Compact User Specific Reconfigurable Intelligent Surface for Uplink Transmission

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Abstract—**New next generation base-station are designed to do more processing with very large-scale antenna arrays. But their is a size constraint beyond which base-station can not be extended also cost is a factor. So as a new emerging technology of IRS can be used to tackle both size and cost constraint of Base station. This is a new way to use IRS, which is using the IRS at user side instead of base station, with a different architecture that most suited this idea. This category of using RIS is called user-specific RIS (US-RIS). Target performance which may be most suited this idea is achieved using a multi-layer architecture of transmissive RIS(s), by using this stricture at the user-equipment we can able to get a new degree of freedom (dof) which is controlling the amplitude of signal with phase. This structure is made very compact i.e very small form factor. First we form expression of a signal to noise ratio (SNR) for this multi-layer structure aided communication, which turns out to be non-convex optimization problem then we introduce a multi-layer design of transmit beam forming which is reley on iterative algorithm fosr settling to a more optimized design. And in last we will show numerical the performance of our design.**

Index Terms—**Reconfigurable intelligent surfaces (RIS), user-specific reconfigurable intelligent surfaves (US-RIS), base statoin specific RIS, multi-layer structure, transmit beamformer design.**

I. Introduction

DUE to increase in advancement in communications like internet of things (IoT) which increased the number of devices exponential and so the demand of access points also will be increases exponentially. In down-link transmission MIMO is evolved technology which increases the performance in downlink transmission.

But in case of uplink transmission, large scale antenna array is very much impossible due to the reason that, large array generates large beam forming gain, which enhances the capacity and area of coverage but with larger number of radio frequency components like RF chain and phased array which gives rise to the bulkiness in the circuit with higher cost and excessively larger power consumption.

Now, question arises what is the remedy to this problem.

A. Motivation

As the previous question suggest, RIS is a new emerging technology which is light, low cost and negligible power consuming device, these properties solves the question. But now question arises that in what fashion does this new RIS concept should be implemented to tackle the problem. Which is clear that a compact multilayer structure of transmissive RIS is being used to give a solution to our scenario.

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B. Contributions

Re-configurable intelligent surface are made of elements taken in large quantity and with low economic price, these elements are able to reflect or transmit the incoming incident electromagnetic waves. If we use this, elements can give a combine effect to direct these wave in desired specific direction by the application of phase shift modification of each individual elements by controlling [1], [2]. Also the important thing is that radio frequency components which are used traditionally are heavy and energy requirements are also high [3], where as the concept which are emerging largely nowadays of RIS are largely passive or require negligible power for operation [4]–[8].

The primary application of RIS which more often used is of using RIS in multi-hope communication protocol, in which RIS is placed at a location between source and destination so that additional path links can be added which results in increasing the signal to noise ration at destination by increasing the diversity gain. [1]. In [9], RIS devices are being used to reduce the total power with optimization of phase shift to get a desired result.

The secondary application is to provide beam forming which is of at base station side with minimal cost and maintenance with the expense of low power. In [10] give us a RIS based architecture for precoding to maximize the final rate.

So as described above one can see that much work has been done in both of the application given above and advances has been done. But till now their is a need to go for an different application using RIS which is obvious that it will used at user side, with some different architectures.

C. Our contributions

To reduces the size and gaining the beam forming advantage from the RIS at user side, we are proposing the a multi-layer architecture of transmissive RIS, with a beam forming design while optimizing the signal to noise ratio. This can be summaries in points as follows.

- we are proposed the a design to tackle the size problem and improve the performance of uplink transmission using the RIS, to get a cheaper and sustainable innovative solution by providing and explaining the concept of user-specific reconfigurable intelligent surface.

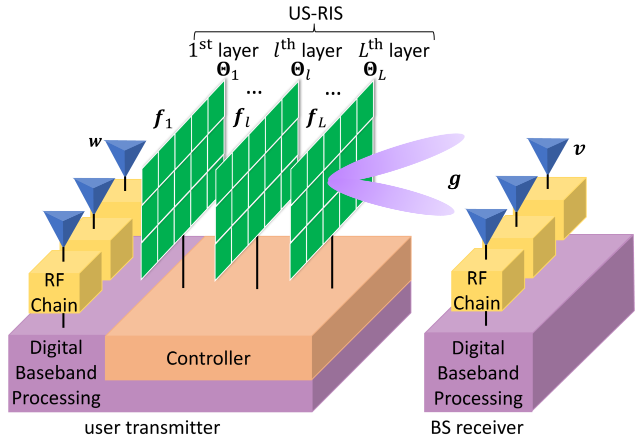
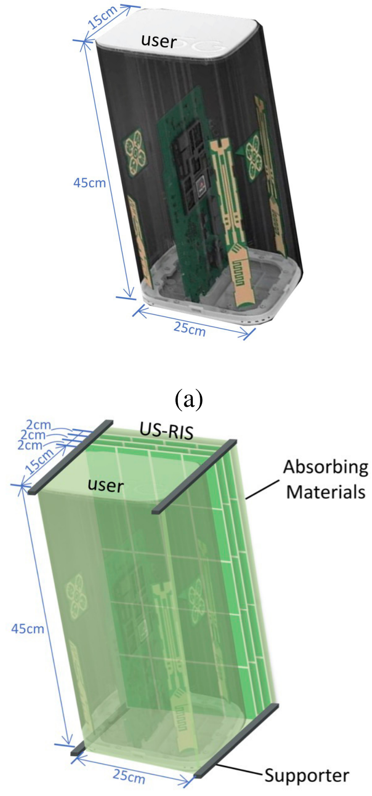


Fig. 1: The uplink transmit beamforming (UL-TBF) vector w, as well as the transmit phase shifter (TPS) matrices $\mathbf{\Theta}_1, \cdots, \mathbf{\Theta}_L$, are used in a system model for US-RIS-aided uplink transmission from a user to the BS. $\mathbf{\Theta}_1, \cdots, \mathbf{\Theta}_L$, Over wireless channels, the receiver combining (RC) vector $\boldsymbol{v}$ communicates..



(b)

Fig. 2: US-RIS structure. (a) A real-world model of customer-premises equipment(CPE) that represents a typical user. (b) The suggested architecture, which includes a multi-layer US-RIS.

- Then we analyze the multi-layer RIS structure which is being proposed in concept part, keeping in mind of space limitency of the users. Here we observe that with phase of the incoming incident we are able to partially control the amplitude also, which result in giving us a neew degree of freedom (dof). This dof will provide us means to increase the performance of proposed concept.
- Now after giving an idea about concept and architecture of this hardware technique, we then give the formualtion for signal to noise ration (snr) optimization problem for achieving maximal value for our us-ris system. We will provide the development of multi-layer beam forming design for which is for controlling phase and amplitude of the incident electromagnetic wave using iterative method. This method is being used as the snr optimization problem is non-convex problem due many independent variables. And at last we show the simulation results of our propose system and calculate the performance increment.

II. System model

Fig. 1 showed the design of our scenario with proper notations, now considering this system, where a multi-layer transmissive IRS are arranged to beam form the electromagnetic waves coming from already existing rf chain in uplink transmission, we design our expressions as below. Let user equipment are base-station tower are having M receive antennas (RAs) and K transmit antennas (TAs) . The user side additional beam-forming architecture is having L layers and number of elements in l-th layer is equal to N_l . For simplicity we can take N_l equal to N for all $l \in [L]$, this will not affect the generality. We can simply identify any element in the whole structure by using notation (l, n)-th which interprets as l-th layer and n-th TA element .

We design the system equation for uplink transmission only. We denoted the symbol which are being transmitted as $s \sim \mathcal{CN}(0, 1)$. This uplink symbol is originated from user equipment and then it goes to the Transmit beam forming by RF chain, which can be showed by taking product of this symbol by UL-TBF vector, $\boldsymbol{w} \in \mathbb{C}^{K\times 1}$ of Fig. 1, Now their is a limit to the power that can be given to this RF chain which mathematically can be represented as constraint $\|\boldsymbol{w}\|_2^2 \leq P_{\max}$.

We are proposing the device architecture as shown in the figure, which is so compact that their is no other link except the user-RIS-BS line-of-sight (LoS), this is because user equipment is inside the device shown in figure so that no other link is possible. It's like wrapping the user equipment in protecting enclosure, which restrict any other path then the one which is open.

Phase shift characteristics of each layer can be given in the form of a diagonal matrix, which is a matrix whose elements are equal to zero expect the ones present in principle diagonal of the matrix. Elements in principle diagonal are the phase shift variables of each element in that layer. Diagonal matrix is chose beacuse if we post multiply a vector to a diagonal matrix it behaves as inner product of elements present at principle digonal to that vector. We call this denotation matrix as transmit phase shifter (TPS).

$$\mathbf{\Theta}_l = \text{diag}\left(\boldsymbol{\theta}_l\right) = \text{diag}\left(\left[\theta_{l,1}, \cdots, \theta_{l,N}\right]^T\right), \tag{1}$$

here $\theta_{l,n} \in \mathcal{F}$ of Fig. 1 is the variable representing the phase shift of the (l, n)-th element in radians and $\mathcal{F}$ is a feasible set of transmission coefficients (TC). We can take.

$$\mathcal{F} = \left\{ \theta \middle| \theta = e^{j\varphi}, \varphi \in [-\pi, \pi] \right\}, \tag{2}$$

This is what also assume that phase shift from each element can be controlled [9]. Now signal received at base station can be modeled as follows.

$$\boldsymbol{y} = \boldsymbol{g}^H \left(\prod_{l=L}^{1} \kappa \boldsymbol{\Theta}_l \boldsymbol{f}_l \right) \boldsymbol{w} s + \boldsymbol{n}, \tag{3}$$

κ is a factor denoting the loss to the electromagnetic wave which is penetrating the each layer. In above equation, $\boldsymbol{f}_1 \in \mathbb{C}^{N \times K}$,$\boldsymbol{g} \in \mathbb{C}^{N \times M}$, and $\boldsymbol{f}_l \in \mathbb{C}^{N \times N}$, $\boldsymbol{n} \sim \mathcal{CN}\left(\boldsymbol{0}_M and \sigma^2 \boldsymbol{I}_M\right)$.

Now the received signal at base station antennas are being recombined to get the final received scalar signal, which can be given by multiplying by the recombining vector. As incoming signal is taken by M distinct antennas, we have to use receiver combining (RC) vector $\boldsymbol{v} \in \mathbb{C}^{M \times 1}$. The final signal which is scalar as transmitted signal was also scalar can be given as.

$$z = \boldsymbol{v}^H \boldsymbol{y} = \boldsymbol{v}^H \boldsymbol{g}^H \left(\prod_{l=L}^{1} \kappa \boldsymbol{\Theta}_l \boldsymbol{f}_l \right) \boldsymbol{w} s + \boldsymbol{v}^H \boldsymbol{n}. \tag{4}$$

III. Design of beamforming

For a proper analysis and implementation of the proposed US-RIS we further go inside the technicality of the system by first giving the formulation of the problem of optimizing to signal to noise ratio (SNR). Then we see that this optimization problem is involving the different variables which are independent of each other this makes the problem formulation a non-convex optimization problem for solving this situation we than proposed a multi layer transmit beam-former design which contains a iterative algorithm to solve this problem. After which we are able to optimize the each independent variable so that we can achieve maximal SNR. For keeping the generality we take number of layer $L \geq 2$ and number of receive antenna $K \geq 1$.

A. Problem formulation

As shown in system model given in Fig. 1 , we are going to maximizing the SNR at the base station (BS) of this US-RIS-aided communication system. As given in the recombined signal at the BS represented as z and the noise introduced also gets recombined as $\boldsymbol{v}^H \boldsymbol{n}$ which will agian a complex Gaussian noise can be represented as $\boldsymbol{v}^H \boldsymbol{n} \sim \mathcal{CN}\left(0, \left\|\boldsymbol{v}^H\right\|_2^2 \sigma^2\right)$. So now the SNR can be calculated as

$$\mathrm{SNR} = \frac{\left| \boldsymbol{v}^H \boldsymbol{g}^H \left(\prod_{l=L}^{1} \kappa \boldsymbol{\Theta}_l \boldsymbol{f}_l \right) \boldsymbol{w} \right|^2}{\left\| \boldsymbol{v}^H \right\|_2^2 \sigma^2}. \tag{5}$$

Where, symbols have their meaning as discussed in the paper. Now, we can formulate an optimization problem which aim for maximizing the SNR with certain variable and some constrains

$$\max_{\boldsymbol{v}, \boldsymbol{\Theta}_1, \cdots, \boldsymbol{\Theta}_L, \boldsymbol{w}} \mathrm{SNR} = \frac{\left| \boldsymbol{v}^H \boldsymbol{g}^H \left(\prod_{l=L}^{1} \kappa \boldsymbol{\Theta}_l \boldsymbol{f}_l \right) \boldsymbol{w} \right|^2}{\left\| \boldsymbol{v}^H \right\|_2^2 \sigma^2}, \tag{6a}$$

$$\text{s.t.} \quad \mathrm{C}_1: \ \|\boldsymbol{w}\|_2^2 \leq P_{\max}, \tag{6b}$$

$$\mathrm{C}_2: \ |\theta_{l,n}| = 1, \ \forall l, n. \tag{6c}$$

It can be seen that C_1 is the constrain of max transmit power from the user and C_2 is showing the power gain by the RIS. It can be seen that the above objective function as non-convexity so the method of jointly optimization of RC vector $\boldsymbol{v}$ and TPS matrices $\boldsymbol{\Theta}_1, \cdots, \boldsymbol{\Theta}_L$ and uplink transmit beamforming (UL-TBF) vector $\boldsymbol{w}$

Now we are introducing the multi layer system to tackle this problem.

Algorithm 1 Multi-Layer Transmit Beamformer Design for US-RIS-Aided Communications

Input: Channel matrices $\boldsymbol{f}_1, \cdots, \boldsymbol{f}_L$, and $\boldsymbol{g}$; maximum transmit power $P_{\max}$.

Output: Optimized RC vector $\boldsymbol{v}$; optimized US-RIS TPS matrices $\boldsymbol{\Theta}_1, \cdots, \boldsymbol{\Theta}_L$; optimized UL-TBF vector $\boldsymbol{w}$; maximized SNR.

1: Initialize $\boldsymbol{v}$, $\boldsymbol{\Theta}_1, \cdots, \boldsymbol{\Theta}_L$, and $\boldsymbol{w}$;
2: **while** no convergence of SNR **do**
3: Update $\boldsymbol{v}^{\text{opt}}$ by (11);
4: Update $\boldsymbol{\Theta}_1^{\text{opt}}, \cdots, \boldsymbol{\Theta}_L^{\text{opt}}$ in turn by (14);
5: Update $\boldsymbol{w}^{\text{opt}}$ by (17);
6: Update SNR by (7);
7: **end while**
8: **return** $\boldsymbol{v}$, $\boldsymbol{\Theta}_1, \cdots, \boldsymbol{\Theta}_L$, $\boldsymbol{w}$, and SNR.

B. Algorithm for finding multi layer beamforming design

The iterative steps for solving the problem formed is given in the **Algorithm 1**. So input to the algorithm are $\boldsymbol{v}$, $\boldsymbol{\Theta}_1, \cdots, \boldsymbol{\Theta}_L$ and $\boldsymbol{w}$ these are the one which have to be optimized alternatively by updating the each variable individually keeping other fix at time. The stopping criteria of this iterative algorithm is convergence indication of the objective function and the output of this algorithm is the optimized beamforming design.

C. Optimized TPS, UL-TBF, and RC of Fig. 1

In this part we analytically derived expression for updating each variable in the previous algorithm. The initial optimization problem SNR was non-convex but we can convert it into the joint convex optimization problem.

we first define

$$\boldsymbol{\xi}_{(p,q)} = \begin{cases} \prod_{l=p}^{q} \kappa \boldsymbol{\Theta}_l \boldsymbol{f}_l, & p \in [L], q \in [L], \\ \boldsymbol{I}_N, & p = L, q = L+1, \\ \boldsymbol{I}_K, & p = 0, q = 1. \end{cases} \tag{7}$$

Now, updates of the variable can be given as

1) Optimized RC: Keeping the RC vector $\boldsymbol{v}$ variables and others fixed the problem (6) can be reformulated as

$$\max_{\boldsymbol{v}} \ \mathrm{SNR} = \frac{\boldsymbol{v}^H \boldsymbol{g}^H \boldsymbol{\xi}_{(L,1)} \boldsymbol{w}\boldsymbol{w}^H \boldsymbol{\xi}_{(L,1)}^H \boldsymbol{g}\boldsymbol{v}}{\|\boldsymbol{v}^H\|_2^2 \sigma^2} := \frac{\boldsymbol{v}^H \boldsymbol{U} \boldsymbol{v}}{\|\boldsymbol{v}^H\|_2^2 \sigma^2}, \tag{8}$$

where it can be seen that $\boldsymbol{U} = \boldsymbol{g}^H \boldsymbol{\xi}_{(L,1)} \boldsymbol{w}\boldsymbol{w}^H \boldsymbol{\xi}_{(L,1)}^H \boldsymbol{g}$ is a positive semi-definite matrix. By doing the matrix analysis, maximum SNR can be formed, when $\boldsymbol{v}$ is a corresponding eigenvector of maximal eigenvalue of $\boldsymbol{U}$, which is defined as

$$\boldsymbol{v}^{\text{opt}} = \psi_{\max}\left(\boldsymbol{g}^H \boldsymbol{\xi}_{(L,1)} \boldsymbol{w}\boldsymbol{w}^H \boldsymbol{\xi}_{(L,1)}^H \boldsymbol{g}\right). \tag{9}$$

2) Optimized US-RIS TPS: We can see that

$$\boldsymbol{\xi}_{(l,1)} \boldsymbol{w} = \mathrm{diag}(\boldsymbol{f}_l \boldsymbol{\xi}_{(l-1,1)} \boldsymbol{w}) \boldsymbol{\theta}_l. \tag{10}$$

SNR can be reframed ascc

$$\begin{aligned} \mathrm{SNR} &= \frac{\left|\boldsymbol{v}^H \boldsymbol{g}^H \boldsymbol{\xi}_{(L,1)} \boldsymbol{w}\right|^2}{\|\boldsymbol{v}^H\|_2^2 \sigma^2} \\ &= \frac{\left|\boldsymbol{v}^H \boldsymbol{g}^H \boldsymbol{\xi}_{(L,l+1)} \boldsymbol{\xi}_{(l,1)} \boldsymbol{w}\right|^2}{\|\boldsymbol{v}^H\|_2^2 \sigma^2} \\ &= \frac{\left|\boldsymbol{v}^H \boldsymbol{g}^H \boldsymbol{\xi}_{(L,l+1)} \mathrm{diag}(\boldsymbol{f}_l \boldsymbol{\xi}_{(l-1,1)} \boldsymbol{w}) \boldsymbol{\theta}_l\right|^2}{\|\boldsymbol{v}^H\|_2^2 \sigma^2}. \end{aligned} \tag{11}$$

Solving the above equation with the constrain given as

$$\boldsymbol{\theta}_l^{\text{opt}} = \exp\left(j\arg\left(\mathrm{diag}\left(\boldsymbol{f}_l \boldsymbol{\xi}_{(l-1,1)} \boldsymbol{w}\right)^H \boldsymbol{\xi}_{(L,l+1)}^H \boldsymbol{g}\boldsymbol{v}\right)\right), \ \forall l \in [L]. \tag{12}$$

3) Optimized UL-TBF: For optimizing the vector $\boldsymbol{w}$, we first optimize the normalized vector $\langle \boldsymbol{w} \rangle$

$$\max_{\langle \boldsymbol{w} \rangle} \ \frac{\left|\boldsymbol{v}^H \boldsymbol{g}^H \boldsymbol{\xi}_{(L,1)} \langle \boldsymbol{w} \rangle\right|^2}{\|\boldsymbol{v}^H\|_2^2 \sigma^2} = \frac{\mathrm{SNR}}{\|\boldsymbol{w}\|_2^2}, \tag{13a}$$

$$\text{s.t.} \quad \mathrm{C}_1: \ \|\langle \boldsymbol{w} \rangle\|_2 = 1. \tag{13b}$$

Now optimized $\langle \boldsymbol{w} \rangle$ can be written as

$$\langle \boldsymbol{w} \rangle^{\text{opt}} = \left\langle \boldsymbol{\xi}_{(L,1)}^H \boldsymbol{g}\boldsymbol{v} \right\rangle. \tag{14}$$

Now after solving the above equations we get

$$\boldsymbol{w}^{\text{opt}} = \sqrt{P_{\max}} \langle \boldsymbol{w} \rangle^{\text{opt}} = \sqrt{P_{\max}} \left\langle \boldsymbol{\xi}_{(L,1)}^H \boldsymbol{g}\boldsymbol{v} \right\rangle. \tag{15}$$

IV. Simulation Results

Matlab simulations are being performed to quantize the performance of the above beamformer design using the above proposed architecture.

A. Simulation setup

We consider 3 dimensional case where we setup different types of RIS which is employed for uplink transmission between BS and user shown in Fig. 3. Consider λ as wavelength of uplink signal transmitted. We have taken user and base station with ULA (uniform linear array) having 2 and 8 number of antenna respectively and antenna spacing is taken $\frac{\lambda}{2}$. For multi-layer US-RIS number of elements is taken 8 x 2 for 2 layer. So with the help of multi layer and multi elements we can increase uplink transmission given in Fig. 3 (a). We also consider another two scenario with single layer US-RIS and BSS-RIS which is having the number of IRS elements as 12 x 16, these single layer scenario is taken at the same position as the first layer multi layer US-RIS is placed given in Fig. 3 (b).

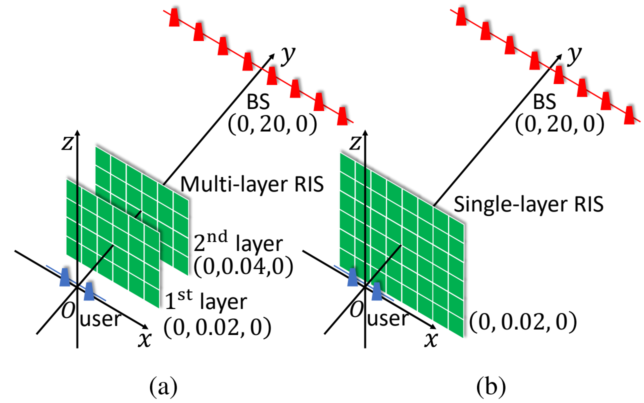


Fig. 3: A simulated scenario in which several sorts of RISs are used to aid communication. (a) Communications facilitated by the US-RIS on many layers. (a) Communications supported by the US/BSS-RIS on a single layer

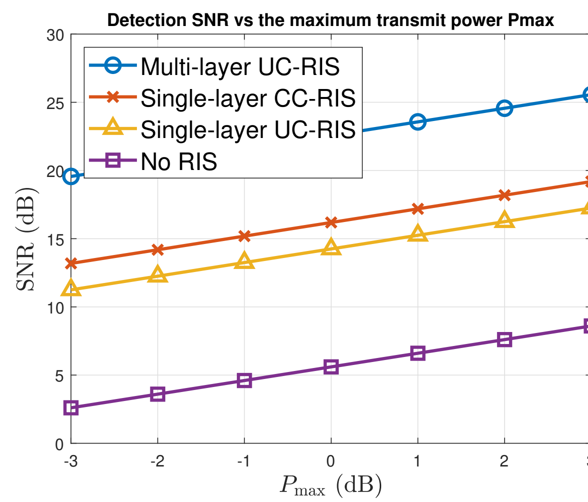


Fig. 4: Detection of SNR vs maximum transmit power $P_{\max}$.

B. Performance in the US-RIS-aided system

We can made observations from Fig. 4 that SNR without RIS have the lowest SNR and one with single layer user specific-RIS supported case have a 1.94 dB loss as compared with single layer Base station specific RIS aided because of amplitude or power loss in traveling of wave in medium of RIS while penetrating the surface. Multi-layer US-RIS-aided case we have achieved SNR of 8.31 dB. We obtained these two SNR by considering the same number of elements in RIS for both the scenario, as a result, this design of transmit beamformer exploits the same DoF in phase. Hence, the increase in detection SNR is logically due to the extra DoF in controlling the amplitude offered by this multi-layer structure, which is a clear advantage over the single-layer construction that we have demonstrated theoretically.

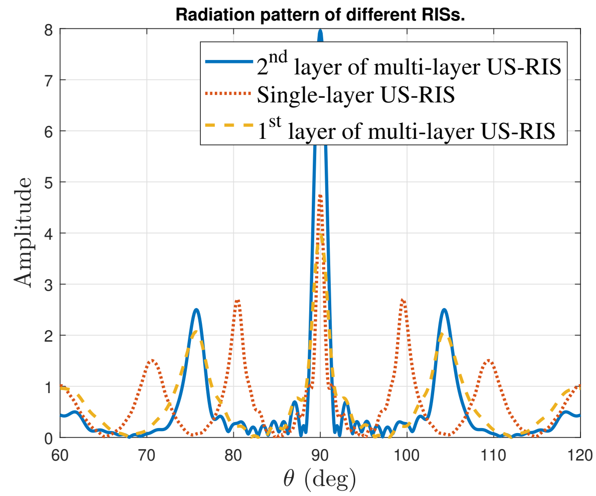


Fig. 5: Radiation pattern of different RISs.

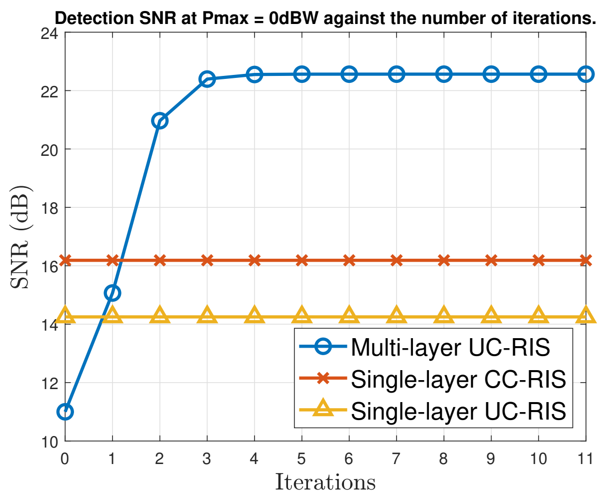


Fig. 6: Detection SNR at $P_{\max} = 0$dBW against the number of iterations.

Observing the Fig. 5 we can interpret that the first layer of multi layer have lower main lobe than the single layer. It is due to the difference in number of elements but when we see the main lobe of second layer of multi layer is higher in all cases this is the proof that there is the new DoF is achieved which is of controlling the amplitude.

C. Convergence of the proposed multi-layer transmit beamformer design

It is found that multi layer design convergence in 4-5 iteration as shown in Fig. But single layer design convergence within 1-2 iterations.

D. EAR Analysis on RIS

For measuring the depth of amplitude controlling, we have implemented the EAR metric, which just tell us what fraction of elements are being active in each layer. This can be done by assigning a minimum threshold value can be as shown in presented in Fig. 7. For our case we take a threshold of $\varepsilon = 1/6$ as shown in Fig. 7. This EAR improvement is very obvious and shows the edge of proposed system.

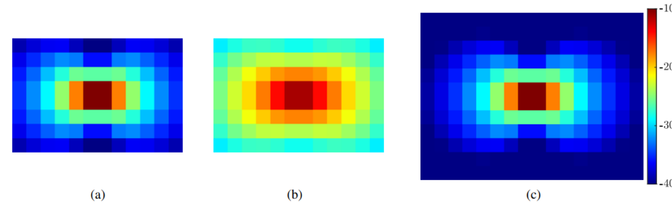


Fig. 7: Multi-layer single-layer US-RIS power distribution (colorbar on right is uniform for three subfigures, unit: dBW), indicating that various RISs have different EARs and The percentage threshold () is set at 1/6. (a) The first layer of the multi-layer US-RIS, which has an EAR of 29.2%. (b) The second layer of the multi-layer US-RIS system, having an EAR of 87.5%. (c) US-RIS single-layer with EAR 22.9%.

V. Conclusions

The simulation results have verified the advantages that this concept have. This is done in theoratical way, it is needed more research as we have assume phase shift by elements continuous, not the practical case. Element correlation neglected, quantity of elements taken freely and transmissive irs needs more study.

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