Selection of Spatially-distributed Relays for Two-way Relaying with Network Coding

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***Abstract*—To help exchanging information between two sources in a two-way relaying network with multiple relays, we consider selecting one "best" relay or a pair of "best" relays that broadcast network-coded information to other nodes (source or relay). Further, we assume that the multiple relays are random distributed in a one-dimensional or two-dimensional space between the sources and we take the *path loss* between the nodes into consideration. We also select the relay(s) based on the max-min criterion in both the Single Relay Selection (SRS) scheme and the Paired-Relay Selection (PRS) scheme. In particular, we propose a *Distributed VIterbi Selection Algorithm* (DVISA) that selects the pair of "best" relays in the PRS scheme and we describe how the nodes exchange information in a frame consisting of 4 time slots. Both our analytical and simulation results show that when the path-loss exponent is large and/or there is a sufficient number of relays to choose from, using two relay nodes can provide a lower outage compared with using only one relay node even under the same total transmit power.**

***Index Terms*—Network coding, relay selection, two-way relaying.**

I. Introduction

Over the past decade, various aspects of wireless cooperative channels and networks such as information theoretic capacity [1], diversity [2], outage performance [3], and cooperative coding [4] were investigated. The two-way relaying network, being a special case of cooperative communication networks, was first studied by Shannon [5]. The network consists of two users who communicate with each other with the help of a single relay. Recently, network coding [6], [7] has emerged as a viable candidate that can improve the network capacity and the diversity gain, particularly in wireless cooperative communication networks.

In [8], [9], a two-way relaying network with network coding has been proposed to reduce the total number of transmission time slots and to improve network efficiency. It has been demonstrated that the joint use of relay and network coding not only improves the information transmission efficiency [10], [11], [12], but also reduces the overall power consumption significantly in communication systems [9], [13].

In [14], [15], multiple relay selection and relay ordering have been proposed, but they have been applied to cooperative communication networks without network coding. In this paper, we propose a paired-relay-selection (PRS) scheme, in which the "best" pair of relays are selected by a novel Distributed VIterbi Selection Algorithm (DVISA) and are used for broadcasting network-coded information to other nodes (source or relay). We have made use of the max-min function as the basis for DVISA to select the pair of relays. Our analysis on the outage performance of the proposed PRS scheme shows that, when the path-loss exponent is large and/or there is a sufficient number of relays to choose from, using two relay nodes can provide a lower outage than using only one relay node, which is also known as the single relay selection (SRS) scheme.

II. Review of Single Relay Selection Scheme

We consider the two-way relaying network shown in Fig. 1. There are two source nodes S_1 and S_2, and a set of K relay nodes, denoted as $\mathcal{R} = \{R_i : i = 1, \ldots, K\}$. We also define $\mathcal{K} = \{1, \ldots, K\}$ as the index set of the relays. We assume that there is no direct link connecting the sources. Thus, the sources have to exchange their information with the help of one or more of the relay nodes.

We denote the distance between (i) S_1 and S_2 by D; (ii) S_1 and R_i by $d_{S_1,i}$; (iii) S_2 and R_i by $d_{S_2,i}$; and (iv) R_i and R_j by $d_{i,j}$. We consider path loss between the nodes and we model the channel coefficients as variables following complex Gaussian distributions, i.e., $\mathcal{CN}(0, \Omega)$ where $\Omega = (d/d_0)^{-\alpha}$, α is the path-loss exponent (typically ranging from 2 to 4), d_0 is a reference distance, and d is the distance between two nodes [16]. We assume that all the channels are reciprocal, which means the channel coefficients are the same in both directions. We further define the complex channel coefficient between (i) S_1 and R_i as $f_i \sim \mathcal{CN}(0, \Omega_{S_1,i})$, (ii) S_2 and R_i as $g_i \sim \mathcal{CN}(0, \Omega_{S_2,i})$, and (iii) R_i and R_j as $h_{i,j} \sim \mathcal{CN}(0, \Omega_{i,j})$; and we assume that the channel coefficients remain fixed over a channel coherence time. In subsequent sections, unless otherwise stated, all signal transmissions occur within one channel coherence time.

Single Relay Selection (SRS) has been widely studied in cooperative relay networks [17]. When there are multiple relays available, there are several different ways to select the "best" relay. They include max-min criterion [2], max-harmonic-mean criterion [18], max-generalized-min criterion [19], nearest-neighbor criterion [20] and max-received-SNR (signal-to-noise-ratio) criterion [21]. For example, in the max-min criterion, the "best" relay R_r is selected using

$$r = \arg\max_{i \in \mathcal{K}} \{\min\{|f_i|^2, |g_i|^2\}\} \tag{1}$$

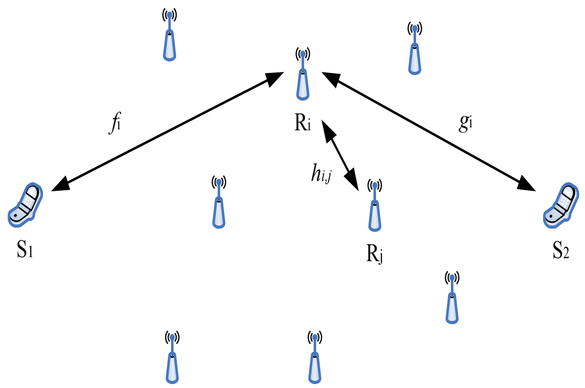


Fig. 1. System model: Two source nodes S_1 and S_2, and K relay nodes R_i $(i = 1, 2, 3, ..., K)$.

where f_i and g_i represent the channel coefficients defined above.

Once the "best" relay has been determined, the exchange of information between the two sources begin. With the use of network coding, it takes three time slots to complete one information-exchange procedure. In the first/second time slot, S_1/S_2 broadcasts its encoded data $\mathbf{x}_1/\mathbf{x}_2$ with a transmit power of P_{S_1}/P_{S_2} After decoding the data $\mathbf{x}_1$ and $\mathbf{x}_2$ successfully, the selected relay perform an XOR operation on the data and broadcasts the XORed results (i.e., $\mathbf{x}_1 \oplus \mathbf{x}_2$) to the two sources with a power of P_r in the third time slot. Then, each source makes use of the received data and its own transmit data to recover the information from the other source.

We consider real signaling. Moreover, we assume that the noise at all nodes (sources or relays) are real, identical and follow a Gaussian distribution with zero mean and variance σ^2, i.e., $\mathcal{N}(0, \sigma^2)$. Then the mutual information from S_1 to R_r and that from S_2 to R_r are given, respectively, by

$$I_{S_1,r} = \frac{1}{2}\log_2\left(1 + \frac{P_{S_1}}{\sigma^2}|f_r|^2\right) \tag{2}$$

and

$$I_{S_2,r} = \frac{1}{2}\log_2\left(1 + \frac{P_{S_2}}{\sigma^2}|g_r|^2\right). \tag{3}$$

As the relay broadcasts the XOR-ed data to both sources, the mutual information of this broadcast channel can be formulated as

$$I_{r,(S_1,S_2)} = \frac{1}{2}\min\left[\log_2\left(1 + \frac{P_r}{\sigma^2}|f_r|^2\right), \log_2\left(1 + \frac{P_r}{\sigma^2}|g_r|^2\right)\right] \tag{4}$$

Consequently, the end-to-end mutual information, which is given by the minimum of the mutual information among all links, can be expressed as

$$I_{\mathrm{SRS}} = \frac{2}{3}\min\left[I_{S_1,r}, I_{S_2,r}, I_{r,(S_1,S_2)}\right]. \tag{5}$$

In the above equation, the coefficient $2/3$ exists because three time slots have been taken to exchange the two data packets between S_1 and S_2. Finally, the outage probability of the SRS two-way relaying system with network coding can be expressed as

$$P_{\mathrm{out,SRS}} = \Pr[I_{\mathrm{SRS}} < T] \tag{6}$$

where T denotes the end-to-end transmission rate in bits per second per hertz (b/s/Hz).

Equal Transmit Power: Suppose the transmit powers of all nodes are the same and are denoted by $P/3$. Using the results in (1) to (5), the outage probability in (6) can be simplified to

$$P_{\mathrm{out,SRS}} = \Pr(\min\{|f_r|^2, |g_r|^2\} \leq \Gamma(T,3)) \tag{7}$$

where $\Gamma(T,l) = \frac{l\sigma^2}{P}(2^{lT} - 1)$ and l represents the total number of transmission time slots in one complete exchange. Moreover, using (i) the fact that the probability density functions (pdfs) of $|f_i|^2$ and $|g_i|^2$ follow exponential distribution ($\lambda e^{-\lambda x}$) with parameters $1/\Omega_{S_1,i}$ and $1/\Omega_{S_2,i}$ [22], respectively; and (ii) *Lemma* below, $P_{\mathrm{out,SRS}}$ can also be expressed as

$$P_{\mathrm{out,SRS}} = \prod_{i=1}^{K}(1 - e^{-\Gamma(T,3)(1/\Omega_{S_1,i} + 1/\Omega_{S_2,i})}). \tag{8}$$

Lemma: Assume that Y_1,Y_2,...,Y_K are random variables following exponential distributions $\frac{1}{\Omega_i}e^{-y/\Omega_i}$ $(i = 1, 2, \ldots, K)$. Let $Y_{\min} = \min\{Y_1, Y_2, \ldots, Y_K\}$. Then the cumulative density function (cdf) of $Y_{\min}$ is given by

$$\begin{aligned}\Pr(Y_{\min} < y) &= 1 - \Pr(Y_{\min} \geq y) = 1 - \prod_{i=1}^{K}\Pr(Y_i \geq y) \\ &= 1 - \prod_{i=1}^{K} e^{-y/\Omega_i}.\end{aligned}$$

III. Paired-Relay Selection Scheme

In this section, we consider a paired-relay selection (PRS) scheme, in which a pair of relays is selected to help the exchanging information between S_1 and S_2. As in the SRS case, there can be different ways to select the "best" pair of relays. Here we use the max-min criterion again for illustration. In other words, the pair of relays $\{R_{p1}, R_{p2}\}$ are chosen where

$$(p_1, p_2) = \underset{(i,j):i,j\in\mathcal{K}, i\neq j}{\arg\max}\{\min\{|f_i|^2, |g_j|^2, |h_{i,j}|^2\}\}. \tag{9}$$

We further design a decentralized protocol, which is called Distributed VIterbi Selection Algorithm (DVISA) and is described in ***Algorithm 1***, for choosing the "best" pair of relays.

1) Information Exchange: After the "best" pair of relays $\{R_{p1}, R_{p2}\}$ has been determined, the information exchange between the two sources can be arranged into frames, each of which consists of 4 time slots. We consider the tth frame. In the first time slot, S_1 broadcasts its data $\mathbf{x}_1[t]$ to R_{p1}. In the second time slot, S_2 broadcasts its data $\mathbf{x}_2[t]$ to R_{p2}. In the third time slot, R_{p1} broadcasts the XORed data $\mathbf{z}_{p1}[t] = \mathbf{x}_1[t] \oplus \mathbf{z}_{p2}[t-1]$ to S_1 and R_{p2}, where $\mathbf{z}_{p2}[t-1]$ denotes the data broadcasted by R_{p2} during the $(t-1)$th frame. Then, in the fourth time slot, R_{p2} broadcasts the XORed data $\mathbf{z}_{p2}[t] =$

Algorithm 1 Distributed VIterbi Selection Algorithm (DVISA)

1: Source S_1 broadcasts its training data and all the relays listen to the training data.

2: We denote the set of relays that can decode the training data correctly by Δ_1. Each R_i in Δ_1 estimates the channel coefficient f_i and computes a back-off timer using $\lambda/|f_i|^2$ [18] where λ is a constant. When the timer expires, R_i broadcasts its own identity and $|f_i|^2$ to all other relays. Assuming that no two relays in Δ_1 have the same back-off timer values, the relays in Δ_1 broadcast one after another. All relays listen to the data broadcasted from relays in set Δ_1.

3: We denote the set of relays that can decode correctly the data from any relay in Δ_1 by Δ_2. If R_j in Δ_2 can decode correctly the data from R_i, it estimates the channel coefficient $h_{i,j}$ and calculates $\min\{|f_i|^2, |h_{i,j}|^2\}$. After all the broadcasts from Δ_1 are completed, R_j selects its "best" partner $R_{i(j)}$ based on the max-min criterion, i.e., $i(j) = \arg\max_{i\in\mathcal{K}_1}\{\min\{|f_i|^2, |h_{i,j}|^2\}\}$ where $\mathcal{K}_1$ is the index set of relays in Δ_1. Again, each R_j in Δ_2 computes a back-off timer using $\lambda/|\hat{h}_j|^2$ where $|\hat{h}_j|^2$ denotes the intermediate value and equals $\min\{|f_{i(j)}|^2, |h_{i(j),j}|^2\}$. When the timer expires, R_j broadcasts its own identity and the value $|\hat{h}_j|^2$ to Source S_2.

4: If S_2 can decode successfully the data from R_j in Δ_2, it estimates the channel coefficient g_j. When all data from R_j in Δ_2 are received, S_2 selects the "best" relay $R_{j(S)}$ based on the max-min criterion, i.e., $j(S) = \arg\max_{j\in\mathcal{K}_2}\{\min\{|g_j|^2, |\hat{h}_j|^2\}\}$ where $\mathcal{K}_2$ is the index set of relays in Δ_2. (Equivalently, the pair of relays are selected according to (9).) S_2 broadcasts that $R_{j(s)}$ is selected as the second relay.

5: $R_{j(s)}$ receives the message from S_2 and in turn broadcasts that $R_{i(j)}$ is selected as the first relay.

6: $R_{i(j)}$ receives the message from $R_{j(s)}$ and further relays the message to S_1.

$\mathbf{x}_2[t] \oplus \mathbf{z}_{p1}[t]$ to S_2 and R_{p1}. Based on the above transmission system, S_1 can decode the data from S_2 using

$$\mathbf{x}_2[t] = \mathbf{z}_{p1}[t+1] \oplus \mathbf{x}_1[t+1] \oplus \mathbf{z}_{p1}[t] \tag{10}$$

while S_2 decodes the data from S_1 using

$$\mathbf{x}_1[t] = \mathbf{z}_{p2}[t] \oplus \mathbf{x}_2[t] \oplus \mathbf{z}_{p2}[t-1]. \tag{11}$$

Note that there are other ways to design the network-coded transmission system such that 4 time slots would suffice for the two sources to exchange information via the pair of relays.

2) Mutual Information and Outage Probability Analysis: The mutual information from S_1 to R_{p1} and from S_2 to R_{p2} are given by, respectively,

$$I_{S_1,p1} = \frac{1}{2}\log_2\left(1 + \frac{P_{S_1}}{\sigma^2}|f_{p1}|^2\right) \tag{12}$$

and

$$I_{S_2,p2} = \frac{1}{2}\log_2\left(1 + \frac{P_{S_2}}{\sigma^2}|g_{p2}|^2\right). \tag{13}$$

Further, the mutual information of R_{p1} to S_1 and R_{p2} equals

$$\begin{aligned} I_{p1,(S_1,p2)} &= \frac{1}{2}\min\left[\log_2\left(1 + \frac{P_{p1}}{\sigma^2}|f_{p1}|^2\right),\right. \\ &\qquad \left.\log_2\left(1 + \frac{P_{p1}}{\sigma^2}|h_{p1,p2}|^2\right)\right] \end{aligned} \tag{14}$$

while that of R_{p2} to S_1 and R_{p1} is computed from

$$\begin{aligned} I_{p2,(S_2,p1)} &= \frac{1}{2}\min\left[\log_2\left(1 + \frac{P_{p2}}{\sigma^2}|g_{p2}|^2\right),\right. \\ &\qquad \left.\log_2\left(1 + \frac{P_{p2}}{\sigma^2}|h_{p1,p2}|^2\right)\right]. \end{aligned} \tag{15}$$

Therefore, the end-to-end mutual information for the proposed paired-relay selection (PRS) scheme equals

$$I_{\mathrm{PRS}} = \frac{2}{4}\min\{I_{S_1,p1}, I_{S_2,p2}, I_{p1,(S_1,p2)}, I_{p2,(S_2,p1)}\} \tag{16}$$

where the coefficient $2/4$ exists because four time slots are used to exchange the two data packets transmission between S_1 and S_2. Consequently, the outage probability of this two-way relaying system with network coding can be expressed as

$$P_{\mathrm{out,PRS}} = \Pr[I_{\mathrm{PRS}} < T]. \tag{17}$$

Equal Transmit Power: Suppose the transmit powers of all nodes are the same and are denoted by $P/4$. Using the results in (12) to (16), the outage probability in (17) can be simplified to

$$P_{\mathrm{out,PRS}} = \Pr[\min\{|f_{p1}|^2, |g_{p2}|^2, |h_{p1,p2}|^2\} < \Gamma(T,4)]. \tag{18}$$

Defining

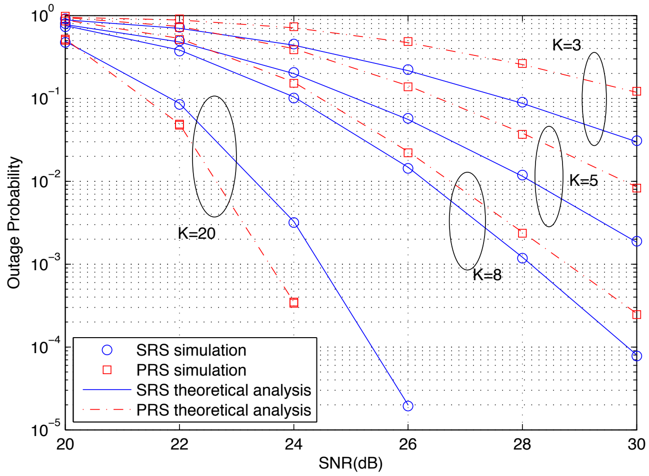
- $E_{1,i}$ as the event that $|f_i|^2 = \min\{|f_i|^2, |g_j|^2, |h_{i,j}|^2\}$ and $|f_i|^2 < \Gamma$;
- $E_{2,(i,j)}$ as the event that $|h_{i,j}|^2 = \min\{|f_i|^2, |g_j|^2, |h_{i,j}|^2\}$ and $|h_{i,j}|^2 < \Gamma$;
- $E_{3,j}$ as the event that $|g_j|^2 = \min\{|f_i|^2, |g_j|^2, |h_{i,j}|^2\}$ and $|g_j|^2 < \Gamma$,

we can further prove that $P_{\mathrm{out,PRS}}$ can be expressed as

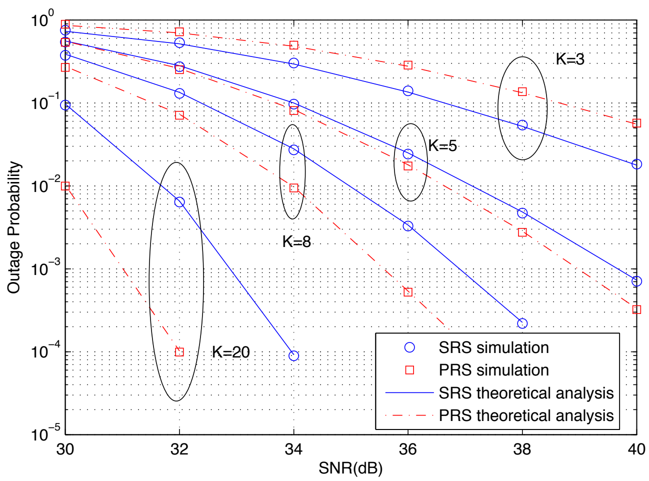
$$\begin{aligned} P_{\mathrm{out,PRS}} &= \prod_{\substack{j=1\\ j\neq i}}^{K}\left[\Pr[E_{3,j}]\sum_{M=1}^{K}\prod_{i\in\Xi^M}\left(\Pr[E_{1,i}] + \Pr[E_{2,(i,j)}]\right)\right. \\ &\qquad \left. + \prod_{i=1}^{K}\left(\Pr[E_{1,i}] + \Pr[E_{2,(i,j)}]\right)\right] \end{aligned} \tag{19}$$

where

$$\begin{aligned} \Pr[E_{1,i}] &= \frac{1}{\Omega_{S_1,i}\cdot\Theta_{i,j}}(1 - e^{-\Gamma(T,4)\Theta_{i,j}}) \\ \Pr[E_{2,(i,j)}] &= \frac{1}{\Omega_{i,j}\cdot\Theta_{i,j}}(1 - e^{-\Gamma(T,4)\Theta_{i,j}}) \\ \Pr[E_{3,j}] &= \frac{1}{\Omega_{S_2,j}\cdot\Theta_{i,j}}(1 - e^{-\Gamma(T,4)\Theta_{i,j}}) \\ \Theta_{i,j} &= (1/\Omega_{S_1,i} + 1/\Omega_{i,j} + 1/\Omega_{S_2,j})^{-1} \end{aligned}$$



(a)



(b)

Fig. 2. Outage probability against SNR(dB) for the SRS and PRS schemes on a one-dimension relay distribution setting. Theoretical results are plotted using lines and simulated ones are shown with symbols. The transmit power of each node in the SRS scheme and the PRS scheme equals $P/3$ and $P/4$, respectively. Number of relays $K = 3, 5, 8, 20$. Path-loss exponent (a) $\alpha = 2$; (b) $\alpha = 3$.

and Ξ^M represents the set containing any M numbers from $\{1, 2, \ldots, K\}$. Due to shortage of space, the detailed proof is omitted here.

IV. Simulation and Numerical Results

In this section, we present the simulation results and the analytical ones. We assume that the distance D between the two sources equals $10d_0$ (d_0 is the reference distance defined in Sect. II). We also assume that the end-to-end transmission rate T equals 2 b/s/Hz. To ensure a fair comparison, the total transmit powers of the SRS and PRS schemes are set to be identical and equal P. We define the SNR as P/σ^2. The number of relays used is $K = 3, 5, 8, 20$.

For each set of SNR and K and for a given relay distribution function, 100 relay distributions have been realized. Moreover,

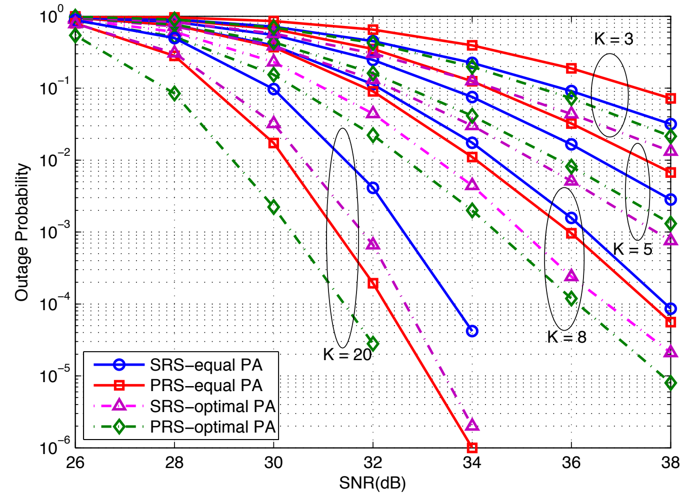


Fig. 3. Simulated outage probability against SNR(dB) for the SRS and PRS schemes on a two-dimension relay distribution setting. Both equal power allocation (PA) and optimal PA have been used. Number of relays $K = 3, 5, 8, 20$. Path-loss exponent $\alpha = 3$.

in each realization, $100,000$ different channel conditions have been simulated so as to evaluate the average outage probability.

A. Relay distribution in one dimension

Firstly, we assume that the relays are randomly distributed on the straight line connecting the two sources. In Fig. 2, we show the outage probabilities when the path-loss exponent α equals 2 and 3. The curves indicate that the theoretical results agree with the simulation results. The results also show that when the path-loss exponent is small ($\alpha = 2$), the SRS scheme (i) produces a better outage probability than the PRS scheme when $K = 3, 5, 8$; (ii) is outperformed by the PRS scheme when $K = 20$. However, when the path-loss exponent is larger ($\alpha = 3$), the SRS scheme is outperformed by the PRS scheme when $K \geq 5$.

B. Relay distribution in two dimensions

We consider the case when the relays are uniform distributed in a circle with a radius of $D/2$ and centre at the mid-point between the two sources. In addition to the equal power allocation (PA), optimal PA is also studied. In the optimal PA, the transmit powers of the nodes in the SRS scheme and the PRS scheme are optimized, respectively, with the constraint sets

$$\begin{aligned} &\text{maximize} && I_{\text{SRS}} \\ &\text{subject to} && P_{S_1} + P_{S_2} + P_r = P, \\ &&& 0 \leq P_{S_1}, P_{S_2}, P_r \leq P \end{aligned} \tag{20}$$

and

$$\begin{aligned} &\text{maximize} && I_{\text{PRS}} \\ &\text{subject to} && P_{S_1} + P_{S_2} + P_{p1} + P_{p2} = P, \\ &&& 0 \leq P_{S_1}, P_{S_2}, P_{p1}, P_{p2} \leq P. \end{aligned} \tag{21}$$

The results in Fig. 3 show that under the same PA mechanism, the SRS scheme (i) produces a better outage probability than the PRS scheme when $K = 3, 5$; (ii) is outperformed by the

PRS scheme when $K = 8, 20$. As expected, the optimal PA mechanism provides a lower outage probability compared with the equal PA. Further, when $K = 20$, the PRS scheme with equal PA can even outperform the SRS scheme with optimal PA.

V. Conclusion and Future Work

We propose a Distributed VIterbi Selection Algorithm (DVISA) that selects a pair of "best" relays to broadcast network-coded information to other nodes (source or relay) in a two-way relaying network with multiple relays. In addition, the relays are random distributed in a one-dimensional or two-dimensional space between the sources. Our study shows that the theoretical outage probabilities of the network agree with the simulation results very well. Assuming the same total transmit power, the proposed Paired-Relay Selection (PRS) scheme outperforms the Single Relay Selection (SRS) scheme in terms of outage when the path-loss exponent between the nodes is large and/or there is a sufficient number of relays in the network. Furthermore, the outage can be reduced in both the PRS and the SRS schemes when the nodes are allowed to transmit with unequal powers.

In our proposed PRS scheme, all relays are involved in determining the "best" pair of relays and the transmission path. Much overhead is spent if there is a large number of relays. To reduce the overhead, we are planning to investigate the scenario when only a limited number of relays with "good" channel conditions are to broadcast their information to other nodes. We will also look into the performance degradation due to such an arrangement. In addition, we intend to evaluate the outage of such two-way relaying networks when other selection criteria, such as max-harmonic-mean and max-received-SNR criteria, are adopted.

Moreover, four time slots are needed to complete one information exchange between the two sources when network coding is applied in the proposed PRS scheme. To further reduce the consumption of time slots, we will investigate ways to improve the PRS scheme by applying physical network coding (PNC) [9].

References

[1] L.-L. Xie and P. R. Kumar, "A network information theory for wireless communication: Scaling laws and optimal operation," *IEEE Trans. Inf. Theory*, vol. 47, no. 5, pp. 748–767, Jan. 2004.

[2] J. N. Laneman and G. W. Wornell, "Distributed space-time coded protocols for exploring cooperative diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2003.

[3] D. Gunduz and E. Erkip, "Opportunistic cooperation by dynamic resource allocation," *IEEE Trans. Wireless Commun.*, vol. 6, no. 4, pp. 1446–1454, Apr. 2007.

[4] A. Stefanov and E. Erkip, "Cooperative coding for wireless networks," *IEEE Trans. Commun.*, vol. 52, no. 9, pp. 1470–1476, Sep. 2004.

[5] C. E. Shannon, "Two-way communication channels," in *in Proc. 4th Berkeley Symp. Math. Stat. and Prob.*, 1961, pp. 611–644.

[6] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. W. Yeung, "Network information flow," *IEEE Trans. Inf. Theory*, vol. 46, no. 4, pp. 1204–1216, Jul. 2000.

[7] S. R. Li, R. W. Yeung, and N. Cai, "Linear network coding," *IEEE Trans. Inf. Theory*, vol. 49, no. 2, pp. 371–381, Feb. 2003.

[8] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, "XORs in the air: practical wireless network coding," in *Proc. ACM SigComm'06*, (Pisa, Italy), 2006, pp. 243–254.

[9] S. Zhang, S. C. Liew, and P. P. Lam, "Hot topic: physical-layer network coding," in *in Proc. ACM MobiCom'06*, (Los Angeles, CA), 2006, pp. 358–365.

[10] L. Xiao, T. Fuja, J. Kliewer, and D. Costello, "A network coding approach to cooperative diversity," *IEEE Trans. Inf. Theory*, vol. 53, no. 10, pp. 3714–3722, Oct. 2007.

[11] S. Fu, K. Lu, Y. Qian, and M. Varanasi, "Cooperative network coding for wireless ad-hoc networks," in *Proc. IEEE Globecom*, Nov. 2007, pp. 812–816.

[12] Z. Han, X. Zhang, and V. H. Poor, "High performance cooperative transmission protocols based on multiuser detection and network coding," *IEEE Trans. Wireless Commun.*, vol. 8, no. 5, pp. 2352–2361, May 2009.

[13] Q. F. Zhou, Y. H. Li, F. C. M. Lau, and B. Vucetic, "Decode-and-forward two-way relaying with network coding and opportunistic relay selection", *IEEE Trans. Commun.*, vol. 58, no. 11, pp. 3070–3076, Nov. 2010.

[14] Z. Yi and I.-M. Kim, "Relay ordering in a multi-hop cooperative diversity network," *IEEE Trans. Commun.*, vol. 57, pp. 2590–2596, Sep. 2009.

[15] M. Ju, I.-M. Kim, and D. I. Kim, "Joint Relay Selection and Relay Ordering for DF-Based Cooperative Relay Networks," *IEEE Trans. Commun.*, vol. 60, no. 4, pp. 908–915, Apr. 2012.

[16] Z. Ren, G. Wang, Q. Chen, and H. Li, "Modelling and Simulation of Rayleigh Fading, Path Loss, and Shadowing Fading for Wireless Mobile Networks," *In Simulation Modelling Practice and Theory (Elsevier)*, Feb. 2011.

[17] Q. F. Zhou, F. C. M. Lau, and S. F. Hau, "Asymptotic analysis of opportunistic relaying protocols," *IEEE Trans. Wireless Commun.*, vol. 8, no. 8, pp. 3915–3920, Aug. 2009.

[18] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[19] X. Chen, Q. F. Zhou, T. W. Siu, and F. C. M. Lau, "Asymptotic analysis of opportunistic relaying based on the maximum-generalized-mean selection criterion," *IEEE Trans. Wireless Commun.*, vol. 10, no. 4, pp. 1050–1057, Apr. 2011.

[20] A. K. Sadek, Z. Han, and K. J. R. Liu, "A distributed relay-assignment algorithm for cooperative communications in wireless networks," in *Proc. IEEE Int. Conf. Commun.*, (Istanbul, Turkey), Jun. 2006.

[21] E. Koyuncu, Y. Jing, and H. Jafarkhani, "Beamforming in wireless relay networks with quantized feedback," *IEEE J. Selected Areas Commun.*, vol. 26, pp. 1429–1439, Oct. 2008.

[22] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*. New York: Academic, 7 ed., 2007.