Adaptive Modulation in Decode-and-Forward Cooperative Communications With Limited Source-Relay CSI

Min-Kuan Chang and Feng-Tsun Chien

***Abstract*—In this letter, we study the problem of adaptive modulation (AM) in cooperative decode-and-forward (DF) relaying systems with limited channel state information (CSI) of the source-relay link. We first develop the signal-to-noise ratio (SNR)-based opportunistic AM and obtain the regions of the source-destination and relay-destination link SNR, by which whether cooperative relaying is needed and what constellation size should be chosen can be determined without requiring the source-relay link CSI. We also propose the probabilistic AM to further enhance the transmission rate. Simulation results demonstrate the effectiveness of the proposed AM criteria.**

***Index Terms*—Multi-node cooperative communications, adaptive modulation, decode-and-forward protocol.**

I. Introduction

Opportunistic adaptive modulations (AM) have been widely studied to enhance the spectral efficiency in cooperative relaying networks [1]–[5]. Ikki *et al.* [2] developed a modulation selection scheme by comparing the signal-to-noise ratio (SNR) to a threshold after maximum-ratio combining (MRC) at the destination. A joint relay and modulation selection algorithm was devised by Altubaishi and Shen [3] for cooperative relaying systems based on received SNR at the destination. Ma *et al.* [4] proposed a relay selection scheme that accounted for the average spectral efficiency (ASE) and chose the modulation scheme using an upper bound of bit error rate (BER). In the aforementioned works, the channel state information (CSI) between the source and each relay was needed to determine the maximum constellation size for transmissions. However, conveying CSI consumes additional resources, and may not be desirable in practical applications.

In this letter, we study the problem of adaptive modulation and relay selection in the decode-and-forward (DF) cooperative system using phase-shift keying (PSK) with no or limited knowledge of source-relay CSI.We first develop the SNR-based *opportunistic AM* and obtain the SNR regions, namely the *cooperation region* and the *stand-alone region*, of the source-destination and relay-destination link SNRs, based on which we determine the constellation size and decide whether cooperative relaying is needed when instantaneous CSI of source-relay link is not available. One unique feature of the proposed opportunistic AM is that whether relaying is needed can be readily determined based on the source- and relay-destination link SNR. On the other hand, if additional quantized CSI of the source-relay link is available to the destination, we propose the *probabilistic AM* to further enhance the ASE. Simulation results show that the probabilistic AM achieves higher average rate than that of the opportunistic AM, particularly in low SNR. Furthermore, both the proposed SNR-based opportunistic AM and probabilistic AM admit a better ASE than the maximum rate scheme [3] and a better average rate than the incremental opportunistic relaying [1], thus realizing a more balanced performance between the average rate and ASE.

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II. System Model

Consider a cooperative communication system with one source $\mathcal{S}$, one destination $\mathcal{D}$ and N relays, with $\mathcal{R}_i$ denoting the ith relay for $i = 1, \ldots, N$. Flat Rayleigh fading channels are assumed between all links. We denote h_{AB} as the circularly symmetric complex Gaussian channel gain between nodes A and B, where $A \in \{\mathcal{S}, \mathcal{R}_1, \cdots, \mathcal{R}_N\}$, $B \in \{\mathcal{D}, \mathcal{R}_1, \cdots, \mathcal{R}_N\}$, $A \neq B$ and A and B can not be relays at the same time, with zero-mean and variance σ^2_{AB}. Besides the direct link from $\mathcal{S}$ to $\mathcal{D}$, we consider that at most one relay is selected to participate in cooperation with DF relaying [6] in which a complete transmission consists of two phases. Suppose the selected relay is $\mathcal{R}_i$. In Phase I, $\mathcal{S}$ broadcasts its signal to $\mathcal{D}$ and $\mathcal{R}_i$. Then the signal received at $\mathcal{R}_i$ and $\mathcal{D}$ can be given respectively by $y_{\mathcal{S}\mathcal{R}_i} = \sqrt{P_1} h_{\mathcal{S}\mathcal{R}_i} x + n_{\mathcal{S}\mathcal{R}_i}$ and $y_{\mathcal{S}\mathcal{D}} = \sqrt{P_1} h_{\mathcal{S}\mathcal{D}} x + n_{\mathcal{S}\mathcal{D}}$, where P_1 is the transmission power at the source, x is the transmitted signal with $\mathbf{E}\{|x|^2\} = 1$, and $n_{\mathcal{S}\mathcal{R}_i}$ and $n_{\mathcal{S}\mathcal{D}}$ are complex white Gaussian noise with variance $\mathcal{N}_0$. With the fading between $\mathcal{S}$ and $\mathcal{R}_i$ being Rayleigh, the received SNR $\gamma_{\mathcal{S}\mathcal{R}_i}$ at relay $\mathcal{R}_i$ is exponential with mean $P_1 \sigma^2_{\mathcal{S}\mathcal{R}_i} / \mathcal{N}_0$.

In Phase II, if $\mathcal{R}_i$ can successfully decode the signal from $\mathcal{S}$, it forwards the re-encoded signal to $\mathcal{D}$. Otherwise, $\mathcal{R}_i$ remains silent. In this work, we assume perfect error detection at each relay, as in [6]. The signal received from $\mathcal{R}_i$ at $\mathcal{D}$ is

$$y_{\mathcal{R}_i\mathcal{D}} = \sqrt{\widetilde{P}_2} h_{\mathcal{R}_i\mathcal{D}} x + n_{\mathcal{R}_i\mathcal{D}},$$

where $n_{\mathcal{R}_i\mathcal{D}}$ is zero-mean complex Gaussian noise with variance $\mathcal{N}_0$ and $\widetilde{P}_2$ is the transmission power in Phase II, where $\widetilde{P}_2$ is equal to P_2 if $\mathcal{R}_i$ decodes successfully and 0 otherwise. With the MRC combining [6], the equivalent received SNR at $\mathcal{D}$ after combining the signals in the two phases is $\gamma_{equiv}(\mathcal{R}_i) = \gamma_{\mathcal{S}\mathcal{D}} + \gamma_{\mathcal{R}_i\mathcal{D}}$, where $\gamma_{\mathcal{S}\mathcal{D}} = |h_{\mathcal{S}\mathcal{D}}|^2 P_1 / \mathcal{N}_0$ and $\gamma_{\mathcal{R}_i\mathcal{D}} = |h_{\mathcal{R}_i\mathcal{D}}|^2 \widetilde{P}_2 / \mathcal{N}_0$ are the received SNR in the $\mathcal{S}\mathcal{D}$ and $\mathcal{R}_i\mathcal{D}$ link, respectively.

Let $\mathrm{SER}_P(\gamma, M)$ denote the symbol error rate (SER) of a point-to-point communication system with M-PSK modulation and received SNR, γ. It is well known [7] that for $M = 2$, $\mathrm{SER}_P(\gamma, 2) = Q(\sqrt{2\gamma})$ and for $M > 2$

$$\mathrm{SER}_P(\gamma, M) \approx 2Q\left(\sqrt{2\gamma}\sin\left(\frac{\pi}{M}\right)\right), \tag{1}$$

where the approximation gets more accurate as M grows. We will use the SER approximation in (1) to obtain the minimum required SNR for a target SER threshold SER_{TH}. In the point-to-point communication systems with a predefined SER threshold SER_{TH}, the system will adopt M-PSK[1] if the received SNR γ satisfies $\Gamma_{\log_2 M} \leq \gamma < \Gamma_{1+\log_2 M}$, where

$$\Gamma_\ell = \begin{cases} \frac{1}{2}\left(Q^{-1}(\mathrm{SER}_{TH})\right)^2, & \text{if } \ell = 1, \\ \frac{1}{2}\left(Q^{-1}\left(\frac{\mathrm{SER}_{TH}/2}{\sin\left(\frac{\pi}{2^\ell}\right)}\right)\right)^2, & \text{if } \ell \geq 2, \end{cases} \tag{2}$$

and $\ell = \log_2 M$. In the cooperative system, if $\mathcal{R}_i$ is selected for DF relaying with M-PSK, the instantaneous SER at $\mathcal{D}$ with MRC combining is [6]

$$\begin{aligned}\mathrm{SER}_{DF}(\mathcal{R}_i, M) &= \mathrm{SER}_P(\gamma_{\mathcal{SD}}, M)\mathrm{SER}_P(\gamma_{\mathcal{SR}_i}, M) \\ &+ \mathrm{SER}_P\left(\gamma_{equiv}(\mathcal{R}_i), M\right)\left(1 - \mathrm{SER}_P(\gamma_{\mathcal{SR}_i}, M)\right). \end{aligned} \tag{3}$$

We will develop the AM schemes with limited source-relay CSI based on the SNR thresholds in (2) and SER in (3).

III. SNR-Based Opportunistic AM

We consider the constellation size selection in this section when the instantaneous source-relay CSI is not available at $\mathcal{D}$. In this case, we average (3) over $\gamma_{\mathcal{SR}_i}$ and have

$$\begin{aligned}\mathrm{SER}_{DF}^{C_M}(\mathcal{R}_i, M) &= \mathrm{SER}_P(\gamma_{\mathcal{SD}}, M)\mathbf{C}_M \\ &+ \mathrm{SER}_P\left(\gamma_{equiv}(\mathcal{R}_i), M\right)\left(1 - \mathbf{C}_M\right), \end{aligned} \tag{4}$$

where $\mathbf{C}_M = \mathbf{E}\{\mathrm{SER}_P(\gamma_{\mathcal{SR}_i}, M)\}$. Letting $g_M = \sin(\frac{\pi}{M})$,

$$\mathbf{C}_M = \frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} \frac{1}{1 + \frac{g_M^2 P_1 \sigma_{\mathcal{SR}_i}^2}{\mathcal{N}_0 \sin^2\theta}} d\theta, \tag{5}$$

which allows a closed-form, but complex, expression [9, Eqn. 2.562]. For each relay $\mathcal{R}_i$, the maximum constellation size $\mathcal{M}_i$ that can be supported while satisfying $\mathrm{SER} \leq \mathrm{SER}_{TH}$ is

$$\mathcal{M}_i = \arg\max_M \left(\mathrm{SER}_{DF}^{C_M}(\mathcal{R}_i, M) - \mathrm{SER}_{TH}\right), \tag{6}$$

subject to $\mathrm{SER}_{DF}^{C_M}(\mathcal{R}_i, M) \leq \mathrm{SER}_{TH}$.

In this letter, the best relay $\mathcal{R}_\kappa$ is selected according to [10]

$$\kappa = \arg\max_i \gamma_{\mathcal{R}_i\mathcal{D}} \tag{7}$$

with corresponding supportable constellation size $\mathcal{M}_\kappa$. This simple relay selection rule can find the relay with maximum constellation size among all relays, when all relays have identical received signal power (i.e., a fixed $\sigma_{\mathcal{SR}_i}^2$ for all i).

We next develop a new mechanism to select the maximal constellation size with target SER (SER_{TH}) solely based on the SNRs $\gamma_{\mathcal{SD}}$ and $\gamma_{\mathcal{R}_\kappa\mathcal{D}}$, and decide whether to activate the best relay for cooperative transmissions or to communicate by direct link only (with silent best relay) in a system with multiple relays. Note that exactly the same constellation size selection method will also hold for the case of only one relay, i.e., $N = 1$. In a multi-relay environment, the proposed constellation size selection combined with the relay selection in (7) can take advantage of the diversity of multiple relays to improve the average rate and the ASE. If direct link can satisfy target SER with appropriately selected constellation size, the best relay will be silent to prevent from reducing the ASE. The SNR region for the relay-assisted and for the direct-link only transmissions is hereafter referred to as the *cooperation region* and *stand-alone region*, respectively.

A. SNR Regions for Selecting $\mathcal{M}_\kappa = 2$

In this subsection, we study the cooperation and stand-alone region for selecting $\mathcal{M}_\kappa = 2$, and extend the development to general $\mathcal{M}_\kappa$ in Section III-B.

1) Cooperative Region: When $\gamma_{\mathcal{SD}} < \Gamma_1$, the direct $\mathcal{S} - \mathcal{D}$ link alone cannot provide the required SER, and assistance from the best relay is therefore needed. With cooperation, we have $\mathcal{M}_\kappa = 2$ if $\mathrm{SER}_{DF}^{C_2}(\mathcal{R}_\kappa, 2) \leq \mathrm{SER}_{TH}$, which gives $\mathrm{SER}_{TH} \geq Q(\sqrt{2\gamma_{\mathcal{SD}}})\mathbf{C}_2 + Q(\sqrt{2(\gamma_{\mathcal{SD}} + \gamma_{\mathcal{R}_\kappa\mathcal{D}})})(1 - \mathbf{C}_2)$. It follows that

$$\gamma_{\mathcal{R}_\kappa\mathcal{D}} \geq \frac{1}{2}\left\{Q^{-1}\left(\mathbf{C}_2'\right)\right\}^2 - \gamma_{\mathcal{SD}}, \tag{8}$$

with $\mathbf{C}_2' = \frac{\mathrm{SER}_{TH} - Q(\sqrt{2\gamma_{\mathcal{SD}}}) \times \mathbf{C}_2}{1 - \mathbf{C}_2}$.

Furthermore, there exists a lower bound on $\gamma_{\mathcal{SD}}$ below which BPSK cannot be supported even with the help of the best relay. This lower bound on $\gamma_{\mathcal{SD}}$ can be obtained by letting $\gamma_{\mathcal{R}_\kappa\mathcal{D}} \to \infty$, which yields $\mathrm{SER}_{TH} \geq Q(\sqrt{2\gamma_{\mathcal{SD}}}) \times \mathbf{C}_2$. We therefore have the lower bound

$$\gamma_{\mathcal{SD}} \geq \frac{1}{2}\left(Q^{-1}\left(\mathrm{SER}_{TH}/\mathbf{C}_2\right)\right)^2 \triangleq \Gamma_{1,\mathrm{Low}}, \tag{9}$$

below which no modulations can be supported.

2) Stand-Alone Region: The stand-alone region of $\gamma_{\mathcal{SD}}$ for $\mathcal{M}_\kappa = 2$ specifies the values of $\gamma_{\mathcal{SD}}$ over which $\mathcal{M}_\kappa = 2$ can be supported by direct link alone but $\mathcal{M}_\kappa = 4$ cannot be adopted even with cooperative relaying (due to insufficient $\gamma_{equiv}(\mathcal{R}_\kappa)$). Thus, to obtain the stand-alone region for $\mathcal{M}_\kappa = 2$, we need to first find the cooperation region for $\mathcal{M}_\kappa = 4$.

When $\Gamma_1 \leq \gamma_{\mathcal{SD}} < \Gamma_2$, the direct-link alone can support at most BPSK transmission while satisfying the SER constraint. However, it is still possible for the cooperative system to adopt QPSK with assistance of the best relay. Note that in supporting QPSK with the DF relaying from $\mathcal{R}_\kappa$, we must have

$$\mathrm{SER}_{DF}^{\mathbf{C}_4}(\mathcal{R}_\kappa, 4) \leq \mathrm{SER}_{TH}, \tag{10}$$

which yields $\gamma_{\mathcal{R}_\kappa\mathcal{D}} \geq \frac{1}{2}(Q^{-1}(\mathbf{C}_4')/\sin(\frac{\pi}{4}))^2 - \gamma_{\mathcal{SD}}$ with $\mathbf{C}_4' = (\mathrm{SER}_{TH} - 2\mathbf{C}_4 Q(\sqrt{2\gamma_{\mathcal{SD}}}\sin(\frac{\pi}{4})))/(2(1 - \mathbf{C}_4))$. Also from (10) and by letting $\gamma_{\mathcal{R}_\kappa\mathcal{D}} \to \infty$, we see only when

$$\gamma_{\mathcal{SD}} \geq \frac{1}{2}\left(Q^{-1}\left(\mathrm{SER}_{TH}/2\mathbf{C}_4\right)/\sin\left(\pi/4\right)\right)^2 \triangleq \Gamma_{2,\mathrm{Low}}$$

can QPSK be supported with cooperative transmissions by selecting $\mathcal{R}_\kappa$ for relaying. Consequently, we have the cooperation

[1]Note that the proposed AM in this letter is also applicable to square M-QAM if we adopt [8, Eqn. (10)] to specify the SNR threshold between different constellation sizes.

region for $\mathcal{M}_\kappa = 4$ as $\Gamma_{2,\text{Low}} \leq \gamma_{\mathcal{SD}} \leq \Gamma_2$ and

$$\gamma_{\mathcal{R}_\kappa\mathcal{D}} \geq \frac{1}{2}\left(Q^{-1}\left(\mathbf{C}'_4\right)/\sin\left(\pi/4\right)\right)^2 - \gamma_{\mathcal{SD}}.$$

As a result, the stand-alone region of $\gamma_{\mathcal{SD}}$ for $\mathcal{M}_\kappa = 2$ is

$$\Gamma_1 \leq \gamma_{\mathcal{SD}} < \Gamma_{2,\text{Low}}.$$

B. SNR Regions for Selecting $\mathcal{M}_\kappa > 2$

With the same argument as in Section III-A, we obtain the cooperation region and stand-alone region for $\mathcal{M}_\kappa > 2$ as follows:

1) Cooperation Region: When the SNRs $\gamma_{\mathcal{SD}}$ and $\gamma_{\mathcal{R}_\kappa\mathcal{D}}$ jointly satisfy $\Gamma_{\log_2 \mathcal{M}_\kappa,\text{Low}} \leq \gamma_{\mathcal{SD}} \leq \Gamma_{\log_2 \mathcal{M}_\kappa}$ and

$$\gamma_{\mathcal{R}_\kappa\mathcal{D}} \geq \frac{1}{2}\left(Q^{-1}\left(\mathbf{C}'_{\mathcal{M}_\kappa}\right)/\sin\left(\pi/\mathcal{M}_\kappa\right)\right)^2 - \gamma_{\mathcal{SD}},$$

where $\Gamma_{\log_2 \mathcal{M}_\kappa,\text{Low}} = \frac{1}{2}\left(\frac{Q^{-1}(\text{SER}_{TH}/2\mathbf{C}_{\mathcal{M}_\kappa})}{\sin(\frac{\pi}{\mathcal{M}_\kappa})}\right)^2$ and $\mathbf{C}_{\mathcal{M}'_\kappa} = \frac{\text{SER}_{TH} - 2\mathbf{C}_{\mathcal{M}_\kappa} Q(\sqrt{2\gamma_{\mathcal{SD}}}\sin(\frac{\pi}{\mathcal{M}_\kappa}))}{2(1-\mathbf{C}_{\mathcal{M}_\kappa})}$, the best relay participates in relaying using $\mathcal{M}_\kappa$-PSK.

2) Stand-Alone Region: When the SNR $\gamma_{\mathcal{SD}}$ satisfies $\Gamma_{\log_2 \mathcal{M}_\kappa} \leq \gamma_{\mathcal{SD}} < \Gamma_{1+\log_2 \mathcal{M}_\kappa,\text{Low}}$, using direct-link alone is sufficient to support at most $\mathcal{M}_\kappa$-PSK.

IV. Probabilistic Adaptive Modulation

In this section, we propose the probabilistic AM if the destination is able to acquire the quantized CSI of the source-relay link. The available quantized CSI can be exploited to enhance the ASE and average rate of the system, especially under low P/N_0 where P is the total transmission power of relays and the source. Three situations are considered: outage region, cooperation region and stand-alone region.

A. Outage Region: $\gamma_{\mathcal{SD}} < \Gamma_{1,\text{Low}}$

To improve the rate and spectral efficiency in the outage region, while avoiding using too much information, we consider a simple quantization rule with the quantized CSI given by

$$|h_{\mathcal{SR}_\kappa}|_q^2 = (n + 1/2)\Delta_h$$

if $n\Delta_h \leq |h_{\mathcal{SR}_\kappa}|^2 \leq (n+1)\Delta_h$ or $n=1,\ldots,2^L$, where $\Delta_h = |h_{\mathcal{SR}_\kappa}^{\max}|^2/2^L$ with $h_{\mathcal{SR}_\kappa}^{\max}$ being determined by $\text{P}\{|h_{\mathcal{SR}_\kappa}|^2 \leq |h_{\mathcal{SR}_\kappa}^{\max}|^2\} = \rho$, and L is the number of bits used in the quantization. When $\rho = 0.99$, we have $|h_{\mathcal{SR}_\kappa}^{\max}|^2 \approx 4.6 \cdot \sigma_{\mathcal{SR}_\kappa}^2$. Note that a more complex quantization rule can be adopted, but with higher computation complexity.

When $\mathcal{M}$-PSK is selected and $|h_{\mathcal{SR}_\kappa}|_q^2 = (n+1/2)\Delta_h$, the average SER of the $\mathcal{S}$-$\mathcal{R}_\kappa$ link at the destination i

$$\hat{\mathbf{C}}_{\mathcal{M}} = \mathbf{E}\left\{\text{SER}_P(\gamma_{\mathcal{SR}_i}, \mathcal{M}) \,|\, |h_{\mathcal{SR}_\kappa}|_q^2 = \left(n + \frac{1}{2}\right)\Delta_h\right\}, \tag{11}$$

which has a closed-form expression as in (5). From (11), the SER in (4) is modified by replacing $\mathbf{C}_{\mathcal{M}}$ with $\hat{\mathbf{C}}_{\mathcal{M}}$. Let $\alpha_{\mathcal{M}}$ be the probability of choosing $\mathcal{M}$-PSK that satisfies

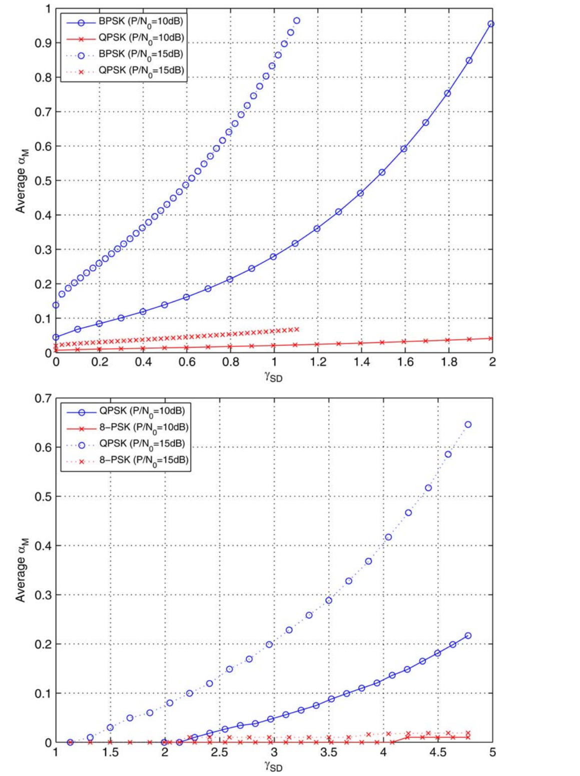

Fig. 1. The average $\alpha_{\mathcal{M}}$ of the probabilistic AM under (Upper) the outage region, and (Lower) the cooperation region when $\sigma_{AB}^2 = 1$ for $A \in \{\mathcal{S}, \mathcal{R}_1, \cdots, \mathcal{R}_N\}$, $B \in \{\mathcal{D}, \mathcal{R}_1, \cdots, \mathcal{R}_N\}$, $A \neq B$ and A and B can not be relays at the same time.

$$\alpha_{\mathcal{M}} \text{SER}_{DF}^{\hat{\mathbf{C}}_{\mathcal{M}}}(\mathcal{R}_\kappa, \mathcal{M}) = \text{SER}_{TH}, \tag{12}$$

where $\alpha_{\mathcal{M}} \text{SER}_{DF}^{\hat{\mathbf{C}}_{\mathcal{M}}}(\mathcal{R}_\kappa, \mathcal{M})$ is the average SER when the probabilistic rule is utilized. It's clear that the value of $\alpha_{\mathcal{M}}$ decreases as $\mathcal{M}$ increases, which suggests smaller modulation order is more likely to be selected. The average values of $\alpha_{\mathcal{M}}$ under different $\gamma_{\mathcal{SD}}$ when $P/N_0 = 10$ dB and 15 dB with $L = 2$ are shown in Fig. 1 (Upper), from which we see that as $\gamma_{\mathcal{SD}}$ nears $\Gamma_{1,\text{Low}}$, α_2 is higher than 0.9. With the probabilistic scheme, transmitting with BPSK is still possible with probability α_2 when $\gamma_{\mathcal{SD}} < \Gamma_{1,\text{Low}}$. For example, if $\alpha_2 = 0.9$, we have $\text{SER} = \text{SER}_{TH}/0.9$. When $\text{SER}_{TH} = 10^{-3}$, this means an error occurs every 900 transmissions of BPSK signals on average. The probabilistic scheme takes advantage of the successful 899 transmissions of BPSK signals. We observe that α_4 is very small and $\alpha_{\mathcal{M}}$ is 0 for $\mathcal{M} \geq 8$. Therefore, the proposed probabilistic AM in the outage region is applicable only for $\mathcal{M} = 2$.

B. Cooperation Region: $\Gamma_{\log_2 \mathcal{M}_\kappa,\text{Low}} \leq \gamma_{\mathcal{SD}} \leq \Gamma_{\log_2 \mathcal{M}_\kappa}$

In this region, $\mathcal{M}_\kappa$-PSK can be supported with the cooperation from the best relay $\mathcal{R}_\kappa$. To further boost the rate and ASE in this region, the concept of the probabilistic AM is also adopted. Let $\alpha_{\mathcal{M}}$ be the probability that $\mathcal{M}$-PSK for $\mathcal{M} \geq \mathcal{M}_\kappa$ is chosen such that

$$\alpha_{\mathcal{M}} \text{SER}_{DF}^{\mathbf{C}_{\mathcal{M}}}(\mathcal{R}_\kappa, \mathcal{M}) + (1 - \alpha_{\mathcal{M}}) \text{SER}_{DF}^{\mathbf{C}_{\mathcal{M}}}(\mathcal{R}_\kappa, \mathcal{M}_\kappa) = \text{SER}_{TH},$$

where $\mathbf{C}_{\mathcal{M}}$ is given in (5). The average values of $\alpha_{\mathcal{M}}$ under different $\gamma_{\mathcal{SD}}$, when $P/N_0 = 10$ dB and 25 dB with $\mathcal{M}_\kappa = 2$, are plotted in Fig. 1 (Lower), from which we see the proposed probabilistic AM has greater impact on the rate when P/N_0 is larger. Likewise, the proposed probabilistic AM in this case is meaningful only for $\mathcal{M} = 4$ when $\mathcal{M}_\kappa = 2$.

C. Stand-Alone Region: $\Gamma_{\log_2 \mathcal{M}_\kappa} \leq \gamma_{\mathcal{SD}} \leq \Gamma_{1+\log_2 \mathcal{M}_\kappa, \mathrm{Low}}$

In this region, the source alone can support $\mathcal{M}_\kappa$-PSK. When $\gamma_{\mathcal{SD}}$ is close to $\Gamma_{1+\log_2 \mathcal{M}_\kappa, \mathrm{Low}}$, the SER is too large as compared to SER_{TH} if the source chooses $2\mathcal{M}_\kappa$-PSK for transmission. Thus, employing the probabilistic AM in this case is not advantageous.

V. Simulation

In the simulation, $\mathrm{SER}_{TH} = 10^{-3}$, $L = 1$, $P_1 = P_2 = P/2$, and $N = 5$. We compare the proposed opportunistic and probabilistic AM with three other modulation selection schemes: 1) the opportunistic relaying scheme [3], in which the best relay is always selected, 2) the incremental opportunistic relaying (IOR) [1], in which the best relay is used only when $\mathcal{S}-\mathcal{D}$ alone is unable to support BPSK, and 3) the maximum spectral efficiency with adaptive modulations (MSE-AM) scheme [8], in which the amplify-and-forward (AF) is utilized and the constellation size is chosen to maximize the overall spectral efficiency. Note that in the case of IOR, when DF relaying is used and $\mathcal{S}-\mathcal{D}$ alone is unable to support BPSK, the constellation size is chosen in the same fashion as [3]. Furthermore, we investigate the average rate and ASE of the MSE-AM scheme with and without a total power constraint. With the total power constraint, each node including the source equally shares the total transmission power. Otherwise, each node including the source has the transmission power of $P/2$.

Fig. 2 shows the comparison of the average rates. We see that the opportunistic AM achieves lower average rate than the probabilistic AM, especially when P/N_0 is small, as the quantized CSI of the source-relay link is further exploited. Both the proposed AM schemes outperform the MSE-AM (with either sequential or simultaneous relaying) and IOR schemes in average rate when P/N_0 is large. In addition, both proposed AM schemes always have better average rate than the MSE-AM approach with a total power constraint. Next, the ASE is compared in Fig. 2 (Lower). Both the opportunistic AM and probabilistic AM have comparable ASE, while the MSE-AM scheme without the total power constraint and the IOR scheme achieve the best ASE. When total power constraint is imposed on the MSE-AM scheme, the ASE is not as promising as in the case without power constraint. Also, since the opportunistic relaying always takes advantage of the best relay, it has the lower ASE as compared to the proposed AM schemes. We observe that MSE-AM with total power constraint has the worst average rate and ASE.

It is worthwhile to note that the proposed AM schemes feature in flexible use of the relay with limited source-relay CSI. This flexibility allows the proposed approaches to outperform the maximum rate scheme in ASE and achieve higher rate than MSE-AM, suggesting that a smart relay selection can balance between average rate and ASE.

VI. Conclusion

The SNR-based opportunistic and the probabilistic AM have been proposed with no or limited source-relay CSI in cooperative systems. We have shown that the proposed AM schemes with flexible relay selection achieve higher average rate than the MSE-AM, both under the power constraint, and yield higher ASE than the opportunistic relaying scheme, where the MSE-AM and the opportunistic relaying schemes all require the instantaneous source-relay CSI.

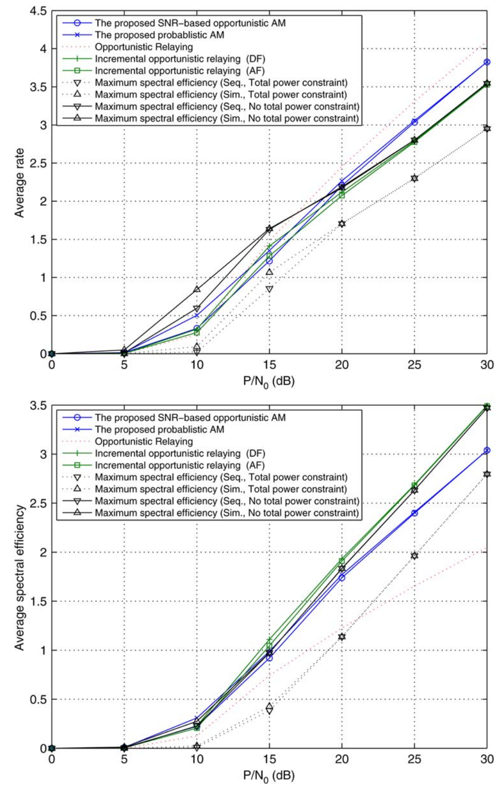

Fig. 2. The average rate (Upper) and the ASE (Lower) achieved by different AM schemes with $\sigma^2_{\mathcal{SR}_i} = \sigma^2_{\mathcal{R}_i\mathcal{D}} = 2\sigma^2_{\mathcal{SD}} = 1$.

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