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List of Acronyms

3GPP: Third Generation Partnership Project

BER: Bit Error Rate

BS: Base Station

CS: Cell Site

ECDF: Empirical Cumulative Distribution Function

EM: Electromagnetic

LOS: Line of Sight

MCU: Microcontroller Unit

MIMO: Multiple Input Multiple Output

MNO: Mobile Network Operator

NDA: Non-disclosure Agreement

OFDM: Orthogonal Frequency Division Multiplexing

QPSK: Quadrature Phase Shift Keying

RAN: Radio Access Network

RF: Radiofrequency

RIS: Reconfigurable Intelligent Surface

RSRP: Reference Signal Received Power

RX: Receiver

SINR: Signal-to-interference-plus-noise Ratio

SISO: Single Input Single Output

SRS: Software Radio Systems

TX: Transmitter

UE: User Equipment

USRP: Universal Software Radio Peripheral

VSWR: Voltage Standing Wave Ratio

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Resumen Ejecutivo

Este informe representa una investigación preliminar sobre los beneficios de incorporar equipos de Superficie Inteligente Reconfigurable (RIS, por sus siglas en inglés) en las Redes de Acceso por Radio (RAN) para mejorar los servicios celulares. Para llevar a cabo esta evaluación, es necesario diseñar un simulador a nivel de sistema capaz de capturar entornos de propagación realistas así como el comportamiento del RIS.

En este trabajo, hemos diseñado dicho simulador utilizando el trazador de rayos Remcom Wireless InSite, una herramienta comercial avanzada para análisis a nivel de radio. Nuestro objetivo es aumentar las capacidades de esta herramienta para ayudar en el despliegue y simulación de RIS, con patrones de radiación específicos derivados de entornos de banco de pruebas de laboratorio. Nos proponemos evaluar el impacto de los repetidores RIS en la mejora de la cobertura de radio, teniendo en cuenta parámetros clave del sistema como el tamaño, la ubicación y la orientación.

Un paso inicial esencial involucró la realización de una campaña de validación para verificar la efectividad del trazador de rayos Remcom Wireless InSite para nuestros objetivos. Recopilamos conjuntos de datos que detallan características críticas de despliegue, incluyendo las ubicaciones de las estaciones base celulares, su sectorización y la potencia de transmisión, de operadores comerciales dentro del Grupo Telefónica. Nuestra investigación se centró predominantemente en la cobertura en Londres, identificando áreas de 100m x 100m con niveles de RSRP por debajo de -100 dBm, lo que indica una cobertura poco fiable. Posteriormente, al desarrollar modelos 3D de estas áreas con datos de OpenStreetMap, produjimos valores de RSRP para ubicaciones geográficas idénticas mediante trazado de rayos. Validamos esta herramienta comparando muestras de RSRP del trazador de rayos con muestras empíricas correspondientes de los conjuntos de datos.

También exploramos varios métodos para mejorar el entorno de simulación de trazado de rayos con un módulo RIS que presenta un patrón de radiación específico. Entre estos, seleccionamos un modelo realista basado en datos de la tecnología RIS que se puede integrar en el simulador de trazado de rayos. Este módulo emula con precisión el comportamiento de un RIS real, reflejando el rendimiento del mundo real con alta fidelidad. Esta precisión del mundo real es crucial para simular escenarios donde las condiciones ambientales, los materiales y otros factores pueden influir en el comportamiento del RIS. Se espera que la utilización de tal modelo basado en experimentación permita realizar un análisis más convincente de los despliegues de RIS utilizando el trazado de rayos.

El resto del documento está redactado en inglés, de cara a maximizar el impacto del trabajo realizado en este proyecto.

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Abstract

This report represents a preliminary investigation into the benefits of incorporating RIS (Reconfigurable Intelligent Surface) equipment into Radio Access Networks (RAN) to enhance cellular services. To conduct this evaluation, it is necessary to design a system-level simulator capable of capturing both realistic propagation environments and the behavior of RIS.

In this work, we have designed such a simulator using the Remcom Wireless InSite ray-tracing tool, an advanced commercial software for radio-level analysis. Our goal is to augment the capabilities of this tool to aid in the deployment and simulation of RIS, featuring specific radiation patterns derived from laboratory test bench environments. We aim to assess the impact of RIS repeaters on radio coverage improvement, taking into account key system parameters such as size, location, and orientation.

An essential initial step involved is conducting a validation campaign to verify the effectiveness of the Remcom Wireless InSite ray tracer for our objectives. We gathered datasets outlining critical deployment characteristics, including the locations of cellular base stations, their sectorization, and transmission power, from commercial operators within the Telefónica Group. Our research predominantly targeted coverage in London, identifying 100m x 100m areas with RSRP levels below -100 dBm, signaling unreliable coverage. Subsequently, by developing 3D models of these areas with OpenStreetMap data, we produced RSRP values for identical geographical locations through ray tracing. We validated this tool by comparing ray-tracer RSRP samples with corresponding empirical samples from the datasets.

We also explored various methods to enhance the ray-tracing simulation environment with an RIS module featuring a specific radiation pattern. Among these, we selected a realistic, data-driven model of RIS technology that can be integrated into the ray-tracing simulator. This module accurately emulates the behavior of an actual RIS, reflecting real-world performance with high fidelity. This real-world precision is crucial for simulating scenarios where environmental conditions, materials, and other factors may influence RIS behavior. Utilizing such an experimentally grounded model is expected to enable more persuasive analysis of RIS deployments using ray tracing.

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1. Introduction

RIS have recently emerged as a promising technology for next-generation mobile systems. These structures are known for their ability to reflect radio signals while altering some of their features, such as phase, which enables passive beamforming gains without the need for expensive and energy-consuming baseband processors or signal amplifiers. Where RIS technology is expected to significantly outperform conventional Base Station (BS) technology (e.g., small cells, active relays, etc.) is in their energy efficiency. Their predominantly passive nature means they consume much less power, an aspect that is particularly valuable in outdoor environments, where maintaining power sources for base stations can be both logistically challenging and expensive. Another defining advantage of RIS is their minimal infrastructure needs, making them a cost-effective solution for outdoor mobile dead zones. This reduced demand for infrastructure, combined with their energy efficiency, underscores the potential of RIS to reshape the future of mobile systems in a cost-effective way.

However, this technology is still in its nascent stage, as there are no RIS devices currently available in the market yet, and only a few prototypes discussed in the literature [Pei21, Tri22, Rao23]. Hence, the cost-performance trade-off of this new technology in large-scale outdoor mobile network deployments remains an open question. To fill this gap, it is necessary to evaluate the integration of realistic RIS deployments into a production mobile network in an outdoor urban environment. Carrying out this evaluation requires the design of a suitable system-level simulator, capable of capturing realistic propagation environments, as well as the RIS behavior.

In this work, we carry out the design of such a system-level simulator from a RIS model, developed from data collected from a real RIS prototype, which is then then integrated into a state-of-the-art 3D ray-tracing tool widely used in the research community for analyzing site-specific radio wave propagation and wireless communication systems [Her23, Xia22, Fu22]. We then plan to examine the potential of large-scale RIS technology to improve coverage in underserved areas. This approach is consistent with the one followed by radio planning teams within commercial mobile network operators (MNOs) when deploying new radio carriers and studying "what-if" scenarios [Ato23, Inf23].

The structure of this report is as follows. Section 2 provides background information on RIS. Section 3 provides an overview of different system-level analysis approaches. Sections 4 and 5 respectively introduce the ray-tracing tool considered and detail its validation. Section 6 discusses the integration of a RIS module. Section 7 presents the next steps foreseen and Section 8 concludes the report. Additionally, Appendix A lists the main features of the ray-tracing tool chosen, whereas Appendix B provides additional details on the RIS prototype at the basis of the corresponding dataset and simulation module.

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2. A Primer on Reconfigurable Intelligent Surfaces

RIS are engineered structures that can modify the way radio waves behave when they hit the surface. By changing its configuration, a RIS can control the direction, strength, polarization, and other properties of the reflected radio waves. RIS are designed to be as passive as possible in terms of power consumption; in fact, no RF chains are involved, as well as no amplification or digital signal processors.

RIS can be implemented using a variety of different types of surfaces, which can span from very sophisticated metasurfaces to arrays of antennas used as reflectors. A metasurface is made of metamaterials, a type of material that has been engineered to have properties that are not found in naturally occurring materials. They are typically composed of arrays of small metallic or dielectric elements whose behavior can be externally controlled. They are complex to build, but can unlock many diverse features [Lia18]. Alternatively, one can utilize an array of passive reflecting elements, such as small metallic patches or dielectric rods, to reflect impinging radio waves in a specific direction. Such property is usually achieved by adapting conventional beamforming techniques where individual reflecting elements apply (different) phase shifts to the reflected signals passively. In this way, the multiple reflections can interfere constructively in the desired direction, while they cancel each other out in other directions [Dun20].

RIS technology enables smart environments where the wireless channel is yet another knob subject of optimization [Dir20]. This contrasts with the conventional view of treating the channel as a given (or estimated) parameter. Smart environments will be crucial for the next-generation mobile systems and can improve the reliability of communication systems by increasing path diversity between BSs and user devices (UE), as depicted in Fig. 1. An example of a specific RIS application is improving the coverage of cellular networks in hard-to-reach areas like underground tunnels, inside buildings, or in complex urban scenarios. We will focus on the latter case in this report.

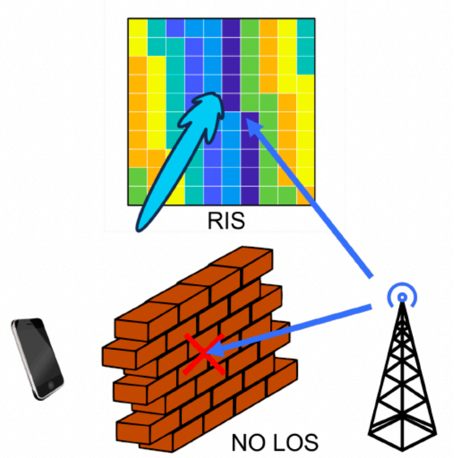

FIGURE 1: ***COMMON RIS USE CASE, WHERE THE DIRECT LOS PATH BETWEEN TRANSMITTER AND RECEIVER IS BLOCKED BY AN OBSTACLE.***

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3. Overview of Available System-Level Analysis Tools

RIS-based networks are envisioned as a configurable platform that integrates communication, sensing, localization, and computing. Thus, RISs need to continuously sense and promptly adapt to the environment. A thorough system-level analysis is needed to evaluate and fully understand the benefits of incorporating RIS equipment into radio access networks (RANs) for service enhancement. Typically, system-level evaluations are conducted either via mathematical modelling and analysis or via numerical simulation.

Mathematical analysis tools: The theoretical analysis of the performance of cellular networks through mathematical tools has been providing invaluable insights on the fundamental principles of network planning for the past few decades. However, this approach—e.g., via stochastic geometry, a commonly used tool to analyze wireless network coverage and interference patterns for random spatial distributions of nodes [Hae09, Win09]—is not ideally suited to drive critical design choices on cellular networks with specific requirements and deterministic deployments of base stations and RIS. Mathematical tools also have limitations in modeling the physical layer in detail, especially when capturing realistic three-dimensional environments, leading to complex or intractable formulations. For these reasons, the approach followed in this project will rely on numerical simulations instead.

Statistical simulation tools: The design and analysis of RIS deployments hinges on accurate models of the electromagnetic propagation. Currently available models, developed by standardization bodies such as the Third Generation Partnership Project (3GPP), are statistical and derived from an ensemble of measurement campaigns conducted by large industry players [TR38.901]. These statistical models are designed to capture multiple scenarios, inevitably with different degrees of realism, rather than a specific environment of interest such as a concrete geographical area corresponding to a city or a neighborhood. For these reasons, statistical 3GPP models are not suitable to evaluate the benefits of incorporating RIS equipment into a specific RAN configuration at a predetermined geographical location.

Ray-tracing tools: Generating a digital replica of a certain propagation environment is possible via ray tracing, thereby enabling system-level simulations that realistically model signal coverage and interference accounting for the wireless medium. The latter, in turn, depends on the peculiarities of the geographical area under consideration and thus on the location and orientation of buildings and cellular base stations. Conducting accurate ray-tracing system-level simulations requires a detailed blueprint of the environment, to appropriately capture the electromagnetic properties of buildings and terrain.

In what follows, we detail the choice made in this project in terms of ray-tracing tool, the validation process carried out to ensure the selected tool accurately captures real-world propagation features, and the approach followed to augment such tool with RIS simulation capabilities.

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4. Choice of the Ray-tracing Tool

Given the extreme complexity involved in developing a ray-tracing simulator—an endeavor whose technical scope and budget fall outside those of the present project—and given the wide availability of ever more sophisticated commercial ray-tracing tools, we decided to rely on one such commercially available tool: Wireless InSite [Remcom]. This decision was taken internally and was further motivated by the fact that system-level simulation modules employed in production could not be used, since their respective licenses do not cover research activities.

To this end—and after seeking and obtaining the due approval—we purchased a license in the framework of the project, thereby investing some of our available funding on software rather than personnel costs. Promptly purchasing this license allowed us to progress on this task and thus accommodate for the delay incurred in starting the project.

Wireless InSite is a suite of radiofrequency (RF) propagation models, providing 3D ray-tracing, fast ray-based methods, and empirical models for the analysis of site-specific radio wave propagation and wireless communication systems. Through its combined modeling, simulation, and post-processing capabilities, it provides efficient and accurate predictions of electromagnetic (EM) propagation and communication channel characteristics in complex urban, indoor, rural and mixed path environments. Some of the key features of Wireless InSite are reported in Appendix A of this report.

Wireless InSite is a ray-tracing tool that is widely known in the wireless communications research community for its capabilities and versatility [Fu22, Zha23]. Members of our team have previously employed this tool for research work, some of which resulted in top-tier publications in wireless communications and networking venues [Her23, Xia20, Kan21, Kan22, Xia22]. For this project, we have established synergies with the vendor to be able to integrate a customized RIS module in the ray-tracing simulator.

Their capabilities notwithstanding, ray-tracing models are constructed making several assumptions on the radio propagation, on the electromagnetic properties of buildings and terrain, and on the hardware and software capabilities of end-user devices. Therefore, an initial step is to validate the accuracy of the tool for our study, as discussed in the sequel.

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5. Validation of the Ray-tracing Tool

To validate the ray-tracing tool, we examined the coverage provided by certain base stations and we compared the results with empirical data. For our study, we rely on real-world datasets that we collect from a large commercial mobile network operator operating in the UK, with a major market share. Our topology dataset captures the geographical location of all the radio cell sites the operator uses, the different radio sectors (i.e., carriers) deployed at each site, and their respective configuration. The process is detailed as follows.

Radio network topology

We considered the topology of a production radio network owned by a commercial mobile network in the UK. We collected datasets that consist of key deployment features, such as cellular base station locations, their sectorization, transmission power, among other information, from commercial operators within the Telefonica corporation, specifically Virgin Media O2 and Movistar Spain. For the validation of the ray-tracing tool, we focused on the mobile radio deployment the operator owns within London.

Empirical data

We employed empirical data of radio coverage measurements. The radio coverage quality (or lack thereof) is the chief complaint that subscribers make to the operator when asked about the quality of their service in periodic surveys. To continuously improve the quality of their service, the operator monitors the radio coverage from the end-user perspective via crowd-sourced measurements. For our study, we considered two such commercial crowd-sourced datasets that the operator provided. The two datasets are similar in that they capture radio signal strength metrics from the end-user device via code embedded in popular apps that run on the end-user device. In particular, we focused our analysis on the Reference Signal Received Power (RSRP). This is a metric that represents the average of reference signal power across a specified bandwidth (in the number of Resource Elements). It is a critical parameter that a User Equipment (UE) needs to measure for tasks such as cell selection, reselection, and handover in cellular communication systems.

We utilized the following two datasets:

- _Dataset1_: Providing the median RSRP per tile unit over a 100x100m grid covering areas of interest, specifically London and the entirety of the UK. The median RSRP value for each tile is based on all measurements taken within that tile during the period of November 2022.
- _Dataset2_: Containing individual measurement samples of the RSRP metric from end-user devices, gathered in November 2022. This dataset comprises more than 600,000 samples, with each sample tagged with its geographical coordinates and the corresponding radio sector identity.

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Together, these datasets helped us understand the coverage the operator offers in terms of RSRP across various regions. Our analysis primarily focused on coverage in London. For example, Fig. 2 displays 100m x 100m tiles where the RSRP is below -100 dBm (indicative of unreliable coverage). The colors highlight instances where coverage issues are detected in Dataset 1, Dataset 2, or both.

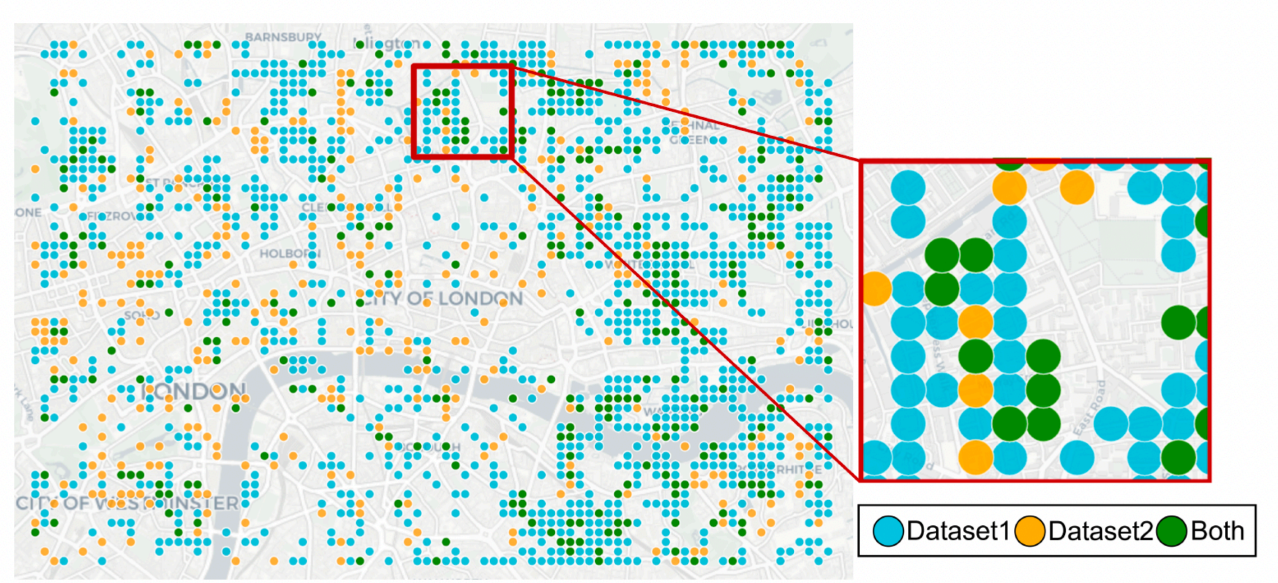

FIGURE 2: ***RADIO COVERAGE MAP FOR THE CITY OF LONDON SHOWING LOCATIONS WITH VALUES OF RSRP < -100 DBM ON EITHER DATASET OR BOTH.***

Ethical considerations on data collection

We note that the data collection and retention at network middle-boxes and elements are in accordance with the terms and conditions of the MNO and the local regulations. All datasets we use in this work are covered by NDAs prohibiting any re-sharing with third parties even for research purposes. Further, raw data has been reviewed and validated by the operator with respect to GDPR compliance (e.g., no identifier can be associated with a person), and data processing only extracts aggregated user information at the postcode level. No personal and/or contract information was available for this study, and none of the authors of this report participated in the extraction and/or encryption of the raw data.

Validation of the ray-tracing tool

To generate RSRP values for the same geographical locations using ray tracing, we built 3D models of the selected neighborhood for this study using data from OpenStreetMap. Fig. 3 displays said map with the locations of two cell sites (CS1 and CS2) from the MNO being analyzed, along with potential locations for the deployment of RIS technology. CS1 has six cells at a height of 15.5 meters, while CS2 has three cells at a height of 20 meters. Each cell is fitted with a 4G 60° sectorial antenna with a transmission power of 40 dBm. Note that the figure also shows potential locations for the implementation of RIS technology, identified from areas exhibiting poor coverage and that will be considered in later stages of this project.

FIGURE 3: ***3D MAP OF THE GEOGRAPHICAL AREA OF INTEREST, LOCATION OF CELL SITES (CELL 1 AND CELL 2), AND POTENTIAL RIS SITES (A–P).***

As mentioned above, we verified the effectiveness of the ray-tracing tool for our analysis. To this end, in Fig. 4 we show the coverage provided by the nine cells using the ray-tracing tool, and we compare the results with the empirical data provided by the aforementioned datasets, which we depict in grey and white squares in the figure. The ray tracer provides mean RSRP samples at a granularity of 100 m2, which we depict as colored circles in Fig. 4.

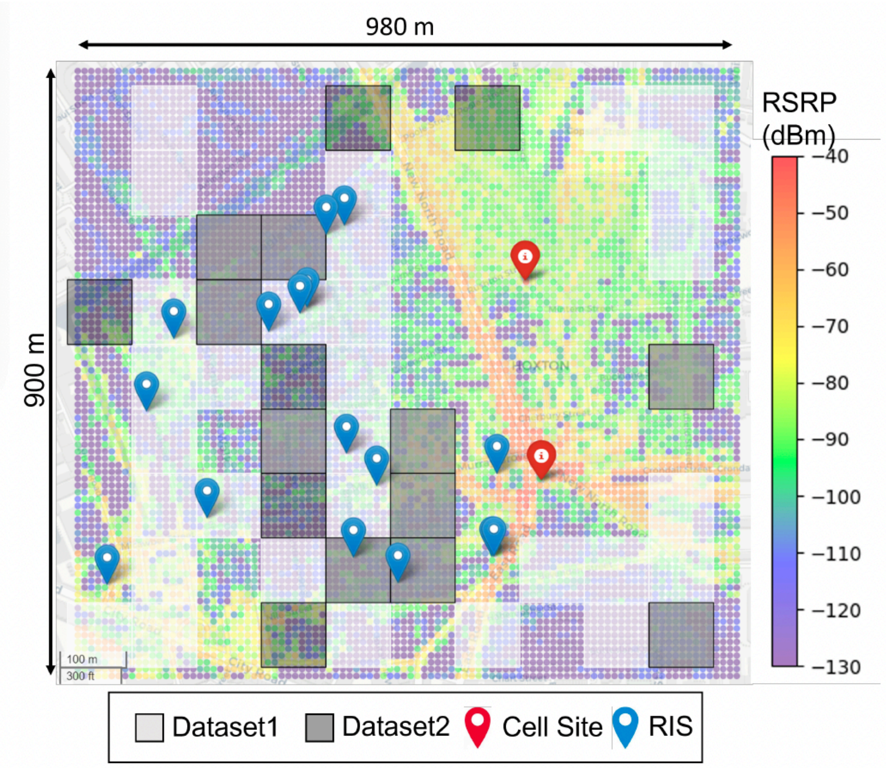

FIGURE 4: ***BASELINE RSRP WITH RAY-TRACING TOOL AND WITH EMPIRICAL DATASETS, LOCATION OF CELL SITES, AND POTENTIAL RIS SITES.***

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To validate the tool, we compared the RSRP samples from the ray tracer with the overlapping empirical samples from the datasets. Fig. 5 indicates a median error of 2.1 dBm for Dataset1 and 4.8 dBm for Dataset2. We consider these errors sufficiently small to continue relying on the ray tracing solution for our subsequent analysis and design work.

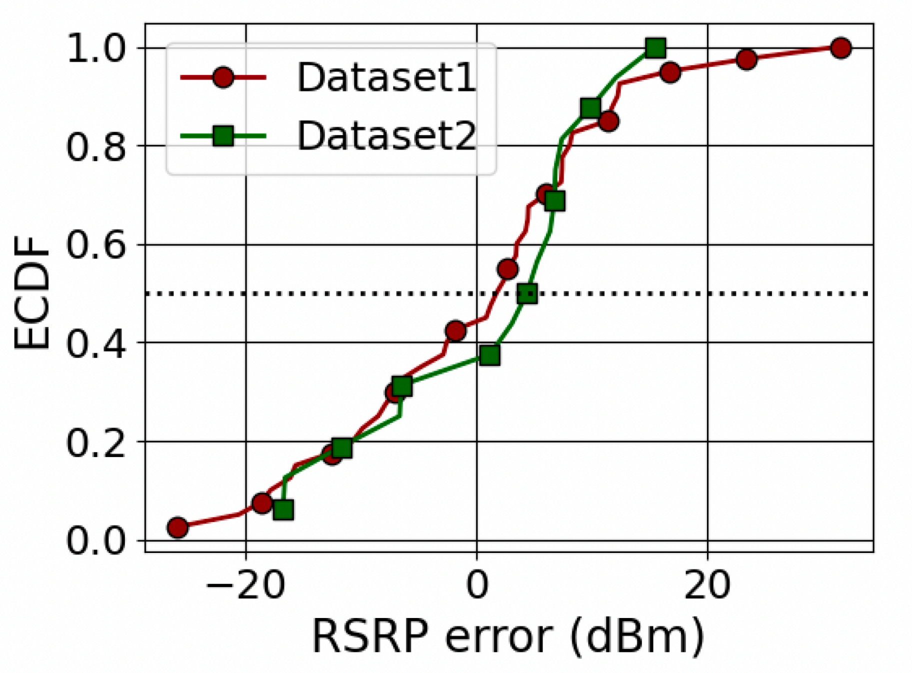

FIGURE 5: ***EMPIRICAL CUMULATIVE DISTRIBUTION FUNCTION (ECDF) OF THE ERROR BETWEEN THE RSRP SAMPLES FROM OUR DATASETS AND THE THOSE PROVIDED BY THE RAY-TRACING TOOL.***

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6. Integration of RIS Module

Once validated, the next step was to ensure the ray-tracing tool is capable of modeling RIS deployments. To this end, we explored different methods to augment the ray-tracing simulation environment with a RIS module and a specific radiation pattern. The resulting tool is expected to allow carrying out radio coverage analysis, while also integrating user-defined objects to recreate the RIS behavior in a specific location, e.g., a rectangular shape that works as a repeater by sensing the received power and retransmitting it with a radiation pattern chosen by the user. To this end, we considered two main approaches, with their respective advantages and disadvantages, as discussed next.

Employing CST Studio Suite software

CST Studio Suite is a high-performance 3D EM analysis software package for designing, analyzing, and optimizing electromagnetic components and systems. Employing CST may allow to create a RIS module with the desired features and then import such module into the Wireless InSite ray-tracer.

Designing a RIS in CST gives complete control over its geometry, materials, and electromagnetic properties. This level of customization allows to tailor the RIS to specific applications and scenarios, accommodating unique design requirements. CST allows to easily optimize the design of RIS by varying the parameters of the unit cells or the arrangement of the elements. This optimization process can be automated to find the best configuration that meets the design goals, such as achieving specific optical properties, beam steering, or frequency selectivity. CST is capable of providing highly detailed and accurate electromagnetic models. Designing RIS in CST allows to leverage the tool's advanced modeling capabilities to account for complex and intricate RIS designs.

However, designing RIS structures in CST can be a complex and time-consuming process, especially for custom or intricate configurations. One may need to create and optimize each unit cell, which may require extensive simulation and parameter tuning. This process can be more challenging compared to using predefined RIS in ray-tracing software, where the design is simplified. Moreover, exporting RIS designs from CST and importing them into a different ray-tracing software may introduce compatibility issues and require data conversion. Ensuring a seamless transfer of designs between different software tools can be problematic and may result in data loss or errors. Furthermore, RIS are known for their ability to adapt to varying environmental conditions, but designing such adaptability within CST and then importing it into a ray tracing software can be challenging. Real-time adaptation and optimization might be more straightforward with predefined RIS that are specifically designed for the ray tracing environment.

Employing an available dataset of RIS empirical modeling

Since RIS are not a mature technology, commercial off-the-shelf solutions are lagging and only a few prototypes have been implemented by researchers in the RIS community. Among

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those, a realistic model of RIS technology that can be integrated in the ray-tracing simulator was developed from the dataset provided by NEC with measurements of an inexpensive RIS prototype. This information is essential to assess realistic (hence, imperfect) RIS technologies at scale, as we will present later. The RIS design and the measurements provided in this dataset, which was produced by NEC and is publicly available in [NEC], are detailed in the Appendix B of this report.

Advantages: Given the relatively recent emergence of RIS technology, it is challenging to capture inherent deficiencies, such as unexpected side lobes, from inexpensive electronics. Therefore, instead of simulating an ideal reflective surface, one may employ a realistic data-driven RIS model of an actual RIS prototype by replicating an object with the same 3D reflection patterns in the ray-tracer. This process helps ensure that the simulation accurately reproduces the behavior of the physical RIS, increasing confidence in the simulation's predictive power. Importing a measured dataset allows to use a unique and custom RIS, which may not be accurately represented by predefined RIS in ray tracing simulators. Customization is particularly valuable for applications that require tailored RIS designs. The measured dataset can be utilized in various ray tracing simulations, making it adaptable to different scenarios and applications. This adaptability can be especially beneficial in complex or changing environments where predefined RIS may not be suitable. Importing measured data can save resources and time that would otherwise be spent on designing, optimizing, and simulating a custom RIS from scratch using CST or a similar tool.

Given the above advantages, we chose to employ the measured dataset, since it represents the actual behavior of the specific RIS, making it highly accurate and reflective of the real-world performance. This real-world accuracy is especially important when simulating scenarios where environmental conditions, materials, and other factors may affect the RIS behavior. The integration of the RIS module into the Wireless InSite ray-tracer was performed by NEC in collaboration with Telefonica Research. While compatibility between a measured dataset and ray-tracing software may in general be an issue, this did not impede our analyses, since Wireless InSite allows to import a data-driven radiation patters and construct a corresponding RIS object in the ray-tracing simulator, and because we created synergies with the ray-tracing vendor.

We expect that employing such an experimentally driven model will allow to conduct a more compelling analysis of RIS deployments using ray tracing.

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7. Planned Next Steps

RIS-enhanced radio coverage simulation

As a next step, we intend to gauge the benefits of including RIS elements towards radio coverage improvement in real-world scenarios. Specifically, we aim to select a crowded city location with a dense topography and an environment including different surfaces that might account for diversity in the propagation radio models. For this setup, we aim to collect the real-world radio network deployment of a commercial network and derive the theoretical radio coverage based on the network deployment. We will then feed this to the RIS-augmented ray-tracing simulator to account for the strategical deployment of RIS within each specific scenario. Our goal is to demonstrate the impact of RIS deployments in different environments and RIS configurations.

Performance impact analysis

Building and analyzing radio coverage and performance maps is the typical approach to assess the availability and performance of radio access technologies in different areas. For these maps to closely reflect the user experienced coverage, contrasting the planned theoretical coverage with the end-user measured coverage is important. However, obtaining measurements across time and space comes with a cost. For example, drive testing campaigns are expensive in terms of time and labor, even though they lead to detailed and reliable measurements in specific places at exact times. Consequently, drive tests are sparingly employed, causing mismatch between actual coverage and predictions obtained from models.

To address this, we plan to explore the design of new algorithms for building efficient and reliable data-driven mobile coverage and performance maps. We plan to investigate estimation algorithms to efficiently predict mobile network performance. By contrasting the expected radio coverage of the network with the actual experience of the end-user (from simulated data and/or empirical measurements), we aim to train the estimation algorithm to accurately predict realistic coverage of commercial networks, which we can then improve using RIS deployments. The novel methodology for building radio coverage maps via an algorithmic approach has great potential of improving a mobile network operator's workflow.

8. Summary and Conclusions

This report specifies our initial steps taken towards demonstrating the potential of RIS technology to significantly enhance cellular service quality within Radio Access Networks. By leveraging the advanced capabilities of the Wireless InSite ray tracer, we designed a system-level simulator that accurately reflects realistic propagation environments. Our validation campaign has confirmed the simulator's effectiveness, with a particular focus on areas demonstrating suboptimal RSRP levels. We further adopted a data-driven RIS model to augment the capabilities of the ray-tracing simulator, to closely emulate real-world RIS performance that is essential for reliable simulation outcomes. Looking ahead, we plan to extend our research by simulating RIS-enhanced radio coverage in densely populated urban settings with complex topographies. This will involve collecting real-world network deployment data and incorporating it into the RIS-augmented ray-tracing simulator to evaluate strategic RIS deployment. Our ultimate goal is to demonstrate and gauge the gains provided by RIS deployments in different scenarios and configurations.

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9. Appendix A: Key Features of the Wireless InSite Ray-tracer

Wireless InSite provides tools to design wireless links, optimize antenna coverage, and assess key channel and signal characteristics for RF and millimeter wave frequency bands. Some of its key features are outlined as follows. Fig. 6 illustrates the typical visual outputs produced.

X3D Propagation Model: A 3D propagation model with no restrictions on geometry shape or transmitter/receiver height. This accurate model includes reflections, transmissions, and diffractions along with atmospheric absorption and diffuse scattering. It supports frequencies up to 100 GHz.

Antenna Modeling: Allows to import measured antenna patterns or create textbook antennas for use in SISO, MIMO, and Massive MIMO transmitter and receivers. Includes frequency-specific pattern data to improve accuracy when using multiple bands or performing frequency sweeps.

MIMO Beamforming and Spatial Multiplexing: Allows to simulate MIMO antennas for 5G, Wi-Fi and other radio technologies. Detailed multipath and mutual coupling effects are used with MIMO techniques such as beamforming, spatial multiplexing, and diversity to predict key channel metrics for one or more MIMO data streams.

Communication Systems Analysis: Calculates SINR, throughput, theoretical capacity, and bit error rate (BER) to visualize and assess wireless device performance.

Materials: Allows to define electrical properties down to the facet level. The installed materials database includes metal, earth, concrete, brick, wood, glass, etc. at various frequencies.

RIS: Allows to model a RIS and evaluate how it modifies the propagation environment to improve connectivity.

Diffuse Scattering: Captures effects of scattering on complex impulse response and received power (including cross-polarization) for mmWave applications.

Geometry Caching: Its X3D Propagation Model automatically caches processed geometry for later use, avoiding geometry processing time when multiple concurrent or subsequent jobs are run with the same geometry.

Fast Ray-Based Methods: Avails of 2D site-specific propagation models designed for urban and long-range rough terrain applications.

Empirical Propagation Models: Includes a suite of empirical models designed for urban and indoor analysis.

Outputs: Users have quick access to outputs such as received power, propagation paths, path loss etc. These ASCII-based files can be plotted in the tool or post-processed externally.

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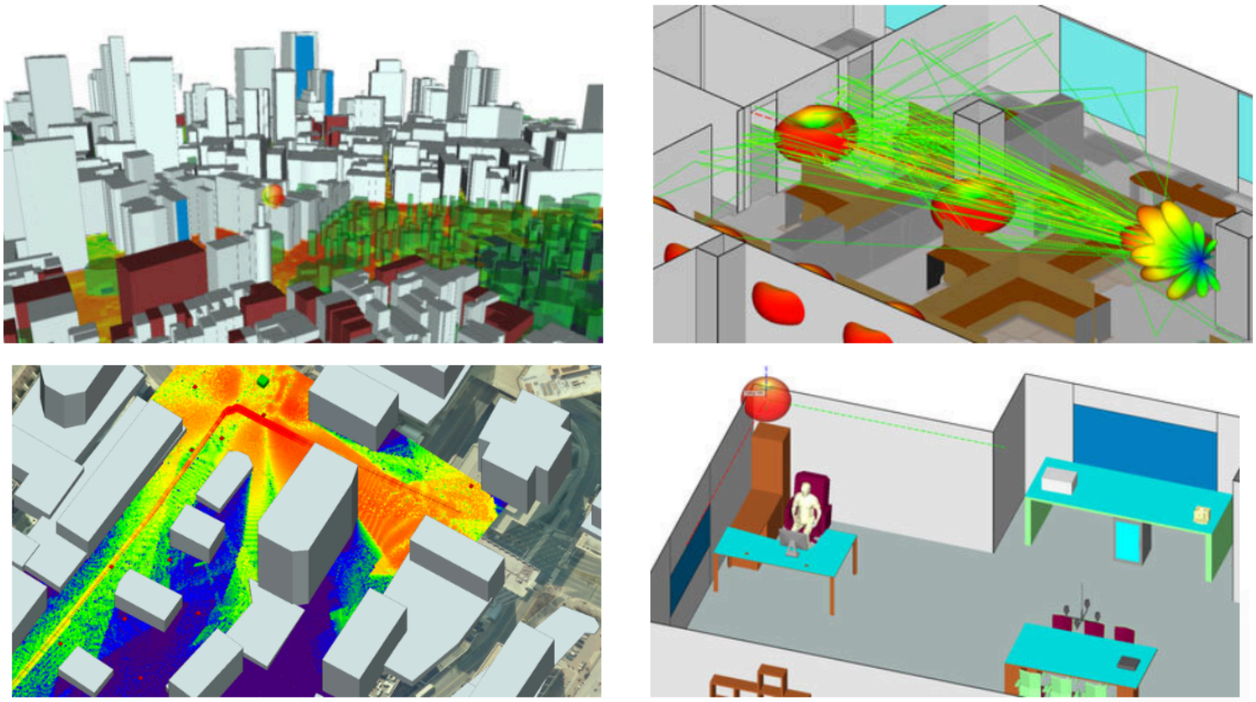

FIGURE 6: ***ILLUSTRATION OF THE TYPICAL VISUAL OUTPUTS PRODUCED BY THE WIRELESS INSITE RAY-TRACING TOOL.***

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10. Appendix B: Available Dataset of RIS Empirical Modeling

The RIS design and the measurements provided in this dataset, which is publicly available at [NEC], are detailed as follows.

The RIS system consists of multiple boards, each providing a 10x10 array of patch antenna elements. Each antenna element operates in sub-6GHz carrier frequency with a bandwidth of 100 MHz and reflects impinging signals with a phase shift controlled by a 3-bit RF switch. Every RF switch is in turn configured by a microcontroller unit (MCU) that, supported by a grid of buses, can access every RF switch in the board to set the desired phase shift on each antenna element. The reconfiguration time of the RIS board is approximately 35 ms and its consumption (mostly due to the MCU) is 60 mW. Fig. 7 depicts the prototype.

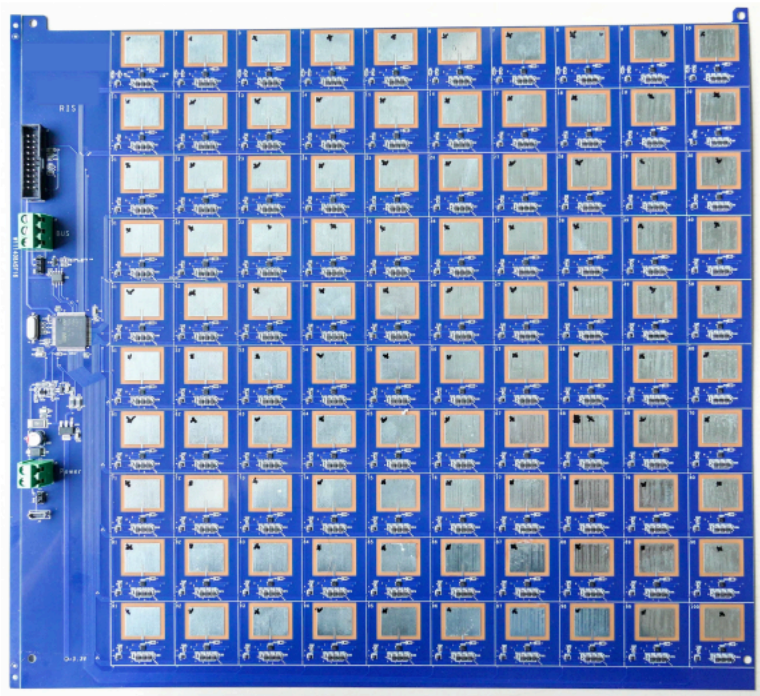

FIGURE 7: *RIS PROTOTYPE FROM [ROS22].*

A dataset with measurements collected in an anechoic chamber is provided in [Ros22]. An anechoic chamber is a controlled environment isolated from external electromagnetic interference and with minimal internal reflections. Therefore, the channel between the transmitter and the receiver only consists of a direct line-of-sight (LoS) link. It is important to note that maintaining a LoS channel is crucial for this purpose as, otherwise, it may be challenging to distinguish between the contribution reflected by the RIS and other multipath scattered signal components.

To collect this data, a RIS board was placed in one extreme of the room, on a rotating table attached to an antenna (TX) that transmits OFDM-modulated signals, as shown in Fig. 8. This setup allows setting the angle of arrival (AoA) of the LoS link between TX and RIS and

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between RIS and a receiving antenna (RX), which is placed in the other extreme of the room and demodulates those signals. The TX and RX were implemented using two horn antennas that operate within a frequency range of 1-8 GHz and show a gain of 13.5 dBi, as well as a voltage standing wave ratio (VSWR) of approximately 1 at the operating frequency of the RIS. The TX was positioned at a distance of 1.1 m from the first top-left element of the RIS, with a fixed azimuth and elevation angles of 90º and −33º, respectively. In turn, the RX was located in front of the RIS with an azimuth angle of 90º and an elevation angle of 3º, positioned 6.3 m away from the top-left antenna element. The rotating table and the RIS configuration were controlled by an off-the-shelf computer outside the room.

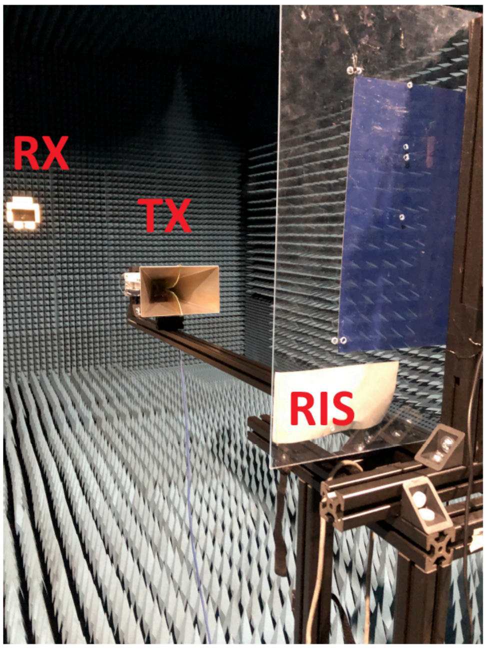

FIGURE 8: ***EXPERIMENTAL SETUP FROM [ROS22].***

The signal sent to the TX was generated by a dual-channel transceiver, specifically the USRP model B210, which can provide continuous RF coverage between 70 MHz and 6 GHz. On the RX side, another USRP B210 was used to sample and decode the incoming signals. Both USRPs utilized the srsRAN software, an open-source SDR 4G/5G suite from Software Radio Systems (SRS), capable of processing 3GPP-compliant OFDM signals. The TX-side USRP was specifically employed to generate a continuous stream of OFDM QPSK-modulated symbols with a bandwidth of 5 MHz, a transmission power of -30 dBm per subcarrier, and numerology that meets the requirements of 3GPP specifications. Meanwhile, the RX-side USRP measured the received power of the reference signal (RSRP), averaged across the bandwidth.

The dataset includes measurements with a pre-defined codebook of RIS configurations. Each configuration was designed to orient the primary beam of the RIS reflection pattern toward a specific and unique direction in space. Specifically, the main beam was scanned within the azimuthal range of [−90º, 90º] and the elevation range of [−45º, 45º], with a step size of 3º in both cases. As a result, the codebook consists of a total of 1891 distinct configurations.

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The turntable was set to move within the azimuthal range of [−90º, 90º] with a step size of 3º. The angle between the surface of the RIS and the RX is denoted as θ_r . For each θ_r value, which corresponds to an equal rotation angle of the table, the RIS board iterated through all the configurations in the codebook, and RSRP power samples were collected. In total, the dataset contains 6.5M samples.

As the channel within the anechoic chamber remains quasi-static, the authors concluded that the primary source of noise affecting the RSRP measurements in the dataset stems from imperfections in either the electronic components utilized in the RIS or the constituent parts of the chamber. To enhance the quality of the data, they employed a Savitzky–Golay filter, a widely used method for smoothing data and performing calculations based on noisy input data. Nevertheless, such imperfections are inherent in inexpensive RIS technologies and are usually ignored in the RIS literature, which relies upon idealized RIS models. Hence, building a data-driven 3D reflection model is key to make a realistic analysis of the impact of real-world RIS in production mobile networks, which was the goal of these experiments.

To this end, using the available data from that measurement campaign, a 2D reflection patterns for all different RIS configurations was first re-created in the dataset. In order to recreate 3D reflection patterns, it is crucial to have data from two 2D planes that are orthogonal to each other. In this specific case, as the relative difference in elevation between the TX, RIS, and RX are constant, the authors relied on the azimuth plane (with a fixed elevation). Nevertheless, due to the squared geometry of the prototype, they took advantage of the symmetry between the azimuth and elevation planes in the reflection patterns for interpolation. As a result, they were able to construct 3D reflection patterns for all the configurations in the RIS prototype, as exemplified in Fig. 9. This information is essential to assess realistic (imperfect) RIS technologies at scale, as explained in Section 5.

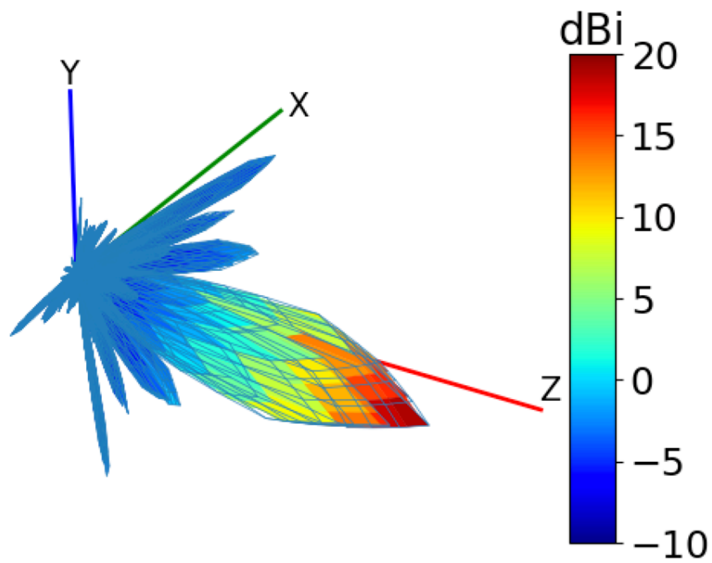

FIGURE 9: ***3D RIS RADIATION PATTERN FROM [ROS22].***

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