Adaptive Modulation in Decode-and-Forward (DF) Cooperative Communications

Chih-Yung Song, Min-Kuan Chang, and Guu-Chang Yang

Graduate Institute of Communication Engineering
Department of Electrical Engineering, National Chung Hsing University, Taichung, Taiwan
E-mail: minkuanc@nchu.edu.tw

***Abstract*—In this work, we will focus on which modulation scheme should be supported given the knowledge of SNRs of all links in a simple DF cooperative communication system where only one relay is present. Two rules are proposed, namely the exact rule and the approximate rules. The exact rule is derived based on the exact SER. However, the decision of which modulation scheme in the exact rule is used for current transmission is not straightforward. This motivates us to derived the approximate rule based on three key observations. The conducted simulation shows that the performance of the exact rule and the proposed approximated rule are similar in terms of average rate.**

***Index Terms*—Multi-node cooperative communications, Adaptive modulation, Decode-and-forward protocol**

I. Introduction

Cooperative communication [1] has been an active field of research recently. Two main popular cooperative protocols are amplify-and-forward (AF) protocol and decode-and-forward (DF) protocol [1]. However, this improvement due to cooperation results in the reduction of the spectral efficiency [2], [3]. In light of this, how to restore the spectral efficiency gains much attention recently.

To restore the spectral efficiency, possible solution is adaptive modulation [4]–[8]. Among [4]–[8], [5]–[8] are assumed the DF protocol are adopted for cooperation. Ikki and his colleagues [5] defined the decoding set based on the target rate. With the defined decoding set, the modulation scheme for transmission is obtained by comparing the MRC-combined SNR at the destination against the predetermined thresholds. These thresholds can be either selected according similar to those in [9] or be optimally determined by the approach similar to [10]. In [9], their thresholds are chosen to meet the target bit error rate (BER) in a point-to-point environment. When these thresholds are adopted in a cooperative environment, the chosen modulation order is smaller than it should be. Hence, the advantage of increased diversity gain due to cooperation cannot be fully utilized. Altubasishi and Shen [7] investigated the adaptive modulation when the forwarding relay is selected based on the defined equivalent SNR. In [7], the thresholds of selecting the modulation scheme for transmission are the same as those in [9]. This becomes the main disadvantage of their approach. Recently, Ma *et. al.* [8] aimed at selecting the optimal relay to provide the maximal spectral efficiency as possible while their proposed upper bound of BER is less than the target BER. Since the upper bound of BER is adopted, the modulation scheme chosen by this scheme could be conservative. However, given the target error rate, the appropriate thresholds of selecting an appropriate modulation scheme based on the exact formula of error probability of DF protocol are not well addressed. This motivates us to work on how to find the appropriate regions of SNR's received at the relay and the destination based on the derived result in [11] so that an appropriate modulation scheme can be chosen and the target error rate can be met.

In this work, we will focus on which modulation scheme should be supported given the knowledge of SNRs of all links in a simple cooperative communication system where only one relay is present. To determine a suitable modulation scheme for transmission in such a system, we will need the information of SNR's received at the relay, between the source and the destination and between the relay and the destination. The region of the support of a particular modulation scheme has to do with these three SNR's. To acquire that region, we first base on the symbol error rate (SER) of 2^M-PSK derived in [11] to determine the range of the aforementioned three SNR'so that 2^M-PSK is chosen for transmission. We call this the exact rule. However, the exact rule involves the computation of the inverse of Q-function and the region of the support of 2^M-PSK is not straightforward like its counterpart in a point-to-point communication system. To have a more concise region, we propose the approximated rule, which is derived according to three key observations. Based on these three key observations and the help of the least square approximation, we are able to establish a concise relationship between the region of the support of 2^M-PSK and the three SNR's in a simple cooperative communication system. The conducted simulation shows that the performance of the exact rule and the proposed approximated rule are similar in terms of average rate.

II. System Model

In this work, we consider a cooperative communication system with single relay. We let $\mathcal{S}$, $\mathcal{D}$ and $\mathcal{R}$ to represent the source node, the destination and the relay, respectively. Let h_{AB} denote the zero-mean complex channel gain between A and B, where $A \in \{\mathcal{S}, \mathcal{R}\}$, $B \in \{\mathcal{D}, \mathcal{R}\}$ and $A \neq B$, with variance σ_{AB}^2.

The DF protocol [11] is utilized as the underlying cooperative protocol in this work. DF protocol consists of two phases. During the first phase, $\mathcal{S}$ broadcasts its signal to $\mathcal{D}$ and the chosen relay, $\mathcal{R}$. The signals received at $\mathcal{R}$ and $\mathcal{D}$ are given respectively by $y_{\mathcal{SR}} = \sqrt{P_1} h_{\mathcal{SR}} x + n_{\mathcal{SR}}$ and $y_{\mathcal{SD}} = \sqrt{P_1} h_{\mathcal{SD}} x + n_{\mathcal{SD}}$, where P_1 is the transmission during the first phase and $n_{\mathcal{SR}}$ and $n_{\mathcal{SD}}$ are the respective zero-mean complex Gaussian noise with variance $\mathcal{N}_0$.

In the second phase, if $\mathcal{R}$ can successfully decode the signal from $\mathcal{S}$, it encodes and forwards that signal to $\mathcal{D}$. Otherwise, $\mathcal{R}$ remains silent in this phase. After that, $\mathcal{D}$ makes use of maximal ratio combining to combine signals in these two phases. The signal received from $\mathcal{R}$ at $\mathcal{D}$ is $y_{\mathcal{R}_i\mathcal{D}} = \sqrt{\widetilde{P}_2}h_{\mathcal{RD}}x + n_{\mathcal{RD}}$, where $n_{\mathcal{RD}}$ is the respective zero-mean complex Gaussian noise with variance $\mathcal{N}_0$ and $\widetilde{P}_2$ is the transmission power in this phase in which $\widetilde{P}_2$ is equal to P_2 if $\mathcal{R}$ can successfully decode the signal from $\mathcal{S}$ and 0 otherwise.

By using the same combining weights as [11], the equivalent received SNR at $\mathcal{D}$ after MRC combining is given by $\gamma_{equiv}(\mathcal{R}) = \gamma_{\mathcal{SD}} + \gamma_{\mathcal{RD}}$, where $\gamma_{\mathcal{SD}}$ and $\gamma_{\mathcal{RD}}$ are the received SNR's of the signals from $\mathcal{S}$ and $\mathcal{R}$ at $\mathcal{D}$, respectively.

When 2^M-PSK is chosen, the instantaneous SER performance of DF protocol is calculated by [11]

$$\begin{aligned} & \mathrm{SER}_{DF}(\mathcal{R}, 2^M) \\ = \ & \mathrm{SER}_P(\gamma_{\mathcal{SD}}, 2^M)\mathrm{SER}_P(\gamma_{\mathcal{SR}}, 2^M) \\ + \ & \mathrm{SER}_P(\gamma_{equiv}(\mathcal{R}), 2^M)(1 - \mathrm{SER}_P(\gamma_{\mathcal{SR}}), 2^M), \end{aligned} \tag{1}$$

where

$$\mathrm{SER}_P(\gamma, 2^M) = \begin{cases} Q\left(\sqrt{2\gamma}\right) & M = 1 \\ 2Q\left(\sqrt{2\gamma}\sin\left(\frac{\pi}{2^M}\right)\right) & M > 1 \end{cases}$$

and γ is the received SNR.

III. Adaptive Modulation in a simple cooperative communication systems

Let SER_{TH} be the SER constraint. The highest possible modulation scheme that can be supported by $\mathcal{R}$ can be obtained by

$$M_{\mathcal{R}} = \min_{M} \mathrm{SER}_{TH} - \mathrm{SER}_{DF}(\mathcal{R}, 2^M) \tag{2}$$

subject to $\mathrm{SER}_{TH} - \mathrm{SER}_{DF}(\mathcal{R}, 2^M) \geq 0$. Based on (1) and (2), the ith relay can support 2^M-PSK if and only if its channel gains of all paths, namely $\gamma_{\mathcal{SD}}$, $\gamma_{\mathcal{SR}}$ and $\gamma_{\mathcal{RD}}$, fulfill $\mathrm{SER}_{DF}(\mathcal{R}, 2^M) \leq \mathrm{SER}_{TH}$ and $\mathrm{SER}_{DF}(\mathcal{R}, 2^{M+1}) > \mathrm{SER}_{TH}$. Equivalently, 2^M-PSK can be supported by $\mathcal{R}$ if and only if

$$\Gamma_M^{(\mathrm{Coop})} \leq \gamma_{\mathcal{RD}} < \Gamma_{M+1}^{(\mathrm{Coop})}, \tag{3}$$

where $\Gamma_M^{(\mathrm{Coop})}$ is shown in (4), $\Gamma_{\mathcal{M}_{\max}+1}^{(\mathrm{Coop})} = \infty$, and $2^{\mathcal{M}_{\max}}$ is the maximal modulation order in the system This rule of the selection modulation scheme provided in (3) is called the exact rule. However, the computation of the thresholds in this rule is not easy. In light of this, an approximated rule will be proposed in the subsection to come.

A. The proposed approximated rule

The rule provided in (2) involves the computation of (4), which is complex. To ease the finding of the most suitable modulation scheme of a relay for transmission, namely the finding of $M_{\mathcal{R}}$, an approximated rule is adopted. Several observations are made use of to derive the proposed approximated rule of selecting a modulation scheme, say 2^M-PSK.

1) Observation I: To develop this observation, we first note that in a traditional point-to-point system, when 2^M-PSK is used for transmission, SER is smaller than SER_{TH} if and only if the received SNR is grater than Γ_M, where

$$\Gamma_M = \begin{cases} \frac{1}{2}(Q^{-1}(\mathrm{SER}_{TH}))^2, & M = 1 \\ \frac{1}{2}\left(\frac{Q^{-1}(\mathrm{SER}_{TH}/2)}{\sin(\frac{\pi}{2^M})}\right)^2, & M \geq 2. \end{cases} \tag{5}$$

and $\Gamma_{\mathcal{M}_{max}+1} = \infty$. This result can help establish this observation. When $\Gamma_M \leq \gamma_{equiv}(\mathcal{R}) < \Gamma_{M+1}$ and $\gamma_{\mathcal{SR}} \geq \Gamma_M$, according to the SNR-based approach [12], 2^M-PSK would be selected and SER performance can be guaranteed to be less than SER_{TH}, which will be validated in Section IV as well.

2) Observation II: Now we discuss the situation when $\gamma_{\mathcal{SR}} \leq \Gamma_M$ and $\Gamma_M \leq \gamma_{equiv}(\mathcal{R})$. First, we observe that (1) is always less than

$$\mathrm{SER}_P(\gamma_{\mathcal{SD}}, 2^M)\mathrm{SER}_P(\gamma_{\mathcal{SR}}, 2^M) + \mathrm{SER}_P(\gamma_{equiv}(\mathcal{R}), 2^M).$$

When $\gamma_{equiv}(\mathcal{R})$ is large, the first term of the above equation becomes dominant and $\mathrm{SER}_P(\gamma_{equiv}(\mathcal{R}), 2^M)$ can be ignored. The criterion of checking whether 2^M-PSK can be selected is simplified to see if $\mathrm{SER}_P(\gamma_{\mathcal{SD}}, 2^M)\mathrm{SER}_P(\gamma_{\mathcal{SR}}, 2^M)$ is less than SER_{TH}. Fig. 1 shows the probability that the received SER is larger than SER_{TH}, where $\mathrm{SER}_{TH} = 10^{-3}$, when this criterion is adopted. As illustrated in Fig. 1, only when P/N_0 is less than 10 dB, the chance of received SER larger than SER_{TH} is noticeable. Otherwise, this probability is close to 0. Hence, the proposed simplified rule is validated. In addition, from simulation as shown in Section IV, the average SER based on this observation can still meet the requirement.

To have a concise relationship between $\gamma_{\mathcal{SD}}$ and $\gamma_{\mathcal{SR}}$ in this region, we first adopt the least square (LS) approach to find the a linear equation to approximate $\mathrm{SER}_P(\gamma_{\mathcal{SD}}, 2^M)\mathrm{SER}_P(\gamma_{\mathcal{SR}}, 2^M) = \mathrm{SER}_{TH}$. Based on the LS approach, this relationship can be approximated by

$$\gamma_{\mathcal{SR}} = -r_1(M)\gamma_{\mathcal{SD}} + \Gamma_M^{(2)}. \tag{6}$$

When $\mathrm{SER}_{TH} = 10^{-3}$ and $\mathcal{M}_{\max} = 6$, we have

I. $r_1(1) = 0.8398$, $r_1(2) = 0.9572$, $r_1(3) = 0.9572$, $r_1(4) = 0.9572$, $r_1(4) = 0.9572$, $r_1(5) = 0.9572$, $r_1(6) = 0.9572$, and $r_1(7) = 1$.

II. $\Gamma_1^{(2)} = 3.3$, $\Gamma_2^{(2)} = 9.4$, $\Gamma_3^{(2)} = 32$, $\Gamma_4^{(2)} = 123$, $\Gamma_5^{(2)} = 487.2$, $\Gamma_6^{(2)} = 1944$, and $\Gamma_7^{(2)} = \infty$.

The approximated linear equation (6) and $\mathrm{SER}_P(\gamma_{\mathcal{SD}}, 2^M)\mathrm{SER}_P(\gamma_{\mathcal{SR}}, 2^M) = \mathrm{SER}_{TH}$ under different M's are shown in Fig. 2. As shown in Fig. 2, there is a gap between these two functions. Through simulation, we find that this gap has less impact on the average rate and average spectral efficiency (ASE), whose definition can be found in [13]. The possible explanation could be the followings. Let $\Pi_M^{(E)}$ and $\Pi_M^{(A)}$ for $M \geq 1$ be the region of choosing 2^M-PSK using the exact relationship, namely $\mathrm{SER}_P(\gamma_{\mathcal{SD}}, 2^M)\mathrm{SER}_P(\gamma_{\mathcal{SR}}, 2^M) = \mathrm{SER}_{TH}$, and the LS approximation, respectively. For example, $\Pi_4^{(E)}$ is the region between QPSK (Exact) and 8-PSK (Exact) and $\Pi_4^{(A)}$ is the

$$\Gamma_M^{(\text{Coop})} = \begin{cases} \frac{1}{2}\left[Q^{-1}\left(\frac{\text{SER}_{TH}-Q(\sqrt{2\gamma_{\mathcal{SD}}})*Q(\sqrt{2\gamma_{\mathcal{SR}}})}{1-Q(\sqrt{2\gamma_{\mathcal{SR}}})}\right)\right]^2 - \gamma_{\mathcal{SD}}, & M=1 \\ \frac{1}{2}\left[Q^{-1}\left(\frac{\text{SER}_{TH}-4*Q(\sqrt{2\gamma_{\mathcal{SD}}}*\sin(\frac{\pi}{2^M}))*Q(\sqrt{2\gamma_{\mathcal{SR}}}*\sin(\frac{\pi}{2^M}))}{2*(1-Q(\sqrt{2\gamma_{\mathcal{SR}}}*\sin(\frac{\pi}{2^M})))}\right)\right]^2 - \gamma_{\mathcal{SD}}, & M \geq 2. \end{cases}, \quad (4)$$

region between QPSK (LS Approximation) and 8-PSK (LS Approximation) as illustrated in Fig. 2. Each $\Pi_M^{(A)}$ can be divided into three areas. One is $\Pi_M^{(A),1} = \Pi_M^{(A)} \cap \Pi_{M-1}^{(E)}$ for $M \geq 2$, where $\Pi_1^{(A),1} = 0$, the other is $\Pi_M^{(A),2} = \Pi_M^{(A)} \cap \Pi_M^{(E)}$ for $M \geq 1$, and another is $\Pi_M^{(A),3} = \Pi_M^{(A)} \cap \Pi_{M+1}^{(E)}$ for $M \geq 1$. Based on the definition of $\Pi_M^{(A),1}$, $\Pi_M^{(A),2}$ and $\Pi_M^{(A),3}$, given $\gamma_{\mathcal{RD}}$, the probability of choosing 2^M-PSK using the original relationship can be found to be

$$\begin{aligned} & \Pr\{(\gamma_{\mathcal{SD}}, \gamma_{\mathcal{SR}}) \in \Pi_{M+1}^{(A),1}\} \\ + & \Pr\{(\gamma_{\mathcal{SD}}, \gamma_{\mathcal{SR}}) \in \Pi_M^{(A),2}\} \\ + & \Pr\{(\gamma_{\mathcal{SD}}, \gamma_{\mathcal{SR}}) \in \Pi_{M-1}^{(A),3}\}. \end{aligned} \quad (7)$$

$\Pi_M^{(A),1}$ is the area of $\gamma_{\mathcal{SD}}$ and $\gamma_{\mathcal{SR}}$, which belongs to the region of choosing 2^{M-1}-PSK when using the exact relationship in this observation. When M gets larger, due to the property of the exponential distribution, the probability that $\gamma_{\mathcal{SD}}$ and $\gamma_{\mathcal{SR}}$ fall into $\Pi_M^{(A),1}$ becomes smaller. The same argument can be applied to $\Pi_M^{(A),3}$. Therefore, (7) is dominated by $\Pr\{(\gamma_{\mathcal{SD}}, \gamma_{\mathcal{SR}}) \in \Pi_M^{(A),2}\}$, especially when M is large. From this, we can see that the proposed LS approximation will choose 2^M-PSK with the similar probability to the case of using the exact relationship in this observation. The simulation is conducted to validate this argument, which will be shown in Section IV. Note that better approximation can be achieved if the higher-order polynomials is utilized to approximate $\text{SER}_P(\gamma_{\mathcal{SD}}, 2^M)\text{SER}_P(\gamma_{\mathcal{SR}}, 2^M) = \text{SER}_{TH}$. With the help of (6), when $\gamma_{\mathcal{SR}} \leq \Gamma_M$, 2^M-PSK can be selected if two conditions are fulfilled:

I. $\gamma_{equiv}(\mathcal{R}) \geq \Gamma_M$
II. $\gamma_{\mathcal{SR}} > -r_1(M) \times \gamma_{\mathcal{SD}} + \Gamma_M^{(2)}$ and $\gamma_{\mathcal{SR}} < -r_1(M+1) \times \gamma_{\mathcal{SD}} + \Gamma_{M+1}^{(2)}$.

3) Observation III: When $\gamma_{\mathcal{SR}} \geq \Gamma_M$ and $\gamma_{equiv}(\mathcal{R}) \geq \Gamma_{M+1}$, (1) is dominated by $\text{SER}_P(\gamma_{\mathcal{SD}}, 2^M) \times \text{SER}_P(\gamma_{\mathcal{SR}_i}, 2^M)$. That is,

$$\text{SER}_{DF}(\mathcal{R}_i, 2^M) \approx \text{SER}_P(\gamma_{\mathcal{SD}}, 2^M)\text{SER}_P(\gamma_{\mathcal{SR}_i}, 2^M),$$

which is less than SER_{TH}. However, to further ensure only 2^M-PSK is supported, according to Observation II, $\gamma_{\mathcal{SD}}$ has to satisfy $\frac{\Gamma_M^{(2)} - \gamma_{\mathcal{SR}}}{r_1(M)} \leq \gamma_{\mathcal{SD}} < \frac{\Gamma_{M+1}^{(2)} - \gamma_{\mathcal{SR}}}{r_1(M+1)}$.

These three observations help us to establish a clear and concise rule of how to select the most suitable modulation scheme for $\mathcal{R}$ when $\gamma_{\mathcal{SD}}$, $\gamma_{\mathcal{SR}}$ and $\gamma_{\mathcal{RD}}$ are known. The approximated rule of finding $M_{\mathcal{R}}$ is illustrated in Fig. 3.

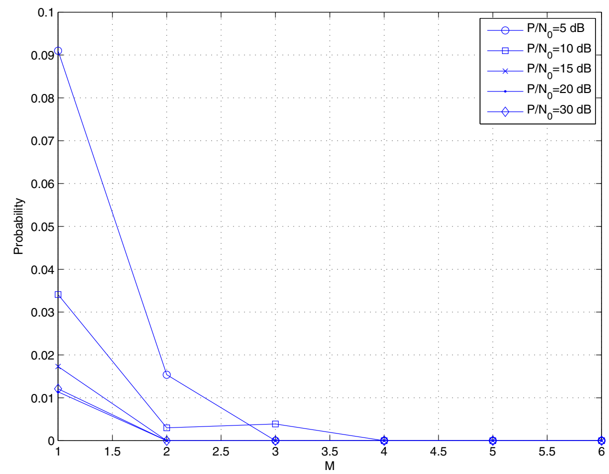

Fig. 1. The probability that SER is larger than SER_{TH} under different P/N_0's when $\text{SER}_{TH} = 10^{-3}$.

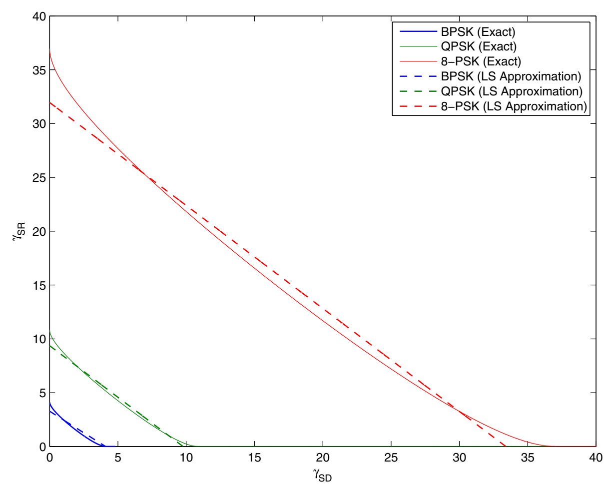

Fig. 2. $\text{SER}_P(\gamma_{\mathcal{SD}}, 2^M)\text{SER}_P(\gamma_{\mathcal{SR}_i}, 2^M) = 10^{-3}$ v.s its LS approximation.

B. Distribution of modulation level based on the proposed approximated rule

In this part, we will evaluate the probability of choosing 2^M-PSK for transmission in a simple cooperative communication system. Here we will use the proposed approximated rule of selection modulation schemes to compute this probability. Let $P_M^{(A)}$ be the probability of selecting 2^M-PSK when the proposed approximated rule is adopted. According to the proposed approximated rule of selecting modulation scheme, $P_M^{(A)}$ is given by (8).

$$
\begin{aligned}
P_M^{(A)} &= \Pr\{\gamma_{\mathcal{SR}} \geq \Gamma_M,\ \Gamma_M \leq \gamma_{equiv}(\mathcal{R}) < \Gamma_{M+1}\} \\
&+ \Pr\left\{\gamma_{\mathcal{SR}} \leq \Gamma_M,\ \gamma_{\mathcal{RD}} \geq \Gamma_M - \gamma_{\mathcal{SD}},\ \frac{\Gamma_M^{(2)} - \gamma_{\mathcal{SR}}}{r_1(M)} \leq \gamma_{\mathcal{SD}} < \frac{\Gamma_{M+1}^{(2)} - \gamma_{\mathcal{SR}}}{r_1(M+1)}\right\} \\
&+ \Pr\left\{\gamma_{\mathcal{SR}} \geq \Gamma_M,\ \gamma_{\mathcal{RD}} \geq \Gamma_{M+1} - \gamma_{\mathcal{SD}},\ \frac{\Gamma_M^{(2)} - \gamma_{\mathcal{SR}}}{r_1(M)} \leq \gamma_{\mathcal{SD}} < \frac{\Gamma_{M+1}^{(2)} - \gamma_{\mathcal{SR}}}{r_1(M+1)}\right\}.
\end{aligned} \quad (8)
$$

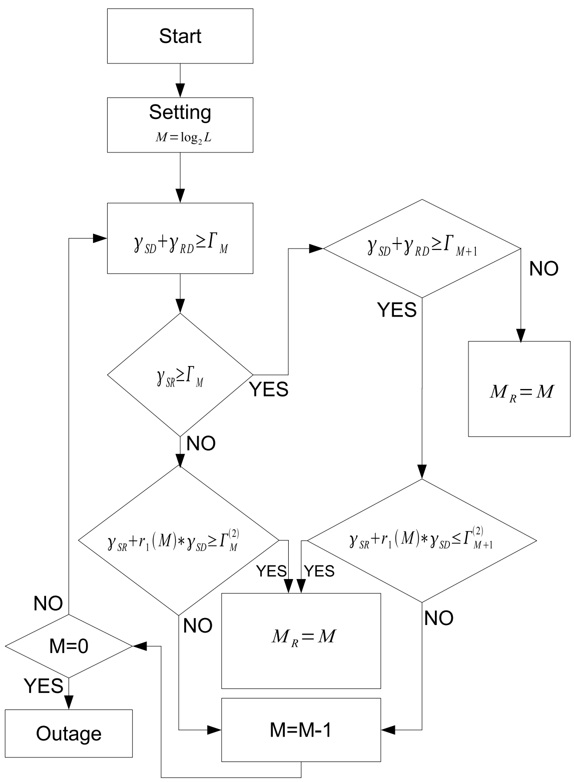

Fig. 3. The approximated rule for finding $M_{\mathcal{R}}$

IV. SIMULATION

In the simulation, we will let $P_1 = P_2 = P/2$, $\text{SER}_{TH} = 10^{-3}$ and $\sigma^2_{\mathcal{SR}_i} = \sigma^2_{\mathcal{SD}} = \sigma^2_{\mathcal{R}_i\mathcal{D}} = 1$. The maximal supportable modulation scheme is 2^6-PSK, namely $\mathcal{M}_{\max} = 6$. We first compare the distributions of modulation schemes between the exact and the approximated rule under Observation I, II and III, which are shown in Fig. 4. As shown in Fig. 4, the distributions of the modulation schemes between these two rules under Observation I coincide. For Observation II, the two distributions due to these two rules are almost identical. This confirms the argument in Section III-A. As for Observation III, these two distributions have slight discrepancy when $P/N_0 = 15$ dB. Other than that particular P/N_0, these two distributions are almost the same.

Last, we will compare the proposed selection method of modulation schemes against two selection methods under these three protocols. One is the SNR-based selection methods. In SNR-based selection methods, the thresholds are the same as (5). For a relay, two modulation schemes are determined, where one is determined at the relay and the other is determined at the destination. The smaller one will be chosen as the modulation scheme that could be supported by this relay. The other method is the method proposed in [8]. The comparison of these three selection methods are shown in Fig. 5 and 6. In Fig. 5, the average rates of the proposed selection method under these three protocols are always higher than those of SNR-based selection methods and the one in [8]. SNR-based approach and the one in [8] have similar performance in terms of the average rate. In addition, the theoretical results of the approximate rule match with the simulated one in all P/N_0's. The comparison of SER performance among these three approaches are shown in Fig. 6. As we can see that these three protocols can all meet the SER requirement. From Fig. 5 and 6, the proposed approach has higher average rate at the expense of higher SER performance.

V. ACKNOWLEDGMENT

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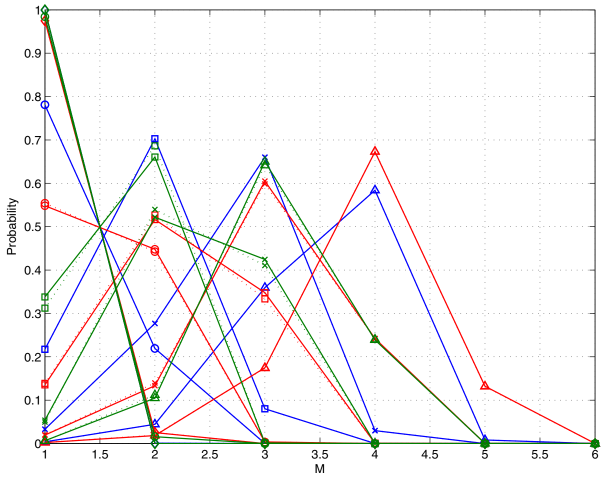

Fig. 4. Comparison of the distributions of modulation between the exact and approximated rules under Observation I to III in a simple cooperative communication system, where those in blue, red and green are for Observation I, II and III, respectively, when $\text{SER}_{TH} = 10^{-3}$. (Solid line: the exact rule, Dotted line: the approximated rule, '$\diamond$': $P/N_0 = 5$ dB, '$\circ$': $P/N_0 = 10$ dB, '$\square$': $P/N_0 = 15$ dB, '$\times$': $P/N_0 = 20$ dB, and '$\cdot$': $P/N_0 = 25$ dB)

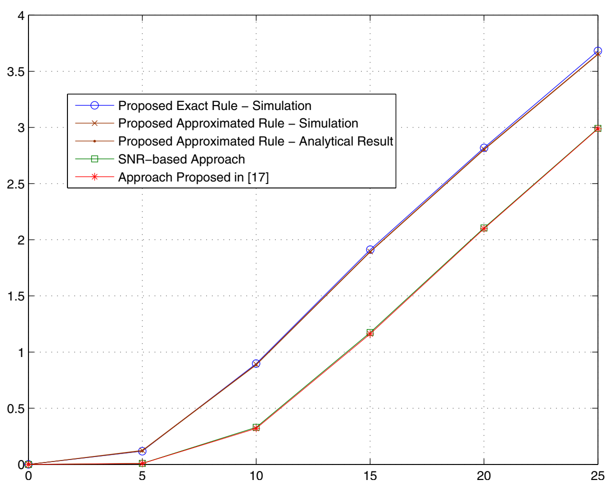

Fig. 5. Comparison of average rate among different protocols.

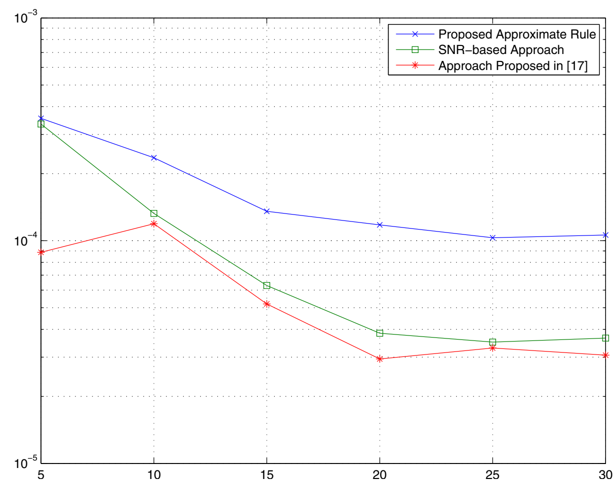

Fig. 6. Comparison of SER among different protocols.

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