SEP OF COOPERATIVE SYSTEMS USING AMPLIFY AND FORWARD OR DECODE AND FORWARD RELAYING

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ABSTRACT

In this paper, we derive the Symbol Error Probability (SEP) of cooperative systems using Amplify and Forward (AF) or Decode and Forward (DF) relaying. In AF relaying, each relay amplifies and retransmits to the destination the received signal from source. The destination combines the signals received from all relays and the source using a Maximum Ratio Combining (MRC) strategy. For DF relaying, each relay decodes the received signal. It forwards the decoded symbol if it decodes correctly. Otherwise, it remains idle. In DF relaying, two protocols are presented. In the first one, each relay decodes only the received signal from the source. In the second one, each relay combines the signals received from the source and the previous m relays. Exact and asymptotic SEP of AF and DF relaying are derived and compared to simulation results.

1. INTRODUCTION

The SEP of cooperative systems using AF or DF relaying has been intensively studied in the literature [1]-[5]. The asymptotic SEP, lower and upper bounds of the SEP of cooperative systems using AF relaying were derived in [1]-[2]. Some of these bounds contain integral expressions. In this paper, we present new simple expressions of the lower bound of the SEP and the asymptotic SEP. The derived asymptotic SEP is tighter than that of [2].

Two DF relaying protocols are studied. In the first one, each relay decodes only the received signal from the source. The SEP of this first DF protocol is derived in [4]. To the best of the author's knowledge, the asymptotic SEP of this DF protocol is not currently available in the literature. We provide exact and asymptotic SEP of this DF protocol. In the second DF protocol, each relay combines the received signals from the source and the previous m relays [5]. Exact and asymptotic SEP of this second DF protocol were derived in [5]. In this paper, we compare the performance of the these two DF relaying protocols using both theoretical and simulation results.

The paper is organized as follows. Sections 2, 3 and 4 derive respectively the SEP of cooperative systems using AF and DF relaying for the first and second protocol. Section 5 gives some numerical and simulation results. Section 6 draws some conclusions.

2. PERFORMANCE ANALYSIS OF AF RELAYING

2.1 System model

We consider a cluster of nodes consisting of a source S, a destination D and M relays R_k. The transmission mode is composed of two phases :

- **Phase 1** : the source transmits the signal to the destination and all relays.

  The received signal at the destination from the source is given by

$$y_{S,D} = \sqrt{E_0} h_{S,D} s + n_{S,D}, \tag{1}$$

where E_0 is the transmitted energy per symbol by the source, s is the transmitted symbol, $h_{X,Y}$ is the channel coefficient for the link between X and Y and $n_{X,Y}$ is an additive complex gaussian noise with a variance equal to N_0.

The received signal at the k-th relay from the source is given by

$$y_{S,R_k} = \sqrt{E_0} h_{S,R_k} s + n_{S,R_k}, 1 \leq k \leq M \tag{2}$$

- **Phase 2** : all relays amplify the received signal from the source and retransmit it to the destination using orthogonal channels (Time, Frequencies, ...).

  The received signal at the destination from relay R_k is given by

$$y_{R_k,D} = h_{R_k,D} G^k y_{S,R_k} + n_{R_k,D}, \tag{3}$$

G^k is the amplification factor

$$G^k = \sqrt{\frac{E_k}{E_0 \left|h_{S,R_k}\right|^2 + N_0}}, \tag{4}$$

The destination combine all received signals using a Maximum Ratio Combining (MRC) strategy.

$$r = \frac{\sqrt{E_0}}{N_0} y_{S,D} h^*_{S,D} + \frac{\sum_{k=1}^{M} y_{R_k,D} h^*_{R_k,D} h^*_{S,R_k} G^k \sqrt{E_0}}{N_0 \left(1 + (G^k)^2 \left|h_{R_k,D}\right|^2\right)}. \tag{5}$$

2.2 Statistical description of the SNR

The Signal to Noise Ratio (SNR) of the direct link is given by

$$\Gamma_{S,D} = \frac{E_0}{N_0} \left|h_{S,D}\right|^2. \tag{6}$$

For Rayleigh fading channels, the Probability Density Function (PDF) of the SNR of the direct link is given by

$$p_{\Gamma_{S,D}}(\gamma) = \frac{1}{\overline{\Gamma}_{S,D}} e^{-\frac{\gamma}{\overline{\Gamma}_{S,D}}} U(\gamma), \tag{7}$$

where $U(\gamma)$ is the unit step function, $\overline{\Gamma}_{S,D} = E(\Gamma_{S,D})$ and $E(.)$ is the expectation operator.

The SNR for the relaying link between the source, relay R_k and the destination is given by [1]

$$\Gamma_{S,R_k,D} = \frac{\Gamma_{S,R_k}\Gamma_{R_k,D}}{1+\Gamma_{S,R_k}+\Gamma_{R_k,D}}, \tag{8}$$

where

$$\Gamma_{S,R_k} = \frac{E_0}{N_0}\left|h_{S,R_k}\right|^2, \tag{9}$$

$$\Gamma_{R_k,D} = \frac{E_k}{N_0}\left|h_{R_k,D}\right|^2. \tag{10}$$

$\Gamma_{S,R_k,D}$ can be tightly upper bounded by

$$\Gamma_{S,R_k,D} < \min\left\{\Gamma_{S,R_k},\Gamma_{R_k,D}\right\} = \Gamma^{up}_{S,R_k,D}. \tag{11}$$

The PDF of $\Gamma^{up}_{S,R_k,D}$ is given by

$$p_{\Gamma^{up}_{S,R_k,D}}(\gamma) = \frac{1}{\overline{\Gamma}^{up}_{S,R_k,D}} e^{\frac{\gamma}{\overline{\Gamma}^{up}_{S,R_k,D}}} U(\gamma). \tag{12}$$

where

$$\overline{\Gamma}^{up}_{S,R_k,D} = \frac{\overline{\Gamma}_{S,R_k}\overline{\Gamma}_{R_k,D}}{\overline{\Gamma}_{S,R_k}+\overline{\Gamma}_{R_k,D}} \tag{13}$$

The SNR at the destination can be written as

$$\Gamma = \Gamma_{S,D} + \sum_{k=1}^{M}\Gamma_{S,R_k,D}. \tag{14}$$

Using (11), the total SNR can be upper bounded by

$$\Gamma < \Gamma^{up} = \Gamma_{S,D} + \sum_{k=1}^{M}\Gamma^{up}_{S,R_k,D}. \tag{15}$$

Assuming that $\Gamma_{S,D}$ and $\Gamma_{S,R_k,D}$ are independent, the Moment Generating Function (MGF) of Γ^{up} can be written as

$$M_{\Gamma^{up}}(s) = M_{\Gamma^{up}_{S,D}}(s)\prod_{k=1}^{M} M_{\Gamma^{up}_{S,R_k,D}}(s), \tag{16}$$

where

$$M_{\Gamma^{up}_{S,R_k,D}}(s) = LT\left(p_{\Gamma^{up}_{S,R_k,D}}(\gamma)\right). \tag{17}$$

$LT(.)$ is Laplace Transform. Using (12) we have

$$M_{\Gamma^{up}_{S,R_k,D}}(s) = \frac{1}{1+s\overline{\Gamma}^{up}_{S,R_k,D}}. \tag{18}$$

Therefore, we have

$$M_{\Gamma^{up}}(s) = \frac{1}{1+s\overline{\Gamma}_{S,D}}\prod_{k=1}^{M}\frac{1}{1+s\overline{\Gamma}^{up}_{S,R_k,D}} \tag{19}$$

Using the MGF of the SNR, we can evaluate the SEP of I-PSK modulations as follows[6]

$$P_e > \frac{1}{\pi}\int_0^{\frac{(I-1)\pi}{I}} M_{\Gamma^{up}}\left(\frac{g_{PSK}}{sin^2(\theta)}\right)d\theta \tag{20}$$

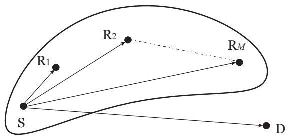

Figure 1: Phase 1 in first DF protocol

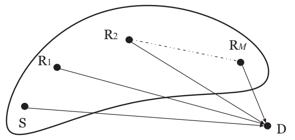

Figure 2: Phase 3 in first DF protocol

where $g_{PSK} = sin^2\left(\frac{\pi}{I}\right)$.

Note that we have a lower bound on the SEP since we have used an upper bound on the SNR.

The SEP for I-QAM is given by [6]

$$\begin{aligned} P_e \quad > \quad & \frac{4}{\pi}\left(1-\frac{1}{I}\right)\int_0^{\frac{\pi}{2}} M_{\Gamma^{up}}\left(\frac{g_{QAM}}{sin^2(\theta)}\right)d\theta \\ & -\frac{4}{\pi}\left(1-\frac{1}{I}\right)\int_0^{\frac{\pi}{4}} M_{\Gamma^{up}}\left(\frac{g_{QAM}}{sin^2(\theta)}\right)d\theta \end{aligned} \tag{21}$$

where $g_{QAM} = 3/(I-1)$

2.3 Asymptotic SEP

By using the same methodology as [7], we can derive the asymptotic SEP of cooperative systems using AF relaying

$$P_e^{AF} \approx \frac{A\, C_{2M+1}^{M+1}}{(2B)^{M+1}}\frac{1}{\overline{\Gamma}_{S,D}}\prod_{k=1}^{M}\frac{1}{\overline{\Gamma}^{up}_{S,R_k,D}} \tag{22}$$

where $C_k^l = \frac{k!}{l!(k-l)!}$, A and B depend on the considered modulation (for example, $A=1$, $B=2$ for BPSK).

3. PERFORMANCE ANALYSIS OF THE FIRST DF RELAYING PROTOCOL

In this section, we evaluate the SEP of the first protocol of DF strategy. Each relay decodes the signal provided from the source (fig. 1). For medium access, the relays are assumed to transmit over orthogonal channels (Time or Frequency), thus no inter-relay interference is considered in the system model. As shown in figure 2, the destination coherently combines using a MRC the received signals from the source and all the relays.

3.1 System model

The cooperation protocol has 3 phases.

- **Phase** 1 : the source broadcast the information. The received signal at the destination and the k-th relay can be modeled respectively by equations (1) and (2).
- **Phase** 2: if the k-th relay correctly decodes, it forwards the decoded symbol with symbol energy E_k to the destination; otherwise, it remains idle.
- **Phase** 3: the destination coherently combines the received signals from the source and the relays using a MRC as follows:

$$y_D = \sqrt{E_0}h^*_{S,D}y_{S,D} + \sum_{k=1}^{M}\sqrt{\widehat{E}_k}h^*_{R_k,D}y_{R_k,D} \tag{23}$$

where $\widehat{E}_k = E_k$ if relay R_k correctly decoded, $\widehat{E}_k = 0$ otherwise.

3.2 Exact SEP

In this section, we derive the exact SEP for I-PSK and I-QAM modulations. Each relay can be in one of two states: either it decoded correctly or not. Let Θ represents the set of relays that have correctly decoded.

The SEP at the destination can be written as:

$$P_e^{DF_1} = \sum_{\Theta} P_{e_D/\Theta}^{DF_1} P(\Theta). \tag{24}$$

the superscript DF_1 refers to the first DF protocol and $P(\Theta)$ is the probability that Θ is the set of relay that correctly decoded

$$P(\Theta) = \prod_{i\in\Theta}(1-P_{R_i}) \prod_{j\notin\Theta} P_{R_j}. \tag{25}$$

P_{R_k} is the SEP at the k-th relay

$$P_{R_k} = \frac{A}{2}\left[1-\sqrt{\frac{\overline{\Gamma}_{S,R_k}}{\frac{2}{B}+\overline{\Gamma}_{S,R_k}}}\right] \tag{26}$$

$\overline{\Gamma}_{S,R_k}$ is the average SNR between the source and R_k

$$\overline{\Gamma}_{S,R_k} = \frac{E_0}{N_0} E\left(\left|h_{S,R_k}\right|^2\right) \tag{27}$$

For a given decoding set Θ, the SEP at destination is given by

$$P_{e/\Theta}^{DF_1} = \frac{A}{2}\sum_{k\in\Theta} t_k \left[1-\sqrt{\frac{\overline{\Gamma}_{R_k,D}}{\frac{2}{B}+\overline{\Gamma}_{R_k,D}}}\right] + \frac{A}{2} t_0 \left[1-\sqrt{\frac{\overline{\Gamma}_{S,D}}{\frac{2}{B}+\overline{\Gamma}_{S,D}}}\right] \tag{28}$$

where

$$t_k = \prod_{\substack{i\in\Theta \\ i\neq k}} \frac{\overline{\Gamma}_{R_k,D}}{\overline{\Gamma}_{R_k,D}-\overline{\Gamma}_{R_i,D}} \frac{\overline{\Gamma}_{R_k,D}}{\overline{\Gamma}_{R_k,D}-\overline{\Gamma}_{S,D}}, \tag{29}$$

$$t_0 = \prod_{i\in\Theta} \frac{\overline{\Gamma}_{S,D}}{\overline{\Gamma}_{S,D}-\overline{\Gamma}_{R_i,D}}. \tag{30}$$

3.3 Asymptotic SEP

At high SNR, all relays correctly decode, the asymptotic SEP is therefore given by [7]

$$P_e^{DF_1} \approx \frac{A\, C_{2M+1}^{M+1}}{(2\,B)^{M+1}} \frac{1}{\overline{\Gamma}_{S,D}} \prod_{k=1}^{M} \frac{1}{\overline{\Gamma}_{R_k,D}} \tag{31}$$

4. PERFORMANCE ANALYSIS OF THE SECOND DF RELAYING PROTOCOL

In this section, we derive the SEP performance analysis of the second scenario using DF protocol. We assume that each relay combines the signal from the source and the previous m relays using a MRC strategy (Fig. 3). The study is valid for $m > 1$. The results presented in section 3 corresponds to $m = 0$.

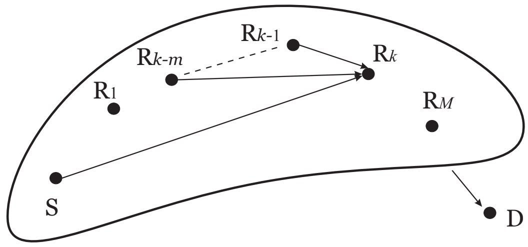

Figure 3: Second DF protocol

4.1 Sytem model

The cooperation protocol has $M+2$ phases.

- **Phase 1**: the signal emitted by the source is received by all the relays and destination. Equations (1) and (2) remain valid.
- **Phase 2**: the first relay decodes the signal received from the source. If it correctly decodes, it forward the decoded symbol to the destination; otherwise, it remains idle.
- **Phase** l ($3 \leq l \leq M+1$): relay R_{l-1} combines the signals received from the source and the m previous relays. The detection variable used by relay R_{l-1} is given by

$$y_{R_{l-1}} = \sqrt{E_0} h_{S,R_{l-1}}^* y_{S,R_{l-1}} + \sum_{j=\max(1,l-1-m)}^{l-2} \sqrt{\widehat{E}_j} h_{R_j,R_{l-1}}^* y_{R_j,R_{l-1}}, \tag{32}$$

where $y_{R_j,R_{l-1}}$ is the received signal at R_{l-1} from R_j modeled as

$$y_{R_j,R_{l-1}} = \sqrt{\widehat{E}_j} h_{R_j,R_{l-1}} s + n_{R_j,R_{l-1}} \tag{33}$$

- **phase** $M+2$: the destination decodes a MRC combination of the signals received from the source and the relays (16).

4.2 Exact SEP

In this section, we give the exact SEP performance analysis for BPSK modulation. Each relay can be in one of two states : either it decoded correctly or not. Let vector $\mathbf{S}_M$ represents the states of the M relays. The k-th entry of $\mathbf{S}_M$ is defined as

$$\mathbf{S}_M(k) = \begin{cases} 1 \text{ if relay } k \text{ correctly decodes} \\ 0 \text{ otherwise} \end{cases}. \tag{34}$$

We denote the state of the network by a decimal number which can take values from 0 to $2^M - 1$.

The state of each relay depends on the sate of the previous relay. Hence, the joint probability of the states is given by

$$P(\mathbf{S}_M) = P(S_M(1))P(S_M(2)/S_M(1))\ldots$$
$$P(S_M(M)/S_M(M-1),\cdots,S_M(M-m)). \tag{35}$$

The SEP for a given Channel State Information (CSI) can be written as

$$P_{e/CSI}^{DF_2} = \sum_{i=0}^{2^M-1} \Pr(e/\mathbf{S}_M = \mathbf{B}_{i,M}) \Pr(\mathbf{S}_M = \mathbf{B}_{i,M}) \tag{36}$$

where e denotes the event that the destination decoded in error and $\mathbf{B}_{i,M} = (B_{i,M}(1)...B_{i,M}(M))$ is the $1 \times M$ binary representation of i. $B_{i,M}(1)$ being the most significant bit.

The conditional SEP for a given network state is given by

$$\Pr(e/\mathbf{S}_M = \mathbf{B}_{i,M}) = \Psi(SNR_D). \qquad (37)$$

where $\Psi(\gamma)$ is SEP for an instantaneous SNR equal to γ. For I-PSK modulations, Ψ is given by [6]

$$\Psi_{PSK}(\gamma) = \frac{1}{\pi}\int_0^{\frac{(I-1)\pi}{I}} e^{\left(-\frac{g_{PSK}\gamma}{\sin^2(\theta)}\right)} d\theta \qquad (38)$$

For I-QAM modulations, we have

$$\Psi_{QAM}(\gamma) = 4CQ\left(\sqrt{g_{QAM}\gamma}\right) - 4C^2Q^2\left(\sqrt{g_{QAM}\gamma}\right) \qquad (39)$$

where $C = 1 - 1/\sqrt{I}$ and $Q(y)$ is the gaussian Q function defined as

$$Q(y) = \frac{1}{\sqrt{2\pi}}\int_y^{\infty} e^{-\frac{t^2}{2}} dt \qquad (40)$$

To compute the SEP, we have to average (36) over all channel realizations

$$\begin{aligned} P_e^{DF_2} &= E(P_{e/CSI}^{DF_2}) \\ &= \sum_{i=0}^{2^M-1} E\left(\Psi(SNR_D)\prod_{k=1}^{M} P_{k,i}^m\right) \end{aligned} \qquad (41)$$

where $P_{k,i}^m$ is the probability that the k-th relay is in state $\mathbf{B}_{i,M}(k)$ given the state of the previous m relays

$$P_{k,i}^m = \begin{cases} \Psi(SNR_{R_k}^m) \text{ if } \mathbf{B}_{i,M}(k) = 0 \\ 1 - \Psi(SNR_{R_k}^m) \text{ if } \mathbf{B}_{i,M}(k) = 1 \end{cases}. \qquad (42)$$

$SNR_{R_k}^m$ is the SNR at the k-th relay.

We then deduce the expression of the SEP [5]

$$\begin{aligned} P_e^{DF} = & \sum_{i=0}^{2^M-1} F\left[\left(1 + \frac{\overline{\Gamma}_{S,D}}{\sin^2(\theta)}\right)\right. \\ & \left.\prod_{j=1}^{M}\left(1 + \frac{B_{i,M}(j)\overline{\Gamma}_{R_j,D}}{\sin^2(\theta)}\right)\right]\prod_{k=1}^{M} G_k^m(B_{i,M}(k)) \end{aligned} \qquad (43)$$

$$G_k^m(x) = \begin{cases} F\left[\left(1 + \frac{\overline{\Gamma}_{S,R_k}}{\sin^2(\theta)}\right)\prod_{j=\max(1,k-m)}^{k-1} \left(1 + \frac{B_{i,M}(j)\overline{\Gamma}_{R_j,R_k}}{\sin^2(\theta)}\right)\right] \text{ if } x=0 \\ 1 - F\left[\left(1 + \frac{\overline{\Gamma}_{S,R_k}}{\sin^2(\theta)}\right)\prod_{j=\max(1,k-m)}^{k-1} \left(1 + \frac{B_{i,M}(j)\overline{\Gamma}_{R_j,R_k}}{\sin^2(\theta)}\right)\right] \text{ if } x=1 \end{cases}$$

For I-PSK modulations, $F(.)$ is defined as

$$F(x(\theta)) = \frac{1}{\pi}\int_0^{\frac{(I-1)\pi}{I}} \frac{d\theta}{x(\theta)} \qquad (44)$$

For I-QAM modulations, we have

$$F(x(\theta)) = \frac{4C}{\pi}\int_0^{\frac{\pi}{2}} \frac{d\theta}{x(\theta)} - \frac{4C^2}{\pi}\int_0^{\frac{\pi}{4}} \frac{d\theta}{x(\theta)} \qquad (45)$$

4.3 Asymptotic BEP

It was shown in [5] that the asymptotic SEP at the destination is given by

$$P_e^{DF_2} \approx \frac{1}{b^{M+1}\overline{\Gamma}_{S,D}} \sum_{j=1}^{M+1} \frac{g(M-j+2)g^{j-1}(1)}{\overline{\Gamma}_{S,D}^{j}\prod_{i=j}^{M}\overline{\Gamma}_{R_i,D}\prod_{l=1}^{j-1}E\left(\left|h_{S,R_l}\right|^2\right)}. \qquad (46)$$

where $b = g_{PSK}$ or $b = g_{QAM}$. For I-PSK modulations,

$$g(x) = \frac{1}{\pi}\int_0^{\frac{(I-1)\pi}{I}} \sin^{2x}(\theta)d\theta, \qquad (47)$$

For I-QAM modulations, we have

$$g(x) = \frac{4C}{\pi}\left[\int_0^{\frac{\pi}{2}} \sin^{2x}(\theta)d\theta - C\int_0^{\frac{\pi}{4}} \sin^{2x}(\theta)d\theta\right], \qquad (48)$$

5. SIMULATION RESULTS

In this section, we give some numerical and simulation results in terms of BEP evolution with respect to E_b/N_0 for a BPSK modulation. We have allocated the same power to all nodes : $E_X = E_b/(M+1)$. In order to take into account of the path loss, the average power of the channel coefficient between X and Y is modeled as follows

$$E\left(\left|h_{X,Y}^l\right|^2\right) = \frac{\beta}{d_{XY}^{\alpha}},$$

where d_{XY} is the normalized distance between X and Y and α is the path loss exponent. Note that $d_{XY} = d_{XY}^{eff}/d_0$, d_{XY}^{eff} is the effective distance in meters between X and Y, d_0 is an arbitrary reference distance and β is the path loss at the reference distance. We have used the following parameters $\beta = 1$ and $d_{XY} = 1$.

Figure 4 compares the theoretical BEP of cooperative systems using AF and DF relaying for the first and the second protocol ($m = 1$) in the presence of $M = 2$ relays. The theoretical results are plotted using (20), (24) and (43). We observe that DF relaying offers better performance than AF relaying. Also, the second DF relaying protocol offers better performance than the first one since each relays uses the signals of the m previous relays. However the time requirement is higher than the first protocol, indeed it requires $M+1$ time slots to transmit a single symbol. Simulation results are also in agreement with the theoretical ones.

Figure 5 shows the derived theoretical BEP of AF relaying for $M = 2$. The derived upper bound (20) and asymptotic BEP (22) are compare to lower and upper bounds derived in [2]. We verify that the derived upper bound is tighter than that of [2].

Figure 6 shows the exact and asymptotic BEP of the first DF relaying protocol. We verify that the asymptotic and exact BEP agree at high SNR.

6. CONCLUSION

In this paper, we have derived the exact and asymptotic SEP of cooperative systems using AF or DF relaying. Two DF protocols were considered. In the first DF protocol, each relay uses only the signal transmitted by the source. In the second one, each relay combines the signals transmitted by the source and the *m* previous relays. The second protocol offers better performance than the first one due to spatial diversity brought by previous relays transmissions. However, transmission delays are larger in the second protocol.

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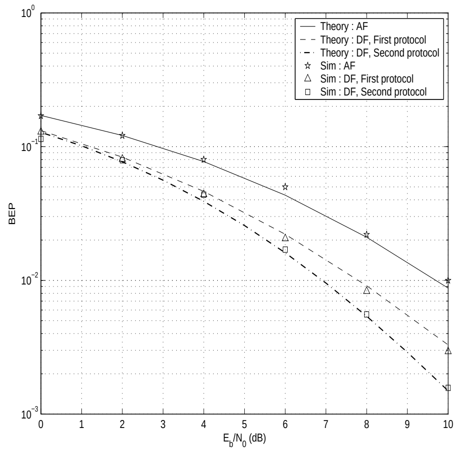

Figure 4: SEP of cooperative systems using AF, DF (first and second protocol) strategy with $M = 2$.

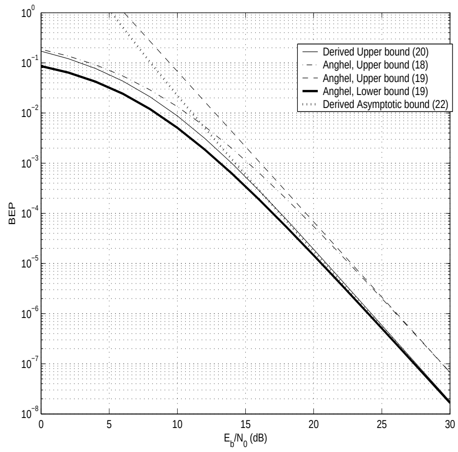

Figure 5: Derived and asyptotic SEP of cooperative systems using AF strategy with $M = 2$

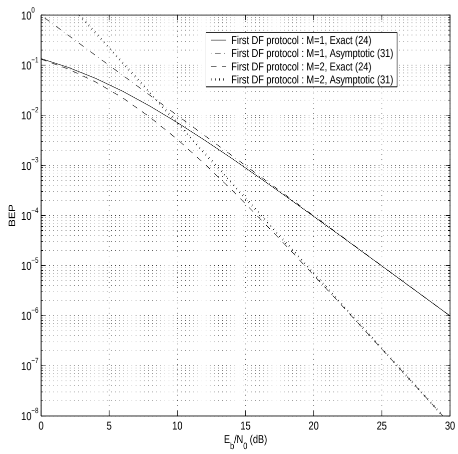

Figure 6: Exact and asymptotic SEP of cooperative systems using the first protocol of DF strategy, for $M = 1$ and $M = 2$.