Scattering Matrix Design of Reconfigurable Intelligent Surface Based on Group Connected Impedance Network in MU-MIMO System

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***Abstract*—Reconfigurable intelligent surface (RIS) is considered as a promising technology for next-generation 6G wireless system by controlling the propagation environment that degrades the quality of received signals in wireless communication. In contrast to the conventional RIS architecture in which an impedance of each RIS element is grounded, the general architecture having an impedance network connected to each other element can more flexibly control the signal. The computational complexity by optimization of the scattering matrix of the general RIS architecture increases according to the size of the channel matrix. Therefore, as the number of users increases, high computational complexity is paid for optimizing the scattering matrix. This paper proposes the effective scattering matrix design for RIS based on group connected impedance network in multi-user multiple-input multiple-output(MU-MIMO) wireless communication systems. By limiting the number of supported users per group to one, it is possible to effectively reduce computational complexity and ensure appropriate performance compared to the optimization of the scattering matrix that maximizes the channel gain of all users.**

***Index Terms*—6G, MU-MIMO, Reconfigurable intelligent surfaces, Impedance network, Non-diagonal scattering matrix, mm Wave.**

I. Introduction

The focus of the wireless research community is currently shifting beyond the fifth-generation (B5G) and sixth-generation (6G) wireless networks, from the perspective that the fifth-generation (5G) does not have a single enabling technology that can support all the requirements of enhanced mobile broadband, ultra-reliable and low-latency communications, and massive machine type communications [1]. Reconfigurable intelligent surface (RIS) also called as intelligent reflecting surface (IRS) is one of the promising communication technologies for B5G and 6G wireless networks, which is a low-cost, energy-efficient, and spectrum-efficient method. RIS allows telecommunication operators to intelligently reconfigure the radio wave environment that degrades the received signal quality, and then significantly improves the data rate and reception reliability without additional spectrum [2].

The conventional RIS is assumed that each element is independently controlled by an adjustable impedance that is always connected to ground [3]. Recently, it has been generalized by connecting all or some of the RIS elements through a reconfigurable impedance network [4], and this architecture allows more flexible beam controlling than conventional RIS [5]. However, since this structure has a non-diagonal scattering matrix in contrast to the diagonal scattering matrix of the conventional architecture [4], high computational complexity is required to optimize the scattering matrix as the size of the channel matrix increases. Therefore, the optimization of the scattering matrices of group and fully connected RIS in a multi-user multiple-input multiple-output (MU-MIMO) wireless communication system results in high computational complexity. Therefore, while the proper performance is enusured, the effective optimization of the general structure for the scattering matrix is a challenging issue.

In this paper, we propose the effective scattering matrix optimization of RIS based on group connected impedance network in MU-MIMO system. First, we select one supported user for each group while unsupported users are eliminated. Second, a scattering matrix that maximizes the channel gain of the selected user for each group is optimized.

II. SYSTEM MODEL & PROBLEM DESCRIPTION

A. NOTATION

Vectors and matrices are denoted with bold lower and bold upper letters, respectively. $|a|$, and $\arg(a)$ refer to the modulus and phase of a complex scalar a, respectively. $[\mathbf{a}]_i$ and $\|\mathbf{a}\|$ refer to the i-th element and 2-norm of vector $\mathbf{a}$, respectively. $\mathbf{A}^T, \mathbf{A}^H$, $[\mathbf{A}]_{i,j}$, and $\|\mathbf{A}\|$ refer to the transpose, conjugate transpose, the (i, j)-th element, and spectral norm of matrix $\mathbf{A}$, respectively. $\mathbb{R}$ and $\mathbb{C}$ denote the real and complex number sets, respectively. $j = \sqrt{-1}$ denotes the imaginary unit. $\mathbf{0}$ and $\mathbf{I}$ denote an all zero matrix and an identity matrix, respectively, with appropriate dimensions. $\mathcal{CN}(\mathbf{0}, \mathbf{I})$ denotes the distribution of a circularly symmetric complex Gaussian random vector with mean vector $\mathbf{0}$ and covariance matrix $\mathbf{I}$ and $\sim$ stands for "distributed as". diag $(a_1, \cdots, a_N)$ refers to a diagonal matrix with diagonal elements with $a_1, \cdots, a_N$. diag $(\mathbf{A}_1, \cdots, \mathbf{A}_N)$ refers to a block diagonal matrix with blocks with $\mathbf{A}_1, \cdots, \mathbf{A}_N$.

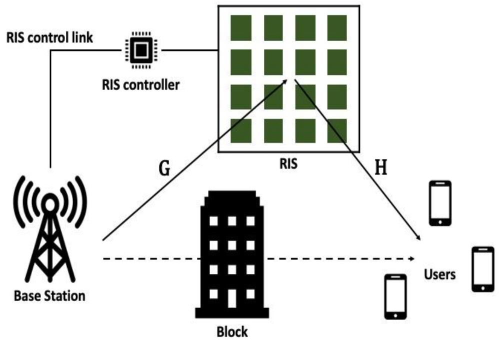

Fig. 1. RIS-aided MU-MIMO wireless communication system model.

B. SYSTEM MODEL

Fig. 1 shows a RIS-aided MU-MIMO wireless communication system, including a base station (BS) equipped N_T transmit antennas, N_K users equipped N_R transmit antennas, and a RIS with N_I passive reflecting elements that are connected to N_I-port reconfigurable impedance network, with scattering matrix $\mathbf{\Theta} \in \mathbb{C}^{N_I \times N_I}$. The reconfigurable impedance network of RIS is dynamically adjusted and determined by a smart controller attached to the RIS, which also acts as a gateway to exchange the control information between the BS and the RIS. Let $\mathbf{s} = \left[s_1; s_2; \cdots; s_{N_K}\right] \in \mathbb{C}^{N_K \times 1}$ be the transmit symbol vector, $\mathbb{E}\left\{\mathbf{s}\mathbf{s}^H\right\} = \mathbf{I}_{N_K}$. The transmit symbols are first precoded at the BS by a precoder matrix $\mathbf{W} = \left[\mathbf{w}_1, \mathbf{w}_2, \cdots, \mathbf{w}_{N_K}\right] \in \mathbb{C}^{N_T \times N_K}$ with the constraint $\|\mathbf{W}\| \leq P_T$, where $\mathbf{w}_k \in \mathbb{C}^{N_T \times 1}\left(k = 1, 2, \cdots, N_K\right)$ is the precoding vector for user k and P_T is the transmitted power from BS. In this paper, we adopt the zero-forcing (ZF) method for the precoder vector.

If the direct channel from the BS to the users is blocked, the channels from the BS and to RIS and from the RIS to users are denoted as $\mathbf{G} = \left[\mathbf{g}_1, \mathbf{g}_2, \cdots, \mathbf{g}_{N_T}\right] \in \mathbb{C}^{N_I \times N_T}$, where $\mathbf{g}_t \in \mathbb{C}^{N_I \times 1}\left(t = 1, 2, \cdots, N_T\right)$ represents the channel vector from the tth BS antenna to the RIS elements and $\mathbf{H} = \left[\mathbf{h}_1; \mathbf{h}_2; \cdots; \mathbf{h}_{N_K}\right] \in \mathbb{C}^{N_R N_K \times N_I}$, where $\mathbf{h}_k \in \mathbb{C}^{N_R \times N_I}\left(k = 1, 2, \cdots, N_K\right)$ represents the channel matrix from the RIS to the kth user respectively. Therefore, the recieved signal is represented as follows,

$$\mathbf{Y} = \mathbf{H\Theta G W s} + \mathbf{n}, \tag{1}$$

where $\mathbf{n} \sim \mathcal{CN}\left(\mathbf{0}, \sigma_n^2 \mathbf{I}\right)$ is the additive white Gaussian noise (AWGN) at the users.

The impedance matrix of the N_I-port reconfigurable impedance network is denoted as $\mathbf{Z}_I \in \mathbb{C}^{N_I \times N_I}$. According to network theory [5] , $\mathbf{\Theta}$ is expressed as follows,

$$\mathbf{\Theta} = (\mathbf{Z}_I + Z_0\mathbf{I})^{-1}(\mathbf{Z}_I - Z_0\mathbf{I}), \tag{2}$$

where Z_0 refers to the refernce impedance and usually is set as $Z_0 = 50\Omega$. And the scattering matrix has equivalent constraints $\mathbf{\Theta} = \mathbf{\Theta}^T, \mathbf{\Theta}^H\mathbf{\Theta} = \mathbf{I}$, therefore, $\mathbf{\Theta}$ should satisfy the complex symmetric unitary matrix. To maximize the power reflected by RIS, $\mathbf{Z}_I$ is purely reactive and is expressed $\mathbf{Z}_I = j\mathbf{X}_I$, where $\mathbf{X}_I \in \mathbb{R}^{N_I \times N_I}$ referes the reactance matrix of the N_I-port reconfigurable impedance network and $\mathbf{X}_I = \mathbf{X}_I^T$. In the group connected architecture, the N_I elements are divided into N_G groups, and each group has $G = N_I/N_G$ elements. Each element is connected to all other elements in its group. Therefor, $\mathbf{X}_I$ is a block diagonal matrix given as follows,

$$\mathbf{X}_I = \text{diag}(\mathbf{X}_{I,1}, \mathbf{X}_{I,2}, \cdots, \mathbf{X}_{I,N_G}), \tag{3}$$

where $\mathbf{X}_{I,g} \in \mathbb{R}^{G \times G}(g = 1, 2, \cdots, N_G)$ satisfies $\mathbf{X}_{I,g} = \mathbf{X}_{I,g}^T$. According to (3), $\mathbf{\Theta}$ is a block diagoanl matrix as follows,

$$\mathbf{\Theta} = \text{diag}(\mathbf{\Theta}_1, \mathbf{\Theta}_2, \cdots, \mathbf{\Theta}_{N_G}), \tag{4}$$

where $\mathbf{\Theta}_g = (j\mathbf{X}_{I,g} + Z_0\mathbf{I})^{-1}(j\mathbf{X}_{I,g} + Z_0\mathbf{I})$ satisfies $\mathbf{\Theta}_g = \mathbf{\Theta}_g^T$ and $\mathbf{\Theta}_g^H\mathbf{\Theta}_g = \mathbf{I}$.

C. PROBLEM FORMULATION

We formulate the channel gain maximization problem in RIS-aided MU-MIMO system and our goal is to design the scattering matrix to maximize the channel gain given by $|\mathbf{H\Theta G}|^2$. Therefore the problem is formulated as follows,

$$\max_{\mathbf{\Theta}} \quad f_o(\mathbf{\Theta}) = |\mathbf{H\Theta G}|^2. \tag{5}$$

III. PROPOSED OPTIMIZATION SCATTERING MATRIX OF THE RIS

Equation (5) is a RIS scattering matrix optimization problem. It is an unconstrained problem which optimizes unconstrained variables $[\mathbf{X}_{I,g}]_{i,j}$ for $i \leq j$. To solve the unconstrained optimization problem, the quasi-Newton method in MATLAB is used [6]. But because of the size of the channel matrix between the RIS to multi-user, computational complexity of optimization is more complex than single-user system. To reduce the computational complexity, each group supports one user with maximum channel gain corresponding the group. When the group selects a user to support, from the $N_G - (N_K - 1)$-th group, the selected users so far are checked. If there are unsupported users, a user from among the unsupported users is selected. Algorithm 1 refers to the supported user selection returned.

To optimize the scattering matrix using the Algorithm 1, the scattering matrix with the maximum channel gain for the selected user is optimized. Therefore the problem is reformulated as follows,

$$\max_{\mathbf{\Theta}_g} \quad \left|[\mathbf{H}]_{\mathbf{k},(\mathbf{g}-\mathbf{1})\mathbf{N_G}+\mathbf{1}:\mathbf{g}\mathbf{N_G}} \mathbf{\Theta_g} [\mathbf{G}]_{(\mathbf{g}-\mathbf{1})\mathbf{N_G}+\mathbf{1}:\mathbf{g}\mathbf{N_G},:}\right|^2. \tag{6}$$

We can solve the equation (6) by using the quasi-Newton method in MATLAB with Broyden–Fletcher–Goldfarb–Shanno (BFGS) update.

Algorithm 1 Supported User Selction per Each Group

INPUT: $N_K, N_G, \mathbf{G}, \mathbf{H}$
OUTPUT: **Selected_User**

```
Selected_User = 0
for i = 1 : N_G dohttp://www.ieee.org/index.html
    HG = |[H]_{k,(i-1)N_G+1:iN_G} [G]_{(i-1)N_G+1:iN_G,:}|^2
    S = max_k |HG|
    if i == N_G - (N_K - 1) then
        NU = 0
        for j = 1 : N_K do
            NU(j) = size(find(Selected_User == j))
        end for
        if size(find(NU == 0)) > N_G - N_K then
            |HG| (NU ≠ 0) = 0
            S = max_k |HG|
        end if
    end if
    Selected_User(i) = S
end for
```

TABLE I
SIMULATION SETTINGS

Parameters	Value
Rician factor	3 [dB]
β	2.2 [dB]
Noise Power	-120 [dBm]
L_0	-30 [dB]
N_T	8
N_R	1
N_K	3
G	4

IV. SIMULATION RESULTS

In this section, we present simulation results of a RIS-aided MU-MIMO system with proposed scattering matrix. In this paper, it is assumed that a three-dimensional (3D) scenario is considered. The BS is located at (0,0,25), the RIS is located (50,5,5) and 3 users is randomly located at a distance of 5m around RIS. For the communication channels, both small-scale and large-scale fading are considered. The distance-dependent pathloss model of large-scale fading is given by $L(d) = L_0(d/d_0)^{-\beta}$, where L_0 refers to the pathloss at the reference distance d_0, d refers to the distance and β is the path loss exponent. Rician fading is assumed for small-scale fading of all channel. The other simulation settings are indicated in Table 1.

Fig. 2 and Fig. 3 show that for all scheme, the sum-rate increases as N_I and P_T increase. And the results show that the Group-connected RIS architecture has higher performance than the conventional RIS architecture. Also, the proposed algorithm has slightly reduced performance over the sum-rate performance of optimal state for all channels. However, when optimization is performed, the computational complexity of the received power in each optimization is given by

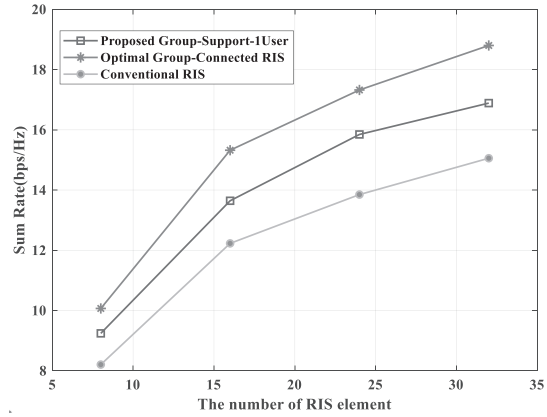

Fig. 2. Sum-rate vs the number of RIS elements when P_T is 50dBm.

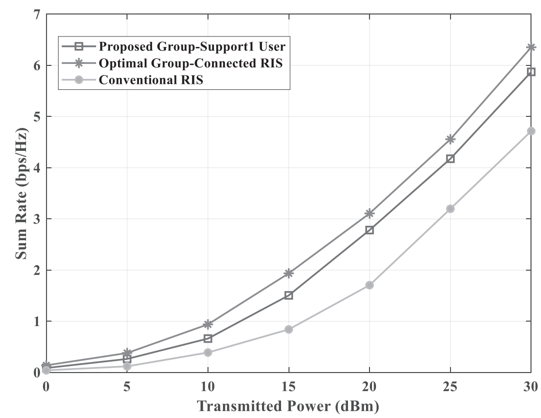

Fig. 3. Sum-rate vs transmitter power when N_I is 8.

$O(N_G^2(N_G-1))(N_G(N_T N_G(N_G-1))))$ for the proposed algorithm and $O(N_K(N_G^2(N_G-1))(N_G(N_T N_G(N_G-1))))$ for the optimal state for all channel, it has a much lower complexity. Accordingly, it can be confirmed that the proposed algorithm reduces complexity and guarantees appropriate sum-rate performance by limiting the number of supported users per group to one in the conventional method.

V. CONCLUSION

In this paper, we propose scattering matrix design of RIS based on group connected impedance network in MU-MIMO wireless communication system. The scattering matrix is obtained through optimization that maximizes the channel gain for the user after selection of the supported user for each group. When users to support by group are selected, there were no unsupported users. The proposed design is lower computational complexity than the optimal state of all user channels and guarantees appropriate sum-rate performance. In future studies, effective impedance network grouping and scattering matrix design in other frameworks for improving sum-rate performance of the system should be considered.

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