Full Space-Time Network Code

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***Abstract*—Cooperative technology could improve communication reliability by exploiting transmit diversity. However, the issue of imperfect frequency and timing synchronization makes it a challenge in practice. In this paper, we propose a novel cooperative communication scheme based on full space-time network code (FSTNC), which can maintain a stable network throughput and overcome the imperfect frequency and timing synchronization. Compared with space-time network code (STNC), FSTNC considers the relay cooperation and transmission order, and thus it further enhances the system reliability and efficiency. To verify the performance of the proposed scheme and reveal its advantage, we derive the exact symbol-error rate (SER) expressions for arbitrary order M-ary Phase Shift Keying ($\mathcal{M}$-PSK) modulation and verify by simulations. The simulation results show that the proposed FSTNC scheme outperforms the conventional STNC scheme in terms of the SER performance. The advantage is more distinct when the relay transmission order is taken into consideration.**

I. Introduction

It is well known that spatial diversity can be utilized to mitigate the multipath effect and help improve the performance of communication systems when operating in radio frequency environments characterized by multipath propagation [1]. To make use of spatial diversity, cooperative communications have recently received much attention [2].

In cooperative communications, relays can retransmit the overheard information to the destination node to improve the transmission reliability by exploiting the advantage of spatial diversity [3]. Various cooperative diversity protocols have been proposed and analyzed [4], [5]. Some researchers in cooperative communications focused on simultaneous transmission by using frequency-division multiple access (FDMA) or code-division multiple access (CDMA) with the assumption of perfect frequency and timing synchronization among cooperative nodes [6]. However, such an assumption is difficult to meet in practice. For timing synchronization, the coordination to make signals received simultaneously at the destination is challenging due to different propagation time among nodes, processing time at each radio and timing estimation error. For frequency synchronization, each node has an independent local oscillator generating a transmit frequency with a certain deviation from the nominal. Therefore, each node has a distinct transmit frequency. Time-division multiple access (TDMA) could overcome the imperfect synchronization issue that hinders two or more nodes from transmitting at the same time. However, the enlarged transmission delay makes it impractical [7].

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In order to solve the issues mentioned above, some researchers proposed space-time network code (STNC) scheme [8]. STNC is a newly designed transmission method, where signals are still transmitted based on the TDMA protocol to eliminate the issue of imperfect frequency and timing synchronization among cooperative nodes, while the relay combines the overheard of multiple signals into a single signal by network coding to reduce the transmission delay. In a network of N source nodes, R relays, and a destination node, STNC provides a diversity order of $(R+1)$ for each symbol with $(N+R)$ time slots. However, the traditional TDMA cooperative communications need $N(R+1)$ time slots, and the FDMA and CDMA based methods need $2N$ time slots for N usually greater than R.

STNC consists of two phases: source transmission phase and relay transmission phase. In the first phase, a source node broadcasts its information to relays. Then, the relays forward the overheard information to the destination node in the second phase cooperatively. Compared with the traditional cooperative communication method, STNC is more practical for utilizing spatial diversity. More recently, STNC has been properly used in the vehicular network [9], where the mobile channel is highly time variant and challenge, and thus encourage many researchers on the channel modeling [10]–[13] and novel techniques [14], [15] to overcome these issues.

In this paper, we propose a full space-time network code (FSTNC) scheme to further improve the spatial diversity. Similar to STNC, FSTNC is also composed of two phases. The main difference between STNC and FSTNC is that in relay transmission phase, the relay cooperation would be considered. The prior forwarding information from a relay will be received by both destination node and the rest of relays.

Furthermore, we optimize the relay transmission order which is determined by the channel conditions between source nodes and relay nodes. With the relay cooperation and transmission order considered, the spatial diversity is enhanced.

Compared with STNC, FSTNC's relay order is optimized

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and relays could not only receive signals from the source nodes, but also from other relays. The simulation results show that the proposed FSTNC scheme has better performance compared with that of the conventional STNC scheme.

The rest of this paper is organized as follows. The system model and the FSTNC scheme are introduced in Section II. Signal detection and SER analysis are provided in Section III. The performance is evaluated in Section IV. Conclusions are drawn in Section V.

II. Proposed FSTNC Scheme

A. A Description of STNC

We consider a wireless network consisting of N source nodes denoted as $\{U_1, U_2, \ldots, U_N\}$, which have their own information to be delivered to a destination node U_0. Assume R relays, denoted as $\{R_1, R_2, \ldots, R_R\}$, help the source nodes forward the transmitted information. The channel between an arbitrary receiver u and transmitter v is denoted as h_{uv} and modelled as the narrow band Rayleigh fading channel with zero mean and variance σ_{uv}^2, i.e., $h_{uv} \sim \mathcal{CN}(0, \sigma_{uv}^2)$. Each node is equipped with a single antenna. Moreover, any two channels are considered to be independent due to the large separation between any two antennas. s_n is the signature waveform corresponding to the signal x_n. The cross correlation between $s_n(t)$ and $s_m(t)$ is $\rho_{nm} = \langle s_n(t), s_m(t)\rangle$, where $\langle s_n(t), s_m(t)\rangle = \frac{1}{T}\int_0^T s_n(t){s^*}_m(t)dt$ is the inner product between $s_n(t)$ and $s_m(t)$ with the symbol interval T. We also have $\rho_{nn} = \langle s_n(t), s_n(t)\rangle = 1$.

Fig. 1 (a) shows the transmitting procedure of STNC. In the source transmission phase, the source node U_n for $n = 1, 2, \ldots, N$ is assigned the time slot T_n to broadcast its symbol x_n to the destination node U_0 and all relays R_r for $r = 1, 2, \ldots, R$ as illustrated in Fig. 1 (b). The signals received at U_0 and R_r are

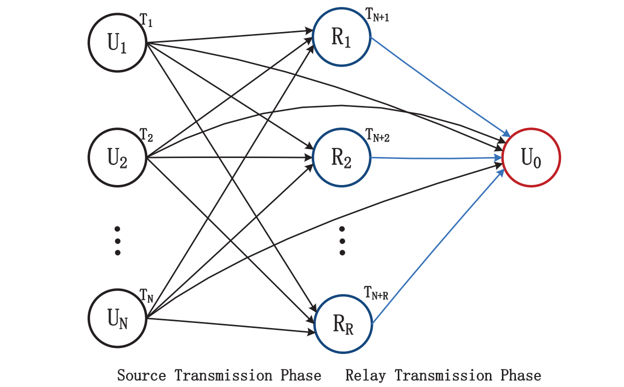
$$y_{0n}(t) = h_{0n}\sqrt{P_{nn}}x_n s_n(t) + w_{0n}(t) \tag{1}$$

and

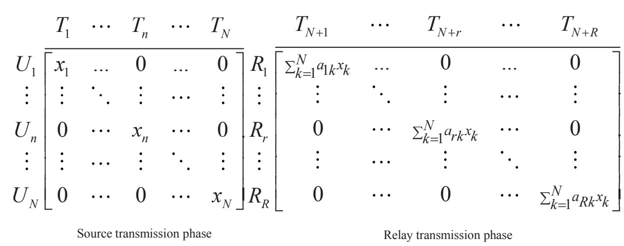
$$y_{rn}(t) = h_{rn}\sqrt{P_{nn}}x_n s_n(t) + w_{rn}(t) \tag{2}$$

respectively, where h_{0n} is the channel condition between source node U_n and destination node U_0, h_{rn} is the channel condition between source node U_n and relay R_r, P_{nn} is the transmit power of source node U_n, and $w_{0n}(t)$ and $w_{rn}(t)$ are zero-mean and N_0-variance additive white Gaussian noise (AWGN) corresponding to the signals $y_{0n}(t)$ and $y_{rn}(t)$, respectively.

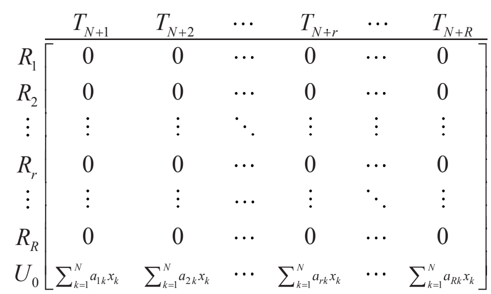
In the relay transmission phase, R_r forms a single linearly coded signal, which is a linear combination of symbols overheard from the N source nodes, and transmits the coded signal to the destination node in its dedicated time slot T_{N+r}. Fig.1 (c) shows the received signals at relays and destination node. The decode and forward (DF) protocol is adopted here and thus each relay decodes the original signals $\{x_1, x_2, ..., x_N\}$ according to Eq. (2) and re-encode them into a linearly coded signal. The detection state, a success or a failure in detecting



(a) The transmitting procedure of STNC



(b) STNC utilizing transform-based coding



(c) Received signals at relays and destination node

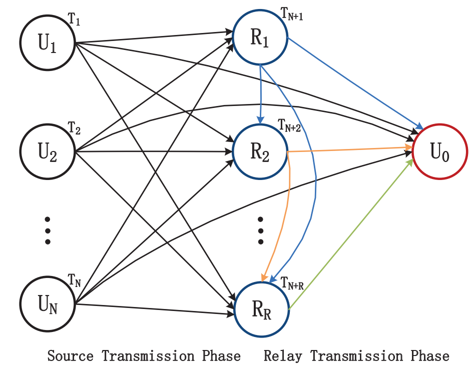
Fig. 1. The STNC scheme

a symbol is determined by the received signal-to-noise ratio (SNR). When SNR is larger than a given threshold, the detection is successful. Otherwise, error occurs [16].

B. System Model of FSTNC

In the proposed FSTNC scheme, the source transmission phase is same with the STNC scheme while the relay transmission phase is different. As illustrated in Fig. 2 (a), the R_r's linear combined symbol is not only overheard from the N source nodes, but also the $(r-1)$ previous transmission relays R_i for $i = 1, 2, ..., (r-1)$. The transmitted coded signal will be received by both the rest relays and the destination node.

FSTNC makes use of the channel conditions between which are not isolated and can hear the signals transmitted by the previous relays. In T_{N+r} slot, not only U_0 could receive the signals, but also R_j for $j = (r+1), (r+2), \ldots, R$ as shown in Fig. 2 (b). With this method, R_j's forwarding probability of success will be improved with the help of R_r. For example, if the channel condition between R_j and source node U_n is bad, R_j would be an inactive relay, which is not able to decode



(a) The tansmitting procedure of FSTNC

	T_{N+1}	T_{N+2}	$\cdots$	T_{N+r}	$\cdots$	T_{N+R}
R_1	0	0	$\cdots$	0	$\cdots$	0
R_2	$\sum_{k=1}^{N} a_{1k}x_k$	0	$\cdots$	0	$\cdots$	0
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$
R_r	$\sum_{k=1}^{N} a_{1k}x_k$	$\sum_{k=1}^{N} a_{2k}x_k$	$\cdots$	0	$\cdots$	0
$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$	$\ddots$	$\vdots$
R_R	$\sum_{k=1}^{N} a_{1k}x_k$	$\sum_{k=1}^{N} a_{2k}x_k$	$\cdots$	$\sum_{k=1}^{N} a_{rk}x_k$	$\cdots$	0
U_0	$\sum_{k=1}^{N} a_{1k}x_k$	$\sum_{k=1}^{N} a_{2k}x_k$	$\cdots$	$\sum_{k=1}^{N} a_{rk}x_k$	$\cdots$	$\sum_{k=1}^{N} a_{Rk}x_k$

(b) Received signals at relays and destination node

Fig. 2. The proposed FSTNC scheme

and forward message. However, if it could receive the signal from R_r and decode it correctly, the inactive relay becomes an active relay.

As mentioned above, the received signal at U_0 and R_j from the rth relay in the relay transmission phase is

$$y_{jr}(t) = h_{jr} \sum_{k=1}^{N} \sqrt{\widetilde{P}_{rk}} x_k s_k(t) + w_{jr}(t) \tag{3}$$

and

$$y_{0r}(t) = h_{0r} \sum_{k=1}^{N} \sqrt{\widetilde{P}_{rk}} x_k s_k(t) + w_{0r}(t) \tag{4}$$

respectively, where h_{jr} is the channel condition between relay R_j and R_r, h_{0r} is the channel condition between relay R_r and destination node U_0, $\widetilde{P}_{rk} = \{0, P_{rk}\}$, where $\widetilde{P}_{rk} = P_{rk}$ when R_r decode x_k correctly and $P_{rk} = 0$ otherwise, and $w_{0r}(t) \sim \mathcal{CN}(0, N_0)$.

C. Issue of Relay Transmission Order

FSTNC also considers the relay transmission order's impact on the active relays number, i.e., the number of relays that can receive the information from source nodes and decode successfully. For example, we consider two relays denoted as R_A and R_B, respectively, and assume that R_A is inactive and R_B is active. If we consider the channel condition properly and let R_B relay before R_A. In this way, R_A can be turned into an active relay.

Therefore, we optimize the relay transmission order. In relay transmission phase, the relays transmission order is based on the average channel state between the N source nodes and the rth relay, which is denoted as o_r and given by

$$o_r = \frac{\sum_{n=1}^{N} |h_{rn}|}{N}. \tag{5}$$

We sort the values of o_r for $r = 1, 2, ..., R$ in descending order, which determines the relay transmission order. Simply to say, the higher the value of o_r is, the earlier the transmission order of R_r is.

III. Signal Detection and SER Analysis

A. Signal Detection

To detect a desired symbol, we assume that receivers have a full knowledge of channel state information, which can be acquired with the preamble in the transmitted signal. For the signal detection at the relays and the destination node U_0, a bank of matched-filtering and the maximal ratio combing (MRC) method are adopted similar to the conventional STNC scheme [8].

For the first relay, R_1 only receives one signal that contain symbol x_n from source node U_n. We use CDMA decoding method. By applying matched-filtering to signal $y_{1n}(t)$ with respect to signature waveform $s_n(t)$ to obtain

$$y_{1nn} = \langle y_{1n}(t), s_n(t) \rangle = h_{1n} \sqrt{P_{nn}} x_n + w_{1nn}. \tag{6}$$

For the relays R_r, $r > 1$, it receives r signals that contain symbol x_n from the source node U_n and the $(r-1)$ previous relays R_i for $i = 1, 2, ..., (r-1)$. It first exacts the rth soft symbols and then adopts the MRC method to detect the desired symbol. Similar to Eq. (6), we have

$$y_{rnn} = \langle y_{rn}(t), s_n(t) \rangle = h_{rn} \sqrt{P_{nn}} x_n + w_{rnn}. \tag{7}$$

For each signal $y_{ri}(t)$ for $i = 1, 2, ..., (r-1)$, R_r applies a bank of matched-filtering to the signal with respect to signature waveforms $s_m(t)$ for $m = 1, 2, ..., N$ to obtain

$$y_{rim} = \langle y_{ri}(t), s_m(t) \rangle = h_{ri} \sum_{k=1}^{N} \sqrt{\tilde{P}_{ik}} x_k \rho_{km} + w_{rim}. \tag{8}$$

Therefore we can form an $N \times 1$ vector comprised of the y_{rim}'s as

$$\mathbf{y}_{ri} = h_{ri} \mathbf{R} \mathbf{A}_i \mathbf{x} + \mathbf{w}_{ri} \tag{9}$$

where $\mathbf{y}_{ri} = [y_{ri1}, y_{ri2}, ..., y_{riN}]^T$, $\mathbf{A}_i = \mathrm{diag}\left\{\sqrt{\widetilde{P}_{i1}}, \sqrt{\widetilde{P}_{i2}}, ..., \sqrt{\widetilde{P}_{iN}}\right\}$, $\mathbf{x} = [x_1, x_2, ..., x_N]^T$, $\mathbf{w}_{ri} = [w_{ri1}, w_{ri2}, ..., w_{riN}]^T \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{R})$, and

$$\mathbf{R} = \begin{bmatrix} 1 & \rho_{21} & \cdots & \rho_{N1} \\ \rho_{12} & 1 & \cdots & \rho_{N2} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{1N} & \rho_{2N} & \cdots & 1 \end{bmatrix}. \tag{10}$$

We know that $\mathbf{R}$ is invertible and the corresponding inverse matrix is $\mathbf{R}^{-1}$. This could be easy to achieve since the combining of symbols is done within a relay node. The signal vector $\mathbf{y}_{ri}$ is then decorrelated to obtain

$$\widetilde{\mathbf{y}}_{ri} = \mathbf{R}^{-1}\mathbf{y}_{ri} = h_{ri}\mathbf{A}_i\mathbf{x} + \widetilde{\mathbf{w}}_{ri} \tag{11}$$

where $\widetilde{\mathbf{w}}_{ri} \sim \mathcal{CN}(0, N_0\mathbf{R}^{-1})$. Since $\mathbf{A}_i$ is a diagonal matrix, the soft symbol of x_n from the relay R_i is

$$\widetilde{y}_{rin} = h_{ri}\sqrt{\widetilde{P}_{in}}x_n + \widetilde{w}_{rin} \tag{12}$$

where $\widetilde{w}_{ri} \sim \mathcal{CN}(0, N_0\varepsilon_n)$ with ε_n being the nth diagonal element of matrix $\mathbf{R^{-1}}$ associated with symbol x_n.

At last, R_i forms an $r \times 1$ signal vector

$$\begin{aligned}\mathbf{y}_{rn} = \Big[&h_{rn}\sqrt{P_{nn}}, h_{r1}\sqrt{\widetilde{P}_{1n}}, h_{r2}\sqrt{\widetilde{P}_{2n}}, ...,\\ &h_{r(r-1)}\sqrt{\widetilde{P}_{(r-1)n}}\Big]^T x_n + \mathbf{w}_{rn}\end{aligned} \tag{13}$$

respectively, where $\mathbf{w}_{rn} \sim \mathcal{CN}(0, \mathbf{K}_{rn})$ and $\mathbf{K}_{rn} = \text{diag}\{N_0, N_0\varepsilon_n, ..., N_0\varepsilon_n, ..., N_0\varepsilon_n\}$. Let $\mathbf{a}_{rn} = \left[h_{rn}\sqrt{P_{nn}}, h_{r1}\sqrt{\widetilde{P}_{1n}}, h_{r2}\sqrt{\widetilde{P}_{2n}}, ..., h_{r(r-1)}\sqrt{\widetilde{P}_{(r-1)n}}\right]^T$ and $\mathbf{b}_{rn} = \left[\frac{h_{rn}\sqrt{P_{nn}}}{N_0}, \frac{h_{r1}\sqrt{\widetilde{P}_{1n}}}{(N_0\varepsilon_n)}, \frac{h_{r2}\sqrt{\widetilde{P}_{2n}}}{(N_0\varepsilon_n)}, ... \frac{h_{r(r-1)}\sqrt{\widetilde{P}_{(r-1)n}}}{(N_0\varepsilon_n)}\right]^T$, . then the desired symbol x_n at R_r can be detected based on

$$\widehat{x}_{rn} \triangleq \mathbf{b}_{rn}^{\mathcal{H}}\mathbf{y}_{rn} = a_{rn}x_n + w_{rn} \tag{14}$$

where $a_{rn} \triangleq \mathbf{b}_{rn}^{\mathcal{H}}\mathbf{a}_{rn} = \frac{P_{nn}|h_{rn}|^2}{N_0} + \sum\limits_{i=1}^{r-1}\frac{\widetilde{P}_{in}|h_{ri}|^2}{N_0\varepsilon_n}$ and $w_{rn} \triangleq \mathbf{b}_{rn}^{\mathcal{H}}\mathbf{w}_{rn} \sim \mathcal{CN}(0, \sigma_{rn}^2)$ with $\sigma_{rn}^2 = a_{rn}$.

Since the signal detection at the destination node U_0 is similar to that of relays, the decoded signal for x_n at U_0 is given by

$$\widehat{x}_{0n} = a_{0n}x_n + w_{0n} \tag{15}$$

where $a_{0n} = \frac{P_{nn}|h_{0n}|^2}{N_0} + \sum\limits_{r=1}^{R}\frac{\widetilde{P}_{rn}|h_{0r}|^2}{N_0\varepsilon_n}$ and $w_{0n} \sim \mathcal{CN}(0, \sigma_{0n}^2)$ with $\sigma_{0n}^2 = a_{0n}$.

B. SER Analysis

In order to verify the proposed FSTNC scheme's performance, we need to analyze the SER performance of the destination node U_0.

According to (14) and (15), the desired symbol x_n's SNR γ_{rn} at R_r and γ_{0n} at U_0 in FSTNC are

$$\gamma_{rn} = \frac{a_{rn}^2}{\sigma_{rn}^2} = \frac{P_{nn}|h_{rn}|^2}{N_0} + \sum_{i=1}^{(r-1)}\frac{\widetilde{P}_{in}|h_{ri}|^2}{N_0\varepsilon_n} \tag{16}$$

and

$$\gamma_{0n} = \frac{a_{0n}^2}{\sigma_{0n}^2} = \frac{P_{nn}|h_{0n}|^2}{N_0} + \sum_{r=1}^{R}\frac{\widetilde{P}_{rn}|h_{0r}|^2}{N_0\varepsilon_n} \tag{17}$$

respectively. As the conditional SER [17] for $\mathcal{M}$-PSK modulation with condition SNR for a generic set of channel coefficients $\{h_{uv}\}$ is

$$SER_{|\{h_{uv}\}} = \psi(\gamma) \triangleq \frac{1}{\pi}\int_0^{(M-1)\pi/M}\exp(-\frac{b\gamma}{\sin^2\theta})d\theta \tag{18}$$

where $b = \sin^2(\pi/M)$ and $\gamma = P|h_{uv}|^2 \Big/ N_0$ where P is the transmit power.

By averaging (18) with respect to the exponential random variable $|h_{uv}|^2$, the SER in detecting the signal transmitted in the channel h_{uv} can be shown as

$$SER = F(1 + \frac{bP\sigma_{uv}^2}{N_0\sin^2\theta}) \tag{19}$$

where $F(x(\theta)) = \frac{1}{\pi}\int_0^{(M-1)\pi/M}\frac{1}{x(\theta)}d\theta$.

Therefore, when $r = 1$, the SER to detect the signal x_n at the relay R_1 is given by

$$SER_{1n} = F(1 + \frac{bP_{nn}\sigma_{1n}^2}{N_0\sin^2\theta}). \tag{20}$$

When $r \geq 2$, let $\beta_{rn} \in \{0, 1\}$ for $r = 2, 3, .., R$ represents a detection state associated with x_n at R_r, then $\widetilde{P}_{rn} = P_{rn}\beta_{rn}$ and (16) could be rewritten as

$$\gamma_{rn|S_n} = \frac{P_{nn}|h_{rn}|^2}{N_0} + \sum_{i=1}^{r-1}\frac{P_{in}\beta_{in}|h_{ri}|^2}{N_0\varepsilon_n}. \tag{21}$$

All β_{rn}'s form a decimal number $S_n = [\beta_{1n}, \beta_{2n}, ...\beta_{rn}]_2$, where $[.]_2$ denotes a base-2 number, which represents one of 2^r network detection states associated with x_n of the r relay nodes. Since the detection is independent among relays, β_{rn}'s are independent Bernoulli random variables with a distribution

$$G(\beta_{rn}) = \begin{cases} 1 - SER_{rn} & if\ \beta_{rn} = 1 \\ SER_{rn} & if\ \beta_{rn} = 0 \end{cases} \tag{22}$$

where SER_{rn} is the SER of detecting x_n at R_r. Hence, the probability of x_n detection in state S_n at relay R_r is

$$P_r(S_n) = \prod_{i=1}^{r-1}G(\beta_{in}). \tag{23}$$

As we have $2^{(r-1)}$ detection state S_n, the conditional SER in detecting x_n can be calculated by

$$SER_{rn|\left\{h_{0n}, h_{in, i=1,2,...,(r-1)}\right\}} = \sum_{S_n=0}^{2^{(r-1)}-1} P_r(\widehat{x}_n \neq x_n|S_n)P_r(S_n) \tag{24}$$

where $P_r(\widehat{x}_n \neq x_n|S_n) = \psi(\gamma_{rn|S_n})$.

By averaging (24) with respect to the exponential random variables $\left\{|h_{0n}|^2, |h_{ri}|^2, i = 1, 2, ..., (r-1)\right\}$, the exact SER_{rn} in detecting x_n at R_r would be

$$\begin{aligned}SER_{rn} = &\sum_{S_n=0}^{2^{(r-1)}-1} F\left(\left(1 + \frac{\text{b}P_{nn}\sigma_{rn}^2}{N_0\sin^2\theta}\right) \times\right.\\ &\left.\prod_{i=1}^{r-1}\left(1 + \frac{bP_{in}\beta_{in}\sigma_{ri}^2}{N_0\varepsilon_n\sin^2\theta}\right)\right) \times \prod_{j=1}^{r-1}G(\beta_{jn}).\end{aligned} \tag{25}$$

With (20) and (25), SER_{rn} can be represented as

$$SER_{rn} = \begin{cases} F\left(1+\frac{bP_{nn}\sigma_{rn}^2}{N_0\sin^2\theta}\right) & \text{if } r=1 \\ \sum_{S_n=0}^{2^{(r-1)}-1} F\left(\left(1+\frac{bP_{nn}\sigma_{rn}^2}{N_0\sin^2\theta}\right)\times\right. & \text{if } r>=2 \\ \left.\prod_{i=1}^{r-1}\left(1+\frac{bP_{in}\beta_{in}\sigma_{ri}^2}{N_0\varepsilon_n\sin^2\theta}\right)\right)\prod_{i=1}^{r-1} G\left(\beta_{in}\right). & \end{cases} \quad (26)$$

After all relays' SER are calculated, we can obtain the SER performance at the destination node U_0 to decode the the symbol x_n, which is denoted as SER_n. Since the signal detection process at U_0 to decode x_n is similar to that at the relays, the formations of SER_n and SER_{rn} are quite alike. Therefore, the SER_n is given by

$$SER_n = \sum_{S_n=0}^{2^R-1} F\left(\left(1+\frac{\mathrm{b}P_{nn}\sigma_{0n}^2}{N_0\sin^2\theta}\right)\times\right.$$
$$\left.\prod_{r=1}^{R}\left(1+\frac{bP_{rn}\beta_{rn}\sigma_{0r}^2}{N_0\varepsilon_n\sin^2\theta}\right)\right)\times\prod_{i=1}^{R} G\left(\beta_{rn}\right). \quad (27)$$

IV. Simulation Results

A. Performance Comparison

In this section, we evaluate the proposed FSTNC scheme by simulations. We set the number of source nodes N as 10 and the modulation mode of BPSK is adopted here. We assume the R relays are placed with equal distance to the destination node U_0 and the N source nodes are placed with equal distance to the R relays. In order to deep evaluate the proposed FSTNC, three simulation scenarios are considered.

In scenario 1, we set $\sigma_{n0}^2 = \sigma_{0n}^2 = 1$, $\sigma_{nr}^2 = \sigma_{rn}^2 = 2$ and $\sigma_{r0}^2 = \sigma_{0r}^2 = \sigma_{rr}^2 = 6$ for all n and r. The transmit power P_n corresponding to x_n is assumed the same for all n and thus denoted as P and the uniform power allocation is used, where $P_{nn} = P/2$ and $P_{nr} = P/(2R)$ [7]. We also assume unit noise variance, i.e., $N_0 = 1$ and unique cross-correlations $\rho_{nm} = \rho$ for $n \neq m$. We take $\rho = 0$ for orthogonal codes.

Fig. 3 shows the SER performances comparison between the proposed FSTNC scheme and the conventional STNC scheme. From Fig. 3, the SER performance gets improved with the proposed FSTNC compared with that of the conventional STNC under the condition $R > 1$, when the number of active relay nodes is increased by exploiting the relay channel diversity gain in the FSTNC. However, under the condition $R = 1$, the FSTNC and STNC perform similarly since there is no relay cooperation.

In scenario 2, we analyze the relay transmission order effect on the SER performance. Assume $\sigma_{n1}^2 = \sigma_{1n}^2 = 1$ and $\sigma_{n2}^2 = \sigma_{2n}^2 = 6$ when the relay number is two. We then assume $\sigma_{n1}^2 = \sigma_{1n}^2 = 1$, $\sigma_{n2}^2 = \sigma_{n2}^2 = 2$ and $\sigma_{n3}^2 = \sigma_{3n}^2 = 6$ when the relay number is three. According to (5), we can calculate the average channel states between the R relays and N source nodes. When the transmission order is according to the descending order of the R average channel states, it is considered to be the best transmission order. Conversely, the worst transmission order is according to the ascending order of the average channel states. Moreover, we define the random order as the transmission order is arranged randomly without considering the channel states.

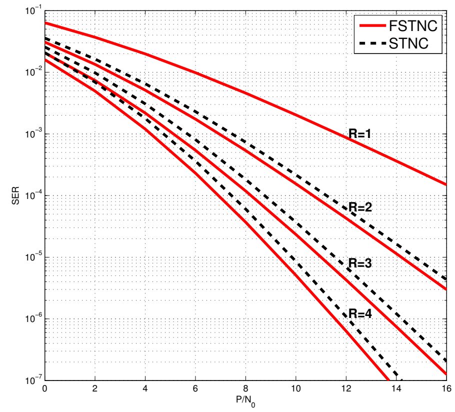


Fig. 3. SER performance comparisons between the proposed FSTNC scheme and the conventional STNC scheme.

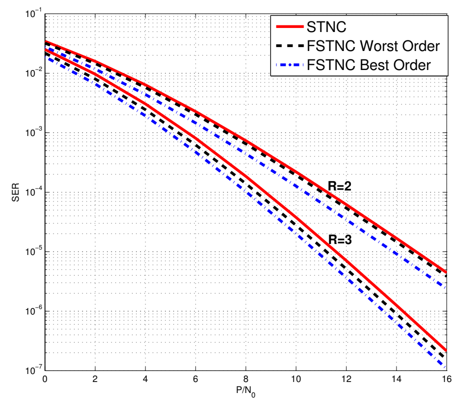


Fig. 4. SER performances comparisons among the proposed FSTNC schemes with different relay transmission orders.

Fig. 4 shows the SER performance comparisons among the proposed FSTNC scheme with different relay transmission orders. It is shown that the proposed FSTNC scheme outperforms the STNC scheme no matter which relay transmission order we adopt. It is observed that the SER performance of FSTNC with worst order is close to that of STNC when $R = 2$. However, when FSTNC works with the best order, the advantage of FSTNC is obvious. This implies that the performance of FSTNC with random order is between that of the best order scheme and the worst order scheme.

In scenario 3, we further verify the impact of the relay transmission order. Assume we have two relays and one source node, and we set one of the channel condition h between source node and relays static and the other one dynamic, then we can get the best order's SER performance and the worst order's SER performance with the help of Eq. (5). We denote the improvement percentage of the proposed FSTNC scheme

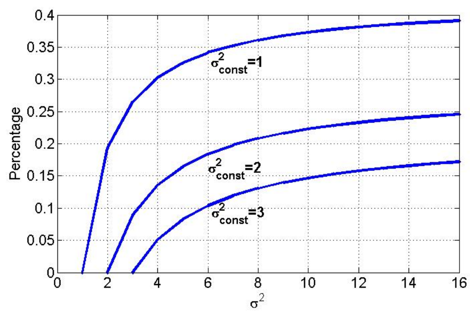


Fig. 5. The performance improvement of the proposed FSTNC scheme with the best relay transmission order.

with the best transmission order as

$$Per = \frac{SER_{\text{WorstOrder}} - SER_{\text{BestOrder}}}{SER_{\text{WorstOrder}}}. \quad (28)$$

Fig. 5 illustrates the performance improvement of the proposed FSTNC scheme with the best relay transmission order. We set $P/N_0 = 10$ dBm and the constant channel variance σ^2_{const} between source node and the relay is 1, 2 and 3, respectively. Label σ^2 represents the average value of the exponential random variable $|h|^2$. From Fig. 5, we know that the order has no effect on SER when the two channel variances are equal, and the maximum percentage is decreased when the channel variance is increased. When the channel variance is increased and larger than a threshold, the active relay number may not be changed and SER may be fixed, no matter we adopt the best transmission order or the worst one. Therefore, the growth curves become smooth and it suggests that the transmission order optimization can be more efficient in the poor channel condition.

B. Complexity and Energy Cost Analysis

The complexity of the proposed FSTNC scheme rarely increased compared with STNC scheme. FSTNC's source transmission phase is identical with STNC scheme. In relay transmission phase, the major difference is that FSTNC's relay could hear and deal with other relays transmitted signals. As the method is same with STNC's relays process source nodes transmitted signals, the time and space complexity are almost not increased. However, the proposed scheme's SER degrades much and the system performance is enhanced in the same circumstance.

Given the same SER, FSTNC and STNC's energy consumption is exactly the same. We know that the value of a special SER is decided by the power of active relays. For power allocation, relays' power are all equal to $P/(2R)$ in both STNC and FSTNC scheme. From (27), we can find that the useful energy consumption is equal when the value of SER is identical. However, FSTNC's energy efficiency is higher than STNC's. Under the same condition, the SER performance of the proposed FSTNC scheme is always better. We set the total power P identical in the two scheme. As the better SER performance means the greater active relay number, the proportion of useful power and total power is higher in the proposed FSTNC scheme. Consequently, FSTNC is more energy efficient.

V. Conclusion

In this paper, we proposed a novel FSTNC scheme and detailed the system model. Considering the relay cooperation and the transmission order, FSTNC helps improve the communication reliability compared with the traditional STNC scheme. We also described the signal detection and derive the exact SER expression to facilitate the performance comparison. The simulation results shows that the FSTNC improves the SER performance effectively.

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