System-Level Modelling and Beamforming Design for RIS-assisted Cellular Systems

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Abstract—Reconfigurable intelligent surface (RIS) is considered as key technology for improving the coverage and network capacity of the next-generation cellular systems. By changing the phase shifters at RIS, the effective channel between the base station and user can be reconfigured to enhance the network capacity and coverage. However, the selection of phase shifters at RIS has a significant impact on the achievable gains. In this letter, we propose a beamforming design for the RIS-assisted cellular systems. We then present in detail the system-level modelling and formulate a 3-dimension channel model between the base station, RIS, and user, to carry out system-level evaluations. We evaluate the proposed beamforming design in the presence of ideal and discrete phase shifters at RIS and show that the proposed design achieves significant improvements as compared to the state-of-the-art algorithms.

Index Terms—Beamforming, phase shifters, reconfigurable intelligent surfaces (RIS), and spectral efficiency.

I. INTRODUCTION

Reconfigurable intelligent surfaces (RIS) is considered as a promising technology for the next generation cellular communications to improve the achievable network capacity and cellular coverage. RIS consists of large number of passive antenna elements (or meta surfaces) which can reflect the incident ray towards the desired direction. By controlling the impedance of the meta surfaces through a passive electronic circuit, an additional phase shift is introduced into the reflected signal, and thus, the signal can be steered to the desired direction. This way, RIS helps in achieving improved signal reception at the users and also providing coverage to the users who are affected by the signal blockages [1]–[4].

In the existing literature, RIS has been extensively analysed and significant improvements are demonstrated for single cell scenario [5]–[7]. In [5], the authors propose a joint beamforming algorithm to maximize the network capacity. In [6], [7], the authors propose a power efficient and sum-rate maximizing algorithms for RIS-assisted systems. In [8], the authors present an initial access protocol for RIS aided cellular systems. However, these works do not consider the multi-cell analysis while quantifying the achievable gains. Note that only in the multi-cell analysis, the impact of the inter-cell interference from the beamformed RIS is captured, and thus, realistic achievable gains can be understood. Additionally, while performing such multi-cell analysis, a 3-dimension channel modelling between the base station (BS) RIS and user has to be considered to quantify the achievable gains. However, very few works in the literature have considered the 3-dimension channel model and carried out multi-cell analysis [9]–[13].

Further, the selection of the phase shifters at RIS has significant impact on the achievable gains with RIS-assisted systems [14]. In [9], the authors consider deploying multiple RIS and using random phase shifters at each RIS. This is a low complex way to enhance the network performance as only a few users whose channel coefficients are aligned with those assigned phase shifters will observe spectral enhancements. In [15], the authors consider random phase shifter allocation in each time slot and assume that the users decode the pilot signals transmitted at the beginning of each slot. Then, the users feedback the channel quality reports to the BS and the users with the best instantaneous channel conditions will be scheduled for the data transmission within the rest of the slot. With this approach the effective channel observed by each user changes from slot to slot and BS schedules the data transmissions according to the channel quality reports to maximize the achievable capacities. However, this procedure requires a large number of active users to realize the desired gains, and also, the feedback from the users within the same time slots is difficult to realize in practice. Hence, there is a need to consider all the aforementioned details and design a practically feasible, low-complex, and yet optimal way of controlling the beamforming at RIS.

Motivated by these facts, we present the following key contributions in this letter.

- We propose an RIS-assisted cellular organization by considering one RIS in each cellular sector to improve the network performance and present in detail the system-level modelling of the same. Note that the proposed design and algorithms in this letter can be easily extended in case multiple RIS are required.
- We present a novel beamforming design and derive the optimal phase shifters to be applied at the RIS.
- We formulate the channel modelling between the BS RIS and the user based on the 3-dimension channel model and carry out extensive system-level simulations.
- We consider ideal and discrete phase shifters at the RIS and show that the proposed beamforming design significantly outperforms the state-of-the-art algorithms.

The rest of the paper is organized as follows. We present system model in Section II. We present the proposed RIS assisted cellular organization and derive optimal phase shifters for beamforming at RIS in Section III. In Section IV, we present the simulation set up and discuss the numerical results under various scenarios. We then provide concluding remarks.
and directions for future work in Section V.

II. SYSTEM MODEL

We consider a cellular network with BS, RIS and users as shown in Fig. 1. We assume \( M, N \) and \( U \) as the number of antenna elements at the BS, RIS and user, respectively, and formulate the equivalent channel \( \mathbf{h}_k \in \mathbb{C}^{U \times M} \) between the BS and user \( k \) as follows.

\[
\mathbf{h}_k = \mathbf{H}_k H + \mathbf{F}_k \mathbf{G}
\]  

(1)

where, \( \mathbf{H}_k \) represents Hermitian operation, and \( \mathbf{G} \in \mathbb{C}^{N \times N} \), \( \mathbf{F} \in \mathbb{C}^{U \times N} \), and \( \mathbf{H} \in \mathbb{C}^{U \times M} \) denote the channel coefficients between the BS to RIS, RIS to the user \( k \), and the direct link between BS and user \( k \), respectively. Further, \( \Theta \in \mathbb{C}^{N \times N} \) denotes the phase shift matrix at the RIS formulated as follows (1), (5).

\[
\Theta = \text{diag}(\theta_1, \theta_2, \ldots, \theta_N), \forall \theta_n \in \mathcal{F}
\]

(2)

\[
\mathcal{F} \triangleq \{ \theta_n | \theta_n \leq 1 \}, \forall 1 \leq n \leq N.
\]

We consider the RIS-assisted downlink transmission for the user \( k \) as follows.

\[
x_k = \sqrt{P_k} \mathbf{s}_k,
\]

where \( s_k \) is the transmitted symbol corresponding to the user \( k \) with unit power i.e., \( \mathbb{E}\{s_k s_k^H\} = \mathbf{I} \) and \( P_k \) is the maximum power the BS can transmit. Thus, we formulate the received signal at the user \( k \) as follows.

\[
y_k = \mathbf{h}_k^H x_k + z_k,
\]

\[
= (\mathbf{H}_k H + \mathbf{F}_k \mathbf{G}) \mathbf{s}_k + z_k.
\]

(2)

where \( z_k \) represents the additive white Gaussian noise at the user \( k \) with zero mean and co-variance \( \Xi_k = \sigma^2 \mathbf{I} \). Thus, the signal-to-noise ratio (SNR) of user \( k \) is formulated as follows.

\[
\Gamma_k = \frac{P_k \mathbf{h}_k^H \mathbf{s}_k}{\Xi_k}
\]

(3)

Next, we formulate the objective function using (1)-(3).

1) **Objective function**: We formulate maximizing of achievable user rate as an optimization problem as follows.

\[
\mathcal{P}_1 : \max_{\Theta} \log_2 (1 + \Gamma_k),
\]

s.t. \( \theta_n \in \mathcal{F}, n \in \{1, \ldots, N\}, \)

(4a)

where \( \mathcal{P}_1 \) in (4a) maximizes the achievable user rate and (4b) ensures that the phase shift values are chosen from the permissible set \( \mathcal{F} \). Next, we explain the RIS organization in detail.

2) **BS, RIS, and user organization**: For the RIS-assisted cellular networks, we propose the RIS organization as shown in Fig. 2. The boresight of the sectors are considered to be in the directions of \([30^\circ, 150^\circ, 270^\circ]\) and the RIS is placed at the edge of each sector with the boresight of RIS elements facing the boresight of the BS. This organization of the BS orientations and positioning of the RIS helps in ensuring RIS access to all the users in the sector. When compared to the scenario with boresight of the sectors in the direction of \([0^\circ, 120^\circ, 240^\circ]\) and RIS placed at cell-edge with its elements facing the boresight of the BS, the proposed organisation has two key benefits as follows. With the proposed organization, the BS to RIS distance is \( \frac{LSD}{2} \) instead of \( \frac{LSD}{3} \), where, \( ISD \) indicates the inter-site distance. Note that the achievable gains with RIS-assisted systems heavily dependent on the path loss observed in the BS-RIS-user link. Thus, with the proposed organisation, the path loss observed by users will be minimal, and hence, enhanced signal reception can be achieved at the user. Further, with the proposed organisation, the interference caused from the beamforming of the RIS to the other sectors is also comparatively minimum, as the nearest neighbour sectors are not in the boresight direction of the RIS. Note that even though we present formulations and results considering one RIS in each sector, all the formulations and discussion in this letter can be easily extended to multiple RIS in a sector.

3) **Channel Model**: Typically, the physical size of the RIS structure is comparatively much smaller than the actual distance of the RIS from the BS and user. Hence, we assume the far-field region while formulating the channel model \( \mathbf{H} \). Further, considering the various existing evaluations in the literature \([10]–[12]\), we adapt the 3rd Generation Partnership Project (3GPP) based 3-dimension channel between the BS.
RIS and user [10], [16]. We define the clusters, sub-clusters, rays, angle of arrivals, angle of departures, pathloss, shadow-fading, and small scale fading as per the channel modelling formulated in [16]. The formulation of channel coefficients between the BS, RIS, and user (excluding the large scale fading parameters such as path loss and shadow fading) is summarized in (5)-(7). \( \phi_{\text{AOA}}, \theta_{\text{AOA}}, \phi_{\text{AOD}}, \) and \( \theta_{\text{AOD}} \) represent the angle of arrivals in azimuth and elevation, and angle of departures in azimuth and elevation, respectively.

Based on the cellular environment (such as urban, rural, etc.), these angles are assigned considering various sub-rays corresponding to various clusters between the transmitter and receiver as per [13], [16]. \( a_k, a_{\text{RIS}}, a_{\text{BS}} \) and \( a_{\text{RIS}}, a_{\text{BS}} \) represent the antenna gains at the user, RIS, and BS respectively. We consider the sectoral antenna pattern as per [13], [16] at the BS and omni directional antenna at the user. We model the transmissions from RIS as just reflections (passive) i.e., with zero additional antenna gain \( \beta_{\text{RIS}}(\cdot) \le 1 \). \( \chi \) captures the cross polarisation powers, \( d \) represents the location vector, and \( r \) represents the spherical unit vector for corresponding antenna elements, respectively. For the planar array shown in Fig. 3, the spherical unit vector is formulated as shown below [16].

\[
\begin{align*}
\mathbf{r} &= \begin{bmatrix} 
\sin \theta \cos \phi \\
\sin \theta \sin \phi \\
\cos \theta
\end{bmatrix} .
\end{align*}
\]

\( \nu_k \) represents the speed of the receiver and the corresponding exponential in (5) and (7) captures the Doppler effect. Note that there is no Doppler term considered in (6), as we consider RIS to be immobile. Further, we also consider the path loss and shadow fading for each cellular environment as per [13].

Next, we explain the proposed beamforming in detail.

### III. Proposed Beamforming

To achieve an optimal solution to the problem formulated in (4a), the BS has to know the complete channel state information between RIS and each user. However, this is not always achievable in practice. Hence, we propose a practically feasible beamforming design as follows. We configure \( B \) number of predefined digital beams at the RIS such that they cover the entire sector, as shown in Fig. 3. The number of beams \( B \) can be decided by the network operator based on the number of antenna elements at the RIS. Given \( B \) beams, the BS can tune the phase shifters at RIS and activate one of the configured beams over various time slots. At the receiver, the user calculates the effective received signal strength from the configured beam and also the direct-link from the BS as shown in (3). The user then reports back the best beam index to the BS in the uplink. For example, the best beam for user 1 and 2 in Fig. 3 are beam-1 and beam-3, respectively. This way, the BS can configure the desired beams at the RIS while scheduling the data to each user. Note that a similar approach can also be adapted for the initial user attach. While transmitting the downlink synchronization signals, the BS can tune the phase shifters at RIS and transmit different beams over various time slots such that the user can lock to the beam from which it receives maximum signal strength.

We explain the selection of the phase shifters at the RIS to steer the beam towards a desired direction as follows. Consider the planar array as shown in Fig. 3 with spacing between the antenna elements in horizontal and vertical as \( dy \) and \( dz \), respectively.

**Lemma 1.** The optimal phase shifters to steer the reflected beam from the RIS towards a direction \((\phi_{\text{AOA}}, \theta_{\text{AOA}})\) w.r.t. RIS is given by

\[
\begin{align*}
\beta_y &= k dy (\sin \phi_{\text{AOA}} \sin \theta_{\text{AOA}} - \sin \phi_{\text{AOD}} \sin \theta_{\text{AOD}}) , \\
\beta_z &= k dz (\cos \phi_{\text{AOA}} \sin \theta_{\text{AOA}} - \cos \phi_{\text{AOD}} \sin \theta_{\text{AOD}}) .
\end{align*}
\]

where, \( \phi_{\text{AOA}} \) and \( \theta_{\text{AOA}} \) are the angle of arrivals in azimuth and elevation at RIS respectively.

**Proof.** With \( \phi_{\text{AOA}} \) and \( \theta_{\text{AOA}} \) as the angle of arrivals in azimuth and elevation, respectively; \( N_x \) and \( N_y \) as the number of elements in horizontal and vertical directions at RIS respectively; using (8), the effective array factor of the RIS as shown in (3).
is given by \[ 16, 17 \]

\[
AF = \sum_{m=1}^{N_x} \sum_{n=1}^{N_y} \left( e^{j(m-1)(kd_y \sin \phi_{AOA} \sin \theta_{AOA} + \beta_y)} \right) \times \\
\left( e^{j(n-1)(kd_z \cos \phi_{AOA} \sin \theta_{AOA} + \beta_z)} \right)
\]  (11)

Thus, for the array factor of the reflected signal to be maximum in a direction \((\phi_o, \theta_o)\), (9)-(10) should hold.

A. Baseline algorithms considered for the evaluation

1) Cellular system without any RIS: We consider cellular system without any RIS as the baseline system for the comparison to understand the achievable gains with the introduction of RIS. Further, to ensure the correctness of the system-level modeling along with channel formulation, we have considered the antenna configuration and simulation parameters of the 3GPP Phase-2 Calibration [13] as the baseline and aligned the results with [13].

2) Random phase shifters at the RIS [9]: We evaluate the performance of the RIS-assisted cellular systems while applying random phase shifters (i.e., values of \(\theta_n\) are assigned from complex random distribution with \(|\theta_n| \leq 1\) at the RIS in each time slot [9]. This is a low-complex algorithm which exploits the achievable antenna array gain at the RIS.

3) Proposed algorithm with discrete phase shifters at the RIS: We consider the evaluation of the proposed algorithm by considering discrete phase shifters at the RIS. We define the discrete phase shifters as follows [14].

\[
F_D \triangleq \left\{ \theta_n \mid \theta_n \in \{ 1, e^{j \frac{\pi}{2}}, \ldots, e^{j \frac{2\pi(D-1)}{D}} \} \right\}.
\]

In this letter, we consider \(D = 2, 8\), and evaluate the two-bit and 8-bit discrete phase shifter scenarios, respectively. Next, we present the simulation results in detail.

IV. Simulation Results and Discussion

The simulation parameters considered for the evaluation of the proposed algorithms are presented in Table I. We consider an urban macro cellular environment for the evaluation, drop the users randomly in each sector, and place the RIS as shown in Fig. 2. We then consider the sectoral antenna pattern as per [13, 16] at the BS omni-directional antenna at the user, and passive antenna at the RIS. We follow [13, 16] while generating the clusters, sub-rays with in a cluster, angle of arrivals, angle of departures, path loss, and shadow fading. For each link between the BS, RIS, and user, we consider the formulations in (5)-(7). We calculate the received signal power at each user from each BS as per (5) and attach the user to the BS from which it has received maximum signal power. We then perform Monte-Carlo simulations in MATLAB and analyze the achievable coupling loss and signal-to-interference-plus-noise ratio (SINR) with all the considered algorithms.

In all our simulation results, we explicitly model the inter-cell and inter-RIS interference by considering wraparound procedure [13].

![Fig. 4: Comparison of achievable coupling loss with various algorithms](image)

We have calculated the coupling loss as the difference between the transmitted power and received power at each user \(k\) as follows.

\[
\text{Coupling loss} = P_t - \Gamma_k \Xi_k,
\]

In Fig. 4, we present the cumulative distribution function (CDF) of the coupling loss observed with various algorithms. The coupling loss for the case without RIS is aligned with the 3GPP Phase 2 Calibration curves presented in [13, 16], thus, ensuring the correctness of our implementation. As compared to the scenario with no RIS, the proposed design with ideal phase shifters achieves 4 dB gain in the received signal power. The gains achievable with random phase shifters while using single RIS are very minimal. Further, the proposed design with
2-bit discrete phase shifters also have significant improvement as compared to the scenario without any RIS. With the 8-bit discrete phase shifters, the coupling loss of the proposed design is similar to the coupling loss of the proposed design with ideal phase shifters.

We have calculated the SINR by explicitly capturing the interference from the neighboring BS and RIS as follows:

$$\text{SINR} = \frac{P_t h_k h_k^H}{\text{IN}_k + \Xi_k},$$  \hspace{1cm} (12)$$

where \(\text{IN}_k\) represents the interference captured from the neighboring BS and RIS transmissions. In Fig. 5, we present the CDF of the SINR observed with various algorithms. The SINR for the scenario without RIS is aligned with 3GPP Phase 2 Calibration curves presented in [13], and thus, ensures the correctness of our simulator. As compared to the scenario with no RIS, the proposed design with ideal phase shifters achieves close to 2 dB improvement in the SINR. Note that despite the maximum of 4 dB gain in the received signal power in Fig. 4, we achieve only 2 dB improvements in the SINR because of the increase in the inter-cell interference because of addition of RIS in the neighbouring sectors. This reduction in SINR also highlights the need for carrying out multi-cell analysis to quantify the practical gains with the inclusion of RIS. Further, for the same reason, all the cell-edge users do not observe similar interference, and hence, the pattern of achievable gains in coupling loss and SINR differ. Note that the performance of the random phase shifters is close to the scenario without any RIS and the performance of the proposed RIS with 2-bit discrete phase shifters is also significantly better than the baseline algorithms. Further, with the 8-bit discrete phase shifters, the SINR of the proposed design are similar to the SINRs of the proposed design with ideal phase shifters.

V. Conclusion

In this letter, we have presented in detail the system-level modelling of the RIS-assisted cellular systems. We have proposed a novel cellular layout and RIS organisation which ensures uniform accessibility of the RIS for all the active users in the desired sector and creates minimal interference to users in the neighboring cells. We have then proposed a beamforming design for the RIS-assisted cellular systems and analyzed the achievable gains with the proposed design by considering ideal and discrete phase shifters. To evaluate the proposed beamforming design we have considered the 3-dimension channel modelling between the BS/RIS and users. Through extensive system-level analysis, we have shown that the proposed design achieves significant improvements in the SINR observed by the users, when compared against the baseline algorithms. These improvements in SINR result in achieving enhanced network capacity and coverage. In future, we plan to evaluate the proposed design on the hardware testbeds.

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