Mobile Relay Amplifying Matrix Design of the Cooperative Distributed MMSE Relaying for AF Wireless Mobile Networks

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***Abstract*—This paper presents an optimal amplify-and-forward (AF) relay scheme for a multiple-input-multiple-output (MIMO) system consisting of M-mobile sources, M-mobile destinations, and N-cooperative distributed mobile relay nodes. A wireless mobile relaying network with channel state information is investigated. The received signals from the mobile sources are exchanged between mobile relays to achieve optimal performance. The main contribution in this paper is the derivation of mobile relaying amplifying matrices (MARMs) designed for cooperative MIMO networks based on the minimum mean square error (MMSE) criterion. By adopting the new proposed MRAMs, the bite error rate (BER) performance of the system is evaluated using Monte-Carlo simulations.**

***Index Terms*—Amplify-and-forward, minimum mean square error, MIMO, mobile relay amplifying matrix, mobile-to-mobile, cascaded Rayleigh.**

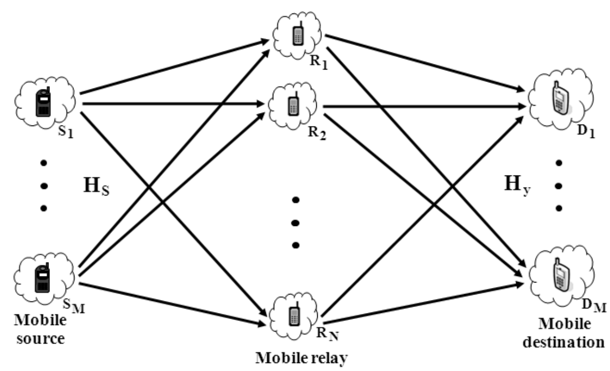

Fig. 1. Cooperative distributed AF MIMO wireless mobile relay network with M-source-M-destination mobile node pairs, N-multibranch mobile relay nodes.

I. Introduction

To improve the end-to-end system performance in wireless networks, diverse relay strategies have recently been investigated [1], [2]. Classical relay strategies have their own variants, but can be generally classified into three categories: 1) nonregenerative amplify-and-forward (AF); 2) regenerative decode-and-forward; and 3) compress-and-forward. The AF relaying applied in this paper is a more practical and general strategy because it has a shorter delay required for processing at the relays compared to the other two strategies.

Using arbitrarily distributed noncooperative relays in a wireless network, the spatial diversity gain can be achieved. The authors in [3], [4] presented the diversity gain of the noncooperative AF single-input-single-output (SISO) wireless relay system. In addition, they designed a relay amplifying matrix (RAM) based on minimum mean square error (MMSE) criterion. The MMSE was applied at the destination to minimize the error between the received signal at the destination node and the originally transmitted signal from the source.

Like the noncooperative relay strategy, the authors in [5]-[9] applied the spatial diversity concept when they studied distributed cooperative wireless relaying networks. Namely, relay cooperation in wireless networks is a potential tactic to enhance the end-to-end system performance. This cooperation is feasible when the relay nodes are located closely. The authors in [8], [9] designed other relay amplifying matrices to improve the overall system performance under different constraints. Due to relay cooperation, the cooperative relay tactics resulted in a better performance than the noncooperative case. Therefore, this paper assumes that all relay nodes can share information on their received signals from source nodes to achieve a better system performance. In [9]-[11], the cooperative distributed AF multiple-input-multiple-output (MIMO) wireless network was studied to improve a system performance. However, they did not present any mobility. Their work focused only on fixed nodes.

The authors of this paper proposed various optimal RAMs based on MMSE criterion for both cooperative and noncooperative fixed AF SISO wireless distributed relay networks under adverse wireless communication environments, such as

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imperfect channel state information and broadband/partialband noise jamming, with/without power constraints in their previous works [8], [12]–[16]. All RAMs were derived only for fixed AF SISO wireless relay networks.

Recently, the authors of this paper in [17] investigated only the noncooperative AF SISO wireless mobile network and determined the mobile RAM (MRAM) based on MMSE criterion between the transmitted signal from the source node and the received signal at the destination node.

However, the authors did not find literature on the cooperative distributed AF MIMO wireless mobile network. In particular, the MRAM in AF MIMO wireless mobile systems was not investigated. In addition, similar to the fixed nodes case, the MMSE relay strategy in mobile wireless network can improve the diversity gain of the source-destination links. Hence, MMSE criterion is chosen in this paper and applied in the design of the optimal MRAM. The objective of this paper is to obtain the optimal MRAM for the AF MIMO wireless mobile relay network and to improve the overall bit error rate (BER) performance with relay cooperation. Special MRAM cases are also part of the investigation, such as multiple-input-single-output (MISO), single-input-multiple output (SIMO), and SISO wireless communication systems. Intentionally, this paper will keep away from the power constraints at the mobile relay nodes because a more desired quality of service can be achieved at the mobile destination node when the mobile relay nodes can have different power usage and the MMSE is applied without power constraints [4], [12].

Currently, there are two main approaches available in the literature to simulate a mobile-to-mobile fading channel. The authors in [18] proposed the double-ring concept based on two rings of uniformly distributed scatters, one applied at the source and another around the destination. In this paper, the cascaded Rayleigh fading channel model, which represents the second approach is employed. The cascaded Rayleigh approach, uses two independent sets of scatter: 1) one around the source, and 2) the second around the destination. The concept for the second approach was initially suggested in [19], while the model that meets the desired statistical properties was presented in [20]. Outdoor measurements were reported in [21], [22], and the cascaded Rayleigh channel to model a mobile-to-mobile channel was recommended.

The remainder of this paper is organized into four sections. Section II describes the system model and the applied data transmission strategies. Section III derives the MRAM for cooperative distributed MMSE mobile relay schemes in the AF MIMO wireless communication system. Special cases such as MISO, SIMO, and SISO systems are also presented. Section IV shows BER simulations results. Finally, Section V concludes the paper.

Notation: Matrices and vectors are denoted, respectively, by uppercase and lowercase boldface characters (e.g., $\mathbf{A}$ and $\mathbf{a}$). The transpose, conjugate, and inverse of $\mathbf{A}$ are denoted, respectively, by $\mathbf{A}^T$, $\mathbf{A}^*$, and $\mathbf{A}^{-1}$. The Hermitian of $\mathbf{A}$ is denoted by $\mathbf{A}^H$, i.e., the conjugate and transpose of $\mathbf{A}$. The $n \times n$ identity matrix and diagonal matrix are, respectively, denoted by $\mathbf{I}_N$ and diag$(a_1, \cdots, a_N)$. The expectation operator is $E[\,\cdot\,]$. Notations $|a|$, $||\mathbf{a}||$, and $||\mathbf{A}||_F$ denote the absolute value of a for any scalar, 2-norm of $\mathbf{a}$, and Frobenius-norm of $\mathbf{A}$, respectively. The real operator is denoted by $\text{Re}\{\mathbf{A}\} = (\mathbf{A} + \mathbf{A}^*)/2$.

II. System Models and Data Transmission

A nonregenerative AF wireless mobile communication system comprising cooperative distributed M-source-M-destination mobile node pairs and N-multibranch mobile relay nodes, is shown in Fig. 1 ($M \le N$). As shown in Fig. 1, there are two stages for message transmission where mobile source nodes broadcast the signal vector $\mathbf{s} \in \mathbf{C}^{M\times 1} = [s_1, \cdots, s_M]^T$ to arbitrarily cooperative distributed mobile relay nodes in Stage I, and all mobile relay nodes retransmit their signals to mobile destination nodes in Stage II.

Let $\mathbf{H}_{sr} \in \mathbf{C}^{N\times M}$ denote the mobile channel complex matrix from mobile source nodes to mobile relay nodes as

$$\mathbf{H}_{sr} = [\mathbf{h}_{sr_1}, \cdots, \mathbf{h}_{sr_M}] \tag{1}$$

where $\mathbf{h}_{sr_m} \in \mathbf{C}^{N\times 1} = [h_{s,m,1}h_{r,m,1}, \cdots, h_{s,m,N}h_{r,m,N}]^T$, $m = 1, \cdots, M$, is a column vector, representing the mobile channel coefficient from the m-th mobile source node to all mobile relay nodes. Let $\mathbf{H}_{yd} \in \mathbf{C}^{M\times N}$ denote the mobile channel complex matrix from mobile relay nodes to mobile destination nodes as

$$\mathbf{H}_{yd} = [\mathbf{h}_{yd_1}, \cdots, \mathbf{h}_{yd_M}]^T \tag{2}$$

where $\mathbf{h}_{yd_m} = \left[h_{y,m,1}h_{d,m,1}, \cdots, h_{y,m,N}h_{d,m,N}\right]$ is a row vector, representing the mobile channel coefficient from all mobile relay nodes to the m-th mobile destination node. Each complex channel coefficient $h_{s,m,i}$, $h_{r,m,i}$, $h_{y,m,i}$, and $h_{d,m,i}$, $i = 1, \cdots, N$, are zero-mean and unit-variance Rayleigh fading channels. However, the product $h_{s,m,i}h_{r,m,i}$ and $h_{y,m,i}h_{d,m,i}$ in [20] are zero-mean and unit-variance cascaded Rayleigh fading channels, representing mobile-to-mobile channels from mobile sources to mobile relays and mobile-to-mobile channels from mobile relays to mobile destinations.

Therefore, the received complex signal column vector $\mathbf{r} \in \mathbf{C}^{N\times 1}$ at the mobile relay nodes is expressed as

$$\mathbf{r} = \mathbf{H}_{sr}\mathbf{s} + \mathbf{v}_s \tag{3}$$

where $\mathbf{v}_s \in \mathbf{C}^{N\times 1} = [v_{s_1}, \cdots, v_{s_N}]^T$ is a zero-mean complex additive white Gaussian noise (AWGN) vector with covariance matrix $\sigma_{v_s}^2 \mathbf{I}_N$ due to the assumption that $\sigma_{v_{s_1}}^2 = \cdots = \sigma_{v_{s_N}}^2 = \sigma_{v_s}^2$. The amplified complex signal column vector $\mathbf{x} \in \mathbf{C}^{N\times 1}$ at the mobile relay node outputs is written as

$$\mathbf{x} = \mathbf{F}\mathbf{r} \tag{4}$$

where $\mathbf{F} \in \mathbf{C}^{N\times N}$ is a MRAM applied by the mobile relay nodes to improve performance at the mobile destination nodes. For mobile relay cooperation, all mobile relay nodes are assumed to share their received signals from the mobile source nodes with each other. This is feasible when the relay nodes are located closely to each other. Therefore, if the wireless mobile relay network is cooperative, the MRAM $\mathbf{F}$ is a nondiagonal matrix. The received complex signal column vector $\mathbf{y} \in \mathbf{C}^{N\times 1}$ at the mobile destination nodes can be written as

$$\mathbf{y} = \mathbf{H}_{yd}\mathbf{F}\mathbf{H}_{sr}\mathbf{s} + \mathbf{H}_{yd}\mathbf{F}\mathbf{v}_s + \mathbf{v}_y \tag{5}$$

where $\mathbf{v}_y \in \mathbf{C}^{M\times 1} = [v_{y_1}, \ \cdots, \ v_{y_M}]^T$ is a zero-mean complex AWGN vector with covariance matrix $\sigma_{v_y}^2 \mathbf{I}_M$, where it is assumed that $\sigma_{v_{y_1}}^2 = \cdots = \sigma_{v_{y_M}}^2 = \sigma_{v_y}^2$.

The objective of this paper is to achieve a better performance by optimizing the MRAM at the mobile relay nodes. In other words, in this paper, the MRAMs are designed for the cooperative distributed AF wireless mobile relay network using the MMSE criterion.

III. Cooperative Distributed MMSE Mobile Relay Scheme

In this section, to determine an optimal nondiagonal MRAM $\mathbf{F}$, the mean square error between the originally transmitted signal vector $\mathbf{s}$ from the mobile source nodes and the signal component $\mathbf{H}_{yd}\mathbf{x}$ of the received signal at the mobile destination nodes is minimized. Therefore, the optimization can be written as

$$\mathbf{F}^{OPT} = \arg\min_{\mathbf{F}} J(\mathbf{F}) \tag{6}$$

where the MMSE cost function $J(\mathbf{F})$ is written as

$$\begin{aligned} J(\mathbf{F}) &= E[||\mathbf{H}_{yd}\mathbf{F}\mathbf{H}_{sr}\mathbf{s} + \mathbf{H}_{yd}\mathbf{F}\mathbf{v}_s - \omega\mathbf{s}||^2] \\ &= \sigma_s^2 \|\mathbf{H}_{yd}\mathbf{F}\mathbf{H}_{sr}\|_F^2 - 2\omega\sigma_s^2 \mathrm{Re}\{\mathbf{H}_{yd}\mathbf{F}\mathbf{H}_{sr}\} \\ &\quad + \sigma_{v_s}^2 \|\mathbf{H}_{yd}\mathbf{F}\|_F^2 + M\omega^2\sigma_s^2 \end{aligned} \tag{7}$$

where $\sigma_{s_1}^2 = \cdots = \sigma_{s_M}^2 = \sigma_s^2$, $E[v_s] = E[v_y] = 0$, the superscript ^{OPT} refers to the optimal nondiagonal MRAM, and a positive constant ω is generated by the designer. In other words, ω is defined as

$$\omega = \sqrt{M\mathrm{SNR}_{\mathrm{TAR}} \left(\frac{\sigma_s^2}{\sigma_{v_y}^2}\right)^{-1}} \tag{8}$$

where $\mathrm{SNR}_{\mathrm{TAR}}$ is the target SNR at the mobile destination nodes [4]. For instance, the choice of ω would ensure a certain target SNR at the mobile destination nodes for cooperative distributed AF wireless mobile relay networks since the MARM $\mathbf{F}$ is nondiagonal. Refer to the Appendix.

To determine the optimization problem, differentiating $J(\mathbf{F})$ with respect to the complex conjugate of $\mathbf{F}$, i.e., $\mathbf{F}^*$, and using the properties of the complex derivative matrix [23] results in

$$\begin{aligned} \frac{\partial J(\mathbf{F})}{\partial \mathbf{F}^*} &= \sigma_s^2 \mathbf{H}_{yd}^H \mathbf{H}_{yd}\mathbf{F}\mathbf{H}_{sr}\mathbf{H}_{sr}^H + \sigma_{v_s}^2 \mathbf{H}_{yd}^H\mathbf{H}_{yd}\mathbf{F} \\ &\quad - \omega\sigma_s^2 \mathbf{H}_{yd}^H \mathbf{H}_{sr}^H = \mathbf{0}_N \end{aligned} \tag{9}$$

where $\mathbf{0}_N$ is an $n \times n$ matrix consisting of all zero entries. Therefore, the optimal nondiagonal MRAM $\mathbf{F}^{OPT}$ for AF MIMO wireless mobile communication systems when $\mathbf{H}_{yd}$ is a square matrix can be obtained as

$$\mathbf{F}^{OPT} = \omega\sigma_s^2 \mathbf{H}^{-1}\mathbf{H}_{yd}^H\mathbf{H}_{sr}^H \left(\sigma_s^2 \mathbf{H}_{sr}\mathbf{H}_{sr}^H + \sigma_{v_s}^2 \mathbf{I}_N\right)^{-1} \tag{10}$$

where a matrix $\mathbf{H}(\in \mathbf{C}^{N\times N}) \triangleq \mathbf{H}_{yd}^H \mathbf{H}_{yd}$.

If $\mathbf{H}_{yd}$ is not a square matrix, i.e., $\mathbf{H}_{yd}$ is any $N \times M$ matrix when $N \neq M$ $(N > M)$, the optimal nondiagonal MRAM $\mathbf{F}_{NSM}^{OPT}$ for AF MIMO wireless mobile communication systems can be written as

$$\mathbf{F}_{NSM}^{OPT} = \omega\sigma_s^2 \mathbf{H}^\dagger \mathbf{H}_{yd}^H\mathbf{H}_{sr}^H \left(\sigma_s^2 \mathbf{H}_{sr}\mathbf{H}_{sr}^H + \sigma_{v_s}^2 \mathbf{I}_N\right)^{-1} \tag{11}$$

where $\mathbf{H}^\dagger$ is the pseudo inverse of $\mathbf{H}$, and the subscript $_{NSM}$ refers to the case that $\mathbf{H}_{yd}$ is not a square matrix.

From (7), the optimal nondiagonal MRAMs for AF MISO, SIMO, and SISO wireless mobile communication systems can be, respectively, derived as follows:

1) **MISO**

$$\begin{aligned} \mathbf{F}_{MISO}^{OPT} &= \omega_{MISO}\sigma_s^2 \mathbf{H}^\dagger{}_{MISO} \\ &\quad \sum_{m=1}^{M} \mathbf{h}_{yd}^H \mathbf{h}_{sr_m}^H \left(\sigma_s^2 \mathbf{H}_{sr}\mathbf{H}_{sr}^H + \sigma_{v_s}^2 \mathbf{I}_N\right)^{-1} \end{aligned} \tag{12}$$

where $\mathbf{h}_{yd} = \left[h_{y,1}h_{d,1}, \ \cdots, \ h_{y,N}h_{d,N}\right]$.

2) **SIMO**

$$\mathbf{F}_{SIMO}^{OPT} = \frac{\omega_{SIMO}\sigma_s^2 \mathbf{H}_{SIMO}^\dagger \sum_{m=1}^{M} \mathbf{h}_{yd_m}^H \mathbf{h}_{sr}^H}{\sigma_s^2 ||\mathbf{h}_{sr}||^2 + \sigma_{v_s}^2} \tag{13}$$

where $\mathbf{h}_{sr} \in \mathbf{C}^{N\times 1} = [h_{s,1}h_{r,1}, \ \cdots, \ h_{s,N}h_{r,N}]^T$.

3) **SISO**

$$\mathbf{F}_{SISO}^{OPT} = \frac{\omega_{SISO}\sigma_s^2 \mathbf{H}^\dagger{}_{SISO} \mathbf{h}_{yd}^H \mathbf{h}_{sr}^H}{\sigma_s^2 ||\mathbf{h}_{sr}||^2 + \sigma_{v_s}^2}. \tag{14}$$

The matrices $\mathbf{H}_{MISO}^\dagger$, $\mathbf{H}_{SIMO}^\dagger$, and $\mathbf{H}_{SISO}^\dagger$ are denoted by the pseudo inverses of $\mathbf{H}_{MISO}(\in \mathbf{C}^{N\times N}) \triangleq \mathbf{h}_{yd}^H\mathbf{h}_{yd}$, $\mathbf{H}_{SIMO}(\in \mathbf{C}^{N\times N}) \triangleq \sum_{m=1}^{M} \mathbf{h}_{yd_m}^H \mathbf{h}_{yd_m}$, and $\mathbf{H}_{SISO}(\in \mathbf{C}^{N\times N}) \triangleq \mathbf{h}_{yd}^H\mathbf{h}_{yd}$, respectively. The subscript $_{SIMO}$, $_{MISO}$, and $_{SISO}$ in $\mathbf{F}$ and ω refer to the case of cooperative distributed AF MISO, SIMO, and SISO wireless mobile relay networks, respectively.

IV. Simulation Results

Monte-Carlo simulations are used in this section to evaluate performance in various scenarios such as MIMO, MISO, SIMO, and SISO. The originally transmitted signals from the mobile source nodes are modulated using 4-ary quadrature amplitude modulation with unit power. It is assumed that all mobile communication nodes use only one antenna for all scenarios. The mobile complex channel matrices $\mathbf{H}_{sr}$ and $\mathbf{H}_{yd}$ are generated from, respectively, zero-mean and unit-variance independent Gaussian random variables. As stated earlier, all nodes have the same thermal noise power, i.e., $\sigma^2_{v_{s_1}} = \cdots = \sigma^2_{v_{s_N}} = \sigma^2_{v_s} = \sigma^2_{v_{y_1}} = \cdots = \sigma^2_{v_{y_M}} = \sigma^2_{v_y}$.

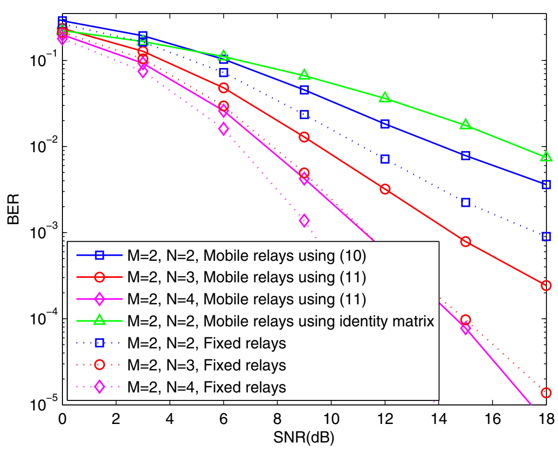

Fig. 2. BER performance of cooperative distributed AF MIMO wireless mobile/fixed relay networks with two mobile/fixed source nodes, two mobile/fixed destination nodes, and N=2, 3, 4, mobile/fixed relay nodes.

The BER is a good criterion to verify the system performance of the proposed strategies because the mean square error is minimized. Therefore, BER is simulated to evaluate system performance of MIMO, MISO, SIMO, and SISO mobile wireless communication systems. The positive constant ω in all scenarios is chosen to be 1 to minimize the mean square error between the originally transmitted signal from the mobile source nodes and the signal component of the received signal at the mobile destination nodes. In addition, for system performance comparison, the simulation results for fixed AF MIMO/SISO wireless relay networks are also included.

Figure 2 shows BER performance of the cooperative distributed AF MIMO wireless mobile/fixed relay networks with two-source-two-destination mobile/fixed pairs and N=2, 3, 4 mobile/fixed relay nodes. A better BER performance using the proposed MRAM was observed compared to the identity RAM (IRAM). For instance, the BER performance applied to the proposed MRAM with $N = 2$ can show approximately 3.0 dB improvement compared to the one applied to the IRAM, i.e., $\mathbf{F}_{IDEN} = \text{diag}(1,\ 1)$, at BER=$10^{-2}$. However, due to communication node mobility, the BER performance applied to the proposed MRAM with $N = 2$ in Fig. 2 and in Fig. 4 can show approximately 3.0 dB degradation compared to the one applied to the fixed RAM, respectively. In addition, as the number of mobile relay nodes increases, a better BER performance can be observed. Namely, using arbitrarily cooperative distributed mobile relays, the diversity gain is achieved.

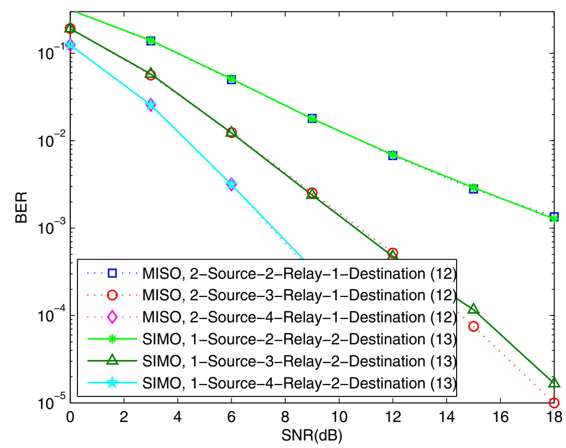

Fig. 3. BER performance of cooperative distributed AF MISO/SIMO wireless mobile relay networks with two mobile sources and one mobile destination for MISO, and with one mobile source and two mobile destinations, and N=2, 3, 4 mobile relays.

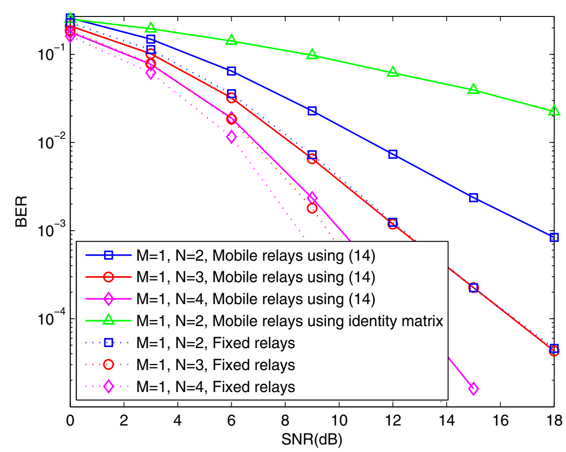

Fig. 4. BER performance of cooperative distributed AF SISO wireless mobile/fixed relay networks with M=1 mobile/fixed source, M=1 mobile/fixed destination node, and N=2, 3, 4, mobile/fixed relay nodes.

Figure 3 provides BER performance of the cooperative distributed AF MISO and SIMO wireless mobile relay networks with different setups. For example, for a MISO case, a two-source and one-destination mobile nodes with $N = 2, 3, 4$ mobile relay nodes are applied, while one-source and two-destination mobile nodes with $N = 2, 3, 4$ mobile relay nodes are used for a SIMO case. In the case of a MIMO wireless mobile relay system, the BER performance of both MISO and SIMO is enhanced as the number of mobile relay nodes increases, respectively. To provide a fair comparison, the same signal in a MISO system was transmitted from two mobile source nodes. BER performances of the MISO and SIMO cases are observed to be almost equivalent.

Figure 4 presents BER performance of the cooperative distributed AF SISO wireless mobile/fixed relay networks with one mobile/fixed source, one mobile/fixed destination node, and N=2, 3, 4, mobile/fixed relay nodes. As in the case of a MIMO wireless mobile system, it can be shown in Fig. 4 that the case of applying the proposed MRAM in (22) shows a better performance than that of employing the IRAM $\left(\mathbf{F}_{IDEN} = \text{diag}[1,\ 1]\right)$. Like MIMO, MISO, and SIMO wireless mobile systems, it is observed in Fig. 4 that BER performance improves as the number of mobile relay nodes increases. In other words, as with the case of MIMO, diversity gain is achieved.

V. Conclusion

An optimal AF mobile relay scheme for a MIMO wireless system consisting of M-mobile sources, M-mobile destinations, and N cooperative distributed mobile relay nodes was designed. The nondiagonal MRAMs were designed by minimizing the mean square error between the originally transmitted signals from the mobile source nodes and the signal component of the received signals at the mobile destination nodes.

It was observed that the BER performance of MIMO, MISO, SIMO, and SISO wireless mobile networks gets better as the number of mobile relay nodes increases. In other words, spatial diversity gain was accomplished by using the arbitrarily distributed cooperative mobile relay nodes in wireless mobile networks. It was also shown that the MISO and SIMO wireless mobile systems show an almost equivalent BER performance. In addition, it was found that the proposed MRAM shows a better performance than the IRAM.

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