Relay-assisted Multiple Access Channel Protocol for Cooperative Diversity

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ABSTRACT

Cooperative diversity is a novel technique to improve diversity gains, capacity gains, and energy saving. This technique involves multiple terminals sharing resources in order to build a virtual antenna array in a distributed fashion. In this paper, we propose a multi-user cooperative diversity protocol called Relay-assisted Multiple Access Channel(R-MAC) that allows multiple source terminals to transmit their signals simultaneously and the relay terminal forwards the aggregated signal received from the source terminals to the destination terminal. The proposed protocol converts the distributed antenna channels into an effective MIMO channel by exploiting a relay, increasing both diversity gain and system throughput. We investigate the performance of the proposed protocol in terms of outage probability and diversity-multiplexing tradeoff where we assume block fading channel environment. Our simulation results show that the proposed protocol outperforms direct transmission in the high spectral efficiency regime where the conventional cooperative diversity protocols cannot outperform direct transmission.

Key Words : Cooperative diversity, Multiuser, Relay, Diversity-multiplexing tradeoff

Ⅰ. Introduction

In wireless networks, signal fading can be mitigated by various diversity techniques such as those of time, frequency, and space diversity. Cooperative diversity is a novel technique to overcome the drawbacks of spatial limitations and correlation in multiple antenna systems.

The idea of cooperative diversity for wireless networks was initially introduced by Sendonaris et al.[1] where two transmitters retransmit the received signal from the other transmitters by repetition. It was shown that the achievable rate region in cooperative diversity can been larged than that in non-cooperative system. Protocols in [1], [2] are based on the full duplex constraint which allows a terminal to receive and transmit data simultaneously in the same frequency band. However, Such RF devices are hard to be implemented in current practical systems. Hence, the most practical cooperative diversity systems take into account protocols based on half duplex constraint [3]-[6]. Laneman et al. [3] analyzed the performance of a half-duplex orthogonal protocols in terms of outage behavior and diversity gain. The authors show that the full spatial diversity gain equal to the total number of antennas in the network can be achieved.

However, as noted in [3], the diversity gains diminished as the transmitted rates increased. More specifically, repetition forms of relaying in conventional protocols such as amplification or repetition coding causes SNR loss especially in the high spectral efficiency regime. In [3], the

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incremental relaying protocol which uses limited feedback to indicate the failure of transmission at the destination is proposed to avoid the drawbacks mentioned above. There are a number of papers which considered solutions to overcome such trade-off limitations. Authors of [4], [5] introduced different cooperative protocol which is spectral efficient, referred to as the non-orthogonal amplify-and-forward (NAF) protocol. Herein, while the relay terminal forwards processed data to the destination terminal in the second time slot, the source terminal continues to transmit independent data streams in the same time. In [5], it is shown that the diversity-multiplexing tradeoff performance of NAF scheme is better than that of Laneman's amplify-and-forward (AF) protocol. The performance enhancement comes from the fact that the source always keeps transmitting its own symbol while relay is transmitting, and MIMO approach. However, the only half of the data streams can obtain diversity gain by repetition via the relay terminal.

In this paper, we propose a multi-user cooperative diversity protocol which is superior to the conventional cooperative protocols which is designed for the single source and single relay fading channel. In the propose protocol, multiple source terminals transmit independent data streams in the same time and the relay terminal forwards the aggregated signals from both two source terminals to the destination terminal in an amplify-and-forward manner. This system model is equivalent to the Multiple Access Channel(MAC) in multiuser environment with additional relay node(R-MAC). We assumed delay-limited or nonergodic coherent channel which is the same assumption considered by Laneman, Tse, and Wornell (LTW) in [3]. We investigate the performance of our protocol in terms of outage probability and diversity-multiplexing tradeoff. And we also evaluate that performances in asymmetrical channel and with the effect of the relay position.

The rest of this paper is organized as follows. Section II shows the system model we assume. Section III introduces conventional cooperative protocols. We propose the multi-user cooperative diversity protocol in section IV. In Section V, we analyze the outage performance and Section VI shows the simulation results. We draw conclusion in Section VII.

Ⅱ. System Model

In our model, we assume Rayleigh flat fading channel with additive white Gaussian noise. The channel is quasi-static so that the channel gains remain constant during a coherence interval and change independently every coherence interval. Our analysis in Section V and VI focuses on the case of slow fading and measures performance by outage probability. Fig. 1 shows fading relay channel for cooperative diversity. Here, channel coefficients $h_{i,j}$, where i is transmit terminal and j is receive terminal, are zero-mean, circularly symmetric complex Gaussian random variables, such that $|h_{i,j}|^2$ are exponentially distributed with mean $\sigma_{i,j}^2$ and phases $\angle h_{i,j}$ are uniformly distributed over $[0, 2\pi)$. $h_{i,j}$ also includes path-loss, shadowing effects. Noises are modeled as zero-mean, mutually independent, circularly-symmetric, complex Gaussian random sequences with variance N_0. We assume that transmitters have no channel knowledge and receivers have perfect channel state information. For our cooperative protocol, all terminals are assumed to operate in half-duplex mode.

All terminals have a single antenna, and the same power constraint. That is, the total consumed energy of the cooperative system does not exceed that of direct transmission. No

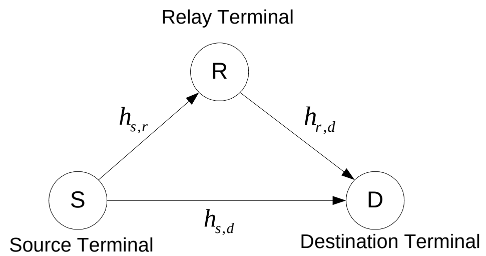

Fig 1. Schematic of fading relay channel

feedback to the source terminal is permitted. Perfect synchronization between cooperating terminals is considered possible.

Ⅲ. LTW-AF and NAF Cooperative Diversity

In this section, we introduce two conventional cooperative diversity protocols where only one source terminal transmits during the first time slot.

3.1 LTW-AF Cooperative Diversity Protocol

Cooperative protocols in this paper take place in two time slots. We assume symbol-by-symbol transmission, and the transmitted signal from the source terminal is denoted as x_i, where $i \in \{1,\ 2\}$ is an index of time slot. We assume that $E[x_i]=0$ and $E\left[|x_i|^2\right]=1$. n_j is additive white Gaussian noise, where $j \in \{1,\ 2,\ 3\}$ is an identifying index. In the LTW-AF cooperative diversity protocol, during the first time slot the source terminal communicates with the relay and destination terminals. The signal received at the destination terminal in the first time slot becomes

$$y_1 = h_{s,d}\sqrt{P_S}\,x_1 + n_1 \tag{1}$$

where PS is the transmit signal power over one symbol period through the source to destination channel. The relay terminal receives signal in the first time slot according to

$$r = h_{s,r}\sqrt{P_S}\,x_1 + n_2 \tag{2}$$

In the second time slot, only the relay terminal communicates with the destination terminal. The relay terminal amplifies the received signal by relay repetition gain and forwards it to the destination terminal. The signal received at the destination terminal during the second time slot is given by

$$y_2 = h_{r,d}\beta r + n_3 = h_{r,d}\beta h_{s,r}\sqrt{P_S}\,x_1 + h_{r,d}\beta n_2 + n_3 \tag{3}$$

In (3), β denotes the relay repetition gain expressed as

$$\beta = \sqrt{\frac{P_R}{P_S\left|h_{s,r}\right|^2 + N_0}} \tag{4}$$

where P_R is the transmit signal power of the relay terminal and N_0 is noise variance [3].

The destination terminal decodes symbols using both two received signals during the first and second time slots. The effective input-output relation for LTW-AF protocol can be rewritten as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \underbrace{\begin{bmatrix} h_{s,d} \\ h_{s,r}\beta h_{s,r} \end{bmatrix}}_{\mathbf{H}}\sqrt{P_S}\,x_1 + \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & h_{s,r}\beta & 1 \end{bmatrix}}_{\mathbf{N}}\begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix} \tag{5}$$

As shown in [3], the instantaneous capacity of LTW-AF protocol is derived as

$$C = \frac{1}{2}\log_2 \det(\mathbf{I}_2 + \frac{1}{N_0}\mathbf{H}\mathbf{H}^{\mathbf{H}}\left(\mathbf{N}\mathbf{N}^{\mathbf{H}}\right)^{-1}) \tag{6}$$

where and are denoted in (5) and the factor explains the two time slots character of cooperative communication. The instantaneous capacity of (6) can be achieved when the transmitted signal xi is i.i.d. zero mean circularly symmetric complex Gaussian. The capacity of LTW-AF protocol can be written as [3]

$$C_{LTW-AF} = \log\left(1 + \frac{P_s\left|h_{s,d}\right|^2}{N_0} + \frac{P_S\left|h_{r,d}\beta h_{s,r}\right|^2}{N_0\left(\left|h_{r,d}\beta\right|^2 + 1\right)}\right) \tag{7}$$

The LTW-AF protocol converts the spatially distributed antenna channel into an effective SIMO channel. Although signal via source to destination channel is deeply faded, the destination terminal can decode signal successfully through relay channel. Therefore this protocol can obtain spatial diversity gain of 2. However, LTW-AF protocol sacrifices spectral efficiency to obtain diversity benefits as employing repetition-based relaying.

3.2 NAF Cooperative Diversity Protocol

In the NAF protocol, the source terminal is allowed to continue transmission over the both time slots, whereas in the LTW-AF protocol the source terminal stops its transmission in the second time slot. For fair comparison, we impose power constraint during the second time slot. That is, the sum of the source power $P_{S,2}$ and the relay power P_R is set to the relay power of LTW-AF protocol during the second time slot, i.e.

$$P_{S,2}^{\text{NAF}} + P_R^{\text{NAF}} = P_R^{\text{LTW-AF}} \quad (8)$$

During the first time slot, the received signals at the relay and destination terminals are the same as those in the LTW-AF protocol. The signal received at the destination during the second time slot is given by

$$\begin{aligned} y_2 &= h_{r,d}\beta r + h_{s,d}\sqrt{P_{S,2}}x_2 + n_3 \\ &= h_{r,d}\beta h_{s,r}\sqrt{P_{S,1}}x_1 + h_{s,d}\sqrt{P_{S,2}}x_2 + h_{r,d}\beta n_2 + n_3 \end{aligned} \quad (9)$$

The effective input-output relation in NAF can be seen as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \underbrace{\begin{bmatrix} h_{s,d}\sqrt{P_{S,1}} & 0 \\ h_{s,r}\beta h_{s,r}\sqrt{P_{S,1}} & h_{s,d}\sqrt{P_{S,2}} \end{bmatrix}}_{\mathbf{H}} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & h_{s,r}\beta & 1 \end{bmatrix}}_{\mathbf{N}} \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix} \quad (10)$$

The instantaneous capacity of NAF protocol can be calculated through (6).

The NAF cooperative protocol converts the spatially distributed antenna system into effective MIMO channel in contrast to that of LTW-AF protocol. This protocol can obtain spatial diversity gain of 2 with lower spectral efficiency loss through continuous-transmitting source terminal. Therefore, NAF protocol outperforms LTW-AF in terms of the diversity-multiplexing tradeoff [5]. However, since only the first half of the symbols is relayed, the other symbols cannot be beneficial of cooperative diversity.

Ⅳ. Multi-User Cooperative Diversity

The cooperative protocols in the previous section allow only one source terminal to broadcast to a relay terminal and a destination terminal. We propose R-MAC, the multi-user

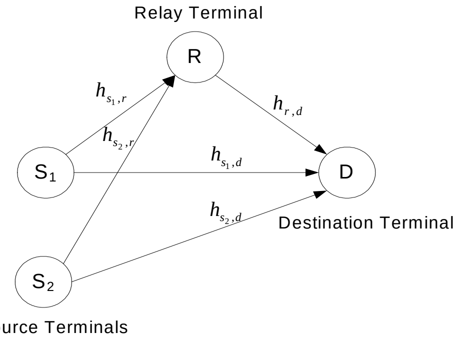

Fig 2. Schematic of fading multi-user cooperative channel

cooperative diversity protocol in which multiple source terminals transmit their independent data streams simultaneously. The relay terminal forwards the aggregated signals from two source terminals to the destination terminal in the amplify-and-forward manner. The source terminals do not continue their transmission in the second time slot. Fig. 2 illustrates the schematic of this multi-user cooperative channel.

During the first time slot, two source terminals transmit their independent data to both relay and destination terminals. The signals transmitted by the source terminals during the first time slot are denoted as s_1 and s_2. We assume $E[s_i]=0$, and $E\left[|s_i|^2\right]=1$, where $i \in \{1, 2\}$ indicates the index of the source terminals. The signal received at the destination terminal in the first time slot is given by

$$y_1 = h_{s_1,d}\sqrt{P_{S_1}}s_1 + h_{s_2,d}\sqrt{P_{S_2}}s_2 + n_1 \quad (11)$$

where P_{S1}, and P_{S2} are the transmit power of source terminals. To ensure fair comparison, the total sum transmit power of both source terminals is equal to that of source power in LTW-AF and NAF cooperative protocol during the first time slot. That is,

$$P_{S_1}^{\text{MU}} + P_{S_2}^{\text{MU}} = P_S^{\text{LTW-AF}} = P_S^{\text{NAF}} \quad (12)$$

The signal received at the relay terminal during the first time slot is given by

$$r = h_{s_1,r}\sqrt{P_{S_1}}s_1 + h_{s_2,r}\sqrt{P_{S_2}}s_2 + n_2 \quad (13)$$

During the second time slot, the relay terminal amplifies the received signals by relay repetition gain and forwards them to the destination terminal while two source terminals stop their transmission. The relay repetition gain is

$$\beta = \sqrt{\frac{P_R}{P_{S_1}\left|h_{s_1,r}\right|^2 + P_{S_2}\left|h_{s_2,r}\right|^2 + N_0}} \quad (14)$$

The signal received at the destination during the second time slot is given by

$$y_2 = h_{r,d}\beta r + n_3$$
$$= h_{r,d}\beta h_{s_1,r}\sqrt{P_{S_1}}s_1 + h_{r,d}\beta h_{s_2,r}\sqrt{P_{S_2}}s_2 + h_{r,d}\beta n_2 + n_3 \quad (15)$$

The destination terminal decodes transmitted data using received signals during the first and second time slot. The effective input-output relation for multi-user cooperative diversity protocol can be seen as

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{s_1,d} & h_{s_2,d} \\ h_{r,d}\beta h_{s_1,r} & h_{r,d}\beta h_{s_2,r} \end{bmatrix} \begin{bmatrix} \sqrt{P_{S_1}}s_1 \\ \sqrt{P_{S_2}}s_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ h_{r,d}\beta n_2 + n_3 \end{bmatrix} \quad (16)$$

The instantaneous capacity of the multi-user cooperative diversity protocol cab be obtained by (6) where

$$\mathbf{H} = \begin{pmatrix} h_{s_1,d}\sqrt{P_{S_1}} & h_{s_2,d}\sqrt{P_{S_2}} \\ h_{r,d}\beta h_{s_1,r}\sqrt{P_{S_1}} & h_{r,d}\beta h_{s_2,r}\sqrt{P_{S_2}} \end{pmatrix}, \mathbf{N} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & h_{r,d}\beta & 1 \end{pmatrix} \quad (17)$$

and the transmitted signals s_1, and s_2 are i.i.d. zero mean circularly symmetric complex Gaussian. The multi-user cooperative diversity protocol converts the spatially distributed antenna system into an effective MIMO channel as in the NAF protocol. However, in contrast to the NAF protocol which transmits the independent data in different time slot, the R-MAC protocol makes both independent signals from multi-user go though the relay channel in order for both signals to obtain diversity gain.

It was shown in [5] that LTW-AF cooperative protocol cannot support multiplexing gains greater than 0.5 in terms of diversity-multiplexing trade-off because of the orthogonal transmission. However, the R-MAC protocol allows multiple source terminals to transmit simultaneously in the first time slot so that it supports the multiplexing gain of more than 0.5. Therefore, we anticipate that the instantaneous capacity of the R-MAC protocol is greater than LTW-AF protocol. Furthermore, the fact that both signals from multi-users obtain diversity gains via the relay channel makes the R-MAC protocol outperform the NAF protocol in the outage performance.

Ⅴ. Performance Analysys

In this section, we analyze outage performance of the R-MAC protocol in terms of diversity-multiplexing-tradeoff [10]. We can express the outage events Oi, and outage probabilities P_i, $i \in \{1,2,12\}$ as

$$P_1 = P[O_1] = \Pr[C_1 < R] = \Pr[I(x_1;\mathbf{y} \mid x_2) < R] \quad (18a)$$
$$P_2 = P[O_2] = \Pr[C_2 < R] = \Pr[I(x_2;\mathbf{y} \mid x_1) < R] \quad (18b)$$
$$P_{12} = P[O_{12}] = \Pr[C_{12} < 2R] = \Pr[I(x_1,x_2;\mathbf{y}) < 2R] \quad (18c)$$

where

$$I(x_1;\mathbf{y} \mid x_2) = \frac{1}{2}\log\det\left[\mathbf{I} + \rho\mathbf{h_1}\mathbf{h_1^H}\left(\mathbf{NN^H}\right)^{-1}\right]$$
$$I(x_2;\mathbf{y} \mid x_1) = \frac{1}{2}\log\det\left[\mathbf{I} + \rho\mathbf{h_2}\mathbf{h_2^H}\left(\mathbf{NN^H}\right)^{-1}\right]$$
$$I(x_1,x_2;\mathbf{y}) = \frac{1}{2}\log\det\left[\mathbf{I} + \rho\mathbf{HH^H}\left(\mathbf{NN^H}\right)^{-1}\right]$$

$\mathbf{h_i}$ denotes i th column of channel H and ρ denotes SNR. Since the outage event for the protocol can be given by the union of each outage events in (18a,b,c).

$$O \triangleq O_1 \cup O_2 \cup O_{12}$$

Then the outage probability of the protocol can be bounded as

$$P_i \le P_O \le P_1 + P_2 + P_{12} \quad (19)$$

where P_i can be either P_1, P_2 or P_{12}, and P_O is the outage probability of the protocol.

Recalling that the outage probability of the system is determined by the slowest decaying rate of the outage events[8,9] and using the result of [8] we can easily find that

$$d_O = d_1 \quad (20)$$

where the each diversity gain corresponds to P_O and P_1 respectively.
The diversity order is defined in [10]

$$d(r)=\lim_{\rho\to\infty}\frac{-\log P_{out}(r\log\rho)}{\log\rho} \qquad (21)$$

where $d(r)$ is a diversity gain and r is the multiplexing gain.
With the above definition of diversity-multiplexing gain, we can derive Lemma 1.

Lemma 1 : The proposed multi-user cooperative protocol R-MAC achieves diversity order of 2 which means

$$d_O=d_1=2 \qquad (22)$$

Proof : From (18a), we have

$$P_1=\Pr\left[\frac{1}{2}\log\left(1+\rho\left(a+\frac{cd}{\frac{1}{\rho}+c+d+e}\right)\right)<r\log\rho\right] \qquad (23)$$

where target rate $R=r\log\rho$ [10].
a, b, c, d and e are i.i.d exponential distribution random variables that corresponds to $|h_{s_1,d}|^2$, $|h_{s_2,d}|^2$, $|h_{r,d}|^2$, $|h_{s_1,r}|^2$ and $|h_{s_2,r}|^2$, respectively.
With the assumption of high SNR, P1isgivenby

$$P_1=\Pr\left[a+\frac{cd}{c+d+e}<\frac{\rho^{2r}-1}{\rho}\right] \qquad (24)$$

Since calculating diversity order from (24) is complicated, we adopt one assumption that

$$e=|h_{s_2,r}|^2=\text{constant} \qquad (25)$$

which means that the channel gain between user 2 and relay is fixed by certain value, not random variable.

By exploiting the the result of [3, (14)] with this assumption and the definition of diversity-multiplexing-tradeoff [10], outage probability P_1 is approximated as

$$P_1=\Pr[C_1<R]\approx\left(\frac{\rho^{2r}-1}{\rho}\right)^2 \qquad (26)$$

Then, (26) shows that this protocol yields a diversity-multiplexing tradeoff of

$$d(r)=2(1-2r) \qquad (27)$$

which is the same with the diversity-multiplexing tradeoff for the repetition scheme that transmits the same symbol from two transmit antenna at a time and (27) also shows that this protocol achieves diversity order of 2.

Ⅵ. Simulation Results

In previous section, the outage performance was analyzed in terms of diversity order and diversity-multiplexing tradeoff. In this section, then, we show the outage probability and SNR gain by simulation. In the case of the R-MAC protocol, we evaluate the outage probability per user. Note that, in the multi-user cooperative diversity protocol, we allocate half transmit power to each source terminal as compared to the power allocated to the source terminal in both LTW-AF and NAF cooperative diversity protocols. Fig. 3 illustrates the outage probability of direct transmission, LTW-AF, NAF, and the proposed multi-user cooperative protocols as a function of the average SNR for a spectral efficiency of $R=2\text{bps/Hz}$.

6.1 Outage Performance

For the cooperative protocol, the relay terminal is located halfway between the source and

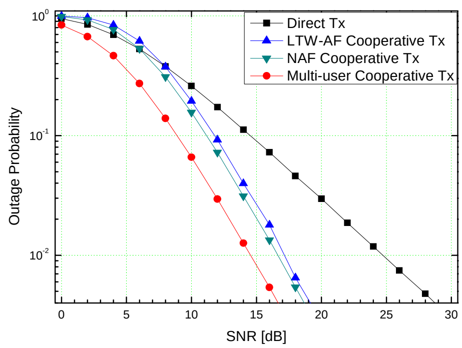

Fig. 3. Outage probability vs. SNR (Spectral efficiency R=2bps/Hz, Relay is located halfway between Source and Destination)

destination terminals. We can see that all cooperative diversity protocols achieve diversity gain of 2, in contrast to direct transmission which achieves a diversity gain of 1. Furthermore, the cooperative protocols have more SNR gain over direct transmission because it can exploit the pathloss saving using relay terminal. When $p_{out}=10^{-2}$, the SNR gain of LTW-AF over direct transmission is 7 dB, and that of NAF 8 dB. The proposed multi-user cooperative protocol has 10 dB SNR gain over direct transmission.

6.2 Spectral Efficiency

Fig. 4 illustrates the SNR gains of cooperative protocols over direct transmission as a function of the spectral efficiency. The conventional cooperative protocols have drawbacks which come from repetition based relaying.

In a high spectral efficiency regime, direct transmission outperforms these cooperative protocols since these protocols allocate resources in an orthogonal manner. We see that as the spectral efficiency increases, the SNR gain of LTW-AF and NAF decreases. Eventually these protocols have lower performance gain over direct transmission so that these protocols are not suitable for high spectral efficiency. However, the proposed R-MAC achieves SNR gains over direct transmission for a high spectral efficiency. This gain comes from two facts that multi-user transmission increase overall transmission rates and that both signals from source terminals can obtain diversity gains.

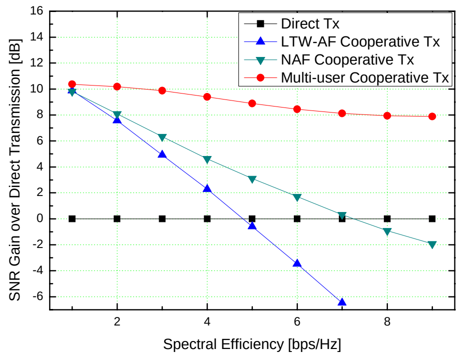

Fig. 4. SNR gain over direct transmission as a function of the spectral efficiency R ($p_{out}=10^{-2}$, Pathloss exponent = 3, Relay position = 0.5)

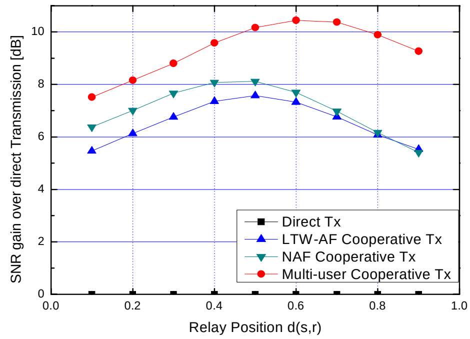

Fig. 5. SNR gain over direct transmission as a function of the spectral efficiency R ($p_{out}=10^{-2}$, Pathloss exponent = 3, Relay position = 0.5)

6.3 Relay Position

According to the position of the relay terminal, cooperative diversity can reduce end-to-end pathloss.

Fig. 5 illustrates the effect of the relay position on the SNR gain when the spectral efficiency is $R=2\text{bps/Hz}$ and outage probability is $p_{out}=10^{-2}$. The relay position is the distance between source and relay terminals is normalized by the distance between source and destination terminals,

$$d(s,r)=\frac{d_{s,r}}{d_{s,d}} \tag{28}$$

It shows that the quality of source-relay channel is dominant in the performance of NAF protocol, but the quality of relay-destination channel is

dominant in the performance of multi-user cooperation.

Ⅶ. Conclusion

In this paper, we developed a multi-user cooperative diversity protocol R-MAC that allows more than one source terminals to transmit each data stream simultaneously during the first time slot to exploit spatial diversity in the effective MIMO channel through user cooperation. We investigated the outage performance in terms of diversity-multiplexing tradeoff and diversity order and evaluated outage probability and SNR gain by simulation. It was shown that the proposed

R-MAC protocol achieved the SNR gain of 10 dB over direct transmission for a spectral efficiency of 2 bps/Hz at an outage probability of $p_{out} = 10^{-2}$. Furthermore, our simulations confirmed that the proposed multi-user cooperative diversity protocol achieved SNR gains over direct transmission even for high spectral efficiency.

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<관심분야> MIMO, Cooperative Communication, Network Coding

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