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A Practical Physical-Layer Network Coding with Spatial Modulation in Two-Way Relay Networks

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In this paper, we consider a two-way relay network consisting of a single relay node and two source nodes, where both the relay node and source nodes are equipped with multiple antennas. Two source nodes are assumed to transmit data with spatial modulation (SM) and the relay node is assumed to try to decode the network-coded packet (via bit-wise exclusive OR operation) of the two packets received from two source nodes, respectively. We propose a maximum-likelihood (ML) signal detection technique for the physical-layer network coded packet with SM for the relay node. Extensive simulation results show that the bit-error rate (BER) at the relay node becomes significantly improved with the proposed SM-based physical-layer network coding (PNC) technique, compared with the conventional PNC technique that achieving the same data rate. In particular, the performance of the proposed technique becomes excellent when the number of antennas at the nodes is large and the data rate is high, which implies that the proposed technique is suitable for the next-generation wireless communication system, i.e. 5G. Note that the proposed SM-based PNC technique does not require channel state information at transmitter (CSIT) and thus it can be implemented easily in practice.

Keywords: wireless communications; physical-layer network coding; multiple antennas; spatial modulation; maximum-likelihood detector

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1. INTRODUCTION

Mobile data traffic has been explosively increasing [1]. The next-generation wireless communication system is being considered for the significant improvement of throughput over the conventional communication systems in order to support the increasing mobile traffic demand [2]. The fifth-generation (5G) wireless/mobile communication system refers to the next major phase of telecommunication standards and 5G does not denote a particular specification in official documents. International telecommunication union radio communication sector (ITU-R) is now defining the service visions and roles of future international mobile telecommunication (*future IMT*) which is termed as 5G wireless communication system in ITU-R [2]. World wireless research forum (WWRF) is also considering the concept of 5G wireless communication system. Wireless technologies such as small cell, massive MIMO, coordinated multi-point transmission (CoMP), heterogeneous networks, interference management, advanced relaying techniques and cognitive radios are being considered in designing the 5G wireless communication system [3].

Among the above technologies, the massive MIMO technique has been considered as one of the most promising techniques [4, 5]. In the massive MIMO system, both transmitter and receiver are equipped with hundreds of antennas (or more). In theory, spectral efficiency (or equivalently data rate) of the system can be linearly increased as the number of antennas increases at both transmitter and receiver. However, the large number of antennas at transmitter and receiver inevitably increases hardware complexity in both digital and radio frequency (RF) analog domains. In order to reduce the complexity of the massive MIMO system, several techniques have been proposed in the literature. As a representative method of reducing the complexity of massive MIMO system, the (generalized) spatial modulation (SM) has been proposed, coping with demerits of the conventional MIMO techniques [6, 7]. The basic idea of SM is to activate one transmit antenna out of all antennas for transmitting data, and the index of the activated antenna implicitly conveys information in addition to the traditional symbol modulation.

In particular, space shift keying (SSK) modulation was mathematically analyzed in terms of bit-error rate (BER) in [8], where a tight upper bound on the BER was derived with maximum-likelihood detector. The SM matches well with the massive MIMO technique since it effectively reduces the required number of *RF chains* which are known to be the most expensive components in mobile communication systems. However, the receiver complexity for estimating the index of the active transmit antenna may increase.

On the other hand, a physical-layer network coding (PNC) has received much attention from both industry and academia since it can significantly increase the spectral efficiency of the two-way relay network (TWRN) [9, 10]. With the PNC in the TWRN, two source nodes can exchange their packets with each other via a relay node and the packet exchange is completed in two phases (time slots): multiple access (MA) and broadcast (BC) phases. In the MA phase, each of two source nodes simultaneously transmits its packet to the relay node by utilizing a pre-equalizer for compensating for its fading channel and the relay node obtains the XORed version of those two packets received from the two source nodes [9]. In the BC phase, the relay node broadcasts the XORed packet to the source nodes. The authors of [9] considered the wireless channel as the additive white Gaussian noise (AWGN) channel by assuming *pre-equalization* technique at two sources. However, it is not feasible in practice because the source nodes may not have the channel state information (CSI) before packet transmission. Koike-Akino *et al.* also proposed an optimized constellation design for the PNC in fading channels without the pre-equalization [11] and extended their work to the channel coded system in [12]. In these schemes, however, the sources need to know ratios of instantaneous channel gain amplitudes of two links before transmission, which are impossible to be obtained in fast fading channels. This also results in significant feedback overhead especially in frequency-selective fading channels. Therefore, practical PNC techniques without CSI at the transmitters are of our interest.

A practical PNC technique without pre-equalization was proposed for fast fading channels in [13], where a maximal-likelihood detection (MLD) based on log-likelihood ratio (LLR) was adopted at the relay node for decoding the superposed signals from two sources and a joint design of the PNC and channel coding was investigated. Ju *et al.* [14] analyzed the *uncoded* BER of the PNC with BPSK modulation at sources over Rayleigh fading channels without pre-equalization or constellation optimization at the source nodes [14]. To *et al.* [15] proposed a combined architecture of convolutional codes (CCs) and the PNC, and they evaluated the BER performance through computer simulations over fading channels. Furthermore, transmit power optimization techniques at the source nodes have been investigated in [16, 17], where the authors assumed slow fading channels and also required full CSI at transmitters (CSIT). In [18], the BER of the PNC with CCs was mathematically analyzed over fast fading channels and the power allocation strategy was also proposed to minimize the BER under sum power constraint at the source nodes based on the BER analysis. Recently, the PNC technique has been applied to multi-pair two-way relaying systems [19] and correlated two-way relaying systems [20].

Recently, the SM technique has been applied to the TWRN with PNC [21–23]. In [21], the denoise-and-forward technique was adopted at the relay node, where the average symbol error probability was also analyzed. However, in [21], two source nodes with multiple antennas consider *only* the SSK modulation, and thus other symbol modulation techniques such as BPSK, QPSK and QAM were not considered. In [22], the SSK modulation was applied to the two-way amplify-and-forward (AF) relay network and its BER performance was analyzed, assuming Nakagami-*m* fading channels. In particular, the relay node is assumed to have *a single* antenna, while two source nodes are assumed to have multiple antennas. By utilizing the knowledge of the transmitted signal at the first phase (MA phase), CSI and the AF relaying property, each source node can eliminate the self-interference at the second phase (BC phase). However, the proposed scheme in [22] cannot be directly applied to the case when multiple antennas are utilized at the relay node. In [23], a space–time coding technique was combined to the PNC with SM technique for TWRNs, where the proposed scheme adjusts the symbol constellation for the network-coded bits as well as the index of active antenna at the relay node in the BC phase according to the wireless channel conditions. However, the optimization procedure may increase the complexity of the relay node and the applicability of proposed scheme is limited to the case when all nodes are equipped with *two* antennas.

In this paper, we proposed a *practical* PNC technique with SM for the TWRN where all communicating nodes (two source nodes and one relay node) are equipped with *multiple* antennas. We assume that all communication nodes adopt the SM and thus the resultant throughput per channel use, N_b, is given by

$$N_b = \lfloor \log_2 \binom{N_t}{1} \rfloor + \log_2 \lfloor |\mathbb{A}| \rfloor, \tag{1}$$

where N_t and $\mathbb{A}$ denote the total number of transmit antennas at the communicating node and the symbol modulation alphabet, respectively. For example, $\mathbb{A} = \{-1, +1\}$ for the BPSK modulation. If $N_t = 4$ and QPSK modulation (i.e. $|\mathbb{A}| = 4$) is used at the transmitter, $N_b = 4$ per wireless link. In order to detect the network-coded packet at the MA phase, the optimal maximum-likelihood (ML)-based signal detection technique is adopted. In addition, we take into account the decode-and-forward (DF) relaying technique because the DF scheme is the most general in practical wireless communication systems. To the best our knowledge, our technique can be considered as a generalized version of the conventional SM-based PNC techniques including [21–23]. Note that the proposed technique only requires CSI at Receiver (CSIR), leading easy implementation in practice.

2. SYSTEM MODEL

Herein, we consider the TWRN consisting of two source nodes and a single relay node, which is depicted in Fig. 1. Two source nodes are equipped with $N_S\,(\geq 2)$ antennas and the SM is adopted for packet transmission, while the relay node is equipped with $N_R\,(\geq 2)$ antennas.

The packet transmission consists of two phases: MA and BC. In the first phase (i.e. MA phase), two source nodes simultaneously send symbol vectors to the relay node with the SM, and thus *a single* antenna is activated among N_S antennas at each source. Then, the received symbol vector at the relay in the MA phase, $\mathbf{y}_R \in \mathbb{C}^{N_R\times 1}$, is given by

$$\mathbf{y}_R = \mathbf{H}_{1R}\mathbf{x}_1 + \mathbf{H}_{2R}\mathbf{x}_2 + \mathbf{z}_R, \tag{2}$$

where $\mathbf{H}_{1R} \in \mathbb{C}^{N_R\times N_S}$, $\mathbf{H}_{2R} \in \mathbb{C}^{N_R\times N_S}$, $\mathbf{x}_1 \in \mathbb{C}^{N_S\times 1}$, $\mathbf{x}_2 \in \mathbb{C}^{N_S\times 1}$ and $\mathbf{z}_R \in \mathbb{C}^{N_R\times 1}$ denote the wireless channel matrix from the first source node to the relay node, the wireless channel matrix from the second source node to the relay node, the transmitted symbol vector of the first source node, the transmitted symbol vector of the second source node and the additive Gaussian noise vector at the relay node, i.e. $\mathbf{z}_R \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{I})$, respectively. It should be noted that both $\mathbf{x}_1$ and $\mathbf{x}_2$ have only a single non-zero element out of N_S elements because the modulated symbol is sent via only one antenna for packet transmission in the SM technique.

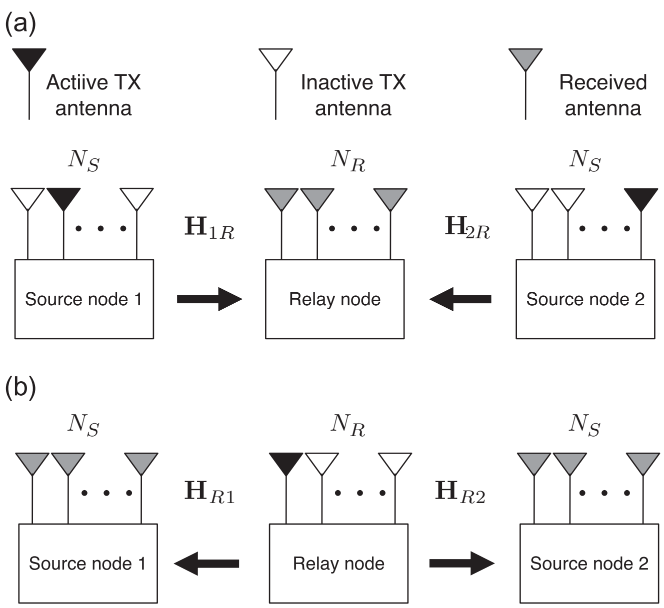

FIGURE 1. System model of the TWRN with SM-based PNC technique. (**a**) Multiple access phase. (**b**) Broadcast phase.

Then, (2) can be simplified as

$$\mathbf{y}_R = \mathbf{h}^i_{1R}x_1 + \mathbf{h}^j_{2R}x_2 + \mathbf{z}_R, \tag{3}$$

where $\mathbf{h}^i_{1R}$, $\mathbf{h}^j_{2R}$, x_1 and x_2 denote the ith column of $\mathbf{H}_{1R}$, the jth column of $\mathbf{H}_{2R}$, the transmit symbol of the source node 1 via the ith transmit antenna and the transmit symbol of the source node 2 via the jth transmit antenna, respectively. The antenna indices i and j are determined by antenna mapping procedure of the SM ($1 \leq i, j \leq N_S$). For example, $i = 2$ and $j = N_S$ in Fig. 1a. We assume that the relay node exactly knows CSIs from two source nodes to itself, i.e. $\mathbf{H}_{1R}$ and $\mathbf{H}_{2R}$. Based on the CSIs, the relay node decodes the received signal in the first phase and produces a *network-coded* packet. We assume that the relay node use the *exclusive OR* (*XOR*) operation as a network coding scheme. We will explain the proposed signal detection technique with LLR computation for SM-based PNC in the next section.

In the second phase (i.e. BC phase), the relay node sends the network-coded packet with XOR operation to two source nodes. Then, the received symbol vector at each source node, $\mathbf{y}_k \in \mathbb{C}^{N_S\times 1} (k \in \{1, 2\})$, is given by

$$\mathbf{y}_k = \mathbf{H}_{Rk}\mathbf{x}_R + \mathbf{z}_k, \tag{4}$$

where $\mathbf{H}_{Rk} \in \mathbb{C}^{N_S\times N_R}$, $\mathbf{x}_R \in \mathbb{C}^{N_R\times 1}$ and $\mathbf{z}_k \in \mathbb{C}^{N_S\times 1}$ denote the wireless channel matrix from the relay node to the kth source node ($k \in \{1, 2\}$), the transmitted symbol vector of the relay node, and the additive Gaussian noise vector at the kth source node ($k \in \{1, 2\}$), i.e. $\mathbf{z}_k \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{I})$, respectively. It is worth noting that $\mathbf{x}_R$ also has only one non-zero element out of N_R elements since the modulated symbol is sent via only one antenna for packet transmission in the SM technique.

Similar to the MA phase, (4) can be simplified as

$$\mathbf{y}_k = \mathbf{h}^l_{Rk}x_R + \mathbf{z}_k, \tag{5}$$

where $\mathbf{h}^l_{Rk}$ and x_R denote the lth column of $\mathbf{H}_{Rk}$ and the transmit symbol of the relay node via the lth transmit antenna, respectively. The antenna index $l\,(1 \leq l \leq N_R)$ is determined by antenna mapping procedure of the SM. For example, $l = 1$ in Fig. 1b. We assume that each source node also knows the exact CSI from the relay nodes to itself, i.e. $\mathbf{H}_{Rk}$. Based on the CSI, each source node tries to decode the received signal from the relay node. After decoding the network-coded packet, each source node obtains the desired information using its own transmitted bits at the MA phase.

In general, it has been known that the number of receive antennas needs to be larger than that of the transmit antennas in order to successfully decode the SM signal [6, 7]. It is required that $N_R \geq N_S$ at the MA phase and $N_S \geq N_R$ at the BC phase. Thus, in this paper, we assume that $N_S = N_R$. We also assume that that each source node transmits N_b bits with the SM at the MA phase, and the relay node also transmits N_b bits at the BC phase with the bit-wise XOR operation. Thus, the total number of transmitted bits per phase (time-slot or channel use) is equal to N_b in the TWRN with the proposed SM-based PNC technique, where N_b is given by (1).

3. SIGNAL DETECTION

3.1. Signal detection in MA phase

In order to clearly explain the signal detection and the network coding at the relay node, we show the transmission and the reception procedure in the MA phase of the SM-based PNC system in detail as illustrated in Fig. 2. Let $\mathbf{b}_1$ and $\mathbf{b}_2$ be the information bits of source node 1 and source node 2, respectively. They are modulated with spatial modulator consisting of symbol modulator and antenna mapper, which can be represented by the following function: $\mathbf{x}_k = \mathcal{M}(\mathbf{b}_k)$ for $k = 1, 2$. We assume the same function, $\mathcal{M}(\cdot)$, for both source nodes. For example, if the number of antennas at each source node is equal to 2, i.e. $N_S = 2$, then $\mathbb{A} = \{+1, -1\}$ (i.e. BPSK modulation). To be more specific, in this case, $\mathbf{x}_k$, $k \in \{1, 2\}$, is given by

$$\mathbf{x}_k \in \left\{ \begin{bmatrix} +1 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ +1 \end{bmatrix}, \begin{bmatrix} 0 \\ -1 \end{bmatrix} \right\}. \tag{6}$$

Then, we can consider the following mapping function:

$$\begin{aligned} [+1\ 0]^T &= \mathcal{M}(00), \\ [-1\ 0]^T &= \mathcal{M}(01), \\ [0\ +1]^T &= \mathcal{M}(10), \\ [0\ -1]^T &= \mathcal{M}(11). \end{aligned} \tag{7}$$

For the mapping function of general case that $N_s > 2$ with M-QAM, refer to [6, 7].

After the spatial modulator, each source node simultaneously sends the symbol vector, $\mathbf{x}_k$, to the relay node.

The received symbol vector at the relay node is given as (2). The relay node tries to detect the transmit symbol vectors from the source nodes, $\mathbf{x}_k$ for $k = 1, 2$, and obtains the information bits sent from both source nodes, $\mathbf{b}_k$ for $k = 1, 2$. Then, it performs the network coding with bit-wise XOR operation by using $\mathbf{b}_1$ and $\mathbf{b}_2$. Let Ω be the set of all possible symbol pairs of $(\mathbf{x}_1, \mathbf{x}_2)$. Then, $|\Omega| = (N_S \cdot |\mathbb{A}|)^2$, where $|\mathbf{B}|$ denotes the cardinality of set $\mathbf{B}$, i.e. the total number of elements in $\mathbf{B}$, and $\mathbb{A}$ denotes the symbol modulation alphabet as defined in (1). In this paper, we adopt the *optimal* MLD at the relay node, which is given by

$$(\hat{\mathbf{x}}_1, \hat{\mathbf{x}}_2)_{\mathsf{ML}} = \arg \min_{(\mathbf{x}_1, \mathbf{x}_2) \in \Omega} \|\mathbf{y}_R - \mathbf{H}_{1R}\mathbf{x}_1 - \mathbf{H}_{2R}\mathbf{x}_2\|_{\mathsf{F}}, \tag{8}$$

where $\|\cdot\|_{\mathsf{F}}$ denotes the Frobenius norm. The computational complexity of the MLD increases according to the number of information bits sent from the source nodes. For example, the MLD in (8) requires 256 computations when $N_S = 4$ and the QPSK modulation is used at the source nodes.

After the MLD at the relay node, the estimate on the transmit symbol vectors, $(\hat{\mathbf{x}}_1, \hat{\mathbf{x}}_2)_{\mathsf{ML}}$, enters into the spatial demodulator of which it converts the transmit vector to the information bits by exploiting the symbol and antenna mapping rule at the source nodes. The spatial demodulator at the relay node can be regarded as the inverse function of the spatial modulator at each source node, which is represented by

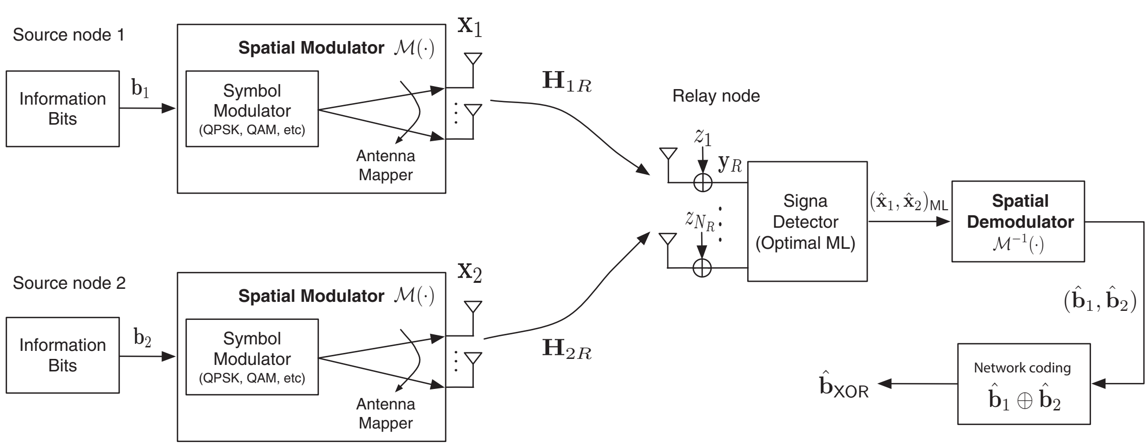

FIGURE 2. Transmission and reception in the MA phase.

$\mathcal{M}^{-1}(\cdot)$. Then, the estimate on the information bits of each source node can be obtained after the spatial demodulator, which is given by $\hat{\mathbf{b}}_k = \mathcal{M}^{-1}(\hat{\mathbf{x}}_k)$ for $k = 1, 2$. If we consider the mapping function in (7), the inverse function is given as

$$\begin{aligned} 00 &= \mathcal{M}^{-1}([+1\ 0]^T), \\ 01 &= \mathcal{M}^{-1}([-1\ 0]^T), \\ 10 &= \mathcal{M}^{-1}([0\ +1]^T), \\ 11 &= \mathcal{M}^{-1}([0\ -1]^T). \end{aligned} \tag{9}$$

Based on these estimates on the information bits, the network coding at the relay node is performed with bit-wise XOR operation. Then, the network-coded bits are obtained as $\hat{\mathbf{b}}_{\mathsf{XOR}} = \hat{\mathbf{b}}_1 \oplus \hat{\mathbf{b}}_2$, where $\oplus$ denotes the bit-wise XOR operator. If the optimal MLD finds the correct transmit symbol vectors, i.e. $(\hat{\mathbf{x}}_1, \hat{\mathbf{x}}_2)_{\mathsf{ML}} = (\mathbf{x}_1, \mathbf{x}_2)$, then the relay node can generate the correct network-coded bits, i.e. $\hat{\mathbf{b}}_{\mathsf{XOR}} = \mathbf{b}_1 \oplus \mathbf{b}_2$. The relay node sends the network-coded bits, $\hat{\mathbf{b}}_{\mathsf{XOR}}$, to the source nodes in BC phase.

3.2. Signal detection in BC phase

To explain the signal detection and the decoding of the network-coded bits at each source node, we show the transmission and the reception procedure in the BC phase of the SM-based PNC system in detail as illustrated in Fig. 3. Let $\mathbf{b}_{\mathsf{XOR}}$ be the network-coded bits of the relay node, and it is sent to two source nodes in the BC phase. It is also modulated with spatial modulator consisting of symbol modulator and antenna mapper as at the source nodes in the MA phase, represented by the following function: $\mathbf{x}_R = \mathcal{M}(\mathbf{b}_{\mathsf{XOR}})$, which is the same function as the function used in the MA phase at the source nodes. For example, if the number of antennas at the relay node is equal to 2, i.e. $N_R = 2$, then $\mathbb{A} = \{+1, -1\}$ (i.e. BPSK modulation). To be more specific, in this case, $\mathbf{x}_R$, is given by

$$\mathbf{x}_R \in \left\{ \begin{bmatrix} +1 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ +1 \end{bmatrix}, \begin{bmatrix} 0 \\ -1 \end{bmatrix} \right\}. \tag{10}$$

After the spatial modulator, the relay node sends the symbol vector, $\mathbf{x}_R$, to the source nodes.

The received symbol vector at the kth source node is given as (4) for $k = 1, 2$. The kth source node tries to detect the transmit symbol vectors from the relay nodes, $\mathbf{x}_R$, and obtains the network-coded bits received from the relay node, $\mathbf{b}_{\mathsf{XOR}}$. Then, it also performs the bit-wise XOR operation by using its own information bits, $\mathbf{b}_k$, which are sent at the MA phase. Let Ω' be the set of all possible candidates of symbol vector of the relay node, $\mathbf{x}_R$. Then, $|\Omega'| = N_R \cdot |\mathbb{A}|$, where $\mathbb{A}$ denotes the symbol modulation alphabet as defined in (1). We also assume the *optimal* MLD at the kth source node, which is given by

$$\hat{\mathbf{x}}_R^{\mathsf{ML}} = \arg \min_{\mathbf{x}_R \in \Omega'} \|\mathbf{y}_k - \mathbf{H}_{Rk}\mathbf{x}_R\|_{\mathsf{F}}. \tag{11}$$

Note that the computational complexity at each source node in the BC phase is proportional to 2^{N_b}, while the computational complexity at the relay node in the MA is proportional to 2^{2N_b}. This comes from the network coding with bit-wise XOR operation at the relay node, which maps two bit-streams into a bit-stream: $(\mathbf{b}_1, \mathbf{b}_2) \rightarrow \mathbf{b}_{\mathsf{XOR}}$.

After the MLD at the kth source node, the estimate on the transmit symbol vector, $\hat{\mathbf{x}}_R^{\mathsf{ML}}$, enters into the spatial demodulator of which it converts the transmit vector to the information bits by exploiting the symbol and antenna mapping rule at the relay node. The spatial demodulator at the kth source node can also be regarded as the inverse function of the spatial modulator at the relay node, which is represented by $\mathcal{M}^{-1}(\cdot)$. Then, the estimate on the network-coded bits of the

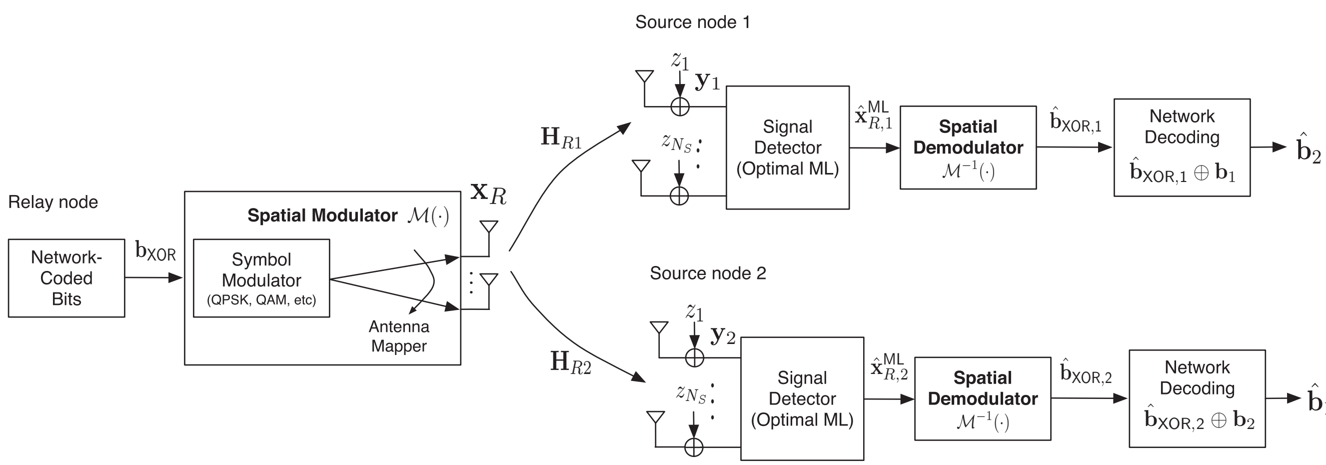

FIGURE 3. Transmission and reception in the BC phase.

relay node can be obtained after the spatial demodulator, which is given by $\hat{\mathbf{b}}_{\mathsf{XOR}} = \mathcal{M}^{-1}(\hat{\mathbf{x}}_R^{\mathsf{ML}})$. Using the estimate on the network-coded bits, the kth source node performs the network decoding with the bit-wise XOR operation in order to obtain the information bits of the other source node. For example, source node 1 obtains the information bits of the source node 2 by performing the bit-wise XOR operation between $\hat{\mathbf{b}}_{\mathsf{XOR}}$ and $\mathbf{b}_1$: $\hat{\mathbf{b}}_2 = \hat{\mathbf{b}}_{\mathsf{XOR}} \oplus \mathbf{b}_1$. Similarly, source node 2 obtains the information bits of the source node 1 via the bit-wise XOR operation between $\hat{\mathbf{b}}_{\mathsf{XOR}}$ and $\mathbf{b}_2$: $\hat{\mathbf{b}}_1 = \hat{\mathbf{b}}_{\mathsf{XOR}} \oplus \mathbf{b}_2$. This bit-wise XOR operation is also called the network decoding in the literature. It is worth noting that each source node exploits its own information bits, which are sent in the MA phase, for obtaining the information bits of the other source node from the network-coded bits.

3.3. BER performance

The overall BER performance of the SM-based PNC technique depends on the BER performances in both MA and BC phases. Let P_b^{MA}, $P_{b,1}^{\mathsf{BC}}$ and $P_{b,2}^{\mathsf{BC}}$ denote the bit-error probability at the relay node in the MA, the bit-error probability at the source node 1 in the BC phase and the bit-error probability at the source node 2 in the BC phase, respectively. They are formally defined as

$$P_b^{\mathsf{MA}} = \Pr\{\hat{\mathbf{b}}_{\mathsf{XOR}} \neq \mathbf{b}_1 \oplus \mathbf{b}_2\}, \tag{12}$$

$$P_{b,1}^{\mathsf{BC}} = \Pr\{\hat{\mathbf{b}}_{\mathsf{XOR},1} \neq \mathbf{b}_{\mathsf{XOR}}\}, \tag{13}$$

$$P_{b,2}^{\mathsf{BC}} = \Pr\{\hat{\mathbf{b}}_{\mathsf{XOR},2} \neq \mathbf{b}_{\mathsf{XOR}}\}, \tag{14}$$

where $\mathbf{b}_{\mathsf{XOR}}$ denotes the network-coded bits sent from the relay node in the BC phase, which may be different from $\mathbf{b}_1 \oplus \mathbf{b}_2$ if there exists bit error in the MA phase. In addition, $\hat{\mathbf{b}}_{\mathsf{XOR},1}$ and $\hat{\mathbf{b}}_{\mathsf{XOR},2}$ denote the estimate on the network-coded bits at source node 1 and source node 2, respectively. It should be noted that $P_{b,1}^{\mathsf{BC}}$ and $P_{b,2}^{\mathsf{BC}}$ depend only on the channel condition from the relay node to source node 1 ($\mathbf{H}_{R1}$) and source node 2 ($\mathbf{H}_{R1}$) in the BC phase, respectively, while P_b^{MA} depends on both channel conditions from source nodes to the relay node ($\mathbf{H}_{1R}$, $\mathbf{H}_{2R}$) in the MA phase.

The overall bit-error probability of the packet from the source node 1 to source node 2 is given by

$$P_b^{1\to 2} = P_b^{\mathsf{MA}}(1 - P_{b,2}^{\mathsf{BC}}) + (1 - P_b^{\mathsf{MA}})P_{b,2}^{\mathsf{BC}}. \tag{15}$$

Similarly, the overall bit-error probability of the packet from the source node 2 to source node 1 is given by

$$P_b^{2\to 1} = P_b^{\mathsf{MA}}(1 - P_{b,1}^{\mathsf{BC}}) + (1 - P_b^{\mathsf{MA}})P_{b,1}^{\mathsf{BC}}. \tag{16}$$

4. SIMULATION RESULTS

In this section, we focus on the MA phase because the signal transmission at the BC phase is exactly the same as the case of the conventional single link transmission except that the transmitted bits are the network-coded bits at the relay node [13]. In addition, the BER performance in the BC phase is the same at the conventional single-link transmission as well. Thus, we evaluate P_b^{MA} in this section, which is defined in (12). We assume that the average channel gains between the relay node and the source nodes are the same. As noted before, we also assume that the number of antennas at the relay node and the number of antennas at the source nodes are the same, i.e. $N_R = N_S$.

Figure 4 shows the BER performance of the proposed SM-based PNC technique when $N_S = N_R = 4$ and the number of bits per channel use is equal to 4, i.e. $N_b = 4$. We compare the BER performance of the proposed technique with the conventional PNC technique with the same throughput (N_b). In the conventional PNC technique, the source nodes have a *single* transmit antenna. Note that the proposed technique also has a single RF chain even though there exist multiple transmit antennas at the source node, and only a single active antenna is used for data transmission. We also show the BER performance of the single-link transmission scheme without PNC as reference systems in the figure, which can be regarded as the upper bound in terms of BER performance for both the conventional PNC technique and the proposed PNC technique. For achieving $N_b = 4$, the conventional PNC technique adopts 16QAM modulation at both source nodes and the relay node tries to detect the transmit symbol set among $16^2 = 256$ candidates in the MA phase. On the other hand, the proposed SM-based PNC technique allocates *two*

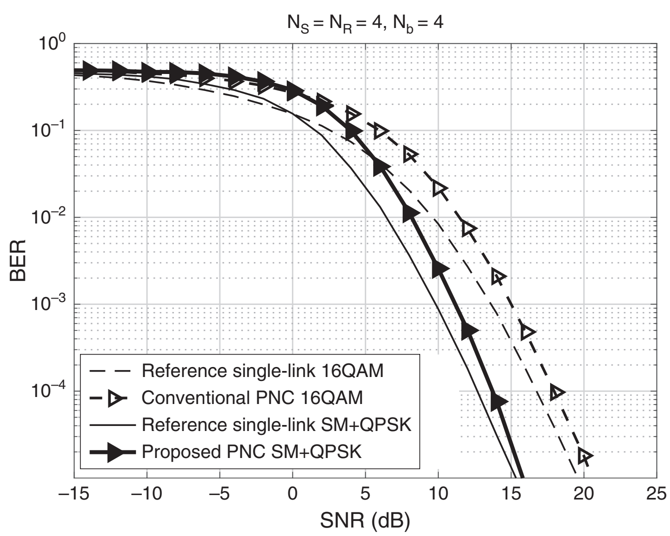

FIGURE 4. BER performance of the proposed SM-based PNC technique in the MA phase when $N_S = 4$, $N_R = 4$ and $N_b = 4$.

bits in antenna domain and *two* bits in symbol constellation domain, utilizing four antennas at each source node and QPSK modulation. Both the conventional and the proposed techniques have the same number of antennas at the relay node and adopt the same MLD at the receiver.

As illustrated in Fig. 4, the proposed SM-based PNC technique results in better performance than the conventional PNC technique with a single antenna at the source node. For example, the required SNR for satisfying 10^{-4} BER performance is 13.5 dB in the proposed technique, while the required SNR for satisfying the same BER performance is 17 dB in the conventional PNC technique. The slope of the BER performance according to SNR of both the conventional and the proposed techniques is the same each other, which implies that both techniques have the same diversity order. In addition, it is observed that the BER performance of the proposed technique approaches to that of the reference single-link technique with the same SM technique, which implies that the performance loss due to the simultaneous transmission in the proposed SM-based PNC technique becomes negligible as SNR increases.

Figure 5 shows the BER performance of the proposed SM-based PNC technique when $N_S = N_R = 4$ and the number of bits per channel use is 5, i.e. $N_b = 5$. For achieving $N_b = 5$, the conventional PNC technique has to adopt 32QAM modulation at both source nodes and the relay node tries to detect the transmit symbol set among $32^2 = 1024$ candidates in the MA phase. On the other hand, the proposed SM-based PNC technique allocates *two* bits in antenna domain and *three* bits in symbol constellation domain, utilizing four antennas at each source node and 8PSK modulation. Both the conventional and the proposed techniques have the same number of antennas at the relay node and adopt the same MLD at the receiver. As illustrated in Fig. 5, the proposed SM-based PNC technique results in better performance than the conventional PNC technique with a single antenna at the source node. For example, the required SNR for satisfying 10^{-4} BER performance is 16 dB in the proposed technique, while the required SNR for satisfying the same BER performance is 21 dB in the conventional PNC technique. Thus, the conventional technique requires 5 dB more transmit power than the proposed technique when $N_b = 5$, while 4.5 dB more transmit power is required when $N_b = 4$ as shown in Fig. 4. In addition, it is also observed that the BER performance of the proposed technique approaches to that of the reference single-link technique with the same SM technique.

In Figs. 4 and 5, we assume that $N_S = N_R = 4$, but we now increase the number of antennas at the source nodes and the relay node. Figure 6 shows the BER performance of the proposed SM-based PNC technique when $N_S = N_R = 8$ and the number of bits per channel use is equal to 5, $N_b = 5$. For achieving $N_b = 5$, the conventional PNC technique adopts 32QAM modulation at both source nodes and the relay node tries to detect the transmit symbol set among $32^2 = 1024$ candidates in the MA phase. On the other hand, the proposed SM-based PNC technique allocates *three* bits in antenna domain and *two* bits in symbol constellation domain, utilizing eight antennas at each source node and QPSK modulation. Both the conventional and the proposed techniques have the same number of antennas at the relay node and adopt the same MLD at the receiver. As illustrated in Fig. 6, the proposed SM-based PNC technique shows much better performance than the conventional PNC technique with a single antenna at the source node. For example, the required SNR for satisfying 10^{-4} BER performance is equal to 7.5 dB in the proposed technique, while the required SNR for satisfying the

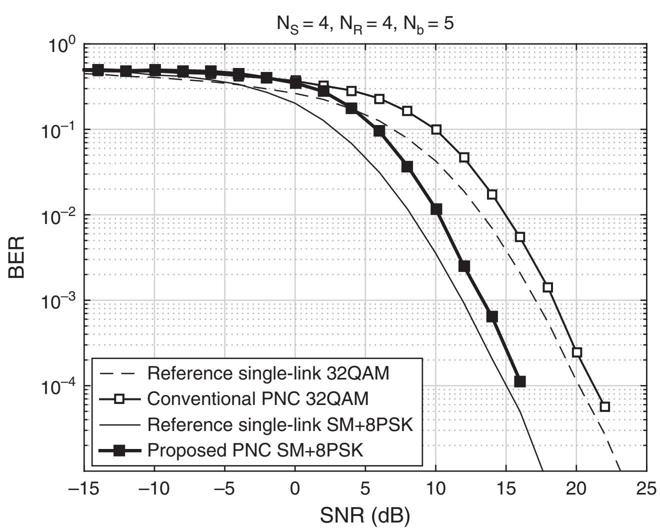

FIGURE 5. BER performance of the proposed SM-based PNC technique in the MA phase when $N_S = 4$, $N_R = 4$ and $N_b = 5$.

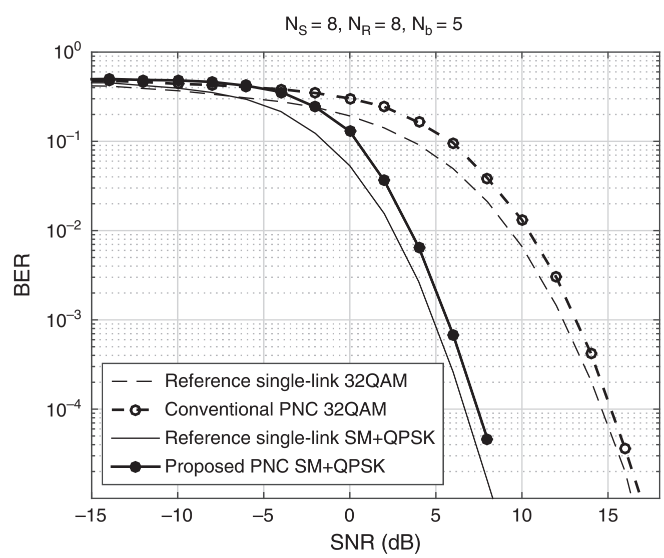

FIGURE 6. BER performance of the proposed SM-based PNC technique in the MA phase when $N_S = 8$, $N_R = 8$ and $N_b = 5$.

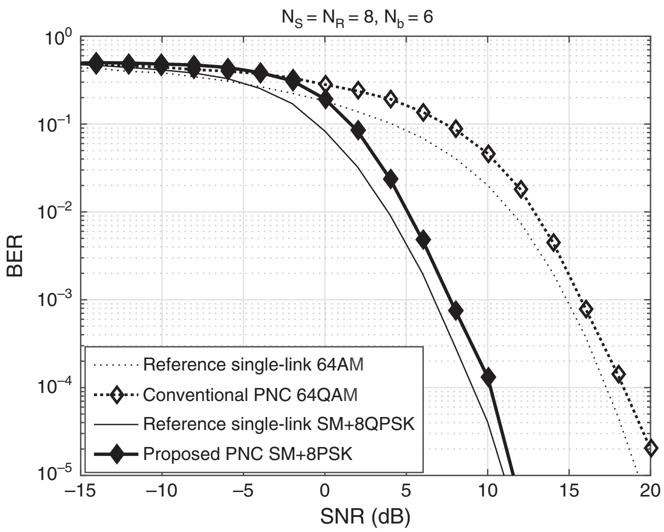

FIGURE 7. BER performance of the proposed SM-based PNC technique in MA phase when $N_S = 8$, $N_R = 8$, and $N_b = 6$.

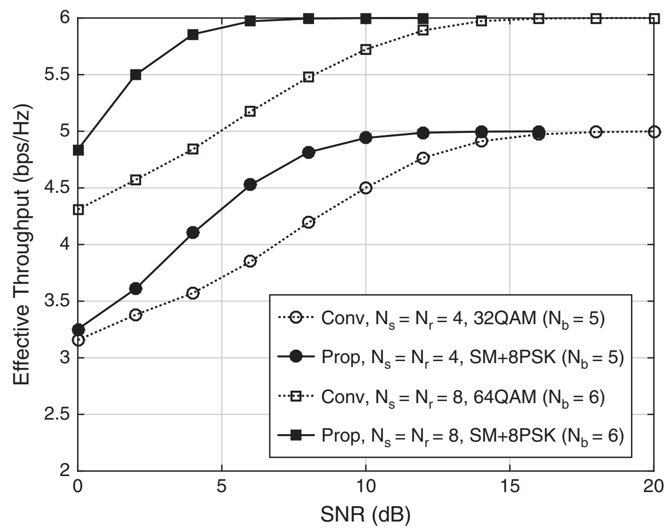

FIGURE 8. Effective throughput comparison between the proposed SM-based PNC technique with the conventional technique.

same BER performance is equal to 15 dB in the conventional PNC technique. The conventional technique requires 7.5 dB more transmit power than the proposed technique in the case that $N_b = 5$, while 5 dB more transmit power is required in the case that $N_b = 4$ as shown in Fig. 5. Thus, the proposed technique becomes more appropriate in the case when the number of antennas is large. Comparing Figs. 5 and 6, we can observe that the BER performances of all techniques are improved more significantly by increasing the number of antennas at both transmitter and receiver.

Figure 7 shows the BER performance of the proposed SM-based PNC technique when $N_S = N_R = 8$ and the number of bits per channel use is equal to 6, $N_b = 6$, such that we now increase the number of bits per channel use (i.e. data rate) compared to previous results. For achieving $N_b = 6$, the conventional PNC technique adopts 64QAM modulation at both source nodes and the relay node tries to detect the transmit symbol set among $64^2 = 4096$ candidates in the MA phase. On the other hand, the proposed SM-based PNC technique allocates *three* bits in antenna domain and *three* bits in symbol constellation domain, utilizing eight antennas at each source node and 8PSK modulation. As illustrated in Fig. 7, the proposed SM-based PNC technique results in much better performance than the conventional PNC technique with a single antenna at the source node. For example, the required SNR for satisfying 10^{-4} BER performance is equal to 10 dB in the proposed technique, while the required SNR for satisfying the same BER performance is equal to 18 dB in the conventional PNC technique. The conventional technique requires 8 dB more transmit power than the proposed technique in the case that $N_b = 6$, while 7.5 dB more transmit power is required in the case that $N_b = 5$ as shown in Fig. 6. Thus, the proposed technique becomes more appropriate in the case when the data rate is high. Comparing Figs. 6 and 7, we can observe that the additional transmit power to increase data rate, N_b, from 5 to 6 is equal to 2.5 dB and 3 dB in the proposed and the conventional PNC technique, respectively.

Figure 8 compares the effective throughput of the proposed SM-based PNC technique with the conventional technique in the MA phase when $N_b = 5, 6$, where the effective throughput is defined as $N_b \cdot (1 - P_b^{\mathrm{MA}})$. In the simulation, we assume that $N_s = N_r = 4$ for $N_b = 5$ and $N_s = N_r = 8$ for $N_b = 6$. From the simulation results, we can confirm that the proposed SM-based PNC technique outperforms the conventional technique in terms of effective throughput.

5. CONCLUSIONS

In this paper, we proposed a PNC coding technique for two-way relay network, which exploits SM at the source nodes and the relay node. In the proposed SM-based PNC technique, single antenna is utilized for data transmission among multiple antennas, and thus the proposed technique is an energy-efficient data transmission technique, operating with only a single RF chain. We explained the transmission and reception procedure at the source nodes and the relay node in both MA phase and the BC phase. The BER of the proposed SM-based PNC technique is validated via extensive computer simulations. Simulation results show that the proposed technique significantly outperforms the conventional PNC technique which has the same data rate in view of BER, especially in the case when the number of antennas at nodes is large and the data rate is high. Moreover, our proposed technique is easy to be implemented in practice due to the use of CSIR.

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