

Performance improvement by MRC combining with multiple relays and receives antennas in AF relay networks

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Abstract—Cooperative networking schemes provide cooperative diversity gain using differently located antennas that combat fadings induced by multipath propagation in wireless networks. In this paper, we present the optimal weight design for the destination in AF (Amplify and Forward) relay system, where the optimally designed MRC (Maximum Ratio Combining) is employed at the destination for $S \rightarrow D$ link (direct link between source and destination) and $R \rightarrow D$ links (indirect links between relays and destination). Simulation results are presented to verify our analysis.

Keywords—AF relay, MRC, diversity, multiple relays & antennas

I. INTRODUCTION

Wireless relaying is a promising solution to overcome the channel impairments and provides high data rate coverage that appears for the next generation mobile communications. Cooperative diversity networks have recently been proposed as a way to form virtual antenna arrays, using the neighbor relay nodes, and each relay assists the source by sending the source information to the destination to achieve spatial diversity [1]-[3].

Cooperative relaying has drawn considerable attention as an efficient strategy to enhance communication reliability in flat fading environments [4], [5]. Without a sort of signal regeneration like in Detect & Forward or Decode & Forward, an AF relay system simplifies relaying operation and is suited to many actual applications with less complexity.

In this paper, we derive the optimal MRC weights at destination using Lagrange multiplier method for the dual hop wireless communication system equipped with multiple AF relays and multiple receive antennas at destination over flat Rayleigh fading channel. We assume that a source node has single antenna, each relay has single antenna and a destination has multiple receive antennas. We compare the BER performance in case of QPSK modulation by varying the number of relays and receive antennas at destination. Although the channels between different nodes are modeled as flat Rayleigh fading channels, this means that each channel

is regarded as a subcarrier channel of OFDM modulation. The remainder of this paper is organized as follows. Section II presents the system model. In section III, we derive the optimal MRC weights at destination by using Lagrange multiplier method for the proposed AF relay system and analyze the receive SNR at destination. We show the simulation results in Section IV. The conclusions are given in section V. We illustrate some of the notations as follows: vectors and matrixes are expressed by bold letters, we use $[\bullet]^T$, $[\bullet]^*$ and $[\bullet]^H$ as transpose of matrix, conjugate of complex variable and transpose conjugate of matrix, respectively.

II. SYSTEM MODEL

We consider a dual-hop cooperative network system consisting of a source with single antenna, N relays equipped with single antenna, and a destination having L receive antennas as shown in Fig.1. Assuming the time division multiplexing scheme is employed, in the first time slot, the source transmits the signal to the relays through the channels denoted as $\mathbf{h}_{SR} \in \mathbb{C}^{N \times 1}$, $\mathbf{h}_{SR_j} \in \mathbf{h}_{SR}$, $j = 1, \dots, N$, ($S \rightarrow R$ links) and to the destination through $\mathbf{h}_{SD} \in \mathbb{C}^{L \times 1}$, ($S \rightarrow D$ link), respectively. In the k -th time slot ($k = 2, \dots, N$), the j -th relay forwards the amplified version of the received signal to the destination through $\mathbf{h}_{RD_j} \in \mathbb{C}^{L \times 1}$ ($R \rightarrow D$ link).

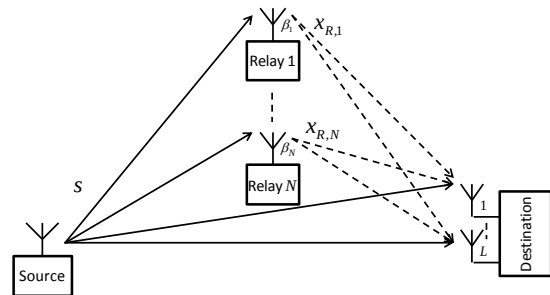


Fig.1. System model

In this paper, we assume that the elements of $\mathbf{h}_{SD}$, $\mathbf{h}_{SR}$ and $\mathbf{h}_{RD}$ are i.i.d. (independently and identically distributed)

complex Gaussian variables, because each flat Rayleigh channel corresponds to a subcarrier channel of wideband OFDM modulation and the OFDM can convert the quasi-static frequency selective Rayleigh fading channel to the flat Rayleigh fading channel at each subcarrier.

The receive signal x_{R_j} , ($j=1, \dots, N$) at the j -th relay and the receive signal vector $\mathbf{x}_D$ at the destination is expressed as

$$\begin{aligned} x_{R_j} &= h_{SR_j} \sqrt{P_s} s + n_{SR_j} \\ \mathbf{x}_D &= \left[\mathbf{h}_{SD}^T \quad \beta_1 \mathbf{h}_{SR_1,D}^T \cdots \beta_j \mathbf{h}_{SR_j,D}^T \cdots \beta_N \mathbf{h}_{SR_N,D}^T \right]^T \sqrt{P_s} s \\ &\quad + \left[\mathbf{n}_{SD}^T \quad \mathbf{n}_{SR_1,D}^T \cdots \mathbf{n}_{SR_j,D}^T \cdots \mathbf{n}_{SR_N,D}^T \right]^T \end{aligned} \quad (1)$$

where P_s is the transmit power at source, $\mathbf{h}_{SR_j,D} = h_{SR_j} \mathbf{h}_{R_j,D}$, $\mathbf{n}_{SR_j,D} = \beta_j n_{SR_j} \mathbf{h}_{R_j,D} + \mathbf{n}_{R_j,D}$. The elements of n_{SR_j} , $\mathbf{n}_{R_j,D}$ and $\mathbf{n}_{SD}$ are assumed to be i.i.d zero mean complex Gaussian random variable and vectors with variances of $\sigma^2 = E\{|n_{SR_j}|^2\}/2$ and the β_j is the amplification factor at the j -th relay.

III. OPTIMAL WEIGHT DESIGN AT DESTINATION

1. Optimal weight design with MRC

In this section, we derive the optimal receive weights by minimizing MSE (Mean Squared Error) under the power constraint. Without loss of generality, we assume $N=1$, $L=1$, $h_1 = h_{SR} \beta h_{RD}$, $h_2 = h_{SD}$. We also assume that w_1 and w_2 are the receive weights corresponding to h_1 and h_2 respectively.

The SNR at destination can be written as

$$\begin{aligned} SNR &= E \left\{ \frac{|[w_1 h_1 + w_2 h_2] s|^2}{|w_1 n_1 + w_2 n_2|^2} \right\} \\ &= E \left\{ \frac{|[w_1 h_1 + w_2 h_2] s|^2}{\left[(w_1 n_1 + w_2 n_2)(w_1 n_1 + w_2 n_2)^* \right]} \right\} \\ &= |w_1 h_1 + w_2 h_2|^2 E |s|^2 / (E(w_1 n_1 w_1^* n_1^*) + E(w_1 n_1 w_2^* n_2^*) \\ &\quad + E(w_2 n_2 w_1^* n_1^*) + E(w_2 n_2 w_2^* n_2^*)) \quad (2) \\ &= \frac{|w_1 h_1 + w_2 h_2|^2}{|w_1|^2 \sigma_1^2 + |w_2|^2 \sigma_2^2} \end{aligned}$$

where $n_1 = h_{RD} \beta n_{SR} + n_{RD}$, $n_2 = n_{SD}$ and $E|n_1| = \sigma_1^2$ and $E|n_2| = \sigma_2^2$.

Under the constraint condition of $|w_1|^2 \sigma_1^2 + |w_2|^2 \sigma_2^2 = c_1$ in the denominator in (2) where c_1 the arbitral is real constant, and by introducing Lagrange multiplier method, we obtain objective function to be maximized

$$\begin{aligned} h(w_1, w_2, \lambda) &= |w_1 h_1 + w_2 h_2|^2 - \lambda (|w_1|^2 \sigma_1^2 + |w_2|^2 \sigma_2^2 - c_1) \\ &= (w_1 h_1 + w_2 h_2)(w_1^* h_1^* + w_2^* h_2^*) - \lambda [w_1 w_1^* \sigma_1^2 + w_2 w_2^* \sigma_2^2 - c_1] \end{aligned}$$

$$= w_1 h_1 w_1^* h_1^* + w_1 h_1 w_2^* h_2^* + w_2 h_2 w_1^* h_1^* + w_2 h_2 w_2^* h_2^* - \lambda (w_1 w_1^* \sigma_1^2 - \lambda (w_2 w_2^* \sigma_2^2 - \lambda c_1) \quad (3)$$

By differentiating h with respect to w_1 , we get

$$\begin{aligned} \frac{\partial h}{\partial w_1} &= h_1 (w_1 h_1 + w_2 h_2)^* - \lambda w_1^* \sigma_1^2 \\ |h_1|^2 w_1^* + w_2^* h_2^* h_1 - \lambda w_1^* \sigma_1^2 &= 0 \\ w_1^* (|h_1|^2 - \lambda \sigma_1^2) &= -w_2^* h_2^* h_1 \end{aligned} \quad (4)$$

From equation (4) we obtain

$$\begin{aligned} w_1^* &= -\frac{h_1 h_2^*}{|h_1|^2 - \lambda \sigma_1^2} w_2^* = \alpha_1 w_2^* \\ \alpha_1 &= -\frac{h_1 h_2^*}{|h_1|^2 - \lambda \sigma_1^2} \end{aligned} \quad (5)$$

Also by differentiating h with respect to w_2 , we obtain

$$\begin{aligned} w_2^* &= -\frac{h_2 h_1^*}{|h_2|^2 - \lambda \sigma_2^2} w_1^* = \alpha_2 w_1^* \\ \alpha_2 &= -\frac{h_2 h_1^*}{|h_2|^2 - \lambda \sigma_2^2} \end{aligned} \quad (6)$$

Accordingly we have

$$\begin{aligned} w_1^* &= \alpha_1 w_2^*; w_2^* = \alpha_2 w_1^* \\ |w_1|^2 \sigma_1^2 + |w_2|^2 \sigma_2^2 - c_1 &= 0 \end{aligned} \quad (7)$$

From (7), λ is calculated as follows

$$\lambda = \frac{|h_1|^2 \sigma_2^2 + |h_2|^2 \sigma_1^2}{(\sigma_1 \sigma_2)^2} \quad (8)$$

Also the weights w_1 and w_2 are derived as follows

$$\begin{aligned} c_1 &= |w_1|^2 \sigma_1^2 + |w_2|^2 \sigma_2^2 \\ &= (w_1 w_1^*) \sigma_1^2 + (w_2 w_2^*) \sigma_2^2 \\ &= (w_1 w_1^*) \sigma_1^2 + (\alpha_2 w_1^*) (\alpha_2 w_1^*)^* \sigma_2^2 \\ &= (w_1 w_1^*) \sigma_1^2 + (w_1 w_1^*) \sigma_2^2 (\alpha_2 \alpha_2^*) \\ &= (w_1 w_1^*) (\sigma_1^2 + \sigma_2^2 (\alpha_2 \alpha_2^*)) \end{aligned} \quad (9)$$

and

$$\begin{aligned} w_1 w_1^* &= \frac{c_1 \left(\frac{|h_2|^2 \sigma_1^2 - |h_1|^2 \sigma_2^2 - |h_2|^2 \sigma_1^2}{\sigma_1^2} \right)^2}{\sigma_1^2 \left(\frac{|h_2|^2 \sigma_1^2 - |h_1|^2 \sigma_2^2 - |h_2|^2 \sigma_1^2}{\sigma_1^2} \right)^2 + \sigma_2^2 |h_2|^2 |h_1|^2} \end{aligned} \quad (10)$$

Consequently, by re-substituting w_1 into (4), we obtain

$$w_1 = \frac{\sqrt{c_1} h_1^* \sigma_2}{\sqrt{|h_1|^2 \sigma_2^2 \sigma_1^2 + (\sigma_1^2)^2 |h_2|^2}} \quad (11)$$

By using the symmetry condition, we also obtain

$$w_2 = \frac{\sqrt{c_1} h_2^* \sigma_1}{\sqrt{|h_2|^2 \sigma_1^2 \sigma_2^2 + (\sigma_2^2)^2 |h_1|^2}} \quad (12)$$

Returning to the beginning of this section and letting the receive weight for S→R→D link by $w_{SRD} = w_1$ and the receive weight for the S→D link by $w_{SD} = w_2$, the optimal receive weights at destination for R→D link and S→D link can be written as follows.

$$w_{SRD} = \frac{1}{\sigma \sqrt{(|h_{RD}|^2 \beta^2 + 1)}} \frac{\sqrt{c_1} (h_{SR} \beta h_{RD})^*}{\sqrt{(|h_{SR} \beta h_{RD}|^2 + (|h_{RD}|^2 \beta^2 + 1) |h_{SD}|^2)}} \quad (13)$$

$$w_{SD} = \frac{\sqrt{c_1} h_{SD}^* \sqrt{|h_{RD}|^2 \beta^2 + 1}}{\sigma \sqrt{|h_{SD}|^2 (|h_{RD}|^2 \beta^2 + 1) + |h_{SR} \beta h_{RD}|^2}}$$

where the AF gain is $\beta = \sqrt{P_r} / \sqrt{P_s |h_{SR}|^2 + \sigma^2}$ and P_r is the transmit power at relay node, and further by assuming

$$\sqrt{c_1} = \frac{\sigma \sqrt{|h_{SD}|^2 (|h_{RD}|^2 \beta^2 + 1) + |h_{SR} \beta h_{RD}|^2}}{\sqrt{|h_{RD}|^2 \beta^2 + 1}} \quad (14)$$

We obtain

$$w_{SRD} = \frac{(h_{SR} \beta h_{RD})^*}{(|h_{RD}|^2 \beta^2 + 1)} \quad (15)$$

$$w_{SD} = h_{SD}^*$$

Then at destination the combined signal is given by

$$x_{D-MRC} = (\beta (h_{SR} \sqrt{P_s} s + n_{SR}) h_{RD} + n_{RD}) w_{SRD} + (h_{SD} \sqrt{P_s} s + n_{SD}) w_{SD} \quad (16)$$

By using the same method, we can also obtain the AF gain and receive weight corresponding to each link where the number of relays is $j=1, \dots, N$ and $L=1$.

$$w_{SR_j D} = \frac{(h_{SR_j} \beta_j h_{R_j D})^*}{(|h_{R_j D}|^2 \beta_j^2 + 1)} \quad (17)$$

$$\beta_j = \sqrt{P_{R_j}} / \sqrt{P_s |h_{SR_j}|^2 + \sigma^2}$$

$$w_{SD} = h_{SD}^*$$

The combined signal at destination in case of multiple relays is expressed as

$$x_{D-MRC} = \sum_{j=1}^N w_{SR_j D} \{ \beta_j (h_{SR_j} \sqrt{P_s} s + n_{SR_j}) h_{R_j D} + n_{R_j D} \} + (h_{SD} \sqrt{P_s} s + n_{SD}) w_{SD}, \quad j=1, 2, \dots, N \quad (18)$$

Similarly, the AF gain and weight in the case of multiple relays with $N > 1$ and multiple receive antennas at destination with $L > 1$ can be expressed as

$$w_{SR_j D} = \frac{(h_{SR_j} \beta_j h_{R_j D})^*}{(|h_{R_j D}|^2 \beta_j^2 + 1)} \quad (19)$$

$$\beta_j = \sqrt{P_{R_j}} / \sqrt{P_s |h_{SR_j}|^2 + \sigma^2}$$

$$w_{SD} = h_{SD}^*$$

$$x_{D-MRC} = \sum_{j=1}^N w_{SR_j D} \{ \beta_j (h_{SR_j} \sqrt{P_s} s + n_{SR_j}) h_{R_j D} + n_{R_j D} \} + w_{SD} (h_{SD} \sqrt{P_s} s + n_{SD}) \quad (20)$$

The above derivations are all based on using $N+1$ time slots. Now let us consider the case of using 2 time slots. In other words, the relays retransmit signals to the destination at the same time, where the channel between relays and receive antennas at destination becomes $N \times L$ MIMO fading channel. The receive signal vector x_D at the destination can be rewritten as

$$x_{D-MRC} = w_{SRD} \left[\sum_{j=1}^N \{ \beta_j (h_{SR_j} \sqrt{P_s} s + n_{SR_j}) h_{R_j D} \} + n_{RD} \right] + (h_{SD} \sqrt{P_s} s + n_{SD}) w_{SD}, \quad j=1, 2, \dots, N \quad (21)$$

and the AF gain and receive weight are expressed as

$$w_{SRD} = \frac{\left(\sum_{j=1}^N h_{SR_j} \beta_j h_{R_j D} \right)^*}{\left(\left| \sum_{j=1}^N h_{R_j D} \beta_j \right|^2 + 1 \right)} \quad (22)$$

$$\beta_j = \sqrt{P_{R_j}} / \sqrt{P_s |h_{SR_j}|^2 + \sigma^2}$$

$$w_{SD} = h_{SD}^*$$

2. Analysis of SNR at destination

For the equation (1), let us define the integrated system channel matrix $\mathbf{H}$ and receive weight $\mathbf{W}$ as

$$\mathbf{H} = [h_{SD}^T \ h_{SR_1 D}^T \ \dots \ h_{SR_N D}^T \ \dots \ h_{SR_N D}^T]^T \quad (23)$$

$$\mathbf{W} = [w_{SD}^T \ w_{SR_1 D}^T \ \dots \ w_{SR_j D}^T \ \dots \ w_{SR_N D}^T]^T$$

The instantaneous average SNR at destination can be expressed as

$$\eta_{SNR} = \frac{P_s |\mathbf{W}^H \mathbf{H}|^2}{(2 \mathbf{W}^H \mathbf{W} + \mathbf{W}^H \beta_j^2 h_{R_j D} \mathbf{W}) \sigma^2} \quad (24)$$

$$= \frac{P_s |w_{SD} h_{SD} + \sum_{j=1}^n w_{SR_j D} \beta_j h_{R_j D} h_{SR_j}|^2}{\left(2 |w_{SD}|^2 + \sum_{j=1}^n |w_{SR_j D}|^2 \beta_j^2 h_{R_j D} \right) \sigma^2}$$

Taking the derivative $\partial \eta_{SNR} / \partial \mathbf{W}$ with respect to $\mathbf{W}$, we can obtain the optimal receive weight $\mathbf{W}_{O-MRC}$ [6], [7].

$$\mathbf{W}_{O-MRC} = \frac{c_2 |\mathbf{W}^H \mathbf{H}|^2}{2\mathbf{W}^H \mathbf{W} + \mathbf{W}^H \beta_j^2 \mathbf{h}_{R,D} \mathbf{W}} \quad (25)$$

where c_2 is the arbitral real constant. Then substituting $\mathbf{W}_{O-MRC}$ into (24), we get the following equation

$$\begin{aligned} \eta_{SNR} &= \frac{P_s |\mathbf{W}_{O-MRC}^H \mathbf{H}|^2}{(2\mathbf{W}_{O-MRC}^H \mathbf{W}_{O-MRC} + \mathbf{W}_{O-MRC}^H \beta_j^2 \mathbf{h}_{R,D} \mathbf{W}_{O-MRC}) \sigma^2} \\ &= \frac{P_s |\mathbf{h}_{SD}|^2}{\sigma^2} + \frac{P_s \sum_{j=1}^N |\beta_j \mathbf{h}_{SR_j}|^2}{\sigma^2} \frac{\sum_{j=1}^N |\mathbf{h}_{R,D}|^2}{1 + \sum_{j=1}^N |\beta_j \mathbf{h}_{R,D}|^2} \end{aligned} \quad (26)$$

It is noticed that the first part of (26) corresponds to the S→D link, and second part does to the S→R→D link. Evidently, by increasing the relay nodes or the number of receive antennas at destination, we can obtain more SNR improvement.

IV. SIMULATION RESULTS

In this section we show the computer simulation results under the simulation conditions shown as in Table 1. Firstly, on using $N+1$ time slots, we consider the following three cases. 1) A source, a relay and a destination with multiple receive antennas (1S→1R→LD). 2) A source, multiple $j(=2, \dots, N)$ relays and a destination with single receive antenna (1S→jR→1D). 3) A source, multiple $j(=2, \dots, N)$ relays and a destination with L receive antennas (1S→jR→LD). Then we compare the BER versus receive SNR per a receive antenna at destination for two-hop system using 2, 3 and 5 time slots, which corresponds to the number of relays 1, 2 and 4 respectively. The MRC combining is used at destination.

Table.1 Simulation parameter

Modulation scheme	QPSK
Number of antenna at Source	1
Number of Relays	$N=1,2,4,6$
Number of receive antennas at Destination	$L=1,2,4,6$
Number of Time Slots (TS) used	TS=2,3,5,7
Relaying scheme	AF relay
Channel fading	i.i.d flat Raleigh fading
Channel State Information (CSI)	Known at destination
Combining scheme at Destination	MRC

Obviously we could show that the increase of the number of receive antenna at destination and/or the number of time slots has the enormous improvement of BER results.

Fig.2 shows the BER improvement for increasing the number of receives antennas at destination. It is noticed that BER improvement can be obtained because we increase the receive antennas at the destination. This is similar to the case of SIMO (Single-Input Multiple-Output).

Fig.3 shows the BER improvement for increasing the number of time slots. From the comparisons (1×1×1), (1×2×1), (1×4×1) and (1×6×1) using 2, 3, 5 and 7 time slots, respectively, we can also obtain the diversity gain, which is the same as the case in Fig. 2. But it is noticed that increasing the number of receive antennas at the destination outperforms increasing the number of relays. This is because the effect of MRC for the S→D link contributes more than combining many time slots. Also since using many time slots leads to the degradation of transmission rate, we can say the BER performances shown in Fig.2 are more preferable and efficient than Fig.3, when comparing Fig.2 with Fig.3.

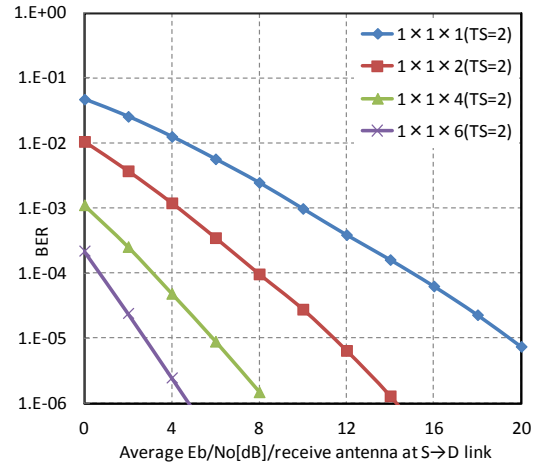


Fig.2. Performance comparison of single relay and multiple receive antennas at destination using 2 time slots

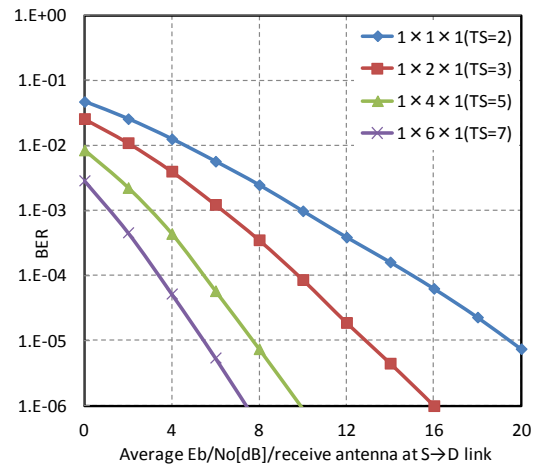


Fig.3. Performance comparison of multiple relays and single antenna at destination using $N+1$ time slots

Fig.4 shows the cases where we use more time slots, i.e., TS=2, 3 and 5, the better BER performance (diversity gain) can be obtained. From the comparison between the cases of (1×2×2) using 2 time slots and the case of (1×2×2) using 3 time slots, about 4 dB improvements can be obtained at the

BER of 10^{-5} . Also from the comparison between $(1 \times 4 \times 2)$ using 2 time slots and $(1 \times 4 \times 2)$ using 5 time slots, about 8 dB improvement can be observed at the BER of 10^{-5} .

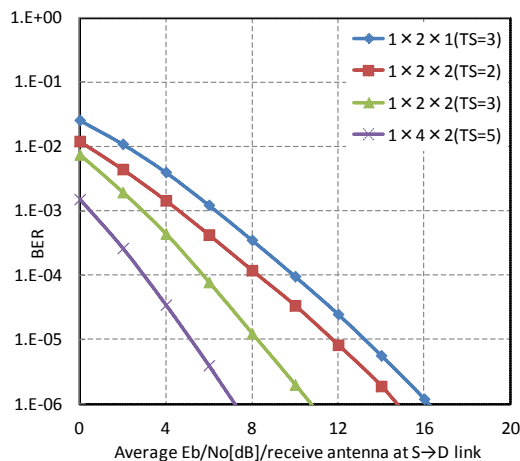


Fig.4 Performance comparison of multiple relays and multiple receive antennas at destination using 2, 3 and 5 time slots

V. CONCLUSIONS

In this paper we derived the optimal MRC weights of dual-hop AF cooperative relay system with a source with single antenna, N relays equipped with single antenna and a destination having L receive antennas on flat Rayleigh fading channels. We presented the BER performances for various combinations of number of relays and number of receive antennas at destination with optimum MRC weights at destination. The BER performance can be largely improved by increasing the number of receive antennas at destination or the number of time slots used for the transmission from relays to destination. This observation seems to be caused from the fact that the effect of amplified and forwarded noises to the destination becomes serious as the number of relays is increased. However, the BER performance of multiple receive antennas at destination is better than the multiple relay case. This seems due to the existence of increased amplified and forwarded noises from multiple relays to destination. By increasing the number of time slots, the AF system with multiple relays can improve the BER performance, but on the other hand the transmission rate decreases. So we can get the best BER results using proposed MRC gains when the number of time slots is taken as $(N + 1)$ and with L receive antennas at destination.

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