MULTIPOINT-TO-POINT AND POINT-TO-MULTIPOINT SPACE-TIME NETWORK CODING

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ABSTRACT

Traditional cooperative communications can improve communication reliability. However, the simultaneous transmissions from multiple relays are challenging in practice due to the issue of imperfect frequency and timing synchronization. In this work, we propose space-time network codes (STNCs) that overcome the issue of imperfect synchronization, reduce the large transmission delay, and still provide full spatial diversity in multipoint-to-point (M2P) and point-to-multipoint (P2M) transmissions. Relays form single linearly-coded signals from the overheard symbols and transmit them to the destination, where multiuser detection is utilized to detect the desired symbol. For a network of N client nodes, M2P and P2M STNCs result in a diversity order of N with only $2N$ time slots, a significant reduction from N^2 time slots in traditional cooperative communications using TDMA.

Index Terms— Space-time network coding, cooperative communications, frequency synchronization, timing synchronization

1. INTRODUCTION

It is well-known that performance of communication systems degrades greatly when operating in radio frequency (RF) environments characterized by multipath propagation such as urban environments. Diversity techniques such as time diversity, frequency diversity, and spatial diversity can improve transmission reliability. Among these techniques, spatial diversity achieved by cooperative communications [1] has become recently attractive.

In cooperative communications, nodes acting as relays retransmit the overheard information to a destination. The distributed antennas among nodes are used to provide spatial diversity without the need to use multiple antennas at the source. Various cooperative diversity protocols have been proposed and analyzed in [2]-[9]. They often consist of two phases: source transmission and relay transmission. In the first phase, a source broadcasts its information to a destination and the relays, which then forward the overheard information to the destination in the second phase. The simultaneous transmissions from two or more relays are challenging in practice due to the imperfect frequency and timing synchronization, especially in mobile conditions where relays move at different speeds and in different directions.

In this work, we propose space-time network codes (STNCs) that overcome the issue of imperfect synchronization, reduce the large transmission delay, and still provide full spatial diversity for multipoint-to-point (M2P) and point-to-multipoint (P2M) transmissions. Relay nodes in a network form single linearly-coded signals from the overheard symbols and transmit them to the destination, where multiuser detection is utilized to detect the desired symbol. For a network of N cooperating nodes, M2P and P2M STNCs require only $2N$ time slots, a substantial reduction from N^2 time slots in traditional cooperative communications using TDMA [7], to achieve a spatial diversity order of N for each transmitted symbol. Both decode-and-forward (DF) and amplify-and-forward (AF) protocols in cooperative communications are considered. We derive the exact and the asymptotic symbol-error-rate (SER) expressions for general M-PSK modulation for DF protocol. For AF protocol, we offer the conditional SER expression given the channel knowledge. Simulations are provided to confirm the performance analysis.

The rest of this paper is organized as follows. After this introduction section, M2P and P2M STNCs are introduced in Section 2. Signal detection is followed in Section 3. The performance analysis is presented in Section 4. The simulations to confirm the analysis are also provided in Section 4. Lastly, we draw some conclusions in Section 5.

2. M2P AND P2M STNCS

We consider a wireless network consisting of $(N+1)$ nodes denoted as $U_0, U_1, U_2, ..., U_N$, where U_0 is a base node and $U_1, U_2, ..., U_N$ are client nodes in M2P and P2M setting. The channels between any two nodes, denoted as h_{uv}, are modeled as narrow-band Rayleigh fading with additive white Gaussian noise (AWGN), i.e., that $h_{uv} \sim \mathcal{CN}\left(0, \sigma_{uv}^2\right)$ with the channel variance σ_{uv}^2. Quasi-static channels are assumed, where the channels remain constant over each time slot and change independently between consecutive slots.

To protect transmitted symbols from interference, we use complex-valued signature waveforms. The cross-correlation between two signature waveforms $s_j(t)$ and $s_i(t)$ is $\rho_{ji} = \langle s_j(t), s_i(t)\rangle$, where $\langle f(t), g(t)\rangle \triangleq \int_0^T f(t)g^*(t)dt$ is the inner product between $f(t)$ and $g(t)$ with the symbol interval T. Each node is assumed to know all the signature waveforms of other nodes.

In M2P transmission, $U_1, U_2, ..., U_N$ wish to transmit symbols $x_1, x_2, ..., x_N$, respectively, to U_0. The STNC comprises source and relay transmission phases and can be represented by matrices

$$\begin{array}{c} \\ T_1 \\ \vdots \\ T_j \\ \vdots \\ T_N \end{array} \begin{array}{c} \begin{array}{ccccc} U_1 & \cdots & U_j & \cdots & U_N \end{array} \\ \left[\begin{array}{ccccc} a_{11}x_1 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \cdots & \vdots \\ 0 & \cdots & a_{jj}x_j & \cdots & 0 \\ \vdots & \cdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & a_{NN}x_N \end{array}\right] \end{array} \quad (1)$$

and

$$\begin{array}{c} \\ T_1 \\ \vdots \\ T_i \\ \vdots \\ T_N \end{array} \begin{array}{c} \begin{array}{ccccc} U_1 & \cdots & U_i & \cdots & U_N \end{array} \\ \left[\begin{array}{ccccc} \sum_{k\neq 1} a_{1k}x_k & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \cdots & \vdots \\ 0 & \cdots & \sum_{k\neq i} a_{ik}x_k & \cdots & 0 \\ \vdots & \cdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & \sum_{k\neq N} a_{Nk}x_k \end{array}\right] \end{array}, \quad (2)$$

respectively, where a_{ij}'s are signal coefficients and will be clarified later and T_i denotes the ith time slot. From the STNC, $2N$ time slots are required for transmissions of the N symbols to U_0. In the source transmission phase, each client node U_j for $j = 1, 2, ..., N$ is assigned a time slot, denoted

T_j, to broadcast its symbol x_j to the base node U_0 and other client nodes U_i, $i \neq j$. After this phase, U_i possesses a set of $(N-1)$ symbols $x_1, ..., x_k, ..., x_N$, $k \neq i$, from which it forms a single linearly-coded signal. U_i can detect the symbols and re-encode them if the decoding is successful [7], the so called DF protocol, or it simply amplifies the signals and combines them to form the single signal, the so called AF protocol. Note that this DF scheme follows selective-relaying protocol in the literature [4]. In the relay transmission phase, U_i transmits the coded signal to U_0 in its own dedicated time slot, denoted T_i.

In contrast with M2P, the single base node U_0 in P2M wants to transmit symbols $x_1, x_2, ..., x_N$ to $U_1, U_2, ..., U_N$, respectively. The STNC also consists of source and relay transmission phases and can be represented by matrices

$$\begin{array}{c} \\ T_1 \\ \vdots \\ T_j \\ \vdots \\ T_N \end{array} \begin{array}{c} U_0 \\ \hline \left[\begin{array}{c} a_{11}x_1 \\ \vdots \\ a_{jj}x_j \\ \vdots \\ a_{NN}x_N \end{array}\right] \end{array} \tag{3}$$

and

$$\begin{array}{c} \\ T_1 \\ \vdots \\ T_i \\ \vdots \\ T_N \end{array} \begin{array}{c} \begin{array}{ccccc} U_1 & \cdots & U_i & \cdots & U_N \end{array} \\ \hline \left[\begin{array}{ccccc} \sum_{k\neq 1} a_{1k}x_k & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \cdots & \vdots \\ 0 & \cdots & \sum_{k\neq i} a_{ik}x_k & \cdots & 0 \\ \vdots & \cdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & \sum_{k\neq N} a_{Nk}x_k \end{array}\right] \end{array}, \tag{4}$$

respectively, where the client nodes help one another in relaying transmitted symbols. As shown in (1)-(4), M2P and P2M STNCs have a similar form; the difference is in the origin of the source signal and the destination of the relaying signals. Due to the space limitation, we only present signal models, signal detection and performance analysis for M2P STNC.

An arbitrary symbol x_j, $j = 1, 2, ..., N$, in M2P is transmitted N times as shown in (1) and (2) by the source node and the relay nodes, and its associated transmit power $P_j = \sum_{i=1}^{N} P_{ij}$ is distributed among the N transmissions, where P_{jj} and P_{ij} are the power allocated at the source node U_j and a relay node U_i, respectively. The received signals at U_0 and U_i in the source transmission phase are

$$y_{j0}(t) = h_{j0}\sqrt{P_{jj}}x_j s_j(t) + w_{j0}(t) \tag{5}$$

and

$$y_{ji}(t) = h_{ji}\sqrt{P_{jj}}x_j s_j(t) + w_{ji}(t), \tag{6}$$

respectively, where $w_{j0}(t)$ and $w_{ji}(t)$ are zero-mean and N_0-variance AWGN. The received signal at U_0 from U_i in the relay transmission phase is

$$y_{i0}(t) = h_{i0}\sum_{\substack{k=1\\k\neq i}}^{N}\sqrt{\widetilde{P}_{ik}}x_k s_k(t) + w_{i0}(t), \tag{7}$$

including symbol x_j when $k = j$. In (7),

$$\widetilde{P}_{ik} = \begin{cases} P_{ik} & \text{if } U_i \text{ decodes } x_k \text{ correctly} \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

for the case of DF and

$$\widetilde{P}_{ik} = \frac{P_{ik}P_{kk}|h_{ki}|^2}{P_{kk}|h_{ki}|^2 + N_0} \tag{9}$$

for the case of AF and $w_{ij}(t)$ is zero-mean and $N_0 f_{i0}$-variance AWGN, where

$$f_{i0} = \begin{cases} 1 & \text{for DF} \\ 1 + \sum_{\substack{k=1\\k\neq i}}^{N} \frac{P_{ik}|h_{i0}|^2}{P_{kk}|h_{ki}|^2 + N_0} & \text{for AF} \end{cases} \tag{10}$$

is a factor representing the impact on U_0 due to the noise amplification at U_i.

3. SIGNAL DETECTION

To detect a desired symbol, a destination is assumed to have a full knowledge of the channel state information (CSI), which can be acquired using a preamble in the transmitted signal as usually done in practice such as IEEE 802.11 systems [10]. In the case of DF, a receiver is also assumed to know the decoding correctness (or the detection state) at the relay nodes. This can be done by using an N-bit indicator in the relaying signal, each bit dedicated to each transmitted symbol.

In M2P, U_0 detects an arbitrary symbol x_j based on N soft symbols extracted from N received signals containing the symbol. The first soft symbol of x_j comes directly from the source node U_j by applying matched-filtering to signal $y_{j0}(t)$ in (5) with respect to signature waveform $s_j(t)$ to obtain

$$y_{j0j} = \langle y_{j0}(t), s_j(t)\rangle = h_{j0}\sqrt{P_{jj}}x_j + w_{j0j}. \tag{11}$$

The remaining $(N-1)$ soft symbols are collected from $(N-1)$ relaying signals $y_{i0}(t)$ for $i \neq j$ in (7) as follows. For each signal $y_{i0}(t)$, U_0 applies a bank of matched-filtering to the signal with respect to signature waveforms $s_m(t)$, $m = 1, 2, ..., N$ and $m \neq i$, to obtain

$$y_{i0m} = \langle y_{i0}(t), s_m(t)\rangle = h_{i0}\sum_{\substack{k=1\\k\neq i}}^{N}\sqrt{\widetilde{P}_{ik}}x_k\rho_{km} + w_{i0m}. \tag{12}$$

Then it forms an $(N-1)\times 1$ vector comprising the y_{i0m}'s as

$$\mathbf{y}_{i0} = h_{i0}\mathbf{R}_i\mathbf{A}_i\mathbf{x}_i + \mathbf{w}_{i0}, \tag{13}$$

where $\mathbf{y}_{i0} = \left[y_{i01}, ..., y_{i0(i-1)}, y_{i0(i+1)}, ..., y_{i0N}\right]^T$, $\mathbf{x}_i = \left[x_1, ..., x_{i-1}, x_{i+1}..., x_N\right]^T$, $\mathbf{w}_{i0} = \left[w_{i01}, ..., w_{i0(i-1)}, w_{i0(i+1)}, ..., w_{i0N}\right]^T \sim \mathcal{CN}\left(\mathbf{0}, N_0 f_{i0}\mathbf{R}_i\right)$ with f_{i0} in (10),

$$\mathbf{R}_i = \left[\begin{array}{cccccc} 1 & \cdots & \rho_{(i-1)1} & \rho_{(i+1)1} & \cdots & \rho_{N1} \\ \vdots & \ddots & \vdots & \vdots & \cdots & \vdots \\ \rho_{1(i-1)} & \cdots & 1 & \rho_{(i+1)(i-1)} & \cdots & \rho_{N(i-1)} \\ \rho_{1(i+1)} & \cdots & \rho_{(i-1)(i+1)} & 1 & \cdots & \rho_{N(i+1)} \\ \vdots & \cdots & \vdots & \vdots & \ddots & \vdots \\ \rho_{1N} & \cdots & \rho_{(i-1)N} & \rho_{(i+1)N} & \cdots & 1 \end{array}\right], \tag{14}$$

and $\mathbf{A}_i = \operatorname{diag}\left\{\sqrt{\widetilde{P}_{i1}}, ..., \sqrt{\widetilde{P}_{i(i-1)}}, \sqrt{\widetilde{P}_{i(i+1)}}, ...\sqrt{\widetilde{P}_{iN}}\right\}$ with $\operatorname{diag}\{.\}$ denoting an diagonal matrix. Note that we have explicitly expressed the above equalities in terms of the index i, not in terms of the indices k and m as in (12). Note further that the soft symbol of x_j from this client node corresponds to the jth row for $i > j$ or the $(j-1)$st row for $i < j$ in the above equalities. The signal vector $\mathbf{y}_{i0}$ is then decorrelated, assuming that $\mathbf{R}_i$ is invertible with the inverse matrix $\mathbf{R}_i^{-1}$ to obtain

$$\widetilde{\mathbf{y}}_{i0} = \mathbf{R}_i^{-1}\mathbf{y}_{i0} = h_{i0}\mathbf{A}_i\mathbf{x}_i + \widetilde{\mathbf{w}}_{i0}, \tag{15}$$

where $\widetilde{\mathbf{w}}_{i0} \sim \mathcal{CN}\left(\mathbf{0}, N_0 f_{i0}\mathbf{R}_i^{-1}\right)$. Since $\mathbf{A}_i$ is a diagonal matrix, the soft symbol of x_j from U_i is

$$\widetilde{y}_{i0j} = h_{i0}\sqrt{\widetilde{P}_{ij}}x_j + \widetilde{w}_{i0j}, \tag{16}$$

where $\widetilde{w}_{i0} \sim \mathcal{CN}\left(0, N_0 f_{i0} r_{ij}\right)$ with r_{ij}, the diagonal element of matrix $\mathbf{R}_i^{-1}$ associated with symbol x_j. That is the jth or the $(j-1)$st diagonal element of the inverse matrix for $i > j$ or $i < j$, respectively. Since there are $(N-1)$ relaying signals from U_i, $i = 1, 2, ..., N$ and $i \neq j$, U_0 obtains $(N-1)$ soft symbols of x_j in the above manner.

Next, from the N soft symbols of x_j in (11) and (16), U_0 forms an $N \times 1$ signal vector

$$\mathbf{y}_{j0} = \mathbf{a}_{j0}x_j + \mathbf{w}_{j0}, \tag{17}$$

where $\mathbf{a}_{j0} = \left[h_{10}\sqrt{\widetilde{P}_{1j}}, ..., h_{j0}\sqrt{P_{jj}}, ..., h_{N0}\sqrt{\widetilde{P}_{Nj}}\right]^T$ and $\mathbf{w}_{j0} \sim \mathcal{CN}\left(0, \mathbf{K}_{j0}\right)$. We can show that $\mathbf{K}_{j0} = \operatorname{diag}\{N_0 f_{10} r_{1j},$

..., $N_0, ..., N_0 f_{N0} r_{Nj}\}$. Let $\mathbf{b}_{j0} = \left[\frac{h_{10}\sqrt{\widetilde{P}_{1j}}}{N_0 f_{10} r_{1j}}, ..., \frac{h_{j0}\sqrt{P_{jj}}}{N_0}, ..., \frac{h_{N0}\sqrt{\widetilde{P}_{Nj}}}{N_0 f_{N0} r_{Nj}}\right]^T$. Then the desired symbol x_j can be detected based on

$$\widehat{x}_{j0} \triangleq \mathbf{b}_{j0}^H \mathbf{y}_{j0} = a_{j0} x_j + w_{j0}, \tag{18}$$

where

$$a_{j0} \triangleq \mathbf{b}_{j0}^H \mathbf{a}_{j0} = \frac{P_{jj}|h_{j0}|^2}{N_0} + \sum_{\substack{i=1\\ i\neq j}}^{N} \frac{\widetilde{P}_{ij}|h_{i0}|^2}{N_0 f_{i0} r_{ij}} \tag{19}$$

and $w_{j0} \triangleq \mathbf{b}_{j0}^H \mathbf{w}_{j0} \sim \mathcal{CN}\left(0, \sigma_{j0}^2\right)$ with $\sigma_{j0}^2 = a_{j0}$.

The detection of x_j at the relay node U_i can follow a matched-filtering to signal $y_{ji}(t)$ in (6) with respect to the signature waveform $s_j(t)$ as

$$y_{ji} = \langle y_{ji}(t), s_j(t)\rangle = h_{ji}\sqrt{P_{jj}} x_j + w_{ji}, \tag{20}$$

where $w_{ji} \sim \mathcal{CN}(0, N_0)$.

4. PERFORMANCE ANALYSIS AND SIMULATIONS

4.1. An Exact SER Expression

For M2P STNC, the detection in (18) provides the maximal conditional signal-to-interference-plus-noise ratio (SINR) γ_{j0} corresponding to the desired symbol x_j as

$$\gamma_{j0} = \frac{a_{j0}^2}{\sigma_{j0}^2} = \frac{P_{jj}|h_{j0}|^2}{N_0} + \sum_{\substack{i=1\\ i\neq j}}^{N} \frac{\widetilde{P}_{ij}|h_{i0}|^2}{N_0 f_{i0} r_{ij}}. \tag{21}$$

For DF protocol, let $\beta_{ij} \in \{0,1\}$, $i = 1, 2, ..., N$ and $i \neq j$, represent a detection state at U_i, a success or a failure in detecting of x_j. Because U_i forwards x_j only if it has successfully detected the symbol, $\widetilde{P}_{ij} = P_{ij}\beta_{ij}$. All β_{ij}'s form a decimal number $S_j = [\beta_{1j}...\beta_{ij}...\beta_{Nj}]_2$, where $[.]_2$ denotes a base-2 number, that represents one of $2^{(N-1)}$ detection states of the $(N-1)$ client nodes U_i's acting as relays. Because the detection is independent from one relay node to the others, β_{ij}'s are independent Bernoulli random variables with a distribution

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

where SER_{ji} is the SER in detection of x_j at U_i. Hence the probability of x_j detection in state S_j is

$$Pr(S_j) = \prod_{\substack{i=1\\ i\neq j}}^{N} G(\beta_{ij}). \tag{23}$$

Given a detection state S_j, we rewrite (21) as

$$\gamma_{j0\,|S_j} = \frac{P_{jj}|h_{j0}|^2}{N_0} + \sum_{\substack{i=1\\ i\neq j}}^{N} \frac{P_{ij}\beta_{ij}|h_{i0}|^2}{N_0 r_{ij}}, \tag{24}$$

where we have used $f_{i0} = 1$ for DF protocol.

In general, the conditional SER for M-PSK modulation with conditional signal-to-noise ratio (SNR) γ for a generic set of channel coefficients $\{h_{uv}\}$ is given by [11]

$$SER_{\,|\{h_{uv}\}} = \Psi(\gamma) \triangleq \frac{1}{\pi}\int_0^{(M-1)\pi/M} \exp\left(-\frac{b\gamma}{\sin^2\theta}\right) d\theta, \tag{25}$$

where $b = \sin^2(\pi/M)$. Based on (20), the SNR in detection of x_j at U_i given the channel gain is $\gamma_{ji} = P_{jj}|h_{0i}|^2/N_0$. By averaging (25) with respect to the exponential random variable $|h_{ji}|^2$, the SER in detecting x_j at U_i can be shown as [11]

$$SER_{ji} = F\left(1 + \left(bP_{jj}\sigma_{ji}^2\right) / \left(N_0 \sin^2\theta\right)\right), \tag{26}$$

where

$$F(x(\theta)) = (1/\pi)\int_0^{(M-1)\pi/M} (1/x(\theta))\, d\theta. \tag{27}$$

Given a detection state S_j, which can take $2^{(N-1)}$ values, the conditional SER in detecting x_j at U_j can be calculated using the law of total probability [12] as

$$SER_{j|\{h_{j0},\, h_{i0}\}} = \sum_{S_j=0}^{2^{(N-1)}-1} Pr\left(\hat{x}_j \neq x_j|S_j\right).Pr(S_j), \tag{28}$$

where $Pr(S_j)$ follows (23) and

$$Pr\left(\hat{x}_j \neq x_j|S_j\right) = \Psi\left(\gamma_{j0|S_j}\right) \tag{29}$$

with $\gamma_{j0|S_j}$ following (24). By averaging (28) with respect to the exponential random variables $\left\{|h_{j0}|^2, |h_{i0}|^2\right\}$, the exact SER in detecting x_j at U_0 can be given by [11]

$$SER_j = \sum_{S_j=0}^{2^{(N-1)}-1} F\left(\left(1 + \frac{bP_{jj}\sigma_{j0}^2}{N_0\sin^2\theta}\right) \times \prod_{\substack{i=1\\ i\neq j}}^{N}\left(1 + \frac{bP_{ij}\beta_{ij}\sigma_{i0}^2}{N_0 r_{ij}\sin^2\theta}\right)\right) \prod_{\substack{i=1\\ i\neq j}}^{N} G(\beta_{ij}), \tag{30}$$

where $G(.)$ and $F(.)$ follows (22) and (27), respectively.

For AF protocol, the conditional SER is

$$SER_{j|\{h_{0ij},\, h_{ij}\}} = \Psi(\gamma_j), \tag{31}$$

where $\Psi(.)$ is defined in (25) and γ_j follows (21) with f_{ij} in (10) for AF protocol.

4.2. An Asymptotic SER Expression

To obtain the asymptotic SER performance, i.e., performance at high SNR, two approximations are required. First, SER_{ji} is sufficiently small compared to 1, and thus assumably $(1 - SER_{ji}) \simeq 1$. Second, the 1's in the argument of $F(.)$ can be ignored. Hence we rewrite (30) as

$$SER_j \simeq \sum_{S_j=0}^{2^{(N-1)}-1} \underbrace{F\left(\left(\frac{bP_j\alpha_{jj}\sigma_{j0}^2}{N_0\sin^2\theta}\right)\prod_{\substack{i=1;i\neq j\\ \beta_{ij}=1}}^{N}\left(\frac{bP_j\alpha_{ij}\sigma_{i0}^2}{N_0 r_{ij}\sin^2\theta}\right)\right)}_{\mathcal{A}} \times \underbrace{\prod_{\substack{i=1;i\neq j\\ \beta_{ij}=0}}^{N} F\left(\frac{bP_j\alpha_{jj}\sigma_{ji}^2}{N_0\sin^2\theta}\right)}_{\mathcal{B}}, \tag{32}$$

where $\alpha_{jj} \triangleq \frac{P_{jj}}{P_j}$ and $\alpha_{ij} \triangleq \frac{P_{ij}}{P_j}$, $\sum_{i=1}^N \alpha_{ij} = 1$, denote the fraction of power P_j allocated at the source node U_j and a relay node U_i.

Let Ω_{j0} and Ω_{j1} denote subsets of the indices of nodes that decode x_j erroneously and correctly, respectively. Then $\Omega_{j0} = \{i:\ \beta_{ij} = 0\}$ and $\Omega_{j1} = \{i:\ \beta_{ij} = 1\}$. Furthermore, $|\Omega_{j0}|$ and $|\Omega_{j1}| \in \{0, 1, ..., (N-1)\}$, and $|\Omega_{j0}| + |\Omega_{j1}| = (N-1)$ for any detection state S_j. Hence in (32), we can show that

$$\mathcal{A} \simeq \left(\frac{N_0}{bP_j}\right)^{1+|\Omega_{j1}|} \frac{g\left(1 + |\Omega_{j1}|\right)}{\alpha_{jj}\sigma_{j0}^2\prod_{i\in\Omega_{j1}}\alpha_{ij}\left(\frac{\sigma_{i0}^2}{r_{ij}}\right)}, \tag{33}$$

$$\mathcal{B} \simeq \left(\frac{N_0}{bP_j}\right)^{|\Omega_{j0}|} \frac{[g(1)]^{|\Omega_{j0}|}}{\alpha_{jj}^{|\Omega_{j0}|}\prod_{i\in\Omega_{j0}}\sigma_{ji}^2}, \tag{34}$$

where

$$g(x) = \frac{1}{\pi}\int_0^{(M-1)\pi/M} [\sin(\theta)]^{2x}\, d\theta. \tag{35}$$

Consequently, (32) can be rewritten as

$$SER_j \simeq \left(\frac{bP_j}{N_0}\right)^{-N}\frac{1}{\sigma_{j0}^2} \times \sum_{S_j=0}^{2^{(N-1)}-1} \frac{g\left(1+|\Omega_{j1}|\right)[g(1)]^{|\Omega_{j0}|}}{\alpha_{jj}^{1+|\Omega_{j0}|}\prod_{i\in\Omega_{j1}}\alpha_{ij}\left(\frac{\sigma_{i0}^2}{r_{ij}}\right)\prod_{i\in\Omega_{j0}}\sigma_{ji}^2}. \tag{36}$$

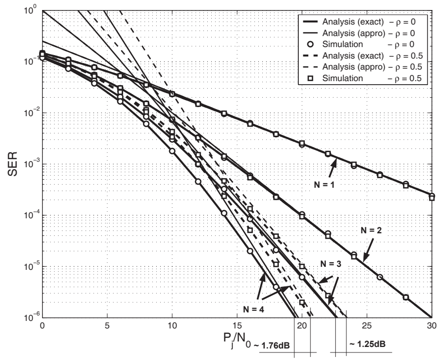

Fig. 1. SER versus SNR performance for BPSK modulation in DF M2P and P2M STNCs.

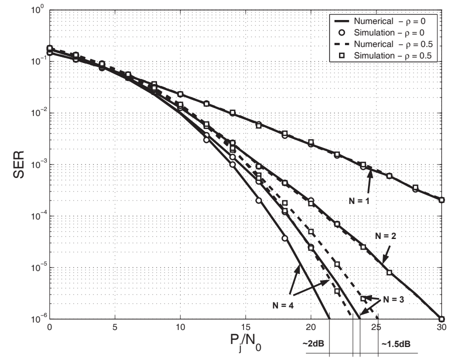

Fig. 2. SER versus SNR performance for BPSK modulation in AF M2P and P2M STNCs.

4.3. Diversity Order and Interference Impact on SNR

Diversity order of a communication scheme is defined as

$$\text{div} = -\lim_{\gamma\to\infty} \frac{\log SER(\gamma)}{\log \gamma}, \qquad (37)$$

where $SER(\gamma)$ is the SER with the SNR $\gamma \triangleq P/N_0$. From (36), x_j is clearly received with a full diversity order of N.

To see the interference impact on the SNR when using $\rho_{ij} \neq 0$, we consider unique cross-correlations $\rho_{ij} = \rho$ for all $i \neq j$. We can show that

$$r_{ij} = \frac{1+(N-3)\rho}{(1-\rho)(1+(N-2)\rho)} \triangleq r, \qquad (38)$$

the same for all i and j. Because $r \geq 1$ and $|\Omega_{j1}| \leq N$, $r^{|\Omega_{j1}|} \leq r^N$. Hence we rewrite (36) as

$$SER_j \lesssim \left(\frac{bP_j}{N_0}\right)^{-N} \frac{r^N}{\sigma_{j0}^2} \times \sum_{S_j=0}^{2^{(N-1)}-1} \frac{g\left(1+|\Omega_{j1}|\right)[g(1)]^{|\Omega_{j0}|}}{\alpha_{jj}^{1+|\Omega_{j0}|}\prod_{i\in\Omega_{j1}}\alpha_{i0}\sigma_{i0}^2\prod_{i\in\Omega_{j0}}\sigma_{ji}^2}. \qquad (39)$$

Based on (39), given the same required SER, the loss in SNR when using unique nonorthogonal codes can be shown at most $\Delta\gamma = 10\log r$ (dB). Furthermore, the maximal loss is

$$\Delta\gamma_{max} \triangleq \lim_{N\to\infty} \Delta\gamma = -10\log(1-\rho)\ (\text{dB}). \qquad (40)$$

4.4. Simulations

Figures 1 and 2 present the SER performance for DF and AF protocols with BPSK modulation. We assume unit variance for AWGN and channel coefficients, i.e., $N_0 = 1$ and $\sigma_{j0}^2 = \sigma_{ji}^2 = 1$ for all j and $i \neq j$. Various values of $N = 1, 2,$ 3, and 4 are used, and the transmit power $P_j = \sum_{i=1}^{N} P_{ij}$ corresponding to x_j is the same for all $j = 1, 2, ..., N$. Furthermore, we assume equal power allocation [7] with $\alpha_{jj} = 1/2$ and $\alpha_{ij} = 1/(2(N-1))$ for $i \neq j$. We also assume a unique cross-correlation $\rho_{ji} = \rho$ for all $i \neq j$, and we take $\rho = 0$ and $\rho = 0.5$ in our simulations.

From the figures, the simulation curves match analytical curves well and that validates our analysis. Moreover, the STNCs clearly provide the expected diversity orders in both DF and AF protocols, i.e., that symbol x_j is received with diversity order N for N client nodes. The figures also show the SNR gaps between $\rho = 0$ and $\rho = 0.5$. In particular for the case of $N = 4$, it requires about 1.76 dB and 2 dB when using $\rho = 0.5$ in DF and AF protocols, respectively.

5. CONCLUSIONS

In this paper, we proposed M2P and P2M STNCs to govern the cooperation among nodes in M2P and P2M transmissions, respectively. The STNCs utilize cooperative communications and linear network coding to overcome the issue of imperfect frequency and timing synchronization and reduce the large required time slots while still providing full spatial diversity as in traditional cooperative communications. For a network of N client nodes and a base node, M2P and P2M STNCs result in a diversity order of N for each transmitted symbol with a total of $2N$ time slots, a substantial reduction in comparison with N^2 time slot required in the traditional cooperative communications using TDMA.

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