Future Wireless Communications Empowered by Reconfigurable Intelligent Meta-Materials

Deliverable 1.7: Final report on the activities and results of Task 1.3 – Algorithmic Frameworks

Grant Agreement Number: 956256
Project Acronym: METAWIRELESS
Project Title: Future Wireless Communications Empowered by Reconfigurable Intelligent Meta-Materials
Funding Scheme: H2020-MSCA-ITN-2020
Project Start Date: 01/12/2020

Type of Document[1]: R

[1] IN = Information Note; R = Report; P = Prototype; PC = Proof of Concept; O = Other.

VERSION DETAILS
Planned Delivery Date: 31 May 2025. **Original Delivery Date:** 1 September 2024 **Status:** Approved by WP1 leader
Dissemination Level[2]: PU

PARTICIPANTS	
Participant	**Name**
NEC-1	
CNIT-2	
CNRS-2	
KTH-1	

DOCUMENT HISTORY			
Version	**Date**	**Responsible**	**Description**
v1.0	22/04/2025	Stefano Buzzi	

DELIVERY REVIEWS			
Version	**Date**	**Reviewed by**	**Conclusion***

***e.g., Accepted, Develop, Modify, Re-edit, Update**

[2] PU = Public; CO = Confidential, only for the members of the Consortium (including the Commission Services)

Contents

Sommario

Executive Summary

Deliverable D1.7 of the project Metawireless consists of a final report on the research activities performed within Task 1.3 of WP1.

WP1 is the work package that deals with all the research activities planned by the Metawireless project in order to achieve the technical objectives defined in the technical annex of the grant agreement. Specifically, Task 1.3 is concerned with the technical Objective 3, i.e.

The development of new communication schemes, optimization protocols, and algorithms for wireless networks employing reconfigurable intelligent surfaces, coping with the large degrees of freedom and the passive nature of metasurfaces.

According to the technical annex of the grant agreement, the activities of Task 1.3 comprise an initial phase of literature review to learn the latest theoretical tools and results that have emerged for the analysis and design of wireless networks based on the use of reconfigurable intelligent surfaces. Afterwards, the research activities will focus on overcoming the state-of-the-art and developing innovative protocols and algorithms capable of operating in practical wireless networks that make use of reconfigurable intelligent surfaces.

The rest of this document is organized as follows. Section 1 provides the results of the state-of-the-art review performed during the first phase of Task 1.3. Section 2 describes the ongoing research activities and the innovative contributions achieved by the ERSs, also providing specific references that are key to the research activities performed by each ESR. Finally, concluding remarks are provided in Section 3. All references are provided in Section 4.

List of Project Beneficiaries and Partner Organizations

- Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT)

- Centre National de la Recherche Scientifique (CNRS)

- KTH Royal Institute of Technology (KTH)

- NEC Laboratories Europe GmbH (NEC)

ACRONYMS

ESR (s)	Early-Stage researcher(s)
ITN	Innovative Training network
MSCA	Marie Skłodowska-Curie Actions
IPR	Intellectual Property Rights
METAWIRELESS	Future Wireless Communications Empowered by Reconfigurable Intelligent Meta-Materials
WP	Workpackage

1. Introduction

In order to be successfully integrated into future wireless networks, a practical algorithmic and protocol suite must be developed to ensure the automatic reconfiguration of reconfigurable intelligent surfaces, with as little as possible direct human intervention. This is essential in order to reduce the operation costs of large-scale wireless networks, and ensure the plug-and-play deployment of reconfigurable intelligent surfaces. Task 1.3 addresses this issue. The results of the state-of-the-art review concerning Task 1.3 can be grouped into three main categories, i.e. channel estimation and channel-aware design techniques; machine learning techniques for network management and operation; metasurface-aided localization and sensing.

Channel-aware design. Channel estimation is a critical issue in networks employing reconfigurable intelligent surfaces, due to the fact that the passive nature of metasurfaces makes it difficult to employ traditional pilot-based techniques. In [1], the authors propose a method for channel estimation that is based on the parallel factor decomposition algorithm in order to unfold the cascaded channel from the transmitter to the receiver. The proposed method is based on an alternating least squares algorithm that iteratively estimates the channel between the transmitter and the metasurface as well as the channel between the metasurface and the users. Simulation results show that the proposed iterative channel estimation method outperforms the benchmark schemes based on genie-aided information. In [2], the authors propose a compressed-sensing-based channel estimation algorithm in which the angular channel sparsity of large-scale arrays that operate at millimeter wave frequencies is exploited to perform channel estimation at a reduced pilot overhead. The authors design pilot signals based on prior knowledge of the line-of-sight-dominated transmitter-to-metasurface channel as well as prior information on the high-dimensional transmitter-to-receiver and metasurface-to-receiver channels, by using compressed sensing methods. A distributed orthogonal matching pursuit algorithm is exploited in order to capitalize on the channel sparsity. In [3], the authors propose a two-stage channel estimation scheme by using iterative re-weighted methods for estimating the channel parameters in a sequential optimization loop. Simulation results show that the proposed method provides better performance than the two-stage orthogonal matching pursuit approach, in terms of channel estimation error and spectral efficiency gain. In [4], the authors propose two novel channel estimation methods by assuming a structured time-domain pattern of pilots and reconfigurable intelligent surface phase shifts. The authors show that the received signal follows a parallel factor tensor model that can be exploited to estimate the involved communication channels in closed-form or iteratively. Numerical results corroborate the effectiveness of the proposed channel estimation methods and highlight the existing tradeoffs. In [5], the authors propose a two-timescale channel estimation framework. The key idea of the framework is to exploit the property that the transmitter-metasurface channel is high-dimensional but quasi-static, while the metasurface-receiver channel is mobile but low dimensional. To estimate the quasi-static transmitter-metasurface channel, the authors propose a dual-link pilot transmission scheme, in which the transmitter emits downlink pilots and receives uplink pilots reflected by the reconfigurable intelligent surface. The authors propose a coordinate descent-based algorithm to recover the transmitter-metasurface channel. With the aid of numerical results, the authors show that the proposed two-timescale channel estimation framework can achieve accurate channel estimation with low pilot overhead. In [6], the authors introduce a general framework for the estimation of the transmitter-metasurface and metasurface-receiver cascaded channel, by leveraging a combined bilinear sparse matrix factorization and matrix completion. In particular, the authors present a two-stage algorithm that includes a generalized bilinear message passing algorithm for matrix factorization and a Riemannian manifold gradient-based algorithm for matrix completion. Simulation results illustrate that the proposed method achieves accurate channel estimation performance for application to metasurface-assisted systems. In [7], the authors present an architecture for reconfigurable intelligent surfaces that comprises an arbitrary number of passive reflecting elements, a simple controller for their adjustable configuration, and a single radio-frequency chain for baseband measurements. By capitalizing on the proposed architecture and by assuming sparse wireless channels in the beamspace domain, the authors introduce an alternating optimization approach for the explicit estimation of the channel gains by relaying on a single radio-frequency chain. Simulation results demonstrate the channel estimation accuracy and achievable performance of the proposed solution as a function of the number of training symbols and the number of reconfigurable intelligent surface reflecting elements.

Machine learning techniques. Machine and especially deep learning have recently emerged as a major technology to enable the automatic operation of wireless networks, without the need of human intervention. Thus, in the context of networks aided by reconfigurable intelligent surfaces, machine learning proves very useful to reduce the complexity of network design, thus coping with the large amount of degrees of freedom that are available if reconfigurable intelligent surfaces are massively employed throughout the network. In [10], the authors put forth the connection between reconfigurable intelligent surfaces and machine learning, arguing that both are needed to realize the vision of smart radio environments. The authors discuss how the use of machine learning is essential to reduce the complexity related to the design of metasurface-based wireless networks, which is anticipated to be higher than in conventional wireless networks. To this end, the authors propose a model-aided deep learning framework, which is further elaborated in [11], which exploits transfer learning to simplify wireless network design by combining together model-based and data-driven methods. The same authors discuss the connection between metasurface-empowered smart radio environments and reinforcement learning in [12]. In [13], the authors introduce a neural-network-based approach for configuring the behavior of tiles in metasurface-based radio environments. The wireless propagation is modeled as a custom, interpretable, back-propagating neural network, in which the reconfigurable intelligent surface elements act as nodes and their cross-interactions as links. After a training phase, the neural network learns how to configure the reconfigurable intelligent surfaces for improving the communication performance. By using a ray tracing simulation environment, the authors show performance gain in agreement with state-of-the-art solutions, but with a distinct gain in reducing the total number of active tiles. In [14], the authors employ deep learning techniques to reduce the design complexity of metasurface-based wireless networks. In particular, the authors propose an unsupervised approach to optimize the reconfigurable intelligent surface phase shifts. In the proposed approach, a customized deep neural network is trained offline by using the objective function to be optimized for training the parameters of the deep neural network. Simulation results show a gain over conventional approaches based on the use of semi-definite relaxation and alternating optimization, even though the considered approach remains heuristic in the sense that no optimality property can be claimed. In [15], the authors propose a joint design of transmit beamforming and phase shifts in a metasurface-assisted multiple-antenna system, by using a deep reinforcement learning framework. The proposed deep reinforcement learning algorithm is shown to be scalable for accommodating various system settings. Instead of utilizing conventional alternating optimization techniques to obtain the transmit beamforming and the reconfigurable intelligent surface phase shifts, the proposed algorithm obtains the joint design simultaneously at the output of a deep neural network whose training is refined in real-time. In [16], the authors propose a deep reinforcement learning framework with reduced training overhead that is able to tune the phase shifts of the reconfigurable intelligent surface elements with reduced training overhead. The proposed approach paves the way to the deployment of distributed reconfigurable intelligent surfaces, which are able of self-configuration and operation without the assistance of base stations or infrastructure nodes. The authors illustrate numerical results that show that the proposed online learning framework is able to approach the same rate as a benchmark system with perfect channel state information. In [17], the authors optimize the design of the phase shifts of a metasurface-aided downlink multiple-input single-output wireless communication system, with the goal of maximizing the received signal-to-noise ratio. Because of the non-convexity of the considered resource allocation problem, the authors employ deep reinforcement learning in order to develop a practical phase shift design algorithm. Numerical results reveal that the developed algorithm can achieve near-optimal signal-to-noise ratio performance with relatively low complexity. In [18], the authors consider the problem of joint system deployment, reconfigurable intelligent surface phase shift control, power allocation, and dynamic decoding order determination in a metasurface-enhanced wireless system, while enforcing individual data rate requirements to the multiple users. To tackle this optimization problem, the authors use machine learning. In particular, the authors propose a novel long short-term memory based echo state network algorithm for predicting the future traffic demands of multiple users based on an empirical dataset. In addition, the authors propose a decaying double deep Q-network based position-acquisition and phase-control algorithm to determine the position and control policy of the reconfigurable intelligent surface. In [19], the authors investigate the use of deep learning for channel estimation in a metasurface-assisted massive multiple-input multiple-output system. In the proposed scheme, each user has an identical convolutional neural network which takes as input the received pilot signals and yields as output an estimate of the direct channel between the transmitter and receiver, and the cascaded channel from the transmitter to the receiver through the reconfigurable intelligent surface. The approach is extended to a multi-user scenario, wherein each user has its own convolutional neural network and estimates its own channel. With the aid of numerical simulations, the approach is compared against state-of-the-art deep learning based techniques and performance gains are shown. In [20], the authors study a metasurface-aided wireless communication system for physical layer security, in which a reconfigurable intelligent surface is deployed to adjust its surface reflecting elements in order to guarantee the secure communication of multiple legitimate users in the presence of multiple eavesdroppers. Aiming at improving the system secrecy rate, a design problem for jointly optimizing the base station beamforming and the reconfigurable intelligent surface beamforming is formulated, under the assumption of different quality of service requirements and time- varying channel condition. As the system is highly dynamic and complex, and it is challenging to address the resulting non-convex optimization problem, the authors propose a deep reinforcement learning secure beamforming approach that approaches the optimal beamforming policy. Furthermore, post-decision state and prioritized experience replay schemes are utilized to enhance the learning efficiency and secrecy performance. Simulation results demonstrate that the proposed secure beamforming approach can significantly improve the system secrecy rate and satisfaction probability.

Metasurface-aided localization and sensing. Future wireless networks will have to support more than just voice and data transfer. Another major service to be provided by future wireless networks is anticipated to be that of sensing the surrounding environment and localizing objects or users of interest. Accordingly, several contributions have emerged that investigate the use of reconfigurable intelligent surfaces to perform sensing and localization tasks. Surveys on this topic have appeared in [21], [22]. In [23], two practical signaling and positioning algorithms, based on an orthogonal frequency division multiplexing downlink system, are proposed along with methods to design the time-varying reflection coefficients of the metasurface. It is shown that by enlarging the size of the metasurface, it is possible to obtain satisfactory performance also in the non-line-of-sight regime. A compressed sensing technique is proposed in [24] to estimate the position of mobile terminals in a network aided by reconfigurable intelligent surfaces. Joint user localization and synchronization is carried out in [25]. Theoretical performance bounds are derived based on the use of the Cramer-Rao bound, also accounting for practical hardware impairments. Similarly, ultimate performance bounds for node localization are derived in [26], by means of the Cramer-Rao bound, for the scenario in which the base station is equipped with multiple antennas. The impact on localization performance of using active reconfigurable intelligent surfaces is investigated in [27]. In [28] it is investigated how to optimize the phase shifts of a reconfigurable intelligent surface to optimize the localization accuracy in indoor scenarios.

2. Description of Activities and Results

2.1 Contribution of CNIT-2 – Overcoming Gap 3.1

The research project of CNIT-2 is meant to address the research Gap 3.1 identified in the technical annex of the grant agreement. Specifically, reconfigurable intelligent surfaces provide a huge amount of degrees of freedom, which enables them to perform sensing and localization tasks with extreme accuracy. However, at present, positioning and sensing based on metasurfaces has never been quantitatively investigated. In order to overcome Gap 3.1, the individual project of CNIT-2 is focused on developing novel localization and tracking that fully exploit the potential of metasurfaces. The adopted approach considers both optimal and sub-optimal algorithms, and the efficiency of the latter ones is to be assessed by the tools of Fisher information and the Cramér-Rao lower-bound. Specific algorithms that account for and harness near-field propagation will be devised, and their impact will be quantified through Fisher information.

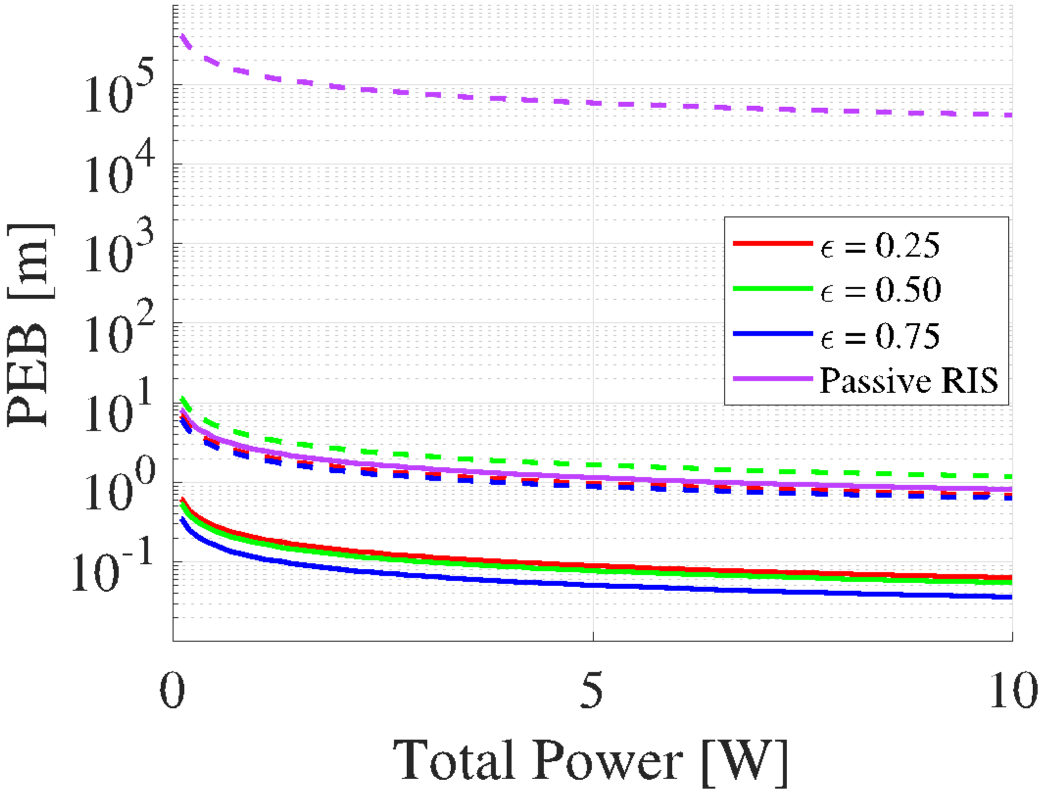
Spatial Awareness and downlink Localization aided by an Active RIS

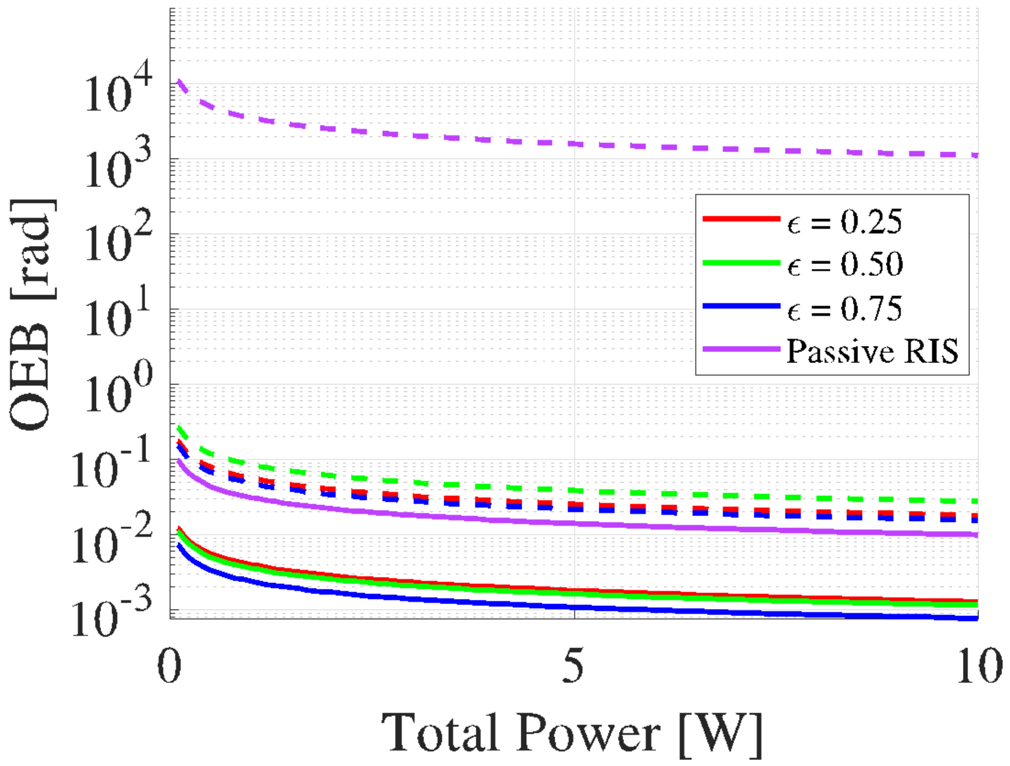
As a first line of investigation, the research activities have addressed the impact of employing active reconfigurable intelligent surfaces to perform joint communication and localization in wireless networks. Conventionally, reconfigurable intelligent surfaces are considered to be passive or quasi-passive devices consisting of elements that reflect the incoming waves, introducing a controllable phase shift. Although passive metasurfaces are helpful in many applications, they are significantly affected by the multiplicative fading of the reflected signals, limiting their practical applications. In other words, the signal reflected by the metasurface is typically much weaker than the direct signal, which limits the usefulness of passive metasurfaces in scenarios in which a strong line of sight channel is present. To cope with this issue, the use of active reconfigurable intelligent surfaces is considered. Analog amplifiers are deployed at the metasurface, which enables each reflecting unit to apply both a phase rotation and an amplitude scaling to the incoming signal. Similarly to what has been described for the research activity of CNIT-1 (see D2.1), the use of an active reconfigurable intelligent surface is expected to address the issue of the multiplicative fading and thus unlock unprecedented localization accuracies. The presence of active components at the metasurface allows amplifying the incoming signal so that the signal that reaches the destination via the reconfigurable intelligent surface can be of comparable power as that of the direct link. Therefore, traditional geometry-based localization techniques based on angle of arrival (AOA) and time of flight (TOF) estimation are made more robust by the aid of a reconfigurable intelligent surface. On the other hand, considering an active reconfigurable intelligent surface significantly alters the structure of the system model, since the power amplification introduces a noise amplification effect, i.e. the signal reflected by the metasurface contains the noise introduced by the power amplifiers. Therefore, all the mathematical expressions for the performance bounds and the analytical expressions for the estimators differ from those found in the literature

The research activity performed by CNIT-2 has achieved three main results:

1. Provide a realistic model of network enabled by an active reconfigurable intelligent surface and derive the theoretical performance bounds. This has been achieved mainly via the Cramer Rao Lower Bound, which enables to obtain closed-form, mathematically-tractable results.
2. Provide analytical expressions for optimal and sub-optimal estimators, commonly used in estimation problems. This has been achieved by leveraging the classical framework of estimation theory, generalizing its use to account for the presence of the reconfigurable intelligent surface.
3. Derive practical and low-complexity localization algorithms that fully exploit the potentialities of the reconfigurable intelligent surface. All algorithms have been tested by numerical simulation performed in MATLAB, which have shown the good performance of the developed estimators.

The above results have been achieved with reference to a user localization problem in a single-user and single-cell scenario with an active reconfigurable intelligent surface. In this context, the reflection coefficients of the active elements of the reconfigurable intelligent surface have been optimized together with the transmit power of the base station. A location estimator based on multiple signal transmissions and particle filtering is proposed. The developed algorithm fully exploits the additional degrees of freedom provided by the active reconfigurable intelligent surface. Moreover, theoretical performance bounds are derived and extensive numerical simulations show the effectiveness of the developed approach with respect to the use of a more traditional passive reconfigurable intelligent surface. The two figures below show the positioning error bound (PEB) and the orientation error bound (OEB), measured in radiants, achieved by the developed technique versus the total available power. Each figure compares the use of an active and a passive metasurface. The parameter ε measures how much of the total power available is used by the active reconfigurable intelligent surface, while the rest is used by the base station. The limit case ε=1 corresponds to a passive reconfigurable intelligent surface and all the available power is used by the base station. It is seen that, as expected, the use of an active reconfigurable intelligent surface can largely outperform its passive counterpart, at the expense of a larger power consumption





This research activity of CNIT-2 has led to the three following papers:

- G. Mylonopoulos, C. D'Andrea and S. Buzzi, Active Reconfigurable Intelligent Surfaces for User Localization in mmWave MIMO Systems, 2022 IEEE 23rd International Workshop on Signal Processing Advances in Wireless Communication (SPAWC), 2022

- G. Mylonopoulos, L. Venturino, S. Buzzi and C. D'Andrea, Maximum-Likelihood User Localization in Active-RIS Empowered mmWave Wireless Networks, 2023 17th European Conference on Antennas and Propagation (EuCAP).

- G. Mylonopoulos, L. Venturino, S. Buzzi, and C. D'Andrea, "Estimation of the User Position and Orientation in mmWave Cellular Networks Aided by an Active RIS," IEEE Open Journal of the Communications Society, vol. 5, pp. 4868–4884, 2024. DOI: 10.1109/OJCOMS. 2024.3437661.

Joint User Detection and Localization with RISs

This activity has considered the problem of jointly detecting active user equipment devices (UEs) and localization in the near-field (NF), wherein the BS is unaware of the number of active (or inactive) UEs and their positions. Therefore, unstructured, random, channel access is considered, which is described as a key challenge in signal detection. The system is equipped with multiple RISs, which provide a low-complexity solution for detection and localization with additional degrees of freedom due to the additional inspection points. Specifically, the RISs are configured to provide spatially aware signal detection, projecting the source of the detected signal into the network's geometry. Within this framework, an intuitive guide is developed for the RIS deployment problem, such that favorable inspection is achieved. In addition, an iterative detection procedure is proposed, allowing the BS to assign pilots to detected UEs, and thereby providing a structured channel access. Finally, the problem of multiple access interference is explored as a limiting performance factor. The results show that, with a proper configuration of the RISs, the proposed scheme can detect/localize UEs, augmenting benchmark detection schemes to spatially aware UE detection.

The results of this research have led to the publication:

G. Mylonopoulos, B. Makki, S. Buzzi, and G. Fodor, "Joint User Detection and Localization in Near-Field Using Reconfigurable Intelligent Surfaces," IEEE Wireless Communications Letters, pp. 1–1, 2024. DOI: 10.1109/LWC.2024.3487116.

and to the patent:

G. Mylonopoulos, B. Makki, S. Buzzi, and G. Fodor, "Detection/Localization of unknown UEs using repeaters", patent filed by Ericsson AB.

RIS-aided Integrated Sensing and Communication

This activity considers the integrated sensing and communication problem for radar-like detection of small non-cooperative airborne targets with the aid of RISs. RISs provide additional degrees of freedom in the system design, as they provide an alternative inspection point, better suited for the considered area. The presence of communicating users leads to beamforming restrictions as the interference of the sensing application needs to be minimized. The energy of the received echoes depends on the power available for the radar function, RIS's beampattern, the target's size and position. The aforementioned constraints, coupled with the need of detecting smaller targets at larger distances, leads to low signal to noise ratio (SNR). In this context, track-before-detect is a scheme that increases the probability of detection as more inspections are jointly considered for a target to be detected. The passive nature of the RIS and its low implementation cost allow for large RISs to be considered. The design of larger RIS is of higher complexity, but exhibits higher spatial flexibility. Numerical results show that the large size of the RIS enables proper inspection of the desired region.

Secondment - Adaptive signaling protocols for wireless sensing.

During the secondment at Ericsson AB, four different sensing scenarios are considered, which can be of immediate interest to the industry, wherein there is a strong motivation for an adaptive signalling protocol. This activity engages a direct and immediate investigation of potential use-case scenarios that involve:

i. **Adaptive resource allocation among detected and undetected UEs**:
ii. **Adaptive downlink localization protocols based on the validity of the NF assumption**: This signaling protocol considers the problem of downlink localization and UEs tracking with an adaptive procedure. The proposed scheme addresses the accuracy-complexity trade-off in detection, localization and tracking of UEs in a broad range of distances. The BS is provided with two different signaling schemes and the UEs with two localization algorithms; one assuming far-field (FF) and the other assuming NF conditions. Moreover, the UEs need to employ a localization algorithm adapted for the employed signaling scheme at the BS side. Since in the proposed scheme the validity of the FF and NF assumptions must be communicated by the UEs back to the BS, a low complexity algorithm is derived that exploits the simplified FF channel model and highlight the practical benefits and the limitations of this assumption
iii. **Extension of conventional feedback protocols for ISAC applications**: This signaling protocol develops similar techniques as those used by communication modules of previous generations for the sensing functionality of 6G networks. Specifically, the concept of extended automatic repeat request (e-ARQ) is introduced for ISAC networks. Various multi-static schemes are presented, in which an active feedback channel is designed to assess the quality of the corresponding sensing application. Such a feature transcends the function of traditional ARQ in communication applications. Specifically, within the ISAC paradigm, the proposed e-ARQ not only indicates when a sensing procedure needs to be repeated, but also acts as an evaluation metric for the current sensing strategy, suggesting a dynamic allocation of communication and sensing resources. The system cognition granted by the proposed e-ARQ procedure boosts the sensing quality in terms of reliability and may lay the groundwork for standardized ISAC networks.
iv. **Consideration of sub-array processing techniques for sensing**: This signaling protocol refers to sub-array processing techniques, which is a novel concept that has shown significant promise in communication applications. With the growing interest in integrating sensing and communication, it is essential to explore sub-array processing from a sensing perspective as well. In this context, target detection, beamforming techniques, and the integration of additional network hardware, such as repeaters, are closely linked to the spatial structure of the array. As arrays increase in size, evaluating the partial correlation between sub-arrays becomes crucial to identify potential processing advantages.

The results of this activity has led to the following publications:

G. Mylonopoulos, B. Makki, S. Buzzi, and G. Fodor, "Adaptive Downlink Localization and User Tracking in Near-Field and Far- Field: A Trade-Off Analysis," arXiv preprint arXiv:2402.06368, 2024.

G. Mylonopoulos, B. Makki, S. Buzzi, and G. Fodor, "Extended Automatic Repeat Request For Integrated Sensing And Communication Networks," arXiv preprint arXiv:2404.10583, 2024.

G. Mylonopoulos, B. Makki, G. Fodor, and S. Buzzi, "Adaptive downlink localization in near-field and far-field," in 2024 IEEE International Conference on Communications Workshops (ICC Workshops), Denver, CO, USA, June 2024, pp. 1017–1022. DOI: 10.1109/ ICCWorkshops59551.2024.10615807.

G. Mylonopoulos, B. Makki, G. Fodor, and S. Buzzi, "Extended ARQ Protocol For Reliable Integrated Sensing and Communication Systems," in 2024 IEEE 25th International Workshop on Signal Processing Advances in Wireless Communication (SPAWC), IEEE, Lucca, Italy, Sept. 2024, pp. 321–325. DOI: 10.1109/SPAWC60668.2024.10694524.

and to the following patents:

G. Mylonopoulos, B. Makki, S. Buzzi, and G. Fodor, "Two-Step UE Localization", patent filed by Ericsson AB. Automatic repeat request in multi-static sensing networks

G. Mylonopoulos, B. Makki, S. Buzzi, and G. Fodor, “Automatic repeat request in multi-static sensing networks”, patent filed by Ericsson AB.

G. Mylonopoulos, B. Makki, S. Buzzi, and G. Fodor, “Multi-static sensing of a non-cooperative object using sub-array processing”, patent filed by Ericsson AB.

2.2 Contribution of CNRS-2 – Overcoming Gap 3.2

The research project of CNRS-2 is meant to address the research Gap 3.2 identified in the technical annex of the grant agreement. Specifically, system-level analytical studies model the environmental objects as entities that can only attenuate the signals, making the links line-of-sight or non-line-of-sight. As a result, there exist no analytical methodologies to analyze reflections, which are instead of great importance to optimize the operation of wireless networks employing reconfigurable intelligent surfaces. In order to overcome Gap 3.2, the research activities of CNRS-2 are focused on developing a new analytical framework to quantify the system-level performance of wireless networks in the presence of reconfigurable intelligent surfaces. The considered approach is based on modeling metasurface-coated objects by means of spatial shapes whose locations, size, orientation, height are randomly distributed. The analytical tool of random shapes can be used to this end with the objective to formulate key performance indicators (e.g., coverage, spectral efficiency, energy efficiency, delay) in analytically tractable forms, and, to optimize, the interconnected network, e.g., to identify the optimal number of reconfigurable intelligent surfaces per unit area to be deployed. Machine learning tools can be utilized, on the other hand, in order to optimize the operation of reconfigurable intelligent surfaces, by first considering link-level network-topologies and by then moving towards system-level studies in the second part of the thesis.

During the reporting period of interest, CNRS-2 has developed a unified mathematical and algorithmic framework for multibeam beamforming in RIS-assisted wireless systems under practical constraints. The focus has been on shaping the reradiation pattern of reconfigurable intelligent surfaces (RIS) to serve multiple users while ensuring compliance with angular power constraints. The system models range from single-antenna to MIMO configurations, and both continuous and discrete RIS phase controls are considered.
Optimization techniques such as semidefinite relaxation and alternating optimization are proposed to solve the non-convex design problems, while neural networks are introduced to approximate complex solutions with reduced computational cost. A greedy algorithm is developed to support discrete-phase RIS hardware. Simulation results confirm that the proposed methods can generate well-focused beams, effectively suppress sidelobes, and satisfy reradiation mask constraints across various scenarios.

A first line of work of CNRS-2 has addressed the development of optimization techniques for RIS-Aided Beamforming with Reradiation Constraints in SISO systems. The system aims to create two independent directional beams toward two distinct users while satisfying reradiation mask constraints—a practical regulatory condition that limits the total power reflected in non-target directions to reduce interference or comply with radiation safety standards.

System model. In the considered system, the transmitter is equipped with a single antenna, and the RIS comprises a uniform planar array of passive reflecting elements. Each RIS element can be individually configured to apply a phase shift to the incident signal, allowing beamforming in the far field. Unlike traditional beamforming which uses multiple RF chains, RIS performs passive beam shaping with minimal energy consumption. The core design challenge lies in configuring the RIS phases such that maximum power is directed toward the desired users while the power in sidelobes is kept under a pre-defined reradiation threshold. To address this challenge, the beamforming design is cast as an optimization problem with quadratic constraints on the signal amplitude across angles. Since the original problem is non-convex and NP-hard, it is relaxed into a Semidefinite Program (SDP) using a matrix lifting technique and solved using standard convex optimization tools. To enable real-time inference and deployment, a deep neural network (DNN) model is trained to approximate the mapping from system parameters (e.g., angles of users, number of RIS elements) to optimized RIS phase configurations. The network is illustrated in Figure 1, takes as input the angular positions of the target users and outputs the predicted complex reflection coefficients. The DNN consists of multiple fully connected layers with ReLU activations, followed by a final normalization layer to ensure unit-modulus phase constraints. The DNN is trained using the optimized solutions obtained from the SDP as ground truth, minimizing the mean squared error between predicted and optimal beam patterns.

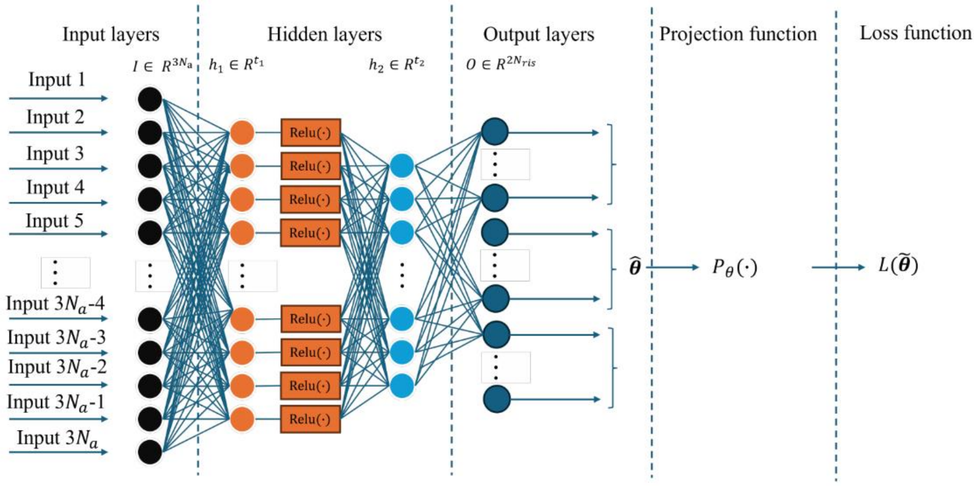


Figure 1: Considered neural network architecture

This hybrid approach enables flexible and fast RIS configuration, combining optimality from convex relaxation with low-latency inference enabled by deep learning.

Simulation results. To evaluate the effectiveness of the proposed beamforming method under reradiation constraints, a representative test case is considered where the incident angle is fixed at 30°, and the desired reflection directions are set to 20° and 40°. The RIS is modeled as a 12×12 square array positioned 20 meters from the transmitter, operating at 27 GHz with a transmit power of 2 W and noise power of −120 dBW. A reradiation mask is applied to all angular directions except for the two main lobes centered at the desired reflection angles.

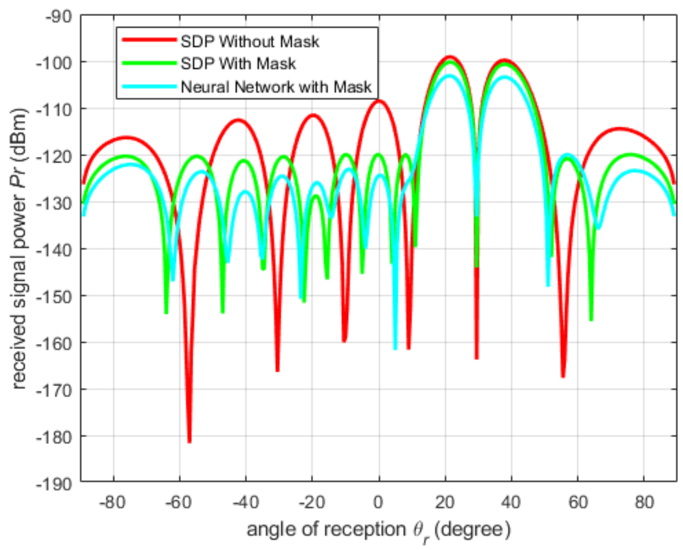


Figure 2: The SISO simulation scenario

Figure 2 illustrates the received power distribution across observation angles for three different beamforming strategies: (i) SDR optimization without the mask, (ii) SDR with the reradiation mask, and (iii) neural network prediction under the mask. Without the mask, high-power sidelobes are observed in non-target directions, violating angular energy constraints. When the mask is applied, these sidelobes are significantly suppressed, while the main lobes remain focused on the desired directions. The neural network achieves a similar pattern to the constrained SDR case, though with a slight reduction in the main lobe gain.

Figure 3 presents the phase configurations of the RIS elements for all three strategies. Without the mask, the RIS phases appear more uniform and structured. In contrast, the mask-constrained cases—both for SDR and neural network—exhibit more complex and adaptive phase patterns, reflecting the need to finely shape the reradiation pattern to comply with the constraint.

Figure 4 displays the corresponding amplitude maps of the RIS elements. In the unconstrained case, nearly all elements exhibit unit amplitude. However, when the mask is imposed, certain RIS elements reduce their amplitude below one. This attenuation is necessary to fulfill the reradiation constraint and results in a slight decrease in reradiation efficiency. The neural network successfully learns this behavior, producing an amplitude profile that qualitatively matches that of the constrained SDR solution.
In summary, these results confirm that the proposed optimization and learning-based methods can effectively shape the RIS reradiation pattern toward desired directions while satisfying regulatory constraints. The neural network provides a feasible, low-complexity alternative to conventional optimization with only marginal performance degradation.

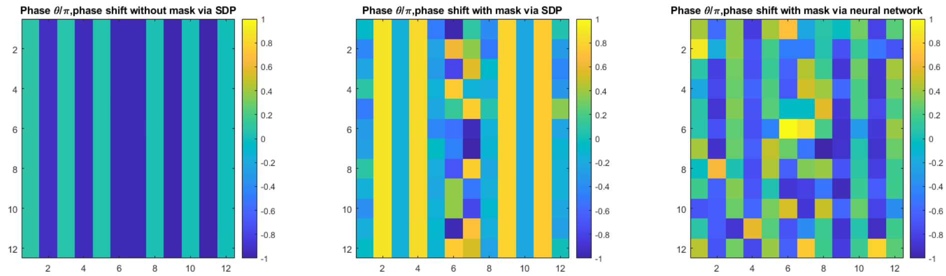


Figure 3: Color map of the RIS phase shifts: SDP without mask (left), SDP with mask (center), neural network with mask

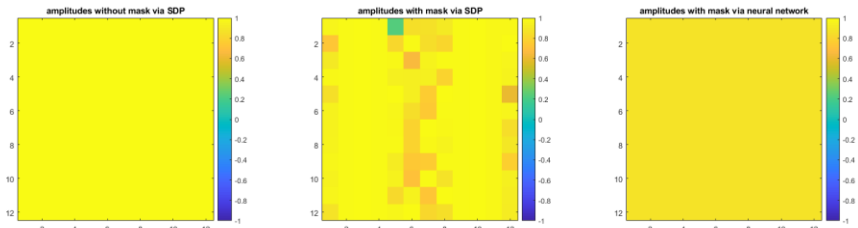


Figure 4: Color map of the RIS amplitudes: SDP without mask (left), SDP with mask (center), neural network with mask

The results of this research have been published in the work:

S. Wang, M. Di Renzo, M. Poulakis, "Multibeam Beamforming Design in RIS-aided SISO Communications Subject to Reradiation Masks – Optimization and Machine Learning Methods", 2024 19th International Symposium on Wireless Communication Systems (ISWCS).

A second line of work of CNRS-2 has been about multi-beam optimization of RIS-aided MIMO systems, with reradiational mask. This research has investigated a two-user MIMO wireless communication system aided by a RIS, with the objective of maximizing the minimum achievable rate between the users while generating multiple directional beams. The system operates in the far field and considers a transmitter equipped with multiple antennas and a uniform planar array RIS with controllable reflection elements. Two types of RIS control constraints are considered: (i) continuous phase shifts, where each RIS element can take arbitrary phase values on the unit circle, and (ii) discrete phase shifts, where elements can only take values from a finite set (e.g., 2-bit or 3-bit resolution), reflecting practical hardware limitations.

System Model and Problem Formulation. We consider a downlink MIMO communication system assisted by a reconfigurable intelligent surface (RIS), where the transmitter is equipped with N_t antennas, and each of the two receivers is equipped with N_{r_1} and N_{r_2} antennas, respectively. The RIS is composed of N_{ris} passive elements arranged in a uniform rectangular array. Direct paths between the transmitter and receivers are blocked; thus, the communication relies entirely on the RIS. The system aims to simultaneously transmit information to both users by forming two directional beams through RIS configuration.

Let $F_1 \in \mathbb{C}^{N_t \times N_{r_1}}$ and $F_2 \in \mathbb{C}^{N_t \times N_{r_2}}$ be the precoding matrices for receivers 1 and 2, respectively. The phase shifts of the RIS are denoted by the vector $\theta = [\theta_1, \cdots, \theta_{N_{ris}}]$, with each $\theta_n \in \mathcal{F}$, where $\mathcal{F}$ is either a continuous or discrete feasible set depending on the case. The goal is to maximize the minimum achievable rate across the two users:

$$min \ \{ R_1(\theta, F_1, F_2), R_2(\theta, F_1, F_2) \}$$

subject to unit-modulus constraints on the RIS and a reradiation mask constraint limiting the total angular power outside the target reflection angles.

Assuming continuous phase control, the RIS elements are allowed to take arbitrary phase shifts on the unit circle. This setting leads to a highly non-convex optimization problem, as both the precoders and the RIS configuration are coupled. To handle this, an alternating optimization (AO) framework is proposed. The overall problem is decomposed into three subproblems: the update of the transmit precoders, the update of auxiliary variables related to the users' rate expressions, and the update of the RIS configuration under unit-modulus constraints. Each subproblem is formulated as a quadratically constrained problem and solved in closed or semi-closed form. The AO algorithm iteratively improves the minimum rate, ensuring convergence to a local optimum. To complement this method and allow for fast inference in time-sensitive applications, a deep neural network is illustrated in Figure 5, is trained to approximate the mapping from geometric parameters—specifically, the incident and reflection angles—to optimal RIS and precoder configurations. The angular information is encoded using a modified one-hot representation, which increases the sensitivity of the input layer to angular differences and allows smoother generalization across continuous domains. While approximate, the neural network significantly reduces computational load during deployment and maintains acceptable performance under the reradiation mask.

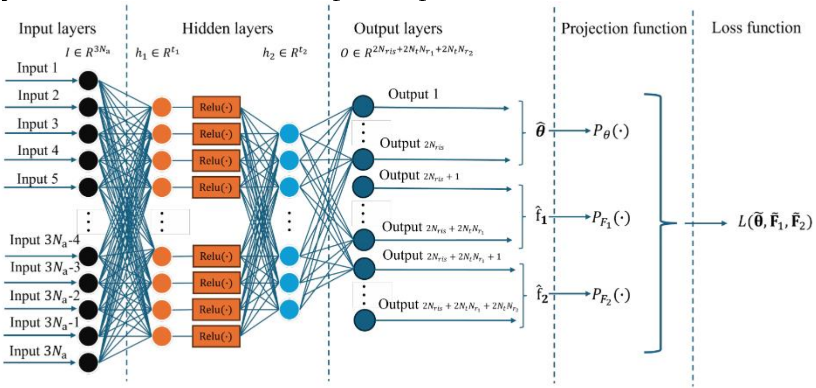


Figure 5: Neural Network Architecture

However, in practical RIS implementations, the phase shifts available at each reflecting element are typically constrained to a discrete set due to hardware limitations. This discrete setting transforms the optimization into a combinatorial problem, as the solution space grows exponentially with the number of RIS elements. To address this, a greedy iterative algorithm is developed. Starting from an initial feasible configuration, the algorithm updates one RIS element at a time. At each step, it selects the phase value from the discrete set that maximizes the current minimum achievable rate while keeping all other variables fixed. This element-wise optimization is performed repeatedly across the RIS until convergence or performance saturation. The greedy method is simple to implement, naturally accommodates discrete phase sets, and avoids the need for relaxation or approximation of the problem structure.

Simulation Results and Analysis. In this section, Simulations are performed to evaluate the effectiveness of the proposed methods in both continuous and discrete RIS settings. The RIS is configured as a 12×12 uniform planar array, and the system operates at 27 GHz with a total transmit power of 2 W. The angle of incidence is fixed at 20°, while the two desired reflection directions are set at 30° and 50°. A reradiation mask is applied to all non-target directions.

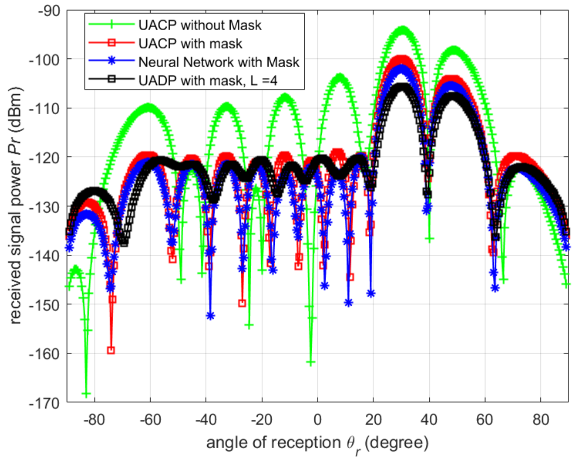


Figure 6: Received power as a function of the angle of observation in $\theta_{inc} = 20^{\circ}$,

$$\theta_{ref1} = 30^{\circ}, \theta_{ref2} = 50^{\circ}$$

Figure 6 shows the received power as a function of observation angle for different beamforming strategies. When the reradiation mask is not applied (UACP without mask), the beamforming performance shows strong main lobes but also significant sidelobes, indicating power leakage toward unintended directions. By enforcing the reradiation mask (UACP with mask), the sidelobes are substantially reduced, while the main beams remain correctly focused. The neural network, trained under mask constraints, reproduces this behavior with a slight reduction in main lobe gain, confirming its ability to generalize the optimized solution. For the discrete phase case (UADP with L=4), the beam is still directed toward the intended angles, but the peak power is slightly lower due to quantization effects.

Figure 7 presents the phase distributions across the RIS elements for each method. Without the mask, the RIS phases are more structured and periodic. When the mask is imposed (either via optimization or learned by neural network), the phase patterns become more irregular and spatially adaptive. This reflects the need to precisely shape the reradiation pattern to avoid non-target angles. The discrete configuration in the UADP case produces blocky phase maps, as expected due to the limited resolution.

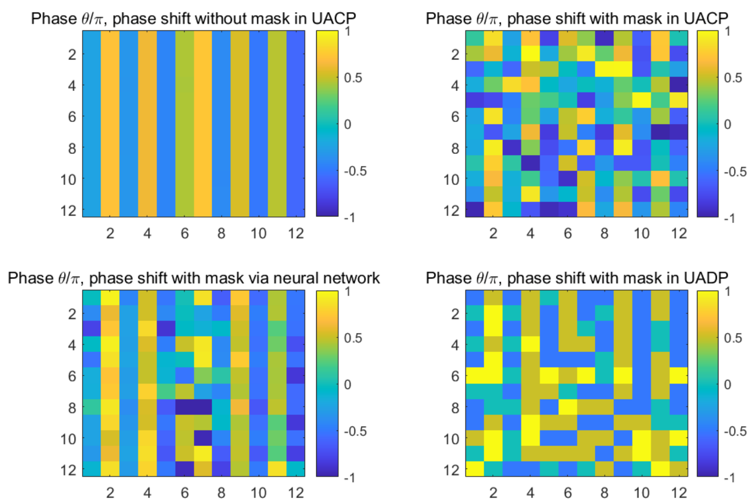


Figure 7: Color map of the RIS phase shifts: UACP without mask (left), UACP with mask (second), neural network with mask (third), UADP with mask

Figure 8 displays the reflection amplitude profiles of the RIS. In the unconstrained continuous case, all elements exhibit unit amplitude. However, with the reradiation mask enforced, some RIS elements reduce their amplitude to values below 1, indicating that the system strategically attenuates certain elements to limit power in undesired directions. This is especially visible in the UACP with mask and neural network results. In the UADP case, the amplitudes remain close to unity, but the limited phase resolution introduces minor degradation in beam shaping.

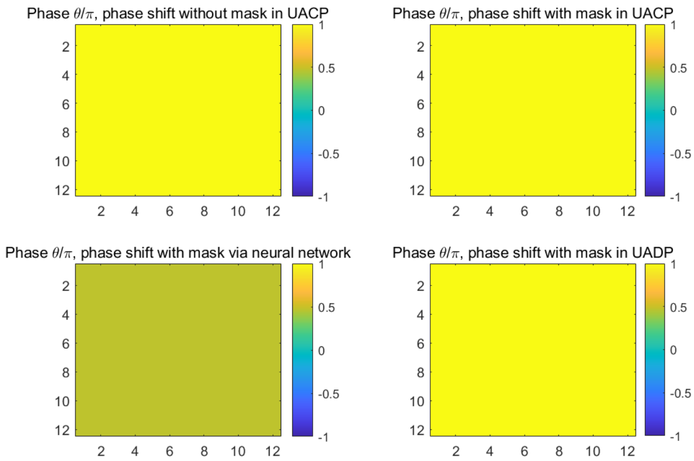


Figure 8: Color map of the RIS amplitudes: UACP without mask (left), UACP with mask (second), neural network with mask (third), UADP with mask

Overall, the simulation results confirm the effectiveness of the proposed methods. Enforcing the reradiation mask successfully suppresses unwanted sidelobes while preserving the directionality of the main beams. The alternating optimization approach offers high performance in the continuous phase case, and the neural network provides a fast approximation with satisfactory accuracy. The greedy method for discrete RIS configurations demonstrates that even with quantized phase shifts, reliable multibeam beamforming can be achieved, although at the cost of slightly reduced beam gain. Importantly, the proposed framework remains robust under both continuous and discrete hardware constraints, making it suitable for real-world RIS-enabled MIMO systems.

Secondment - Machine learning design of globally passive RIS through physics-aided methods.

CNRS-2 spent a three-month visit to the NEC. During this period, he collaborated closely with his NEC supervisors — Dr. Placido Mursia, Dr. Francesco Devoti, and Dr. Vincenzo Sciancalepore — as well as his Main supervisor, Prof. Marco Di Renzo, on machine learning design of globally passive RIS, with a focus on physics-aided methods. This research work is currently being finalized and it will be submitted for publication.

2.3 Contribution of KTH-1 – Overcoming Gap 3.3

The research activity of KTH-1 is meant to address the research Gap 3.1 identified in the technical annex of the grant agreement. Specifically, due to the fact that reconfigurable intelligent surfaces are nearly-passive devices, traditional channel estimation methods are not applicable, since they are based on pilot sequences and thus require the intelligent surface to have transmit/receive modules as well as digital signal processing abilities. Innovative channel estimation algorithms that account for the passive nature of reconfigurable intelligent surfaces are needed. In order to overcome Gap 3.3, the research activity of KTH-1 is focused on developing low-overhead channel estimation algorithms and feedback signaling mechanisms, where end-to-end channel estimation is performed only at the transmitters and receivers without requiring any signal processing and transmission at the metasurface.

In the sixth generation of wireless communication systems (6G), there exist multiple candidate enabling technologies that help the wireless network satisfy the ever-increasing demand for speed, coverage, reliability, and mobility. Among these technologies, reconfigurable intelligent surfaces (RISs) extend the coverage of a wireless network into dead zones, increase capacity, and facilitate integrated sensing and communications (ISAC) tasks by consuming very low power, thus contributing to energy efficiency as well.

RISs are meta-material-based devices whose electromagnetic reflection characteristics can be controlled externally to cater to the needs of the communication links. Most ubiquitously, this comes in the form of adding a desired phase shift to an incident wave before reflecting it, which can be used to phase-align multiple incident waves to increase the strength of the signal at the receiver and provide coverage to an area that otherwise would be a dead zone.

While this portrays an image of a dream technology that would boost the existing wireless networks significantly, RISs do not come without engineering problems. First of all, the individual elements do not exhibit ideal reflection characteristics, that is, they attenuate the incident signal in a fashion depending on the configured phase shift. This creates the phenomenon called "phase-dependent amplitude". Another problem caused by RISs is the channel estimation overhead. In a multiple-antenna communication system, the channel between two terminals is as complex as the product of the number of antennas at each end. However, when an RIS comes into the equation, the cascade of the transmitter-RIS and RIS-receiver channels has a complexity further multiplied by the number of RIS elements. Consequently, the channel estimation process to utilize the RIS effectively becomes more demanding, that is, more pilot signals are required to estimate the channel for coherent reception. This adversely affects the effective data rate within a communication system since more resources need to be spent for pilot transmission and fewer resources can be allocated for data transmission. While there exists some work on reducing the channel dimensions by exploiting the channel structure, this problem persists for unstructured channels. In addition, for the wireless networks using multiple RISs, a new kind of pilot contamination arises, which is the main topic of this thesis.

In the first part of his work, KTH-1 studied the problem of pilot contamination in a multi-operator context, where two operators provide services to their respective served users and share a single site. Each operator has a single dedicated RIS and they use disjoint frequency bands, but each RIS inadvertently reflects the transmitted uplink signals of the user equipment devices in multiple bands. Consequently, the concurrent reflection of pilot signals during the channel estimation phase introduces a new inter-operator pilot contamination effect. The implications of this effect in systems with either deterministic or correlated Rayleigh fading channels has been investigated, specifically focusing on its impact on channel estimation quality, signal equalization, and channel capacity. The numerical results demonstrate the substantial degradation in system performance caused by this phenomenon and highlight the pressing need to address inter-operator pilot contamination in multi-operator RIS deployments. To combat the negative effect of this new type of pilot contamination, KTH-1 proposed to use orthogonal RIS configurations during uplink pilot transmission, which can mitigate or eliminate the negative effect of inter-operator pilot contamination at the expense of some inter-operator information exchange and orchestration.

In the second part of his work, KTH-1 revisited the inter-operator pilot contamination. This time, however, he investigated the use of multiple antennas at the base stations to eliminate inter-operator pilot contamination. While orthogonalizing the RIS configurations as in the single antenna case eliminates pilot contamination, it doubles the number of pilots required to perform channel estimation. Considering the extant pilot overhead problem in RIS-aided communication systems, an alternative approach that does not increase the number of pilots to be transmitted is necessary. To this end, KTH-1 proposed using receive beamforming and null forming to eliminate inter-operator pilot contamination. We show that it is possible to eliminate inter-operator pilot contamination by placing nulls toward the signal coming from the other operator's RIS.

In the third part of this thesis, KTH-1 considered a single-operator-two-RIS ISAC system where the single user is both a communication terminal and a positioning target. Based on the uplink positioning pilots, the base station aims to estimate both the communication channel and the user's position within the indoor environment by estimating the angle of arrival (AoA) of the impinging signals on both RISs and then exploiting the system and array geometries to estimate the user position and user channels respectively. Although there is a single operator, due to the presence of multiple RISs, pilot contamination occurs through the same physical means as multi-operator pilot contamination unless the channel estimation process is parameterized. Since the communication links are considered to be pure line-of-sight (LOS), their structure allows the reduction of the number of unknown parameters. Consequently, the reduction of information caused by pilot contamination does not affect the channel estimation procedure, hence the pilot contamination is overcome. In addition, the position of the user is determined by intersecting the lines drawn along the AoA estimates. KTH-1 adopted the Cramér-Rao Lower Bound (CRLB), the lower bound on the mean squared error (MSE) of any unbiased estimator, for both channel estimation and positioning. Our numerical results show that it is possible to utilize positioning pilots for parametric channel estimation when the wireless links are LOS.

The fourth part of the research activities considered the domain of near-field communications. Here, KTH-1 considered the estimation of parametric channels in the uplink of a multi-user multiple-input-multiple-output (MU-MIMO) communication system where the users are located within the radiative near field (Fresnel region) of the base station's aperture antenna. In this setup, he considered near-field channel models characterized by the users' distances and azimuth angles relative to the aperture array. He derived the CRLB to estimate these location parameters and the parametric channel estimates in closed form. Moreover, he considered using the 2D-MUSIC algorithm to estimate these parameters and compare the performance of the 2D-MUSIC algorithm with the CRLB. The obtained results indicate that the 2D-MUSIC algorithm is asymptotically consistent and efficient.

The results of this research appeared in the papers:

1. D. Gürgünoğlu, G. Fodor, E. Björnson, "Impact of Pilot Contamination Between Operators With Interfering Reconfigurable Intelligent Surfaces", *IEEE International Black Sea Conference on Communications and Networking 2023*, July 2023, Istanbul, Türkiye.
2. D. Gürgünoğlu, G. Fodor, E. Björnson, "Combating Inter-Operator Pilot Contamination in Reconfigurable Intelligent Surfaces Assisted Multi-Operator Networks", *IEEE Transactions on Communications*, 2024.
3. D. Gürgünoğlu, Z. Gülgün, G. Fodor, E. Björnson, "Receive Beamforming Schemes to Mitigate Inter-Operator Pilot Contamination in RIS-Aided MIMO Networks", *Signal Processing (submitted, under review),* 2025.
4. D. Gürgünoğlu, G. Fodor, E. Björnson, "Joint Pilot-Based Localization and Channel Estimation in RIS-Aided Communication Systems", *IEEE Wireless Communications Letters,* 2024.
5. D. Gürgünoğlu, A. Kosasih, P. Ramezani, Ö.T. Demir, G. Fodor, E. Björnson, "Performance Analysis of a 2D-MUSIC Algorithm for Parametric Near-Field Channel Estimation", *IEEE Wireless Communications Letters,* 2025.

Secondment - RIS-aided Integrated sensing and communications

Between 01.11.2023 and 30.06.2024, KTH-1 did an 8-month secondment at Ericsson AB, Stockholm, Sweden. While his secondment supervisor coincided with his Main supervisor, the experience was still different from working at KTH. During the secondment, KTH-1 has worked on integrated sensing and communications

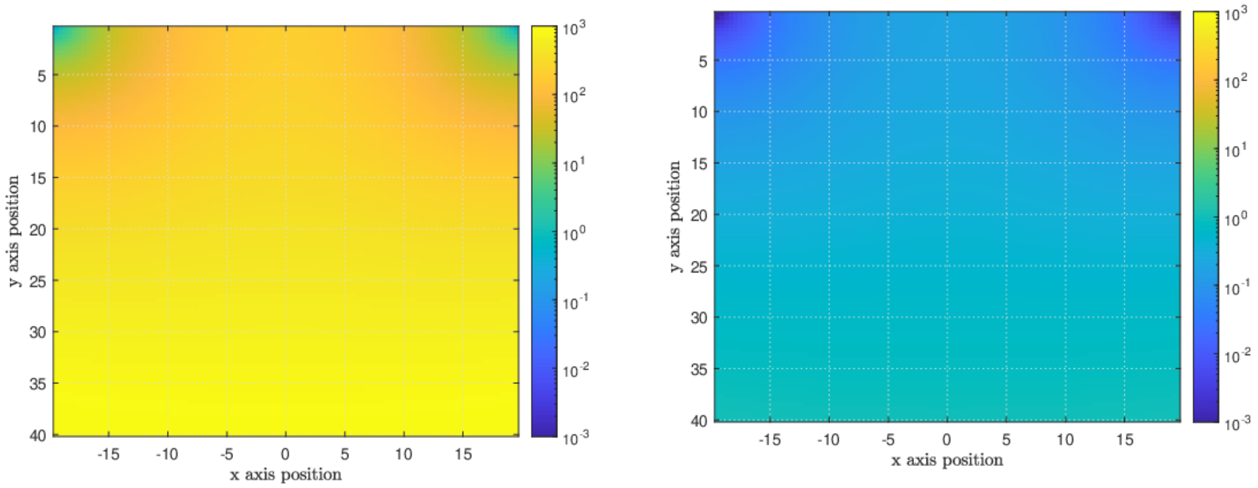


Fig. 1: Non-parametric vs. parametric channel estimation CRLBs.

(ISAC) problems, performing a CRLB analysis on how we can exploit the parametric structure of certain channels in RIS-aided systems to obtain lower bounds on channel estimation MSE, and obtain location information at the same time.

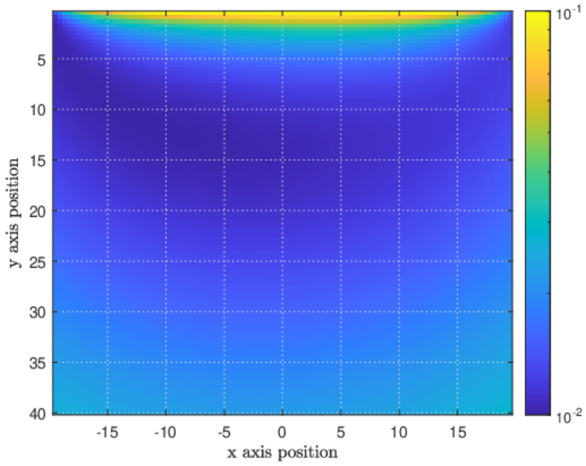


Fig. 2: Localization error bound for parametric channels.

The results of this research appeared in the paper

"Joint Pilot-Based Localization and Channel Estimation in RIS-Aided Communication Systems", IEEE Wireless Comunications Letters.

2.4 Contribution of NEC-1 – Overcoming Gap 3.4

The research activity of NEC-1 is meant to address the research Gap 3.4 identified in the technical annex of the grant agreement. Specifically, at present there are no algorithms and protocols for reconfiguring and operating large-scale networks employing reconfigurable intelligent surfaces. Coping with the sudden changes in the propagation environment and with the users' heterogeneous traffic demands, requires embedding the nodes of the network with the intelligence to behave autonomously. Accordingly, the research activity of NEC-1 focuses on developing distributed algorithms for controlling and programming the operation of wireless networks employing reconfigurable intelligent surfaces in a scalable manner. The approach that is being followed is based on leveraging machine learning tools to reduce the amount of data to exchange (low overhead) and devise fast-implementable and performance-guarantee algorithms whose parameters can be optimized by using the data sensed by the metasurfaces.

A Cost-effective RISs Deployment to abate the Coverage Problem in B5G Networks

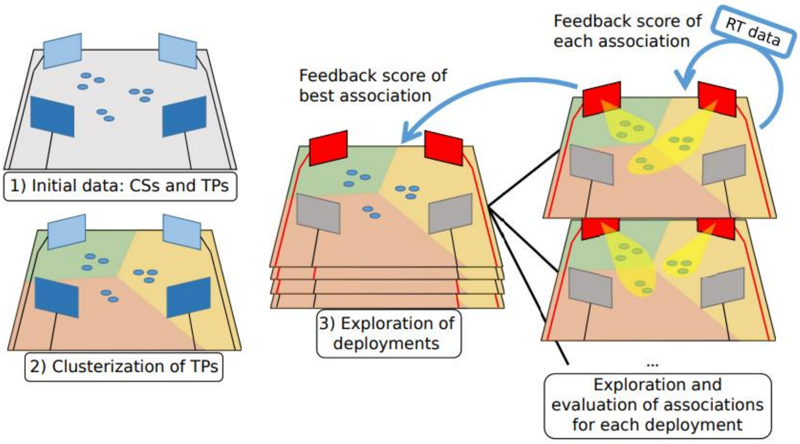
The results of this research have appeared in the paper:

G. Encinas-Lago, A. Albanese, V. Sciancalepore, X. Costa-Pérez, A. Banchs and D.-T. Phan-Huy, accepted for publication in IEEE Transactions on Wireless Communications.

A. Albanese, G. Encinas-Lago, V. Sciancalepore, X. Costa-Pérez, D.-T. Phan-Huy, and S. Ros, *RIS-Aware Indoor Network Planning: The Rennes Railway Station Case*, 2022 IEEE International Conference on Communications (ICC), 2022.

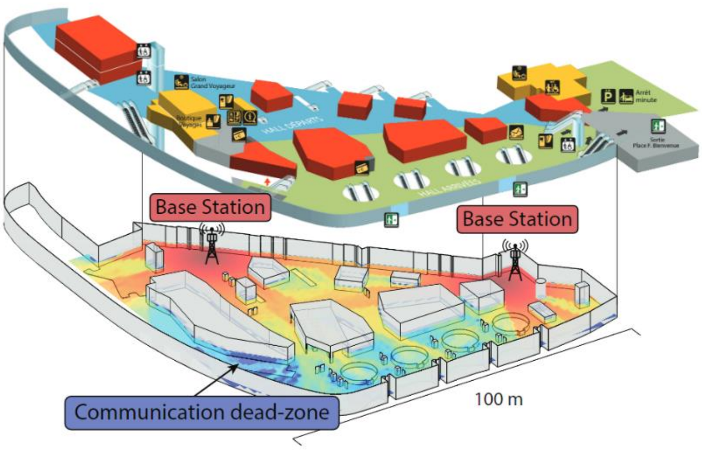
The problem of RIS deployment while assuming very limited reconfiguration capabilities is studied. We compare two different approaches. In the first, RISA, the deployment is formulated as an optimization problem and approximate solutions are found through Convex Optimization, Continuous Relaxation, and Alternate

Optimization, among other techniques. In the second approach, AI-RISA, BIRCH clustering is adopted for TPs and Q-Learning to create a viable reinforcement learning architecture, able to solve the problem using a simulator that evaluates the candidate solutions, as shown in the figure below.



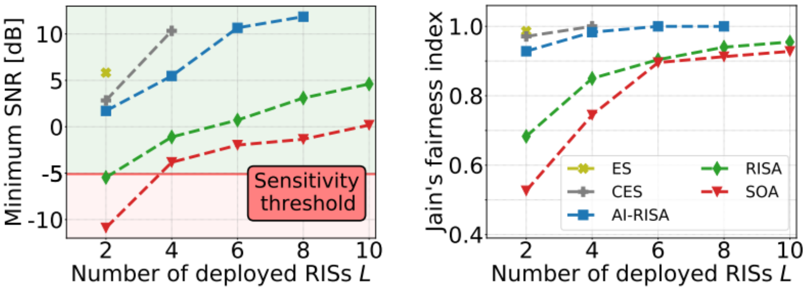
Overview of AI-RISA process blocks.

To guide AI-RISA and evaluate and compare solutions both from RISA and AI-RISA, a digital twin of the Rennes Railway Station has been built. A 3D model has been created based on the architectural plans, and it was combined with a commercial ray tracer engine. We then process the resulting propagation information together with mathematical models of RIS reflective capabilities based on Beam Broadening and Flattening. The results follow the same observations as done by the operator in the real-life counterpart of the station (figure below), providing some degree of confirmation the validity of the digital twin, in particular at predicting the loss of coverage in some areas.



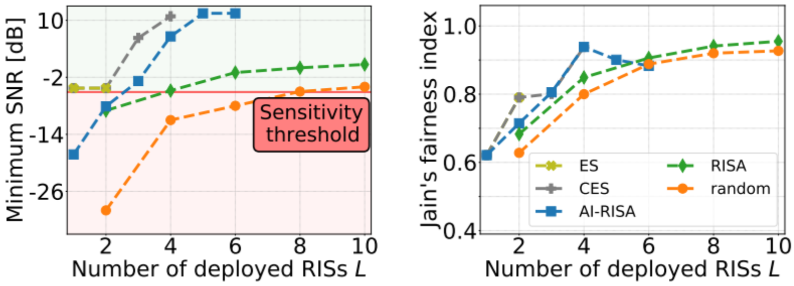
Railway station topographic map and related power heatmap showing the dead-zone problem (Rennes, France).

It has been found that the Exhaustive Search (ES) finds the best solutions, unmatched by any other method, but only viable to deploy a small number of RISs due to the increasing computation time needed. When assisted by a clustering step, referred to as Clustered Exhaustive Search (CES), we can extend a bit the number of deployed RISs but at the expense of the performance of the solutions. It can be seen how RISA (which does not employ clustering) is able to improve over the existing deployment methods and is able to be executed even when many devices are to be deployed. On the other hand, AI-RISA obtains much better performance, still falling a bit short of the optimal solutions and not being able to deploy large number of devices, due to the limitations inherent to Q-learning.



RISA and AI-RISA performance against SoA (adapted to our scenario), ES and clustered exhaustive search (CES) with different numbers of deployed RISs via Monte Carlo simulations considering synthetic topologies. © 2024 IEEE.

In the next step a test over the 3D model of the Rennes Station has been performed, with CSs chosen according to the architectural characteristics of the building and TPs placed in the areas where low coverage has been observed and predicted using the simulator (Figure below). With this setup, a similar behavior of the algorithms involved in the comparison has been observed, with the notable change in the clustering, which does not impose a performance penalization in this case.



RISA and AI-RISA performance obtained via RT simulations for different numbers of deployed RISs and available Candidate Sites (CSs) in a realistic environment (Rennes station), compared to CES, ES, and random solutions. © 2024 IEEE.

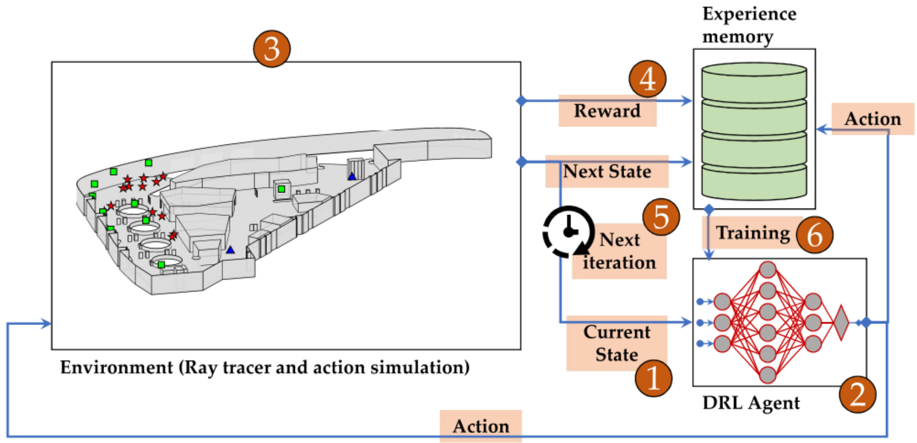
These results confirm that RISs can be used as an alternative to BSs to improve network coverage and the usefulness of machine learning and digital twin techniques for RIS-related problems. This work motivates further research to refine our deployment methods.

Unlocking Metasurface Practicality for B5G Networks: AI-assisted RIS Planning

The results of this line of work have appeared in the paper:

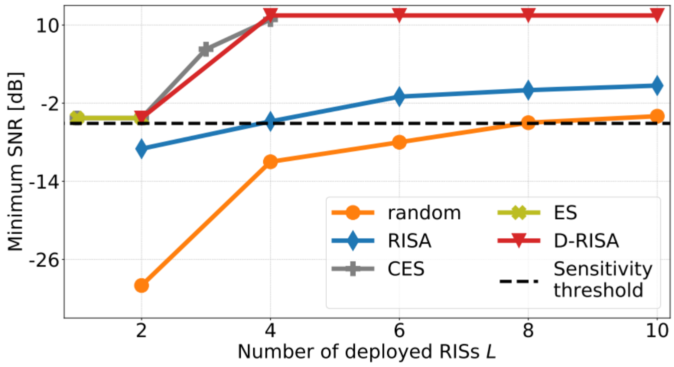
G. Encinas-Lago, A. Albanese, V. Sciancalepore, M. Di Renzo, X. Costa-Pérez, IEEE Global Communications Conference (GLOBECOM) 2023.

This work expands the previous efforts on the deployment problem. A more advanced solution is proposed, based on DQL (figure belwo). This architecture, despite the similar name, is completely different, as it substitutes the core of Q-Learning, the Q-value table, with a neural network.



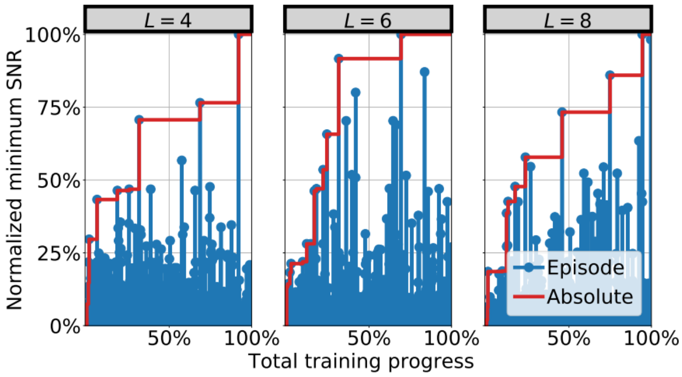
D-RISA's building blocks showing the training process for a given frame. In the 3D map, the candidate sites (CSs) for the RIS deployment are shown in green, the BSs in blue, and test points (TPs) in red.

The new architecture provides several benefits: on one hand the memory and state space size constraints are not an issue anymore, allowing us to solve the deployment and association problems in a single stroke, avoiding the nested architecture we used before, and in the other hand the agent is able to recognize patterns in the training, being able to decide what to do based on similar (but not necessarily identical) situations experienced in the past. An additional benefit is the elimination of the discretization requirement: traditional Q-Learning can only handle discrete states (solutions) and actions, while DQL can handle continuous ones. Nevertheless this was not exploited to improve comparability: both architectures are exposed to exactly the same problem in the same conditions.
The results of testing D-RISA against previous installments under the same RIS capability assumptions are truly impressive: D-RISA matches exhaustive searches and clustered exhaustive searches in all the cases that those solutions are known, and the reduction in memory constraints also allows it to solve the full range initially considered for the problem, able to deploy the maximum 10 RISs we initially considered (figure below).

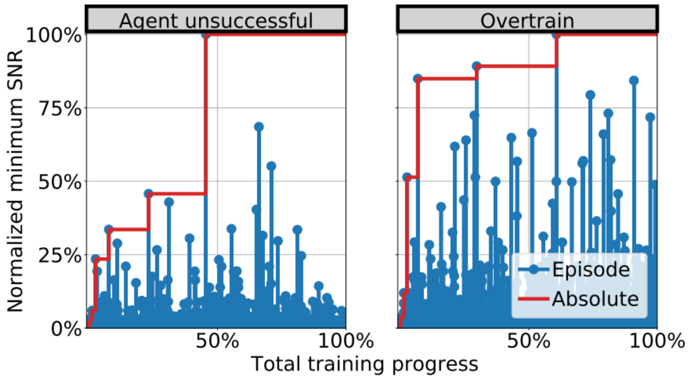


D-RISA performance against benchmark methods and SOA RISA [13] for a different number of deployed RISs in terms of minimum SNR. © 2023 IEEE.

One of the central ideas to be underlined is that the developed solution does not need to produce an agent able to do the deployment (which is not always feasible, in particular when computational capabilities are limited). The reinforcement learning agent training process is only employed to find optimal solutions to the problem. If the training is successful (as in the figure below), the developed architecture will obviously find a solution to the problem, but if the training is unsuccessful, it is not able to produce a working agent (as depicted below, where we can see how the agent performance decreases towards the end of the training). This is because, during the training, the actions taken by the agent are combined in varying ratios with "exploratory" actions, and even if the agent alone does not produce a solution, the combination of both provides one.



Solution evolution in terms of normalized minimum SNR for a different number of deployed RISs. © 2023 IEEE.



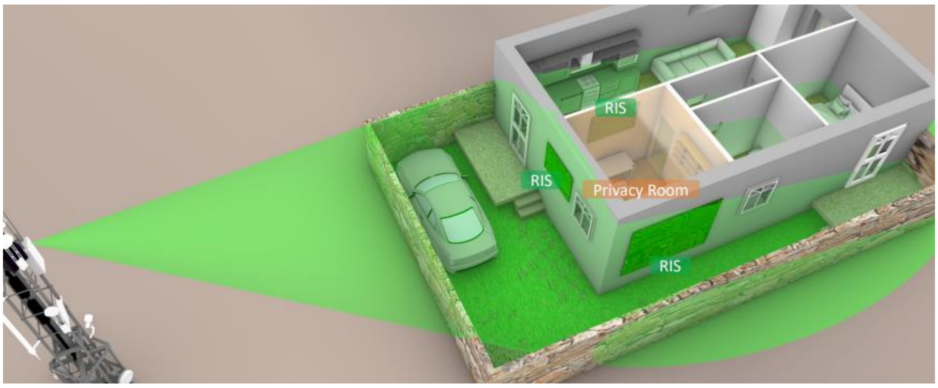
Solution evolution in terms of normalized minimum SNR for a different number of deployed RISs: (left) unsuccessful D-RISA agent and (right) overtrained D-RISA agent. © 2023 IEEE.

RIShield: Enabling Electromagnetic Blackout in Radiation-Sensitive Environments

The results of this line of research have appeared in the paper:

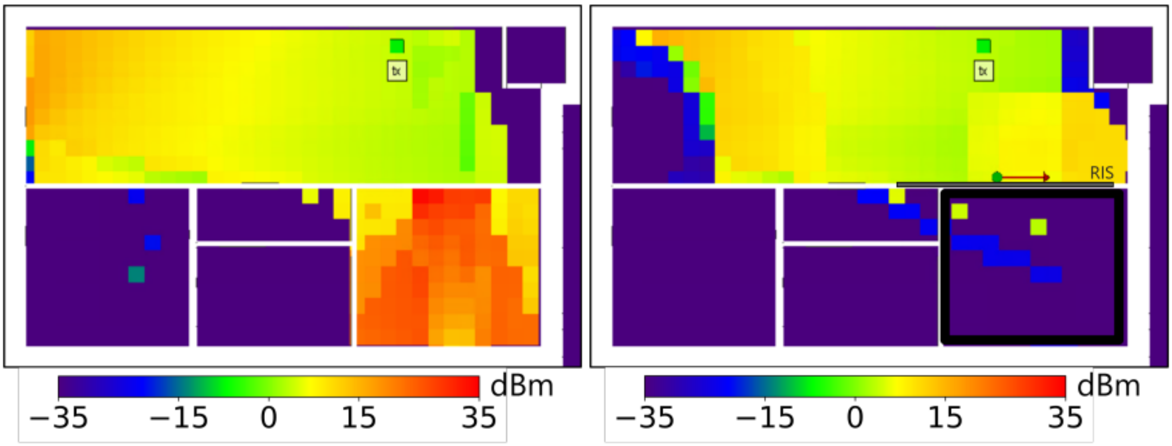
G. Encinas-Lago, M. Rossanese, V. Sciancalepore, M. Di Renzo, X. Costa-Pérez, IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP) 2023.

This paper introduces *RIShield*, a novel framework that leverages RIS to create controlled electromagnetic blackout areas, also known as electromagnetic shadowing (figure below). The primary goal of this work is to utilize RIS technology to block or redirect electromagnetic waves, thereby establishing zones where wireless signals are significantly weakened or completely obstructed. These blackout areas have potential applications in enhancing privacy, protecting sensitive locations, and mitigating interference in dense wireless environments.



RIS used to guarantee privacy and isolation in real environments

The core of the research focuses on determining the optimal configuration of RIS elements to achieve the desired shadowing effect. By precisely adjusting the phase shifts of the RIS elements, it is possible to manipulate the propagation of electromagnetic waves, steering them away from specific regions and creating a controlled blackout zone. The optimization problem is solved to ensure that the RIS configuration maximizes the shadowing effect while energy consumption and resource utilization remains minimal due to the passive nature of RISs.



Conventional 2D indoor scenario (4 rooms) with 1 indoor transmitter. The signal propagates mostly in the entire considered area through walls without the RIS (Fig. 2, left). The right-hand side room is isolated when the RIS is enabled as a shield (Fig. 3, right).

Simulations are conducted in Remcom WirelessInSite, a powerful electromagnetic simulation tool, to validate the effectiveness of the proposed RIShield framework. Through these simulations, we demonstrate the feasibility of creating reliable blackout areas under various environmental conditions and deployment scenarios. The results show that RIShield can be an effective solution for scenarios where signal blocking or electromagnetic protection is required, offering a new dimension of control in wireless communication systems.

Secondment. During the secondment we have continued working on the main, ongoing activities of the ESR contract, while also engaged in other, new lines of work with the teams of the host institution. Main activities in the secondment have been:

- A co-authorship of a paper studying RIS capabilities, employing a prototype of NEC Laboratories Europe GmbH., evaluated in the premises and with the equipment of the host institution.
- The development of an embedded prototype implementing low power neural networks to assist RISs in the localization of connected users.
- An active effort to engage in interaction with host institution personnel working in similar topics to ours but with different approaches, leading to highly valuable share of ideas.

3. Conclusions

The research activities concerning Task 1.3 reached the planned goals. All ESRs have completed the tasks of their individual research projects and closed the corresponding research gap. In particular:

- CNIT-2 has developed novel and practical techniques and algorithms for user localization in wireless networks employing reconfigurable intelligent surfaces. The developed techniques make use of active metasurfaces to boost the localization accuracy, outperforming the use of passive metasurfaces. Then, the research activities of CNIT-2 have focused on developing novel detection and tracking techniques to further improve the localization and sensing performance, also considering specific use-cases, which has led to several patents.

- CNRS-2 has developed a new analytical framework to quantify the system-level performance of wireless networks in the presence of reconfigurable intelligent surfaces. Leveraging machine learning techniques, the framework provides the optimized reflection coefficients of a reconfigurable intelligent surface as the output of a neural network. Then, CNRS-2 has refined the developed framework, considering practical scenarios and employing deep learning techniques, such as deep unfolding.

- **KTH-1** has developed practical techniques for joint channel estimation and design of wireless networks employing reconfigurable intelligent surfaces. The framework operates without requiring any signal processing and transmission at the reconfigurable intelligent surfaces, requiring a very limited signaling overhead, which makes it amenable for practical scenarios. Besides, KTH-1 has also developed techniques for RIS-based joint communication and sensing in wireless networks.

- **NEC-1** has developed deployment techniques for large-scale wireless networks empowered by reconfigurable intelligent surfaces. The developed methodologies have considered both traditional optimization tools and the use of deep reinforcement learning and machine learning techniques. A simulation environment has been produced to emulate the network deployment and operation in a realistic wireless environment. In addition, the research activities of NEC-1 have focused on the operation of large-scale networks that employ reconfigurable intelligent surfaces. AI and deep learning have been used to reduce the overhead related to the huge amount of data to exchange and enable scalable RIS deployments.

4. Bibliography

[1] L. Wei, C. Huang, G. C. Alexandropoulos, and C. Yuen, *Parallel factor decomposition channel estimation in RIS-assisted multi- user MISO communication*, 2020 IEEE 11th Sensor Array and Multichannel Signal Processing Workshop (SAM), 2020.

[2] Z. Wan, Z. Gao, and M.-S. Alouini, *Broadband channel estimation for intelligent reflecting surface aided mmwave massive MIMO systems*, 2020 IEEE International Conference on Communications (ICC), 2020.

[3] J. He, M. Leinonen, H. Wymeersch, and M. Juntti, *Channel estimation for RIS-aided mmwave MIMO channels*, IEEE Transactions on Wireless Communications, vol. 20, no. 9, pp. 5786 – 5797, Sep. 2021.

[4] G. T. de Araujo and A. L. de Almeida, *PARAFAC-based channel estimation for intelligent reflective surface assisted MIMO system*, 2020 IEEE 11th Sensor Array and Multichannel Signal Processing Workshop (SAM), 2020.

[5] C. Hu and L. Dai, S. Han, X. Wang, *Two-timescale channel estimation for reconfigurable intelligent surface aided wireless communications*, IEEE Transactions on Communications, vol. 69, no. 11, pp. 7736 – 7747, Nov. 2021.

[6] Z.-Q. He and X. Yuan, *Cascaded channel estimation for large intel- ligent metasurface assisted massive MIMO, IEEE Wireless Communications Letters*, vol. 9, no. 2, pp. 210–214, Feb. 2020.

[7] G. C. Alexandropoulos and E. Vlachos, *A hardware architecture for reconfigurable intelligent surfaces with minimal active elements for explicit channel estimation*, 2020 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2020.

[8] S. Buzzi, C. D'Andrea, A. Zappone, M. Fresia, Y.-P. Zhang, S. Feng, *RIS configuration, beamformer design, and power control in single-cell and multi-cell wireless networks*, IEEE Transactions on Cognitive Communications and Networking, vol. 7, no. 2, pp. 398 – 411, June 2021

[9] A. Zappone et al. *Overhead-Aware Design of Reconfigurable Intelligent Surfaces in Smart Radio Environments*, IEEE Transactions on Wireless Communications, vol. 20, no. 1, pp. 126 – 141, January 2021.

[10] A. Zappone, M. Di Renzo, M. Debbah, T. T. Lam, and X. Qian, *Model-aided wireless artificial intelligence: Embedding expert knowl- edge in deep neural networks for wireless system optimization*, IEEE Vehicular Technology Magazine, vol. 14, no. 3, pp. 60–69, Sep. 2019.

[11] A. Zappone, M. Di Renzo, and M. Debbah, *Wireless networks design in the era of deep learning: Model-based, AI-based, or both?* IEEE Transactions on Communications, vol. 67, no. 10, pp. 7331–7376, Oct. 2019.

[12] H. Gacanin and M. Di Renzo, *Wireless 2.0: Towards an intelligent radio environment empowered by reconfigurable meta-surfaces and artificial intelligence*, IEEE Vehicular Technology Magazine, vol. 15, no. 4, pp. 74 – 82, Dec. 2020.

[13] C. Liaskos, A. Tsioliaridou, S. Nie, A. Pitsillides, S. Ioannidis, and I. Akyildiz, *An interpretable neural network for configuring programmable wireless environments*, 2019 International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), 2019.

[14] J. Gao, C. Zhong, X. Chen, H. Lin, and Z. Zhang, *Unsupervised learning for passive beamforming*, IEEE Communications Letters, vol. 24, no. 5, pp. 1052 – 1056, May 2020.

[15] C. Huang, R. Mo, and C. Yuen, *Reconfigurable intelligent surface assisted multiuser MISO systems exploiting deep reinforcement learning*, IEEE Journal on Selected Areas in Communications, vol. 38, no. 8, pp. 1839 – 1850, Aug. 2020.

[16] A. Taha, Y. Zhang, F. B. Mismar, and A. Alkhateeb, *Deep reinforcement learning for intelligent reflecting surfaces: Towards standalone operation*, 2020 IEEE 21st International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), 2020.

[17] K. Feng, Q. Wang, X. Li, and C.-K. Wen, *Deep reinforcement learning based intelligent reflecting surface optimization for MISO communication systems, IEEE Wireless Communications Letters*, vol. 9, no. 5, pp. 745 – 749, May 2020.

[18] X. Liu, Y. Liu, Y. Chen, and H. V. Poor, *RIS enhanced massive non-orthogonal multiple access networks: Deployment and passive beamforming design*, IEEE Journal on Selected Areas in Communications, vol. 39, no. 4, pp. 1057 – 1071, April 2021,

[19] A. M. Elbir, A. Papazafeiropoulos, P. Kourtessis, and S. Chatzinotas, *Deep channel learning for large intelligent surfaces aided mm-wave massive MIMO systems*, IEEE Wireless Communications Letters, vol. 9, no. 9, pp. 1447 – 1451, Sep. 2020

[20] H. Yang, Z. Xiong, J. Zhao, D. Niyato, and L. Xiao, *Deep reinforcement learning based intelligent reflecting surface for secure wireless communications*, IEEE Transactions on Wireless Communications, vol. 20, no. 1, pp. 375 – 388, Jan. 2021.

[21] A. Elzanaty, A. Guerra, F. Guidi, D. Dardari, and M.-S. Alouini, *Towards 6g holographic localization: Enabling technologies and perspectives*, arXiv:2103.12415, 2021.

[22] H. Wymeersch, J. He, B. Denis, A. Clemente, and M. Juntti, *Radio localization and mapping with reconfigurable intelligent surfaces: Challenges, opportunities, and research directions*, IEEE Vehicular Technology Magazine, vol. 15, no. 4, pp. 52–61, Dec. 2020.

[23] D. Dardari, N. Decarli, A. Guerra, and F. Guidi, *Los/Nlos nearfield localization with a large reconfigurable intelligent surface*, IEEE Transactions on Wireless Communications, vol. 21, no. 6, pp. 4282 – 4294, June 2021.

[24] O. Rinchi, A. Elzanaty, and M.-S. Alouini, *Compressive near-field localization for multipath RIS-aided environments*, IEEE Communications Letters, vol. 26, no. 6, pp. 1268 – 1272, June 2022.

[25] B. Ceniklioglu, D. A. Tubail, A. E. Canbilen, I. Develi, and S. Ikki, *Error analysis of the joint localization and synchronization of RIS-assisted mm-wave MISO-OFDM under the effect of hardware impairments*, IEEE Open Journal of the Communications Society, vol. 3, pp. 2151 – 2161, 2022.

[26] R. Long, Y.-C. Liang, Y. Pei, and E. G. Larsson, *Active reconfigurable intelligent surface-aided wireless communications*, IEEE Transactions on Wireless Communications, vol. 20, no. 8, pp. 4962–4975, 2021.

[27] H. Zhang, H. Zhang, B. Di, K. Bian, Z. Han, and L. Song, *Metalocalization: Reconfigurable intelligent surface aided multi-user wireless indoor localization*, IEEE Transactions on Wireless Communications, vol. 20, no. 12, pp. 7743–7757, 2021.

[28] A. Elzanaty, A. Guerra, F. Guidi, and M.-S. Alouini, *Reconfigurable intelligent surfaces for localization: Position and orientation error bounds*, IEEE Transactions on Signal Processing, vol. 69, pp. 5386–5402, Aug. 2021.

[29] J. G. Andrews, F. Baccelli, and R. K. Ganti, *A Tractable Approach to Coverage and Rate in Cellular Networks*, IEEE Transactions on Communications, vol. 59, no. 11, pp. 3122–3134, 2011.

[30] E. Amaldi, A. Capone, and F. Malucelli, *Planning UMTS base station location: optimization models with power control and algorithms*, IEEE Transactions on Wireless Communications, vol. 2, no. 5, pp. 939–952, 2003.

[31] E. Moro, I. Filippini, A. Capone, and D. De Donno, *Planning Mm-Wave Access Networks With Reconfigurable Intelligent Surfaces*, 2021 IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2021.

[32] H. Lu, Y. Zeng, S. Jin, and R. Zhang, *Aerial Intelligent Reflecting Surface: Joint Placement and Passive Beamforming Design With 3D Beam Flattening*, IEEE Transactions on Wireless Communications, vol. 20, no. 7, pp. 4128–4143, 2021.