Opportunistic Scheduling for Multi-User Two-Way Relay Systems with Physical Network Coding

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***Abstract*—This letter considers a multi-user wireless communication system employing physical network coding (PNC), where a pair of users communicates with each other via a relay. To attain reliable communication over time varying channels, we apply an opportunistic scheduling scheme for the PNC to both the broadcast channel phase and the multiple access channel phase. We propose two criteria for selecting users based on the channel norm and the minimum distance. Also, an efficient method to compute the minimum distance for superposed QPSK signals is introduced. Simulation results show that the proposed scheduling for PNC provides a significant improvement over conventional schemes.**

***Index Terms*—Physical network coding, opportunistic scheduling, two-way relay systems.**

I. Introduction

RELAY networks have been intensively studied over several years [1]–[3]. Recently, multi-user wireless communication systems with network coding at the relay have received much attention [4]–[6]. The network coding was first proposed in [7] as a network-layer technique in wired networks. The basic concept of the network coding is that a transmitter combines packets intended for different destinations using the exclusive-or (XOR) operation and broadcasts the combined packets. By adopting the network coding at the relay, we can reduce the number of time slots required to transmit data to users.

Additionally, by extending the network coding to the physical layer, which is referred to as physical network coding (PNC) [8], we can reduce the required time slots for the multiple access channel (MAC) phase as well as the broadcast channel (BC) phase. There are several related works on the PNC. An information theoretic approach of PNC was investigated in [9]. A PNC method to design network coding adaptively according to channel conditions was proposed in [10], as conventional XOR network coding may not be suitable for some channel conditions. In addition, adaptive modulation with precoding was introduced in [11].

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On the other hand, for practical wireless relaying systems where channel characteristics vary over time, various opportunistic techniques have been presented to improve the system performance. In [12], relay selection schemes for network coding was proposed and its asymptotic bit error rate (BER) was derived. Also, the relay selection of amplify-and-forward (AF) relaying systems was studied in [13], and the user selection approaches for the AF protocol were examined in [14] and [15]. However, user selection methods for PNC have not been investigated.

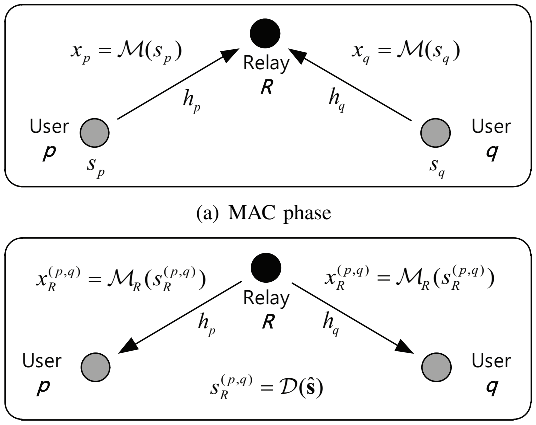
In this letter, we consider a scheduling scheme which selects a pair of users who exchange data for a two-way relay channel (TWRC). We propose new schemes for determining a pair of users by employing the PNC including both XOR and the adaptive scheme in [10]. First, we utilize the magnitude of the instantaneous channels for each user. Next, we adopt a criterion based on the minimum distance between the signals of the superposed constellation at the relay. Since the minimum distance based approach require a large search size, we also propose an efficient method to obtain the minimum distance without any search. Simulation results show that the proposed techniques outperform conventional schemes.

The rest of this letter is organized as follows: In Section II, we describe the multi-user two-way relay channel model used in this letter. Section III proposes two criteria for the user selection over fading channels. Section IV presents an efficient method to obtain the minimum distance of the constellation for the PNC employing QPSK. In Section V, we provide numerical results to compare with conventional schemes. Section VI concludes the letter with further research directions.

II. System Descriptions

We consider the multi-user two-way relay channel model in this letter. There are N users and one relay denoted by R. Among N users, a pair of users is selected and exchanges their information via the relay. We assume that there is no direct communication link among user nodes. Without the network coding, four time slots are required to complete the communication between the given pair of users, because the relay receives and broadcasts data from two users separately. If the relay employs the network coding, the required time slots for the BC phase is reduced to half, since the relay can broadcast the network coded data instead of delivering individual data. Then each user can decode the data from the other users by using its own data.

To further reduce the number of the required time slots, we consider a scheme where two users transmit to the relay simultaneously during the MAC phase. As a result, the required number of time slot becomes one for the MAC phase. In this



(a) MAC phase

(b) BC phase

Fig. 1. PNC between two users.

letter, a pairwise PNC is applied for both the MAC phase and the BC phase as shown in Fig. 1. At the relay, the noise impact is removed by a maximum-likelihood (ML) detector and the network coding mapper, which is referred to as denoising.

Now we describe the TWRC system between users p and q. We denote $s_i \in \{0, 1, 2, \cdots, L-1\}$ ($i = p,\ q$) as the transmitted data from user i, where L indicates the modulation level. The constellation mapper $\mathcal{M}$ generates the transmitted signal as $x_i = \mathcal{M}(s_i)$. The transmitted signals are assumed to have a unit energy, *i.e.*, $\mathbb{E}[|x_i|^2] = 1$. Also, we assume that perfect channel estimation is available at the receiver side. During the MAC phase in Fig. 1(a), the received signal at the relay is then given by

$$y_R^{(p,q)} = h_p x_p + h_q x_q + z_R^{(p,q)} \tag{1}$$

where the channel gains h_i ($i = p,\ q$) are independent complex Gaussian random variables with unit variance and $z_R^{(p,q)} \sim \mathcal{N}(0, \sigma^2)$ indicates the complex Gaussian noise.

The relay detects $\hat{\mathbf{s}} = (\hat{s}_p, \hat{s}_q)$ based on the received signal $y_R^{(p,q)}$ in (1) by employing an ML detector as

$$\hat{\mathbf{s}} = \arg\min_{(s_p, s_q)} |y_R^{(p,q)} - (h_p x_p + h_q x_q)|^2. \tag{2}$$

Then, the denoising mapper $\mathcal{D}(\cdot)$ generates the codeword $s_R^{(p,q)} = \mathcal{D}(\hat{\mathbf{s}})$ using the ML output in (2). One conventional denoising mapper is the XOR operation, *i.e.*, $\mathcal{D}_{\text{XOR}}(\hat{\mathbf{s}}) \triangleq \hat{s}_p \oplus \hat{s}_q$. When QPSK is employed at the users, the adaptive denoising mapper $\mathcal{D}_{\text{AD}}$ proposed in [10] can also be considered which yields either 4-ary or 5-ary alphabets.

Fig. 1(b) illustrates the BC phase where the relay R broadcasts $x_R^{(p,q)} = \mathcal{M}_R(s_R^{(p,q)})$ to users p and q. Here, $\mathcal{M}_R$ represents the constellation mapper at the relay. For QPSK, the cardinality of $\mathcal{D}_{\text{XOR}}$ is 4, while that of $\mathcal{D}_{\text{AD}}$ is either 4 or 5. Thus, $\mathcal{M}_R$ with the denoising mapper $\mathcal{D}_{\text{AD}}$ is either QPSK or 5QAM as in [10]. The received signal at node p and q are obtained by

$$y_i = h_i x_R^{(p,q)} + z_i \qquad \text{for} \quad i = p,\ q$$

where $z_i \sim \mathcal{N}(0, \sigma^2)$ indicates the complex Gaussian noise.

For simplicity, we assume reciprocity between the MAC and the BC phases. Then, each node decodes a codeword from the relay as

$$\hat{s}_{R,i}^{(p,q)} = \arg\min_{s_R^{(p,q)}} |y_i - h_i x_R^{(p,q)}|^2 \quad \text{for} \quad i = p,\ q. \tag{3}$$

From the output (3), nodes p and q can decode s_q and s_p using their own data s_p and s_q, respectively, as long as the denoising mapper is appropriately designed. When the channel coefficients change over time, we can improve the performance by opportunistically selecting a user pair based on the channel condition. In the next section, we present a selection scheme proposed in this letter.

III. Opportunistic Selection Criteria

Since the channel distributions are assumed to be identical, all users have the same channel quality on average. Our goal is to identify a pair of users who minimize the probability of error among all possible user pairs. However, computing an exact instantaneous error rate of PNC for TWRC would be quite complicated[1]. Thus, we propose two simple criteria for selecting the best user pair in this section.

A. Channel Norm Criterion

One simple criterion is to find two users with two largest channel norms as

$$(\hat{p}, \hat{q}) = \arg\max_{\substack{p,q \in U \\ p \neq q}} \left(|h_p| + |h_q|\right)$$

where U represents a set of users. Although this criterion provides a good performance improvement over the fixed selection scheme, choosing a user pair based only on the channel norm may be suboptimal. Thus, we propose another criterion which provides better performance in the following.

B. Minimum Distance Criterion

For opportunistic scheduling, we provide a better selection criterion which selects a user pair with respect to the minimum distance between signals at the relay, since a minimum distance based approach provides an adequately tight prediction of the error rate [17]. To obtain the minimum distance for users p and q, denoted as $d_{\min}^{(p,q)}$, we first calculate the Euclidean distance between two different points $\mathbf{s} = (s_p, s_q)$ and $\tilde{\mathbf{s}} = (\tilde{s}_p, \tilde{s}_q)$ as

$$\begin{aligned} d_{\mathbf{s}-\tilde{\mathbf{s}}}^{(p,q)} &= \left|\left(h_p x_p + h_q x_q\right) - \left(h_p \tilde{x}_p + h_q \tilde{x}_q\right)\right| \\ &= \left|h_p \delta_p + h_q \delta_q\right| \end{aligned} \tag{4}$$

where $\delta_p = x_p - \tilde{x}_p$ and $\delta_q = x_q - \tilde{x}_q$.

The distance between the signal points mapped to the same codeword is excluded since this does not contribute to the BER. Then the minimum distance associated with the node pair (p, q) is given by

$$d_{\min}^{(p,q)} \triangleq \min_{\mathcal{D}(\mathbf{S}) \neq \mathcal{D}(\tilde{\mathbf{S}})} d_{\mathbf{s}-\tilde{\mathbf{s}}}^{(p,q)}. \tag{5}$$

[1]A method to obtain the exact instantaneous BER of PNC was recently proposed in [16] only for BPSK.

After computing the minimum distance of (5) for all possible pairs of users, we select the user pair with the largest minimum distance as

$$(\hat{p}, \hat{q}) = \arg \max_{\substack{p,q \in U \\ p \neq q}} d_{\min}^{(p,q)}.$$

Note that the channel norm criterion requires channel magnitude information only, while the minimum distance criterion additionally needs channel phase information which may be sensitive to carrier offsets. It will be shown in the simulation section that the minimum distance criterion significantly outperforms the channel norm criterion. In the following section, we will describe how to calculate $d_{\min}^{(p,q)}$ efficiently.

IV. Computation of Minimum Distance

In this section, we propose a technique for obtaining the minimum distance of the superposed constellation for given channels. For BPSK, it is easy to show that the minimum distance is simply related to the magnitude of the smaller channel gain, *i.e.*, $d_{\min}^{(p,q)} = 2\min(|h_p|, |h_q|)$. Therefore, the channel norm criterion and the minimum distance criterion become equivalent for the BPSK case.

However, for QPSK, the computation of the minimum distance becomes more complicated. The QPSK constellation mapper at user nodes is represented as

$$\mathcal{M}_{\mathrm{QPSK}}(s_p) \in \left\{ \frac{1+j}{\sqrt{2}}, \frac{-1+j}{\sqrt{2}}, \frac{1-j}{\sqrt{2}}, \frac{-1-j}{\sqrt{2}} \right\}.$$

There are 16 signal points in the received signal at the relay since the QPSK signals from two users are superposed at the relay during the MAC phase. Hence, the search size of $\binom{16}{2} = 120$ is required to find the minimum distance for a given user pair. In the following, we describe an efficient method to compute the minimum distance.

For simple descriptions, we define the maximum and the minimum channels as

$$h_{\max} = \arg \max_{h \in \{h_p, h_q\}} |h| \quad \text{and} \quad h_{\min} = \arg \min_{h \in \{h_p, h_q\}} |h|. \quad (6)$$

Also the channel ratio for a given user pair p and q is denoted as

$$\gamma \triangleq \frac{h_{\min}}{h_{\max}} = \alpha + j\beta. \quad (7)$$

Using (6) and (7), we can rewrite (4) as

$$d_{\mathbf{s}-\tilde{\mathbf{s}}}^{(p,q)} = |h_{\max}| \cdot |\delta_{\max} + \gamma \delta_{\min}|$$

where $\delta_{\max} = \delta_p$, $\delta_{\min} = \delta_q$ if $|h_p| > |h_q|$ and $\delta_{\max} = \delta_q$, $\delta_{\min} = \delta_p$ otherwise.

To identify the pair $(\mathbf{s}, \tilde{\mathbf{s}})$ which contributes to the minimum distance, we investigate the distance normalized by $|h_{\max}|$ as

$$\bar{d}_{\mathbf{s}-\tilde{\mathbf{s}}}^{(p,q)} \triangleq \frac{d_{\mathbf{s}-\tilde{\mathbf{s}}}^{(p,q)}}{|h_{\max}|} = |\delta_{\max} + \gamma \delta_{\min}|.$$

After some manipulations, $\bar{d}_{\mathbf{s}-\tilde{\mathbf{s}}}^{(p,q)}$ can be written as

$$\bar{d}_{\mathbf{s}-\tilde{\mathbf{s}}}^{(p,q)} = \sqrt{|\delta_{\max}|^2 + |\delta_{\min}|^2(\alpha^2 + \beta^2) + 2A\alpha + 2B\beta}$$

where $A = \Re[\delta_{\max}\delta_{\min}^*]$ and $B = \Im[\delta_{\max}\delta_{\min}^*]$. Here, $\Re[\cdot]$, $\Im[\cdot]$ and $(\cdot)^*$ stand for the real and imaginary part and complex conjugate, respectively. Therefore, $\bar{d}_{\mathbf{s}-\tilde{\mathbf{s}}}^{(p,q)}$ are determined by four parameters $|\delta_{\max}|^2$, $|\delta_{\min}|^2$, A and B. Among 120 combinations of these four parameters, there exist only 20 distinct combinations of the parameters as listed in Table I.[2]

TABLE I
Parameters for the Minimum Distance

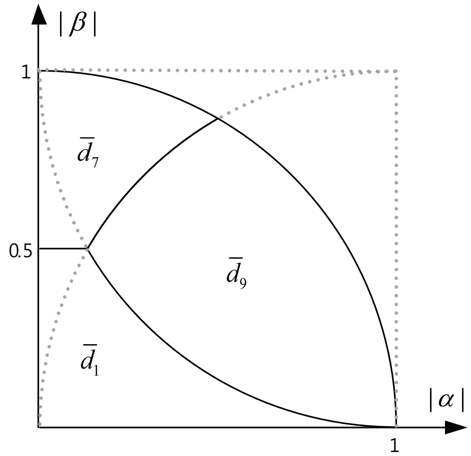
Group	$\lvert\delta_{\max}\rvert^2$	$\lvert\delta_{\min}\rvert^2$	A	B	$\bar{d}^2/2$
1	0	2	0	0	$\alpha^2+\beta^2$
2	0	4	0	0	$2(\alpha^2+\beta^2)$
3	2	0	0	0	1
4	4	0	0	0	2
5	2	2	± 2	0	$1+\alpha^2+\beta^2 \pm 2\alpha$
6	4	4	± 4	0	$2(1+\alpha^2+\beta^2 \pm 2\alpha)$
7	2	2	0	± 2	$1+\alpha^2+\beta^2 \pm 2\beta$
8	4	4	0	± 4	$2(1+\alpha^2+\beta^2 \pm 2\beta)$
9	2	4	± 2	± 2	$1+2(\alpha^2+\beta^2) \pm 2\alpha \pm 2\beta$
10	4	2	± 2	± 2	$2+\alpha^2+\beta^2 \pm 2\alpha \pm 2\beta$

We first consider $\mathcal{D}_{\mathrm{XOR}}$ as the constellation mapper at the relay. The distances in group 5 and 6 in Table I can be excluded from the candidate of the minimum distance because we have $\mathcal{D}_{\mathrm{XOR}}(\mathbf{s}) = \mathcal{D}_{\mathrm{XOR}}(\tilde{\mathbf{s}})$. Also, since the distances in group 2, 4, and 8 are twice of those in group 1, 3, and 7, respectively, group 2, 4, and 8 can be removed from the list. Moreover, the distances in group 3 and 10 are always greater than or equal to those in group 1 and 9 since $\alpha^2 + \beta^2 < 1$. Thus, we can further exclude the distances in group 3 and 10. In group 7 and 9, the distance which contributes to the minimum distance is determined by the sign of α and β. As a result, we can reduce the number of candidates for the minimum distance to three (one each in group 1, 7, and 9) as

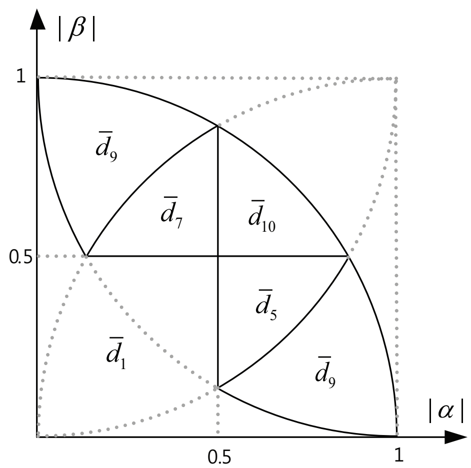
$$\bar{d}_1^2 = 2\alpha^2 + 2\beta^2 \quad (8)$$
$$\bar{d}_7^2 = 2\left(1 + \alpha^2 + \beta^2 - 2|\beta|\right) \quad (9)$$
$$\bar{d}_9^2 = 2 + 4\left(\alpha^2 + \beta^2 - |\alpha| - |\beta|\right). \quad (10)$$

Now we further present a method to determine the minimum distance among (8), (9), and (10) based on the values of α and β without direct evaluations. In case when $\bar{d}_1$ is the minimum distance, two inequalities $\bar{d}_1 < \bar{d}_7$ and $\bar{d}_1 < \bar{d}_9$ should be satisfied. The first inequality $\bar{d}_1 < \bar{d}_7$ is equivalent to $\bar{d}_7^2 - \bar{d}_1^2 = 2 - 4|\beta| > 0$, which results in $|\beta| < 0.5$. Similarly, from the second inequality $\bar{d}_1 < \bar{d}_9$, we have $\bar{d}_9^2 - \bar{d}_1^2 = 2 + 2\alpha^2 + 2\beta^2 - 4|\alpha| - 4|\beta| > 0$, which yields $(\alpha-1)^2 + (\beta-1)^2 > 1$. From these relations, $\bar{d}_1$ is minimum in the region of $\left\{|\beta| < 0.5\right\} \bigcap \left\{(\alpha-1)^2 + (\beta-1)^2 > 1\right\}$. Similarly, we can calculate the regions for $\bar{d}_7$ and $\bar{d}_9$. Since $\alpha^2 + \beta^2 < 1$, we finally obtain Fig. 2(a) which shows three regions where each distance $\bar{d}_1$, $\bar{d}_7$, and $\bar{d}_9$ becomes the minimum distance according to the channel ratio parameters α and β. Due to symmetry, only the first quadrant is illustrated.

[2] In Table I, the distances associated with 20 different combinations of parameters are listed in 10 different groups. From group 5 to 10, the sign for α and β follows A and B, respectively. Also, group 9 and 10 have four different distances associated with different combinations of the sign of A and B.



(a) XOR denoising, $\mathcal{D}_{\mathrm{XOR}}$



(b) Adaptive denoising, $\mathcal{D}_{\mathrm{AD}}$

Fig. 2. Region maps of the minimum distance.

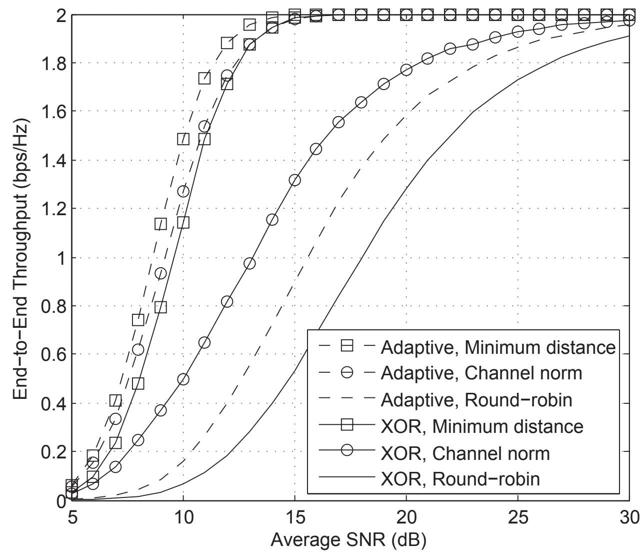


Fig. 3. End-to-end throughput of different selection criteria for QPSK with 10 users.

Utilizing the region map with $\bar{d}_1$, $\bar{d}_7$, and $\bar{d}_9$, we can calculate the minimum distance with the given channels. For example, if the values of α and β fall in the region for $\bar{d}_7$, we can calculate the minimum distance as

$$\begin{aligned} d_{\min}^{(p,q)} &= \max(|h_p|,|h_q|)\cdot \bar{d}_7 \\ &= \max(|h_p|,|h_q|)\sqrt{2+4\left(\alpha^2+\beta^2-|\alpha|-|\beta|\right)}. \end{aligned}$$

Next we consider the case where the relay employs $\mathcal{D}_{\mathrm{AD}}$ as a constellation mapper. Unlike the region map for $\mathcal{D}_{\mathrm{XOR}}$, the region map for $\mathcal{D}_{\mathrm{AD}}$ illustrated in Fig. 2(b) is obtained through computer simulations, since its analytical derivations are quite complicated. As shown in the figure, we need to include two more distances in group 5 and 10 for the candidate of the minimum distance as

$$\begin{aligned} \bar{d}_5^2 &= 2\left(1+\alpha^2+\beta^2-2|\alpha|\right) \\ \bar{d}_{10}^2 &= 4+2\left(\alpha^2+\beta^2-2|\alpha|-2|\beta|\right). \end{aligned}$$

Note that the regions for $\bar{d}_1$ in Fig. 2(a) and (b) have a special property. In these regions, the minimum distance is simply calculated as $d_{\min}^{(p,q)}=\sqrt{2}\min(|h_p|,|h_q|)$. Thus, the minimum distance criterion results in the same user pair as the channel norm criterion for these regions.

In summary, using the proposed method for obtaining the minimum distance, the minimum distance can be determined directly from α and β without comparing different distance pairs. For example, for 5 users with QPSK, the exhaustive search needs search size of $\binom{5}{2}\times 120 = 1200$, while, the search size of $\binom{5}{2}=10$ is required with our schemes.

V. Simulation Results

In this section, we evaluate the end-to-end throughput performance of the proposed selection schemes. The average SNR at the relay is defined as $1/\sigma^2$. The selected users transmit data packets of 256 symbols simultaneously. We assume uncoded systems and the channel dose not change during a packet length. Each node employs QPSK.

Fig. 3 shows the throughput of different selection criteria with $\mathcal{D}_{\mathrm{XOR}}$ and $\mathcal{D}_{\mathrm{AD}}$. The number of users is set to 10. As shown in the figure, the minimum distance criterion provides an improvement over the channel norm criterion. When the relay employs $\mathcal{D}_{\mathrm{XOR}}$, the channel norm criterion and the minimum distance criterion exhibit gains of 5.4 dB and 11.3 dB at 1.6 bps/Hz, respectively, over the round-robin selection system. For the case of $\mathcal{D}_{\mathrm{AD}}$, 8.6 dB and 9.4 dB gains at 1.6 bps/Hz are observed for the channel norm criterion and the minimum distance criterion, respectively. Since the neighboring signal points are clustered into the same group by $\mathcal{D}_{\mathrm{AD}}$, regions for $\bar{d}_1$ in Fig. 2(b) are larger than those in Fig. 2(a). Hence, the minimum distance is dominantly determined by the channel norm, and the performance gap between the channel norm criterion and the minimum distance criterion reduces with $\mathcal{D}_{\mathrm{AD}}$ compared with $\mathcal{D}_{\mathrm{XOR}}$.

Fig. 4 illustrates the throughput curves where the number of users varies from 2 to 16 with $\mathcal{D}_{\mathrm{XOR}}$. We see from the figure that the performance of both the channel norm criterion and the minimum distance criterion improves as the number of users increases. However, it is observed that the performance gap between two selection criterions become larger as the number of users grows. This can be explained by the fact

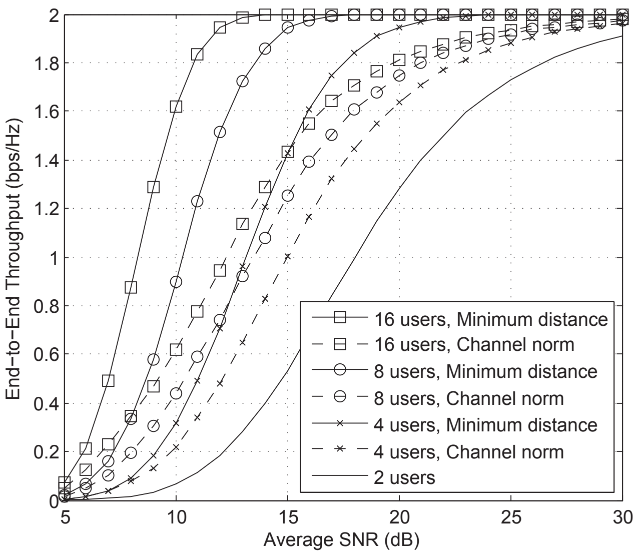


Fig. 4. End-to-end throughput of different selection criteria for QPSK and $\mathcal{D}_{\mathrm{XOR}}$ with 2 to 16 users.

that the minimum distance reflects the system performance better. From the simulation results, it is clear that our proposed schemes are very effective for multi-user relaying systems.

VI. Conclusion

In this letter, we have proposed an opportunistic user selection scheme for multi-user two-way relay channels. We have introduced two selection criteria based on the channel norm and the minimum distance. Moreover, we have derived an efficient method for computing the minimum distance between the signal points for the superposed QPSK signals. This approach made in this letter can be extended to higher modulation level. The proposed opportunistic scheduling schemes are shown to significantly outperform conventional systems without scheduling. It would be interesting to apply the proposed schemes to the system where users and the relay are equipped with multiple antennas. A design of a relay selection strategy for the system with multiple relays is another interesting future direction.

References

[1] B. Rankov and A. Wittneben, "Spectral efficient protocols for half-duplex fading relay channels," *IEEE J. Sel. Areas Commun.*, vol. 25, pp. 379–389, Feb. 2006.

[2] K.-J. Lee, J.-S. Kim, G. Caire, and I. Lee, "Asymptotic ergodic capacity analysis for MIMO amplify-and-forward relay networks," *IEEE Trans. Wireless Commun.*, vol. 9, pp. 2712–2717, Sep. 2010.

[3] K.-J. Lee, H. Sung, E. Park, and I. Lee, "Joint optimization for one and two-way MIMO AF multiple-relay systems," *IEEE Trans. Wireless Commun.*, vol. 9, pp. 3671–3681, Dec. 2010.

[4] M. Chen and A. Yener, "Multiuser two-way relaying: detection and interference management strategies," *IEEE Trans. Wireless Commun.*, vol. 8, pp. 4296–4305, Aug. 2009.

[5] C.-H. Liu and A. Arapostathis, "Joint network coding and superposition coding for multi-user information exchange in wireless relaying networks," in *Proc. 2008 IEEE Globecom*.

[6] S. Katti, D. Katabi, W. Hu, H. Rahul, and M. Medard, "The importance of being opportunistic: practical network coding for wireless environments," in *Proc. 2005 Annual Allerton Conference on Communication, Control and Computing*, pp. 756–765.

[7] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network information flow," *IEEE Trans. Inf. Theory*, vol. 46, pp. 1204–1216, July 2000.

[8] S. Zhang, S. Liew, and P. Lam, "Hot topic: physical-layer network coding," in *Proc. 2006 ACM MobiCom*, pp. 358–365.

[9] P. Popovski and H. Yomo, "Physical network coding in two-way wireless relay channels," in *Proc. 2007 IEEE ICC*, pp. 707–712.

[10] T. Koike-Akino, P. Popovski, and V. Tarokh, "Optimized constellations for two-way wireless relaying with physical network coding," *IEEE J. Sel. Areas Commun.*, vol. 27, pp. 773–787, June 2009.

[11] T. Koike-Akino, P. Popovski, and V. Tarokh, "Adaptive modulation and network coding with optimized precoding in two-way relaying," in *Proc. 2009 IEEE Globecom*.

[12] Y. Li, R. H. Y. Louie, and B. Vucetic, "Relay selection with network coding in two-way relay channels," *IEEE Trans. Veh. Technol.*, vol. 59, pp. 4489–4499, Nov. 2010.

[13] L. Song, "Relay selection for two-way relaying with amplify-and-forward protocols," *IEEE Trans. Veh. Technol.*, vol. 60, pp. 1954–1959, May 2011.

[14] J. Joung and A. H. Sayed, "User selection methods for multiuser two-way relay communications using space division multiple access," *IEEE Trans. Wireless Commun.*, vol. 9, pp. 2130–2136, July 2010.

[15] Y.-U. Jang and Y. H. Lee, "Performance analysis of user selection for multiuser two-way amplify-and-forward relay," *IEEE Commun. Lett.*, vol. 14, pp. 1086–1088, Nov. 2010.

[16] M. Park, I. Choi, and I. Lee, "Exact BER analysis of physical layer network coding for two-way relay channels," in *Proc. 2011 IEEE VTC – Spring*.

[17] D. J. Love and R. W. Heath, "Limited feedback unitary precoding for orthogonal space-time block codes," *IEEE Trans. Signal Process.*, vol. 53, pp. 64–73, Jan. 2005.