Sum MSE Minimization for Downlink Multi-Relay Multi-User MIMO Network

Young-Min Cho[1], Janghoon Yang[2], Jeongwook Seo[3], and Dong Ku Kim[1]
[1]School of Electric and Electronic Engineering, Yonsei University
Seoul, Korea
[e-mail: datem38@yonsei.ac.kr, dkkim@yonsei.ac.kr]
[2]Department of Newmedia, Korean German Institute of Technology
Seoul, Korea
[e-mail: jhyang@kgit.ac.kr]
[3]Department of Information and Communication Engineering, Namseoul University
Chungcheongnam-do, Korea
[e-mail: jwseo@nsu.ac.kr]
*Corresponding author: Dong Ku Kim

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Abstract

We propose methods of linear transceiver design for two different power constraints, sum relay power constraint and per relay power constraint, which determine signal processing matrices such as base station (BS) transmitter, relay precoders and user receivers to minimize sum mean square error (SMSE) for multi-relay multi-user (MRMU) networks. However, since the formulated problem is non-convex one which is hard to be solved, we suboptimally solve the problems by defining convex subproblems with some fixed variables. We adopt iterative sequential designs of which each iteration stage corresponds to each subproblem. Karush-Kuhn-Tucker (KKT) theorem and SMSE duality are employed as specific methods to solve subproblems. The numerical results verify that the proposed methods provide comparable performance to that of a full relay cooperation bound (FRCB) method while outperforming the simple amplify-and-forward (SAF) and minimum mean square error (MMSE) relaying in terms of not only SMSE, but also the sum rate.

Keywords: MIMO, relay, MSE duality, precoding, transceiver optimization

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1. Introduction

Mutiple-input multiple-output (MIMO) and relay have been spotlighted as serviceable technologies which greatly contribute to the current and beyond fourth generation (4G) wireless system [1]. Series of literatures mentioned in [1] suggest there are still many research problems which should be resolved for wide employment in a practical wireless network. Amplify-and-forward (AF) and decode-and-forward (DF) are conventional relaying protocols [2], which are also known as non-regenerative and regenerative relaying, respectively. In a practical implementation perspective, AF relaying has been a preferred protocol for its simplicity. However, its usage is most often limited to coverage extension in a practical wireless system. To deal with this limited application, there have been many studies to improve the effect of cooperation among relays, or between base station (BS) and relays, with the exploitation of MIMO technologies. Therefore, transceiver design issues for AF-MIMO relay have been treated as an active research topic for many years.

Optimal relay precoders for a single relay single user MIMO network have been designed in [3]-[6]. Muñoz et al. proposed a diagonal relaying scheme to maximize mutual information of a conventional three-node relay network [3]. Mo and Chew proposed a joint BS and relay precoder design for an AF MIMO relay network [4] which uses primal decomposition to divide the primal non-convex problem into several subproblems. Rong [5] considered a direct transmission between a BS and relay in the system model of [4] and proposed a sequential alternating scheme to minimize MSE, which updates the BS transmitter and relay precoder in an iterative fashion. Song et al. proposed a closed form design of a near optimal relay precoder based on an MMSE criterion including a non-negligible direct link [6]. They also provided the diversity and multiplexing tradeoff (DMT) performance upper bound of the MMSE-based three-node cooperative relaying systems.

Meanwhile, [7]-[9] dealt with a multi-user (MU) network with a single relay. Chae et al. investigated upper and lower bounds on the sum rate with scheduling consideration [7]. Several relaying techniques such as all-pass relaying, singular-value-decomposition (SVD) relaying, and relay water-filling with fixed zero-forcing (ZF) precoder at BS were presented in [7]. Zhang et al. [8] proposed an iteration-based joint BS transmitter and a relay precoder design to minimize the sum power of BS and relay satisfying each user's individual target signal to interference-plus-noise ratio (SINR). In addition, Jang et al. [9] proposed a joint BS transmitter and relay precoder design to minimize the sum MSE (SMSE) of all the users, which is an alternative view of [8] from a design perspective.

For a multi-relay single user (MRSU) system, Shi et al. [10] proposed a matrix triangularization scheme which transforms each MIMO relay channel into a triangular channel by QR decomposition so that both distributed array gain and intra-node array gain can be achieved. Behbahani et al. [11] proposed joint relay precoders and a user receiver design with receiver power constraint and target SNR. Finally, [12] and [13] addressed precoder designs in a multipoint-to-multipoint network with multiple relays. Oyman and Paulraj introduced matched filter (MF), ZF, and linear MMSE relaying and provided performance verification of those schemes in terms of per stream signal to interference ratio (SIR) distribution in [12]. Chalise and Vandendorpe [13] proposed a relay precoder design to satisfy each user's target SINR in the most recent research, to the best of the author's knowledge. Zhang and Lau considered the multiple relay selection problem [14], where a low overhead multiple relay selection protocol was proposed to support multi-stream transmission for an MRSU system.

Uplink-downlink dualities are useful tools to resolve the difficulty in transceiver design for various MIMO networks. Viswanath and Tse [15] founded multiple access channel (MAC)-broadcasting channel (BC) duality in a MIMO network, and this work contributes to discover the capacity of downlink multi-user MIMO system. Yu and Lan [16] presented another approach to analyze the uplink-downlink SINR duality by Lagrangian duality of the convex optimization theory. Yu has proved that SINR duality holds in a MIMO network with per antenna power constraint (PAPC) in a downlink MU-MIMO system [16]. Next, Yang and Kim [17] provided SINR duality for a multicell MIMO environment with linear beamforming constraint and per base station power constraint (PBPC). Hunger et al. [18] established MSE duality of three levels of SMSE, per user MSEs and streamwise MSEs in a MU-MIMO system with theoretical proof by uplink-downlink power conversion and non-negative matrix theory. Duality results on relay-aided networks have been published in recent years. In [19], Gomadam and Jafar showed that SINR duality holds in a MIMO relay network. Useful MSE duality in a MIMO relay network was developed recently by Jang et al. [20], where MSE dualities with three different levels of power constraints were nontrivially extended to a MIMO relay network.

If data sharing among physically distributed multiple MIMO relays is possible through wireless backhaul connected to a BS so that cooperation among them is practically implementable, then the QoS of multiple end-user can be sufficiently improved. Literature on the three-node MIMO relay and MRSU MIMO network were presented recently in [6] and [14]. However, joint design of BS transmitters, relay precoders, and user receivers in an multi-relay multi-user (MRMU) MIMO network has not been properly addressed. Although [12] and [13] dealt with multiple BSs, AF relays, and users, their focus was limited to the optimization of relay precoders so that many properties of ultimate SMSE and sum rate of MRMU MIMO networks have yet to be investigated. It should be noted that there are still many research problems to be studied for regarding the general scope of the MRMU MIMO investigation. SMSE duality [20] is useful to transceiver design for single relay multi-user (SRMU) MIMO network. However, it cannot be trivially adapted to multiple relay network or trivially provide methods of designing transceivers for MRMU network. Finding a disjoint solution for each relay based on [20] bring about inferior performance due to interference among relays. To obtain cooperation effect among multiple relays, relay precoders should be designed jointly with considering precoder structure and channel state information of other relays.

MRMU network has been dealt with in several literatures. Long et al. [21] proposed an energy efficient relaying scheme for the network where only the BS employed multiple antennas. They determined the coefficient of each relay to minimize transmit power of relays. They assumed that BS transmitter is fixed to the ZF precoder in order to make the problem be more tractable, which is not an optimal way. In addition, the scheme cannot be applied for the network where relays employ multiple antennas. Zhao et al. [22] proposed BS transmitter and relay precoders for the two user network with two DF relays and single BS. BS transmitter is chosen to perform singular value decomposition (SVD) [23] of the 1st hop link and two relay precoders are chosen for each user's desired data stream to be combined with maximum ratio combining (MRC) [23] for the 2nd hop link. However, the relay precoders cannot be applied for the network where there are arbitrary numbers of relays and users. Talebi et al. [24] proposed a DF relay precoder for the network where BS and each relay employ multiple antennas and each user employs single antenna. The design criterion was to increase sum rate. They assumed that BS transmitter is fixed to ZF-dirty paper coding (DPC) precoder [25] and single antenna is equipped to each user. That is, most of existing research on MRMU network assumes that relays or users are assumed to employ single antenna and BS transmitter is fixed to ZF or ZF-DPC precoder for simplicity. If all nodes employ multiple antennas and BS transmitter is not predefined, the transceiver design becomes much more formidable.

In this paper, we propose a joint linear transceiver design to determine BS transmitter, relay precoders, and user receivers from SMSE minimization criterion under relay sum power constraint (RSPC) and per relay power constraint (PRPC). We assume that all relays operate as AF mode. To achieve ultimate performance of the network, we may have to consider information theoretic schemes, which are still open problems. We consider general network configurations in the sense that there is no specific constraint on the number of relays or users, with the assumption that full channel state information (CSI) of both the 1st and the 2nd hop channels, which are called global CSI throughout this paper, are available at a central processing unit. The optimization problem formulated to design the transceivers is hard to be solved due to its non-convex structure. Thus, we modify the original problem into the composition of several subproblems, each of which has convex structure. We find suboptimal solutions based on sequential iteration of solving the subproblems. For two kinds of power constraints of RSPC and PRPC, individual design procedures which comply with each constraint are proposed. Karush-Kuhn-Tucker (KKT) theorem [26] and SMSE duality [20] are employed as specific method to solve subproblems in the case of RSPC, while only KKT theorem is used to solve subproblems in the case of PRPC. It is demonstrated using numerical results that the proposed schemes achieve noticeable gain in terms of SMSE compared to conventional relaying schemes of simple AF (SAF) and MMSE relaying [12] for various network configurations. Furthermore, although SMSE minimization is the primary design criterion, the proposed schemes also provide superior sum rate performance to those of SAF and MMSE relaying. We select SMSE minimization as main design criterion. Due to the quadratic structure of MSE, SMSE is more tractable to work with than SINR. Sum rate is used as an ultimate performance measure of the multi-user communication system, while optimal SMSE does not guarantee an optimal sum rate. However, there is well known relationship between individual single data stream of MMSE and SINR, that is $\text{SINR} = \frac{1}{\text{MMSE}} - 1$ [27] [28]. With given fixed transmitter, MMSE filter at the receiver is designed to minimize the MSE of each individual data stream and so thus to maximize the SINR of each data stream. SMSE is spontaneously minimized from the summation of minimized individual MSEs. On the other hand, with given fixed receiver, MMSE filter at the transmitter which minimizes SMSE is not guaranteed to minimize every individual data stream. Hence it is also not guaranteed to provide the best sum rate. However, even though all the MSEs of data streams do not decrease, the amount of decrease in MSE from some data streams certainly dominates that of increase in MSE from the other streams. Accordingly, we can expect in most cases the amount of increase in sum rate certainly dominate that of decrease in sum rate. Therefore the schemes which are designed based on SMSE minimization criterion provide performance gain in terms of sum rate. Similarly, even if our proposed schemes is not guaranteed to provide the best sum rate, they provide improved sum rate to an extent compared to previous schemes, which will be verified by numerical results. Furthermore, SMSE itself with which several transceiver design problem has been investigated in [5][6] and [9].

The rest of the paper is organized as follows. In section II, we describe the system model with mathematical expressions. Next, the design procedures of schemes with RSPC and per relay power constraint (PRPC) are described respectively in section III and IV. In section V, we provide numerical results on the performances of the proposed schemes compared to baseline schemes. Finally, we make some conclusions on the proposed schemes in section VI.

The following notations are introduced for the rest of the paper. Boldface uppercase and lowercase fonts denote matrices and vectors, respectively. $\mathbf{C}^{M\times N}$ denotes the complex matrix of M rows and N columns. We use $\mathbf{A}^T$, $\mathbf{A}^H$, $\|\mathbf{A}\|_F$, and $\mathrm{tr}[\mathbf{A}]$ for transpose, Hermitian, the Frobenius norm, and the trace operator, respectively, of matrix $\mathbf{A}$. $\mathrm{blkdiag}[\cdot]$ denotes the block diagonal matrix composed of $[\cdot]$. $\mathrm{E}_{\mathbf{b}}[\cdot]$ denotes the expectation of $[\cdot]$ over vector $\mathbf{b}$. Finally, $\mathbf{I}_X$ denote the identity matrix of rank X.

2. System Model

2.1 System-Wide Expression of Signal Model

We consider a downlink MRMU MIMO network as shown in **Fig. 1** which consists of a single BS, R relays and K user. L_k denotes the number of the k^{th} user's desired data stream and BS transmits $L=\sum_{k=1}^{K}L_K$ data streams totally. The number of antennas at BS, each relay and each user, are denoted as N_S, N_R, and N_U, respectively, The k^{th} user's data $\mathbf{x}_k\in\mathbf{C}^{L_k\times 1}$ is transmitted from BS to all the relays after being precoded by matrix $\mathbf{T}_k\in\mathbf{C}^{N_S\times L_k}$. For notational convenience, we write the overall precoder $\mathbf{T}=\begin{bmatrix}\mathbf{T}_1 & \mathbf{T}_2 & \cdots & \mathbf{T}_K\end{bmatrix}_k\in\mathbf{C}^{N_S\times L}$. Likewise, we express all the users' desired data streams as $\mathbf{x}=\begin{bmatrix}\mathbf{x}_1^H & \mathbf{x}_2^H & \cdots & \mathbf{x}_K^H\end{bmatrix}^H\in\mathbf{C}^{L\times 1}$, where all entries of $\mathbf{x}$ are assumed to follow i.i.d. Gaussian distribution with zero mean and variance one. $\mathbf{G}_r\in\mathbf{C}^{N_R\times N_S}$ denotes the 1$^{\text{st}}$ hop channel matrix from BS to the r^{th} relay, and $\mathbf{n}_{1,r}$ denotes noise at the r^{th} relay. As similar to above, the overall expressions $\mathbf{G}=\begin{bmatrix}\mathbf{G}_1^H & \mathbf{G}_2^H & \cdots & \mathbf{G}_R^H\end{bmatrix}^H\in\mathbf{C}^{N_R R\times N_S}$ and $\mathbf{n}_1=\begin{bmatrix}\mathbf{n}_{1,1}^H & \mathbf{n}_{1,2}^H & \cdots & \mathbf{n}_{1,R}^H\end{bmatrix}^H\in\mathbf{C}^{N_R R\times 1}$ are introduced. Then, the system-wide received signal in the 1$^{\text{st}}$ hop channel can be written as,

$$\mathbf{y}=\mathbf{GTx}+\mathbf{n}_1 \tag{1}$$

where $\mathbf{y}=\begin{bmatrix}\mathbf{y}_1^H & \mathbf{y}_2^H & \cdots & \mathbf{y}_R^H\end{bmatrix}^H\in\mathbf{C}^{N_R R\times 1}$ denotes all the relays' received signal and its element $\mathbf{y}_r$ denotes the received signal at the r^{th} relay.

Since all relays are assumed to be AF relays, each relay precodes its own received signal by $\mathbf{W}_r\in\mathbf{C}^{N_R\times N_R}$ without decoding the symbols. We also denote overall precoders of all the relays as $\mathbf{W}=\mathrm{blkdiag}\begin{bmatrix}\mathbf{W}_1 & \mathbf{W}_2 & \cdots & \mathbf{W}_R\end{bmatrix}\in\mathbf{C}^{N_R R\times N_R R}$. The 2$^{\text{nd}}$ hop MIMO channel between the r^{th} relay and the k^{th} user is represented by $\mathbf{H}_{kr}\in\mathbf{C}^{N_U\times N_R}$ and three kinds of stacked matrices are introduced.

$$\begin{aligned}
\mathbf{H}_r &= \begin{bmatrix}\mathbf{H}_{1r}^H & \mathbf{H}_{2r}^H & \cdots & \mathbf{H}_{Kr}^H\end{bmatrix}^H\in\mathbf{C}^{N_U K\times N_R}\\
\hat{\mathbf{H}}_k &= \begin{bmatrix}\mathbf{H}_{k1} & \mathbf{H}_{k2} & \cdots & \mathbf{H}_{kR}\end{bmatrix}\in\mathbf{C}^{N_U\times N_R R}\\
\mathbf{H} &= \begin{bmatrix}\mathbf{H}_1 & \mathbf{H}_2 & \cdots & \mathbf{H}_R\end{bmatrix}\in\mathbf{C}^{N_U K\times N_R R}
\end{aligned} \tag{2}$$

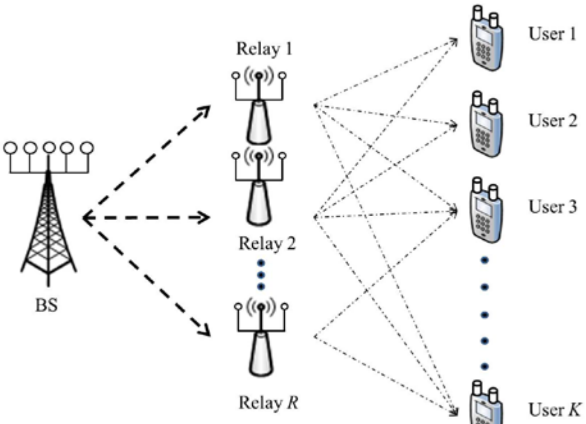

Fig. 1. System model of downlink MRMU MIMO Network

where $\mathbf{H}_r$ denotes the 2nd hop channel between the r^{th} relay and all the users, and $\hat{\mathbf{H}}_k$ denotes the 2nd hop channel between all the relays and the k^{th} user. $\mathbf{H}$ denotes the system-wide 2nd hop channel between all the relays and all the users. The received signal at the k^{th} user is written as,

$$\mathbf{z}_k = \hat{\mathbf{H}}_k \mathbf{W}\left(\mathbf{GTx} + \mathbf{n}_1\right) + \mathbf{n}_{2,k} \tag{3}$$

where the additive noise at the receiver of the k^{th} user is denoted by $\mathbf{n}_{2,k}$. The system wide received signal can be written as,

$$\mathbf{z} = \mathbf{HW}\left(\mathbf{GTx} + \mathbf{n}_1\right) + \mathbf{n}_2 \tag{4}$$

where $\mathbf{z} = \left[\mathbf{z}_1^H \quad \mathbf{z}_2^H \quad \cdots \quad \mathbf{z}_K^H\right]^H \in \mathbf{C}^{N_U K\times 1}$ denotes all the users' received signal and the stacked notation $\mathbf{n}_2 = \left[\mathbf{n}_{2,1}^H \quad \mathbf{n}_{2,2}^H \quad \cdots \quad \mathbf{n}_{2,K}^H\right]^H \in \mathbf{C}^{N_U K\times 1}$ are introduced. All entries of $\mathbf{n}_1$ and $\mathbf{n}_2$ follow i.i.d. Gaussian distribution with zero mean and variance σ_1^2 and σ_2^2, respectively.

Finally, the k^{th} user equalizes the received signal by linear filter $\mathbf{R}_k \in \mathbf{C}^{L_k \times N_U}$ in order to recover its desired data streams $\hat{\mathbf{x}}_k$, i.e. $\hat{\mathbf{x}}_k = \mathbf{R}_k \mathbf{z}_k$. The overall receiver matrix and recovered data streams of all the users are given by $\mathbf{R} = \text{blkdiag}\left[\mathbf{R}_1 \quad \mathbf{R}_2 \quad \cdots \quad \mathbf{R}_K\right] \in \mathbf{C}^{L\times N_R R}$ and $\hat{\mathbf{x}} = \left[\hat{\mathbf{x}}_1^H \quad \hat{\mathbf{x}}_2^H \quad \cdots \quad \hat{\mathbf{x}}_K^H\right]^H \in \mathbf{C}^{L\times 1}$, respectively. The error covariance matrix of the network is defined as the expectation of the difference between original $\mathbf{x}$ and recovered $\hat{\mathbf{x}}$ as follows.

$$\begin{aligned}
\mathbf{E} &= \mathrm{E}_{\mathbf{x},\mathbf{n}_1,\mathbf{n}_2}\left[\left(\mathbf{x} - \hat{\mathbf{x}}\right)\left(\mathbf{x} - \hat{\mathbf{x}}\right)^H\right] \\
&= \mathrm{E}_{\mathbf{x},\mathbf{n}_1,\mathbf{n}_2}\left[\left(\mathbf{x} - \mathbf{RHWGTx} - \mathbf{RHWn}_1 - \mathbf{Rn}_2\right)\left(\mathbf{x} - \mathbf{RHWGTx} - \mathbf{HWn}_1 - \mathbf{Rn}_2\right)^H\right] \\
&\overset{(a)}{=} \mathrm{E}_{\mathbf{x}}\left[\mathbf{xx}^H\right] + \mathbf{RHWGT}\mathrm{E}_{\mathbf{x}}\left[\mathbf{xx}^H\right]\mathbf{T}^H\mathbf{G}^H\mathbf{W}^H\mathbf{H}^H\mathbf{R}^H + \mathbf{RHW}\mathrm{E}_{\mathbf{n}_1}\left[\mathbf{n}_1\mathbf{n}_1^H\right]\mathbf{W}^H\mathbf{H}^H\mathbf{R}^H \\
&\quad + \mathbf{R}\mathrm{E}_{\mathbf{n}_2}\left[\mathbf{n}_2\mathbf{n}_2^H\right]\mathbf{R}^H + \mathrm{E}_{\mathbf{x}}\left[\mathbf{xx}^H\right]\mathbf{T}^H\mathbf{G}^T\mathbf{W}^H\mathbf{H}^H\mathbf{R}^H + \mathbf{RHWGT}\mathrm{E}_{\mathbf{x}}\left[\mathbf{xx}^H\right] \\
&\overset{(b)}{=} \left(\mathbf{RHWGT} - \mathbf{I}_L\right)\left(\mathbf{RHWGT} - \mathbf{I}_L\right)^H + \sigma_1^2\mathbf{RHWW}^H\mathbf{H}^H\mathbf{R}^H + \sigma_2^2\mathbf{RR}^H
\end{aligned} \tag{5}$$

where (a) follows from the fact that the cross correlation matrices among $\mathbf{x}$, $\mathbf{n}_1$, and $\mathbf{n}_2$ become zero matrices. (b) follows from $\mathrm{E}_{\mathbf{x}}\left[\mathbf{x}\mathbf{x}^H\right]=\mathbf{I}_L$, $\mathrm{E}_{\mathbf{n}_1}\left[\mathbf{n}_1\mathbf{n}_1^H\right]=\sigma_1^2\mathbf{I}_{N_R R}$, and $\mathrm{E}_{\mathbf{n}_2}\left[\mathbf{n}_2\mathbf{n}_2^H\right]=\sigma_2^2\mathbf{I}_{N_U K}$.

2.2 Transmission Scenario and Problem Statement

The 1st hop transmission from BS to multiple relays can be considered as (physical layer) multi-casting of downlink multi-user MIMO network in the sense that all the users' desired data streams are transmitted to all the relays. However, the difference is that AF relays do not decode each user's individual data stream at all. Actually, full decoding at a relay is fundamentally impossible unless the relay can support the sufficient number of antenna which is larger than that of total number of data streams. The r^{th} relay processes its received signal, where all the users' desired data streams are mixed implicitly by $\mathbf{W}_r$ in a way of minimizing SMSE. Thus, all the relays contribute to all the users, which leads to a partial cooperation effect among relays.

The optimization problem to determine a desirable BS transmitter and relay precoders with SMSE minimization criterion is formulated as follows.

$$\begin{aligned}&\min_{\mathbf{T},\,\mathbf{W}_r,\forall r,\,\mathbf{R}_k,\forall k}\ \mathrm{tr}\left[\mathbf{E}\right]\\&\mathrm{tr}\left[\mathbf{T}\mathbf{T}^H\right]\le P_{\mathrm{BS}}\ \left(\text{BS Power Constraints}\right)\\&\mathrm{tr}\left[\mathbf{W}\left(\mathbf{G}\mathbf{T}\mathbf{T}^H\mathbf{G}^H+\sigma_1^2\mathbf{I}_{N_R R}\right)\mathbf{W}^H\right]\le P_{\mathrm{relay}}^{\mathrm{total}}\ \left(\text{RSPC}\right)\\&\mathrm{tr}\left[\mathbf{W}_r\left(\mathbf{G}_r\mathbf{T}\mathbf{T}^H\mathbf{G}_r^H+\sigma_1^2\mathbf{I}_{N_R}\right)\mathbf{W}_r^H\right]\le P_{\mathrm{relay}},\ r=1,\cdots,R\ \left(\text{PRPC}\right)\end{aligned}\tag{6}$$

where P_{BS} denotes the maximum power of a BS, $P_{\mathrm{relay}}^{\mathrm{total}}$ denotes the maximum power of total relays, and P_{relay} denotes the maximum power of individual relay. Both schemes which are introduced in order in the next two sections are designed by choosing either RSPC or PRPC in (6). Since (6) is non-convex optimization problem over $\mathbf{T}$, $\mathbf{W}_r$, $\forall r$ and $\mathbf{R}_k$, $\forall k$, it is hard to derive a jointly optimal solution. To make the problem tractable, we decompose it into subproblems, each of which is convex problem. Each subproblem is to determine the BS transmitter with fixed relay precoders and user receivers, to determine relay precoder by fixing the other matrices, and to determine user receiver in a similar way, respectively. We adopt iteration-based methods whose basic iteration stage corresponds to each subproblem. Its iteration continues until the SMSE value finally converges. The proposed design is feasible through a central processing unit with a perfect global CSI.

3. SMSE Minimization under RSPC

3.1 SMSE Duality for MIMO Relay Network

To develop algorithms for efficiently solving $\mathbf{T}$, $\mathbf{W}$, and $\mathbf{R}$ under RSPC, we apply SMSE duality by an SRMU network [20], which is illustrated in **Fig. 2** and described as follows. SMSE duality is a property which means that the SMSE in downlink can be also achieved in dual uplink, and vice versa while the power consumption in downlink is preserved in dual uplink. Assume that a downlink network in which there are single BS, single relay, and K users, and multiple antennas are equipped to all nodes. Predefined transmitter $\mathbf{T}$, precoder $\mathbf{W}$

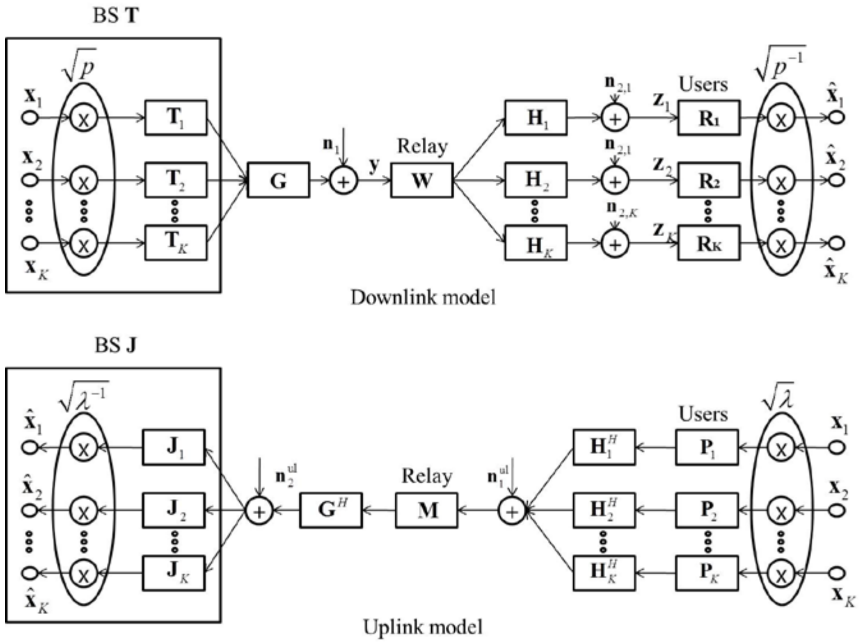

Fig. 2. System model illustration for SMSE duality

and receiver filters $\mathbf{R}_k$ are given to BS, relay and the k^{th} user, respectively. From the given downlink network, we can imagine a network of which the communication direction is reversed and channels are flipped $\left(\mathbf{G} \rightarrow \mathbf{G}^H \text{ and } \mathbf{H} \rightarrow \mathbf{H}^H\right)$. This reversed network is called as dual uplink network. In this network, BS and users act as a receiver and transmitters, respectively. Then we can set up the corresponding dual uplink that consists of a BS receiver $\mathbf{J}$, relay precoder $\mathbf{M}$, and user transmitters $\mathbf{P}_k$. MSE matrices for downlink and dual uplink are given respectively by,

$$\mathbf{E}_{\text{dl}} = \left(\mathbf{RHWGT} - \mathbf{I}_L\right)\left(\mathbf{RHWGT} - \mathbf{I}_L\right)^H + \frac{1}{p}\left(\sigma_1^2 \mathbf{RHWW}^H \mathbf{H}^H \mathbf{R}^H + \sigma_2^2 \mathbf{RR}^H\right) \tag{7}$$

$$\mathbf{E}_{\text{ul}} = \left(\mathbf{JG}^H \mathbf{MH}^H \mathbf{P} - \mathbf{I}_L\right)\left(\mathbf{JG}^H \mathbf{MH}^H \mathbf{P} - \mathbf{I}_L\right)^H + \frac{1}{\nu}\left(\mathbf{JG}^H \mathbf{MM}^H \mathbf{GJ}^H + \mathbf{JJ}^H\right) \tag{8}$$

where $\mathbf{P} = \text{blkdiag}\left[\mathbf{P}_1 \quad \mathbf{P}_2 \quad \cdots \quad \mathbf{P}_K\right]$ the scaling factors p and ν for downlink and uplink, respectively, are employed for power conservation. It is noted in (5) that $\frac{1}{p}$ was already implicitly included in $\mathbf{T}$. Thus, (5) and (7) are essentially equivalent although they have different forms. The downlink power consumptions at BS and relay are given respectively by $P_{\text{BS}}^{\text{dl}} = p\left\|\mathbf{T}\right\|_F^2$ and $P_{\text{relay}}^{\text{dl}} = p\left\|\mathbf{WGT}\right\|_F^2 + \left\|\mathbf{W}\right\|_F^2$. Similarly, uplink power consumptions at users and the relay are given respectively by $P_{\text{user}}^{\text{ul}} = \lambda\left\|\mathbf{P}\right\|_F^2$ and $P_{\text{relay}}^{\text{ul}} = \lambda\left\|\mathbf{MH}^H \mathbf{P}\right\|_F^2 + \left\|\mathbf{M}\right\|_F^2$. SMSE duality provides the rule how to determine $\mathbf{J}$, relay precoder $\mathbf{M}$, and user transmitters $\mathbf{P}$ in dual uplink from given $\mathbf{T}$, $\mathbf{W}$, and $\mathbf{R}$ in downlink, in order for that $\mathrm{tr}\left[\mathbf{E}_{\mathrm{dl}}\right]=\mathrm{tr}\left[\mathbf{E}_{\mathrm{ul}}\right]$ to be hold while conserving power consumption. Following equations explain the rule.

$$\begin{aligned}&\mathbf{J}=\sqrt{\alpha}\mathbf{T}^{H},\ \mathbf{M}=\frac{1}{\sqrt{\alpha}}\mathbf{W}^{H},\ \mathbf{P}=\mathbf{R}^{H}\\&\alpha=\sigma_{1}^{2}\frac{\nu\left\|\mathbf{RHW}\right\|_{F}^{2}+\left\|\mathbf{W}\right\|_{F}^{2}}{p\left\|\mathbf{T}\right\|_{F}^{2}},\ \ \nu=\frac{\left\|\mathbf{WGT}\right\|_{F}^{2}p+\left\|\mathbf{W}\right\|_{F}^{2}}{\left\|\mathbf{R}\right\|_{F}^{2}}\end{aligned}\tag{9}$$

Then $P_{\mathrm{user}}^{\mathrm{ul}}=P_{\mathrm{relay}}^{\mathrm{dl}}$, $P_{\mathrm{relay}}^{\mathrm{ul}}=P_{BS}^{\mathrm{dl}}$ and $\mathrm{tr}\left[\mathbf{E}_{\mathrm{dl}}\right]=\mathrm{tr}\left[\mathbf{E}_{\mathrm{ul}}\right]$. One can easily prove (9) and power conservation rule straightforwardly by some mathematical manipulations, and thus detailed derivation is omitted. In summary, SMSE duality means that SMSE in uplink can be maintained to be same as SMSE in downlink, while power consumption at the users in dual uplink is preserved to the same as power consumption at the relay in downlink, and power consumption at the relay in dual uplink is preserved to the same as power consumption at BS in downlink. SMSE duality is useful to make transceiver design problem be more tractable. For example, a problem to design BS transmitter is switched into receiver design problem, where receiver design problem is generally easier to be solved since it can be modeled as unconstrained optimization problem without power constraints.

3.2 SMSE Minimization Algorithm under RSPC

SMSE duality [20] in a single relay environment can be extended to a multi-relay environment under RSPC since the duality holds in an arbitrary relay matrix which includes a block diagonal structure. The next proposition informs us of relay precoders for SMSE minimization under RSPC in MRMU network.

Proposition 1*: In the downlink MRMU network under RSPC, the* r^{th} *relay precoder for SMSE minimization is given by*

$$\begin{aligned}\mathbf{W}_{r}=&\left(\mathbf{H}_{r}^{H}\mathbf{R}^{H}\mathbf{R}\mathbf{H}_{r}+\lambda_{r}^{\mathrm{RSPC}}p\mathbf{I}_{N_{R}}\right)^{-1}\left(\mathbf{H}_{r}^{H}\mathbf{R}^{H}\mathbf{T}^{H}\mathbf{G}_{r}^{H}-\sum_{l\neq r}\mathbf{H}_{r}^{H}\mathbf{R}^{H}\mathbf{R}\mathbf{H}_{l}\mathbf{W}_{l}\mathbf{G}_{l}\mathbf{T}\mathbf{T}^{H}\mathbf{G}_{r}^{H}\right)\\&\times\left(\mathbf{G}_{r}\mathbf{T}\mathbf{T}^{H}\mathbf{G}_{r}^{H}+\frac{1}{p}\mathbf{I}_{N_{R}}\right)^{-1},\ \forall r=1,\cdots,R\end{aligned}\tag{10}$$

where $\lambda_{r}^{\mathrm{RSPC}}$ is chosen to meet the r^{th} relay's power constraint (12) which will be given below.

Proof: We can expand the objective function in the following way through some matrix manipulations. We work with (7) instead of (5) so that SMSE duality is directly applicable.

$$\begin{aligned}\mathrm{tr}\left[\mathbf{E}_{\mathrm{dl}}\right]=L+\mathrm{tr}\Bigg[&\sum_{k=1}^{K}\sum_{r=1}^{R}\sum_{s=1}^{R}\mathbf{R}_{k}\mathbf{H}_{kr}\mathbf{W}_{r}\mathbf{G}_{r}\mathbf{T}\mathbf{T}^{H}\mathbf{G}_{s}^{H}\mathbf{W}_{s}^{H}\mathbf{H}_{ks}^{H}\mathbf{R}_{k}^{H}\\&+\frac{1}{p}\sum_{k=1}^{K}\sum_{r=1}^{R}\mathbf{R}_{k}\mathbf{H}_{kr}\mathbf{W}_{r}\mathbf{W}_{r}^{H}\mathbf{H}_{kr}^{H}\mathbf{R}_{k}^{H}\\&-\frac{1}{p}\sum_{k=1}^{K}\sum_{r=1}^{R}\mathbf{R}_{k}\mathbf{H}_{kr}\mathbf{W}_{r}\mathbf{G}_{r}\mathbf{T}-\frac{1}{p}\sum_{k=1}^{K}\sum_{r=1}^{R}\mathbf{T}^{H}\mathbf{G}_{r}^{H}\mathbf{W}_{r}^{H}\mathbf{H}_{kr}^{H}\mathbf{R}_{k}^{H}+\frac{1}{p}\sum_{k=1}^{K}\mathbf{R}_{k}\mathbf{R}_{k}^{H}\Bigg]\end{aligned}\tag{11}$$

where subscript k indicates the index of each user and subscript r and s indicate the index of each relay and they are used in those ways for the rest of the paper. In the standpoint the r^{th} relay, subscript l indicates the other relay except for the r^{th} relay, which will be introduced in the rest immediately. It is noted that block diagonal matrix $\mathbf{W}$ can be decomposed into individual block elements as in (11). If we assume that $\mathbf{T}$, $\mathbf{R}$ and $\mathbf{W}_l$, $\forall l \neq r$ are fixed, the problem in (6) can be rewritten as a simpler subproblem composed of input variable $\mathbf{W}_r$, objective function (11) and the r^{th} relay's own power constraint. In this case, the power constraint is given by

$$\mathrm{tr}\left[\mathbf{W}_r\left(\mathbf{G}_r\mathbf{T}\mathbf{T}^H\mathbf{G}_r^H + \sigma_1^2\mathbf{I}_{N_R}\right)\mathbf{W}_r^H\right] \leq P_{\text{relay}}^{\text{total}} - \sum_{l \neq r}\mathrm{tr}\left[\mathbf{W}_l\left(\mathbf{G}_l\mathbf{T}\mathbf{T}^H\mathbf{G}_l^H + \sigma_1^2\mathbf{I}_{N_R}\right)\mathbf{W}_l^H\right] \quad (12)$$

which is determined by modifying RSPC in (6). The simpler subproblem is quadratic constrained quadratic programming (QCQP) since the objective function is quadratic over $\mathbf{W}_r$ and the quadratic constraint on $\mathbf{W}_r$ is given. By the KKT theorem, the desired solution (10) is found. This completes the proof.

As in (10), the determination of $\mathbf{W}_r$ requires the information of other relays' 1st hop channels and the 2nd hop effective channels (denoted by $\mathbf{H}_l\mathbf{W}_l$ in (10)). Moreover, the power constraint of the determination stage of $\mathbf{W}_r$ is coupled with $\mathbf{W}_l$, $\forall l \neq r$ as in (12). Thus relay precoders are sequentially computed in ascending order of index from 1 to R.

In the next step, SMSE duality plays a key role in the determination of the BS transmitter. Using conversion equation (9), the downlink network with fixed $\mathbf{W}$ and $\mathbf{R}$ switches into uplink with fixed $\mathbf{M}$ and $\mathbf{P}$. In the dual uplink network, BS has a role as a receiver. Thus, the optimal $\mathbf{J}$ is determined to be the MMSE receiver as the solution of an unconstrained convex optimization problem. The detailed structure is given by,

$$\mathbf{J} = \mathbf{P}^H\mathbf{H}\mathbf{M}^H\mathbf{G}\left[\mathbf{G}^H\mathbf{M}\mathbf{H}^H\mathbf{P}\mathbf{P}^H\mathbf{H}\mathbf{M}^H\mathbf{G} + \frac{1}{\nu}\left(\mathbf{G}^H\mathbf{M}\mathbf{M}^H\mathbf{G} + \mathbf{I}_{N_S}\right)\right]^{-1} \quad (13)$$

After $\mathbf{J}$ is updated, the optimal $\mathbf{T}$ is achieved instantly by uplink to downlink conversion in a similar way to the above switching method. For given $\mathbf{T}$ and $\mathbf{W}$, the receiver of each user can be determined to following MMSE receiver.

$$\mathbf{R}_k = \mathbf{T}_k^H\mathbf{G}^H\mathbf{W}^H\hat{\mathbf{H}}_k^H\left[\hat{\mathbf{H}}_k\mathbf{W}\left(\mathbf{G}\mathbf{T}\mathbf{T}^H\mathbf{G}^H + \frac{1}{p}\mathbf{I}_{N_R R}\right)\mathbf{W}^H\hat{\mathbf{H}}_k^H + \frac{1}{p}\mathbf{I}_{N_U}\right]^{-1} \quad (14)$$

As we can observe from (14), the determination of $\mathbf{R}_k$ does not need knowledge of $\mathbf{R}_l$, $\forall l \neq r$, which makes it possible to update each $\mathbf{R}_k$ individually. Returning to the stage that updates the relay precoders, the overall design procedure repeats iteratively until the termination criterion is satisfied. The whole procedure is summarized in **Fig. 3**.

3.3 Convergence Property

The subproblem to determine $\mathbf{W}_r$ with given fixed $\mathbf{T}$, $\mathbf{R}$ and $\mathbf{W}_l$, $\forall l \neq r$ is QCQP, which is well known to belong to the categories of convex optimization problem. Thus, the updated $\mathbf{W}_r$ in (10) always provides the global optimal value of the subproblem, which makes the SMSE of the original problem get smaller. Next, downlink to uplink conversion guarantees that SMSE is conserved by SMSE duality in (9). The MMSE receiver at uplink is also achieved as a solution of convex subproblem with given fixed $\mathbf{M}$ and $\mathbf{P}$. Thus, it causes the SMSE to get smaller since the updated SMSE is kept same by uplink to downlink conversion from SMSE duality. Every user determines its own receiver to be the MMSE receiver in (14) as a solution of convex subproblem with fixed $\mathbf{T}$ and $\mathbf{W}$, which results in smaller SMSE. Since SMSE is naturally bounded by zero due to the positive definite structure of MSE matrix and the solution of each subproblem causes SMSE to gradually decrease, the SMSE always converges. However, we cannot guarantee the optimality of the converging point since the original problem is non-convex.

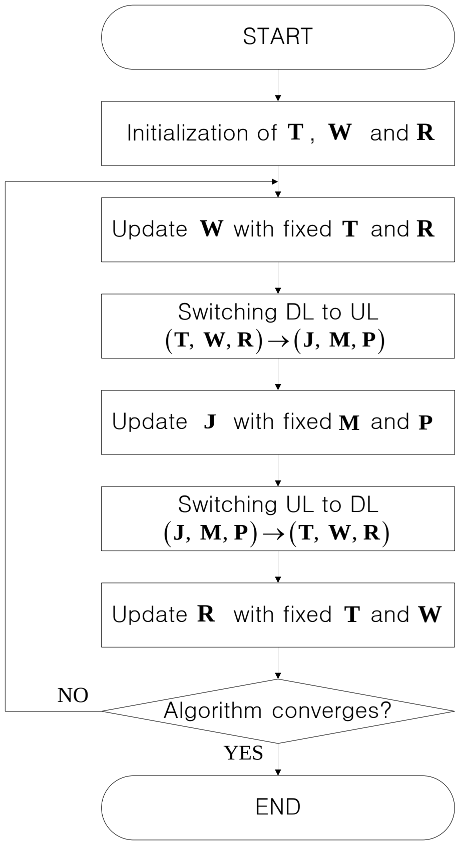

Fig. 3. Flow chart of SMSE minimization under RSPC

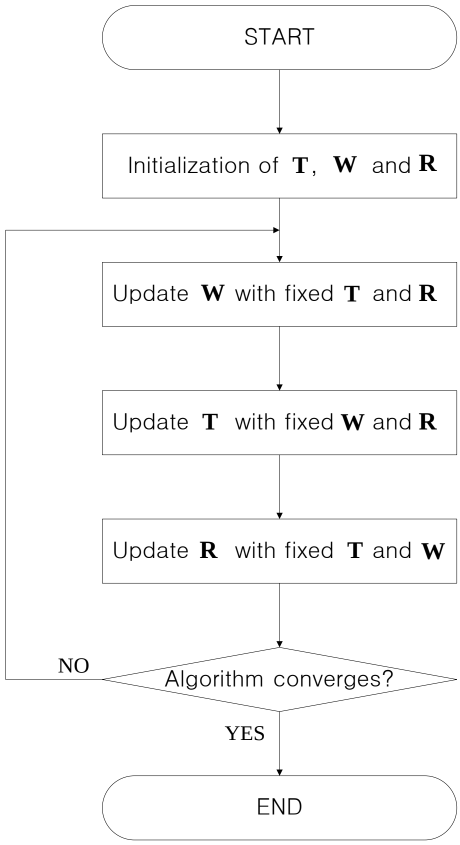

Fig. 4. Flow chart of SMSE minimization under PRPC

4. SMSE Minimization under PRPC

As the first step for investigation on the SMSE achievability in MRMU MIMO network, we assumed RSPC. However, RSPC is not suitable for practical systems since power transfer among multiple relays is impossible. Thus, we continue to discuss a design method for PRPC considering a more practical situation. BS transmitter and relay precoders for SMSE minimization under PRPC are explained in the following proposition. The whole procedure is summarized in **Fig. 4**.

Proposition 2: *In the downlink MRMU system under PRPC, BS transmitter and the r^{th} relay's precoder for SMSE minimization are given respectively by*

$$\mathbf{T} = \left(\mathbf{G}^H \mathbf{W}^H \mathbf{H}^H \mathbf{R}^H \mathbf{R} \mathbf{H} \mathbf{W} \mathbf{G} + \mu_0 \mathbf{I}_{N_S} + \sum_{r=1}^{R} \mu_r \mathbf{G}_r^H \mathbf{W}_r^H \mathbf{W}_r \mathbf{G}_r \right)^{-1} \mathbf{G}^H \mathbf{W}^H \mathbf{H}^H \mathbf{R}^H \tag{15}$$

$$\begin{aligned} \mathbf{W}_r = & \left(\mathbf{H}_r^H \mathbf{R}^H \mathbf{R} \mathbf{H}_r + \lambda_r^{\text{PRPC}} \mathbf{I}_{N_R} \right)^{-1} \left(\mathbf{H}_r^H \mathbf{R}^H \mathbf{T}^H \mathbf{G}_r^H - \sum_{l \neq r} \mathbf{H}_r^H \mathbf{R}^H \mathbf{R} \mathbf{H}_l \mathbf{W}_l \mathbf{G}_l \mathbf{T} \mathbf{T}^H \mathbf{G}_r^H \right) \\ & \times \left(\mathbf{G}_r \mathbf{T} \mathbf{T}^H \mathbf{G}_r^H + \mathbf{I}_{N_R} \right)^{-1}, \forall r = 1, \cdots, R \end{aligned} \tag{16}$$

Proof: The derivation of $\mathbf{W}$ follows much the same way as in proposition 1, except that the individual relay power constraint is suspended. Meanwhile, if we assume that $\mathbf{R}_k$, $\forall k$ and $\mathbf{W}_r$, $\forall r$ are fixed, the problem in (6) can be rewritten as a simpler subproblem of input variable $\mathbf{T}$. In this case, $R+1$ power constraints are given as follows.

$$\text{tr}\left[\mathbf{T}\mathbf{T}^H \right] \le P_{\text{BS}} \tag{17}$$

$$\text{tr}\left[\mathbf{T}^H \mathbf{G}_r^H \mathbf{W}_r^H \mathbf{W}_r \mathbf{G}_r \mathbf{T} \right] \le P_{\text{relay}} - \sigma_1^2 \text{tr}\left[\mathbf{W}\mathbf{W}^H \right], \ \forall r = 1, \cdots, R \tag{18}$$

This subproblem is QCQP since the objective function is quadratic over $\mathbf{T}$ and quadratic constraints on $\mathbf{T}$ are given. The desired solution of (15) is directly achieved by KKT theorem. This completes the proof.

It is noted that the main difference of transceiver design between PRPC and RSPC is in the means of determining BS transmitter. In the design under RSPC, BS transmitter is determined indirectly by using SMSE duality. BS transmitter which is equivalent to a receiver in a dual uplink is determined to be an MMSE receiver. On the contrary, we cannot exploit SMSE duality in the design under PRPC since there are no proper duality studies in any existing literature. We should determine BS transmitter by directly solving the constrained optimization problem directly using the KKT theorem, which is shown in Proposition 2. A one-dimensional or multidimensional search algorithm is used to calculate KKT multipliers of BS transmitter in PRPC, and the rest of the parts including updates of relay precoders and user receivers follow almost the same way as in the RSPC case. $\mathbf{R}_k$ is determined to be an MMSE receiver in (14) with setting $p=1$.

As in the iteration procedure of the SMSE minimization under RSPC, matrix update at each stage yields a non-increasing SMSE value that is lower bounded by zero. The subproblem to determine $\mathbf{T}$ with given fixed $\mathbf{W}$ and $\mathbf{R}$ is QCQP, which is a convex problem. Thus, this causes the SMSE to get smaller. The determination of $\mathbf{W}$ and $\mathbf{R}$ follow exactly the same procedure as RSPC. Thus, the SMSE finally converges through some number of iterations. However, the convergence to local optimum does not always guarantee the achievability of global optimum, since the problem is non-convex as in the case of RSPC.

5. Numerical Results

In this section, SMSE and sum rate performance of the proposed schemes are numerically illustrated. The unit of sum rate is bit per second per hertz (bps/Hz). We denote our proposed schemes as joint BS and multiple relay (JBMR) in this section. Network configuration is specified by (R, K). The number of data streams is assumed to be symmetric over all the users, which means that $L_k = \frac{L}{K}, \forall k$ where L is set to be some multiple of K. Both the 1st hop and the 2nd hop channels experience uncorrelated Rayleigh block fading with unit variances. $P_{\text{relay}}^{\text{total}}$ in JBMR-RSPC is set to be equal to P_{BS}, where relays in JBMR-PRPC have the same transmit power with $P_{\text{relay}} = \frac{P_{\text{BS}}}{R}$. In following figures, SNR is defined as $\frac{P_{\text{BS}}}{\sigma_1^2}$, and $\sigma_1^2 = \sigma_2^2 = 1$. PRPC and RSPC in legends denote JBMR-PRPC and JBMR-RSPC, respectively. Factor p in JBMR-RSPC is initialized to be one, and it is updated at each iteration of the JBMR-RSPC algorithm. Since factor p is meaningless in JBMR-PRPC, however, it is fixed at one in the JBMR-PRPC algorithm operation. For both schemes, initial $\mathbf{T}$ and $\mathbf{W}$ are set as in (19) before the algorithm starts. Each algorithm terminates if the SMSE difference between iterations becomes smaller than a predefined accuracy ε, which is set to be 10^{-6} for both schemes in this subsection. All the users which are distributed in the network are assumed to be simultaneously served by a two-hop relay aided BS simultaneously without consideration of scheduling. Even though the feasibility of the two algorithms are guaranteed on the conditions, $L_k \le N_U, \forall k$ and $L \le \min(N_R R, N_S)$, the number of antennas are assumed for simplicity to be related as $N_S = N_R R = N_U K$, where N_S is set to be some multiple of R and K.

SAF relaying and MMSE relaying, which are denoted respectively by SAF and MMSE in legends, are the most referred schemes in many literatures of MSE performance of relay aided network. For SAF relaying, we set BS transmitter and relay precoders respectively as follows.

$$\mathbf{T} = \sqrt{\frac{P_{\text{BS}}}{L}}\mathbf{I}_{N_S}(1:L),\ \mathbf{W}_r = \sqrt{\frac{P_{\text{relay}}}{\text{tr}\left[\mathbf{G}_r\mathbf{T}\mathbf{T}^H\mathbf{G}_r^H + \sigma_1^2\mathbf{I}_{N_R}\right]}}\mathbf{I}_{N_R}, \forall r = 1, \cdots, R \tag{19}$$

Another noticeable observation can be made from comparison with FRCB. If we assume that full data sharing is available by ideal wireline backhaul over multiple relays, overall relays are effectively equivalent to a single giant relay of all relay antennas. Certainly, the SMSE of FRCB outperforms our proposed scheme. [9] has developed a joint design method of BS transmitter and relay precoder in a single relay aided environment which provides the best SMSE performance, to the best of author's knowledge. The SMSE minimization scheme in [9] is applicable to a single giant relay network, which we denote as FRCB. Since our research lays emphasis on observing the ultimate achievability in MRMU MIMO network, we will compare JBMR-RSPC and JBMR-PRPC with the single giant relay of the SMSE minimization scheme [9], which we think will give some insight into the effectiveness of our proposed algorithm.

5.1 Comparison of Power Consumption at Relays and Convergence Speed

Fig. 5 compares average total power consumptions at relays of JBMR-RSPC and JBMR-PRPC with maximum power P_{BS} in a $(2,3)$ network when $L = N_S = 6$. In all SNR regions, power consumptions at all relays satisfy relay power constraint. JBMR-PRPC consumes about 83.91% of P_{BS} when SNR = 40 dB, while it requires maximum power when SNR = 0 dB. This implies that proper transmit power control would be needed to achieve optimal SMSE in an interference limited region of high SNR, while it would not be effective in the noise limited region of low SNR. This is due to the fact that unnecessarily large power of relays may produce interstream interference in the interference limited region. JBMR-RSPC is observed to consume about 98.89% of P_{BS} when SNR = 40 dB which is higher than that of JBMR-PRPC. Since JBMR-RSPC has a more relaxed power constraint than JBMR-PRPC, it can perform more flexible power controls over multiple relays within the maximum power limit P_{relay}^{total} . Thus, JBMR-RSPC can provide slightly improved SMSE and sum rate performance, which is to be verified through SMSE results in as **Fig. 7** and **Fig. 8.** Detailed explanation of **Fig. 7** and **Fig. 8** will be presented in the following subsection.

Fig. 6 illustrates sample realizations of two schemes to verify their convergence when SNR = 20 dB in the same network configuration. SMSE converges within about 10 iterations, expecting that one can achieve the convergence without an excessively large number of iterations. It also monotonically decreases the SMSE, as expected in section 3 and 4.

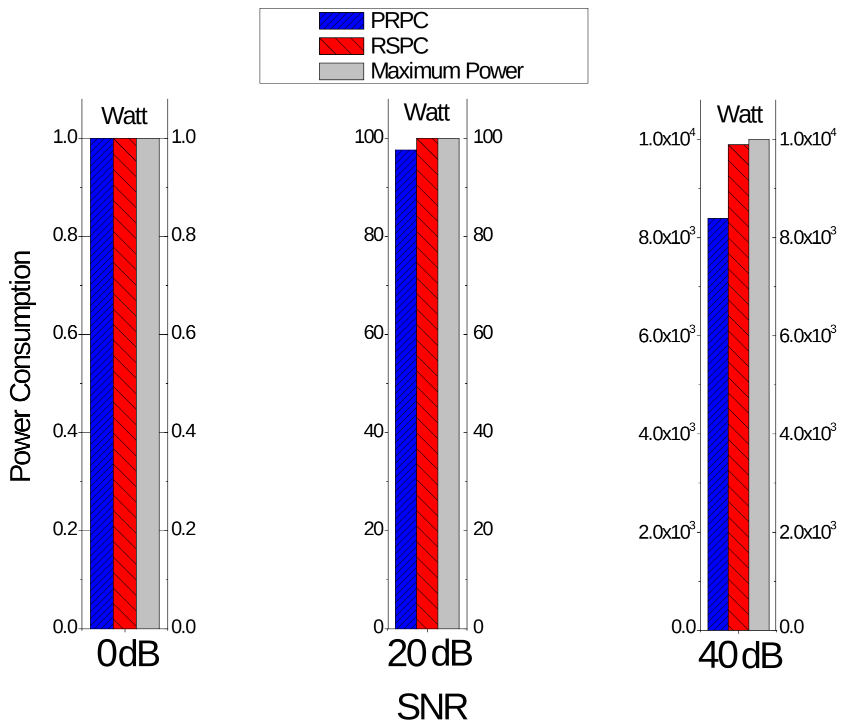

Fig. 5. Required Power at Relays when $L = N_S = 6$ in the $(2,3)$ network

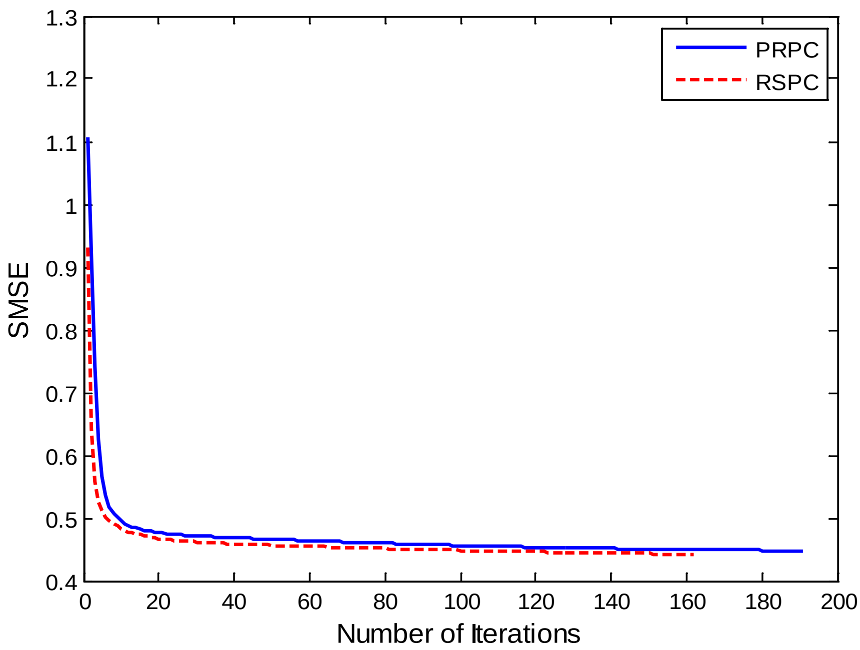

Fig. 6. Convergence of JBM-RSPC and JBMR-PRPC with $\varepsilon = 10^{-6}$ when $L = N_S = 6$ in the $(2,3)$ network

5.2 Comparison of SMSE

Fig. 7 and **Fig. 8** display the comparisons of SMSE in the $(2,3)$ network with $N_S = 6$, and $(2,4)$ network with $N_S = 8$, respectively. In a high SNR region, JBMR-RSPC and JBMR-PRPC provide approximately the same SMSE. JBMRs are shown to outperform SAF and MMSE relaying schemes for both network configurations. In the $(2,3)$ network of L=3, JBMR-PRPC achieve about 9 dB gain over MMSE relaying at an SMSE of 10^{-2}. In the $(2,4)$ network of L= 4, JBMR-PRPC obtain 10.5 dB gain over MMSE relaying at SMSE of 10^{-2}. When data streams are transmitted with full rank (in the cases of L = 6 and L = 8 in **Fig. 7** and **Fig. 8**, respectively), SMSE of MMSE relaying are significantly degraded in all SNR regions, while SMSE of JBMRs keep decreasing with increasing SNR. This indicates that interstream and inter-user interference cannot be mitigated by SAF and MMSE relaying when full rank data streams are transmitted. In contrast, JMBRs control interstream and inter-user interference successfully.

Remarkably, it is shown that JBMR-RSPC and JBMR-PRPC provide comparable SMSE with FRCB in all SNR ranges. In the $(2,4)$ network, JBMR-PRPC are 1 dB from FRCB at an SMSE of 10^{-1} if L = 8 and only 0.5 dB from FRCB at an SMSE of 10^{-2} if L = 4. A similar result is observed for the case of $(2,3)$ network. Other various network configurations simulations showed similar trends, which have been omitted due to the limited space of this section. Thus, it is noted that comparable performance to that of a single giant relay can be achieved by partial cooperation of multiple relays if a global CSI is available at the node with central processing.

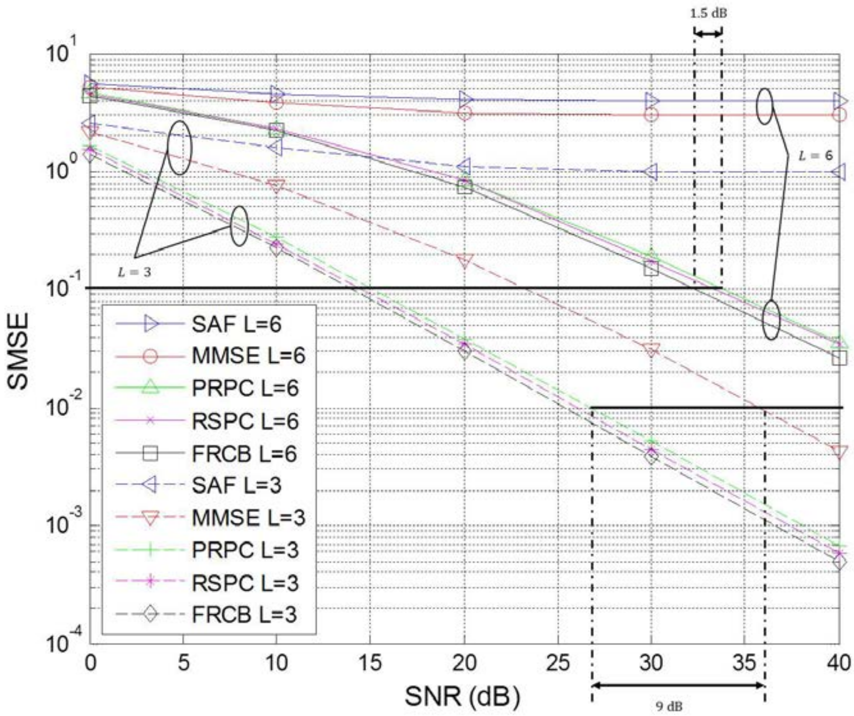

Fig. 7. SMSE comparison of various relaying schemes when L =3, 6 and $N_S = 6$ in the $(2,3)$ network

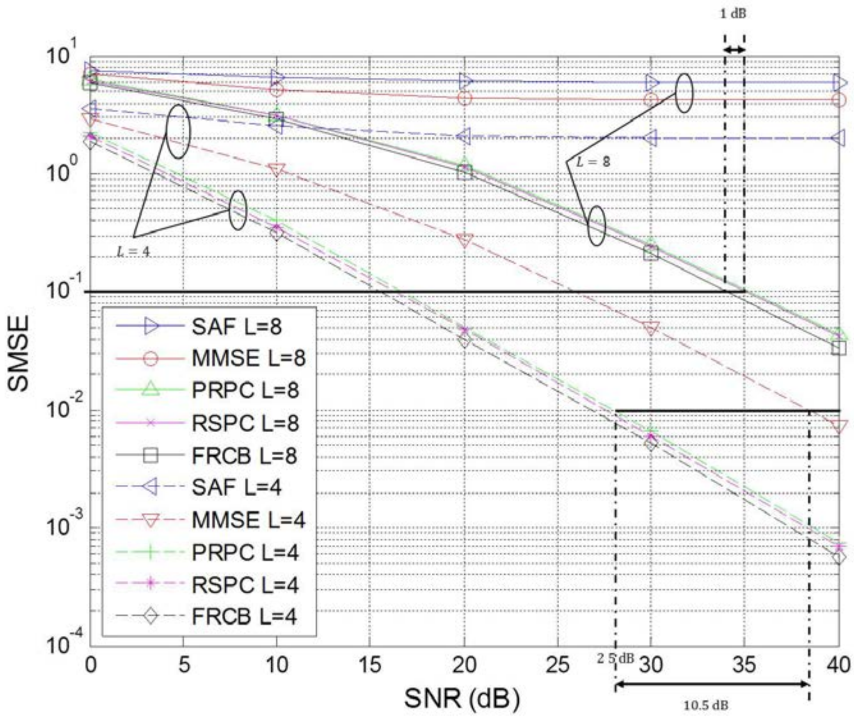

Fig. 8. SMSE comparison of various relaying schemes when L = 4, 8 and $N_S = 8$ in the $(2,4)$ network

5.3 Comparison of Sum Rate

For the same relaying networks in the preceding subsection, sum rate performances are compared in **Fig. 9** and **Fig. 10**. It is observed that characteristics of sum rate performance exactly follow those of SMSE in **Fig. 7** and **Fig. 8**. That is, JBMR-RSPC and JBMR-PRPC always outperform SAF and MMSE relaying in sum rate performance, and they provide comparable sum rate performances to that of FRCB. More specifically, JBMR-PRPC outperform MMSE relaying in sum rate by about 52.01% and 50.2%, respectively, in the $(2,3)$ network with $L=3$ and the $(2,4)$ network with $L=4$ when SNR = 30 dB. In addition, sum rates achieved by JBMR-PRPC are about 98% of that of FRCB and 97.1%, respectively, in the $(2,3)$ network with $L=6$ and the $(2,4)$ network with $L=8$ when SNR = 30 dB. The SMSE and sum rate performances verify that the JBMR-RSPC and JBMR-PRPC is a very efficient relaying scheme which can be an alternative to FRCB.

Sum rate performances for the $(2,4)$ network with $N_S=16$ are compared according to various numbers of data streams in **Fig. 11**. Simulation result implies that JBMR provides near optimal performance in terms of sum rate despite of convergence to local optimal point. Even though relays do not share received data at each relay, BS does a crucial role of sharing and processing data so that it can improve sum rate. Thus, joint processing of BS and relay can be considered as a single giant node with some minor constraints, which makes it possible for JBMR to achieve performance close to that of FRCB.

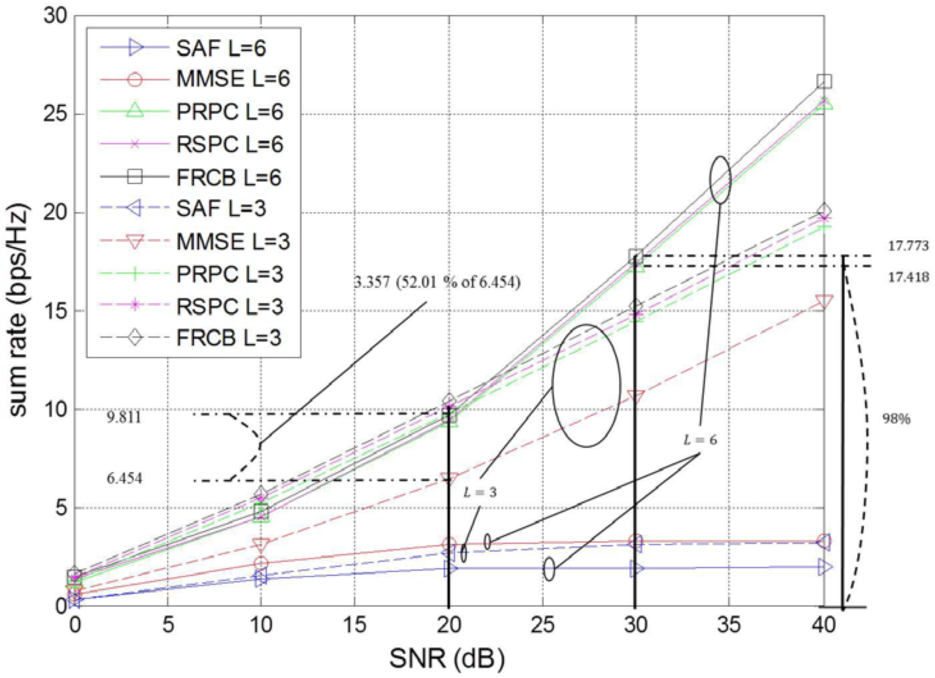

Fig. 9. Sum rate comparison of various relaying schemes when L =3, 6 and $N_S=6$ in the $(2,3)$ network

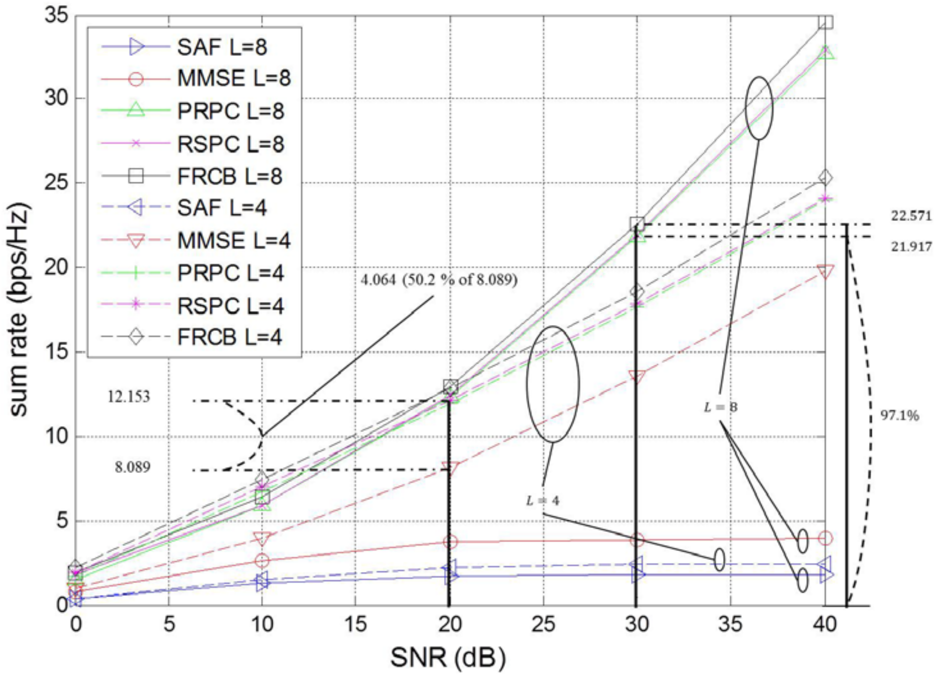

Fig. 10. Sum rate comparison of various relaying schemes when $L = 4$, 8 and $N_S = 8$ in the $(2,4)$ network

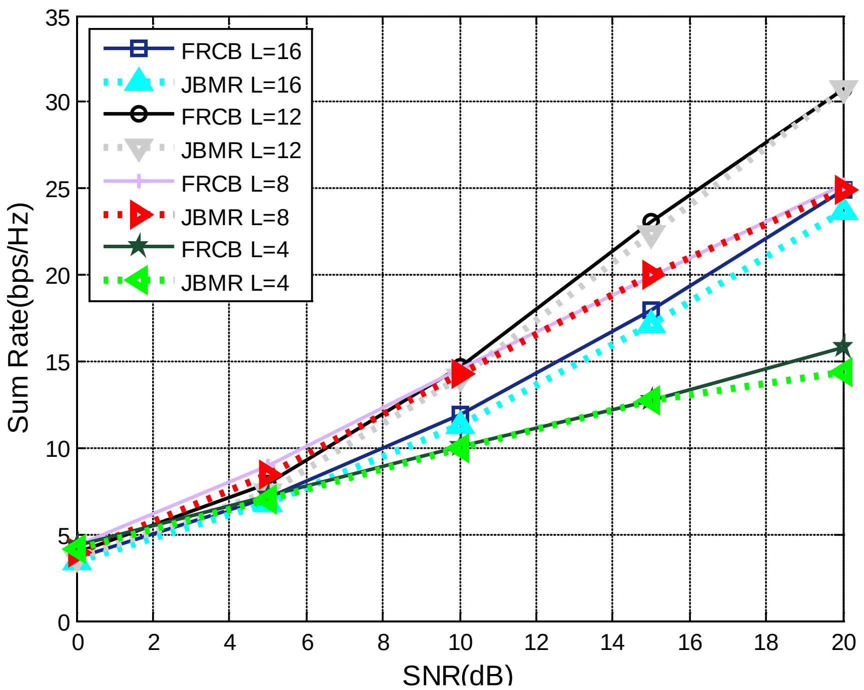

Fig. 11. Sum rate comparison of JBMR and FRCB with various number of data streams when $N_S = 16$ in the $(2,4)$ network

It is observed that the number of data streams which achieves the largest sum rate depends on SNR. As in conventional single user MIMO in a point to point communication, the number of data streams achieving the largest sum rate gets larger with increasing SNR. L = 8 and L = 12 are found to be the best for SNRs of 5dB and 15dB, respectively. Sum rate of L = 16 outperform others in the higher SNR region than 80dB, which is omitted in the figure since it is unrealistic region.

6. Conclusion

In this paper, we proposed an iterative joint linear transceiver design of BS transmitter, relay precoders, and receivers for users of MRMU MIMO network. Exploiting both uplink-downlink duality and the KKT theorem in the convex optimization theory, the proposed transceiver with RSPC design could be easily calculated to minimize the SMSE. SMSE minimization design with PRPC could be easily achieved only by the KKT theorem. We adopted suboptimal sequential iteration designs and both schemes surely converged. The numerical results showed that the proposed design provided very good performance close to the FRCB while outperforming the conventional MMSE relaying schemes in terms of both SMSE and sum rate. Even though the proposed scheme made a step to investigate transceiver design for MRMU MIMO network, there are still many issues yet to be resolved. The perfect CSI cannot be available in practice due to limited backhaul capacity. Imperfect CSI should be additionally considered for robust transceiver design. Furthermore, PAPC environment should be considered as the most realistic power constraint. These problems will be addressed thoroughly in future research.

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Young-Min Cho received his B. S. degree in Electrical and Electronic Engineering from Yonsei University, Seoul, Korea, in 2007, where he is currently working toward the Ph. D. degree since 2007. His main research interests include multi-cell multi-user MIMO, cooperative relay, energy efficient coomunication network.

Janghoon Yang received his Ph.D. in Electrical Engineering from University of Southern California, Los Angeles, USA, in 2001. He is currently an Assistant Professor at the Department of Newmedia, Korean German Institute of Technology, Seoul, Korea. From 2001 to 2006, he was with communication R&D center, Samsung Electronics. From 2006 to 2009, he was a Research Assistant Professor at the Department of Electrical and Electronic Engineering, Yonsei University. He has been a Professor in the Department of Korean German Institute of Technology, Seoul, since 2010. He has published numerous papers in the area of multi-antenna transmission and signal processing. His research interest includes wireless system and network, artificial intelligence, neuroscience, and brain computer interface.

Jeongwook Seo received the B.S. and M.S. degrees from the Department of Telecommunication and Information Engineering, Korea Aerospace University, Gyeonggi, Korea, in 1999 and 2001, respectively, and the Ph.D. degree from the School of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea, in 2010. He is currently an Assistant Professor at the Department of Information and Communication Engineering, Namseoul University, Chungcheongnam-do, Korea. From 2001 to 2013, he was with Network Convergence Research Center in Korea Electronics Technology Institute, Seoul, Korea. His research interests include statistical signal processing for communications and networking, protocol design for Machine-to-Machine/Internet of Things, and software development of next-generation broadcasting and communication systems.

Dong Ku Kim received the B. Eng. Degree from Korea Aerospace University, Korea, in 1983, and the M. Eng. and the Ph. D. degrees from the University of Southern California, Los Angeles, in 1985 and 1992, respectively. He was a Research Engineer with the Cellular Infrastructure Group, Motorola by 1994, and he has been a Professor in the School of Electrical and Electronic Engineering, Yonsei University, Seoul, since 1994. He was a Director of Radio Communication Research Center at Yonsei University and also a Director of Qualcomm Yonsei CDMA Joint Research Lab since 1999. His main research interests are next generation (5G) communication, small cell technology, interference alignment, cooperative relaying network, and compressive sensing. Prof. Kim is currently a director of Journal of Communications and Networks.