Multi-Source Relay Networks Exploiting Cooperative Network Coding

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***Abstract*—In this paper, we develop effective multi-source relay schemes which, by exploiting cooperative network coding, are designed to achieve a high diversity gain and coding efficiency. Key to the proposed schemes lies in two ingredients: (1) Utilization of the high-capacity channels between closely spaced intra-cluster nodes to enable efficient information exchange among these nodes; (2) Proper distributed network coding that provides high diversity gain. Outage probability analysis and numerical results are provided and evidently demonstrate higher diversity gain and coding efficiency that the proposed schemes achieve compared to other comparable network coding schemes.**

I. Introduction

Cooperative communications offer flexible design of wireless networks for enhanced spectral and energy efficiency and more reliable connectivity [1], [2]. In particular, cooperation among closely spaced single-antenna nodes can enjoy the benefit of multi-sensor arrays to achieve diversity as well as array gains [3], [4]. A recent trend is the consideration of multi-source network delivering information to distant destinations relayed by a number of collocated or distributed relay sensors [4], [5], [6], [7].

One important advance in recent cooperative network is network coding which receives attention for its potential advantages of improving throughput and enhancing robustness for multi-source systems (e.g., [8], [9], [10], [11], [12]). The fundamental principle of network coding is to linearly combine multiple independent information flows into one flow to transmit. Network coding strategies differ significantly depending on the network topology and applications. Two-way traffic networking is a well suited example for network coding [11], [13], [14]. Recently, a number of works have extended to more challenging multi-source scenarios (e.g., [15], [16]).

In this paper, we consider effective network coding designs in a multi-source multi-hop relay network where the source nodes and the destination nodes are distant. In such a network, it is effective to choose source and relay nodes in their respective clusters with close intra-cluster distances, whereas the relay cluster maintains much longer inter-cluster distances to the source cluster as well as to the destination nodes.

The network geometry considered in this paper includes multiple source nodes and multiple relay nodes. We use coded information transmission in both source-relay and relay-destination phases to achieve high transmit spatial diversity. To make this happen in a very effective fashion, an important feature of the proposed scheme is to utilize high capacity information exchange between intra-cluster nodes. This enables high-efficiency cooperative network coding to be implemented with a very low overhead. The proposed schemes achieve higher diversity gain and coding efficiency compared to other comparable network coding schemes and their superior performance is clearly demonstrated through outage probability analysis and numerical results.

II. System Model

We consider a wireless network consisting of multiple source nodes and multiple relay nodes. For clarity and convenience of presentation, we assume that the network consists of 2 single-antenna source nodes, denoted as S_l ($l = 1, 2$), and 2 single-antenna relay nodes, denoted as R_k ($k = 1, 2$), as shown in Fig. 1. The extension to more source and delay nodes is straightforward. There could be multiple destination nodes. Due to symmetry, we only consider one destination node, denoted as D, which desires to recover the information transmitted from both source nodes.

We assume that the source nodes and the destination node are distantly separated, and relay nodes are required to bridging the source and destination node. Due to the closer intra-cluster node distance compared to the source-relay and relay-destination links, the intra-cluster link capacity (i.e., between S_1 and S_2, and between R_1 and R_2) is much higher than the inter-cluster link capacity (i.e., between S_1, S_2 and R_1, R_2, or between R_1, R_2 and the destination node). The direct links between the source nodes and destination node are highly attenuated and thus their capacity becomes negligible. We further assume that a source or relay node that transmits or retransmit information does not have the exact channel state information at the transmitter (CSIT), but a relay or destination node that receives information can estimate the channel state information at the receiver (CSIR) for data decoding. CSIR estimation can be achieved by using pilot signals for training.

In addition, we make the following assumptions: 1)The nodes work in half-duplex mode, i.e., they cannot transmit and receive simultaneously; 2) All channels are quasi-static. Due to different propagation distances, the intra-cluster channels can reasonably be considered as an additive white Gaussian

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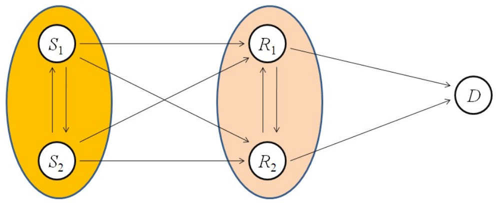
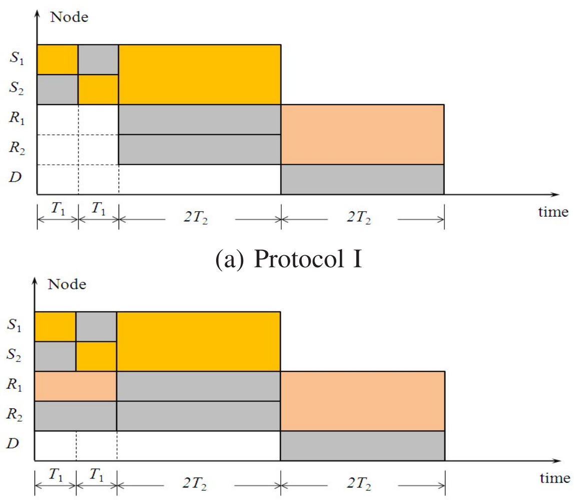


Fig. 1. System diagram of the proposed cooperative network.



(a) Protocol I

(b) Protocol II

Fig. 2. Proposed schemes.

noise (AWGN) channel, whereas the inter-cluster source-relay and relay-destination channels experience frequency-flat Rayleigh block-fading with independent realizations across blocks; and 3) Transmission/reception between the nodes is symbol synchronized. The last assumption can be relaxed if diagonal space-time codes are applied [17].

III. Protocols for Cooperation Networks

A. Proposed Protocols

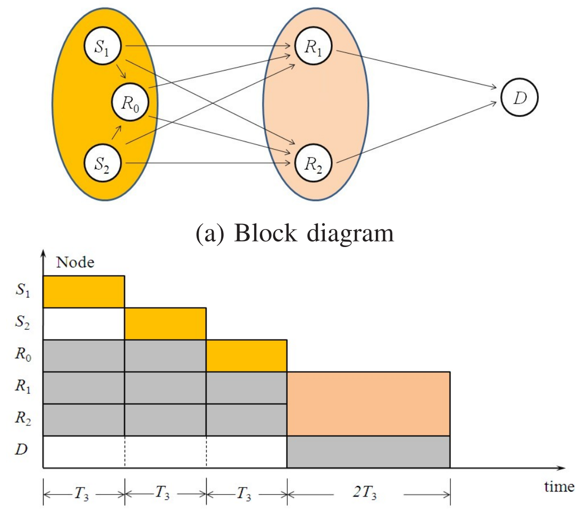
The information transmission from the source node pair S_1 and S_2 to a relay node R_k, $k = 1$ or 2, resembles to a simple cooperative structure that has been intensively studied (see, for example, [1], [2], [3]). Therefore, it is well known that, by incorporating the cooperative communication techniques, more reliable communication links between the source nodes to a relay node can be established.

The protocols for the proposed cooperative network are illustrated in Fig. 2. In the plots, gray color represents nodes in a receive mode, whereas the other colors imply a transmit mode. In the following, we first address in detail the first protocol depicted in Fig. 2(a), then the description for the variant shown in Fig. 2(b) will follow.

a) Protocol I

The protocol corresponding to Fig. 2(a) is presented in the following two phases.

1) Source-Relay Phase: This phase is divided into two steps. (i) During the first step (intra-source cluster information sharing), the two source nodes individually transmit their respective source information in a TDMA fashion within a time period of $2T_1$. The intended receiver is the other source node, and thus a high data rate is applied to take advantage of the high channel capacity between them. While any information overheard at the relay nodes can be used as side information to improve the source-relay link quality, it is not considered in this paper. (ii) In the second step (source nodes broadcast), the two source nodes decode the respective data received from the other source node, and then transmit coded information to the relay nodes within $2T_2$. Because both source nodes have the information of both source flows, they can form any space-time codes developed in the multiple-input multiple-output (MIMO) context.
2) Relay-Destination Phase: During this phase, the two relay nodes respectively decode the signal transmitted from the source nodes, and retransmit the data to the destination node through the decode-and-forward scheme within $2T_2$. The relay nodes adopt a space-time coding strategy that can be the same as or different to that used in the source nodes. Finally, the destination node recovers the two original messages.



(a) Block diagram

(b) Protocol

Fig. 3. XOR-based scheme.

For the convenience of implementation and comparison, we assume in Protocol I that the total transmit power is maintained the same at all the active time.

b) Protocol II

This protocol modifies Protocol I, as depicted in Fig. 2(b), by introducing an information sharing mechanism between relay nodes only when one of the relay nodes fails to decode the signals received from the sources nodes. In this protocol, if one relay node fails, the successful relay node will send the decoded data to the failed one through the intra-relay-cluster high-capacity channel. The relay nodes take this action at the same time of a period of $2T_1$ when the source nodes exchange their information, for the data they received immediately before the action. Therefore, such information sharing between the relay nodes does not require additional time, but the data will be buffered in the relay nodes for an additional cycle. The other processing remains the same as Protocol I.

B. XOR-based Protocol

For comparison, we consider another structure that exploits commonly used network coding that generates XORed result in an auxiliary relay node. The block diagram and the protocol are shown in Fig. 3. This protocol is stated as following.

1) Source-Relay Phase: This phase is also divided into two steps. (i) In the first step (source broadcast), the two source nodes sequentially broadcast their respective source information in a TDMA fashion to the relay within $2T_3$. (ii) In the second step (auxiliary relay), an auxiliary relay node (denoted as R_0), which belongs to the source cluster and is closely located to both source nodes, decodes the data received from both source nodes and performs an XOR operation and then broadcasts the result toward the other two relay nodes within another T_3.
2) Relay-Destination Phase: During this phase, the two relay nodes respectively perform network decoding to retrieve the signal transmitted from the two source nodes and that forwarded by the auxiliary relay R_0. The relay nodes adopt a space-time coding strategy similar to the proposed protocols and retransmit the data to the destination node within $2T_3$. Data retrieving operation is then performed at the destination node.

Note that, for the XOR-based protocol, we do not introduce information exchange between relay nodes as doing so will require additional time slot and thus is not necessarily efficient.

IV. Outage Probability

Denote the channel between the two source nodes as h_s, which is assumed to be common for both directions for notational simplicity. Also denote the channel between the ith source node to the kth relay node as $h_{k,i}$, $i = 1,2, k = 1,2$. We assume that h_s is an AWGN channel, whereas $h_{k,i}$ are Rayleigh channels with independent and identically distributed (i.i.d.) block fading. For notational simplicity, we drop the time-dependence notation for the channel states because they are considered quasi-static.

A. Proposed Protocol I

Because h_s is an AWGN channel, the outage probability for the intra-source-node link, P_s, takes binary values. Therefore, we can consider $P_s = 0$ provided that the data volume to be transmitted from one source node to the other within a time period of T_1 is properly chosen to satisfy $R < BT_1 \log\left(1 + \rho|h_s|^2\right)$ bits, where B denotes channel bandwidth, $\rho = \Gamma_s/\sigma_0^2$ is the source signal-to-noise ratio (SNR), Γ_s is the signal power, and σ_0^2 is the variance of AWGN at the receiver.

The two source nodes, with each other's information received, can be arranged to perform space-time coding and thus act as a pair of multi-sensor terminal. Therefore, assuming no CSIT, the capacity between the two source nodes and the kth relay, $k = 1,2$, within a time period of $2T_2$, is expressed as

$$C_{k,s} = 2BT_2 \log\left(1 + \frac{1}{2}\rho(|h_{k,1}|^2 + |h_{k,2}|^2)\right). \tag{1}$$

Because data volume to be delivered during this time period is $2R$, the outage probability between the two source nodes and the kth relay, $k = 1,2$, using the results developed in [18], is

$$\begin{aligned}\Pr[C_{k,s} < 2R] &= \Pr\left[\frac{1}{2}(|h_{k,1}|^2 + |h_{k,2}|^2) < \frac{2^{R/BT_2} - 1}{\rho}\right] \\ &= 1 - \frac{\sigma_{k,1}^2 \exp\left(-\frac{2^{R/BT_2}-1}{\rho\sigma_{k,1}^2/2}\right) - \sigma_{k,2}^2 \exp\left(-\frac{2^{R/BT_2}-1}{\rho\sigma_{k,2}^2/2}\right)}{\sigma_{k,1}^2 - \sigma_{k,2}^2},\end{aligned} \tag{2}$$

where $|h_{k,i}|$ is Rayleigh distributed. For the specific case where $\sigma_{k,1}^2 = \sigma_{k,2}^2 = \sigma_k^2$, the above result becomes [19]

$$\Pr[C_{k,s} < 2R] = \gamma_2\left(\frac{2^{R/BT_2} - 1}{\rho\sigma_k^2/2}\right), \tag{3}$$

where $\gamma_M(x) = \frac{1}{(M-1)!}\int_0^x t^{M-1}e^{-t}dt$ is the lower incomplete Gamma function.

Now we turn into the relay-destination phase. When both relays successfully received the information of both users, the outage probability at the destination node is expressed, similar to (2) and (3), as

$$\begin{aligned}&\Pr[C_{d,r} < 2R] \\ &= \Pr\left[2BT_2 \log\left(1 + \frac{1}{2}\rho(|h_{d,1}|^2 + |h_{d,2}|^2)\right) < 2R\right] \\ &= \begin{cases} \gamma_2\left(\frac{2^{R/BT_2} - 1}{\rho\sigma_d^2/2}\right), & \sigma_{d,1}^2 = \sigma_{d,2}^2 = \sigma_d^2, \\ 1 - \frac{\sigma_{d,1}^2 \exp\left(-\frac{2^{R/BT_2}-1}{\rho\sigma_{d,1}^2/2}\right) - \sigma_{d,2}^2 \exp\left(-\frac{2^{R/BT_2}-1}{\rho\sigma_{d,2}^2/2}\right)}{\sigma_{d,1}^2 - \sigma_{d,2}^2}, & \text{otherwise,} \end{cases}\end{aligned} \tag{4}$$

where $h_{d,k}$, $k = 1,2$, is the Rayleigh distributed channel between the kth relay node and the destination node, and $\sigma_{d,k}^2$, is the corresponding channel variance. When only the kth relay successfully decoded the information of both users, the outage probability becomes

$$\begin{aligned}\Pr[C_{d,k} < 2R] &= \Pr\left[2BT_2 \log\left(1 + \rho|h_{d,k}|^2\right) < 2R\right] \\ &= \Pr\left[|h_{d,k}|^2 < \frac{2^{R/BT_2} - 1}{\rho}\right] \\ &= 1 - \exp\left(-\frac{2^{R/BT_2} - 1}{\rho\sigma_{d,k}^2}\right).\end{aligned} \tag{5}$$

Consequently, the overall outage probability at the destination node can expressed as

$$\begin{aligned}&P_e = 1 - (1 - P_s) \\ &\cdot[(1-\Pr[C_{1,s} < 2R])(1-\Pr[C_{2,s} < 2R])(1-\Pr[C_{d,r} < 2R]) \\ &\quad + (1-\Pr[C_{1,s} < 2R])\Pr[C_{2,s} < 2R](1-\Pr[C_{d,1} < 2R]) \\ &\quad + \Pr[C_{1,s} < 2R](1-\Pr[C_{2,s} < 2R])(1-\Pr[C_{d,2} < 2R])].\end{aligned} \tag{6}$$

B. Proposed Protocol II

In Protocol II, if a relay fails to receive the signals, the other relay will retransmit the decoded data for recovery. Therefore, the outage probability at relay node k becomes

$$P_e(k) = \Pr[C_{k,s} < 2R] \cdot \{\Pr[C_{j,s} < 2R] + P_r - \Pr[C_{j,s} < 2R] P_r\}, \quad (7)$$

where $j = 3 - k$, and P_r is the outage probability for the link between the relay nodes. Similar to the intra-source-node channel, we also assume h_r to be AWGN, and thus $P_r = 0$ provided that $R < BT_1 \log\left(1 + \rho|h_r|^2\right)$ is satisfied. In this case,

$$P_e(1) = P_e(2) = \Pr[C_{1,s} < 2R] \cdot \Pr[C_{2,s} < 2R], \quad (8)$$

and the overall outage probability at the destination node is expressed as

$$P_e = 1 - [1 - P_e(1)] \left(1 - \Pr[C_{d,r} < 2R]\right). \quad (9)$$

It is worth noting that Protocol II consumes additional power when the intra-relay-node transmission is active. However, such additional power consumption is negligible in the normal operation conditions as the probability of activating such transmission is very small.

C. XOR-based Protocol

Because the auxiliary relay node, R_0, is closely located to the source nodes, and the channel between the source nodes and the auxiliary relay node can be considered as AWGN channels as well. Therefore, as the source nodes transmit their respective information to the relay nodes, it is reasonable to consider that the auxiliary relay node can make error-free decoding of both signal flows. The channels between the auxiliary relay node to the two relay nodes, however, are considered to experience Rayleigh fading.

For notation simplicity, we denote the auxiliary node as the 0th source node. As such, the outage probability for the link between the ith source node and kth relay node can be written as

$$P^{\text{xor}}_{k,i} = \Pr\left[BT_3 \log\left(1 + \rho|h_{k,i}|^2\right) < R\right] = \Pr\left[|h_{k,i}|^2 < \frac{2^{R/BT_3} - 1}{\rho}\right], \quad (10)$$

where $i = 0, 1, 2$ and $k = 1, 2$. Note that $P^{\text{xor}}_{k,i}$ is identical to $P_{k,i}$ for $i = 1, 2$ and $k = 1, 2$. Analogously, when $|h_{k,i}|$ is Rayleigh with channel variance $\sigma^2_{k,i}$, the above outage probability can be expressed as

$$P^{\text{xor}}_{k,i} = 1 - \exp\left(-\frac{2^{R/BT_3} - 1}{\rho\sigma^2_{k,i}}\right). \quad (11)$$

In the XOR-based protocol, a relay node can successfully decode the information from both source nodes when at least two out of three links from the source nodes and the auxiliary relay node are reliable. As a result, the outage probability at the kth distant relay node is given by

$$P^{\text{xor}}_{R_k} = P^{\text{xor}}_{k,1} P^{\text{xor}}_{k,2} (1 - P^{\text{xor}}_{k,0}) + (1 - P^{\text{xor}}_{k,1}) P^{\text{xor}}_{k,2} P^{\text{xor}}_{k,0} + P^{\text{xor}}_{k,1} (1 - P^{\text{xor}}_{k,2}) P^{\text{xor}}_{k,0} + P^{\text{xor}}_{k,1} P^{\text{xor}}_{k,2} P^{\text{xor}}_{k,0}. \quad (12)$$

As there is no intra-cluster link between the relay nodes, the overall outage probability at the destination becomes

$$P^{\text{xor}}_e = 1 - [(1 - P^{\text{xor}}_{R_1}) \cdot (1 - P^{\text{xor}}_{R_2}) \cdot (1 - \Pr[C_{d,r} < 2R]) + P^{\text{xor}}_{R_2} \cdot (1 - P^{\text{xor}}_{R_1}) (1 - \Pr[C_{d,1} < 2R]) + P^{\text{xor}}_{R_1} \cdot (1 - P^{\text{xor}}_{R_2}) \cdot (1 - \Pr[C_{d,2} < 2R])]. \quad (13)$$

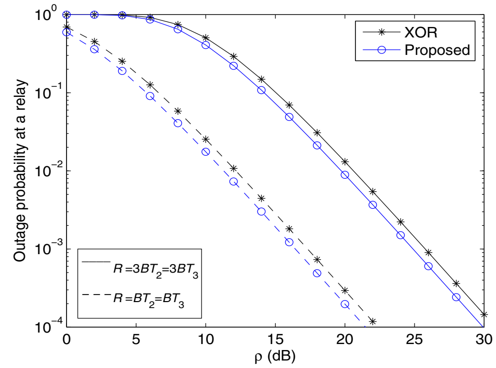


Fig. 4. Relay node outage probability.

V. NUMERICAL RESULTS

In this section, numerical results are provided to display the performance of the proposed cooperative protocols. Without loss of generality, we choose $2T_1 = T_2 = T_3$ for the convenience of comparison between the three protocols. The overall time period used to transmit information R from each of the source node to the destination is $5T_2 = 5T_3 = 10T_1$ for all three protocols. We consider two cases where $R = BT_2 = BT_3$ and $R = 3BT_2 = 3BT_3$, respectively. Unless otherwise specified, the channels between the source nodes as well as the auxiliary node to the two relay nodes are Rayleigh distributed with unit variance. Because the relay-destination link has a lower diversity gain, the channel gains between the relay nodes and the destination node are assumed to be 5. In practice, this implies that the relay nodes are slightly closer to the destination than to the source nodes, depending on the propagation environment. For simplicity, $P_s = 0$ and $P_r = 0$ are reasonably assumed because the intra-cluster nodes, as we discussed earlier, are closely spaced and their channels are AWGN ones with much higher gain.

We first depict the outage probability at a relay node, where the parameters are default as described above. Throughout this section, we use solid lines to depict the $R = 3BT_2$ case whereas dashed lines for the $R = BT_2$ case. As illustrated in Fig. 4, all the curves show the same diversity gain of 2, but the proposed protocols with source information-sharing achieve about 0.9 dB gain in the SNR comparing to their respective counterparts. When the required throughput R increases from BT_2 to $3BT_2$, an 8.45 dB increase of SNR, which can be derived from (3), is needed to remain the same outage probability level.

Now we consider the overall outage probability at the destination node. In the default setting, the results are depicted in Fig. 5. Compared to the XOR-based protocol, the proposed protocols achieve better outage performance, especially in moderate SNR regime. Information sharing between the relay nodes in Protocol II further improves the outage performance. Such improvement diminishes as the SNR increases, where the relay-destination link, which has a lower diversity gain than the source-relay link, becomes the bottleneck. The turning SNR level at which the relay-destination link dominates the performance degradation depends on the quality of the relay-destination channels compared to that of the source-relay links.

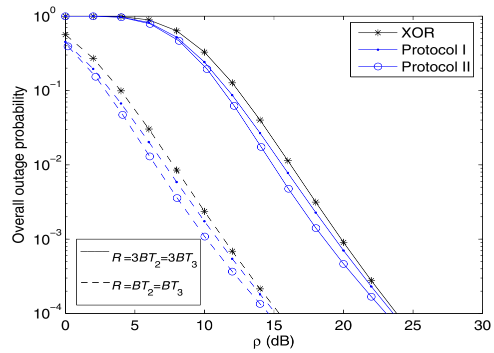


Fig. 5. Destination outage probability ($\sigma_{k,i}^2 = 1$ and $\sigma_{d,k}^2 = 5$ for $i = 1, 2$ and $k = 1, 2$).

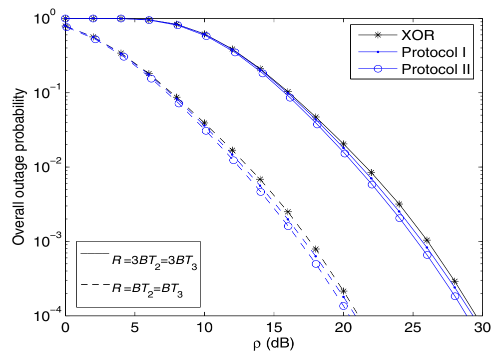


Fig. 6. Destination outage probability (same as Fig. 5 except $\sigma_{k,1}^2 = 0.01$ for $k = 1, 2$).

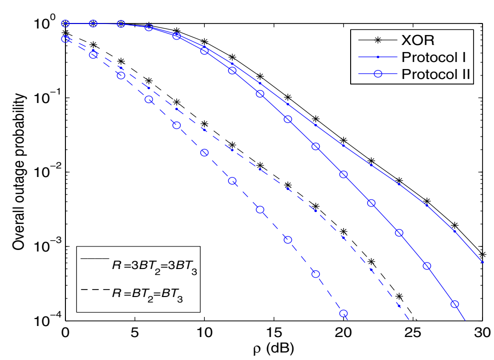


Fig. 7. Destination outage probability (same as Fig. 5 except $\sigma_{1,i}^2 = 0.01$ for $i = 0, 1, 2$).

Similar to the outage probability at a relay node, an 8.45 dB increase of SNR is required to remain the same outage probability level when R increases from BT_2 to $3BT_2$.

Next, we consider two non-symmetric channel scenarios. In the first such scenario, source node 1 experiences low-gain channels to both relay nodes, i.e., $\sigma_{k,1}^2 = 0.01, k = 1, 2$. The outage performance is illustrated in Fig. 6. In this case, the effect of low relay-destination diversity gain does not appear as a problem because the source-relay links now have the same diversity gain. Both proposed schemes outperform the XOR-based scheme. In the second example, relay node 1 experiences channel impairment to all the source and auxiliary relay nodes. In this case, by utilizing intra-relay-node link, Protocol II yields substantial diversity gain and SNR improvement over Protocol I and the XOR-based approaches. While the XOR-based protocol can also utilize in the same way, doing so, as we previously described, requires an additional time slot and thus may not necessarily be effective. Note that, as Protocol II in this case yields higher probability of data retransmission from relay 2 to relay 1, the entire system will need to consume up to 20% (i.e., 0.8 dB) more power. This is compensated in Fig. 7 so it reflects a fair comparison under the same average power for all the three protocols.

VI. Conclusion

In this paper, we have proposed new network coding schemes for multi-user multi-relay cooperative networks that effectively utilize the high-capacity intra-cluster communications to achieve high diversity gain and coding efficiency. Outage probability analysis and numerical results evidently demonstrated their superior performance compared to conventional network coding approaches.

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