

# Space-Time Analog Network Coding for Multiple Access Relay Channels<sup>†</sup>

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**Abstract**—Network coding is a paradigm for modern communication networks by allowing intermediate nodes to mix messages received from multiple sources. Recently, space-time analog network coding (STANC) has been proposed for non-regenerative multi-way relaying, where multiple nodes are exchanging information through the multi-antenna relay without direct links. In this paper, we investigate STANC in multiple-access relay channels, where multiple nodes communicate to a common destination through a multi-antenna relay with direct links. We discuss several different possible schemes including STANC with Alamouti scheme under three time slots constraints and compare the sum rate and error rate performance.

**Index Terms**—multiple access relay channel, analog network coding, cooperative, space-time coding.

## I. INTRODUCTION

Since the pioneering research work of Ahlswede *et al.* in 2000 [1], network coding (NC) has rapidly emerged as a major research area in electrical engineering and computer science. NC is a generalized routing approach that breaks the traditional assumption of simply forwarding data, and allows intermediate nodes to send out functions of their received packets, by which the multicast capacity given by the max-flow min-cut theorem can be achieved. Subsequent works of [2]-[4] made the important observation that, for multicasting, intermediate nodes can simply send out a linear combination of their received packets. Linear network coding with random coefficients is considered in [5].

In order to address the broadcast nature of wireless transmission, physical layer network coding (PLNC) [6] was proposed to embrace interference in wireless networks in which intermediate nodes attempt to decode the modulo-two sum (XOR) of the transmitted messages. Compute-and-forward network coding, based on the linear algebraic structure of lattice codes, is proposed in [7]-[8], in which a relay will decode and forward a linear combination of source messages according to the observed channel coefficients. Subsequent work to design compute-and-forward coefficients matrix for multi-source multi-relay channels is discussed in [9] and for two-way relay channels in [10]. Analog network coding (ANC) is presented in [11] where relays simply amplify-and-forward received mixed signals. Several other network coding realizations in wireless networks are discussed in [12]-[14].

Regarding network coding in wireless multiple access relay channels, throughput analysis is given in [15] under collision model. Complex field network coding is presented in [16]. Analog network coding mappings in multiple access relay channels with direct links and without direct links is discussed in [17]. Multiple-access relay channels with compute-and-forward relays are studied in [18]-[19]. Regarding network coding with MIMO space time coding technique, Alamouti scheme [20] is applied to decode-and-forward (DF) network coding for two-way relay channels with multiple antenna relay in [21]-[22]. Different schemes for multiple access relay channels with two sources are discussed in [23].

Recently, space-time analog network coding (STANC), which combines analog network coding with space-time coding techniques in MIMO systems has been proposed in [24]. The authors in [24] consider non-regenerative multi-way relaying, where multiple nodes are exchanging information through the multi-antenna relay without direct links, with the assumption that the channels are stationary and channel state information is not available at the multi-antenna relay. The term space time analog network coding is used to differentiate with the conventional space-time block coding (STBC) due to the fact that the relay sends the received mixture signals of all nodes simultaneously to all nodes after power amplification, subject to per-antenna power constraint at the relay [24].

In this paper, instead of the multi-way relaying channels, we investigate space-time analog network coding (STANC) in multiple-access relay channels (MARC), where multiple nodes communicate to a common destination through a multi-antenna relay with direct links. To apply STANC strategy, we propose a MARC system model with three sources. The relay is with two antennas, while sources and destination only with one antenna. We discuss several possible transmission schemes under three time slots constraint:

- Direct Transmission (DT);
- Analog Network Coding (ANC);
- Space-Time Analog Network Coding with Alamouti scheme (STANC-Alamouti).

We describe in details those different schemes under the system model with transmission time slots constraints, and compare the sum rate and bit error rate performance at the destination.

The notations used in this paper are as follows.  $\{\cdot\}^T$  and  $\{\cdot\}^H$  denotes the transpose and Hermitian transpose operation.  $\mathbb{C}^n$  denotes the  $n$  dimensional complex field.  $\mathbf{0}_2 = [0, 0]^T$  is

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the all-zero column vector in two dimension.  $\mathbf{I}_n$  denotes the identity matrix of size  $n \times n$ . Assume that the log operation is with respect to base 2. We use boldface lowercase letters to denote column vectors and boldface uppercase letters to denote matrices.

The rest of this paper is organized as follows. Section II presents the system model of multiple access relay channel with three sources. Section III discusses different schemes under three time slots constraint. Simulation studies is given in Section IV. A few concluding remarks are drawn in Section V.

## II. SYSTEM MODEL

Consider the system model setting with three sources  $S_1$ ,  $S_2$ ,  $S_3$  communicating with destination  $\mathcal{D}$  via a relay  $\mathcal{R}$ , with direct links from sources to destination, as shown in Fig. 1. We assume sources  $S_1$ ,  $S_2$ ,  $S_3$  and destination  $\mathcal{D}$  are equipped with single antenna, while relay  $\mathcal{R}$  is equipped with two antennas.

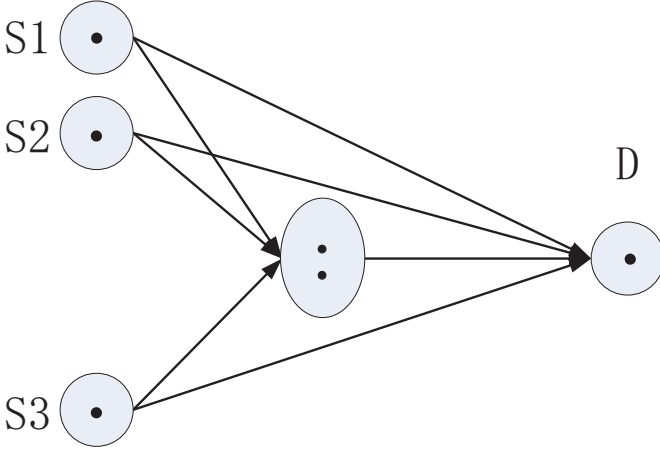


Fig. 1. Type II system model A: Three sources, Three time slots

We will discuss several possible transmission strategies for this system model. One realization of the information transmission will be performed within three time slots for all those strategies.

## III. DIFFERENT SCHEMES

### A. Scheme 1: Direct transmission (DT)

In this scheme, we assume the relay will keep silent during all transmission realization and the sources will communicate to the destination one by one, which also takes three time slots. In the first time slot,  $S_1$  will transmit; in the second time slot,  $S_2$  will transmit and  $S_3$  will transmit in the third time slot.

Let  $f_i$  be the direct link channel coefficient between source  $S_i$  to destination  $\mathcal{D}$ ;  $x_i$  be the transmit signal from node  $S_i$  which satisfies the power constraint

$$E\{|x_i|^2\} \leq P_x. \quad (1)$$

$n_{Di}$  be the additive Gaussian noise that follows normal distribution.

Then, the received signals at destination  $\mathcal{D}$  during three time slots are

$$y_{D1} = f_1 x_1 + n_{D1}, \quad (2)$$

$$y_{D2} = f_2 x_2 + n_{D2}, \quad (3)$$

$$y_{D3} = f_3 x_3 + n_{D3}, \quad (4)$$

which can be combined to

$$\mathbf{y}_{DT} = \begin{bmatrix} y_{D1} \\ y_{D2} \\ y_{D3} \end{bmatrix} = \underbrace{\begin{bmatrix} f_1 & 0 & 0 \\ 0 & f_2 & 0 \\ 0 & 0 & f_3 \end{bmatrix}}_{\mathbf{A}_{DT}} \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} n_{D1} \\ n_{D2} \\ n_{D3} \end{bmatrix}}_{\mathbf{z}_{DT}}. \quad (5)$$

Note that  $\mathbf{x}$  is the transmit data vector of three sources  $\mathbf{x} \triangleq [x_1, x_2, x_3]^T$  and

$$\mathbf{x} \in \Omega_{\mathbf{x}}, \quad (6)$$

where  $\Omega_{\mathbf{x}}$  is the data vector alphabet set. Hence the decoding procedure for DT scheme will simply be

$$\hat{\mathbf{x}}_{DT} = \arg \min_{\mathbf{x} \in \Omega_{\mathbf{x}}} \|\mathbf{y}_{DT} - \mathbf{A}_{DT} \mathbf{x}\|^2. \quad (7)$$

The sum rate at destination  $\mathcal{D}$  for DT scheme will be

$$R_{DT} = \frac{1}{3} \log \det (\mathbf{I}_3 + P_x \mathbf{A}_{DT} \mathbf{A}_{DT}^H). \quad (8)$$

The one-third factor above is the natural consequence of time sharing.

### B. Scheme 2: Analog Network Coding (ANC)

Regarding this scheme, in the first phase all source nodes transmit simultaneously to relay  $\mathcal{R}$  and destination  $\mathcal{D}$  in one time slot; while the second phase is the transmission from relay  $\mathcal{R}$  to destination  $\mathcal{D}$  during the remaining two time slots.

At the end of first phase, the received signal at destination  $\mathcal{D}$  through direct links is

$$\begin{aligned} y_D^{[1]} &= f_1 x_1 + f_2 x_2 + f_3 x_3 + n_D^{[1]} \\ &= [f_1, f_2, f_3] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + n_D^{[1]} \\ &= \mathbf{f}^T \mathbf{x} + n_D^{[1]}, \end{aligned} \quad (9)$$

where superscript  $\{\cdot\}^{[1]}$  denotes the first phase; the direct link channel vector  $\mathbf{f} \in \mathbb{C}^3$  is defined as

$$\mathbf{f} \triangleq [f_1, f_2, f_3]^T. \quad (10)$$

Additive Gaussian noise is denoted as  $n_D^{[1]}$  and follows normal distribution.

The received signal at relay  $\mathcal{R}$  at the end of first phase is

$$\begin{aligned} \mathbf{y}_R &= \begin{bmatrix} y_{R1} \\ y_{R2} \end{bmatrix} \\ &= \underbrace{\begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \end{bmatrix}}_{\mathbf{H}} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \mathbf{n}_R, \end{aligned} \quad (11)$$

or equivalently

$$\mathbf{y}_R = \mathbf{H}\mathbf{x} + \mathbf{n}_R, \quad (12)$$

where  $\mathbf{y}_R = [y_{R1}, y_{R2}]^T$  is the received vector at relay with two antennas;  $\mathbf{n}_R = [n_{R1}, n_{R2}]^T$  is the additive Gaussian noise vector at relay;  $h_{ri}$  is the channel coefficient between source node  $\mathcal{S}_i$  and relay antenna  $r$ .

If we denote the channel vector of all sources to relay antenna  $r$  as

$$\mathbf{h}_r = [h_{r1}, h_{r2}, h_{r3}]^T \in \mathbb{C}^3, \quad (13)$$

the overall channel matrix between all sources and relay  $\mathcal{R}$  is

$$\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2]^T. \quad (14)$$

All channel coefficients and additive noise elements are generated i.i.d. according to a normal distribution  $\mathcal{CN}(0, 1)$ .

In the second phase, first, relay  $\mathcal{R}$  constructs the following signal vector  $\mathbf{t}$  based on the received signals on each antenna ( $y_{R1}$  and  $y_{R2}$ ),

$$\begin{aligned} \mathbf{t} &= \begin{bmatrix} t_1 \\ t_2 \end{bmatrix} = \begin{bmatrix} \beta_1 y_{R1} \\ \beta_2 y_{R2} \end{bmatrix} \\ &= \underbrace{\begin{bmatrix} \beta_1 & 0 \\ 0 & \beta_2 \end{bmatrix}}_{\mathbf{B}} (\mathbf{H}\mathbf{x} + \mathbf{n}_R). \end{aligned} \quad (15)$$

where  $\beta_r$ ,  $r = 1, 2$  is the scaling factor to meet the per-antenna power constraint  $P_R$  at relay  $\mathcal{R}$  given by

$$\begin{aligned} \beta_r &= \sqrt{\frac{P_R}{E\{|y_{Rr}|^2\}}} \\ &= \sqrt{\frac{P_R}{P_x \|\mathbf{h}_r\|^2 + 1}}. \end{aligned} \quad (16)$$

Then, relay  $\mathcal{R}$  will transmit  $t_1$  and  $t_2$  in two time slots as follows,

$$[y_D^{[2]}(1), y_D^{[2]}(2)] = [g_1, g_2] \begin{bmatrix} t_1 & 0 \\ 0 & t_2 \end{bmatrix} + [n_D^{[2]}(1), n_D^{[2]}(2)], \quad (17)$$

where superscript  $\{\cdot\}^{[2]}$  denotes the second phase;  $g_r$ ,  $r = 1, 2$ , is the channel coefficient between relay antenna  $r$  and destination  $\mathcal{D}$ .

Equivalently, equation (17) can be written as

$$\begin{aligned} \mathbf{y}_D^{[2]} &= \begin{bmatrix} y_D^{[2]}(1) \\ y_D^{[2]}(2) \end{bmatrix} \\ &= \begin{bmatrix} g_1 & 0 \\ 0 & g_2 \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \end{bmatrix} + \mathbf{n}_D^{[2]} \\ &= \mathbf{G}_0 \mathbf{t} + \mathbf{n}_D^{[2]}, \end{aligned} \quad (18)$$

where matrix  $\mathbf{G}_0$  is defined as

$$\mathbf{G}_0 \triangleq \begin{bmatrix} g_1 & 0 \\ 0 & g_2 \end{bmatrix}, \quad (19)$$

and  $\mathbf{n}_D^{[2]} = [n_D^{[2]}(1), n_D^{[2]}(2)]^T$ .

Plug in  $\mathbf{t}$  of (15) into equation (18), we will have the received signal at destination  $\mathcal{D}$  at the end of the second phase as

$$\mathbf{y}_D^{[2]} = \mathbf{G}_0 \mathbf{B} \mathbf{H} \mathbf{x} + \mathbf{G}_0 \mathbf{B} \mathbf{n}_R + \mathbf{n}_D^{[2]}. \quad (20)$$

Recall the received signals in the first phase as equation (9) and in the second phase as equation (20) at destination  $\mathcal{D}$  for this scheme, we have

$$\begin{cases} y_D^{[1]} = \mathbf{f}^T \mathbf{x} + n_D^{[1]}, \\ \mathbf{y}_D^{[2]} = \mathbf{G}_0 \mathbf{B} \mathbf{H} \mathbf{x} + \mathbf{G}_0 \mathbf{B} \mathbf{n}_R + \mathbf{n}_D^{[2]}. \end{cases} \quad (21)$$

Then, after one transmission realization, we can combine received signals at destination  $\mathcal{D}$  during two phases (three time slots), based on which to decode the data vector  $\mathbf{x}$ , as follows,

$$\mathbf{y}_{ANC} = \begin{bmatrix} y_D^{[1]} \\ \mathbf{y}_D^{[2]} \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{f}^T \\ \mathbf{G}_0 \mathbf{B} \mathbf{H} \end{bmatrix}}_{\mathbf{A}_{ANC}} \mathbf{x} + \underbrace{\begin{bmatrix} n_D^{[1]} \\ \mathbf{G}_0 \mathbf{B} \mathbf{n}_R + \mathbf{n}_D^{[2]} \end{bmatrix}}_{\mathbf{z}_{ANC}}. \quad (22)$$

Hence the decoding procedure for ANC scheme will be

$$\hat{\mathbf{x}}_{ANC} = \arg \min_{\mathbf{x} \in \Omega_{\mathbf{x}}} \|\mathbf{y}_{ANC} - \mathbf{A}_{ANC} \mathbf{x}\|^2. \quad (23)$$

Let  $\mathbf{K}_{ANC}$  be the covariance matrix of effective noise vector  $\mathbf{z}_{ANC}$  at destination, i.e.,

$$\begin{aligned} \mathbf{K}_{ANC} &\triangleq \mathbb{E}\{\mathbf{z}_{ANC} \mathbf{z}_{ANC}^H\} \\ &= \begin{bmatrix} 1 & \mathbf{0}_2^T \\ \mathbf{0}_2 & \mathbf{G}_0 \mathbf{B} \mathbf{B}^H \mathbf{G}_0^H + \mathbf{I}_2 \end{bmatrix}, \end{aligned} \quad (24)$$

where  $\mathbb{E}\{\cdot\}$  is the expectation operation;  $\mathbf{0}_2 = [0, 0]^T$  is the all-zero column vector in two dimension.

The sum rate at destination  $\mathcal{D}$  for ANC scheme will be

$$R_{ANC} = \frac{1}{3} \log \det (\mathbf{I}_3 + P_x \mathbf{A}_{ANC} \mathbf{A}_{ANC}^H \mathbf{K}_{ANC}^{-1}). \quad (25)$$

### C. Scheme 3: Space-Time Analog Network Coding with Alamouti (STANC-Alamouti)

In this scheme, the first transmission phase will be the same as in ANC scheme. In other words, at the end of first phase, the received signal at the destination  $\mathcal{D}$  will be as equation (9) and the received signals at the relay  $\mathcal{R}$  will be as equation (12).

After constructing the signal vector  $\mathbf{t}$  as equation (15), relay  $\mathcal{R}$  will combine analog network coding with Alamouti scheme. According to Alamouti scheme, after obtaining  $\mathbf{t} = [t_1, t_2]^T$ , relay  $\mathcal{R}$  will transmit  $[t_1, t_2]^T$  in the second time slot and  $[-t_2^*, t_1^*]^T$  in the third time slot.

Denote the corresponding received signals at destination  $\mathcal{D}$  in the second phase (with two time slots) as  $y_D^{[2]}(1)$  and  $y_D^{[2]}(2)$ , then

$$[y_D^{[2]}(1), y_D^{[2]}(2)] = [g_1, g_2] \begin{bmatrix} t_1 & -t_2^* \\ t_2 & t_1^* \end{bmatrix} + [n_D^{[2]}(1), n_D^{[2]}(2)]. \quad (26)$$

Destination  $\mathcal{D}$  arranges the received signals into a vector  $\mathbf{y}_D^{[2]} = [y_D^{[2]}(1), -y_D^{[2]}(2)^*]^T$ , which can be rewritten as

$$\begin{aligned} \mathbf{y}_D^{[2]} &= \begin{bmatrix} y_D^{[2]}(1) \\ -y_D^{[2]}(2)^* \end{bmatrix} \\ &= \begin{bmatrix} g_1 & g_2 \\ -g_2^* & g_1^* \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \end{bmatrix} + \mathbf{n}_D^{[2]} \\ &= \mathbf{G}_1 \mathbf{t} + \mathbf{n}_D^{[2]}, \end{aligned} \quad (27)$$

where matrix  $\mathbf{G}_1$  is defined as

$$\mathbf{G}_1 \triangleq \begin{bmatrix} g_1 & g_2 \\ -g_2^* & g_1^* \end{bmatrix}, \quad (28)$$

and  $\mathbf{n}_D^{[2]} = [n_D^{[2]}(1), -n_D^{[2]}(2)^*]^T$ .

Plug in  $\mathbf{t}$  of (15) into equation (18), we will have the received signal at destination  $\mathcal{D}$  at the end of the second phase as

$$\mathbf{y}_D^{[2]} = \mathbf{G}_1 \mathbf{B} \mathbf{H} \mathbf{x} + \mathbf{G}_1 \mathbf{B} \mathbf{n}_R + \mathbf{n}_D^{[2]}. \quad (29)$$

Recall the received signals in the first phase as equation (9) and in the second phase as equation (29) at destination  $\mathcal{D}$  for this scheme, we have

$$\begin{cases} y_D^{[1]} = \mathbf{f}^T \mathbf{x} + n_D^{[1]}, \\ \mathbf{y}_D^{[2]} = \mathbf{G}_1 \mathbf{B} \mathbf{H} \mathbf{x} + \mathbf{G}_1 \mathbf{B} \mathbf{n}_R + \mathbf{n}_D^{[2]}. \end{cases} \quad (30)$$

Finally, after one transmission realization, we combine received signals at destination  $\mathcal{D}$  based on which to decode the data vector  $\mathbf{x}$ , during two phases (three time slots) as

$$\begin{aligned} \mathbf{y}_{STANC} &= \begin{bmatrix} y_D^{[1]} \\ \mathbf{y}_D^{[2]} \end{bmatrix} \\ &= \underbrace{\begin{bmatrix} \mathbf{f}^T \\ \mathbf{G}_1 \mathbf{B} \mathbf{H} \end{bmatrix}}_{\mathbf{A}_{STANC}} \mathbf{x} + \underbrace{\begin{bmatrix} n_D^{[1]} \\ \mathbf{G}_1 \mathbf{B} \mathbf{n}_R + \mathbf{n}_D^{[2]} \end{bmatrix}}_{\mathbf{z}_{STANC}}. \end{aligned} \quad (31)$$

The decoding procedure can be expressed as

$$\hat{\mathbf{x}}_{STANC} = \arg \min_{\mathbf{x} \in \Omega_{\mathbf{x}}} \|\mathbf{y}_{STANC} - \mathbf{A}_{STANC} \mathbf{x}\|^2. \quad (32)$$

Let  $\mathbf{K}_{STANC}$  be the covariance matrix of effective noise vector  $\mathbf{z}_{STANC}$  at destination, i.e.,

$$\begin{aligned} \mathbf{K}_{STANC} &\triangleq \mathbb{E} \{ \mathbf{z}_{STANC} \mathbf{z}_{STANC}^H \} \\ &= \begin{bmatrix} 1 & \mathbf{0}_2^T \\ \mathbf{0}_2 & \mathbf{G}_1 \mathbf{B} \mathbf{B}^H \mathbf{G}_1^H + \mathbf{I}_2 \end{bmatrix}. \end{aligned} \quad (33)$$

The sum rate at destination  $\mathcal{D}$  for STANC scheme will be

$$R_{STANC} = \frac{1}{3} \log \det (\mathbf{I}_3 + P_x \mathbf{A}_{STANC} \mathbf{A}_{STANC}^H \mathbf{K}_{STANC}^{-1}). \quad (34)$$

The comparison of different schemes within three slots is shown in Table 1.

Table 1: Different Schemes for MARC model

MARC model	Time Slot 1	Time Slot 2	Time Slot 3
DT	$S_1 : x_1$	$S_2 : x_2$	$S_3 : x_3$
ANC	$S_1 : x_1$ $S_2 : x_2$ $S_3 : x_3$	$R : \begin{bmatrix} t_1 \\ 0 \end{bmatrix}$	$R : \begin{bmatrix} 0 \\ t_2 \end{bmatrix}$
STANC-Alamouti	$S_1 : x_1$ $S_2 : x_2$ $S_3 : x_3$	$R : \begin{bmatrix} t_1 \\ t_2 \end{bmatrix}$	$R : \begin{bmatrix} -t_2^* \\ t_1^* \end{bmatrix}$

#### IV. SIMULATION STUDIES

In this section, we present numerical results to evaluate the performance of all possible schemes for MARC system model. Let  $P_x = P_R$ , i.e., the transmission power constraint at sources and relay are equivalent. Assume that each transmission experiences independent fading paths and the corresponding fading channel coefficients are assumed to be zero-mean Gaussian random variables of equal power, while the additive zero-mean white Gaussian noise is with standard variance.

With the average of 100000 randomly generated channel realizations, we show in Fig. 2 the sum rate comparisons of three possible schemes. We can see that ANC and STANC outperforms direct transmission unless the signal power is extremely low. Furthermore, STANC has additional 1.5-2dB gain over ANC scheme.

In Fig. 3, with the same simulation setup, we investigate the bit error rate with different schemes. Still ANC and STANC outperforms direct transmission and STANC further improves the performance.

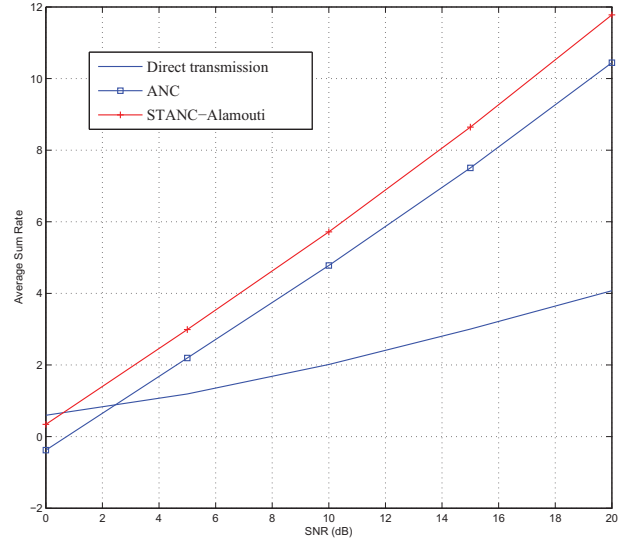


Fig. 2. Sum Rate Comparison for Different Schemes

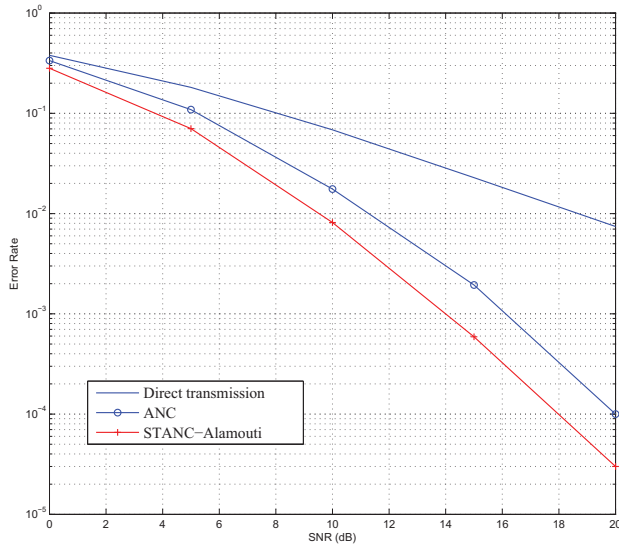


Fig. 3. BER Comparison for Different Schemes

## V. CONCLUSIONS

In this paper, we investigate space-time analog network coding (STANC) in multiple-access relay channels (MARC) system model, where three sources communicate to a common destination through a two-antenna relay with direct links. We discuss several possible transmission schemes under three time slots constraint: (i) direct transmission (DT); (ii) analog network coding (ANC); (iii) space-time analog network coding with alamouti scheme (STANC-Alamouti). Simulation studies show that STANC with alamouti scheme outperform other schemes regarding sum rate and bit error rate performance at the destination.

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