

Channel state information estimation for reconfigurable intelligent surfaces based on received signal analysis

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Article Info

Article history:

Received May 29, 2022

Revised Sep 22, 2022

Accepted Oct 27, 2022

Keywords:

5G

6G

Channel state information estimation

Multiple signal classification

Reconfigurable intelligent surfaces

Spectral efficiency

ABSTRACT

Recently, reconfigurable intelligent surfaces have an increasing role to enhance the coverage and quality of mobile networks especially when the received signal level is very weak because of obstacles and random fluctuation. This motivates the researchers to add more contributions to the fields of reconfigurable intelligent surfaces (RIS) in wireless communications. A substantial issue in reconfigurable intelligent surfaces is the huge overhead for channel state information estimation which limits the system's performance, oppressively. In this work, a newly proposed method is to estimate the angle of arrival and path loss at the RIS side and then send short information to the base station rather than huge overhead as in previous research. The estimated channel state information is used to beamform the downlink waveform toward users accurately. The simulation results indicate that the proposed algorithm calculated the angle of arrival of users, admirably especially at a high signal-to-noise ratio. Moreover, a considerable spectral efficiency enhancement is obtained as compared to the traditional methods.

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1. INTRODUCTION

With the swift growth in the number of mobile devices, traditional wireless spectrum technologies become incapable of following the demand for high data rates. Wherefore, researchers' efforts are headed toward finding new technologies to exploit the wireless spectrum efficiently. One of the key techniques to improve the usage of the wireless spectrum is massive multiple-input multiple-output (massive MIMO). Massive MIMO shows high spectral efficiency improvements [1], [2]. The gain from working with a higher degree of freedom or working with high power help MIMO to meet the needs of the newer mobile communication network generations [3]–[5]. Therefore, attention turned to wide-band transmission technique that enriches the network and achieves a higher wireless spectral efficiency such as adopting systems with larger constellation size [6] or working with higher bandwidth using millimeter-wave (mmWave) [7], [8] or equipping a large number of antennas using massive-MIMO [1], [2], [9], [10].

Yet, the bases for the sixth generation (6G) network are not decided nor the techniques that can be used to meet the goals. As a promising tool to improve network throughput, reconfigurable intelligent surfaces (RIS) is shown as a good tool for that purpose. Especially, it offers a settlement to the impairs from the wireless free-space path losses results from using a large number of antenna arrays in massive MIMO and using higher

frequencies at mmWaves [11]. RIS is a reflecting surface that can be controlled to alter the direction of the reflected rays to the desired direction, passively [12], [13]. However, the channel state information (CSI) of the users has to be known at the transmitter for beamforming purposes. Therefore, the CSI estimation of RIS has been receiving a lot of attention. The availability of accurate CSI is a crucial issue because it controls the beamforming along with designing the joint beamformer at transceivers. For both time division duplex (TDD) and frequency division duplex (FDD), an extra burden will be added as overhead in the feedback which might decrease the spectral efficiency. Several types of research have been done to find substitutional solutions for reducing CSI training overhead [13]–[15]. Initial work adopted the conventional CSI estimation methods by minimizing the number of pilots, by closely arranging the spaces between RIS's elements to generate highly correlated channel elements which lead to minimizing the additional gain of beamformer [16], [17]. An alternative approach is by estimating the channel of each element of RIS, individually [18].

In this work, an algorithm for parametric CSI estimation which reduces the training overhead within coherence time is proposed. The algorithm estimates the angle of arrival (AoA) and path loss at the RIS. The received covariance matrix is decomposed into an AoA, angle of departure (AoD), and path loss. The estimated parameters are sent to the base station (BS). The BS uses the estimated parameters for precoding. This method saves a huge amount of coherence time and increases spectral efficiency. It alleviates the complexity issue because it helps to transmit the necessary parameters to BS solely [19]–[21]. That can be possible when RIS is equipped with a processing unit. Thus, CSI estimation at RIS decreases the extra training overhead that has to be transferred from RIS to BS. So far and to the best of our knowledge, there is no existing work that addresses this issue in the RIS environment.

2. SYSTEM MODEL

In this paper, a BS equipped with L antennas serves a single antenna K user. The direct link between BS and users $\mathbf{h}_{b,k}$ is blocked. Therefore, an RIS is considered to solve this issue and maintain a stable connection. RIS consists of a large number of tiny elements which are called meta-elements ($e_{m,n}$). Meta-elements are electromagnetic materials controlled with an integrated electronic circuit; the meta-element passively reflects the falling waves. Each single RIS array is equipped with $M \times N$ meta elements [12].

The channel matrix between BS and RIS is denoted by $\mathbf{G} \in \mathbb{C}^{L \times (M \times N)}$. The downlink channel between RIS and user k is denoted by $\mathbf{h}_{r,k} \in \mathbb{C}^{(M \times N) \times 1}$, while the uplink channel vector is denoted by $\mathbf{h}_{k,r} \in \mathbb{C}^{1 \times (M \times N)}$. Due to the reciprocity within block time the two channels are the transpose of each other therefore we use TDD.

The direct link between BS and user k is blocked the transmitted waves travel and fall on RIS with an incident angle ψ_k and are reflected in the user k with a reflection angle ϕ_k . The received signal at user k , is represented by (1):

$$y_k = h_{k,b}^H x + h_k^H \Phi G \Omega s_k + n_k \quad (1)$$

The matrix Ω is a precoding matrix for the link between BS and RIS G . The received signal from the user k at RIS's elements is represented:

$$y_k = h_{k,r} s_k \quad (2)$$

where the vector $s_k \in \mathbb{C}^{1 \times K}$ is the transmitted message from the user k to BS using RIS. The received signal at RIS is given by (3):

$$Y_r = \sum_1^K h_{k,r} s_k + N_k \quad (3)$$

The covariance matrix of the received signal at RIS is given as (4):

$$COV(Y_r) = R = \frac{1}{K} \sum Y_r Y_r^H \quad (4)$$

3. PROBLEM FORMULATION

Accurate acquisition of users' CSI is a major problem in 5G networks, especially, for the RIS network which involves two links, the BS-RIS link and the RIS-users link. Due to the fact that BS and RIS have

fixed positions, the first link can be easily estimated, and it is assumed to be stable for long period. At RIS, the conventional handling of the channel of K users using $M \times N$ elements is a complex issue. Therefore, parameterizing the wireless channel into spatial parameters and sending those parameters solely alleviates this issue. We considered CSI estimation and decomposition at the RIS side to alleviate this issue which is a feasible consideration [19], [20]. We assumed that RIS is equipped with a processing unit that can be used to process the received signals [22]. Multiple signal classification (MUSIC) is used to calculate the channel parameters which is a super-resolution direction-finding algorithm.

The MUSIC algorithm estimates the AoA without any prior knowledge of the incoming signal directions or powers, the MUSIC algorithm uses the available information at the receiver to construct the AoA vector [23]. MUSIC is a high-resolution algorithm that exploits the eigenstructure of the input covariance matrix to calculate the AoA of the received signal. The main idea of the MUSIC algorithm is, to calculate the noise subspace from the spatial spectrum, thus, the dominant peaks of the spectrum are used to calculate AoA. For higher resolution, the root-MUSIC is adopted which is a developed version of MUSIC algorithm. Root-Music is suitable for linear arrays and uses the roots of the polynomial $J(z)$ that is calculated from the generated subspace to estimate the AoA, where $J(z)$ is formed as:

$$J(z) = v^H Q Q^H v = 0 \quad (5)$$

where v is the steering vector and Q is the subspace of the the span of the eigenvectors.

$$v = [1, z^{-1}, z^{-2}, \dots, z^{-(M-1)}]^H \quad (6)$$

where z is given by (7):

$$z = e^{j \frac{2\pi d}{\lambda} \sin \theta} \quad (7)$$

Accordingly, the angle of arrival for each root is calculated and given by (8):

$$\theta_j = \arcsin\left[\frac{\lambda}{2\pi d} \arg(z_j)\right] \quad (8)$$

Depending on the array layout whether linear or planner, the MUSIC algorithm processes the received signals and calculates AoAs for users. For the linear array, the root-MUSIC algorithm calculates azimuth angle ϕ_k only, while for the planner array MUSIC algorithm calculates both azimuth and elevation angles (ϕ_k, θ_k), respectively [24], [25]. In this paper for simplicity, we have confined to a linear array. The received channel matrix for the K users is given:

$$H = [h_1, h_2, \dots, h_K] \quad (9)$$

The channel signature vector for the user k is given:

$$h = \alpha_k \exp\left(\frac{-2j\pi d \sin(\phi)(M \times N)}{\lambda}\right) \quad (10)$$

where d is RIS's antennas (elements) spacing, α_k is free space path loss component.

In this paper, RIS's processing unit process the received signals from all users which is given in (9). At RIS's PU the covariance of the received matrix (3) is calculated. MUSIC algorithm decomposes the received channel matrix from all users into several parameters. For the conventional channel transition, RIS forwards the received channel matrix H itself to BS without any further preprocessing. The main contribution of this paper to alleviate this issue is minimizing the dimensions of the transmitted channel array. Thus, RIS forwards the vector of AoA and path loss component to BS, solely. Consequently, BS processes the transmitted signal regarding the knowledge of users' AoA. The achievable rate at user k is given by (11):

$$R_k = \frac{1}{K} \sum_{k=1}^K \log(1 + \gamma_k) \quad (11)$$

where γ_k is the signal to noise ratio at users k which is given by (12):

$$\gamma_k = \frac{p_k |\hat{h}_{r,k} h_{r,k}^H|^2}{\sigma_k^2 + p_k \sum_{i=1, i \neq k}^K |\hat{h}_{r,i} h_{r,i}^H|^2} \quad (12)$$

where p_k is power allocated to user k , σ^2 is Gaussian noise variation, and $\hat{h}_{r,k}$ is the estimated user's k channel information (at RIS). While the matrix \hat{H} is the channel information of all users except user k after precoding.

$$\hat{H} = [\hat{h}_{r,1}, \hat{h}_{r,2}, \dots, \hat{h}_{r,k-1}, \hat{h}_{r,k+1}, \dots, \hat{h}_{r,K}] \quad (13)$$

The proposed CSI estimation reduces the overhead significantly. Within a coherence time the CSI estimation, uplink and downlink should be done. The overhead is used for CSI estimation. Hence, the increasing overhead will decrease the throughput. The dilemma of RIS is sending pilot carriers to the BS through RIS because of the huge overhead. In this proposed method, the RIS sends two parameters to the BS for each user, while in the previous system MNK needs to be sent per user. The complexity of the proposed system depends on the algorithm that computes the channel parameters from the covariance matrix $O(N^2)$ [24].

4. SIMULATION AND RESULTS

This section shows the simulation results that uphold our proposed algorithms, MATLAB software was used to simulate this paper's results. All generated simulations were made by averaging out 1,000 trails. We assumed the first link between BS and RIS is stable. Two users were considered as shown in the system model given in Figure 1. The AoAs of the two users are $\theta_k \in \{-15, 45\}$. In all coming figures, the averaged sum rate was calculated for user k . The distance between RIS and user k is set to $r_k = 50m$, attenuation coefficient (path loss) is $\alpha_k = \frac{1}{r_k}$.

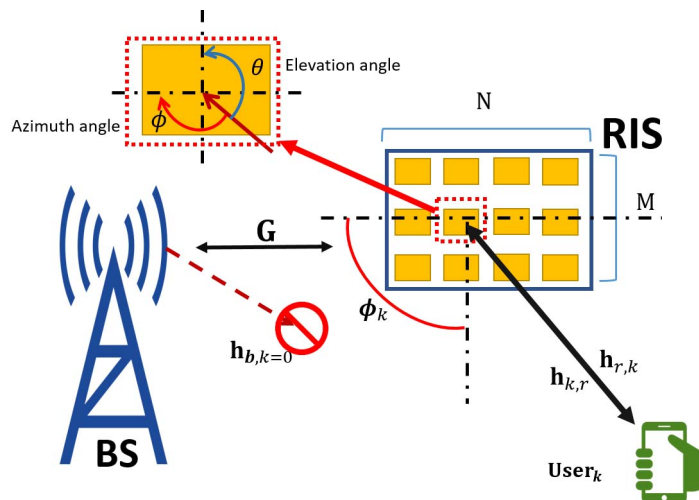


Figure 1. System model: BS, RIS, and users. RIS directs the messages in between BS and users

Figure 2 shows the spectral efficiency of user k given in (11) versus SNR with a fixed number of RIS elements $M \times N = 150$. This figure shows that as the SNR grows the output spectral efficiency increases respectively. The proposed algorithm almost matches the perfect CSI estimation techniques.

Figure 3 shows the spectral efficiency of user k with RIS elements for two different SNR $\in \{6, 8\}$ dB values. This figure shows the number of RIS elements increases the spectral efficiency increases respectively. For both Figure 2 and Figure 3, the growth in the SNR or the number of RIS elements shows a considerable enhancement in the performance that converges to the perfect CSI estimation. Which is an expected performance gain due to root-MUSIC algorithm sensitivity. Figure 4 shows the quality of the root-MUSIC algorithm by capturing the angle of arrival for each user, accurately. As aforementioned, two AoA have been selected $\theta_k \in \{-15, 45\}$, and the root-MUSIC successfully estimated the users' AoA at the RIS side from users' uploaded messages.

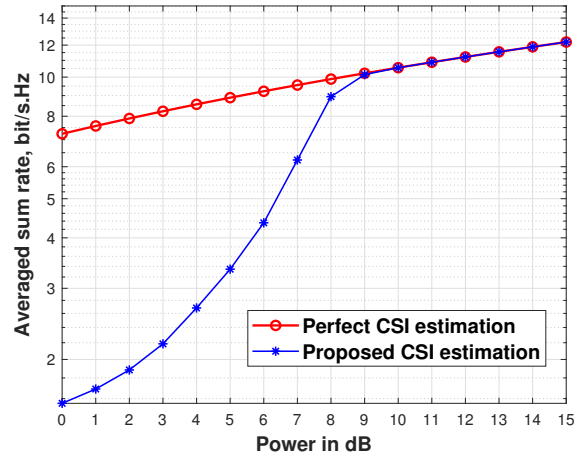


Figure 2. Averaged sum rate verses SNR

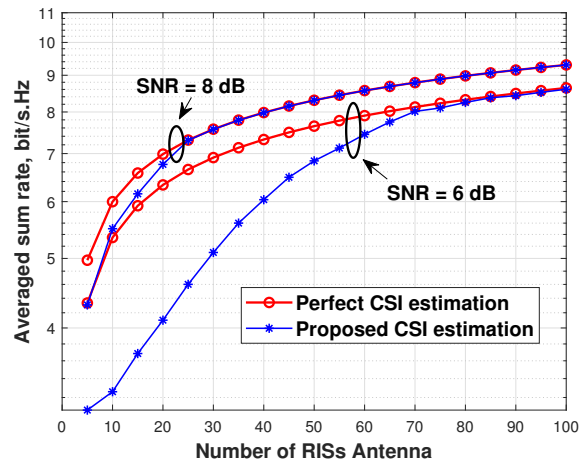


Figure 3. Averaged sum rate verses number of RIS's antennas

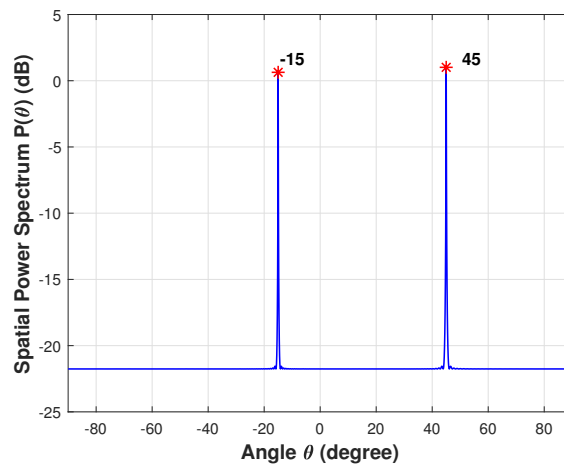


Figure 4. AoA estimated by root-MUSIC algorithm

5. CONCLUSION

The demand for high data rates and limited bandwidth attracted researchers to study and enhance wireless systems. RIS is considered one of the recent systems that have significant coverage and data rate improvement. A major problem in RIS systems is the huge overhead within coherence time which decreases the spectral efficiency substantially. Therefore, a proposed method to solve this problem is presented. In the proposal, RIS calculated the AoA and channel path loss then send this information to the respective BS. In this way, a significant portion of the coherence time will be saved for data transmission and consequently increases spectral efficiency. The simulation results show that the proposed system offers good quality improvement, especially at high SNR.




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