레일레이 페이딩 채널의 무선 네트워크에서 $\frac{3}{4}$ STBC를 사용한 협력신호 구조에 관한 연구

Ho Van Khuong† · 공 형 윤†† · 최 정 호†††

요 약

최근 협력통신은 안테나의 물리적인 배치 없이 공간 다중화를 얻을 수 있는 효과적인 방법으로 많은 주목을 받고 있다. 따라서 협력적인 위치를 가진 다중 안테나 시스템에서 잘 알려진 시공간 블록 코드(STBC, Space Time Block Code)는 분산환경 하의 단일 안테나 사용자들에게도 이용될 수 있다. 본 논문에서는 3/4 시공간블록 코드를 사용한 협력적인 신호 구조를 제안하고, 수학적으로 증명한 전송 전력 제한과 네트워크 기하학을 이용하여 이론상의 BER (Bit Error Ratio) 표현을 유도한다. 다양한 환경에서의 시뮬레이션과 잘 증명된 수학적인 결과는 파트너가 적절한 위치에 있을때, 직접 전송보다 매우 성능이 우수한 협력 통신을 증명하였다.

키워드 : 협력통신, 레일레이 페이딩, AWGN, 네트워크 기하학, STBC

A Cooperative Signaling Structure using the $\frac{3}{4}$ -rate STBC in Wireless Networks with Rayleigh Fading Channels

Ho Van Khuong† · Hyung-Yun Kong†† · Jeong-Ho Choi†††

ABSTRACT

Cooperative communications (CC) have received a great deal of attention recently as an efficient way to obtain the spatial diversity without physical arrays. Thus, space-time block codes (STBC) which are well-known for use in co-located multi-antenna systems can be still utilized for single-antenna users in a distributed fashion. In this paper, we propose a cooperative signaling structure using the $\frac{3}{4}$-rate STBC and derive closed-form BER expression which takes the effect of network geometry and transmit power constraint into account. A variety of simulated and numerical results demonstrated the cooperation considerably outperforms the direct transmission when partners are located in appropriate positions.

Key Words : Cooperative Communications, Rayleigh Fading, AWGN, Network Geometry, STBC

1. Introduction

Broadcast nature of wireless medium makes many wireless users be able to receive the same signal simultaneously from a certain transmitter. Relaying the signals they obtain to an intended destination forms a virtual antenna array by chance and thus, a spatial diversity is achievable. Such kind of diversity is called cooperative diversity [1]-[14]. Different from co-located multi-antenna systems where the antenna spacing is usually insufficient to eliminate the correlation between transmitted signals, cooperative communications among single-antenna users far apart to each other makes it possible (the receiver gets several copies of the original information through independent paths). Moreover, the intermediate users are normally located near the source or the destination and so, path-loss reduction can assist the information transmission more reliably.

Space-time block coding (STBC) can achieve full transmit diversity specified by the number of transmit antennas while allowing a very simple maximum-likelihood decoding algorithm, based only on linear processing of the received signals [15]. As a result, it has attracted a considerable

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† 준 회 원 : 울산대학교 전기 전자정보시스템공학과 박사과정
†† 정 회 원 : 울산대학교 전기전자정보시스템공학부 부교수
††† 준 회 원 : 울산대학교 전기 전자정보시스템공학과 석사과정
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attention in recent years as a powerful coding technique to mitigate fading in wireless channels and improve robustness to interference. However, its advantages are unachievable in some cases where wireless mobiles may not be able to support multiple antennas due to size or other constraints [1]. An efficient way to overcome this problem is to exploit the above mentioned cooperative communications.

In this paper, we propose a cooperative signaling structure to take advantage of the $\frac{3}{4}$-rate STBC. This is possible when two idle users, namely relays, agree to cooperate with the source to form a distributed antenna array. In addition, we introduce the decoding technique as well as the exact BER expression formulation under the strict power constraint. Moreover, the network geometry is considered. The numerical results show that the cooperation is not always better than non-cooperative counterpart unless the relays are located in proper positions.

The rest of the paper is organized as follows. Section 2 presents a cooperative signaling structure as well as the closed-form expression derivation for the error probability. Then the numerical and simulation results that compare the performance of the proposed cooperative communications with direct transmission are exposed in section 3. Finally, the paper is concluded in section 4.

2. Proposed cooperative transmission protocol

Consider a cooperative transmission in a generic wireless network where the information is transmitted from a source mobile S to a destination mobile D with the assistance of two relay terminals. All terminals equipped with single-antenna transceivers share the same frequency band and each terminal cannot transmit and receive signal at the same time. Time division multiplexing is used for channel access and the signal format of each entity is shown in the Fig. 1.

				Relay 1			
Source				$-z_{1,2}$	$z_{1,1}$	$-z_{1,4}$	$z_{1,3}$
x_1	x_2	x_3	x_4	Relay 2			
				$-z_{2,3}$	$z_{2,4}$	$z_{2,1}$	$-z_{2,2}$
Time slot 1				Time slot 2			

(Fig. 1) Proposed cooperative signaling structure

For simplicity of exposition, we use complex baseband-equivalent models to express all the signals. During its own time slot (represented as time slot 1), the source terminal broadcasts four BPSK-modulated symbols x_1, x_2, x_3, x_4 which will be received by the destination and two relays. Assuming that the channels among users (inter-user channels) and between the users and the destination (user-destination channels) are independent of each other. Moreover, all channels experience frequency flat fading and are quasi-static, i.e. they are constant during a 4-symbol period and change independently to the next. Therefore, the signals received at the destination and two relays have the common forms as follows

$$y_{Si,1} = \varepsilon_0 \alpha_{Si} x_1 + n_{Si,1} \quad (1a)$$

$$y_{Si,2} = \varepsilon_0 \alpha_{Si} x_2 + n_{Si,2} \quad (1b)$$

$$y_{Si,3} = \varepsilon_0 \alpha_{Si} x_3 + n_{Si,3} \quad (1c)$$

$$y_{Si,4} = \varepsilon_0 \alpha_{Si} x_4 + n_{Si,4} \quad (1d)$$

where

- $y_{Si,j}$ is a signal received at the terminal i from the source S during the j^{th} symbol duration (i=*1, 2, D* mean relay *1*, relay *2* and the destination *D*, respectively); j=*1, 2, 3, 4*.
- α_{Si} is a fading realization associated with each link from the source S to the target i which is assumed to be a Rayleigh-distributed random variable with average fading power λ_{Si}^2.
- $n_{Si,j}$ is a zero-mean additive noise sample of variance σ_{Si}^2 at terminal i in the j^{th} symbol interval.
- $\varepsilon_0 = \sqrt{P_S}$ is an amplification factor at the source where P_S is average source power.

In the second time slot, the relays are to simply amplify the signals received from the source and forward them simultaneously to the destination. These amplified signals obey the format in Fig. 1. Specifically, they are given by

$$z_{i,j} = \varepsilon_i y_{Si,j} \quad (2)$$

Here i=*1, 2* represent relay *1* and relay *2*, correspondingly; ε_i is the scaling factor at relay i which is chosen as

$$\varepsilon_i = \sqrt{\frac{P_i}{E\left[\left|y_{Si,j}\right|^2\right]}} = \sqrt{\frac{P_i}{P_S \lambda_{Si}^2 + \sigma_{Si}^2}} \quad (3)$$

where P_i denotes the average power of the relay i and *E[.]* represents an expectation operator. Selection of ε_i as in Eq. (3) ensures that an average output power is maintained [9].

The signal processing at terminal D must be delayed until the relays have transmitted signal sequences $z_{i,j}$. In order to avoid inter-symbol interference at the destination terminal, we assume that the time delay between the two propagation paths containing a relay is negligible. After collecting all signals from the relays, the D is to simply add the relays' received signals synchronously together with those from the source which are delayed a time-slot duration on the symbol-by-symbol basis. For further simplification, we drop the time indices. Then the signal sequence of 4 consecutive symbols received at the D are given explicitly by

$$r_1 = \underbrace{\left(-\alpha_{1D}z_{1,2} - \alpha_{2D}z_{2,3} + n_{D,1}\right)}_{\textit{from}\text{ relay 1 and relay 2 in the 2nd time-slot}} + \underbrace{\left(\varepsilon_0\alpha_{SD}x_1 + n_{SD,1}\right)}_{\textit{from}\text{ the source in the 1st time-slot}}$$
$$= \begin{pmatrix} -\alpha_{1D}\left[\varepsilon_1\left(\alpha_{S1}\varepsilon_0 x_2 + n_{S1,2}\right)\right] - \\ \alpha_{2D}\left[\varepsilon_2\left(\alpha_{S2}\varepsilon_0 x_3 + n_{S2,3}\right)\right] + n_{D,1} \end{pmatrix} + \left(\varepsilon_0\alpha_{SD}x_1 + n_{SD,1}\right)$$
$$= \varepsilon_0\alpha_{SD}x_1 - \varepsilon_0\varepsilon_1\alpha_{1D}\alpha_{S1}x_2 - \varepsilon_0\varepsilon_2\alpha_{2D}\alpha_{S2}x_3 - \alpha_{1D}\varepsilon_1 n_{S1,2} - \alpha_{2D}\varepsilon_2 n_{S2,3} + n_{SD,1} + n_{D,1} \qquad (4a)$$

$$r_2 = \left(\alpha_{1D}z_{1,1} + \alpha_{2D}z_{2,4} + n_{D,2}\right) + \left(\varepsilon_0\alpha_{SD}x_2 + n_{SD,2}\right)$$
$$= \begin{pmatrix} \alpha_{1D}\left[\varepsilon_1\left(\alpha_{S1}\varepsilon_0 x_1 + n_{S1,1}\right)\right] + \\ \alpha_{2D}\left[\varepsilon_2\left(\alpha_{S2}\varepsilon_0 x_4 + n_{S2,4}\right)\right] + n_{D,2} \end{pmatrix} + \left(\varepsilon_0\alpha_{SD}x_2 + n_{SD,2}\right)$$
$$= \varepsilon_0\alpha_{SD}x_2 + \varepsilon_0\varepsilon_1\alpha_{1D}\alpha_{S1}x_1 + \varepsilon_0\varepsilon_2\alpha_{2D}\alpha_{S2}x_4 + \alpha_{1D}\varepsilon_1 n_{S1,1} + \alpha_{2D}\varepsilon_2 n_{S2,4} + n_{SD,2} + n_{D,2} \qquad (4b)$$

$$r_3 = \left(-\alpha_{1D}z_{1,4} + \alpha_{2D}z_{2,1} + n_{D,3}\right) + \left(\varepsilon_0\alpha_{SD}x_3 + n_{SD,3}\right)$$
$$= \begin{pmatrix} -\alpha_{1D}\left[\varepsilon_1\left(\alpha_{S1}\varepsilon_0 x_4 + n_{S1,4}\right)\right] + \\ \alpha_{2D}\left[\varepsilon_2\left(\alpha_{S2}\varepsilon_0 x_1 + n_{S2,1}\right)\right] + n_{D,3} \end{pmatrix} + \left(\varepsilon_0\alpha_{SD}x_3 + n_{SD,3}\right)$$
$$= \varepsilon_0\alpha_{SD}x_3 - \varepsilon_0\varepsilon_1\alpha_{1D}\alpha_{S1}x_4 + \varepsilon_0\varepsilon_2\alpha_{2D}\alpha_{S2}x_1 - \alpha_{1D}\varepsilon_1 n_{S1,4} + \alpha_{2D}\varepsilon_2 n_{S2,1} + n_{SD,3} + n_{D,3} \qquad (4c)$$

$$r_4 = \left(\alpha_{1D}z_{1,3} - \alpha_{2D}z_{2,2} + n_{D,4}\right) + \left(\varepsilon_0\alpha_{SD}x_4 + n_{SD,4}\right)$$
$$= \begin{pmatrix} \alpha_{1D}\left[\varepsilon_1\left(\alpha_{S1}\varepsilon_0 x_3 + n_{S1,3}\right)\right] - \\ \alpha_{2D}\left[\varepsilon_2\left(\alpha_{S2}\varepsilon_0 x_2 + n_{S2,2}\right)\right] + n_{D,4} \end{pmatrix} + \left(\varepsilon_0\alpha_{SD}x_4 + n_{SD,4}\right)$$
$$= \varepsilon_0\alpha_{SD}x_4 + \varepsilon_0\varepsilon_1\alpha_{1D}\alpha_{S1}x_3 - \varepsilon_0\varepsilon_2\alpha_{2D}\alpha_{S2}x_2 + \alpha_{1D}\varepsilon_1 n_{S1,3} - \alpha_{2D}\varepsilon_2 n_{S2,2} + n_{SD,4} + n_{D,4} \qquad (4d)$$

where a_{mD} are path gains of the channels between relay m and the destination D; $m=1, 2$.

In the above expressions, n_{Dj} is an additive noise sample at the destination in j^{th} symbol duration of time slot 2. The quantities n_{Dj} are modeled as zero-mean complex Gaussian random variables (ZMCGRVs) with variance σ_{SD}^2. Also, due to the assumption of slow and flat Rayleigh fading, a_{mD} are Rayleigh-distributed random variables with average fading powers λ_{mD}^2.

To take the effect of path loss into account, we reuse the same model as discussed in [14] where

$$\lambda_{ij}^2 = \left(\frac{d_{SD}}{d_{ij}}\right)^{\beta}$$

Here d_{ij} is the distance between transmitter i and receiver j and β is the path loss exponent. For free-space path loss, we have $\beta=2$ and only this case is considered in the sequel.

We can rewrite the received signals r_j in more compact forms as

$$r_1 = h_1x_1 - h_2x_2 - h_3x_3 + n_1 \qquad (5a)$$

$$r_2 = h_1x_2 + h_2x_1 + h_3x_4 + n_2 \qquad (5b)$$

$$r_3 = h_1x_3 - h_2x_4 + h_3x_1 + n_3 \qquad (5c)$$

$$r_4 = h_1x_4 + h_2x_3 - h_3x_2 + n_4 \qquad (5d)$$

by letting

$$h_1 = \varepsilon_0\alpha_{SD} \qquad (6a)$$

$$h_2 = \varepsilon_0\varepsilon_1\alpha_{1D}\alpha_{S1} \qquad (6b)$$

$$h_3 = \varepsilon_0\varepsilon_2\alpha_{2D}\alpha_{S2} \qquad (6c)$$

$$n_1 = -\alpha_{1D}\varepsilon_1 n_{S1,2} - \alpha_{2D}\varepsilon_2 n_{S2,3} + n_{SD,1} + n_{D,1} \qquad (6d)$$

$$n_2 = \alpha_{1D}\varepsilon_1 n_{S1,1} + \alpha_{2D}\varepsilon_2 n_{S2,4} + n_{SD,2} + n_{D,2} \qquad (6e)$$

$$n_3 = -\alpha_{1D}\varepsilon_1 n_{S1,4} + \alpha_{2D}\varepsilon_2 n_{S2,1} + n_{SD,3} + n_{D,3} \qquad (6f)$$

$$n_4 = \alpha_{1D}\varepsilon_1 n_{S1,3} - \alpha_{2D}\varepsilon_2 n_{S2,2} + n_{SD,4} + n_{D,4} \qquad (6g)$$

Due to the fact that all additive noise r.v.'s are mutually independent of each other, conditional on the channel attenuations, n_j (j=1, 2, 3, 4) are also independent ZMCGRVs with the same variance

$$\sigma_n^2 = \alpha_{1D}^2\varepsilon_1^2\sigma_{S1}^2 + \alpha_{2D}^2\varepsilon_2^2\sigma_{S2}^2 + 2\sigma_{SD}^2$$
$$= a\varepsilon_1^2\sigma_{S1}^2 + b\varepsilon_2^2\sigma_{S2}^2 + 2\sigma_{SD}^2 \qquad (7)$$

where $a=\alpha_{1D}^2$, $b=\alpha_{2D}^2$ are exponentially distributed r.v.'s with mean values $\lambda_{1D}^2, \lambda_{2D}^2$; that is, $f_a(a)=\lambda_a e^{-\lambda_a a}$, $f_b(b)=\lambda_b e^{-\lambda_b b}$ in which a, b $\geq$ 0 and $\lambda_a=1/\lambda_{1D}^2$, $\lambda_b=1/\lambda_{2D}^2$, are pdf's of r.v.'s a, b, respectively.

Eq. (5) is actually equivalent to the analytical expressions of the STBC of code rate $\frac{3}{4}$ with transmission matrix given by

$$\begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2 & x_1 & -x_4 & x_3 \\ -x_3 & x_4 & x_1 & -x_2 \end{bmatrix}$$

As a consequence, the maximum likelihood decoding can be applied and results in the decision statistics for the transmitted signals x_i as [15]

$$\bar{x}_i = \sum_{j\in\chi(i)} sig_j(i) r_j h_{\phi_j(i)} \quad (8)$$

where i= 1, 2, 3, 4; $\chi(i)$ is the set of columns of the transmission matrix in which x_i appears; $Ø_j(i)$ represents the row position of x_i in the j^{th} column and the sign of x_i in the j^{th} column is denoted by $sig_j(i)$. Specifically, we have

$$\begin{aligned}\bar{x}_1 &= r_1h_1 + r_2h_2 + r_3h_3 \\ &= \left(h_1^2+h_2^2+h_3^2\right)x_1 + h_1n_1 + h_2n_2 + h_3n_3 \\ &= \lambda x_1 + N_1 \end{aligned} \quad (9a)$$

$$\begin{aligned}\bar{x}_2 &= -r_1h_2 + r_2h_1 - r_4h_3 \\ &= \left(h_1^2+h_2^2+h_3^2\right)x_2 - h_2n_1 + h_1n_2 - h_3n_4 \\ &= \lambda x_2 + N_2 \end{aligned} \quad (9b)$$

$$\begin{aligned}\bar{x}_3 &= -r_1h_3 + r_3h_1 + r_4h_2 \\ &= \left(h_1^2+h_2^2+h_3^2\right)x_3 - h_3n_1 + h_1n_3 + h_2n_4 \\ &= \lambda x_3 + N_3 \end{aligned} \quad (9c)$$

$$\begin{aligned}\bar{x}_4 &= r_2h_3 - r_3h_2 + r_4h_1 \\ &= \left(h_1^2+h_2^2+h_3^2\right)x_4 + h_3n_2 - h_2n_3 + h_1n_4 \\ &= \lambda x_4 + N_4 \end{aligned} \quad (9d)$$

Here

$$\begin{aligned} N_1 &= h_1n_1 + h_2n_2 + h_3n_3 \\ N_2 &= -h_2n_1 + h_1n_2 - h_3n_4 \\ N_3 &= -h_3n_1 + h_1n_3 + h_2n_4 \\ N_4 &= h_3n_2 - h_2n_3 + h_1n_4 \end{aligned}$$

$$\begin{aligned}\lambda &= h_1^2 + h_2^2 + h_3^2 \\ &= u + v + k \end{aligned}$$

$$u = \varepsilon_0^2\alpha_{SD}^2 \quad (10a)$$

$$v = \varepsilon_0^2\varepsilon_1^2\alpha_{1D}^2\alpha_{S1}^2 = \varepsilon_0^2\varepsilon_1^2 a\alpha_{S1}^2 \quad (10b)$$

$$k = \varepsilon_0^2\varepsilon_2^2\alpha_{2D}^2\alpha_{S2}^2 = \varepsilon_0^2\varepsilon_2^2 b\alpha_{S2}^2 \quad (10c)$$

Eq. (9) shows that the proposed cooperative transmission protocol can provide exactly performance as the 3-level receive maximum ratio combining.

It is straightforward to infer that N_j (j=1,2,3,4) is also independent ZMCGRVs, given the channel realizations, with the same variance

$$\sigma_N^2 = \lambda\sigma_n^2 \quad (11)$$

By observing Eq. (9), we find that x_j are attenuated and corrupted by the same fading and noisy level, their error probability is equal. As a result, BER (bit error rate) of x_1 is sufficient to evaluate the performance of system. For BPSK transmission, the recovered bit of x_1 is given by

$$\hat{x}_1 = sign\left(\mathrm{Re}\{\bar{x}_1\}\right)$$

where $sign$(.) is a signum function and Re{.} is the real part of a complex number.

Then the error probability of x_1 conditional on channel realizations is easily found as

$$P_e = Q\left(\sqrt{2\gamma}\right) \quad (12)$$

where $\gamma = \lambda^2/\sigma_N^2 = \lambda/\sigma_n^2$ can be interpreted as the signal-to-noise ratio at the output of Gaussian channel.

To find the average error probability, we must know the pdf of γ. Expressing γ explicitly results in the following formula

$$\gamma = \frac{\lambda}{\sigma_n^2} = \frac{u+v+k}{\sigma_n^2}$$

Since σ_n^2 is a function of only two r.v.'s a and b, we can find the pdf of u+v+k given a and b. From Eq. (10), we realize that u, v and k have exponential distribution with mean values $\varepsilon_0^2\lambda_{SD}^2$, $\varepsilon_0^2\varepsilon_1^2 a\lambda_{S1}^2$, $\varepsilon_0^2\varepsilon_2^2 b\lambda_{S2}^2$; that is, $f_u(u)=\lambda_u e^{-\lambda_u u}$, $f_v(v)=\lambda_v e^{-\lambda_v v}$, $f_k(k)=\lambda_k e^{-\lambda_k k}$ in which $\lambda_u = 1/\left(\varepsilon_0^2\lambda_{SD}^2\right)$, $\lambda_v = 1/\left(\varepsilon_0^2\varepsilon_1^2 a\lambda_{S1}^2\right)$, $\lambda_k = 1/\left(\varepsilon_0^2\varepsilon_2^2 b\lambda_{S2}^2\right)$ and u, v, k≥0, are pdf's of r.v.'s u, v, k, correspondingly.

The pdf of w=u+v is computed by using convolution theorem

$$f_{u+v}(w)=\int_0^w \lambda_u e^{-\lambda_u x_1}\lambda_v e^{-\lambda_v(w-x_1)}dx_1=\frac{\lambda_u\lambda_v}{\lambda_u-\lambda_v}\left[e^{-\lambda_v w}-e^{-\lambda_u w}\right]$$

Then repeating that process, we can obtain the pdf of $\lambda=w+k$ as

$$\begin{aligned}f_\lambda(\lambda)&=f_{u+v}(\lambda)\circ f_k(\lambda)\\&=\left[\frac{\lambda_u}{\lambda_u-\lambda_v}\lambda_v e^{-\lambda_v\lambda}-\frac{\lambda_v}{\lambda_u-\lambda_v}\lambda_u e^{-\lambda_u\lambda}\right]\circ\left(\lambda_k e^{-\lambda_k\lambda}\right)\\&=\frac{\lambda_u}{\lambda_u-\lambda_v}\frac{\lambda_v\lambda_k}{\lambda_v-\lambda_k}\left[e^{-\lambda_k\lambda}-e^{-\lambda_v\lambda}\right]-\frac{\lambda_v}{\lambda_u-\lambda_v}\frac{\lambda_u\lambda_k}{\lambda_u-\lambda_k}\left[e^{-\lambda_k\lambda}-e^{-\lambda_u\lambda}\right]\\&=\frac{\lambda_u\lambda_v\lambda_k\left[e^{-\lambda_k\lambda}(\lambda_u-\lambda_v)-e^{-\lambda_v\lambda}(\lambda_u-\lambda_k)+e^{-\lambda_u\lambda}(\lambda_v-\lambda_k)\right]}{(\lambda_u-\lambda_v)(\lambda_v-\lambda_k)(\lambda_u-\lambda_k)}\end{aligned}\tag{13}$$

where is the convolution operator.

Finally, the pdf of γ given a and b is easily found as

$$f_{\gamma|a,b}(\gamma|a,b)=\frac{\sigma_n^2\lambda_u\lambda_v\lambda_k}{(\lambda_u-\lambda_v)(\lambda_v-\lambda_k)(\lambda_u-\lambda_k)}\begin{bmatrix}e^{-\lambda_k\sigma_n^2\gamma}(\lambda_u-\lambda_v)-\\e^{-\lambda_v\sigma_n^2\gamma}(\lambda_u-\lambda_k)+\\e^{-\lambda_u\sigma_n^2\gamma}(\lambda_v-\lambda_k)\end{bmatrix}$$

Now we can calculate the average error probability as follows

$$P_{eAVG}=\int_0^\infty\int_0^\infty\left[\int_0^\infty P_e f_{\gamma|a,b}(\gamma|a,b)d\gamma\right]f_a(a)f_b(b)dadb\tag{14}$$

where the integral inside the square bracket can be reduced as

$$\begin{aligned}&\int_0^\infty Q(\sqrt{2\gamma})\sigma_n^2\lambda_k e^{-\lambda_k\sigma_n^2\gamma}\frac{\lambda_u\lambda_v}{(\lambda_v-\lambda_k)(\lambda_u-\lambda_k)}d\gamma-\\&\int_0^\infty Q(\sqrt{2\gamma})\sigma_n^2\lambda_v e^{-\lambda_v\sigma_n^2\gamma}\frac{\lambda_u\lambda_k}{(\lambda_u-\lambda_v)(\lambda_v-\lambda_k)}d\gamma+\\&\int_0^\infty Q(\sqrt{2\gamma})\sigma_n^2\lambda_u e^{-\lambda_u\sigma_n^2\gamma}\frac{\lambda_v\lambda_k}{(\lambda_u-\lambda_v)(\lambda_u-\lambda_k)}d\gamma\\&=\frac{\lambda_u\lambda_v}{2(\lambda_v-\lambda_k)(\lambda_u-\lambda_k)}\left[1-\sqrt{\frac{1}{1+\sigma_n^2\lambda_k}}\right]-\\&\frac{\lambda_u\lambda_k}{2(\lambda_u-\lambda_v)(\lambda_v-\lambda_k)}\left[1-\sqrt{\frac{1}{1+\sigma_n^2\lambda_v}}\right]+\\&\frac{\lambda_v\lambda_k}{2(\lambda_u-\lambda_v)(\lambda_u-\lambda_k)}\left[1-\sqrt{\frac{1}{1+\sigma_n^2\lambda_u}}\right]\end{aligned}\tag{15}$$

By replacing the term in Eq. (15) into Eq. (14), we obtain the closed-form BER expression for the proposed cooperative transmission scheme. The integrals in Eq. (15) can be approximated as sums [16].

For the case of non-cooperation (without relays), the average BER is given by [17]

$$P_{en\_avg}=\frac{1}{2}\left[1-\sqrt{\frac{P_S\lambda_{SD}^2/\sigma_{SD}^2}{1+P_S\lambda_{SD}^2/\sigma_{SD}^2}}\right]\tag{16}$$

3. Numerical Results

For a fair comparison, it is essential that the total consumed energy of the cooperative system does not exceed that of corresponding direct transmission system. This is a strict and conservative constraint; allowing the relays to add additional power can then only increase the attractiveness of cooperation. Therefore, complying this energy constraint requires $P_1=P_2=P_S/2$.

Monte Carlo simulations are performed to verify the accuracy of the closed-form BER expression in Eq. (14). The results are shown in Fig. 2 where the locations of entities in the network are depicted in Fig. 3 and D1=D2=0.5. The direct path length S-D is normalized to be 1 and the angle between the S-D path and S-R_1 (or S-R_2) path is h^0. In addition, the noise variances at the relays and destination are set to be equal $\sigma_{SD}^2=\sigma_{S1}^2=\sigma_{S2}^2=1$. In all relevant figures, the x-axis represents the global signal-to-noise ratio $SNR=P_S/\sigma_{SD}^2$.

Fig. 2 reveals that the simulation results are consistent with the theoretical ones in Eq. (14). This proves that the analysis is completely exact. Also, Fig. 2 compares the performance between non-cooperation and the proposed collaboration with respect to different relay positions. We find that the network geometry which is closely related to the path-loss significantly impacts on the quality of the received signal. Scenarios where the relays lie near the direct link S-D ($h\le 60^0$) provide the considerable benefit for the cooperation over the whole range of SNR since the cooperation achieves both possible advantages of spatial diversity (diversity order of 3) and path loss reduction in comparison to the direct transmission. Moreover, because the slope of BER curve of the cooperative scheme is steeper than that of non-cooperation, the BER enhancement keeps dramatically increasing proportionally to the increase in SNR. However in other cases where the relays are far away from the source and the destination, the cooperation can be negligibly beneficial or even worse than the direct transmission. As an illustration, the case of $h=80^0$ shows the cooperation's inferiority to non-cooperation for the low values of SNR.

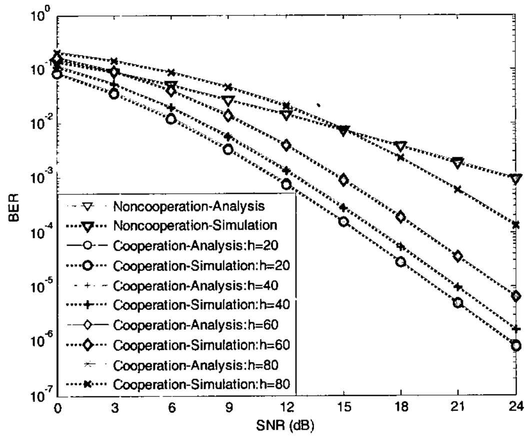

Fig. 2 BER performance of the proposed model for D1 = D2 = 0.5

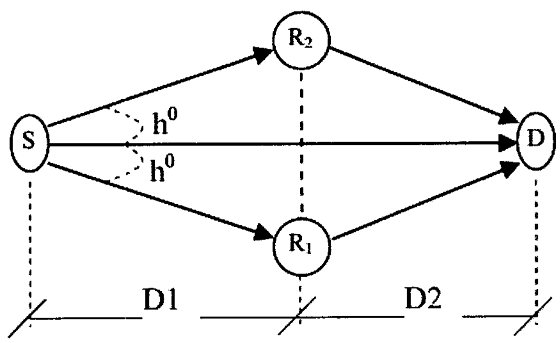

Fig. 3 Network geometry for BER evaluation in Fig. 2

Cooperation performances for some typical relay positions D1=0.1 (both relays are on the half plane close to the source) and D1=0.9 (both relays are on the half plane close to the destination) are demonstrated in Figs. 4 and 5, respectively. For D1=0.1, the cooperation is superior to the non-cooperation over the whole range of SNR and for any h. In addition, the cooperation performance is slightly degraded with respect to h. However as D1 increases (D1=0.9), the cooperation is significantly deteriorated with h and even is worse than non-cooperation for h greater than 60^0 at the low SNRs. This comes from the fact that when the relays are far away from the source, the path loss increases and the noise amplification at relays is considerably enhanced, leading to the performance degradation at the destination.

In general, the relaying cooperation is usually expected to reduce the path loss, corresponding to the situation that the relays are placed closely to the source or the destination, and make use of spatial diversity at most. Therefore, it is better to cooperate with the relays on the direct link S-D. Fig. 6 investigates the performance degradation of collaborative communications in the signal attenuation due to the path loss when the relays move apart from the source (*L1* and *L2* change where L1=d_{SR1} and L2=d_{SR2}). It shows that the symmetric scenarios; that is, L1 approximates L2, such as (L1=0.1-L2=0.9), (L1=0.3-L2=0.6), (L1=0.3-L2=0.7) and (L1=0.5-L2=0.5), offers the better performance for the cooperation than the others ((L1=0.1-L2=0.3), (L1=0.1-L2=0.5) and (L1=0.1-L2=0.6)). Although the performance is deteriorated due to inappropriate locations of relays, the cooperation always outperforms non-cooperation for any value of SNR.

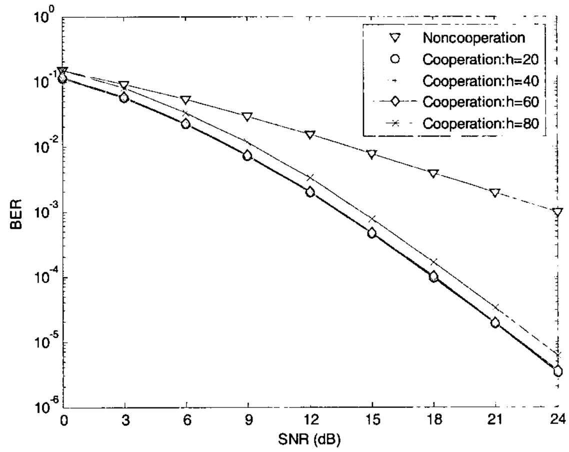

Fig. 4 BER performance of the proposed model for D1 = 0.1

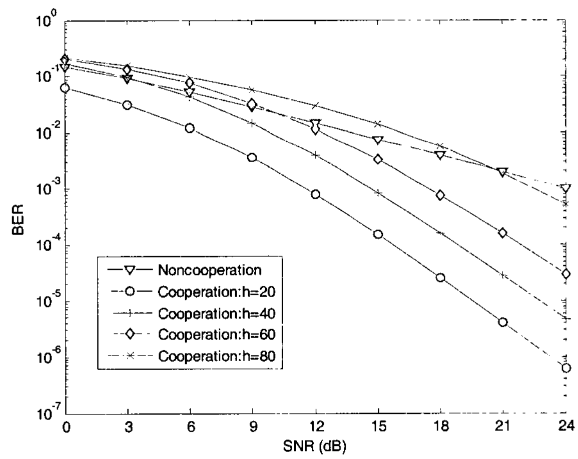

Fig. 5 BER performance of the proposed model for D1 = 0.9

4. Conclusion

Performance analysis of the $\frac{3}{4}$-rate STBC in the cooperative transmission scenario was presented and its closed-form error probability expression was also derived. Under the Rayleigh fading channel plus Gaussian noise, the numerical results demonstrate that the proposed cooperation considerably improves the performance over the non-cooperation regardless of the faded noisy inter-user channels. Moreover, the receiver structure with ML detector can be implemented with negligible hardware complexity. Therefore, deploying STBCs in the distributed diversity manner is feasible and is a promising technique for the future wireless networks where there exist idle users to take advantage of system resources efficiently.

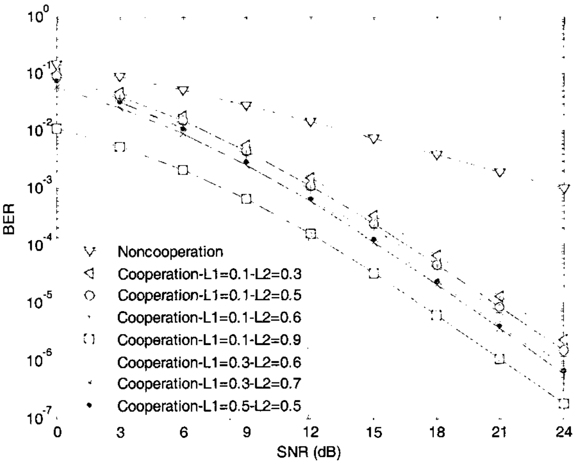

Fig. 6 Performance comparison between non-cooperation and proposed model with relays on the direct path

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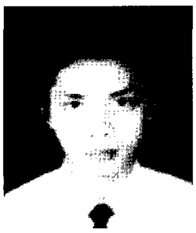


Ho Van Khuong

e-mail : khuongho21@yahoo.com

2001년 베트남 HoChiMinh City University of Technology 전기전자공학과(학사)

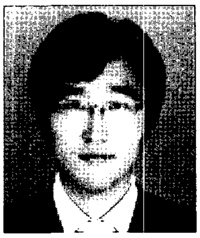
2003년 베트남 HoChiMinh City University of Technology 전기전자공학과(석사)

2004년~현재 울산대학교 전기전자정보시스템공학과 박사과정

관심분야 : OFDM, MC-CDMA, 협력 통신, 채널 추정

공 형 윤

e-mail : hkong@mail.ulsan.ac.kr
1989년 미국 New York Institute of Technology 전자공학과(학사)
1991년 미국 Polytechnic University 전자공학과(석사)
1996년 미국 Polytechnic University 전자공학과(박사)
1996년~1996년 LG전자 PCS 팀장
1996년~1998년 LG전자 회장실 전략사업단
1998년~현재 울산대학교 전기전자정보시스템공학부 부교수
관심분야 : 코딩(LDPC, Turbo) 및 모듈레이션 (OFDM, QAM), 멀티코드, Wireless Sensor Network 등



최 정 호

e-mail : k9813013@mail.ulsan.ac.kr
2005년 울산대학교 전기전자정보시스템공학부(학사)
2005년~현재 울산대학교 전기전자정보시스템공학과 석사과정
관심분야 : OFDM, MC-CDMA, QAM, 멀티코드, 협력 통신