Financiado por la Unión Europea NextGenerationEU

MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL

Plan de Recuperación, Transformación y Resiliencia

E2. Initial report on RIS network integration, joint communicating and sensing

Project: RISC-6G

PROGRAMA DE UNIVERSALIZACIÓN DE INFRAESTRUCTURAS DIGITALES PARA LA COHESIÓN UNICO I+D 5G 2021

Fecha: 30/04/2023

Versión: 1.0

1. Deliverable Information

Description: Initial specification of RIS network architecture and solutions for 6G communicating and sensing, including RIS network integration and control plane concepts. The first version of a testbed for the RIS system is presented and tested for its integration with mobile architectures. Accurate yet low-overhead sensing mechanisms are introduced.

Due date: 30/04/2023

Responsible: IMDEA Networks

Partners involved: IMDEA Networks + NEC Laboratories Europe & NEC Ibérica + Telefonica

2. RIS Technologies in 6G Networks

Native integration of reconfigurable intelligent surfaces in 6G systems, addressing their main research challenges and practical implementation aspects.

2.1. A4 RIS network integration in 6G networks

In this deliverable, we introduce the novel concepts behind the emerging Reconfigurable Intelligent Surface (RIS) technology showing how this disruptive paradigm will change how the radio propagation environment is conceived. In addition, we briefly summarize the Open-RAN (O-RAN) network architecture to show the inter-operability that can be enabled between a RIS-empowered network and the O-RAN-compliant architecture.

Finally, we present the design of a RIS optimization algorithm that will jointly control base station (BS) and RIS configurations. Preliminary results are shown to demonstrate the feasibility of our proposal.

2.1.1 Preliminary definition of architectural components for supporting RIS control and operation

Reconfigurable Intelligent Surfaces:

RIS is a cutting-edge technology expected to have a critical role in future 6G mobile networks. RISs are cost-effective and energy-efficient devices that can dynamically redirect incoming waves in a programmable manner, providing precise control over the propagation environment. This capability can be optimized to enhance communication key performance indicators (KPIs) [1]. RIS technology has several applications, including performance enhancement, electromagnetic field exposure reduction, localization, and sensing [2].

Open RAN (O-RAN):

The O-RAN (Open Radio Access Network) architecture is a set of open standards for designing and implementing 5G and future wireless networks. It aims at disaggregating and virtualize the traditional monolithic radio access network (RAN) into open and interoperable components that can be developed, deployed, and managed by multiple vendors. The O-RAN architecture comprises of the following key components:

- **RAN Intelligent Controller (RIC):** It is a software-defined, programmable control plane that orchestrates and manages the RAN functions. RIC is responsible for tasks such as dynamic spectrum sharing, interference management, and network optimization;
- **Open Distributed Unit (O-DU):** It is responsible for processing the baseband signals and managing the radio resources at the cell site. O-DU can be implemented as software running on commodity hardware or as dedicated hardware;
- **Open Radio Unit (O-RU):** It is responsible for transmitting and receiving radio signals over the air. O-RU interfaces with the O-DU and provides the physical connectivity to the user devices;
- **Open Fronthaul (O-FH):** It is an interface that connects the O-DU and O-RU; it allows for interoperability between different vendors' equipment. Open Fronthaul uses open interfaces to enable multi-vendor deployments and reduce vendor lock-in;
- **Central Unit (CU):** It is responsible for higher-level processing tasks such as coordination between multiple DUs, network management, and control plane functions. CU can be implemented as software running on commodity hardware or as dedicated hardware.

In the O-RAN architecture, there are two types of RAN Intelligent Controllers (RICs): Near Real-Time RIC (Near-RT RIC) and Non-Real-Time RIC (Non-RT RIC).

Near-RT RIC handles real-time and near-real-time functions in the RAN, such as dynamic configuration, resource allocation, and interference management. It operates with low latency and fast response times, enabling adaptive and efficient RAN operations.

Non-RT RIC handles non-real-time functions in the RAN, such as network planning, resource optimization, and policy-based controls. It operates with longer timeframes and focuses on strategic decision-making for network-wide optimizations.

The separation of Near-RT RIC and Non-RT RIC allows for efficient and scalable management of the RAN, with Near-RT RIC focusing on real-time optimizations and Non-RT RIC handling longer-term planning and optimizations. Together, they enable intelligent and dynamic RAN operations in the O-RAN architecture.

Additional architectural components enabling RIS control

Several RIS components can be flexibly deployed in the service area, and adaptively configured according to the real-time scenario conditions and specific application requirements [1]. However, the integration of RIS into the Radio Access Network (RAN) requires additional logical components that interact with each other and with existing legacy components, enabling seamless integration and orchestration of these devices.

The envisioned components for the RIS integration process might include (not limited to):

- **RIS (Reconfigurable Intelligent Surface):** An intelligent surface that reflects electromagnetic waves using technologies such as reflect-array or meta-material. RIS devices typically consist of discrete unit cells arranged in a grid with sub-wavelength spacing. The electromagnetic response of each unit cell can be programmatically controlled by altering parameters such as phase, amplitude, polarization, and frequency. Recently, proposed RIS hardware designs also incorporate channel sensing capabilities [3], [4]. Each RIS in the network is associated with a RIS actuator that controls the RIS surface with a time granularity on the order of 10-100 ms.

- **RISA (RIS actuator):** The logical entity responsible for executing commands received from the RISC (as defined below) and translating them into configurations of the RIS, i.e., the reflection properties of the surface. RISA may provide feedback to the RISC, such as contextual information from the sensing capabilities of the RIS, to enhance network context. The expected time granularity of RISA is on the order of 1-20 ms. Referring to the O-RAN architecture, RISA lies at the same hierarchical level of O-CU and O-DU and can communicate directly with them towards the F1-x interface.

- **RISC (RIS controller):** The controller associated with a RIS actuator that generates logical commands for switching between different states/configurations of the RIS elements. This can include predefined or custom phase shift configurations at the RIS. The RISC can embed smart algorithms to autonomously derive the desired RIS configurations, or it can receive commands from other network elements to set up the RIS configuration. In the former case, the RISC autonomously optimizes the RIS surface as part of network optimization operations, while in the latter case, the RISC acts as an interface that controls the RIS based on external instructions, such as joint optimization of RIS configuration with other network operations. The expected time granularity of RISC is on the order of 20-100 ms. The RISC component lies at the same hierarchical level of the Near Real Time RIC and can communicate directly with it through the R1 interface.

- **RISO (RIS orchestrator):** A logical component located at a higher hierarchical level, responsible for orchestrating multiple RISCs in the network. The time granularity of RISO depends on the application and is expected to be on the order of 100ms-1s. The RISO component lies at the same hierarchical level of the Non-Real Time RIC and can communicate directly with it through the R0 interface.

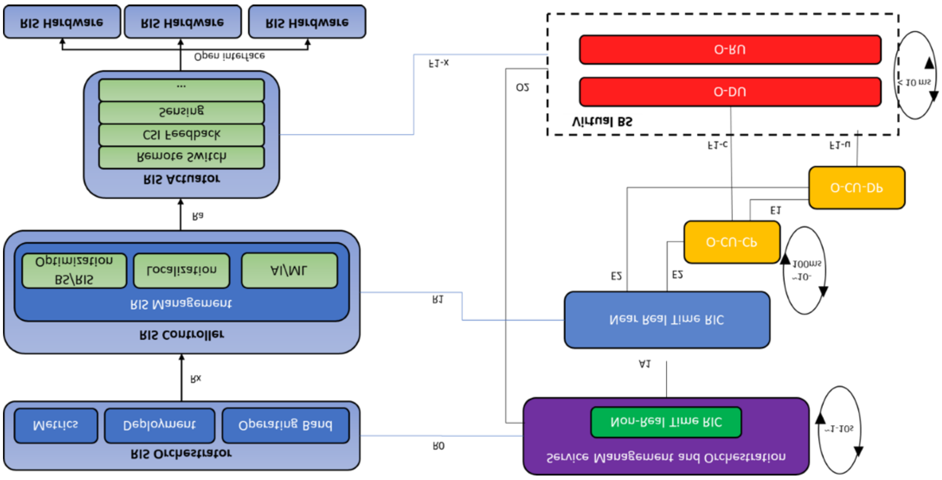


Figure 1 architecture supporting RIS integration in O-RAN

Figure 1 exemplifies the architecture of RIS-aided control in the RAN, in conjunction with the O-RAN architecture. The RISA and its associated RISC and RISO, can be deployed in virtualized form and abstracted to either edge or central clouds, while the physical RF (Radio Frequency) devices are situated on-site. The RISA directly interacts with the RIS devices, and the interface should be capable of connecting various RIS technologies with different characteristics. Depending on the specific RIS technology employed, the RISA can incorporate different functions to support the capabilities of each individual RIS device, such as CSI (Channel State Information) feedback, sensing, etc. Consequently, the RISA provides an open interface that facilitates the seamless integration of capabilities from diverse RIS devices with heterogeneous hardware capabilities and operating bands.

2.1.2 Centralized RIS control and optimization

Scenario Description

While integrating relevant RIS components into the existing network architecture appears challenging, it involves a number of theoretical challenges to be carefully addressed. The centralized control shall jointly optimize both the active beamforming at the base station (BS) and the passive beamforming at the RIS.

In our work [5], we address the joint optimization of active and passive beamforming by formulating an objective function that ensures high-performance solutions while maintaining efficiency and scalability. Interestingly, we observe that the chosen metric, called the Signal Mean Squared Error (SMSE), exhibits a convex structure when optimizing the transmitter's precoding strategy and the RIS parameters separately. This convexity allows us to design efficient iterative algorithms for RIS control operations.

The designed solution jointly optimizes the beamforming strategy at the BS and the RIS parameters to provide high-bandwidth and low-cost connectivity in massive Internet of Things (IoT) scenarios. Notably, unlike prior work, our proposal leverages the convex nature of the optimization problem separately for the two variables, ensuring scalability, efficiency, and provable convergence without the need to set any system parameters.

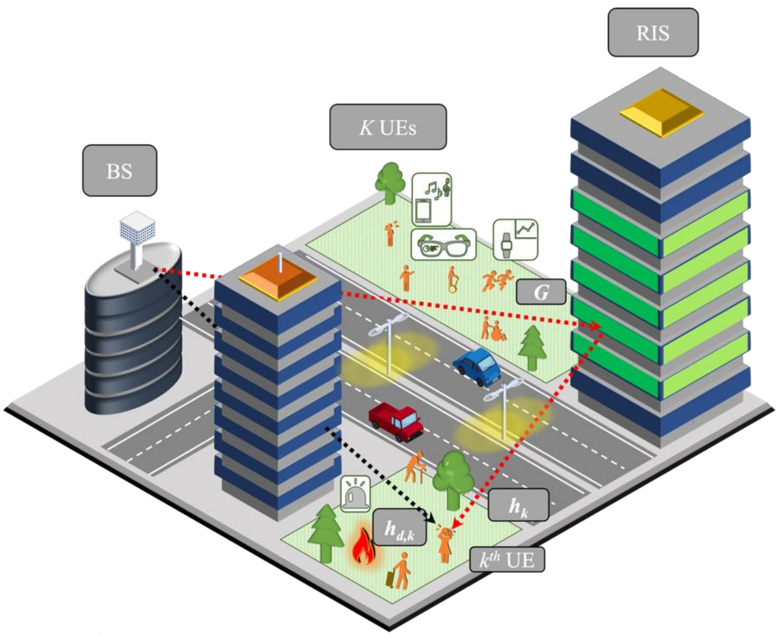


Figure 2 RIS empowered scenario for connectivity enhancement

In the scenario illustrated in Figure 2, a BS equipped with M antennas serves a set of K single-antenna user equipment (UEs). The connection is established using a nearly-passive RIS installed on the building glasses, which comprises N equivalent antenna elements. We focus on the downlink data transmission, where the BS communicates with each UE via a direct link consisting of a line-of-sight (LoS) path and a non-line-of-sight (NLoS) multipath link. Additionally, the BS can utilize a combined link from the BS to the RIS, which reflects the incoming signal towards the UE. The latter link is decomposed into the LoS BS-RIS path and a set of scattered NLoS paths, along with the RIS-UE link that includes a LoS path and a multipath NLoS link. All channels follow a quasi-static flat-fading model, remaining constant over the transmission time of a codeword. We also assume perfect channel state information (CSI) is available at the BS, and the BS operates in time-division duplexing mode, where uplink and downlink channels are reciprocal. Thus, the downlink channel can be estimated through uplink training from the UEs via a separate control channel.

Proposed Approach

We propose a problem formulation to minimize the Signal Mean Squared Error (SMSE) of all user equipments (UEs) in the system by optimizing both the active beamforming at the base station (BS) and the passive beamforming at the reconfigurable intelligent surface (RIS). We consider the downlink transmission scenario as a broadcast channel, and we establish a duality between broadcast and uplink multiple access channels. In the dual multiple access channel, the classical relationship between Mean Squared Error (MSE) and maximum Signal-to-Interference-plus-Noise Ratio (SINR) of each UE holds for linear filters. This motivates us to study the SMSE in order to optimize the system sum rate in the downlink.

Remarkably, the problem we are addressing exhibits convexity in the two optimization variables when considered separately. This enables us to exploit alternating optimization and develop an optimization algorithm. Such algorithm, namely RISMA, iteratively converges between two closed-form solutions, namely the active beamforming at the BS and the passive beamforming at the RIS.

Furthermore, it is designed to accommodate practical constraints, such as using low-resolution RISs with binary activation coefficients. To address the above-mentioned scenario, we propose a low-resolution variant of the algorithm, which decouples the optimization of the binary activation coefficients and the quantized phase shifts. The former is optimized using semi-definite relaxation, while the latter are projected onto the quantized space.

Preliminary Results

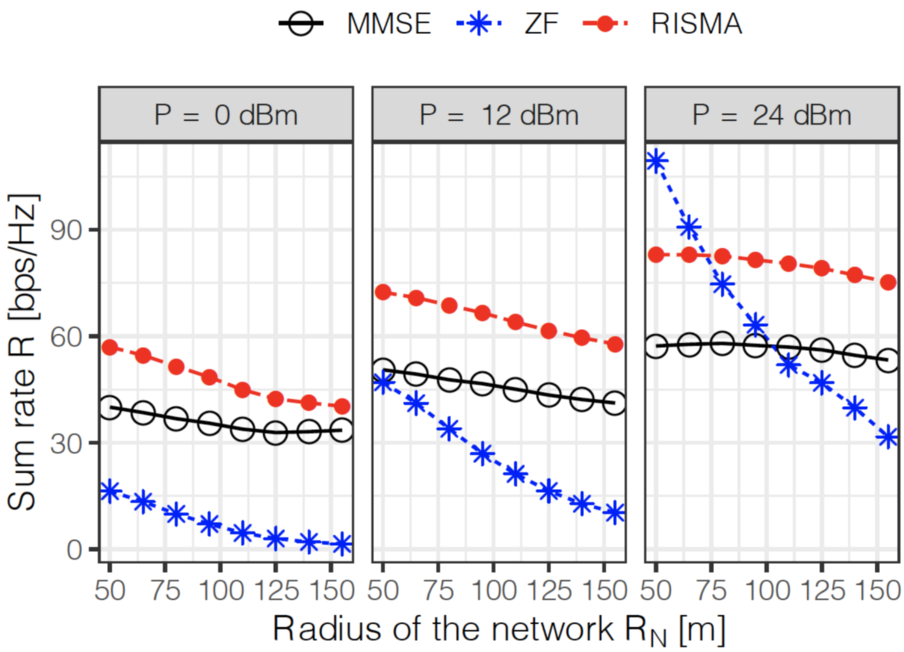


Figure 3 Average sum rate obtained with RISMA and conventional MMSE and ZF precoding against different network radius and transmit power.

We apply the proposed solution to the context of coverage enhancement, showcasing how the use of reconfigurable intelligent surfaces (RISs) can significantly increase the coverage area while maintaining a given target performance.

In the conducted experimental campaign, we consider a scenario where 12 user equipment (UEs) are randomly distributed on a circular area with a radius of R_N centered at the base station (BS). In Figure 3, we have evaluated the performance of the RISMA approach in terms of sum rate, comparing it with conventional minimum mean squared error (MMSE) and zero-forcing (ZF) precoding methods, which are state-of-the-art precoding solutions without the use of RISs. We analyze the performance gain achieved by the proposed approach for different values of transmit power P at the BS and varying network radius R_N.

2.2. A5 RIS control plane in 6G networks

The goal of this Deliverable is to present our current advancement in terms of activity A5, which is related to the RIS control plane in emerging networks (6G networks)

We discuss here a case study on how Reconfigurable Intelligent Surfaces (RIS) can enhance radio coverage across a realistic urban environment simulated with Wireless inSite, a state-of-the-art Ray Tracer. We first determine areas with poor radio coverage in the city of London based on the Base station (BS) locations and datasets containing users' device feedback (i.e., power measurements) that we collect from a live mobile operator.

Our ultimate goal is to determine whether RIS deployments can significantly impact the increment of Reference Signal Received Power (RSRP) in the area and whether large RIS can compete with a full-fledged BS. With this, we will then propose a complete control pipeline to recommend the radio optimization teams locations for RIS deployment.

2.2.1 Data collection from the live radio access network of the operator:

We collaborate with Telefonica operators (specifically, Virgin Media O2 UK) to collect the status of the radio access network, and understand how the users experience the connectivity service. Specifically, we aim to focus on 4G coverage. We collect the end-user perspective measurements for the 4G/5G RSRP and RSRQ. We first build this dataset of a period of several weeks (4 weeks) in order to get a meaningful picture of the radio coverage within different areas as experienced by real users (e.g., using crowd-sourcing solutions).

RIS technology is still in its early stages: no RIS devices can be found on the market, and only a few prototypes have been shown in the literature. One of the ultimate goals of the research on RIS would be how to make this technology operate within the already existing infrastructures, such as BSs or access points, but just little interest in the matter can be perceived in the literature. Our work focuses on how to make RIS technology a valuable player in the already existing network systems in urban environments. In particular, the goal is to analyze RIS devices' impact on real scenarios with poor radio coverage proven by users' feedback analytics, provided by a telco operator. Furthermore, the analysis is performed using a validated RIS radiation pattern taken from experimental data.
We performed our simulations utilizing Wireless inSite, a latest-generation ray tracer.[1] This 3D ray-tracing simulator is widely employed in the research community for analyzing site-specific radio wave propagation and wireless communication systems. The selected propagation model employed in the simulations was the X3D Ray Model, known for its high accuracy achieved through precise path calculations.

2.2.2 Selection of target validation areas

We based our decisions to determine suitable areas with poor radio coverage in the city of London on several factors, such as vicinity with BSs, and two datasets containing analytics on users' device feedback provided by a telco operator. The region we are looking for has the following characteristics: it is enough densely populated, such as a residential area, or visited by a lot of people during the day, close enough to BSs, and at least a few high buildings to evaluate the contributions of placing RIS on high positions. We integrate RIS devices in an LTE urban environment rather than 5G because the latter is still in the roll-out phase and therefore more information about the former is available. The selected band is Band1, with a center frequency of 2100 MHz. However, the method we design is also valid for 5G or mmWave frequency thanks to the flexibility of the Ray Tracer.

We filtered the two datasets on users' analytics based on the operational frequency and for Reference Signal Received Power (RSRP) below -100 dBm. RSRP 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. This threshold is strongly dependent on the type of area, and it is usually determined with drive tests. Since we are working in a residential area, we choose the value of -100 dBm as the signal strength threshold below which we experience poor connectivity and we would like to have a greater RSRP. This is summarized in Figure 4 with data we collected from November 2022.

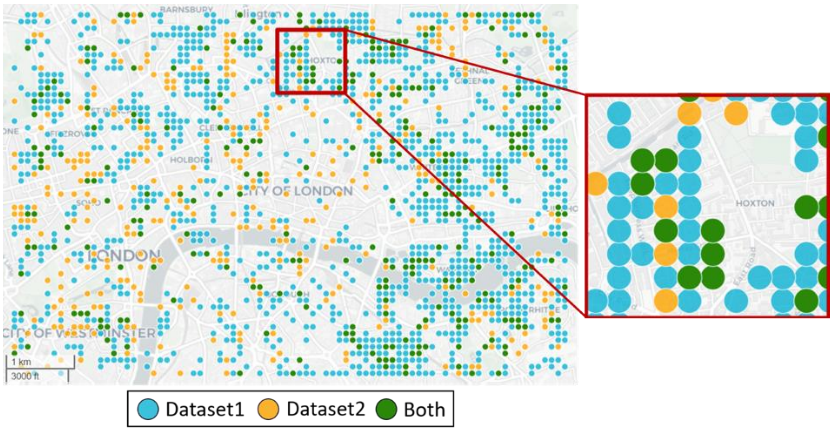


Figure 4. Radio coverage map for city of London with RSRP < -100 dBm.

By considering these factors, we were able to identify an area of 980m x 900m where to perform our study, Hoxton, in the London Borough of Hackney, England, part of the historic core of wider East London. The space is divided into a grid, where each sector, or Tile, is a square of 100 $m2$ area.

Successively, the neighborhood of Hoxton is imported as 3D objects into Wireless inSite from the open geographic database, OpenSteeetMap, which provides reliable information on the elevation of the soil and the heights of the buildings. The soil is treated as asphalt and the buildings as concrete In Wireless Insite.

2.2.3 Next steps

We plan to continue our work to evaluate the benefits of deploying RIS in the areas we identify as suffering from poor radio coverage. For this, we will rely on Wireless InSite and an NEC-owned RIS prototype. Specifically, we aim to use experimental data of radiation patterns from a validated RIS prototype to model the RIS devices in the Wireless InSite simulator.

2.3. A6 Communicating and sensing support for RIS networks

In this deliverable, we investigate the potential of using outdated channel estimates for RIS configuration and its impact on the performance of a RIS-enabled mmWave network. The performance of a RIS-assisted network critically depends on the channel estimation, as these estimates are used to configure the RIS elements. As the channel estimate ages, the performance degrades, which can be addressed by estimating the channel more frequently. However, perfect instantaneous channel state information (CSI) is hard to come by, especially for mmWave networks, where the channel conditions change rapidly over time. Also, mmWave networks use large antenna arrays at the transmitter and receiver to compensate for the higher path loss, which makes the channel estimation even more difficult for RIS-enabled mmWave networks. Moreover, the signaling overhead associated with acquiring perfect CSI is very high for RIS-enabled mmWave networks because the corresponding channel matrices are extremely large due to the presence of an intermediate RIS. Since a RIS itself cannot estimate the channel, the BS performs the estimation for the end-to-end communication channel through feedback links, which results in large delays and higher complexity. Beyond that, with higher user mobility, acquiring perfect channel estimates would entail extremely high signaling overhead and even larger delays, which consequently has the potential to evolve into a bottleneck for channel estimation.

2.3.1 Problem Formulation

Keeping in mind the challenges discussed above, it is imperative to see the impact of outdated channel estimates on the RIS configuration and, consequently, on the overall system performance of a RIS-enabled mmWave network. These considerations raise several questions on the estimation quality of a RIS-enabled mmWave channel. First and foremost, how often should a RIS-enabled mmWave channel be estimated given different network conditions? How much signaling overhead would that cause, and how it will affect the overall performance of the network? Intuitively, the higher the quality of estimation, the higher the overhead, and vice versa, which requires finding the right tradeoff to optimize channel capacity. Second, in the case of outdated CSI (to maintain a manageable signaling overhead), what is the tradeoff between the outdatedness of the CSI and RIS configuration, and again, what impact does it have on the network performance? In other words, how optimized should the RIS configuration be for the current CSI that is known to be outdated? Last but not least, given the outdated CSI, how should the system parameters be designed to guarantee good performance while keeping the complexity and cost associated with channel estimation to a minimum? These questions are extremely important, particularly for mmWave networks, because in these networks, the RIS uses narrow beams to communicate with the user. If the RIS is configured using outdated channel estimates, and if the user is mobile, the transmit beam might miss the user entirely, which will cause an outage.

2.3.2 Considered System Model

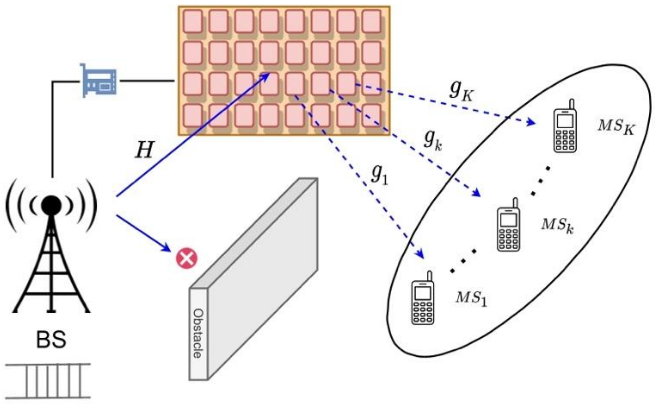


Figure 5: RIS-enabled mmWave communication network for multiple single-antenna users.

We consider the downlink of a RIS-enabled mmWave communication network, as shown in Figure 1, in which the BS is equipped with N_B antennas to communicate with K single-antenna mobile stations (MSs) with the assistance of a RIS with N_R passive reflecting elements. Each RIS element is capable of independently adjusting its phase shift to reflect the incident signals toward desired users. For the channel, we consider that the direct link between BS and MS is blocked by obstacles and only the reflected/cascaded link (via the RIS) is available for transmission. The transmit antennas at the BS and the RIS elements are placed in a uniform linear array (ULA) and a uniform rectangular array (URA), respectively. To reduce the propagation loss for the link between BS and RIS and the link between RIS and MS, we assume that the ULA and URA elements can adaptively adjust the weights on each omnidirectional antenna element at the BS and each RIS element, respectively, for beamforming.

2.3.3 Proposed Approach

We aim to leverage the effective capacity analytical tool, a link-layer model, to analyze the RIS-enabled mmWave network when the BS has only outdated channel estimates. The effective capacity is an analytical tool to find the maximum constant arrival rate that can be supported by the time-varying channel conditions while satisfying the statistical quality-of-service (QoS) guarantees imposed at the transmitter’s queue. It is defined as the log moment generating function of the cumulative channel service process [6]. This analysis would allow us to examine a combined effect of the QoS constraints imposed at the BS and the outdatedness of the channel estimates on the system performance of the RIS-enabled mmWave network.

2.3.4 Preliminary Results

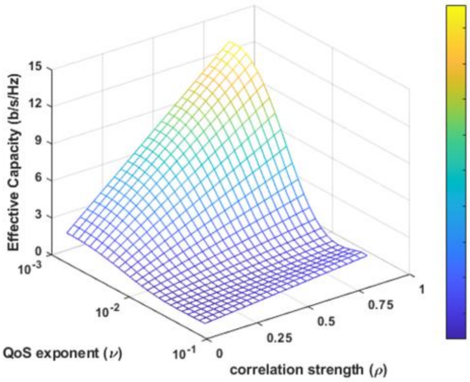


Figure 6: Impact of correlation strength on the effective capacity

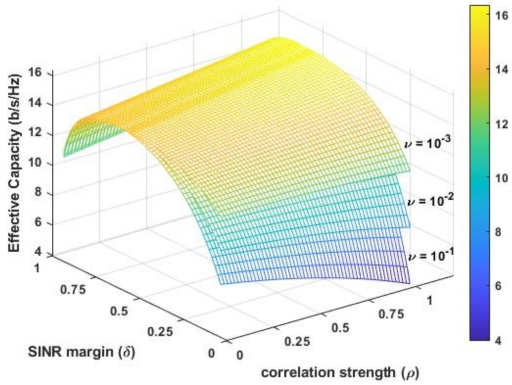


Figure 7: A search to find the optimal SINR margin given correlation strength and QoS guarantees

We apply our proposed approach to a multi-user RIS-enabled mmWave network and find the closed-form expression for the effective capacity. Here, we realize that the effective capacity critically depends on various factors, including the correlation strength between the instantaneous and outdated CSI, the QoS constraints imposed at the BS transmission queue, and the packet scheduling used by the BS. To this end, Figure 6 presents the effective capacity versus the correlation strength between the instantaneous and outdated CSI given different QoS constraints imposed at the BS. We observe that effective capacity almost remains the same when the correlation strength is low, but it increases rapidly as the CSI becomes less outdated. It is because, as the correlation strength increases, the probability of a higher received SINR also increases and, consequently, the effective capacity. Further, Figure 7 presents a combined effect of correlation strengths, SINR margins, and QoS exponents on effective capacity. We observe that there exists an optimal value of the SINR margin on which a maximum effective capacity is achieved, and when the BS schedules the packets by following this optimal value, the impact of the outdatedness of the CSI becomes less significant.

2.3.5 Next steps

To further understand the optimal system design of a RIS-assisted mmWave network, we plan to investigate the impact of the distance between the RIS and the BS and the users (near and far-field scenarios) on the optimal selection of a beam pattern, especially when the system operates under outdated channel conditions. This analysis can provide insights into the RIS deployment strategy for mmWave networks in centralized and distributed RIS deployments. Moreover, we plan to expand our system model to joint communication and sensing, and there, we would like to see how the outdated channel estimates affect the sensing and communication performance.

3. Sensing Algorithms

Technological enhancements enabled by 6G technologies (large bandwidth, large number of antennas and pervasive deployment) to design algorithms for object detection and activity recognition.

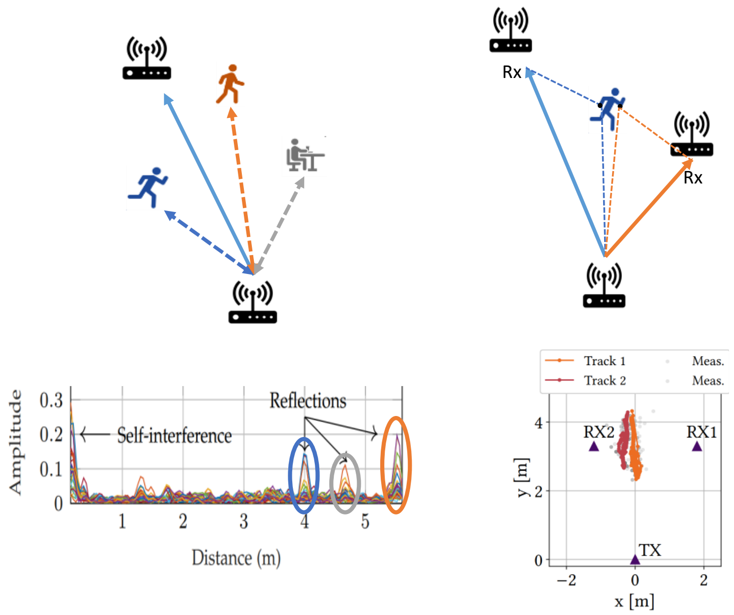
3.1. A7. Activity recognition

This deliverable aims to study cellular and non-cellular signals for activity recognition and object detection of active or device-free targets. To this end, we have started working on solving the limitations of practical bi-static and multi-static configurations in the context of mmWave systems. Most of the prior works in this area are either based on simulation-only environments or showcased by experiments until heavily controlled environments that prevent their applicability in real scenarios. Some of those limitations are the frequency offset between the different devices in the Integrated Sensing and Communication (ISAC) network topology and the absence or intermittence of (at least) a clear path that allow the tracking mechanisms to work. Moreover, we are also working on extending the capabilities of the Mimorph testbed [7] to handle ISAC configurations. With this work, we aim to ease the use of the Mimorph testbed in dense deployment scenarios, which are of special interest in the context of multi-static ISAC scenarios.

3.1.1. Preliminary Results

We apply our proposed approach to mono-static and multi-static ISAC configurations to investigate sensing and localization accuracy. Some of the preliminary results are presented in Figure 8. In these results, we transmit regular IEEE 802.11ad/ay packets where a few training units are appended in the tail of the packets. The access point has the capability to operate in a full-duplex communication mode. By analyzing the channel impulse response, we can estimate the distance of the user from the access point by getting peak locations in the range space (17cm resolution with 1.76 GHz bandwidth), as shown in Figure 8(a). Moreover, to estimate the angle, different amplitudes in the channel impulse response are used. Further, for the multi-static configuration, we experienced the following challenges (also shown in Figure 8(b))

- Resolution heavily depends on the geometry of the deployment
- Coordination between devices in the network
- Multiple viewpoints of the target with different shapes and characteristics



(a) (b)

Figure 8: Current efforts towards localization; (a) mono-static ISAC configuration, (b) multi-static ISAC configuration

3.1.2. Next steps

Next, we plan to investigate multi-band ISAC systems by considering the main advantages of low (sub-6GHz frequency band) and high (mmWave frequency band) frequency systems. In a multi-band ISAC system, sub-6 GHz is characterized by a rich multi-path profile, which allows for coarsely detect targets in the environment. However, its resolution does not allow separate targets that are close in space because of the limited available bandwidth. On the other hand, mmWave systems employ high bandwidth and achieve a high resolution that allows to resolve multiple paths that are close in space. Even though it provides benefits over conventional sub-6GHz systems, it requires the beam of the transmitted signal to exactly hit the targets for them to be detected; thus, requires a rigorous beamforming mechanism.

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