Fairness in RIS Assisted Networks for Resource Allocation

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Abstract

Reconfigurable intelligent surfaces (RISs) have emerged as transformative technology for next-generation wireless networks, offering dynamic control over electromagnetic wave propagation to enhance spectral efficiency, coverage, and energy efficiency. However, to provide equal resource allocation, RIS implementation should also consider multiple user fairness by examining how RIS-assisted networks might reduce user-to-user differences in signal quality, data rates, and access possibilities. This research investigates RIS from a fairness standpoint. We examine current fairness designs, optimization strategies, and RIS implementation issues to improve fairness in diverse networks.

I. Introduction

Reconfigurable intelligent surfaces (RISs) are an array of passive reflective elements that adjust phase shifts to enhance signal propagation, improving the transmission efficiency and coverage of next-generation (NG) networks. RIS passively controls wireless channels to strengthen signals and lessen interference. Nevertheless, uniform service quality across different locations remains an important challenge when studying these reflective surfaces [1].

RIS improves communication capabilities but creates inequitable access to opportunities owing to the capture effect. This causes users to experience unfair priorities, which cause stronger signals from RIS-assisted users to prevail in channel access due to power imbalance and/or unbalanced receiving rate [2].

In this study, we are investigating the role of RIS in improving and prioritizing the equity of resources shared between multiple users via the applicable fairness metrics in a phase shift optimization.

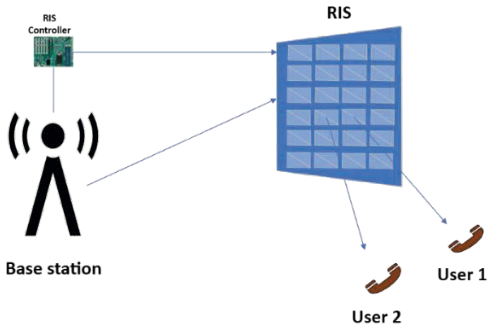

Fig. 1: RIS assisted wireless network whereby RIS is controlled by BS for its optimal performance while providing fair communication services to users.

II. Fairness in RIS Assisted Networks

Regardless of a user's location or channel circumstances, fairness in networks guarantees that all users receive fair service quality. Hence, equitable distribution of resources in wireless networks is highly desirable.

In this work, we study quantitative and qualitative metrics to measure fairness, considering a resource, in this case, time allocation, whose total amount is τ with N users sharing the resource, where $\boldsymbol{W} = (\tau_1, \dots, \tau_N)$ implies the allocated resources in which τ_n is the amount of resources allocated to an individual user $n = 1,2,\dots,N$. The total amount, expressed as follows, must be less than or equal to the sum of the resources allotted separately as $\sum_{i=1}^{n} \tau_n \leq \tau$ [3].

Jain's Index measures system-wide fairness, assessing networks by evaluating user throughput and SNR distribution, giving the quantitative aspect of measurement.

$$f(\boldsymbol{R}) = \frac{[\sum_{n=1}^{N} R_n]^2}{N \sum_{n=1}^{N} R_n^2},$$

where $0 \leq f(\boldsymbol{R}) \leq 1$ where 0 shows unfair allocation and 1 means a fair allocation [4].

Several types of fairness methodologies exist, among which Max-Min fairness prevents the starvation of weak users by allocating more resources to them. On the other hand, proportional fairness balances fairness and efficiency by maximizing the logarithmic utility by optimizing weighted rates [3].

III. System Model

We consider a base station (BS) in a downlink system with a single antenna transmitting to N users with K RIS elements. Total bandwidth $\boldsymbol{W}$ is divided into L orthogonal sub-channels, where each sub-channel is assigned to one user served by time division multiple access (TDMA) to avoid co-channel interference.

We consider no line of sight (NLoS) links from BS to the user, but there is a line of sight (LoS) RIS-assisted link from BS to RIS to n-th user considered. $\boldsymbol{g} \in \mathbb{C}^{K\times 1}$ and $\boldsymbol{f}_n \mathbb{C}^{K\times 1}$ denote the narrow band quasi-static Rician fading channels from BS to RIS and RIS to user, respectively. The phase shift matrix given by $\boldsymbol{\varphi} = diag\left(\sqrt{\beta_1} e^{j\theta_1}, \dots, \sqrt{\beta_K} e^{j\theta_K}\right)$. Where β is the amplitude and θ is the phase shift. The signal received arriving at the user is

$$y_k = (\boldsymbol{f}_n^H \boldsymbol{\varphi} \boldsymbol{g}) s_n + z_n,$$

where, s_n is a transmitted symbol and $z_n \sim \mathcal{CN}(0, \sigma^2)$ is the additive white Gaussian noise (AWGN) at the n-th user. As a result, achievable rate (R_n) for user n is given as

$$R_n = \tau_n \log_2 \left(1 + \frac{p_n |(\boldsymbol{f}_n^H \boldsymbol{\varphi} \boldsymbol{G})|^2}{\tau_n \sigma^2}\right),$$

where τ_n denotes time allocation factor representing the portion of the timeslot provided to each user.

IV. Fairness optimization in RIS and challenges

Real-time RIS reconfiguration is necessary due to shifting channel circumstances. While distributed methods are more scalable, RIS optimization mostly requires centralized control for global fairness. For equitable resource allocation, RIS must cooperatively optimize phase shifts, power, and bandwidth among multiple users.

Considering the problem of jointly optimizing channel assignment, transmit power, time allocation factor and RIS phase vectors, with Max-Min fairness, we made the Max-Min Fairness optimization problem and presented it below:

$$\max_{v,\varphi,p,\tau} \min_{n} \sum_{n=1}^{N} v_n R_n \quad s.t\ v_n \in \{0,1\}, \forall_n \in N$$
$$R_n \geq \gamma_n, \forall_n \in N$$
$$|\beta_m| = 1, \forall_m \in \mathcal{M}$$
$$\theta \in [0,2\pi), \forall_m \in \mathcal{M}$$
$$p_n \geq 0,\ \forall_n \in N$$
$$\sum_{i=1}^{I} p_n \leq P_{max}$$
$$\tau_n \leq 1, \forall_n \in N$$

Where v_n is the channel assignment.

Algorithm: Alternating optimization for Fairness

1: **Initialize:** Channel assignment and tolerance ϵ setting t = 0
2: **Repeat:** $t = t + 1$
3: Time allocation and optimal power with Max-Min fairness
4: Optimize the phase shift of the passive RIS
5: **Solution:** $p^*, \tau^*, \boldsymbol{\varphi}^*$

We first optimize transmit power and time allocation with a fixed phase shift from RIS, then, with fixed power and time allocation, we optimize the phase shift vectors.

V. Simulation Results

We considered the transmit power of the BS to be at 2W, $M = 60$ and the distance between BS to RIS is 50m, and from RIS to users, the distance is 5m, whereby users are deployed in a circle around the RIS (at a fixed radius of 5m). For channel modelling, the Rician fading channel model is used, in which the Rician factor is 2.

Fig. 2 plots a comparison of resource allocation with max-min fairness. In max-min fairness, we can see a similar user rate for all users, but when just maximizing rate in RIS, it favours strong users, boosting high-rate users. In this case, Jain's fairness is at 1 for max-min fairness.

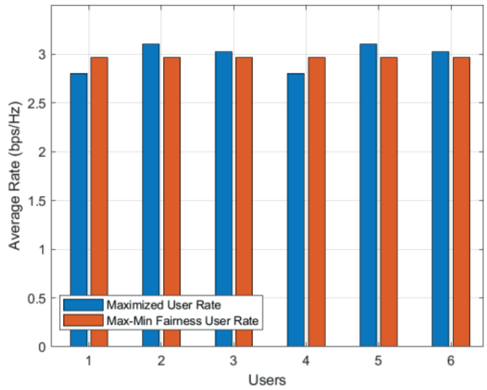

Fig. 2: Comparing User Rate Maximization with Max-Min Fairness Rate of Users

VI. Conclusion

RIS offers a viable way to improve wireless network speed, but while implementing it, fairness needs to be considered. We can see that various measuring techniques can be used to achieve fairness, such as Max-Min fairness. Future studies can be further made using machine learning, which may be set up to guarantee fair service distribution, and we can study setting up RIS to be dynamically adjusted using reinforcement learning to preserve equity.

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