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협동 중계 시스템을 이용한 분산 Alamouti 시공간 블록 부호

(Distributed Alamouti Space Time Block Coding Based On Cooperative Relay System)

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요 약

본 논문에서는 하나의 기지국, 세 개의 중계국, 하나의 수신국으로 이루어진 중계 기반 협동 시스템을 이용하는 새로운 분산 Alamouti 시공간 블록 부호화 기법을 제안하였다. 세 개의 중계국 중에서 선택한 두 개의 중계국과 통신이 이루어지도록 기지국은 두 개의 빔(beam)으로 구성된 array를 사용하는 개별적인 두 개의 안테나로 이루어졌다고 가정하였다. 첫 번째 시간 슬롯(slot) 동안, 기지국의 한 안테나로부터 전송된 개별적인 두 개의 신호가 하나의 중계국에 의하여 선택되고, 더해지고, 증폭되고, 수신국으로 보내진다. 이 전송 기법은 중계국과 수신국 사이의 채널에서 생성될 수 있는 새로운 분산 Alamouti 시공간 블록 부호를 나타낸다. 심벌의 등가 행렬 표현을 이용하여 처노프(Chernoff) 상계(upper bound) 쌍 오류 확률(PEP)의 관점에서 제안된 시공간 블록 부호의 성능을 분석하였다. 또한, 수신 신호 성능 관점에서 기지국의 두 개의 안테나 사이의 전력 배분에 따라 결정되는 계수 α의 효과를 평가하였다. 컴퓨터 모의실험을 통하여 α의 값이 $\frac{2}{3}$일 때에만 세 개의 중계국에서의 수신 신호가 같은 분산을 갖는다는 것을 확인할 수 있었다. 결과적으로 수신국에서 더 나은 성능을 얻을 수 있었다. 이 분석 결과를 통하여 제안된 기법을 이용할 경우 기존의 기법에 비하여 중계국에서의 다이버시티 이득, PEP, 복잡성 관점에서 뛰어난 성능을 얻을 수 있다는 것을 확인할 수 있었다.

Abstract

In this paper, we propose a new distributed Alamouti space-time block coding scheme using cooperative relay system composed of one source node, three relay nodes and one destination node. The source node is assumed to be equipped with two antennas which respectively use a 2-beam array to communicate with two nodes selected from the three relay nodes. During the first time slot, the two signals which respectively were transmitted by one antenna at the source, are selected by one relay node, added, amplified, and forwarded to the destination. During the second time slot, the other two relay nodes implement the conjugate and minusconjugate operations to the two received signals, respectively, each in turn is amplified and forwarded to the destination node. This transmission scheme represents a new distributed Alamouti space-time block code that can be constructed at the relay-destination channel. Through an equivalent matrix expression of symbols, we analyze the performance of this proposed space-time block code in terms of the chernoff upper bound pairwise error probability (PEP). In addition, we evaluate the effect of the coefficient $\alpha\,(0 \le \alpha \le 1)$ determined by power allocation between the two antennas at the source on the received signal performance. Through computer simulation, we show that the received signals at the three relays have same variance only when the value of α is equal to $\frac{2}{3}$, as a consequence, a better performance is obtained at the destination. These analysis results show that the proposed scheme outperforms conventional proposed schemes in terms of diversity gain, PEP and the complexity of relay nodes.

Keywords : cooperative relay, Alamouti code, multibeam antenna, pairwise error probability(PEP), Diversity Gain.

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Ⅰ. INTRODUCTION

The multiple-input and multiple-output (MIMO) systems for wireless communication systems were demonstrated to provide a potential capacity gain compared to the single-antenna communication systems[1]. In order to approach the capacity of the MIMO system, the space time codes (STC) have received the significant amount of attentions[2].

At present, people become more concerned with the cooperative diversity technique by reason that cooperative relaying is a promising extension to the recent research field of relay networks where several relay stations transmit jointly to the same destination node. In [3], based on repetition for frequency non-selective half duplex systems, a variety of cooperative diversity protocols with low complexity are proposed. However, full spatial diversity benefits of the repetition based on cooperative diversity algorithms will decrease bandwidth efficiency with the number of cooperative users. As a consequence, in order to improve the bandwidth efficiency of the algorithms, an alternative approach based on space time codes is proposed in [4], which allows all partners to transmit on the same subchannel. Full diversity without any feedback can be achieved through space time coded cooperative diversity schemes which have more computational complexity in the mobile devices. And a major drawback is that these schemes require coherent reception at both the partner and the destination. Besides, these schemes will waste the power of both users when interuser communication incurs error. And many kinds of the cooperative relay channel models are mentioned in [5].

In [6], the Multibeam antenna can be used to reduce the signal-to-intermodulation interference ratio and provide a good antenna gain, in an N-beam array with single channel per beam the input signal of l^{th} amplifier of an array is the sum of the N steered signals, and can be represented by

$$x(l,t) = \sum_{n=1}^{N} A_{nl} e^{j(2\pi f_n t + \phi_{nl})}, \tag{1}$$

where A_{nl} is the amplitude of the n^{th} channel at the l^{th} element where this work is assumed constant over time t, ϕ_{nl} is the corresponding phase, and f_n is the carrier frequency at the given channel.

In this paper, we propose a new distributed Alamouti space time block coding scheme based on cooperative relay systems, where the source node is assumed to be equipped with two antennas which separately use a 2-beam array to communicate with the relay nodes and the relay nodes carry out different operations and forward signals to the destination node. In the following, A^*, A^t, A^H, $\det(A)$ and $Tr(A)$ denote the conjugate, the transpose, the conjugate transpose identical to Hermitian, the determinant and the trace of matrix A, respectively. $\|\bullet\|_F^2$ denote the Frobenius norm.

Ⅱ. SYSTEM MODEL

The proposed communication network consists of one source node, three relay nodes and one destination node over a wireless multi-hop channel, where the source node has two antennas and the other nodes have a single antenna respectively, as shown in Fig. 1. We assume that the communication system is performed over a complex, additive white Gaussian noise (AWGN) coherent fading channel, and the distance from the source node to the destination node is so far that the source node can not communicate with the destination node directly.

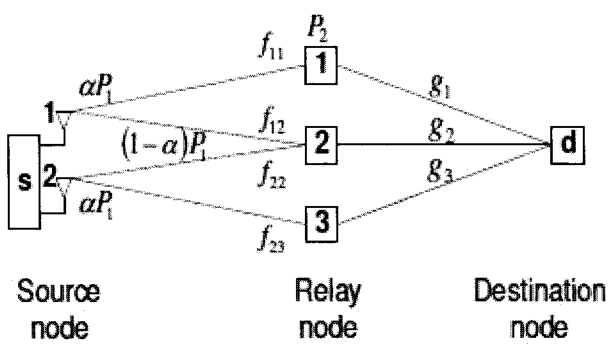


그림 1. 협동 중계 시스템을 이용한 분산 Alamouti 시공간 블록 부호화의 통신 모델

Fig. 1. The communication model of distributed Alamouti space time block coding based on cooperative relay system.

At the source node, information sequences are modulated into N length complex symbol codebook $X=\{x_1,x_2,\cdots,x_N\}$, where $E=[x_l^* x_l]=1$ for all $l=1,2,\cdots,N$. Each time interval, a pair of complex symbols are selected and transmitted at the source node. Also, we propose that the transmitted power of each source antenna is divided into two parts by Multibeam antenna[6]. Each part can only communicate with one relay node, with the power allocation coefficient, $\alpha=\frac{A_{1l}^2}{A_{1l}^2+A_{2l}^2}$ (based on Eq. (1) and $f_1=f_2$). At each relay node, the received signals are carrying out different operations and forwarded to the destination node. We denote the channel state information from the i^{th} source antenna to the j^{th} relay node as f_{ij} and the channel state information from the j^{th} relay node to the destination node as g_j for $i=1,2$ and $j=1,2,3$. The noises of different paths are denoted as for $k=1,2,\cdots,6$.

In the proposed system model, the following suppositions have been given :

- The destination node knows all the channel state information f_{ij} and g_j.
- The channel state information f_{ij} , g_j and the noises n_k are $CN(0,1)$ and i.i.d.
- All nodes have been subjected to half duplex pattern.

Transmission from the source node to the destination node is carried out in two phases. In phase 1, the source node transmits a pair of complex symbols from different source antenna at the τ^{th} time slot of time interval T, where $T=\{1^{th},2^{th},\cdots,\tau^{th}\}$ and the complex symbols can contain either the symbols $x_1,x_2,\cdots,x_N$, or their conjugate $x_1^*,x_2^*,\cdots,x_N^*$. Let us denote the transmit sequence from antenna one and two by s^1 and s^2, respectively. We assume $T=1$, $s^1=\{x_1\}$, $s^2=\{x_2\}$, and have

$$\begin{aligned} r_1 &= \sqrt{\alpha P_1}\,x_1 f_{11}+n_1, \\ r_2 &= \sqrt{(1-\alpha)P_1}\,(x_1 f_{12}+x_2 f_{22})+n_2, \\ r_3 &= \sqrt{\alpha P_1}\,x_2 f_{23}+n_3, \end{aligned} \tag{2}$$

and $E[r_1^* r_1]=E[r_3^* r_3]=1+\alpha P_1$, $E[r_2^* r_2]=1+2(1-\alpha)P_1$, where P_1 is the average power at each source antenna, r_1, r_2 and r_3 denote received signals at the relay node 1, 2 and 3, respectively. In phase 2, the received signals are carrying out different operations at each relay node, as following,

- At the relay node 1 or node 3, the received signals are employing the conjugate operation and multiplied by $(-1)^{\tau+1}$ or $(-1)^{\tau}$ operation, respectively. After that the signals are amplified and forwarded.
- At the relay node 2, the received signals are only amplified and forwarded to the destination node directly.

The transmitted signals at the relay node 1, 2 and 3 denote as t_1, t_2 and t_3, respectively,

$$\begin{aligned} t_1 &= \hat{\beta}_1 r_1^* = \beta_1 x_1^* f_{11}^* + \hat{n}_1, \\ t_2 &= \hat{\beta}_2 r_2 = \beta_2 (x_1 f_{12}+x_2 f_{22}) + \hat{n}_2, \\ t_3 &= \hat{\beta}_1(-r_3^*) = -\beta_1 x_2^* f_{23}^* + \hat{n}_3, \end{aligned} \tag{3}$$

where

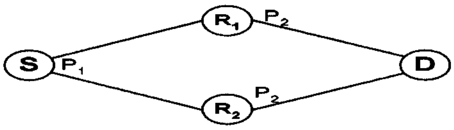
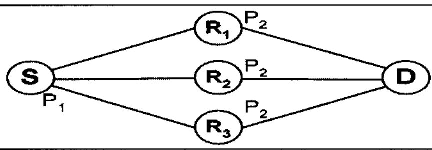
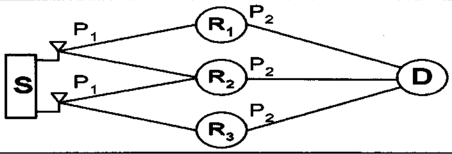
$\hat{\beta}_1=\sqrt{\frac{P_2}{1+\alpha P_1}}$, $\hat{\beta}_2=\sqrt{\frac{P_2}{1+2(1-\alpha)P_1}}$, $\beta_1=\sqrt{\alpha P_1}\,\hat{\beta}_1$, $\beta_2=\sqrt{(1-\alpha)P_1}\,\hat{\beta}_2$, $\hat{n}_1=\hat{\beta}_1 n_1^*$, $\hat{n}_2=\hat{\beta}_2 n_2$, $\hat{n}_3=-\hat{\beta}_1 n_3^*$, and P_2 is the average power at each relay node.

At the destination node, the signals can be received in two time slots. we have

$$\begin{aligned} r_{d_1} &= t_2 g_2 + n_4 = \beta_2 f_{12} g_2 x_1 + \beta_2 f_{22} g_2 x_2 + \tilde{n}_1, \\ r_{d_2} &= t_1 g_1 + t_3 g_3 + n_5 = \beta_1 f_{11}^* g_1 x_1^* - \beta_1 f_{23}^* g_3 x_2^* + \tilde{n}_2, \end{aligned} \tag{4}$$

where $\tilde{n}_1=\hat{n}_2 g_2+n_4$, and $\tilde{n}_2=\hat{n}_1 g_1+\hat{n}_3 g_3+n_5$. So we can get $=(\tilde{n}_1\ \ \tilde{n}_2)^t$ with zero-mean and variance

표 1. 각 모델의 성능 비교
Table 1. Compare the performance of corresponding models.

	Power Coefficient α	Diversity Gain	Corresponding Relay channel
Model 1	$\alpha = 1$	2	
Model 2	$\alpha = \frac{2}{3}$	3	
Model 3	$0 \le \alpha \le 1$	4	

$\sigma_n^2 = E[\quad ^H] = diag(\sigma_1^2 + \sigma_2^2) = diag(1+\beta_2^2,\ 1)$.

Let $S = \begin{bmatrix} c_1 & 0_2 \\ 0_2 & c_2 \end{bmatrix}$, and c_1, c_2 and 0_2 are a 1×2 block matrix, where $c_1 = (x_1 \ \ x_2)$, $c_2 = (-x_2^* \ \ x_1^*)$, and $0_2 = (0 \ \ 0)$,

$H = (\beta_2 f_{12} g_2 \ \ \beta_2 f_{22} g_2 \ \ \beta_1 f_{11} g_1^* \ \ \beta_1 f_{11}^* g_1)^t$, and the vector $_d$ equals $(r_{d_1} \ \ r_{d_2})^t$, we can get an equivalent matrix expression of symbols,

$$_d = SH + \quad . \tag{5}$$

From Eq. (4), we know that different operations at relay nodes can make the relay-destination channel having a similar structure as Alamouti model[1]. Also, we can have the equation

$$\begin{bmatrix} r_{d_1} \\ r_{d_2}^* \end{bmatrix} = \begin{bmatrix} \beta_2 f_{12} g_2 & \beta_2 f_{22} g_2 \\ \beta_1 f_{11} g_1^* & -\beta_1 f_{23} g_3^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \tilde{n}_1 \\ \tilde{n}_2^* \end{bmatrix} \tag{6}$$

III. PAIRWISE ERROR PROBABILITY

In this section, we will evaluate the Chernoff upper bound of the pairwise error probability (PEP) of signals. Though implementing different operations at the relay nodes, a new distributed Alamouti code can be constructed at the relay-destination channel. The transmission matrix S is a space time block code, where the rows and the columns of the matrix S denote time and space domain, respectively.

We assume that S_l and S_k are two arbitrary distributed codeword matrices in the communication system, S_k is the right transmission matrix, and x_l^k and x_l^l denote the signal x_l of S_k and S_l, respectively. For the coherent relay channel, from Eq. (5), the received conditional signal $_d|S_k$ is Gaussian random vector with mean $S_k H$ and variance σ_n^2. The condition of the maximum likelihood (ML) decoding is given by

$$arg \max_{S_k} P(\ _d|S_k) = arg \max_{S_k} \| \ _d - S_k H \|_F^2. \tag{7}$$

The received signal has conditional probability[7]

$$p(\ _d|S_k) = \frac{e^{-tr([\sigma_n^2]^{-1} BB^H)}}{\pi^2 \det(\sigma_n^2)}, \tag{8}$$

where $B = \ _d - S_k H$. To simplify calculation, we choose $[\sigma_n^2]^{-1} = diag(k_1, k_1)$, where $k_1 = \max\left\{\frac{1}{\sigma_1^2}, \frac{1}{\sigma_2^2}\right\}$. Employing Eq. (8), we can get

$$p(\ _d|S_k) = \frac{e^{-(B^H[\sigma_n^2]^{-1}B)}}{\pi^2 \det(\sigma_n^2)} = \frac{e^{-(H^H(S-S_k)^H(S-S_k)H)}}{\pi^2 \det(\sigma_n^2)} \tag{9}$$

From the Chernoff bound $P_{kl} \leq \frac{1}{2}e^{\mu(\lambda)}$ in [7] and [8], where $\mu(\lambda) = \ln E\{e^{[\lambda(\ln p(\ {}_d|S_l) - \ln p(\ {}_d|S_k))]}\}$, and the parameter λ $(0 \leq \lambda \leq 1)$ can properly be chosen to minimize $\mu(\lambda)$ at $\lambda = \frac{1}{2}$. We can calculate to get

$$
\begin{aligned}
P_{kl} &\leq \frac{1}{2} \underset{fij,gj,N}{E} [\exp(\lambda(\ln p(\mathrm{r_d}|S_l) - \ln p(\mathrm{r_d}|S_l)))] \\
&= \frac{1}{2} \underset{fij,gj}{E} \int \frac{\exp(\lambda(\ln p(\mathrm{r_d}|S_l) - \ln p(\mathrm{r_d}|S_l)) - \mathrm{n}^H\mathrm{n})}{2\pi} dn \\
&= \frac{1}{2} \underset{fij,gj}{E} [\exp(-\frac{1}{4}\mathrm{H}^{H}(S_k - S_l)^H(S_k - S_l)\mathrm{H})]
\end{aligned}
\tag{10}
$$

where $\ln p(\ {}_d|S_l) - \ln p(\ {}_d|S_k) = -(H^H(S_k - S_l)^H (S_k - S_l) + H^H(S_k - S_l)^H \ + \ {}^H(S_k - S_l)H)$

Based on Eq. (10), integrating over f_{ij}, we evaluate the PEP of the upper bound of the relay-destination channel. Since $H = gf$, $g = diag(\beta_2 g_2, \beta_2 g_2, \beta_1 g_3, \beta_1 g_1)$ and $f = (f_{12} f_{22} f_{23}^* f_{11}^*)^t$, and the value of expression is not changed, we have

$$
\begin{aligned}
P_{kl} &\leq \frac{1}{2} \underset{fij,gj}{E} [\exp(-\frac{1}{4}\mathrm{f}^H\mathrm{g}^H(S_k - S_l)^H(S_k - S_l)\mathrm{gf})] \\
&= \frac{1}{2} \underset{gj}{E} \int [\exp(-\frac{1}{4}\mathrm{f}^H\mathrm{g}^H(S_k - S_l)^H(S_k - S_l)\mathrm{gf})] p(\mathrm{f}) df \\
&= \frac{1}{2} \underset{gj}{E} [\det{}^{-1}[I_4 + \frac{1}{4}(S_k - S_l)^H(S_k - S_l)G]]
\end{aligned}
\tag{11}
$$

where $p(f)$ is the joint PDF of Gaussian random variables. $G = diag(\beta_2^2|g_2|^2, \beta_2^2|g_2|^2, \beta_1^2|g_3|^2, \beta_1^2|g_1|^2)$. Simply calculation, we get

$$
\begin{aligned}
P_{kl} \leq \frac{1}{2} \underset{gj}{E} [&(1 + \beta_2^2|g_2|^2|\hat{x}_1|^2 + \beta_2^2|g_2|^2|\hat{x}_2|^2) \\
&(1 + \beta_1^2|g_1|^2|\hat{x}_1|^2 + \beta_1^2|g_3|^2|\hat{x}_2|^2)]^{-1}
\end{aligned}
\tag{12}
$$

where $\hat{x}_l = x_l^k - x_l^l$.

Next, according to optimal power allocation[8], the total transmission power P, the optimum power allocation is such that the source node uses half of the total power and relay nodes share the other half, i.e., $2P_1 = 3P_2 = \frac{P}{2}$.

To discuss the effect of the power allocation coefficient α $(0 \leq \alpha \leq 1)$. from Eq. (12), we define

$$
\begin{aligned}
F(\alpha) = &\left(1 + \beta_2^2|g_2|^2|\hat{x}_1|^2 + \beta_2^2|g_2|^2|\hat{x}_2|^2\right) \\
&\left(1 + \beta_1^2|g_1|^2|\hat{x}_1|^2 + \beta_1^2|g_3|^2|\hat{x}_2|^2\right).
\end{aligned}
\tag{13}
$$

In order to reduce the computational complexity, we assume that $E[g_j^* g_j] = 1$, $E[\hat{x}_l^* \hat{x}_l] = 1$, and total power $P = 1$. So we get

$$
E[F(\alpha)] = 1 + 2\beta_1^2 + 2\beta_2^2 + 4\beta_1^2\beta_2^2. \tag{14}
$$

Using first derivative test, we can get the function $E[F(\alpha)]$ with maximum value for $\alpha = \frac{2}{3}$. It implies that the proposed model has a better performance when the received signal has the same variance at each relay node.

Ⅳ. MODEL ANALYSIS AND SIMULATION RESULTS

In this section, we present the comparison results of the proposed distribution Alamouti cooperative relay model with previous models (see Table 1). First, in proposed channel model, we assume each relay node only uses the AF protocol, and two source antennas transmit the same signal. Controlling the power allocation coefficient α, if the coefficient α is equal to 1 or $\frac{2}{3}$, and two source antennas can be combined to become one antenna, we get the equivalent model 1 or model 2, respectively. Also, let the model 1 and model 2 use LD space-time code[8~9] and compare the PEP and the complexity of relay nodes with the proposed model. The LD space-time code is used in the model 1 and model 2, where the space domain comes from the relay nodes and the time domain comes from the time interval τ of the source node. It means that τ equals at least 2. Both of the space domain and the time domain of the proposed model come from the relay nodes, the proposed model can also accomplish distributed space-time code when T is equal to 1. Without loss of generality, we select time interval $T=2$. In model 1 and model 2, the equivalent transmit matrix $Q=\left[A_1 s+B_1 s^*, A_2 s+B_2 s^*, \cdots, A_n s+B_n s^*\right]$, where s is a signal vector, A_n and B_n are arbitrary $T\times T$ unitary matrices[9]. This is by reason of the fact that the PEP of the model has relation to the equivalent transmission matrix. It means that we select the different equivalent transmission matrix in one model, it will have the different PEP. It is well known that orthogonal space time codes have full diversity and linear decoding complexity, and their property leads to good performance. Let's try our best to select the orthogonal code as the equivalent transmission, if it exists. Specially we choose $Q_{model\ 1}=\begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix}$ and $Q_{model\ 2}=\begin{bmatrix} x_1 & x_2 & x_1 \\ x_2 & -x_1 & x_2 \end{bmatrix}$. In the proposed model, we have the transmit sequence from antennas, $s^1=\{x_1, -x_2^*\}$, $s^2=\{x_2, x_1^*\}$. Also, we get the equivalent transmission matrix

$$S=\begin{bmatrix} c_1\, 0_2 \\ 0_2\, c_2 \\ c_2\, 0_2 \\ 0_2\, c_1 \end{bmatrix}=\begin{bmatrix} x_1 & x_2 & 0 & 0 \\ 0 & 0 & -x_2^* & x_1^* \\ -x_2^* & x_1^* & 0 & 0 \\ 0 & 0 & x_1 & x_2 \end{bmatrix} \tag{15}$$

From the distance matrix $Q^H Q$ (where $Q\in(\{Q_{model\ 1}, Q_{model\ 2}\})$, $S^H S$ and Eq. (11), we know the diversity gain of the proposed model is improved, obviously.

Also, considering the complexity of the relay nodes, the proposed model only need simply conjugate operations, and the relay nodes of model 1 and 2 should be used some matrix operations, where the relay nodes need more additions, multiplications and registers.

In the performance simulation, as shown in Fig. 2, we assume that the length of the pairwise transmission signals equal 100,000, and ML detection is used at the destination node. The data symbols are selected from QPSK constellation and the total power P is equal to one. We further assume that the chanel state information (CSI) is perfectly known at the destination node. We compare the performances of model 1, model 2 and the proposed model ($\alpha=\frac{2}{3}$). The simulation results show that the proposed model with optimal power coefficient α has approximately 3dB advantages.

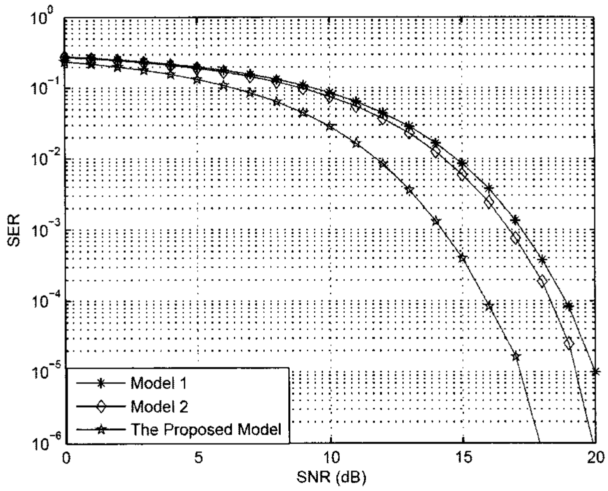


그림 2. 평탄(Flat) 페이딩 중계 채널에서의 각 모델의 성능 비교

Fig. 2. Performance of some models over flat fading relay channel.

V. DISCUSSION AND CONCLUSIONS

In this paper, we propose a new distributed Alamouti cooperative relay transmission scheme, which has one source node, three relay nodes and one destination node. The relay nodes carry out different operations to realize transmitting with Alamouti code at the relay-destination channel. Now, compare trace criteria and diversity gain between the proposed model and the other for $T=2$.

1. Trace Criteria and Diversity Gain

A good design criterion is to maximize the minimum distance $\|(S_k-S_l)\|_F$ among all possible

$k \neq l$. This is called "trace criterion"[10] because $\| (S_k - S_l) \|_F^2 = Tr\left[(S_k - S_l)^H (S_k - S_l)\right]$. At the relay nodes, the received signals are generating the equivalent transmission matrix and forwarded to the destination node. We make use of trace criterion to analyze the equivalent transmission matrix of three models and get $2(|\hat{x}_1|^2 + |\hat{x}_2|^2)$, $3(|\hat{x}_1|^2 + |\hat{x}_2|^2)$ and $4(|\hat{x}_1|^2 + |\hat{x}_2|^2)$ respectively. The proposed model can maximize the minimum distance. As we know, since $Q_{model\ 2}$ is non-orthogonal transmission matrix, it has a higher diversity than that of $Q_{model\ 1}$, so the performance of model 2 has only a little better than that of model 1. Also, from Eq. (11), it is obvious that the rank r of the matrix $\left[I_4 + \frac{1}{4}(S_k - S_l)^H (S_k - S_l) G\right]$ is equal to four, the diversity gain rn_{R_d} is also equal to four, where n_{R_d} denotes the number of antennas at the destination node. In previous papers, the diversity gain is always equal to the number of relay nodes. The proposed model has a higher diversity gain than that of model 1 and 2 because the second relay node has combined signals.

Through an equivalent matrix expression of symbols, we evaluate the Chernoff upper bound of the pairwise error probability (PEP) of signals. We have already proved that the system has the best performance when the received signals have the same variance at each relay node ($\alpha = \frac{2}{3}$). The analysis results show that the proposed scheme outperforms conventional proposed schemes in terms of diversity gain, PEP and the complexity of relay nodes.

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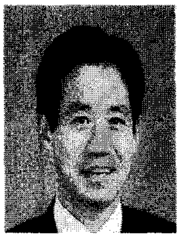

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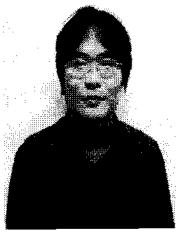

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