RECONFIGURABLE INTELLIGENT SURFACES: PERFORMANCE ASSESSMENT THROUGH A SYSTEM-LEVEL SIMULATOR

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ABSTRACT
Reconfigurable intelligent surfaces (RISs) are considered a promising technology for boosting the coverage and for enhancing the spectral efficiency of wireless systems, as well as for taming the wireless environment. The potential benefits of RISs are currently being analyzed and various approaches are being proposed to address the challenges for their integration in wireless networks. Currently available studies to quantify the potential gains of deploying RISs in wireless networks are limited to simple network topologies, while no system-level assessments have been reported to date. Network-level, for example, on the scale of hundreds of square meters, simulations are, however, the first step to quantify the actual value of emerging technologies and the steppingstone before considering large-scale system-level experimental evaluations and network deployments. Toward this direction, this article reports the first system-level simulation results and analysis of an RIS deployment in a typical urban city that is served by a fifth-generation cellular network. The obtained system-level simulation results unveil that the benefits of RISs vary depending on the operating frequency and the size of the surfaces. Specifically, we investigate the performance improvement that RISs can provide, in terms of outdoor and indoor coverage and per resource block rate, when deployed in mid (C-band) and high (millimeter-wave) frequency bands. For example, the obtained results unveil that the deployment of RISs enhances the coverage probability from 77 percent to 95 percent in the C-band and from 46 percent to 95 percent (92 percent in the presence of network interference) in the millimeter-wave band.

INTRODUCTION
Reconfigurable intelligent surfaces (RISs) constitute an emerging transmission technology that is under evaluation for possible integration in future programmable wireless networks. For example, the European Telecommunications Standards Institute (ETSI) has recently launched a focused industry specification group whose objective is to coordinate current research and development efforts on RISs for facilitating the potential adoption of this technology in future telecommunication standards (https://www.etsi.org/committeee/1966-ris).

An RIS is an engineered (intelligent) surface, which is made of electromagnetic metamaterials and is equipped with simple electronic circuits (e.g., diodes or tunable capacitors), that is capable of intentionally and smartly controlling the propagation of the electromagnetic waves in complex wireless propagation environments, so as to boost the signal quality in a cost-effective and energy-efficient manner [1]. The potential benefits of RISs in wireless networks depend on the carrier frequency. In particular, an RIS deployed in the mid frequency spectrum, for example, the C-band, of fifth-generation (5G) cellular networks is expected to primarily enhance the rate of cell-edge users, to improve the channel rank of multiple-input multiple-output (MIMO) transmission links, and to suppress the network interference. An RIS deployed in the high frequency spectrum, for example, the millimeter-wave (mmWave) band, is expected to primarily enhance the signal-to-noise-ratio (SNR) in weak coverage areas and blind zones, by overcoming non-line-of-sight propagation conditions and by enhancing outdoor-to-indoor communications. In this context, an RIS may constitute a cost-effective, smart, reconfigurable, and easy to deploy alternative to relays, which is able to operate in full-duplex mode without self-interference [1]. Besides their use as RISs, engineered surfaces are currently being investigated for several wireless applications, which include the implementation of low-complexity active transceivers for extremely massive MIMO communications. This kind of engineered surfaces is usually referred to as holographic surfaces (HoloS) [2].

While the potential advantages and gains of deploying RISs in wireless networks are under discussion and analysis, it is acknowledged that several important design challenges need to be tackled for possibly integrating RISs in future telecommunication standards. These include the definition of electromagnetically consistent models for metasurfaces, as well as a derivation of channel models for RIS-aided links and their integration into ray tracing simulators [3], the development of scalable algorithms for optimizing the opera-
tion, the placement and deployment of RISs [4], the design of efficient channel estimation algorithms and feedback channels for controlling and configuring RISs [5], as well as the ownership and interference management in multi-operator networks. In addition, the identification of the most suitable use cases and deployment scenarios for RISs is currently being discussed. Examples of use cases that were showcased at the Docomo Open House 2021 include the deployment of transparent RISs for enabling outdoor-to-indoor communication in the mmWave frequency band (https://docomo-openhouse.jp/2021/en/exhibition/022/) by using, for example, transparent metamaterial films that do not spoil the appearance of windows (https://www.sekisui.co.jp/electronics/en/application/film.html).

Testbed validations, real-world experiments, and field trials are essential needs to demonstrate, in existing 5G network deployments, the actual value of emerging technologies like RISs. In the literature, various testbed platforms have recently been reported. Examples of hardware prototypes include two-state digital surfaces for anomalous reflection in the sub-6 GHz [6] and mmWave frequency [7] bands, four-state digital surfaces for anomalous reflection in the sub-6 GHz and mmWave frequency bands [3, Table I], varactor-controlled surfaces with continuous phase shift capabilities [3, Table II], and omni-cover surfaces that are endowed with joint reflection and refraction capabilities [8]. By contrast, a limited number of real-world measurement campaigns have been publicly reported. These include the demonstration of an RIS testbed that was deployed by Docomo and Metawave in a real urban environment in Japan for expanding the coverage of outdoor non-line-of-sight links at 28 GHz [9], and a one-bit digitally-controlled RIS prototype that was successfully tested for data transmission over a 500 m communication link [10].

The available testbed prototypes and the field trials reported to date constitute fundamental proof-of-concept evaluations of the potential gains of RISs in realistic but small-scale deployments. To evaluate the potential benefits of deploying RISs in existing and future wireless networks, large-scale simulations and field trials in realistic propagation environments and network topologies are needed. The present article is a first attempt to evaluate the potential performance gains provided by RISs when they are deployed in a large-scale urban environment and when they are integrated into an existing 5G cellular network. Compared with the available results for small-scale network topologies, the significance of the present system-level study lies in considering a realistic network deployment, which includes the presence of buildings, vegetation, and reference channel models (Table 1).

The performance studies available to date are, on the other hand, based on simplified assumptions according to which, for example, the presence of buildings is modeled through blocking probabilities that do not depend on the network topology. In addition, the present study accounts for realistic transmission distances, which correspond to an already deployed 5G network and are known to highly determine the potential gains offered by near-field passive RISs [1, 11].

The simulation study reported in this article is the first of its kind and relies on the Coffee Grinder Simulator©. The aim of our study is to quantify the expected performance gains offered by RISs, as a function of their size, deployment density, and frequency of operation, when they are deployed in an existing 5G cellular network. Specifically, we analyze and compare the deployment of RISs in the mid frequency band (the C-band at 3.5 GHz) and in the low mmWave frequency band (at 28 GHz). Several numerical results are illustrated and discussed. For example, it is shown that the deployment of RISs enhances the coverage probability from 77 percent to 95 percent at 3.5 GHz in the absence of network interference, as well as from 46 percent to 95 percent and from 46 percent to 92 percent at 28 GHz in the absence and in the presence of network interference, respectively.

### System-Level Simulation Platform

To quantify the performance gains offered by the deployment of RISs in a typical urban environment that is served by a 5G network infrastructure, we employ the Coffee Grinder Simulator. Coffee Grinder is a proprietary simulation platform for fast wireless systems exploration, which is developed and maintained by Huawei Technologies Sweden–Gothenburg Research Center. Coffee Grinder is an advanced link-level and system-level simulator that is designed for analyzing low and high frequency bands. The simulation platform is characterized by the agility of configuration in space and runtime, as well as the visualization of results.

| City/Area (m²)       | C-Band Frequency  | mmWave Band Frequency |
|----------------------|------------------|-----------------------|
| City/Area (m²)       | Urban Hangzhou, China / 800 × 800 m² | 28 GHz |
| Bandwidth (MHz)      | 3.5 GHz          | 200 MHz               |
| Number of BS         | 1                | 5                     |
| BS Height (m)        | 30 m             | 24.54 m               |
| BS Transmit Power    | 50 dBm           | 32 dBm                |
| BS Array Gain        | 23 dBi           | 30 dBi                |
| UE Array Gain        | 3 dBi            | 10 dBi                |
| UE Placement         | Indoor and Outdoor | Outdoor         |
| 3D UE Measurement Grid | 1 UE / 100 m² (Ground/Floor) – Uniform distribution |
| UE Noise Figure      | 7 dB             | 10 dB                 |
| Thermal Noise        | -91 dBm          | -88 dBm               |
| RIS Width (m) (square shape) | 2.70 m / 3.80 m / 5.30 m | 0.33 m / 0.48 m / 0.67 m |
| RIS Elements         | 3.136 / 6.241 / 12.100 | 2.916 / 6.241 / 12.321 |
| RIS Reflection Losses | 0 dB             | 0 dB                  |
| Number of Candidate RIS 3D Positions | 4,000  | 34,000          |
| Channel Models       | Metis2020 Propagation Model | COST231 Vegetation Model |
| Cell-edge Target SNR Coverage Target | 10 dB (95 %) | |
Coffee Grinder provides realistic urban and rural 5G and beyond 5G network deployments. Compared with other system-level simulators, Coffee Grinder integrates the OpenStreetMap API for modeling buildings, streets, vehicles, and it supports map-based channels based on the METIS 5G channel model, which includes vegetation and atmospheric attenuation. Hybrid three-dimensional ray tracing models are supported based on a sparse point cloud method, that is, a deterministic map-based channel model is employed for modeling surfaces and corners, while environmental small scale features are included through a diffuse scattering model.

The propagation channels are calculated at discrete frequency bins and all the components of the channel model are computed for all frequency bins, in order to obtain frequency-dependent realistic and accurate results that account for the antenna elements, beam squint, material properties, Doppler shift and spread, Fresnel zones, and rain attenuation. The ray bundles are explored for all candidate routes and each ray is evaluated by applying Jones’s calculus to the antennas, and to the reflected, diffracted, penetrated, and scattered waves. Several material models are supported, including custom materials and materials specified by the METIS channel model. The antenna models of the base station (BS) and user equipment (UE) are fully customizable. High-level physical layer algorithms are supported as well.

In Fig. 1, as an example, we illustrate the grid-based representation of the potential positions of the UEs in an urban environment, as well as an example of ray bundles that account for thousands of paths. As far as this article is concerned, the most important feature of the Coffee Grinder Simulator is the support of realistic models for RISs, which include anomalous reflections, and the computation of the RIS locations for an optimized deployment.

Coffee Grinder was initially designed in Matlab and was subsequently migrated to Python with a GPU acceleration support (Nvidia Optics).

**SIMULATION SETUP AND RIS MODELING**

In this section, we describe the network simulation environment, the simulation setup, and how the RISs are modeled and incorporated into the system-level simulator.

In Table 1, we report the simulation setup. The considered network scenario corresponds to an urban area in the city of Hangzhou, China, which is identified by the geographical coordinates (30° 16’ 58.8” N, 120° 9’ 21.6” E). The area is covered by BSs that are located according to a real life grid. The number of BSs and RISs depends on the operating frequency. In this study, two typical carrier frequencies for 5G networks are analyzed: the C-band at 3.5 GHz (mid frequency band) and the mmWave band at 28 GHz (high frequency band). The focus of the analysis reported in this article is on downlink (DL) transmissions. A similar analysis for the uplink (UL) can be performed. It is pertinent to note, however, that the DL-UL reciprocity may not necessarily hold in RIS-aided channels, and that it depends on the specific characteristics of the RISs [6]. The impact of the DL-UL reciprocity in RIS-aided networks is postponed to a further research work.

It is worth mentioning that the system-level study reported in this article provides results that are specific to the urban region where the evaluation is conducted. The analysis is, however, representative of a typical urban environment where a 5G network is already deployed. The objective of the present article is in fact, to understand whether the deployment of RISs in a realistic 5G cellular network results in substantial performance gains when a realistic propagation environment, which includes the presence of buildings, vegetation, and reference channel models, is considered (Table 1).

To evaluate the performance of the considered RIS-aided cellular network in terms of coverage probability and rate, we compute coverage maps across the entire considered geographic area, where the potential UEs may be located in indoors and outdoors. The UEs are assumed to be located on a grid-based layout with a density of 1 UE per 100 m². Specifically, the UEs are uniformly distributed in the considered deployment, since we are interested in quantifying, thanks to the deployment of RISs, the enhancement of the coverage probability and rate throughout the entire region of interest. The optimal locations of the RISs are affected by this assumption. The evaluation of the performance of UEs with a different spatial distribution can be performed analogously, but the optimal locations of the RISs are expected to be different.

As far as the optimal locations of the RISs are concerned, they are obtained by evaluating thousands of different three-dimensional candidate locations that are tested for improving the outdoor and indoor coverage. Specifically, a UE is typically considered to be in coverage if the received
SNR is greater than 0 dB. Besides this typical case study, we consider an SNR-boosted scenario in which the UEs are in coverage if the SNR is greater than 10 dB at the considered operating frequency. We assume that multiple RISs can assist the transmission of each UE. To better analyze the gains offered by the deployment of RISs, the BSs are assumed not to be equipped with (massive) MIMO antennas. The use of (massive) MIMO antennas is expected to further improve the coverage and rate, but it may render more difficult to identify the actual gains offered by RISs. Also, the UEs are assumed to be equipped with omnidirectional antennas. The array gains of the single-antenna BSs and single-antenna UEs are reported in Table 1.

As far as the RISs are concerned, we model them as bidimensional antenna-arrays [7]. The elements of each RIS are patch antennas with a cosine-shaped power radiation pattern, whose half-power beam width is 120 degrees and whose directivity is 6 dB. The inter-distance between the RIS elements is 0.56λ, where λ is the signal wavelength. This choice provides a good trade-off between the number of RIS elements and the presence and intensity of grating lobes. Specifically, no grating lobes exist if the angle of reradiation is no larger than 51 degrees with respect to the angle of incidence [12]. For a given size of the RIS, the corresponding number of radiating elements is given in Table 1. The path-loss model considered for the RISs is compliant with recently reported measurement campaigns at different frequency bands [6, 7].

We assume that each RIS is configured as an anomalous reflector and that it introduces a linear phase shift that depends on the difference between the angle of incidence and the desired angle of reflection. This is the typical geometrical optics approximation [3, Eq. (94)] with a unit amplitude constraint, which can be applied in the far-field region of the RIS. It is known, however, that configuring an RIS as an anomalous reflector is a suboptimal design in the near-field region of the RIS [11]. From a practical point of view, the deployment of RISs configured as anomalous reflectors is convenient, since it is easier to estimate the directions of the UEs as compared with their exact locations. The accuracy of the far-field approximation is further discussed in the sequel (see Fig. 4). Unless stated otherwise, the RISs are assumed to apply continuous-valued phase shifts to the incident signals. A recent evaluation of the impact of quantizing the phase shifts and other practical constraints for the implementation of RISs can be found in [13].

A worst-case analysis of the impact of these effects in terms of network-level interference is reported next (see Fig. 3). In addition, the RISs are optimized according to a local design and no average power conservation is enforced, which usually results in local power amplifications [3]. These assumptions constitute a sort of “worst case” design for the RISs, which allows us to better understand the fundamental gains that they can offer in realistic 5G cellular network deployments.

As mentioned, MIMO antennas are not utilized at either the BSs or the UEs. In addition, the analyzed sizes of the RISs, their linear phase shift configuration that is nearly-optimal in the far-field region and a practical assumption in general, as well as the typical transmission distances in the considered network scenario (an urban area in Hangzhou, China) make the BS-RIS-UE links behave as typical double-scattering (also known as keyhole or pinhole) channels, which are rank-deficient channels that cannot typically support multi-stream transmission. As a result, we consider single-stream transmission. Accordingly, each deployed RIS is designed to reflect, in each orthogonal physical resource (a resource block), a single electromagnetic wave that impinges upon it from a given direction of incidence (determined by the location of the serving BS) toward a single direction of reradiation (determined by the location of the served UE). Furthermore, we assume that the communication between one BS and one UE can be assisted by multiple RISs, and that the same RIS cannot be utilized by two different BSs (the RISs are not shared between cells). This is because an RIS is most useful when deployed either close to the BSs or close to UE-populated areas [4, 14]. Therefore, relevant metrics that quantify the achievable performance brought by the deployment of RISs are the per-UE coverage probability and the per-UE rate, that is, the coverage probability and achievable rate in a generic resource block. The distributions of the coverage probability and rate are obtained as a function of the spatial deploy-
ment of the UEs. Generalization of our analysis to the multi-RIS MIMO broadcast channel (i.e., multi-stream transmission) is possible by using the algorithms in [14], provided that the channel supports multi-stream transmission.

As an illustrative example, Fig. 1 shows the SNR coverage maps obtained with the Coffee Grinder Simulator when the carrier frequency is 28 GHz. The maps are generated by assuming that the target SNR for the cell-edge (5th percentile) UEs is 10 dB. We see that 46 percent of the UEs are in coverage (or 77 percent if the SNR target is only 0 dB) in the absence of RISs, while 95 percent of the UEs are in coverage when all the RISs in the network are utilized. It is apparent, therefore, that the deployment of RISs is beneficial for boosting the SNR in weak coverage areas and blind spots, which in turn enhances the coverage probability and the per resource block rate.

The system-level evaluation reported in this article is primarily focused on quantifying the coverage probability and the achievable rate (per resource block) of an RIS-aided cellular network. Intra-cell interference is not present in the considered network deployment, since, as mentioned, only single-stream transmission is supported by the considered system and channel models. Inter-cell interference is not present in the C-band, since a single BS is deployed in the considered area, and we are hence mainly interested in analyzing the SNR improvement, for example, in blind-spot areas, due to the deployment of RISs. In the mmWave band, on the other hand, inter-cell interference is present, but it is limited due to the sparse deployment of the BSs (5 BSs in the considered case study) and the high directivity of the transmit and receive antennas. In general, however, inter-cell interference cannot be ignored. In the mmWave band, therefore, we analyze the network-level performance in the absence (noise-limited) and in the presence of inter-cell interference, and compare these two scenarios when the RISs are and are not deployed in the network. Unless stated otherwise, for ease of exposition, the simulation results are referred to the noise-limited setup. The impact of the other-cell interference is discussed next (see Fig. 3).

**RIS DEPLOYMENT ALGORITHM**

The Coffee Grinder Simulator offers the provision of deploying a large number of RISs throughout the considered geographical area. In addition, it offers the possibility of optimizing the locations of the RISs given those of the UEs and BSs. Specifically, the candidate locations for the RISs are assumed to be in line-of-sight with the available BSs and to form a finite grid. This grid includes locations corresponding to walls, roofs, and corners. Algorithm 1 is utilized for optimizing the locations of the RISs.

Specifically, the algorithm for optimizing the positions of the RISs works as follows. First, the target SNR threshold is set for the cell-edge UEs (e.g., a cell-edge UE is in coverage if the SNR is greater than 10 dB). The implemented algorithm is iterative: One new RIS is added at each iteration of the algorithm until the target SNR threshold is fulfilled. The placement of each RIS is obtained by utilizing a brute-force method (exhaustive search): The best location for the RIS is determined by evaluating all the possible combinations that account for the locations of the BSs and the candidate locations of the RISs on the considered grid, so that the largest number of UEs fulfill the target SNR threshold. In this optimization process, specifically, it is implicitly considered that the same RIS cannot be utilized by two different BSs. The considered approach is time consuming, since
a large number of computations are needed and all the propagation paths need to be evaluated. Based on a sequential ordering, however, the algorithm returns the locations of the RISs that improve the SNR coverage. Therefore, it serves the main purpose and objective of our research work. The development of computationally efficient network deployment algorithms for RISs is postponed to a future research contribution.

**SYSTEM-LEVEL SIMULATION RESULTS**

In this section, we report the system-level simulation results obtained with the Coffee Grinder Simulator in the RIS-aided 5G urban network deployment illustrated in Fig. 1. The system-level performance evaluation encompasses the coverage probability and the per resource block rate at different carrier frequencies and for different sizes of the RISs. The analysis accounts for UEs located in indoor and outdoor.

Specifically, the key performance indicator of interest is the cumulative distribution function (CDF) of the SNR at the UEs in the absence and in the presence of RISs, that is, the outage probability. In other words, the complementary CDF (CCDF) represents the fraction (or percentage) of locations of the UEs where the received SNR is greater than the predefined target SNR threshold, that is, the UE at the specified location is in coverage. From the obtained curves of CDF and CCDF, the performance gains obtained through the deployment RISs are quantified. The following two sections report the results for a 5G network deployment in the C-band and in the mmWave band, respectively.

Special focus is put on the impact of the size of the RISs at different carrier frequencies. As a benchmark, we consider the case study when the RISs are not deployed in the network. In our analysis, the RISs are deployed on existing surfaces (e.g., the walls of buildings). This implies that the existing surfaces that are not coated with RISs behave as non-controllable scatterers. Depending on their size and the material that these surfaces are made of, they behave as equivalent diffuse or specular reflecting RISs [13]. Thus, the “No RIS” scenario considered in the present study is a sensible and realistic benchmark for comparison.

**CASE STUDY: C-BAND AT 3.5 GHz**

In Fig. 2, we report the system-level results for the 5G network deployment at 3.5 GHz. The outage probability and the SNR coverage are illustrated as a function of the size and the number of available RISs. Also, the received SNR for various percentiles of UEs is reported, including the median (often referred to as the typical) UEs (the 50th percentile) and the cell-edge UEs (the 5th percentile). The 5G network scenario encompasses one BS and several square-shaped RISs having three possible sizes: 2.7 m × 2.7 m (size 1), 3.8 m × 3.8 m (size 2), 5.3 m × 5.3 m (size 3).

The two illustrations at the top of Fig. 2 show the SNR outage probability and the SNR coverage improvement when the target SNR threshold is set to 10 dB, which is a good SNR value for cell-edge UEs. In the absence of RISs, the SNR coverage for the considered target SNR threshold is 77 percent. A suitable target in RIS-aided networks is to attain the 95 percent of coverage for the same target SNR threshold of 10 dB, and by considering both indoor and outdoor UEs. The figure shows that this target is achieved if 21, 12, and 9 RISs of size 1, size 2 and size 3 are deployed in the network, respectively. As expected, the smaller the size of the RISs is the larger the number of surfaces to deploy is. In the considered case study at 3.5 GHz, a good compromise is obtained by using RISs whose size is 3.8 m × 3.8 m (size 2). Notably, we evince that only 5 RISs are needed for 90 percent of the UEs to be in coverage, even though the target SNR threshold is 10 dB.

The two illustrations at the bottom of Fig. 2 show the received SNR for different percentiles of UEs. We note that the deployment of RISs provides a significant increase of the received SNR. The SNR of the typical user (the 50th of UEs) increases of 3.1 dB and 4.4 dB if the size of the RISs is 2.7 m × 2.7 m (size 1) and 5.3 m × 5.3 m (size 3), respectively. It is worth noting that the SNR curves are steeper for a small number of RISs, which shows that the deployment of a few RISs may result in substantial performance gains.

**CASE STUDY: mmWAVE AT 28 GHz**

In Fig. 3, we report the system-level results for the 5G network deployment at 28 GHz in the absence (top and center illustrations) and in the presence (bottom illustrations) of network interference. The figure is tantamount to Fig. 2, but the size of the RISs is chosen to ensure a number of RIS elements similar to the case study in the C-band (Table 1). More precisely, the sizes of the RISs are 0.33 m × 0.33 m (size 1), 0.48 m × 0.48 m (size 2), and 0.67 m × 0.67 m (size 3). As summarized in Table 1, a main difference between the case study at 3.5 GHz and the case study at 28 GHz is that the number of BSs is increased from one to five. The results shown in Fig. 3 are similar to those in Fig. 2, but there are some differences, qualitatively and quantitatively. First, we note that the coverage probability in the absence of RISs is only 46 percent, even though only the outdoor UEs are considered in light of the high penetration losses in the mmWave band. The use of RISs that operate as refracting surfaces may overcome this limitation, as envisioned in some recent use cases put forth by Docomo. The analysis of this deployment scenario is postponed to a future investigation.

From the two illustrations at the top of Fig. 3, we see that, with the aid of RISs, the coverage probability increases from 46 percent to 95 percent (still ensuring a target SNR threshold of 10 dB) by deploying, on average per BS, 20, 12, and 8 RISs of size 1, size 2, and size 3, respectively, which corresponds to a deployment of 100, 56, and 37 RISs in the considered geographic region. At 28 GHz, we evince, therefore, that RISs whose...
size is $0.48 \times 0.48$ m (size 2) may be a suitable trade-off option for ensuring that 95 percent of the UEs are in coverage by deploying 10 RISs per BS. Furthermore, the deployment of only 2 RISs per BS guarantees that more than 70 percent (size 2) and 75 percent (size 3) of the UEs are in coverage.

From the two illustrations at the bottom of Fig. 3, we unveil the impact of network interference in the mmWave frequency band for different user percentiles. For example, the received SNR of the 5th percentile of UEs (cell-edge UEs) increases by 20 dB if, for each BS, 20 RISs of size 1 or 8 RISs of size 3 are deployed. We see a large improvement of the SNR even for the median UEs (the 50th percentile), since the increase of SNR is of the order of 9.8 dB (size 1) and 13.1 dB (size 3). The slope of the curves is steeper when the first RISs are added in the network, which implies that large SNR gains may be obtained even if a few RISs per BS are deployed.

As far as the per resource block ergodic rate is concerned, meaningful conclusions can be drawn. In the absence of RISs and network interference, the per resource block rate of the cell-edge UEs is only $0.96$ bps/Hz at 3.5 GHz and $0.13$ bps/Hz at 28 GHz. On the other hand, the per resource block rate that corresponds to a received SNR equal to 10 dB is, according to Shannon’s formula in a noise-limited scenario, equal to $3.46$ bps/Hz. Therefore, there is a substantial margin for improvement. Theoretically, in particular, the per resource block rate could be increased by 260 percent and 2,561 percent at 3.5 GHz and 28 GHz, respectively. From Table 2, we evince that the deployment of a few RISs per BS, and that it may not be negligible for the cell-edge UEs. For example, 7 RISs per BS are sufficient for the cell-edge UEs to attain the SNR target of 10 dB in the absence of network interference. In the presence of interference, on the other hand, the cell-edge UEs can only attain an SINR approximately equal to 6-7 dB if the same number of RISs per BS is deployed. Nonetheless, the positive impact of deploying RISs is apparent in the presence of network interference as well.

Achievable Coverage and Rate Improvement

Quantitatively, the main findings of the conducted system-level simulation study are summarized in Table 2. Specifically, the table reports the achievable coverage and the improvement of the per resource block rate by factors that are consistent with the theoretical optimum. If an appropriate number of RISs per BS is deployed, specifically, the per resource block rate is increased by a factor of 3.5 and by a factor of 25 in the C-band and in the mmWave band, respectively. It is worth noting that the deployment of RISs is not beneficial only for the cell-edge UEs, but the per resource block rate of the median (or typical) UEs is increased as well. In the absence of RISs, in fact, the per resource block rate is 7.9 bps/Hz at 3.5 GHz and 4.8 bps/Hz at 28 GHz. In the mmWave frequency band, the per resource block rate of the typical UEs is increased by a factor of 1.5. In the presence of network interference at mmWave frequencies, we obtain similar results, with almost the same gain, while the per resource block rate is increased by a factor of 8 at 3.5 GHz and 2.8 at 28 GHz. However, the deployment of RISs is shown to offer substantial performance gains, even in the presence of network interference. Overall, the results reported in Table 2 provide us with insights on the trade-offs that emerge for

The fine-grained analysis for different percentiles of UEs unveils that the negative impact of network interference depends on the number of deployed RISs per BS, and that it may not be negligible for the cell-edge UEs. For example, 7 RISs per BS are sufficient for the cell-edge UEs to attain the SNR target of 10 dB in the absence of network interference. In the presence of interference, on the other hand, the cell-edge UEs can only attain an SINR approximately equal to 6-7 dB if the same number of RISs per BS is deployed. Nonetheless, the positive impact of deploying RISs is apparent in the presence of network interference as well.

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Quantitatively, the main findings of the conducted system-level simulation study are summarized in Table 2. Specifically, the table reports the achievable coverage and the improvement of the per resource block rate by factors that are consistent with the theoretical optimum. If an appropriate number of RISs per BS is deployed, specifically, the per resource block rate is increased by a factor of 3.5 and by a factor of 25 in the C-band and in the mmWave band, respectively. It is worth noting that the deployment of RISs is not beneficial only for the cell-edge UEs, but the per resource block rate of the median (or typical) UEs is increased as well. In the absence of RISs, in fact, the per resource block rate is 7.9 bps/Hz at 3.5 GHz and 4.8 bps/Hz at 28 GHz. In the mmWave frequency band, the per resource block rate of the typical UEs is increased by a factor of 1.5. In the presence of network interference at mmWave frequencies, we obtain similar results, with almost the same gain, while the per resource block rate is increased by a factor of 8 at 3.5 GHz and 2.8 at 28 GHz. However, the deployment of RISs is shown to offer substantial performance gains, even in the presence of network interference. Overall, the results reported in Table 2 provide us with insights on the trade-offs that emerge for
In Fig. 4, motivated by these considerations, the system-level simulation results illustrated so far are obtained under the assumption that the RISs are configured as anomalous reflectors, and, therefore, they apply a linear phase modulation to the incident electromagnetic waves, which depends on the angle of incidence and the desired angle of reflection. As mentioned, this configuration of the RISs is suboptimal in the near-field region of the surface, while it is close to the optimum in the far-field region. Therefore, it is instructive to analyze the optimality of the obtained results from the point of view of utilizing RISs that are configured as anomalous reflectors.

This analysis can be performed by resorting to the concept of Fresnel’s zones [15]. By definition, the ratio of the diameter of the first Fresnel zone and the width of the RIS is greater than one, we conclude that RISs configured as anomalous reflectors are close to optimal. If the size of the RISs is 5.3 m × 5.3 m (size 3) in the C-band, we observe, however, that about 30 percent of the UEs may be in positions at which configuring an RIS as an anomalous reflector is not optimal anymore. In this case, the RISs need to be operate as focusing lenses. By taking into account that it may likely occur, or it may be added as an optimization constraint, that the optimal locations of the RISs provide a ratio between the diameter of the first Fresnel zone and the width of the RIS that is greater than one, we conclude that RISs designed as anomalous reflectors may be a pragmatic choice for realistic network deployments. In fact, such RISs are usually easier to realize and to optimize, since it is simpler to estimate and track the angles of arrival of the electromagnetic waves as compared with the exact locations of the UEs.

### Closing Remarks

RIS is an emerging technology for improving the coverage and rate of wireless systems without requiring active power amplifiers, multiple radio frequency chains, and complex digital signal processing units. In this article, for the first time in the open technical literature, we have reported a system-level performance evaluation study of an RIS-aided 5G network that is deployed in a typical urban environment for operation at 3.5 GHz (C-band) and 28 GHz (mmWave). The study is performed by leveraging the Coffee Grinder Simulator that integrates a specifically designed algorithm for optimizing the locations of the RISs throughout the network, as a function of their size, operating frequency, and reflection capabilities. In particular, the RISs are modeled as anomalous reflectors for serving UEs located in the far-field region.

| RIS — Size | Achievable Coverage Probability [Number of RISs per BS] | Improvement of the Per Resource Block Rate [Number of RISs per BS] |
|------------|--------------------------------------------------------|---------------------------------------------------------------|
| 1 at 3.5 GHz | 77 % [0] 88 % [5] 95 % [21] | 3 % [1] 34 % [5] 253 % [21] |
| 2 at 3.5 GHz | 77 % [0] 90 % [5] 95 % [12] | 5 % [1] 59 % [5] 253 % [12] |
| 3 at 3.5 GHz | 77 % [0] 92 % [5] 95 % [9] | 11 % [1] 115 % [5] 258 % [9] |
| 1 at 28 GHz | 46 % [0] 76 % [5] 95 % [20] | 0 % [1] 38 % [5] 2508 % [20] |
| 2 at 28 GHz | 46 % [0] 86 % [5] 95 % [11.2] | 8 % [1] 238 % [5] 2508 % [11.2] |
| 3 at 28 GHz | 46 % [0] 91 % [5] 95 % [7.4] | 46 % [0] 92 % [7.4] |

**TABLE 2.** Coverage probability and per resource block rate by deploying RISs of different size in the C-band and mmWave band.
The benefits of adding RISs have been evaluated in terms of coverage probability and per resource block rate for different user percentiles, which include the typical UEs (the 50th percentile of UEs) and the cell-edge UEs (the 5th percentile of UEs), by assuming that a UE is in coverage if the received SNR is greater than 10 dB in order to create coverage-booster areas. Overall, the system-level simulations reveal that the deployment of RISs enhances the coverage probability of the UEs from 77 percent to 93 percent in the C-band and from 46 percent to 89 percent in the mmWave band. The deployment of only 5 RISs per BS whose size is 3.8 m × 3.8 m in the C-band and 0.67 m × 0.67 m in the mmWave band ensures that 90 percent of the UEs are in coverage. If 12 RISs per BS of the same size are deployed, the per-resource block rate of the cell-edge UEs increases by a factor of 3.5 and by a factor of 25 in the C-band and mmWave band, respectively. In the mmWave band, the SNR of the cell-edge UEs increases by 20 dB if, for each BS, 20 RISs whose size is 0.33 m × 0.33 m or 8 RISs whose size is 0.67 m × 0.67 m are deployed. In the presence of network interference, in addition, the SINR coverage probability increases from 46 percent to 92 percent if, for each BS, 8 RISs whose size is 0.67 m × 0.67 m are deployed.

In terms of general design guidelines, the conducted study unveils that the deployment of RISs significantly enhances the coverage and per resource block rate of a typical 5G cellular network, in the absence and in the presence of network interference. More specifically, the deployment of a few RISs of sufficiently large size is shown to compensate, in a realistic environment, the far-field path-loss of RISs, that is, the fact that the received power depends on the product of the square of the BS-RIS and RIS-UE distances.

The evaluation of RIS-aided cellular networks with integrated communication, and radio localization and sensing capabilities.

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