Future Wireless Communications Empowered by Reconfigurable Intelligent Meta-Materials

Deliverable 1.4: Intermediate report on the activities and results of Task 1.4 – System-level simulator

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Contents

Executive Summary

Deliverable D1.4 of the project Metawireless consists of an intermediate report on the research activities performed within Task 1.4 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 technical annex of the grant agreement. Specifically, Task 1.4 is concerned with the technical Objective 4, i.e.

The development of metasurface-tailored ray tracing modules and building of the first open access simulation (software) platform to analyze, optimize, and test large-scale metasurface-based intelligent radio environments.

According to the technical annex of the grant agreement, the activities of Task 1.4 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 developing a ray-tracing module and open access network simulator for large-scale wireless environments employing 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 1.4. 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

- Technische Universität Wien (TUW)

- Nokia Bell Labs (NOK)

- Telefonica I+D (TID)

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

The existing research on metasurface-aided communication primarily focuses on theoretical frameworks and treats the impact of different parameters separately. Very few literature contributions are concerned with the development of ray-tracing modules and large-scale system-level simulators that support the use of reconfigurable intelligent surfaces. In particular, to the best of our knowledge there is no open-access ray tracer or system-level simulator that supports reconfigurable intelligent surfaces in complex wireless environments. The influence of the number of reflecting elements of the metasurfaces, channel model, interference, cell association, and other essential network parameters are not evaluated through system-level simulations. In addition, the system performance of metasurface-aided large-scale wireless network has not been verified through system-level simulation. An efficient metasurface-tailored system-level simulator that allows very large simulation scenarios and investigations on more performance measures is currently missing in the open literature.

Most available contributions are focused on the small-scale simulators or measurement campaigns in controlled environments. The MIT's RFocus [1] and the NTT-DOCOMO [2] platforms are two notable examples of promising research activities towards the realization of reconfigurable intelligent surfaces that are specifically designed for wireless applications. In [3] the authors report the design of a smart reflectarray that is designed for enhancing indoor connectivity in the millimeter-wave frequency band. The reflector panel is fabricated to operate in the 60 GHz frequency band, and its dimensions are 337 mm, 345 mm, and 0.254 mm for its length, height, and thickness, respectively. The reflector panel is made of 224 reflector units, whose inter-distance is larger than one wavelength. Therefore, this design does not fall into the definition of metasurface. The authors show that the proposed solution enables the communication of multiple users in the same indoor area, over the same spectrum band, at the same time, and without suffering any significant interference, as well as the reduction of the link outage probability. A few other research groups around the world have built prototypes for realizing smart surfaces that are made of large arrays of inexpensive antennas. Notable fully-functional experimental testbeds and experimental activities along this line of research include the LAIA (large array of inexpensive antenna) prototype [4], and the ScatterMIMO prototype [5]. As far as the realization of smart surfaces based on metasurfaces is concerned, a relevant example is the

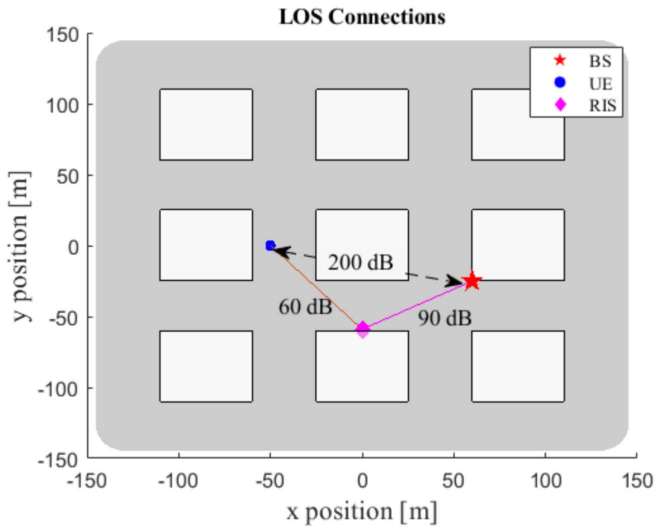
HyperSurface hardware platform: a software-defined, controllable, and programmable metasurface structure that is capable of shaping the electromagnetic waves in reconfigurable ways. In [6], the authors report a new type of high-gain yet low-cost reconfigurable intelligent surface made of 256 elements. The proposed reconfigurable intelligent surface combines the functions of phase shift and electromagnetic radiation on a surface where PIN diodes are used to realize two-bit phase shifts for beamforming. This proposed design forms the basis for the world's first wireless communication prototype that realizes a reconfigurable intelligent surface having 256 two-bit elements. The prototype consists of modular hardware and flexible software that encompass the hosts for parameter setting and data exchange, universal software radio peripherals for baseband and radio frequency signal processing, as well as modules for signal transmission and reception. Experimental results confirm the feasibility and efficiency of reconfigurable intelligent surfaces for wireless communications. In particular, at 2.3 GHz the proposed reconfigurable intelligent surface can achieve a 21.7 dBi antenna gain. At the millimeter wave frequency of 28.5 GHz, it attains a 19.1 dBi antenna gain. Furthermore, it is shown that the developed prototype is capable of significantly reducing the power consumption. In [7], the authors design a radio frequency sensing system for posture recognition based on reconfigurable intelligent surfaces. The proposed system can actively customize the environment in order to provide the desirable propagation properties and diverse transmission channels. The prototype has a size of 69 cm × 69 cm × 0.52 cm, and it is composed of a two-dimensional array of electrically controllable unit elements. Each row/column of the array contains 48 unit elements, which corresponds to a surface made of 2,304 unit elements. Each unit element has a size of 1.5 cm × 1.5 cm × 0.52 cm, and it is composed of four rectangle copper patches printed on a dielectric substrate. Any two adjacent copper patches are connected by a PIN diode that is controlled by applying appropriate voltages. By combing simulation and experimental results, the authors show that the posture recognition accuracy increases with the size of the reconfigurable intelligent surface and with the number of independently controllable elements. In [8], the authors report the world's first experimental measurements to characterize the path-loss experienced by electromagnetic waves in the presence of metasurfaces. The authors report experiments, which are conducted in an anechoic chamber, for three samples of manufactured metasurfaces with 10,200, 1,700, and 256 unit cells, respectively, and whose size is 1.02 m × 1 m at 10.5GHz, 0.34 m × 0.5 m at 10.5GHz, and 0.384 m × 0.096 m at 4.25 GHz, respectively. The authors prove that the path-loss as a function of the transmission distance depends on several parameters, which include the size of the metasurface, the function applied by the metasurface, and whether the system operates in the radiative near-field or in the far-field. In [9], [10], [11], [12], [13], the authors report the design and some experimental results on multiple prototypes of reconfigurable metasurfaces that implement single-radio-frequency transmitters. In particular, the prototype reported in [10] is designed to have a full 360 degrees phase response and a reflectivity of about 85% at a working frequency of 4.25 GHz. The fabricated metasurface sample is made of 8 × 32 unit cells. The size of a unit cell is 12 mm × 12 mm × 5 mm, which approximately corresponds to 0.17λ × 0.17λ × 0.07λ at 4.25 GHz. The capacitance of the unit cell is dominated by a varactor diode, which indicates that the phase response of the metasurface can be tuned through the bias voltage of the varactor diode. This bias voltage has an approximate linear relationship with the phase of the reflected wave and can achieve 360 degrees phase modulation. For example, the authors prove that the designed metasurface prototype is capable of mimicking the phase response of an eight phase shift keying modulation scheme.

2. Description of Activities and Results

2.1 Contribution of TUW-1 – Overcoming Gap 4.1

The research project of TUW-1 is meant to address the research Gap 4.1 identified in the technical annex of the grant agreement. Specifically, available network simulators are based on the assumption that the environmental objects reflect and refract the radio waves based on conventional Snell's laws. Developing efficient system-level simulators for wireless networks that employ reconfigurable intelligent surfaces requires solving two main issues: **i)** current ray-tracing modules need to be generalized in order to account for generalized Snell's laws; and **ii)** these modules need to be integrated in open-access system-level simulators for their wide use. In order to overcome Gap 4.1, TUW-1 research work is focused on extending the Vienna System-Level Simulator available at TUW to make it suitable for analyzing and optimizing wireless networks in the presence of reconfigurable intelligent surfaces.

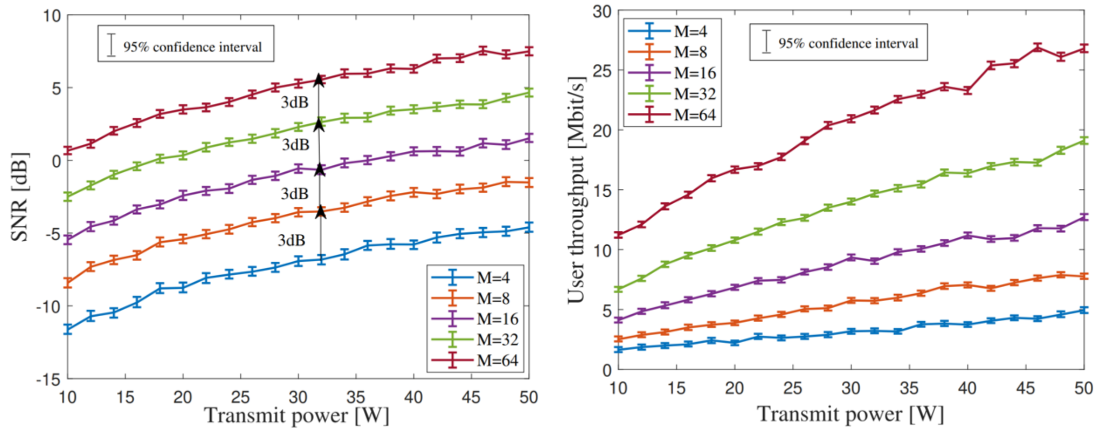
TUW-1 has implemented novel software modules that have been embedded into the Vienna System Level Simulator to provide support for wireless environments in the presence of reconfigurable intelligent surfaces. Specifically, the simulator is now capable of handling the main features of wireless propagation in the presence of metasurfaces, such as metasurface modelling, phase shifts optimization, channel modelling, path-loss modelling, metasurface deployment, cell association, blockage and interference management. In addition, the average system performance of the metasurface-aided single-input single-output (SISO) scenario is evaluated through Monte-Carlo simulation and compared with known results available in the open literature. The simulation scenario is shown in the figure below. In particular, one base station antenna, one metasurface with *M* elements, and one user equipment with a single antenna have been simulated. The path-loss for the channels between the base station and the metasurface, between the metasurface and user equipment, and between the base station and user equipment links are set as 90 dB, 60 dB and 200 dB, respectively. The Rayleigh channel model is used in the simulation, the carrier frequency is 2 GHz and the bandwidth is 20 MHz. The metasurface is equipped with *M* elements, and the impact on the network signal-to-noise ratio (SNR) and throughput is analyzed.



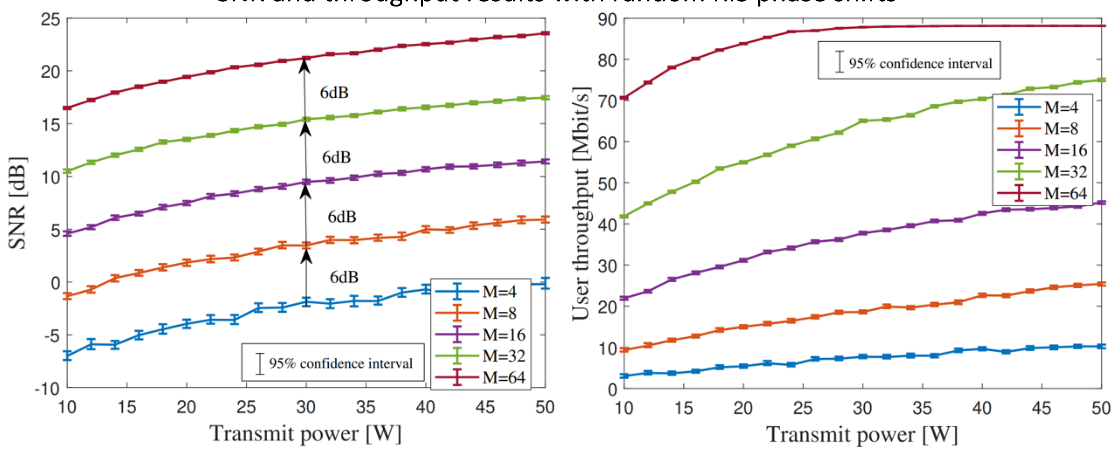
The SISO simulation scenario

Simulation results compare the performance between the optimized phase shifts of and random phase shift allocation at the metasurface. As shown in the two figures below, the results from the system-level simulator are consistent with the power scaling law for metasurfaces. This means a 3dB gain upon performing the optimization with respect to the baseline method of random phase allocation.

The simulated SISO scenario is a stepping-stone for further system-level simulations in metasurface-based multiple-input multiple-output (MIMO) and multi-user scenarios.



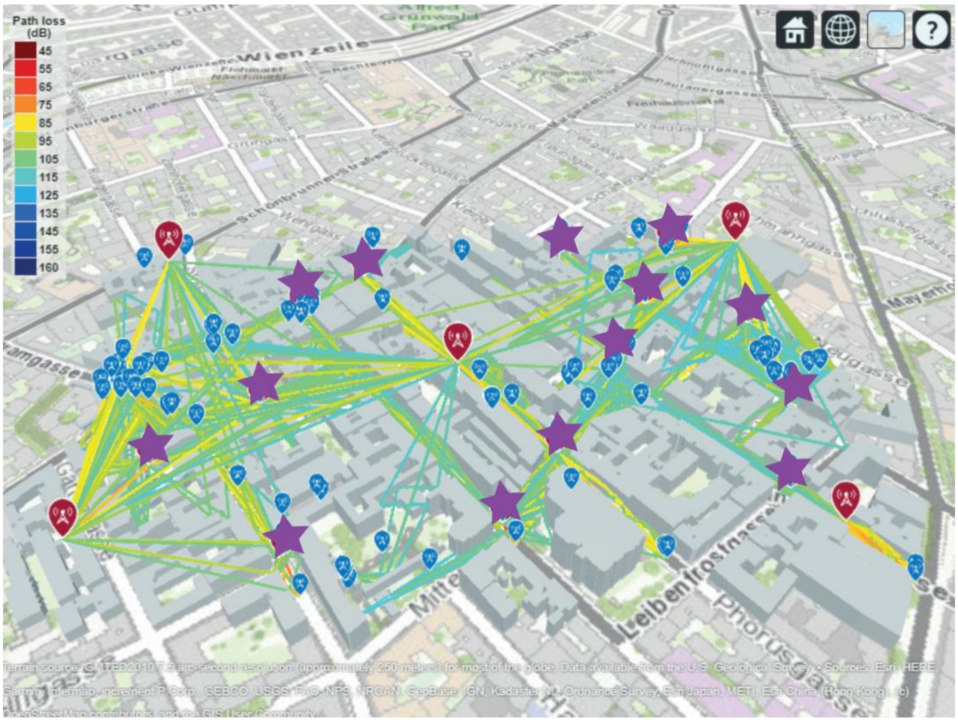
SNR and throughput results with random RIS phase shifts



SNR and throughput results with optimized RIS phase shifts

Next, TUW-1 has integrated the MATLAB Raytracer with the Vienna system-level simulator. The ray tracing module is used to improve the accuracy of the macroscopic fading in the system-level simulator, while more realistic paths can be generated between each network node in realistic scenarios. The two figures below show the simulation scenarios without any reconfigurable intelligent surfaces and with a reconfigurable intelligent surface, respectively. The blockages due to buildings and realistic environment setups were taken from the open street map. The developed ray-tracer can simulate the same scenario as in the Vienna system-level simulator.

Scenario without RIS



Scenario with RIS

Next, TUW-1 has extended the results described above to the case in which a multi-user multiple-input multiple-output (MU-MIMO) network is considered. In this case, in order to deal with the presence of multi-user interference, zero-forcing (ZF) precoding has been used to completely cancel the intra-cell interference, while the fractional frequency reuse (FFR) approach is used as an alternative approach when a mitigation of the inter-cell interference is aimed at, rather than a complete suppression. In addition, different user grouping algorithms, i.e., Semi-Orthogonal User Selection (SUS), Single Path Random Sampling (SPRS), and exhaustive search, are being considered and compared in the system-level simulator.

It should be mentioned that TUW-1 and NOK-1 have worked together on developing and verifying the ray-tracer module. Indeed, according to the technical annex of the grant agreement, Gap 4.1 is jointly addressed by TUW-1 and NOK-1.

The above results have appeared in the following research article**:**

L. Hao, A. Fastenbauer, S. Schwarz, M. Rupp, *Towards System Level Simulation of Reconfigurable Intelligent Surfaces,* 2022 International Symposium ELMAR, 2022, 81-84. doi: 10.1109/ELMAR55880.2022.9899799

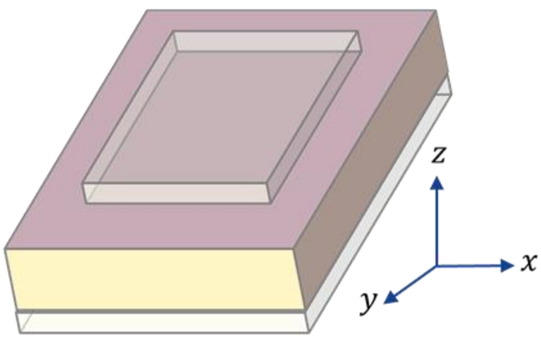
2.2 Contribution of NOK-1 – Overcoming Gap 4.1

The research project of NOK-1 is meant to address the research Gap 4.1 identified in the technical annex of the grant agreement. Specifically, Available network simulators are based on the assumptions that the objects reflect and refract the radio waves based on conventional Snell's laws. Developing efficient system-level simulators for wireless networks that employ reconfigurable intelligent surfaces requires solving two main issues: **i)** current ray-tracing modules need to be generalized in order to account for generalized Snell's laws; and **ii)** these modules need to be integrated in open-access system-level simulators for their wide use.

In order to overcome Gap 4.1, NOK-1 research work is focused on the development of novel ray-tracing modules capable of handling the presence of metasurfaces in the propagation environment, by extending the Nokia Bell Labs ray tracing simulator "WiSE".

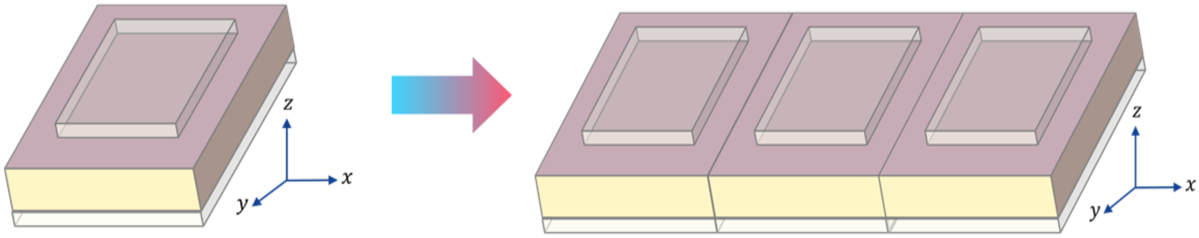
Specifically, a first line of research followed by NOK-1 is about developing circuit-based models of reconfigurable intelligent surfaces. The specific aim of this research is to develop optimizable perfect anomalous reflectors using patch arrays with circuit modeling to diminish the complexity by moving the complex metasurface setup to the circuit domain to optimize the scattering behavior and adequately set controllable loads in realistic topology for reconfigurable intelligent surfaces. The main purpose of this research line is to find a computationally effective, but accurate, method to model and optimize anomalous reflectors for predicting the scattering characteristics of an extensive or infinite array with supercells. At present, for larger arrays, the optimal approach for the optimization of the scattering pattern is a brute force method which performs simulations for every case using electromagnetic simulators. Clearly, this method is not time-efficient. The current state-of-the-art research is to predict the scattering behavior for large arrays, and the achieved results allow fast optimization of finite arrays, bringing an in-depth understanding of optimally configured realistic metasurface structures.

The considered approach of NOK-1 has been to start focusing on the prediction formulation for receive antennas and continued modeling of scattering behavior of loaded dipoles and infinite arrays of such dipoles to predict the reradiated field using the receiving antenna theory. Then, NOK-1 focused on predicting the reradiated field behavior using patches since simple patch design could help the development of new metasurface structures as one of the main objectives of this research line, as illustrated in the figure below.



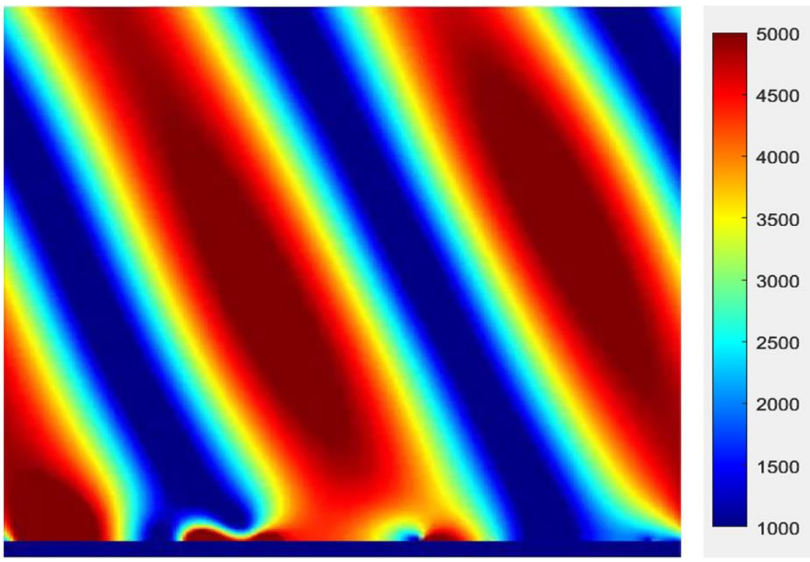
An infinite planar array design with λ/2 periodicity and lossless materials at 28 GHz

NOK-1 started investigating this methodology for the infinite planar array model and extended it to a supercell array setup. The supercell array is designed to function as anomalous reflectors by utilizing an optimizable set of loading impedances.



Three-patch supercell anomalous reflector design

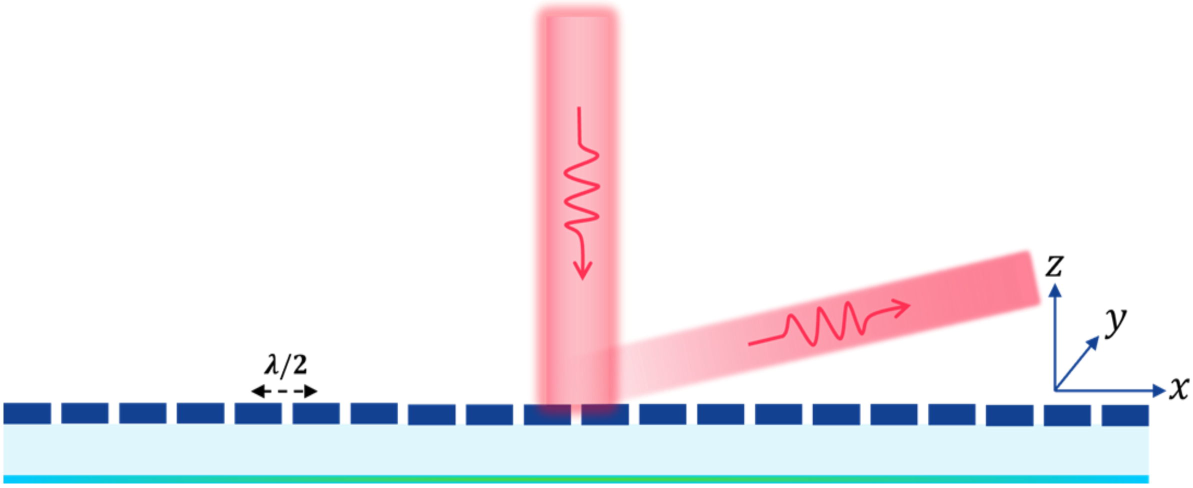
NOK-1 developed a technique to optimize the reactive loads to acquire the maximum reflection amplitude for anomalous reflection, and the simulation results agree with the predicted optimized results. The figure below shows the scattered E-field distribution normal to the plane animation for the propagating mode of anomalous reflection into +70° for normal incidence. The plot contains the magnitude values of the real part of the E-field at the nominal zero phases. For maximum reflection magnitude for anomalous reflection, a pure plane wave propagating in the +70◦ direction can be observed.



The scattered E-field distribution normal to the plane animation for propagating mode of anomalous reflection into 70° for normal incidence

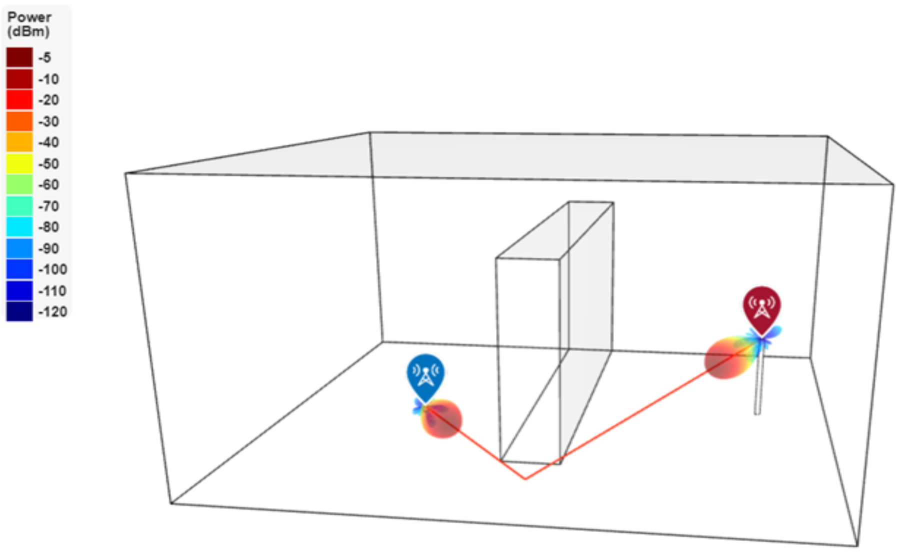
NOK-1 has compared the optimized results with the conventional reflectarray design method, confirming the superior performance of the new design method. Preliminary results ensure that the proposed method allows fast design of optimized reflectarrays capable of nearly perfect anomalous reflection into arbitrary angles, surpassing the fundamental limitations of conventional designs of reconfigurable intelligent surfaces.

Currently, NOK-1 is working on medium-size finite patch arrays with half-wavelength spacing between the elements to target a practical metasurface design, as demonstrated in the below figure. In addition, NOK-1 has formulated an optimization problem to optimize the radiation pattern for the desired direction and defined constraints to suppress scattering into unwanted propagating modes.

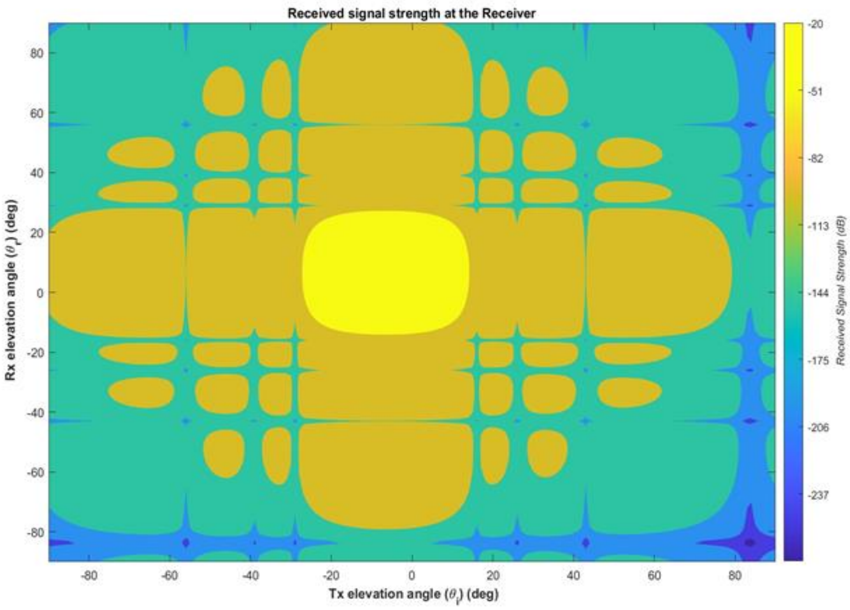


A medium-size finite patch arrays with half-wavelength periodicity

Another line of investigation of NOK-1 is the modeling of metasurface characteristics to develop a metasurface-compliant ray tracer and integrating it into the Vienna 5G system level simulator. To this end, NOK-1 started working on a MATLAB ray tracer, as it is easily accessible and convenient to integrate into the Vienna 5G system level simulator. Moreover, it uses an object-oriented programming code structure. Primarily, the starting point of the research aims at generating a scenario to verify that the received signal strength is maximum under the usual reflection law for a perfect reflector, as the scenario depicted in the figures below.



The maximum received signal strength for a considered block scenario with walls and blocks covered with a perfectly reflecting surface material.



Received signal strength for arbitrary angle of incidence and arrival

NOK-1 worked jointly with TUW-1 on the MATLAB ray tracer to calculate the received signal strength and path-loss for both single-path and multipath propagation, and verified the results with analytical formulas related to multipath interference by using a phasor sum. NOK-1 and TUW-1 have also worked on creating different 3D indoor scenarios in the STL format using freely available software like Blender or Vectary, which are readable using the MATLAB ray tracer. The results achieved by NOK-1 have led to the following journal article:

S. K. R. Vuyyuru, D.-H. Kwon, R. Valkonen, and S. A. Tretyakov, *Optimized Anomalous Reflector Based on a Novel Scattered Field Prediction Technique*, submitted to IEEE Antennas and Wireless Propagation Letters, 2022.

2.3 Contribution of TID-1 – Overcoming Gap 4.2

The research project of TID-1 is meant to address the research Gap 4.2 identified in the technical annex of the grant agreement. Specifically, metasurface-based networks are envisioned as a configurable platform that integrates communication, sensing, localization, and computing. Thus, reconfigurable intelligent surfaces need to continuously sense and promptly adapt to the environment. Conventional system-level simulators are designed only for communications. So, they need to be enhanced with specific modules for network orchestration.

TID-1 has been recently recruited, with planned start date set to December 12th, 2022. Accordinlgy, no activity can be reported for the considered reporting period.

3. Conclusions

The research activities concerning Task 1.4 are progressing as planned, with the exception of the research project of TID-1. This ESR has been just recruited and will start working on December 12th. All other ESRs have completed the initial literature review phase, which started in M7, and are currently developing innovative designs to tackle the specific challenge of their individual research project and close the corresponding research gap. In particular:

TUW-1 developed novel routines to add support for metasurfaces to the Vienna system-level simulator available at TUW and has started working jointly with NOK-1 to the integration with ray-tracing modules in simple network setups. In the second half of the project, the research activities of TUW-1 will focus on extending the developed software to handle more complex network setups.

NOK-1 developed new ray-tracing modules to account for the presence of metasurfaces in simple wireless environments and has started working jointly with TUW-1 to integrate them in the system-level simulator developed by TUW-1. In the second half of the project, the research activities of NOK-1 will focus on extending the developed ray-tracing modules to handle more complex propagation scenarios and integrate them into the system-level simulator developed by TUW-1.

4. Conclusions

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