Performance of Cooperative Relaying with Adaptive Modulation and Selection Combining

Wei Song, Peijian Ju, and Dizhi Zhou
Faculty of Computer Science
University of New Brunswick, Fredericton, Canada
E-mails:{wsong,i1689}@unb.ca, dizhiz@acm.org

***Abstract*—Taking advantage of the broadcast nature of wireless medium, a relay node can forward an overheard signal from the source to enhance the receiving quality. Many previous studies on cooperative relaying focus on maximal ratio combining (MRC) to exploit the spatial diversity. However, it is complex to enable different modulation levels with MRC so as to better address varying channel conditions. There has been some existing work on the performance of cooperative relaying with selection combining (SC). In this paper, we further consider adaptive modulation and coding (AMC) in a cooperative relaying scenario with selection combining. Based on the bit error rate (BER) analysis, the minimum signal-to-noise ratio (SNR) thresholds are determined to activate different modulation modes at the relay node, such that the overall BER at the destination is no greater than a target BER constraint. Simulations are conducted to verify the accuracy of the BER analysis. The numerical results demonstrate the performance gain of cooperative relaying with adaptive modulation and selection combining.**

***Index Terms*—Cooperative communications, relay, selection combining, adaptive modulation and coding.**

I. Introduction and Related Work

Cooperative diversity provides an effective approach to address slow fading in a wireless environment by forming a virtual antenna array. The next generation multi-radio wireless networks will further promote cooperative networking [1,2]. In the literature, many relay selection algorithms have been proposed for cooperative relaying to optimize the cooperation gain [3,4]. In [3], a distributed relay assignment algorithm is proposed for cooperative communications. The nearest neighbor to the user towards the base station (access point) is chosen to be the relay. The dynamic relay selection scheme in [4] further addresses user mobility by using a constrained Markov decision process in relay selection. Many such studies consider maximal ratio combining (MRC) to exploit cooperative diversity and enhance the received signal-to-noise ratio (SNR).

These relay selection schemes aim to determine an optimal relay node in a centralized or distributed manner, depending on certain optimization objectives and channel models. However, the real scenarios in practical networks can be much more complex. It is possible that an optimal relay node does not exist or the ideal relay node may leave the cooperation region due to user mobility. Before a best relay node is located, a practical solution is to make good use of an available relay node with appropriate modulation and coding. Nonetheless, it is not straightforward to directly apply adaptive modulation and coding (AMC) with maximal ratio combining (MRC) for cooperative relaying. In [5], soft-bit MRC is proposed to enable combining of signals of different modulation levels. However, it can be challenging in practice due to the implementation complexity. In [6], selection combining is analyzed for signals received from a direct path and a relaying path but with different modulation levels. The selection scheme based on bit error rate (BER) is shown to greatly outperform the conventional SNR-based scheme.

This research was supported by a research grant from Natural Sciences and Engineering Research Council (NSERC) of Canada.

In view of the attractive features, we consider the BER-based selection combining and extend the analytical approach in [6] to investigate adaptive modulation and coding for cooperative relaying. The relay node determines the modulation scheme used to forward the overheard signal from the source node, depending on the SNR estimates of the direct path and the relay path. The minimum SNR requirement is determined to activate a modulation mode at the relay node, so that the overall BER at the destination node with selection combining is no greater than a target BER constraint. As such, we can minimize the average transmission time to send a frame from the source to the destination via cooperative relaying, while satisfying a BER constraint. Simulations are conducted to verify the accuracy of the analytical method that is used to determine the SNR thresholds for AMC. The numerical results that cooperative relaying with AMC and selection combining significantly outperforms the direct path transmission and relaying with a fixed modulation mode.

The remainder of this paper is organized as follows. Section II specifies the system model. In Section III, we introduce an analytical approach to investigate adaptive modulation for cooperative relays with selection combining. Numerical results and conclusions are given in Sections IV and V, respectively.

II. System Model

Consider a typical network scenario shown in Fig. 1. A source node located at the coverage edge of the base station (BS) or access point (AP) usually experiences poor transmission quality. It is likely that a neighbor node, which is closer to the source node and the destination node (BS or AP), can relay the signal sent from the source to achieve a better received quality at the destination.

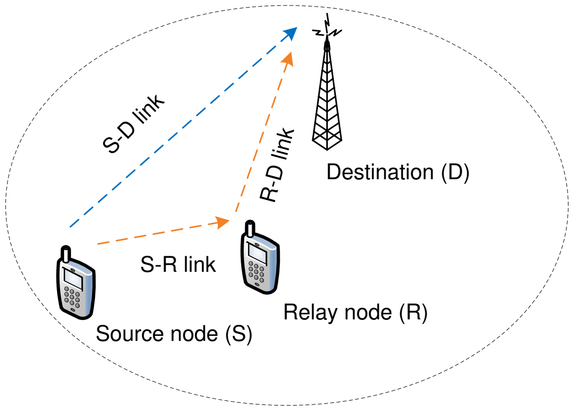

Fig. 1. System model with cooperative relaying.

In some previous works such as [7], the source node can evaluate and compare the transmission quality of the direct path and the two-hop relay path *a priori* via additional signaling exchange. If the relay path is found to be superior, the source sends the signal over the two hops through the relay. Appropriate modulation and coding schemes can be selected respectively for the link from the source to the relay and the link from the relay to the destination. Nonetheless, the extra signaling for advance relay selection may introduce non-negligible overhead. In this study, we consider that the relay node just overhears the signal sent from the source and only relays the signal to the destination if correctly decoded. Both the relayed signal and the signal sent over the direct path are aggregated at the destination by using selection combining. Due to independent fading over the two paths, the spatial diversity enhances the overall received signal quality.

Assume that the links among the source, relay, and destination nodes are subject to Rayleigh flat fading. The average SNRs of the S-D, S-R, and R-D links are denoted by $\bar{\gamma}_{SD}$, $\bar{\gamma}_{SR}$, $\bar{\gamma}_{RD}$, respectively. Both the source and the relay nodes use square *M*-ary quadrature amplitude modulation (*M*-QAM) with Gray code. Let M_S and M_R denote the number of constellation points of the modulation scheme used at the source node and the relay node, respectively. As the source node may have little knowledge of the link conditions of the relay path, a fixed modulation mode (M_S) is applied at the source node. In contrast, once the relay node overhears the signal from the source, it can estimate the SNR of the S-R link and dynamically adapt the modulation mode (M_R) to forward the signal towards the destination. Given N possible modulation modes, the SNR range is partitioned into $(N+1)$ non-overlapping consecutive intervals, with the boundaries denoted by γ_n $(n = 0, 1, ..., N+1)$, where $\gamma_0 = 0$ and $\gamma_{N+1} = +\infty$. The relay node selects a modulation mode i when the SNR over the R-D link falls within the range of $[\gamma_i, \gamma_{i+1})$. The destination node applies the BER-based selection combining technique proposed in [6]. That is, the receiver calculates the BER of the direct S-D link and the R-D link and only decodes the signal from the branch with the minimum BER.

III. Adaptive Modulation for Cooperative Relay with Selection Combining

To determine the SNR thresholds for different modulation modes, we need to evaluate the ultimate BER at the destination with relaying and selection combining. Based on the analysis in [6], the average BER at the destination is obtained as

$$B_e = P_{SR} B_{SD} + (1 - P_{SR}) \cdot B_{SRD} \tag{1}$$

where P_{SR} is the average packet error rate over the S-R link, B_{SD} is the average BER of the direct S-D link, and B_{SRD} is the average BER at the destination with selection combining. That is, if the packet is not correctly decoded at the relay, only the signal via the direct path contributes to the received information at the destination. Here, B_{SD} and P_{SR} are expressed as [8]

$$B_{SD} \approx c_{M_S} Q\left(\sqrt{2d_{M_S}^2 \gamma_{SD}}\right) \tag{2}$$

$$P_{SR} \approx 1 - \left[1 - \log_2(M_S) B_{SR}\right]^{\frac{L}{\log_2(M_S)}} \tag{3}$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2}\, dt. \tag{4}$$

In addition, L is the packet length in bits and B_{SR} is the BER of the S-R link, given by

$$B_{SR} \approx c_{M_S} Q\left(\sqrt{2d_{M_S}^2 \gamma_{SR}}\right). \tag{5}$$

In (2) and (5), γ_{SD} and γ_{SR} are the instantaneous SNR of the S-D link and the S-R link, respectively. Both follow an exponential distribution with a mean $\bar{\gamma}_{SD}$ and $\bar{\gamma}_{SR}$, respectively. Moreover, the parameters c_{M_S} and d_{M_S} depend on the modulation scheme at the source node, given by

$$c_{M_S} = \begin{cases} 1, & M_S = 2 \\ 2\frac{1-1/\sqrt{M_S}}{\log_2\sqrt{M_S}}, & M_S \geq 4 \end{cases} \tag{6}$$

$$d_{M_S} = \begin{cases} 1, & M_S = 2 \\ \sqrt{\frac{3}{2(M_S-1)}}, & M_S \geq 4. \end{cases} \tag{7}$$

According to the BER-based selection combining technique, the destination node calculates the BER of the direct S-D link and the R-D link, and only decodes the signal from the branch with the minimum BER. Similar to the BER of the S-D link in (2), the BER of the R-D link is evaluated by

$$B_{RD} \approx c_{M_R(i)} Q\left(\sqrt{2d_{M_R(i)}^2 \gamma_{RD}}\right) \tag{8}$$

where $M_R(i)$ varies with the modulation mode i of the relay node for transmission over the R-D link. The parameters $c_{M_R(i)}$ and $d_{M_R(i)}$ can be obtained as in (6) and (7). Following the result in [6], we define the region Ψ_r when $B_{RD} \leq B_{SD}$ and the signal from the R-D link is decoded as

$$\Psi_r \approx \left\{(\gamma_{SD}, \gamma_{RD}) : d_{M_R(i)}^2 \gamma_{RD} \geq d_{M_S}^2 \gamma_{SD}\right\}. \tag{9}$$

Likewise, when $B_{SD} < B_{RD}$, the signal from the direct S-D path is decoded. The corresponding region Ψ_d is given by

$$\Psi_d \approx \left\{(\gamma_{SD}, \gamma_{RD}) : d_{M_R(i)}^2 \gamma_{RD} < d_{M_S}^2 \gamma_{SD}\right\}. \tag{10}$$

In [6], the BER at the destination with selection combining is derived by

$$B_{SRD} = \iint_{\Psi_r} B_{RD}(\gamma_{RD}) f(\gamma_{SD}, \gamma_{RD})\, d\gamma_{SD}\, d\gamma_{RD} + \iint_{\Psi_d} B_{SD}(\gamma_{SD}) f(\gamma_{SD}, \gamma_{RD})\, d\gamma_{SD}\, d\gamma_{RD} \tag{11}$$

where $f(\gamma_{SD}, \gamma_{RD})$ is the joint probability density function (PDF) of the SNR of the S-D link and the R-D link, given by

$$f(\gamma_{SD}, \gamma_{RD}) = \frac{1}{\bar{\gamma}_{SD}} e^{-\frac{1}{\bar{\gamma}_{SD}}\gamma_{SD}} \frac{1}{\bar{\gamma}_{RD}} e^{-\frac{1}{\bar{\gamma}_{RD}}\gamma_{RD}}. \tag{12}$$

However, the evaluation of (11) in [6] does not consider adaptive modulation at the relay node. Extending the analysis, we further assume that a modulation mode i is applied at the relay node only when the instantaneous SNR over the R-D link falls within the range $[\gamma_i, \gamma_{i+1})$. Then, we have the BER in mode i with selection combining as follows:

$$\begin{aligned} B_{SRD} &\\ = &\int_{\gamma_i}^{\gamma_{i+1}} c_{M_R(i)} Q\Big(\sqrt{2 d_{M_R(i)}^2 \gamma_{RD}}\Big) \frac{1}{\bar{\gamma}_{RD}} e^{-\frac{1}{\bar{\gamma}_{RD}}\gamma_{RD}}\, d\gamma_{RD} \\ &\int_0^{\frac{d_{M_R(i)}^2}{d_{M_S}^2}\gamma_{RD}} \frac{1}{\bar{\gamma}_{SD}} e^{-\frac{1}{\bar{\gamma}_{SD}}\gamma_{SD}}\, d\gamma_{SD} \\ &+ \int_{\gamma_i}^{\gamma_{i+1}} \frac{1}{\bar{\gamma}_{RD}} e^{-\frac{1}{\bar{\gamma}_{RD}}\gamma_{RD}}\, d\gamma_{RD} \\ &\int_{\frac{d_{M_R(i)}^2}{d_{M_S}^2}\gamma_{RD}}^{\infty} c_{M_S} Q\Big(\sqrt{2 d_{M_S}^2 \gamma_{SD}}\Big) \frac{1}{\bar{\gamma}_{SD}} e^{-\frac{1}{\bar{\gamma}_{SD}}\gamma_{SD}}\, d\gamma_{SD}. \end{aligned} \tag{13}$$

To numerically evaluate (13) to obtain B_{SRD}, we define the following function similar to that in [6]:

$$\begin{aligned} &H(x, y; a, b, c) \\ &\triangleq \int_x^y aQ\left(\sqrt{2bt}\right) \frac{1}{c} e^{-\frac{1}{c}t}\, dt \\ &= \frac{1}{2}a\Bigg[e^{-\frac{x}{c}}\Big(1 - erf(\sqrt{xb})\Big) - e^{-\frac{y}{c}}\Big(1 - erf(\sqrt{yb})\Big) \\ &\quad + \sqrt{\frac{bc}{bc+1}}\Bigg(erf\Big(\sqrt{x\frac{bc+1}{c}}\Big) - erf\Big(\sqrt{y\frac{bc+1}{c}}\Big)\Bigg)\Bigg] \end{aligned} \tag{14}$$

where the error function $erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\, dt$. Specifically,

$$H(0, \infty; a, b, c) = \frac{1}{2}a\left(1 - \sqrt{\frac{bc}{bc+1}}\right) \tag{15}$$

$$H(x, \infty; a, b, c) = H(0, \infty; a, b, c) - H(0, x; a, b, c). \tag{16}$$

Let E_r and E_d denote the first term and the second term of the summation in (13), respectively. Then, we easily obtain

$$\begin{aligned} E_r = &H(\gamma_i, \gamma_{i+1}; c_{M_R(i)}, d_{M_R(i)}^2, \bar{\gamma}_{RD}) \\ &- H\Bigg(\gamma_i, \gamma_{i+1}; c_{M_R(i)} \frac{d_{M_S}^2 \bar{\gamma}_{SD}}{d_{M_S}^2 \bar{\gamma}_{SD} + d_{M_R(i)}^2 \bar{\gamma}_{RD}}, \\ &\qquad d_{M_R(i)}^2, \bar{\gamma}_{RD} \frac{d_{M_S}^2 \bar{\gamma}_{SD}}{d_{M_S}^2 \bar{\gamma}_{SD} + d_{M_R(i)}^2 \bar{\gamma}_{RD}}\Bigg). \end{aligned} \tag{17}$$

To evaluate the second term E_d of (13), we further define the following function:

$$\begin{aligned} J(u, w, z; a, b, c, d) &\triangleq \int_w^z H(0, ut; a, b, c) \frac{1}{d} e^{-\frac{1}{d}t}\, dt \\ &= H(0, \infty; a, b, c)\left(e^{-\frac{w}{d}} - e^{-\frac{z}{d}}\right) \\ &\quad - H\Big(0, z; \frac{ac}{c+du}, ub, \frac{cd}{c+du}\Big) \\ &\quad + H\Big(0, w; \frac{ac}{c+du}, ub, \frac{cd}{c+du}\Big) \\ &\quad + H\Big(0, z; a\sqrt{\frac{bc}{bc+1}}, \frac{u(bc+1)}{c}, d\Big) \\ &\quad - H\Big(0, w; a\sqrt{\frac{bc}{bc+1}}, \frac{u(bc+1)}{c}, d\Big). \end{aligned} \tag{18}$$

Specifically,

$$\begin{aligned} &J(u, 0, \infty; a, b, c, d) \\ &\quad = \frac{1}{2}a\frac{ud}{c+ud}\left(1 - \sqrt{\frac{ubcd}{c+ud+ubcd}}\right) \end{aligned} \tag{19}$$

$$\begin{aligned} &J(u, w, \infty; a, b, c, d) \\ &\quad = J(u, 0, \infty; a, b, c, d) - J(u, 0, w; a, b, c, d). \end{aligned} \tag{20}$$

Therefore, the term E_d is given by

$$\begin{aligned} E_d = &H(0, \infty; c_{M_S}, d_{M_S}^2, \bar{\gamma}_{SD})\left(e^{-\frac{\gamma_i}{\bar{\gamma}_{RD}}} - e^{-\frac{\gamma_{i+1}}{\bar{\gamma}_{RD}}}\right) \\ &- J\left(\frac{d_{M_R(i)}^2}{d_{M_S}^2}, \gamma_i, \gamma_{i+1}; c_{M_S}, d_{M_S}^2, \bar{\gamma}_{SD}, \bar{\gamma}_{RD}\right). \end{aligned} \tag{21}$$

Denoting a target BER at the destination by ε, i.e., $B_e \leq \varepsilon$, we can obtain $B_{SRD} \leq \varepsilon_0$ according to (1) such that the overall BER constraint is satisfied. Then, the following algorithm similar to the one proposed in [9] can be applied to determine the SNR thresholds $\gamma_1, ..., \gamma_N$ for AMC at the relay node. Here, the threshold γ_i defines the minimum SNR required for the R-D link so that the relay node can use the modulation mode i to forward the decoded signal to the destination.

Algorithm 1 Determine SNR thresholds for AMC.

```
Set γ_0 = 0 and γ_{N+1} = ∞
for i = N, N − 1, ...1 do
    Set search range for SNR threshold: γ ∈ [0, γ_{i+1}).
    Find minimum required γ_min such that B_SRD ≤ ε_0
    Set γ_i = γ_min
end for
```

TABLE I
MODULATION MODES OF RELAY NODE.

Mode	1	2	3	4	5	6
Modulation	BPSK	QPSK	8-QAM	16-QAM	32-QAM	64-QAM
Bits/symbol	1	2	3	4	5	6
Rate (Mbit/s)	1	2	3	4	5	6

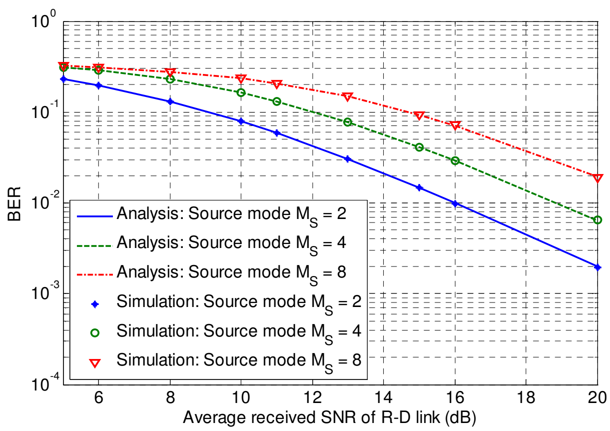

Fig. 2. Analytical results and simulation results of average BER at the destination with selection combining and adaptive modulation at the relay.

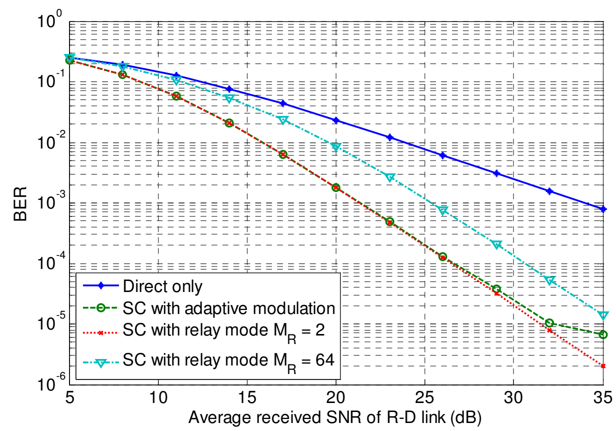

Fig. 3. Comparison of direct transmission and cooperative relaying with adaptive modulation in terms of BER.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we present example numerical results to verify the accuracy of the analysis and evaluate the performance of cooperative relaying with adaptive modulation. In particular, we consider the six modulation modes in Table I. The packet length $L = 264$ bits. By default, we assume that the modulation mode at the source node is $M_S = 2$ and $\bar{\gamma}_{SD} = \bar{\gamma}_{RD} - 10$ dB and $\bar{\gamma}_{SR} = \bar{\gamma}_{RD} + 10$ dB.

In the BER analysis, we take into account adaptive modulation at the relay node, so that the relayed signal can more efficiently contribute to the final received signal at the destination. To verify the analysis accuracy, we use MATLAB 7.10.0 (R2010a) to simulate the cooperative relaying scenario and measure the statistics of bit errors. To remove the random effects, we run multiple rounds to collect the average BER. Fig. 2 compares the analytical results and simulation results of the average BER at the destination with selection combining. It can be seen that the analytical results agree well with the simulation results. There is always a good match even when the modulation mode at the source node (M_S) varies.

In Fig. 3, we compare the BER performance of direct transmission to that of cooperative relaying with and without adaptive modulation at the relay node. As seen, the BER of cooperative relaying with adaptive modulation and selection combining is substantially lower than that of direct transmission. There is a maximum performance gain of 99.34% when $\bar{\gamma}_{RD} = 32$ dB. Moreover, we examine the performance when the relay node applies a fixed modulation mode as in [6] rather than dynamically adapts its modulation mode. As we focus on the six modulation modes shown in Table I, Fig. 3 presents the BER performance when the relay node applies a fixed modulation mode $M_R = 64$ or $M_R = 2$. These are the two extreme cases in Table I, where the mode $M_R = 64$ is most rate-efficient and the mode $M_R = 2$ is most robust to errors. We can observe in Fig. 3 that, given a fixed modulation mode $M_R = 64$ at the relay, the BER of cooperative relaying with selection combining still greatly outperforms that of direct transmission. When the relay node takes the fixed modulation mode $M_R = 2$, it is quite intuitive that the BER performance is even better. Nonetheless, it is interesting to observe that the BER performance with adaptive modulation at the relay node approaches that of the fixed relay mode $M_R = 2$. This is because we can apply the AMC algorithm in Section III to determine the SNR thresholds so that the average BER is upper bounded by certain constraint.

Although cooperative relaying greatly improves error performance via selection combining, the relay takes an additional time to forward the signal overheard from the source to the destination. Fig. 4 illustrates the average transmission time of direct transmission and cooperative relaying with and without adaptive modulation at the relay node. As seen, if both the source node and the relay node take a modulation mode $M_S = M_R = 2$, the transmission time of cooperative relaying doubles that of direct transmission. To reduce the overhead time, the relay node is motivated to apply efficient modulation modes depending on the R-D link condition. For instance, when the relay node takes a rate-efficient modulation mode $M_R = 64$, the overall transmission time is significantly reduced. However, as shown in Fig. 3, a fixed modulation mode $M_R = 64$ for cooperative relaying cannot provide satisfactory error performance. In contrast, it is observed in Fig. 4 that cooperative relaying with adaptive modulation at the relay

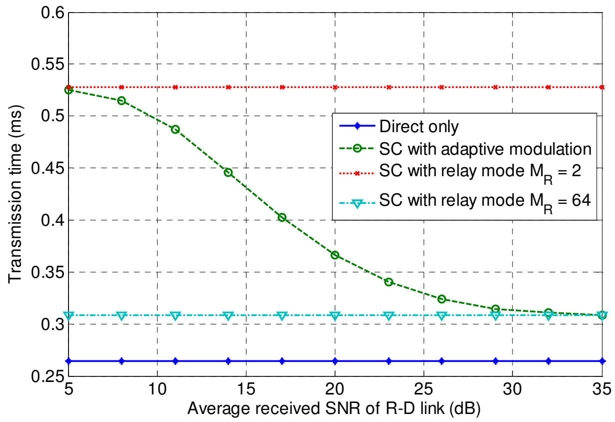

Fig. 4. Comparison of direct transmission and cooperative relaying with adaptive modulation in terms of transmission time.

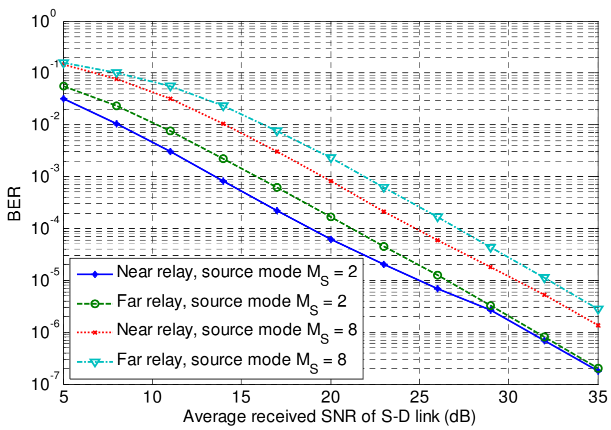

Fig. 5. Average BER at the destination with different relays and various modulation modes at the source.

achieves a good trade-off between the BER performance and transmission time. Depending on the R-D link condition, rate-efficient modulation modes can be enabled to minimize the transmission time while the BER constraint is respected.

Furthermore, we evaluate the cooperative relaying performance with adaptive modulation when the relay link conditions vary. Here, we focus on two representative scenarios, where a relay is closer to the source or closer to the destination. Fig. 5 shows the BER performance with different relays. With the "near relay", we have $\bar{\gamma}_{SR} = \bar{\gamma}_{SD} + 15$ dB and $\bar{\gamma}_{RD} = \bar{\gamma}_{SD} + 10$ dB. In contrast, the "far relay" has $\bar{\gamma}_{SR} = \bar{\gamma}_{SD} + 10$ dB and $\bar{\gamma}_{RD} = \bar{\gamma}_{SD} + 15$ dB. As seen, a relay near to the source is favorable to enhance the BER at the destination, especially when the SNR of the links among the nodes is relatively low. On the other hand, Fig. 6 shows the corresponding transmission time with different relays. It can be seen that a relay closer to the destination is preferred to reduce the transmission time. This is intuitive since more rate-efficient modulation modes can be enabled with a better R-D link condition. Therefore, when adaptive modulation is considered in cooperative relaying, it is crucial to balance the BER performance and transmission time in relay selection.

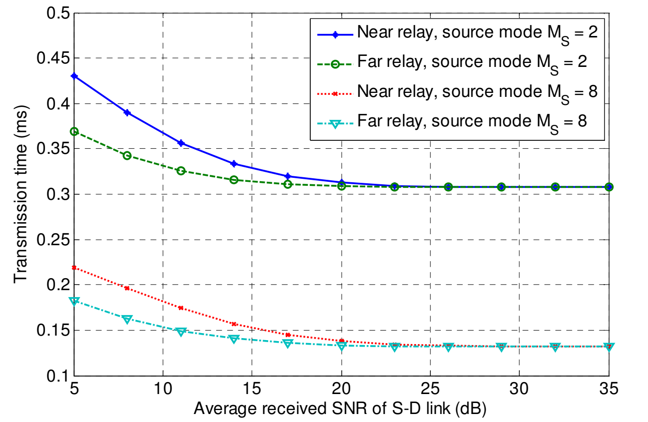

Fig. 6. Average transmission time to the destination with different relays and various modulation modes at the source.

V. Conclusions and Future Work

Cooperative diversity can be exploited by using relays to form a virtual antenna array. Although there have been many studies on cooperative relaying, most previous work focuses on maximal ratio combining. In this study, we consider adaptive modulation and coding in a cooperative relaying scenario with selection combining. Based on the BER analysis, we can determine the SNR thresholds to enable different modulation modes at the relay node. It is observed in the numerical results that cooperative relaying with AMC significantly outperforms direct transmission. Compared with a fixed modulation mode at the relay node, AMC-based relaying achieves a good trade-off to minimize BER and transmission time. The relaying performance directly depends on the link conditions at the relay node with respect to the source and the destination. In the future, we would develop a dynamic algorithm to adjust the SNR thresholds so as to achieve an optimal trade-off between the minimization of bit errors and transmission time.

References

[1] Y. Cheng, H. Li, and P. Wan, "A theoretical framework for optimal cooperative networking in multi-radio multi-channel wireless networks," *IEEE Wireless Commun. Mag.*, vol. 19, no. 2, pp. 66–73, April 2012.

[2] D. Zhou, P. Ju, and W. Song, "Performance enhancement of multipath TCP with cooperative relays in a collaborative community," in *Proc. IEEE PIMRC*, 2012.

[3] A. Sadek, Z. Han, and K. Liu, "A distributed relay-assignment algorithm for cooperative communications in wireless networks," in *Proc. IEEE ICC*, June 2006, pp. 1592–1597.

[4] Y. Li, P. Wang, D. Niyato, and W. Zhuang, "A dynamic relay selection scheme for mobile users in wireless relay networks," in *Proc. IEEE INFOCOM*, April 2011, pp. 256–260.

[5] A. B. Sediq and H. Yanikomeroglu, "Performance analysis of soft-bit maximal ratio combining in cooperative relay networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 4934–4939, October 2009.

[6] A. B. Sediq and H. Yanikomeroglu, "Performance analysis of selection combining of signals with different modulation levels in cooperative communications," *IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1880–1887, May 2011.

[7] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. S. Panwar, "CoopMAC: A cooperative MAC for wireless LANs," *IEEE J. Select. Areas Commun.*, vol. 25, no. 2, pp. 340–354, February 2007.

[8] B. Sklar, *Digial Communications*. McGraw-Hill, 2000.

[9] Q. Liu, S. Zhou, and G. B. Giannakis, "Queuing with adaptive modulation and coding over wireless links: Cross-layer analysis and design," *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 1142–1153, May 2005.