Towards System Level Simulation of Reconfigurable Intelligent Surfaces

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***Abstract*—Reconfigurable Intelligent Surfaces (RISs) have emerged as an essential technology for the next generation of wireless communication systems. They have the potential of improving system throughput, coverage, and energy efficiency. An RIS is a planar surface that consists of multiple reflecting elements with configurable phase shifts that can modify impinging signals and steer reflected waves in any direction. To evaluate the benefits of deploying RISs in future wireless networks, it is essential to conduct system-level simulations for RIS-aided large-scale multi-cell networks. Thus, a reliable system-level simulator is in urgent need. This paper introduces an extension for RIS-aided transmission for the Vienna 5G system-level simulator. Most of the system-level concerns for RIS-based wireless networks are addressed, such as RIS modeling, RIS phase shifts optimization, large-scale fading, small-scale fading, and cell association. In addition, the average system performance of the RIS-aided single-input single-output (SISO) scenario is evaluated through Monte-Carlo simulations and compared with known theory. Simulation results are compared between optimized and random RIS phase shifts. The results from the system-level simulator are consistent with the power scaling law for RIS. The SISO scenario performance verification is a stepping-stone for further system-level simulations in RIS-based multiple-input multiple-output (MIMO) scenarios.**

***Keywords*—reconfigurable intelligent surface; intelligent reflecting surface; system level simulation; power scaling law; 6G**

I. Introduction

Reconfigurable intelligent surfaces (RIS) have recently emerged in wireless communications as a promising technique, because they can improve the spectral efficiency and energy efficiency of a wireless system by artificially altering the wireless propagation environment [1]. An RIS is a planar surface made up of many reflecting components with configurable phase shifts that can change impinging signals and steer reflected waves in any desired direction [2]. Usually, it is a passive device that does not require active power amplifiers or radio frequency chains, but it needs an external electric power to control the phase shifts and the operation of the surface. Furthermore, RISs are simple and inexpensive to manufacture, and can be installed on walls, street lamps, and building facades [3]. As a result of these compelling benefits, RIS is expected to be one of the essential technologies for sixth-generation (6G) wireless networks.

Several fundamental design issues must be tackled to incorporate RIS into future telecommunication standards. These issues include RIS modeling, channel estimation, system optimization, RIS deployment, and interference management in multi-cell networks. Some of these issues have been studied in recent literature. For example, the authors in [4] compiled a list of the most often utilized RIS communication models and compared different RIS designs. Several system optimization methods were compared in [5] to improve the performance of RIS-aided wireless communication system. In [6], the authors investigated the impact of a large-scale RIS deployment on the cellular network performance, as well as techniques to improve the cellular network performance by overcoming blockages with a subset of nearby RISs.

However, existing research on the effectiveness of RIS-aided communication primarily focuses on theoretical frameworks and treats the impact of different parameters separately. Very little literature is concerned with a large-scale system-level simulation of RIS-aided systems. To the best of our knowledge, so far, the only system-level evaluation for RIS-based wireless networks was introduced in [7]. The simulation results reveal that the performance improvement of deploying RIS depends on the operating frequency and RIS size. However, the influence of the RIS element number, channel implementation, interference, cell association, and other essential and detailed information is missing: no system model for RISs is provided and the system performance is not verified. A more efficient RIS-tailored system-level simulator that allows even larger simulation scenarios and investigations on more performance measures is needed.

In order to address these shortcomings, the aim of this paper is to evaluate the system performance of RIS-aided large-scale communication network from the Vienna 5G System Level Simulator [8]. In this paper, we introduce how the RIS-tailored system-level simulator tackles the system-level challenges of RIS-aided wireless network, such as RIS modeling, RIS phase shifts optimization, cell association, macroscopic and small-scale fading, blockage, etc. In addition, we run Monte-Carlo simulations to analyze the system performance, which is further verified by known theory, e.g., the power scaling law explained in [9]. With extensive and flexible parameter choices, the simulator can be used to comprehensively evaluate the system performance of RIS-aided multicell or single-cell networks. It is efficient enough to simulate thousands of nodes. The results can contribute to the implementation of RISs in

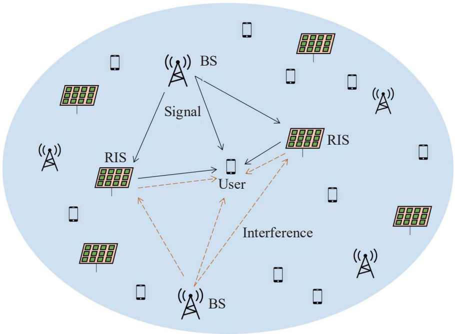


Figure 1. RIS-aided multi-cell wireless network.

real-life situations in the future.

This paper is organized as follows. Section II describes the RIS-tailored system-level simulator. In Section III, simulation results in a relatively simple scenario are discussed for further reference. Finally, conclusions are drawn in Section IV.

II. RIS-TAILORED SYSTEM LEVEL SIMULATOR

With regard to large-scale system-level analysis, the experiment is not a preferred method due to the significant expense and time commitment. As an alternative, a system-level simulator plays a vital role in system performance analysis and optimization. Among existing simulators such as LTE-Sim, SimuLTE and Coffee Grinder Simulator, the Vienna 5G System Level Simulator can simulate large-scale networks with thousands of network nodes and very flexible to extend. In addition, it is free for academic use. The Vienna 5G System Level Simulator is currently being expanded to include an RIS module. As shown in Fig. 1, the RIS implementation aims to simulate RIS-aided large-scale multi-cell wireless networks. When there are many BSs, users and RISs, aspects such as cell association, interference and blockage should be considered.

In the system-level simulator, RISs are created as new network nodes in addition to base stations (BSs) and users in a chosen scenario. Various RIS deployment options exist, e.g., Poisson distributed, on facades of buildings or user-defined. RIS-aided links usually suffer a severe path loss since the signal has to propagate first from the BS to the RIS and then from the RIS to the user. As a result, an RIS should be placed where it has line-of-sight (LoS) connection with both BS and user, to help improve the receive signal strength in the block-spot area and improve the system coverage. Therefore, we provide an option to remove/deactive RISs that do not have LoS connections, as they have only little effect on the system performance. This allows to reduce the simulation complexity, by only considering relevant RISs.

To start from a simple case, the RIS is modeled as an ideal phase shift model from [1], i.e., the reflection coefficient of the m-th element is $V_m = \beta_m e^{j\theta_m}$, where $m \in 1, ..., M$ and M is the element number of the RIS. The terms $\beta_m \in [0, 1]$ and $\theta_m \in [-\pi, \pi)$ denote the amplitude and the phase shift of the m-th element, respectively. In order to observe the maximum gain from an RIS, we set $\beta_m = 1$ as default value. Accordingly, a diagonal matrix $\mathbf{\Phi} = \mathrm{diag}(e^{j\theta_1}, ..., e^{j\theta_M})$ represents the RIS phase shifts. Here $\mathrm{diag}(\mathbf{x})$ denotes a square diagonal matrix with the components of $\mathbf{x}$ on its main diagonal. It is worth noting that a far-field assumption is considered in the system-level simulator, which refers to the distance from the transmitting/receiving antenna to the surface being much larger than the size of the antenna and the wavelength. Hence, the wave directions and channel gain are approximately the same from all RIS elements in the array to the antennas.

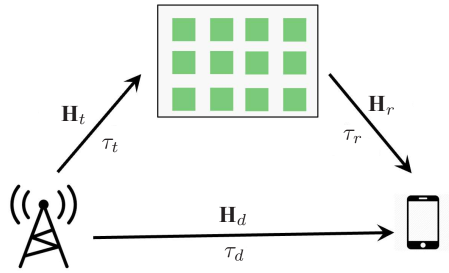


Figure 2. Channels and delays

Both the small scale fading and macroscopic fading (MF) are included in the simulator. The MF of BS-user, BS-RIS and RIS-user links are calculated as MF $= G_t -$ PL $-$ WL. For a BS-RIS and a BS-user link, G_t is the antenna gain from the BS. For an RIS-user link $G_t = 0$ since an RIS is a passive device that has no antenna gain. PL is the path loss, and WL is the wall loss. The simulator supports various models to calculate the distance dependent path loss, such as free space, urban, suburban path loss models, etc. Wall loss is a parameter defined from blockage modeling. In the simulator, regular or arbitrary city layouts with streets and building blocks can be generated. Each blockage wall is assigned to a wall loss.

Small scale channel fading is generated according to the parameter setups of BS, user and RIS. The frequency selective channels should be taken into account in wideband communications. When the user side receives signals from both direct link and RIS-aided links, the extra delays from BS-RIS and RIS-user links should be considered. As shown in Fig. 2, $\mathbf{H}_d \in \mathbb{C}^{N_t \times N_r}$, $\mathbf{H}_t \in \mathbb{C}^{N_t \times M}$ and $\mathbf{H}_r \in \mathbb{C}^{M \times N_r}$ represent the channels of BS-user, BS-RIS and RIS-user links, respectively. Here $\mathbb{C}^{n \times m}$ denotes the space of $n \times m$ complex-valued matrices, N_t and N_r are the number of antennas at the BS and user, respectively. The corresponding delays of these channels are τ_d, τ_t and τ_r, which are calculated according to the geometrical distances of the network nodes. The delay difference between the RIS-aided link and the direct link is $\Delta\tau = \tau_t + \tau_r - \tau_d$. The extra delays for BS-RIS and RIS-user links can be calculated as $\Delta\tau_t = \Delta\tau \cdot \frac{\tau_t}{\tau_t + \tau_r}$ and $\Delta\tau_r = \Delta\tau \cdot \frac{\tau_r}{\tau_t + \tau_r}$, respectively. The extra delays are then added to the corresponding channels: $\mathbf{H}_{t'} = \mathbf{H}_t \cdot \exp(j2\pi f \Delta\tau_t)$ and $\mathbf{H}_{r'} = \mathbf{H}_r \cdot \exp(j2\pi f \Delta\tau_r)$, where f is subcarrier frequency. The channel of an RIS-aided link can be written as $\mathbf{H}_{\text{RIS}} = \mathbf{H}_{t'} \cdot \mathbf{\Phi} \cdot \mathbf{H}_{r'}$.

For large-scale multi-cell wireless networks, each user should be assigned to a cell, which leads to the cell association problem. Two cell association strategies are implemented in the simulator: maximum receive power and maximum signal to interference and noise ratio (SINR). The received power or SINR from both the direct link and RIS-aided links are

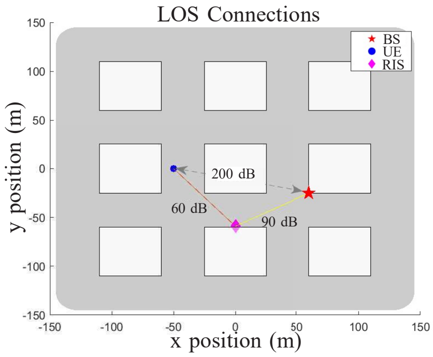


Figure 3. Simulation scenario

calculated respectively for each user. The receive power is calculated according to the MF, i.e., $P_r = P_t(\mathrm{MF}_d + \mathrm{MF}_t \cdot \mathrm{MF}_r)$, where P_t is the transmit power in Watt, MF_d, MF_t and MF_r are the MF in Watt of the BS-user, the BS-RIS and RIS-user links, respectively. Small scale fading and RIS phase shifts are not involved in this process. The user is then assigned to the BS that leads to the highest receive power or SINR. The assigned BS is also the desired BS for RIS-aided links. Other BSs are regarded as interference. When users are moving, the cell association will be updated accordingly.

The RIS phase shifts can be chosen as random or optimized for the SISO scenario in the simulator. In order to receive maximum power at the user, the RIS phase shifts are usually designed to achieve a constructive coherent combination of the direct link and RIS-aided link. In reality, the RIS phase cannot be subcarrier-dependent, as the same phase shifts have to be applied for all subcarriers. Thus, the frequency selective channels H_d, $\mathbf{H}_{t'}$ and $\mathbf{H}_{r'}$ are averaged over subcarrier domain first, then the optimized RIS phase shifts are calculated as $\theta_m = \arg(H_d) - \arg(\mathbf{H}_{t',m} \cdot \mathbf{H}_{r',m})$. Here the non-bold letter H_d denotes a single value because $N_t = N_r = 1$ in SISO case, and $\arg(\mathbf{x})$ represents the phase of the corresponding element in $\mathbf{x}$. The optimized RIS phase shifts are also calculated according to the associated BS, i.e., using the H_d and $\mathbf{H}_{t',m}$ from the desired BS. When the cell association is updated, the phase shifts will be changed according to the assigned BS. Because in the real world, RISs cannot have different phase shifts for different BSs. The phase shifts should be all the same for all available BSs. Currently, the optimization process is done for each user one by one, interference between different users are not involved. RIS phase shift optimization for multi-user multiple-input multiple-output (MU-MIMO) scenarios in the simulator is postponed to further research work.

III. Simulation Results

A system-level simulation in a simple scenario is always the first step to assess the developing technologies and acts as a stepping-stone for large-scale system-level simulations. Hence, performing system level simulations in a SISO scenario first and comparing the results with known theory is essential for developing a reliable system-level simulator.

The simulation scenario is shown in Fig. 3, which includes one BS with one antenna, one RIS and one single-antenna user. Rayleigh channel model and fixed path loss model are selected. The path loss of BS-user, BS-RIS and RIS-user links is set as 200 dB, 90 dB, and 60 dB, respectively. The center frequency and bandwidth are 2 GHz and 20 MHz, respectively. The BS-user link is blocked by a building with high wall loss, the BS-RIS and RIS-user links are LoS links. We sweep over the transmit power at the BS to observe the performance with different RIS element numbers. The simulation results with optimized RIS phase shifts and random RIS phase shifts are compared. According to the power scaling law addressed in [9], the signal-to-noise ratio (SNR) grows as M^2 in the far-field with optimized RIS phase shifts. So the SNR will increase 6 dB when doubling M. However, for random RIS phase shifts, the SNR can only improve 3 dB when doubling M.

As a simulation result, the SNR is calculated as follows:

$$\mathrm{SNR} = \frac{P_t|\sqrt{\mathrm{MF}_d} \cdot H_d + \sqrt{\mathrm{MF}_t \cdot \mathrm{MF}_r} \cdot H_{\mathrm{RIS}}|^2}{\sigma^2}, \tag{1}$$

where σ^2 denotes the noise power at the receiver. We use the non-bold letter H_{RIS} because the channel becomes a single value in the SISO scenario.

A. Results of Random RIS Phase Shifts

This section shows the simulation results with random RIS phase shifts. With the same simulation setup, we perform 1 000 Monte-Carlo simulation runs and investigate the average performance. The SNR and user throughput are shown in Fig. 4. The curves are all plotted with a 95% confidence interval, indicating that after running a large number of independent simulations, 95% of values will fall into this range.

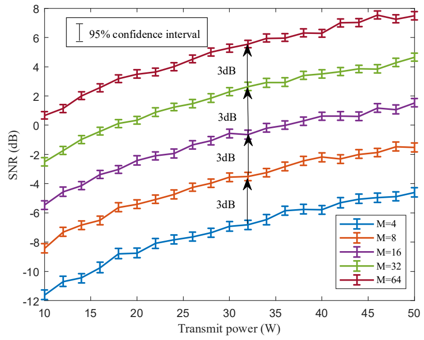
Fig. 4a and Fig. 4b show that the SNR and user throughput increase with the transmit power as expected, since the received power increases when the transmit power increases. In addition, when the RIS element number is increased from 4 to 8, 16, 32 and 64, we can observe 3 dB gain in SNR for every doubling of RIS elements, which is consistent with the power scaling law. The system-level simulation and performance evaluation in more complex MIMO scenarios are postponed to further research work.

From Fig. 4b we can observe that the user throughput increases monotonically with transmit power. In addition, when the RIS element number grows, the user throughput also increases, which is consistent with conclusions in the existing literature.

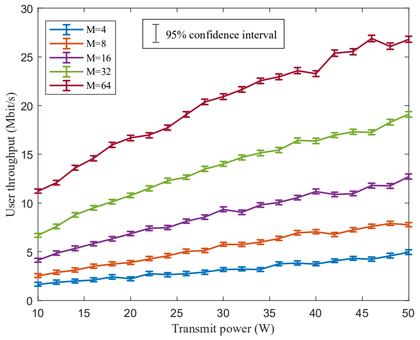
B. Results of Optimized RIS Phase Shifts

This section exhibits the simulation results with optimized RIS phase shifts. The simulation setup and parameters are identical to simulations in III-A. The average results are obtained from 250 Monte-Carlo simulation runs.

From Fig. 5, we notice that the SNR and user throughput improve when increasing the transmit power and RIS element number. Compared with Fig. 4, the SNR achieves a 6 dB gain when doubling the number of RIS elements, which fulfills the power scaling law. We also find that the optimized RIS phase

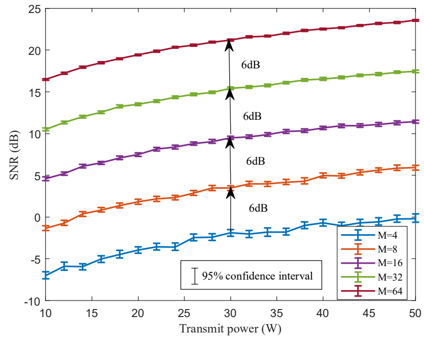


(a) SNR

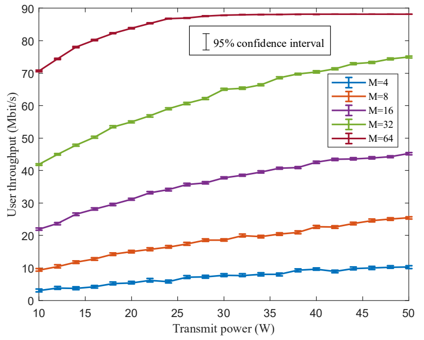


(b) User throughput

Figure 4. Simulation results with random RIS phase shifts.



(a) SNR



(b) User throughput

Figure 5. Simulation results with optimized RIS phase shifts.

shifts can achieve much higher SNR and user throughput than random RIS phase shifts with the same RIS element number. For example, with 64 RIS elements, the SNR obtained from optimized phase shifts is around 17 dB higher than the SNR with random phase shifts. The user throughput has improved by about 63 Mbit/s. The throughput also grows faster with the transmit power in optimized phase shifts case than in random phase shifts case. For instance, with 32 RIS elements, the throughput increases from 42 to 75 Mbit/s in the optimized phase shifts case, while in the random phase shifts case, the variation is only from 7 to 18 Mbit/s.

IV. Conclusion

RIS is an attractive technology for the next generation of wireless communication systems, since it can modify the environment. With the rapid speed of RIS-related studies, system-level simulation is urgently needed to evaluate the performance of RIS-aided wireless networks. This paper introduces the RIS module implemented in the Vienna 5G system-level simulator, where many challenges for RIS-based wireless networks at the system-level have been considered. Especially the RIS modeling, RIS deployment, macroscopic fading, small scale fading, cell association, and RIS phase shift optimization are explained. Furthermore, simulation results in a SISO scenario have been analyzed and compared with theory. Results show that the SNR and user throughput are both improved when increasing the RIS element number. The optimized RIS phase shifts lead to a much higher SNR and throughput than the random RIS phase shifts. The results from the system-level simulation show consistency with the known theory. This is the first step for further large-scale system-level simulations in more complex MIMO scenarios.

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