or space-time coding) chosen in the MAC phase. B_m depends on the MIMO transmission schemes in both MAC and BC phases. Choice of B_m will be discussed in Sec. II-D.

In space-time MIMO transmissions, each element of $\mathbf{M}_i$ can be written as linear combination of data symbols and their conjugates [8], as

$$\mathbf{M}_i = \sum_{n=1}^{N} \left(\mathbf{\Phi}_n x_n^{(i)} + \mathbf{\Psi}_n x_n^{(i)*} \right), \tag{1}$$

$$\mathbf{x}^{(i)} = \left[x_1^{(i)} \; x_2^{(i)} \; \cdots \; x_N^{(i)} \right]^T, \tag{2}$$

where $x_n \in \mathbb{A}_1$ is complex data symbol[2] from the modulation alphabet $\mathbb{A}_1$ (e.g., M-QAM/M-PSK) used in the MAC phase, N is the number of data symbols in the MAC phase, and $\mathbf{\Phi}$'s and $\mathbf{\Psi}$'s are the weight matrices. We can consider the operation in (1) as a mapping from information symbol vector $\mathbf{x}^{(i)}$ of length N to the space-time coded matrix $\mathbf{M}_i$. The weight matrices and hence this mapping is known at the relay. Let E_s denote the average energy of each entry in $\mathbf{M}_i$.

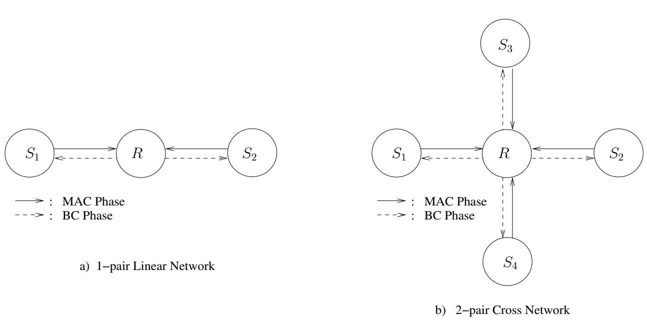

Fig. 1. Bidirectional Wireless Relay Networks.

[2]Gray mapping of $m_1 = \log_2 |\mathbb{A}_1|$ bits to data symbol is assumed.

Let $\mathbf{H}_i$ denote the $n_R \times n_S$ sized channel matrix between node i and relay during the MAC phase. The entries of $\mathbf{H}_i$'s are assumed to be i.i.d. Gaussian with zero mean and unit variance. These fade coefficients are assumed to be constant over the MAC phase. The received sum signal at the relay is given by

$$\begin{aligned} \mathbf{Y}_R &= \sum_{i=1}^{2K} \mathbf{H}_i \mathbf{M}_i + \mathbf{N}_R \\ &= \widetilde{\mathbf{H}} \widetilde{\mathbf{M}} + \mathbf{N}_R, \end{aligned} \tag{3}$$

where $\mathbf{Y}_R$ is the received signal matrix and $\mathbf{N}_R$ is the noise matrix, each of size $n_R \times T_m$, $\widetilde{\mathbf{H}} = \left[\mathbf{H}_1 \, \mathbf{H}_2 \, \cdots \, \mathbf{H}_{2K} \right]$, $\widetilde{\mathbf{M}} = \left[\mathbf{M}_1^T \, \mathbf{M}_2^T \, \cdots \, \mathbf{M}_{2K}^T \right]^T$. Each entry of $\mathbf{N}_R$ is complex Gaussian with zero mean and σ_R^2 variance, where $\sigma_R^2 = \frac{2K n_S E_s}{\gamma_R}$ and γ_R is the average received SNR at the relay.

B. Decoding and XORing at Relay

We assume perfect knowledge of $\mathbf{H}_i$'s at the relay. The ML decoding rule at the relay is given by

$$\widehat{\mathbf{M}} = \underset{\mathbf{P} \in \mathbb{S}^{2K n_S \times T_m}}{\arg\min} \; \| \mathbf{Y}_R - \widetilde{\mathbf{H}} \mathbf{P} \|^2, \tag{4}$$

where $\widehat{\mathbf{M}} = \left[\widehat{\mathbf{M}}_1^T \, \widehat{\mathbf{M}}_2^T \, \cdots \, \widehat{\mathbf{M}}_{2K}^T \right]^T$ and $\widehat{\mathbf{M}}_i$ is an estimate of $\mathbf{M}_i$ at the relay, $i = 1, \cdots, 2K$.

The relay demaps matrix $\widehat{\mathbf{M}}_i$ to the constituent information symbol vector $\widehat{\mathbf{x}}^{(i)}$. Let $\mathbf{x}_R^{(k)}$ denote the $N \times 1$ sized symbol vector constructed by the relay by XORing the decoded and demapped information symbol vectors from the kth node pair (S_{2k-1}, S_{2k}), i.e.,

$$\mathbf{x}_R^{(k)} = \widehat{\mathbf{x}}^{(2k-1)} \oplus \widehat{\mathbf{x}}^{(2k)}, \quad k = 1, \cdots, K, \tag{5}$$

where the XOR operation in (5) is performed bit-wise on the bits demapped from the symbols in the entries of $\widehat{\mathbf{x}}^{(i)}$. Let $\mathbb{A}_2$ be the modulation alphabet used in the BC phase. Now, $\mathbf{x}_R^{(k)}$ is converted into bit vector of size $N m_1 \times 1$, and $m_2 = \log_2 |\mathbb{A}_2|$ XORed bits are mapped to a modulation symbol belonging to alphabet $\mathbb{A}_2$ to obtain a $N_b \times 1$ sized vector $\mathbf{z}_R^{(k)}$ corresponding to kth node pair. Note that $N_b = \frac{N m_1}{m_2}$.

Let T_b denote the total number of channel uses in one BC phase. The relay constructs the network coded matrix $\mathbf{Z}_R$ to be broadcast in $T_b = t_b B_b$ channel uses. t_b is the number of channel uses in one MIMO encoded block used in the BC phase. B_b is the number of MIMO encoded blocks in the BC phase, which depends on the MIMO transmission schemes used in both MAC and BC phases. Choice of B_b will be presented in Sec. II-D.

Note that $\mathbf{Z}_R$ will have $K N m_1$ bits that have to be transmitted in T_b channel uses using n_R transmit antennas and alphabet $\mathbb{A}_2$. Let $\mathbf{z}$ be the $N_b K \times 1$ sized vector obtained by $vec(.)$ operation on $\mathbf{z}_R^{(k)}$'s, i.e.,

$$\begin{aligned} \mathbf{z} &= vec\left[\mathbf{z}_R^{(1)} \, \mathbf{z}_R^{(2)} \, \cdots \mathbf{z}_R^{(K)} \right] \\ &\stackrel{\triangle}{=} \left[z_1 \; z_2 \; \cdots \; z_{N_b K} \right]^T. \end{aligned} \tag{6}$$

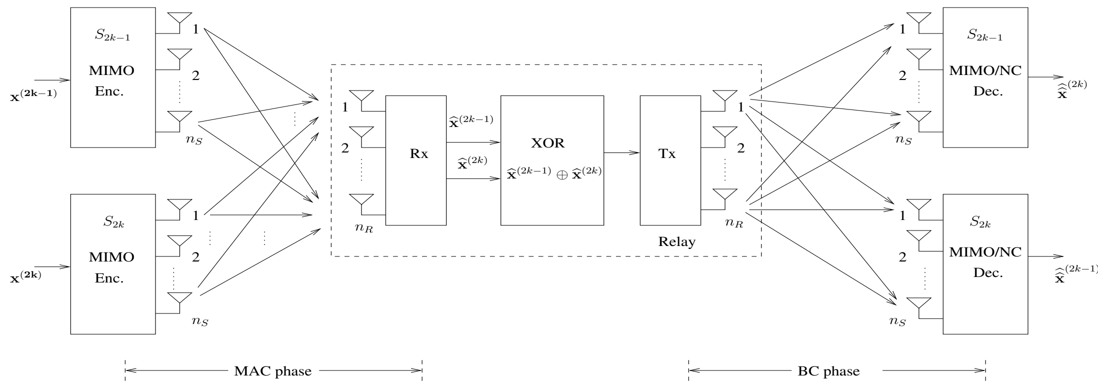

Fig. 2. Two-phase MIMO Bidirectional Relaying Protocol between kth pair of nodes (S_{2k-1}, S_{2k}) and relay in K-pair network.

Now, the network space-time coded matrix $\mathbf{Z}_R$ is formed as follows:

$$\mathbf{Z}_R = \sum_{n=1}^{N_b K} \left(\mathbf{\Phi}_n^R z_n + \mathbf{\Psi}_n^R z_n^* \right), \tag{7}$$

where $\mathbf{\Phi}_n^R$ and $\mathbf{\Phi}_n^R$ are the weight matrices at the relay. These weight matrices and hence the mapping of $\mathbf{z}$ to $\mathbf{Z}_R$ is known at all the nodes. The relay broadcasts this network coded $\mathbf{Z}_R$ matrix in T_b channel uses in the BC phase.

C. Tx/Rx Signal Model in BC Phase

Let $\mathbf{G}_i$ denote the $n_S \times n_R$ sized channel matrix between the relay and node i during the BC phase. The entries of $\mathbf{G}_i$'s are assumed to be i.i.d. Gaussian with zero mean and unit variance, which are assumed to be constant over the BC phase. Also, the fades during MAC phase and BC phase are assumed to be independent. The received signal at node S_i in the BC phase can be written as

$$\mathbf{Y}_{S_i} \quad = \quad \mathbf{G}_i \mathbf{Z}_R + \mathbf{N}_{S_i}, \tag{8}$$

where $\mathbf{Y}_{S_i}$ is the received signal matrix and $\mathbf{N}_{S_i}$ is the noise matrix, each of size $n_S \times T_b$. Each entry of $\mathbf{N}_{S_i}$ is complex Gaussian with zero mean and $\sigma_{S_i}^2$ variance, where $\sigma_{S_i}^2 = \frac{n_R E_r}{\gamma_{S_i}}$, E_r is the average energy of each entry in $\mathbf{Z}_r$, and γ_{S_i} is the average received SNR at node S_i. At node S_i, obtain the ML decision

$$\mathbf{W}^{(i)} \quad = \quad \underset{\mathbf{Q} \in \mathbb{B}^{n_R \times T_b}}{\arg\min} \; \|\mathbf{Y}_{S_i} - \mathbf{G}_i \mathbf{Q}\|^2, \tag{9}$$

Now, node S_i demaps $\mathbf{W}^{(i)}$ and recovers an $N_b K \times 1$ sized vector $\mathbf{a}_i$ which is an estimate of $\mathbf{z}$,

$$\mathbf{a}_i \quad \triangleq \quad \left[a_1^{(i)} \; a_2^{(i)} \; \cdots \; a_{N_b K}^{(i)} \right]^T. \tag{10}$$

Let $\mathbf{a}_i^{(k)}$, for $k = 1, \cdots, K$, denote the $N_b \times 1$ sized subvectors of $\mathbf{a}_i$, where the pth element of $\mathbf{a}_i^{(k)}$ is given by $a_t^{(i)}$, where $t = (k-1)N_b + p$. Note that $\mathbf{a}_i^{(k)}$ is an estimate of $\mathbf{z}_R^{(k)}$. Now, $\mathbf{a}_i^{(k)}$ is converted into a $N_b m_2$ sized bit vector, and $m_1 = \log_2 |\mathbb{A}_1|$ bits are mapped to a modulation symbol belonging to alphabet $\mathbb{A}_1$ to obtain a $N \times 1$ sized vector $\mathbf{q}_i^{(k)}$ corresponding to k th node pair. Note that $\mathbf{q}_i^{(k)}$ is an estimate of $\mathbf{x}_R^{(k)}$ in (5).

Therefore, nodes S_{2k-1} and S_{2k} can use $\mathbf{q}_{2k-1}^{(k)}$ and $\mathbf{q}_{2k}^{(k)}$ to obtain estimates of $\mathbf{x}^{(2k)}$ and $\mathbf{x}^{(2k-1)}$, respectively, by the following operations. Let $\widehat{\widehat{\mathbf{x}}}^{(2k)}$ and $\widehat{\widehat{\mathbf{x}}}^{(2k-1)}$ denote the estimates of $\mathbf{x}^{(2k)}$ and $\mathbf{x}^{(2k-1)}$, respectively. At node S_{2k-1}, $\widehat{\widehat{\mathbf{x}}}^{(2k)}$ (the message sent to it by node S_{2k}) is obtained as

$$\widehat{\widehat{\mathbf{x}}}^{(2k)} = \mathbf{q}_{2k-1}^{(k)} \oplus \mathbf{x}^{(2k-1)}. \tag{11}$$

Similarly, at node S_{2k}, $\widehat{\widehat{\mathbf{x}}}^{(2k-1)}$ (the message sent to it by node S_{2k-1}) is obtained as

$$\widehat{\widehat{\mathbf{x}}}^{(2k-1)} = \mathbf{q}_{2k}^{(k)} \oplus \mathbf{x}^{(2k)}. \tag{12}$$

At node S_i, the decoded symbols in $\widehat{\widehat{\mathbf{x}}}^{(i)}$ are demapped to get the information bits.

D. Choice of B_m and B_b

We need to choose the number of channel uses in MAC and BC phases, T_m and T_b, such that the number of bits sent in both phases are matched. Let C_m and C_b denote the number of bits in one MIMO encoded block from each node in MAC phase and from relay in BC phase, respectively. Let Γ denote the number of MIMO encoded blocks in MAC phase per MIMO encoded block in BC phase, i.e.,

$$\Gamma = \frac{C_b}{K C_m}. \tag{13}$$

Now, to match the number of bits in both MAC and BC phases, B_m is chosen as $B_m = \Gamma \Omega$, where Ω is the smallest positive integer such that B_m is an integer, and B_b is chosen as $B_b = \Omega$.

E. System Throughput and Diversity Order

System throughput: We define the throughput of the system to be the total number of bits exchanged per channel use. The total number of bits exchanged in one MAC and one BC phase is $2KNm_1$. The number of channel uses in one MAC and one BC phase is $T_m + T_b$. So the system throughput η in units of bits per channel use (bpcu) is given by

$$\eta = \frac{2KNm_1}{T_m + T_b}. \tag{14}$$

Diversity order: Let d_m and d_b denote the diversity order in MAC phase and BC phase, respectively. Since the overall performance is dominated by the phase which has the lower diversity order, we define the overall system diversity to be $min(d_m, d_b)$.

Tables-I and II give the system throughput and diversity order for different antenna configurations and transmission schemes in 1-pair linear network and 2-pair cross network, respectively, for 4-QAM modulation in both MAC and BC phases. In Table-I, the throughput and diversity of SISO relaying without network coding (conventional relaying) [2], SISO relaying with network coding [18], SISO physical network coding (PNC) [3], MIMO network coding (MINEC) in [5], and MIMO network coding using OSTBC, V-BLAST, NO-STBC [16] are compared. Two messages are exchanged in 4, 3, 2 channel uses in conventional SISO relaying without NC, SISO relaying with NC, and SISO PNC, respectively, achieving 1, 1.33, 2 bpcu for 4-QAM. Since these three schemes are SISO, the diversity order is 1. MINEC [5] uses 2×2 V-BLAST in MAC phase and Alamouti OSTBC in the BC phase, which achieves 2 bpcu and 2nd order diversity. We see that much better throughput and diversity are possible if other MIMO transmission schemes are used. For example, if Alamouti OSTBC is used in both MAC and BC, 2 bpcu with an increased diversity order of 4 is achieved. On the other hand, if V-BLAST is used in both MAC and BC, the throughput gets doubled (4 bpcu) compared to MINEC, but the diversity order remains at 2. This is because V-BLAST gives full rate but does not give transmit diversity, whereas Alamouti OSTBC gives full transmit diversity but there is no rate increase. Both throughput and diversity order get doubled (4 bpcu and 4th order diversity) when NO-STBC in [16] is used in both MAC and BC. It is noted that the V-BLAST and NO-STBC schemes in Table-I are underdetermined in the MAC phase. Detailed simulated BER performance of these schemes are presented in Sec. III.

In Table-II, the time/frequency sharing scheme in [14], the node pairs transmit to the relay in separate channel uses, whereas in MIMO NC schemes all the nodes transmit their data simultaneously. This leads to higher throughput in MIMO NC schemes compared to time-frequency sharing. Both the schemes in 5 and 6 use the 2×2 NO-STBC in [16] in MAC phase. In BC phase, however, schemes 5 and 6 differ. Scheme 5 uses 4×4 NO-STBC in [17] which sends 8 complex symbols in 4 channel uses using 4 antennas. Whereas scheme 6 uses 4×4 NO-STBC in [16] which sends 16 complex symbols in 4 channel uses using 4 antennas. Because of this difference in the BC phase schemes 5 and 6 differ in throughput while achieving the same overall system diversity. Also, as in the 1-pair linear network, here also NO-STBC scheme achieves high rate and high diversity.

III. Results and Discussion

We evaluate the BER performance of various MIMO NC schemes through simulations. ML detection is used at the relay and the receive nodes. In case of underdetermined systems generalized sphere decoder proposed in [19] is used. We assume that $\gamma_R = \gamma_{S_i} = \gamma, \quad \forall i = 1, \cdots, 2K$. Figure 3 shows the BER results for Schemes 4, 5, 6, 7 in Table-I for 1-pair linear network using 4-QAM in MAC and BC phases. It can be seen from the figure that BER curves of Scheme 5 (MIMO NC (OSTBC)) and Scheme 7 (MIMO NC (NO-STBC in [16])) have the best slope, followed by BER curves of Scheme 4 (MINEC in [5]) and Scheme 6 $\big($MIMO NC (V-BLAST)$\big)$. The BER curve of Scheme 3 (PNC in [3]) has the worst BER performance owing to its first order diversity as shown in Table-I. MIMO NC schemes with OSTBC and NO-STBC both show diversity order of 4 but the BER performance of OSTBC scheme is better than NO-STBC scheme due to the fully-determined nature of both MAC and BC phases in OSTBC Scheme. In the figure, both MIMO NC scheme with V-BLAST and MINEC scheme in [5] show second order diversity which can also be seen from Table-I. Among the schemes with highest throughput ($\eta = 4$), NO-STBC outperforms the V-BLAST scheme due to its higher diversity order.

Figure 4 shows the comparison between BER performances of Schemes 1, 2, 3, 4, 5 and 6 in Table-II for 2-pair cross network using 4-QAM in MAC and BC phases. It can be seen from the figure that the BER curves of the Schemes 1 (Time/ Freq. sharing in [14]), 2 (Time/ Freq. sharing) and 4 (MIMO NC (V-BLAST)) are parallel, showing the same order of diversity. From Table-II, it can be seen that all these three Schemes have 2nd order diversity. It can also be seen from the figure that Schemes 5 (NO-STBC in [16], [17]) and 6 (NO-STBC in [16]) have better BER performances, owing to diversity order of 8 available in these two schemes. Scheme 5 $\big($MIMO NC (OSTBC)$\big)$ has the best BER performance due to the use of orthogonal codes and fully/over-determined nature of its MAC and BC phases, but has a very low throughput of 2.67 as shown in Table-II. Among the schemes with highest throughput ($\eta = 8$), NO-STBC outperforms the V-BLAST scheme due to its higher diversity order.

IV. Conclusion

We developed a generalized wireless network coding framework that modeled various MIMO encoding schemes that can be employed at the nodes and relay in bidirectional multi-pair networks in a unified way. Our current work has presented a unified signal model for two-phase half-duplex protocol employing wireless XOR at the relay and MIMO transmission schemes including V-BLAST, OSTBC, and NO-STBC in both MAC and BC phases. Enhanced throughput and diversity were achieved by allowing simultaneous transmission by all nodes and through the use of NO-STBCs. Simulation results on BER performance showed that NO-STBC MIMO encoding in MAC and BC phases is attractive.

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No.	Transmission Scheme	(n_S, n_R)	(C_m, C_b)	(T_m, T_b)	N	Throughput η, bpcu	Diversity order $min(d_m, d_b)$
1.	Conventional relay [2]	$(1,1)$	$(2,2)$	$(2,2)$	1	1	1
2.	NC relay [18]	$(1,1)$	$(2,2)$	$(2,1)$	1	1.33	1
3.	PNC [3]	$(1,1)$	$(2,2)$	$(1,1)$	1	2	1
4.	MINEC [5]	$(1,2)$	$(2,4)$	$(2,2)$	2	2	2
5.	MIMO NC (OSTBC)	$(2,2)$	$(4,4)$	$(2,2)$	2	2	4
6.	MIMO NC (V-BLAST)	$(2,2)$	$(4,4)$	$(1,1)$	2	4	2
7.	MIMO NC (NO-STBC [16])	$(2,2)$	$(8,8)$	$(2,2)$	4	4	4

TABLE I

SYSTEM THROUGHPUT AND DIVERSITY ORDER COMPARISON FOR DIFFERENT MIMO TRANSMISSION SCHEMES IN **1-pair linear network** ($K = 1$). 4-QAM IN BOTH MAC AND BC PHASES.

No.	Transmission Scheme	(n_S, n_R)	(C_m, C_b)	(T_m, T_b)	N	Throughput η, bpcu	Diversity order $min(d_m, d_b)$
1.	Time/Freq. sharing [14]	$(2,2)$	$(2,4)$	$(2,1)$	1	2.67	2
2.	Time/Freq. sharing	$(2,4)$	$(4,4)$	$(2,2)$	2	4	2
3.	MIMO NC (OSTBC)	$(2,4)$	$(4,8)$	$(2,4)$	2	2.67	4
4.	MIMO NC (V-BLAST)	$(2,4)$	$(4,8)$	$(1,1)$	2	8	2
5.	MIMO NC (NO-STBC [16],[17])	$(2,4)$	$(8,16)$	$(2,4)$	4	5.33	8
6.	MIMO NC (NO-STBC [16])	$(2,4)$	$(8,32)$	$(4,4)$	8	8	8

TABLE II

SYSTEM THROUGHPUT AND DIVERSITY ORDER COMPARISON FOR DIFFERENT MIMO TRANSMISSION SCHEMES IN **2-pair cross network** ($K = 2$). 4-QAM IN BOTH MAC AND BC PHASES.

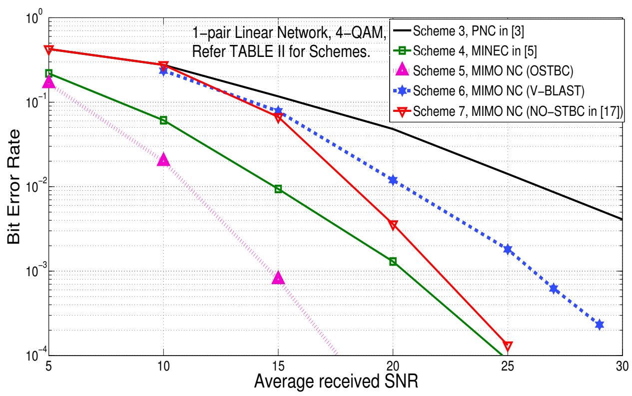

Fig. 3. Overall end-to-end BER performance for various MIMO NC schemes in Table-I for 1-pair linear network using 4-QAM in MAC and BC phases.

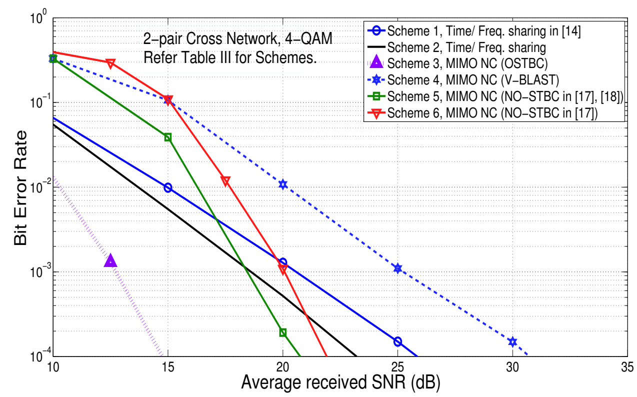

Fig. 4. Overall end-to-end BER performance for various MIMO NC schemes in Table-II for 2-pair cross network using 4-QAM in MAC and BC phases.

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