Future Wireless Communications Empowered by Reconfigurable Intelligent Meta-Materials

Deliverable 1.2: Intermediate report on the activities and results of Task 1.2 – Theoretical Frameworks

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

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Contents

Executive Summary

Deliverable D1.2 of the project Metawireless consists of an intermediate report on the research activities performed within Task 1.2 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 1.2 is concerned with the technical Objective 2, i.e.

The development of new mathematical techniques to introduce a novel communication theory that overcomes conventional Shannon's theory and unveils the ultimate performance of wireless networks based on the use of reconfigurable intelligent surfaces.

According to the technical annex of the grant agreement, the activities of Task 1.2 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 frameworks for modeling, analyzing, and optimizing 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 1.2. 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

- Aalto-korkeakoulusäätiö (AAL)

- Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT)

- Centre National de la Recherche Scientifique (CNRS)

- Universitat Pompeu Fabra (UPF)

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 use of reconfigurable intelligent surface has emerged as a key candidate technology for future wireless networks. Yet, at present, little is known about the ultimate performance it can provide. The aim of Task 1.2 is to close this gap. The results of the state-of-the-art review concerning Task 1.2 can be divided into two main branches, i.e. theoretical studies on performance analysis of networks employing reconfigurable intelligent surfaces, and studies on the ultimate attainable performance upon optimal allocation of the network radio resources.

Performance analysis. Since their inception, reconfigurable intelligent surfaces have been under study for unveiling their fundamental performance limits and the impact of the imperfect knowledge of various systems parameters on their achievable performance. In this context, several exact, approximate, and asymptotic analytical frameworks have been developed in order to quantify the advantages and limitations of reconfigurable intelligent surfaces in different network scenarios. In [1], the authors study the impact of the finite resolution of the reconfigurable intelligent surface phase shifts on the achievable performance. In particular, the authors introduce an approximated expression of the achievable data rate of a metasurface-aided communication system, and derive the minimum number of phase shifts that is necessary in order to guarantee a data rate degradation constraint. In [2], the authors study the asymptotic rate of a metasurface-based uplink channel in which an reconfigurable intelligent surface is equipped with a large number of reflecting elements. Also, the authors take channel estimation errors and spatially correlated multi-user interference in account. It is shown that channel hardening effects occur, similar to massive MIMO systems. Moreover, it is shown that the impairments due to thermal noise, interference, and channel estimation errors become negligible as the number of reconfigurable intelligent surface reflectors increases. This leads to results comparable with those of massive MIMO systems, but at a reduced deployment area and costs. In [3], the authors study the downlink channel of a single-cell multi-user system in which a base station equipped with multiple antennas communicates with several single- antenna users through a reconfigurable intelligent surface. The minimum signal-to-interference-plus-noise-ratio (SINR) among the mobile users is asymptotically analyzed, by considering the case studies in which the line-of-sight channel matrix between the base station and the reconfigurable intelligent surface has unit rank and full rank. In the unit rank case, the minimum SINR is shown to be bounded by a quantity that goes to zero as the number of users increases. In the full rank case, on the other hand, deterministic approximations are derived and are used to optimize the reconfigurable intelligent surface phase shifts by using the gradient ascent method. In [4], the authors compute the outage probability, the average symbol error probability, and the achievable rate of a metasurface-aided system. It is proved that the accuracy of the obtained analytical expressions becomes tighter as the number of reconfigurable intelligent surface elements grows large. The achievable diversity order is quantified by deriving single-polynomial approximations in the high signal-to-noise-ratio regime. The diversity order is shown to be equal to the number of reconfigurable intelligent surfaces elements. In [5], the authors study the transmission through a reconfigurable intelligent surface in the presence of phase errors. The authors show that the metasurface-based composite channel is equivalent to a point-to-point Nakagami fading channel. This equivalent representation allows the authors to perform theoretical analysis of the performance and to study the interplay between the performance, the distribution of phase errors, and the number of reflectors. Numerical evaluation of the error probability for a limited number of reflectors confirms the theoretical prediction and shows that the performance of reconfigurable intelligent surfaces is remarkably robust against the phase errors. In [6], the authors present an analytical framework for the performance evaluation of random rotation-based metasurface-aided communications. Under this framework, the authors propose four low-complexity and energy efficient techniques based on two approaches: A coding-based and a selection-based approach. Both approaches depend on random phase rotations and require no channel state information. In particular, the coding-based schemes use time-varying random phase rotations in order to produce a time-varying channel. The selection-based schemes select a partition of the reconfigurable intelligent surface elements at each time slot based on the received signal power at the destination. Analytical expressions for the outage probability and energy efficiency of each scheme are derived. The authors demonstrate that all schemes can provide significant performance gains and full diversity order. In [7], the authors investigate the capacity region of a multiple access channel in which two users send independent messages to an access point that is aided by M reflecting elements. The authors study two practical deployment strategies: A distributed deployment in which the M reflecting elements form two reconfigurable intelligent surfaces that are deployed in the vicinity of two users; and a centralized deployment in which the M reflecting elements are deployed in the vicinity of the access point. As for the distributed deployment, the authors derive the capacity region in closed-form. As for the centralized deployment, the authors derive a capacity region outer bound and propose an efficient rate-profile based method to characterize an achievable rate region. Based on the obtained analytical frameworks, the authors show that the centralized deployment outperforms the distributed deployment under practical channel setups, and that the capacity gain is higher when the user rates are asymmetric. In [8], the authors characterize the spatial throughput of a single-cell multiuser system aided by multiple reconfigurable intelligent surfaces that are randomly deployed in the cell. By using analysis and simulations, the authors prove that an metasurface-aided system outperforms full-duplex relaying in terms of spatial throughput, provided that the number of reconfigurable intelligent surfaces elements exceeds a certain value. Moreover, the authors show that different deploying strategies for reconfigurable intelligent surfaces and relays should be adopted for their respective throughput maximization. Finally, it is shown that, for a given total number of reflecting elements, the system spatial throughput increases if fewer reconfigurable intelligent surfaces, each having a larger number of reflecting elements, are deployed. However, this comes at the cost of higher spatially varying user rates.

Radio resource optimization. Optimization of the system radio resources is one of the most researched topics in the context of metasurface-based systems. A significant share of research articles has considered the problem of passive and active beamforming in multiple-input single-output (MISO) systems, i.e., the optimization of the transmit (active) beamforming and the (passive) reconfigurable intelligent surface phase shifts, by resorting to the popular tool of alternating maximization, but sub-optimally solving the inner optimization problems. In the seminal work [9], the authors consider the maximization of the spectral and energy efficiency in a multi-user MISO downlink network, by alternatively optimizing the base station beamforming and the reconfigurable intelligent surface phase shifts. The power allocation problem is optimally solved by a water-filling-like solution, while two methods are developed for optimizing the reconfigurable intelligent surface phase shifts. The first method employs a gradient search approach, while the second method exploits the framework of sequential optimization. Both methods provide phase shifts allocations that are stationary points of the spectral and energy efficiency. Moreover, numerical results show that the use of reconfigurable intelligent surface significantly improves the energy efficiency compared to the use of amplify-and-forward relays, while a gap is observed with respect to the spectral efficiency. This is due to the fact that reconfigurable intelligent surfaces are passive devices, while amplify-and-forward relays are able to apply signal amplification. In [10], the authors develop a phase shift model that relates the reconfigurable intelligent surface phase shifts to the amplitude of the reflection coefficient. A single-user MISO link is considered, and, based on the new phase shift model, the problem of maximizing the system achievable rate with respect to the transmit beamforming and to the reconfigurable intelligent surface phase shifts is formulated. In order to cope with the non-convexity of the problem, alternating optimization is employed to obtain a low-complexity algorithm, in which the transmit beamforming and the reconfigurable intelligent surface phase shifts are iteratively optimized. In [11], the authors consider the downlink of a metasurface-enabled heterogeneous network, in which a multiple-antenna base station serves single-antenna users. In this context, the authors develop an algorithm that jointly allocates the base station transmit power and the reconfigurable intelligent surface phase shifts, in order to maximize the SINR and the sum-rate at the small cell users, subject to a minimum SINR constraint on the rate of the macro-cell users. An algorithm based on alternating maximization coupled with semi-definite relaxation is developed to tackle the sum-rate maximization problem, by trading off complexity and optimality. In [12], the authors consider the problem of maximizing the spectral efficiency in metasurface-aided MISO systems under nonlinear proportional rate constraints. The problem is tackled by alternatively optimizing the transmit power at the base station and the reflecting phase shifts at the reconfigurable intelligent surface, which enables the authors to develop a practical algorithm even though no optimality properties can be guaranteed. Numerical simulations based on the proposed alternating optimization algorithm show that reconfigurable intelligent surfaces are beneficial for improving the network data rate. In [13], the authors study a metasurface-aided system model and propose a practical transmission protocol and channel estimation algorithm, by assuming an orthogonal frequency division multiplexing (OFDM) transmission scheme and a frequency-selective channel. The problem of maximizing the achievable rate by jointly optimizing the transmit power allocation and the reconfigurable intelligent surface reflection coefficients is analyzed. The resulting optimization problem is non-convex, and the authors propose an efficient algorithm by solving the power allocation problem and the optimization of the phase shifts in an iterative manner. Simulation results show that reconfigurable intelligent surfaces significantly improve the performance of OFDM systems. In [14], the authors consider a metasurface-aided OFDM-based system and tackle the problem of maximizing the system rate by optimizing the reflection coefficients over different time slots within each channel coherence block. The resulting optimization problem is shown to be non-convex, and it is tackled by using alternating optimization with respect to the resource block assignment, the transmit power over each resource block, and the reconfigurable intelligent surface phase shifts. Numerical results show that reconfigurable intelligent surfaces are capable of increasing the system rate. In [15], the authors consider a metasurface-aided multi-user MISO system and investigate the problem of robust beam- forming under the assumption of imperfect knowledge of the cascaded channel from the base station to the users. Alternating optimization is adopted to minimize the transmit power subject to worst-case rate constraints under the assumption of a bounded channel error model, and subject to rate outage probability constraints under a statistical channel state information error model. The results reveal that the number of reconfigurable intelligent surface elements may have a negative impact on the system performance if the cascaded channel is not properly estimated. In [16], the authors study the symbol error probability of a metasurface-aided multiuser MISO downlink network. An expression of the symbol error probability is derived and alternating optimization is used to optimize the symbol-level base station precoder and the reconfigurable intelligent surface phase shifts. The resulting algorithm is guaranteed to yield a stationary solution for the non-convex symbol error probability minimization problem. Simulation results demonstrate that the use of reconfigurable intelligent surfaces reduces the bit error probability, especially if a large number of reconfigurable intelligent surface elements is deployed. In [17], the authors consider a wireless network wherein multiple reconfigurable intelligent surfaces are deployed to cooperatively assist the communication between a multi-antenna base station and multiple single-antenna cell-edge users. The goal is to maximize the weighted sum rate of all cell-edge users by jointly optimizing the base station transmit beamforming and the reconfigurable intelligent surfaces phase shifts. Optimal beamforming at the base station is found by using the Lagrangian method, while the reconfigurable intelligent surface phase shifts are obtained based on the Rienmann manifold conjugate gradient method. In [18], the authors investigate the design of a metasurface-assisted single-user MISO wireless communication system, by jointly optimizing the beamformer at the base station and the phase shifts at the reconfigurable intelligent surface. The resulting non-convex optimization problem is tackled by resorting to the branch-and-bound algorithm, which enables the authors to handle the non-convex unit modulus constraints that need to be enforced on the reconfigurable intelligent surface phase shifts, at the expense of an exponential complexity of the overall optimization algorithm. In [19], the authors introduce the concept of metasurface-aided cell-free network, which is aimed at improving the network capacity at a low cost and power consumption. In a wideband scenario, the authors formulate the problem of optimizing the base station beamforming and the reconfigurable intelligent surface phase shifts, with the aim of maximizing the weighted sum-rate under a transmit power constraint at the base station and under unit-modulus phase shifts constraints at the reconfigurable intelligent surface. A general joint precoding framework is proposed to solve the resulting problem. In [20], the authors consider a distributed metasurface-empowered communication network architecture, in which multiple source-destination pairs communicate through multiple distributed reconfigurable intelligent surfaces. In this scenario, the authors study the problem of maximizing the network achievable sum-rate as a function of the transmit power vector at the sources and the phase shift matrix at the distributed reconfigurable intelligent surfaces. The resulting non-convex problem is tackled by employing alternating optimization, in which each sub-problem is cast as a fractional programming problem. In [21], the authors consider a large-scale MIMO system in which a reconfigurable intelligent surface that employ discrete phase shifts aids the downlink transmission. Passive precoding methods are used at the base station and at the reconfigurable intelligent surface. The objective is to minimize the sum power of multi-user interference by jointly optimizing the reconfigurable intelligent surface beamforming and the base stations precoding vectors. A trellis-based joint reconfigurable intelligent surface and base station precoding design is introduced, according to which the base station precoding in each cell is performed individually. By applying stochastic optimization, a low-overhead trellis-based optimization technique is introduced, and performance improvements are obtained by minimizing the inter-cell and intra-cell interference. In addition, semi-definite relaxation is applied to develop benchmark methods for comparison. In [22], the authors investigate a metasurface-assisted multi-user communication system, in which a single-antenna access point sends independent information to multiple single- antenna users with the aid of a reconfigurable intelligent surface that is capable of applying discrete phase shifts. The authors consider the bi-objective maximization of the system ergodic capacity and the delay-limited capacity, and characterize the corresponding Pareto boundary. The authors show that the ergodic capacity can be achieved by using an alternating transmission strategy in which the reconfigurable intelligent surface phase shifts are dynamically changed. In order to achieve the delay-limited capacity, the authors show that the reconfigurable intelligent surface phase shift matrix needs to be fixed at a specific value.

2. Description of Activities and Results

2.1 Contribution of AAL-2 – Overcoming Gap 2.1

The research project of AAL-2 is meant to address the research Gap 2.1 identified in the technical annex of the grant agreement. Specifically, present meta-surfaces are typically assumed to provide ideal reflection coefficients and arbitrary phase shifts along the surface. However, such models are considered over-simplistic and lack reasoning from a physics point of view. For instance, practical meta-surfaces will exhibit a coupling between the reflection coefficients and the phase shifts. Thus, practical electromagnetic models are needed to unveil the actual performance limits of metasurface-based networks. At present, there exist no appropriate equivalent circuital models for the meta-surfaces, which can be used in communication theory. In order to overcome Gap 2.1, the research activities of AAL-2 focus on developing equivalent circuital models for meta-surfaces, which account for the properties of the unit cells (e.g. their material, size, and distance among reflecting elements), the angle of incidence and of reflection/refraction of the electromagnetic signals, and the size and locations of the transmitter and receivers with respect to the meta-surface. The proposed approach consists of introducing equivalent surface impedances for the intelligent surfaces under the assumption that their thickness is sufficiently small to be ignored in practice. This approach is aimed at unveiling unknown relations between the tangential electromagnetic fields at the two sides of the intelligent surface, which will allow communication theorists to mathematically treat them as electromagnetic discontinuities in space. The objective is to develop simple, but accurate, equivalent transmission models for reconfigurable intelligent surfaces, which allow identifying the size, inter-distance, and period of the metasurfaces and how this impacts the performance of wireless networks.

Within this context, at present, the research activity of AAL-2 have focused on two main lines of work, which are described below.

Comparison between the conventional known periodical anomalous reflectors. Reconfigurable intelligent surfaces propose a unique opportunity for the next generation of communication networks by designing reconfigurable reflectors that allow one to have real-time scanning properties and cover all possible areas for clients. In order to fulfill this mandatory need in future networks, the knowledge about all characteristics of different designs of reconfigurable intelligent surfaces is warranted. Most previous works in this field focused on the scattering properties of anomalous reflectors or just studied a few of these properties for a single, specific design goal. However, it is important to integrate all of these methods for a full comparison of prominent features of anomalous reflectors to notice in each scenario of interest which one of these methods provides the best performance. By performing a comprehensive, study we can select the best method for our purpose in a smart way and make our structure reconfigurable to operate in future networks. Therefore, this line work has focused on developing diverse design methods for planar anomalous reflectors (from classical phase gradient methods to approaches with perfect power efficiency) and then make a fair comparison (with the same structure shape and material properties) between them not only for scattering properties but also other noticeable aspects of a reflector-based metasurface e.g. the angular response as well as the far-field pattern for finite size structures.

Often reconfigurable structures are designed based on the conventional structures with the addition of tunable elements. Perhaps, the most classical approach to manipulate wave propagation is used in phased-array antennas. Because of the differences in ray propagation path lengths, the phase distribution at the antenna aperture can be tuned, so that all the rays can be tilted at the same angle. Generalizing this principle, similar functionality can be realized in a planar reflector if the reflection phase is made non-uniform over the surface, realizing a so-called reflectarray. Using this approach one can direct the reflected wave at will, beating the conventional law of reflection and realizing so-called anomalous reflection. The main drawback of this method is the efficiency at large angles. Impedance mismatch between the incident and the reflected waves becomes significant and it causes more scattering into parasitic propagating modes. In order to compensate the reduced efficiency at large angles, it was proposed to use active devices in the metasurface. It is worth mentioning, that average power produced by the surface would be zero, however some parts of it must produce energy and the other parts should absorb, which is quite impractical. Another approach proposed to use completely passive structures, where auxiliary surface waves are properly tuned. Optimization of the evanescent modes can be performed in several different ways: based on 1) Input (surface) impedance, also known as impenetrable impedance boundary condition (IBC). 2) Grid (sheet) impedance, that is also known as penetrable IBC. In this method, dispersion of the grounded dielectric layer is taken into account in addition to the input impedance. The optimization process in this case considers a more practical structure, that treats surface waves inside the substrate in a more complete way compared to the first method. In both these methods, locally periodical approximation is considered. It means that the reflection properties of a metasurface can be defined by ”local reflection coefficients” and it can be controlled by changing the geometrical parameters of the unit-cell. Strong coupling between the inclusions in the unit-cell makes this approximation rather rough which spoils theoretically predicted efficiency. 3) Direct optimization of the whole structure or non-local structures so that it allows to design the structure entirely, taking into account all features of the topology. The optimization does not rely on the input or grid impedance. Interestingly, Poynting vector along the surface becomes positive and negative, mimicking active-lossy behavior, although the structure remains completely passive. The drawback of this approach lies in the direct optimization, which usually requires heavy computational facilities and might also become time consuming. 4) Considering non-planar (power conformal) structures. AAL-2 has overviewed the first 3 methods in addition to the phase-gradient realization method.

Double functional reconfigurable intelligent surfaces for anomalous reflection and sensing angular of arrival. Creation of ISAC (Integrated Sensing and Communication) offers breakthrough advantages. Obviously, the enabling components of these future systems will be the future communication devices (especially antennas) that will be capable of not only radiating and receiving signals, but also sensing the propagation environment. This line of work of AAL-2 has developed the first prototypes of such ISAC components, based on novel reconfigurable intelligent surfaces. Metasurfaces are electromagnetically thin sheets with complex and tunable electromagnetic properties, designed for engineering wireless communication environments in real time. They consist of subwavelength controllable unit cells which can collectively redirect incoming waves into prescribed directions. Within the known paradigm, reconfigurable intelligent surface is reconfigured based on information about the positions of moving users and the propagation channel parameters that are obtained from some other devices and systems. AAL-2 has introduced, studied, and developed reconfigurable intelligent surface that will autonomously tune themselves to the optimal regime and, at the same time, determine the direction of arrival of waves illuminating the surface. The measured data about the propagation environment can then be encoded into the reflected waves and sent to other devices of the communication system for use in global optimization of the system performance. The use of subwavelength cells will allow us to overcome the fundamental limitations of reflectarrays and realize nearly arbitrary field transformations of reflected waves. AAL-2 has explored the opportunity to simultaneously perform sensing (localization and angle of arrival (AoA) estimation) and dynamic optimization of communication channels in a single reconfigurable intelligent surface. The driving idea is based on the fact that electrical currents on a metasurface that is optimized for reflection into the desired direction also contain currents that are in phase synchronism with the waves that are incident on the reflector. This is because the optimal currents also create waves that compensate for specular reflection. This fundamental property can allow us to find the arrival directions by calculating the spatial Fourier transform of the optimized current.

The approach has a straightforward implementation once the frequency of incident waves is known and does not require any pre-computed sets of data. Consequently, it can be used without modifications in most practical scenarios, e.g. when signals from an arbitrary number of transmitters impinge at the reconfigurable intelligent surface at arbitrary azimuthal and polar angles and with arbitrary polarizations. Reconfigurable intelligent surfaces automatically perform *in-situ* optimization of its surface impedance profile that results in the maximization of the signal reflected towards the prescribed receiver position (location of the receiver is assumed to be known). Thus, instead of executing sensing of AoA with subsequent readjustments of the reconfigurable intelligent surface local reflection coefficient distribution, with the present approach, the developed design is able to directly maximize the signal reception without the knowledge and regardless of AoA. Consider the reconfigurable intelligent surface illuminated at some unknown angle and the receiver is at an angle r. Before the optimization, the reconfigurable intelligent surface has some random impedance configuration which results in some complicated scattered fields and a non-uniform surface-averaged current distribution at the loads IL(x). Next, the reconfigurable intelligent surface performs optimization of the values of *lossless* load impedances $Z_{L,n}$ in each unit cell, which is equivalent to the optimization of the surface impedance profile. At each iteration of the optimization, the current distribution at the loads is measured, say IL(x), and its Fourier transform F{IL(x)}=IL($k_{||}$) is computed, where $k_{||}$ is the tangential wave-vector or spatial frequency. The goal of the optimization is to maximize the value of the specific spatial frequency of the current, that is expressed as in the formula below

$$IL(\omega/c \sin \theta r).$$

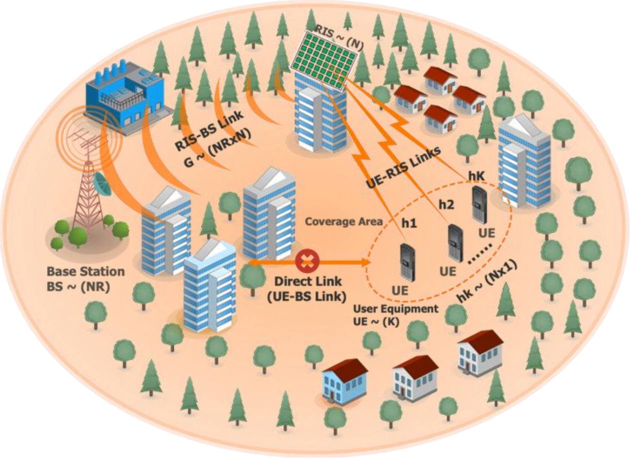
Such a current spatial frequency is responsible for the generation of a reflected plane wave at the desired angle θ_r. Remarkably, since all the load impedances are lossless ($Z^*_{L,n} =-Z_{L,n}$), maximization of this current spatial frequency automatically implies maximization of the efficiency of anomalous reflection of the reconfigurable intelligent surfaces, for arbitrary unknown angle of incidence. Interestingly, in the optimized case, the total current IL($k_{||}$) will include one stronger spatial frequency, that is,

$$IL(\omega/c \sin(\theta_{inc}),$$

that will be naturally generated and responsible for cancelling out the plane wave, specularly reflected from the ground plane of the reconfigurable intelligent surface. Current research activities are now focusing on how to tackle the aforementioned optimization problem.

2.2 Contribution of CNIT-1 – Overcoming Gap 2.2

The research project of CNIT-1 is meant to address the research Gap 2.2 identified in the technical annex of the grant agreement. Specifically, baseline resource allocation techniques for the optimization of networks empowered by reconfigurable intelligent surfaces are suboptimal and based on heuristics that do not allocate optimally the system radio resources. A novel optimization framework is needed to perform optimal radio resource allocation in metasurface-based networks at an affordable computational complexity. In order to overcome Gap 2.2, the research activity of CNIT-1 is focused on developing radio resource allocation algorithms that strike the best trade-off between performance and complexity. Novel optimization algorithms have been developed in order to jointly optimize the main communication performance of wireless networks, e.g. achievable rate, energy efficiency, latency, reliability, by merging diverse optimization frameworks, e.g. sequential optimization. Specifically, the research activity of CNIT-1 has considered the use of both passive and active reconfigurable intelligent surfaces, comparing their pros and cons as far the system achievable rate and energy efficiency are concerned. The considered setup is depicted in the figure below. In an uplink communication, the mobile, single-antenna, user equipments (UEs) communicate with a base station equipped with multiple (N_R >1) antennas, through a reconfigurable intelligent surface. The direct communication link has been assumed to be absent due to the presence of blockages, e.g. buildings.



In this context, the research activity of CNIT-1 has followed two main lines of work:

1) While the use of nearly-passive reconfigurable intelligent surfaces (i.e. without the use of any power amplifier) has been the first to have been proposed, more recently, the use of active reconfigurable intelligent surfaces has been put forth, in which reflection-type amplifiers are equipped on the surfaces in order to amplify the incoming signal. Clearly, while this is anticipated to provide gains in terms of achievable rate, it also leads to higher power consumptions, and thus the behavior of the energy efficiency is not clear and deserves to be investigated. In this context, CNIT-1 has developed provably convergent radio resource allocation methods to optimize both the achievable rate and, above all, the energy efficiency of the system, with respect to the allocation of the mobile users' transmit powers, the reflection coefficients of the reconfigurable intelligent surface elements, and the choice of the linear receive filters at the base station.

2) A second direction of investigation has been the consideration of reconfigurable intelligent surfaces with global reflection capabilities. Present intelligent surfaces are equipped with a number of reflecting elements that are individually capable of applying a reflection coefficient to the incoming electromagnetic signal. This scenario is referred to as local reflection, and in this case each reflecting element of the surface can apply a reflection coefficient whose modulus is at most one, for the case of passive surfaces. Instead, a novel type of reconfigurable intelligent surface has been put forth in [23], and is capable of global reflection constraints, i.e. each reflecting element can apply a coefficient that needs not be bounded by one, provided however, that the overall power reflected by the intelligent surface does not exceed the incoming power. In this context, CNIT-1 has developed provably convergent radio resource allocation methods to optimize both the achievable rate the energy efficiency of the system, with respect to the allocation of the mobile users' transmit powers, the reflection coefficients of the reconfigurable intelligent surface elements, and the choice of the linear receive filters at the base station.

With reference to the first line of work, the algorithms developed by CNIT-1 have employed the theoretical optimization tools of fractional programming, alternating optimization, sequential optimization, semi-definite relaxation, together with the general framework of convex optimization theory. This has allowed the development of two provably convergent resource optimization methods, which require only the solution of a sequence of convex optimization methods. Thus, the overall complexity of the proposed methods is polynomial in the number of optimization variables, and therefore the proposed methods lend themselves to being implemented in practical networks.

More in detail, the first method iteratively optimizes the UEs' transmit powers, the intelligent surfaces reflection coefficients, and the linear receivers at the base station. The transmit powers and reflection coefficients sub-problems are optimally solved by the sequential fractional programming method, while the optimal linear filters are identified as the linear minimum mean squared error receivers. Instead, the second method works by embedding the optimal linear receive structures in the objective functions (i.e. the system achievable rate and energy efficiency), and then alternatively optimizes the transmit powers and reflection coefficients. Both methods have been numerically tested in a realistic wireless setup by numerical simulation performed through the software MATLAB. Specifically, a cell of a wireless network has been considered, in which four UEs transmit over the same frequency block, thus interfering with one another. The base station is equipped with four antennas and the reconfigurable intelligent surface has N=100 reflecting elements. A communication bandwidth of B=20 MHz has been considered, with a maximum amplification power of the active intelligent surface of 10 W. The mobile users are randomly placed in an area with radius 100 m around the intelligent surface, while the base station is placed 50 m away from the surface. Path-loss effects with a power decay factor of 4 have been considered, while the fading component of all channels follow the Rice model, with Ricean factor equal to 4 for the channel from the intelligent surface to the base station and equal to 2 for the channels from the UEs to the intelligent surface.

The figure below shows the energy efficiency achieved by:

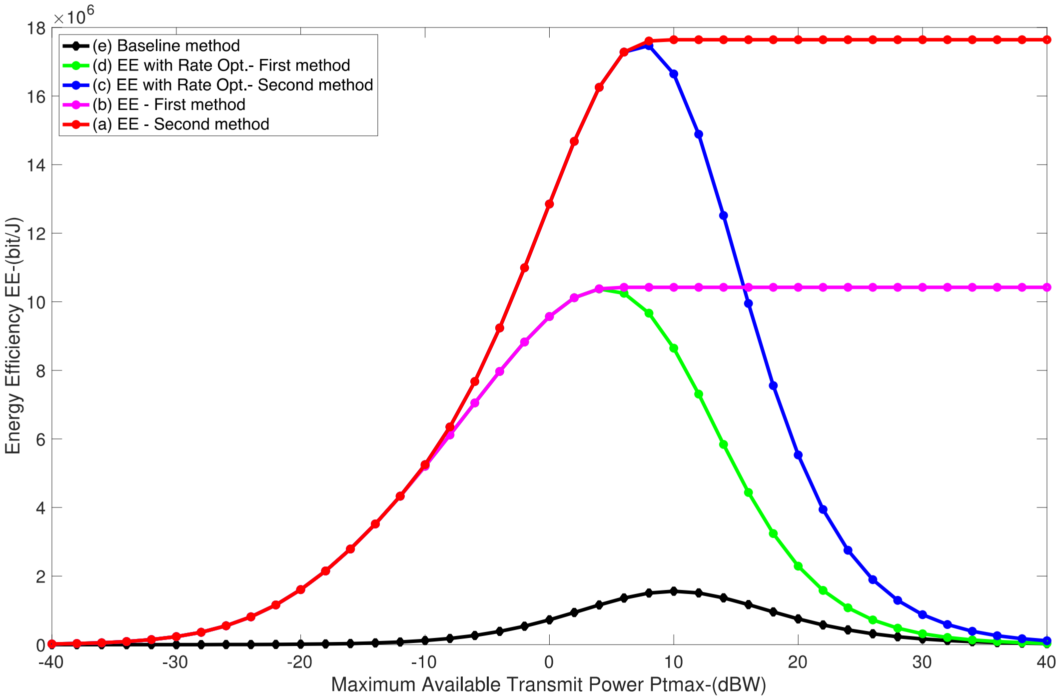
(a) maximizing the energy efficiency by the first developed optimization method.

(b) maximizing the energy efficiency by the second developed optimization method.

(c) the resource allocation obtained by maximizing the system achievable rate by the first developed optimization method.

(d) the resource allocation obtained by maximizing the system achievable rate by the second developed optimization method.

(e) uniform power allocation and random reconfigurable intelligent surface phases, i.e. the baseline energy efficiency that can be obtained without the developed optimization algorithms.



As expected, both developed methods (a) and (b) provide a huge gain over the baseline approach (e). Moreover, the second developed optimization method outperforms the first developed method. This is explained observing that the second method exploits the mathematical structure of the linear receive filters, whereas the first method does not. On the other hand, the second optimization method requires handling a more involved mathematical structure of the optimization problems, and thus requires a slightly larger computational complexity.

The following figure considers a similar scenario as in the previous figure, with the difference that the metric that is reported is the system achievable rate. Specifically, the figure below shows the achievable rate obtained by:

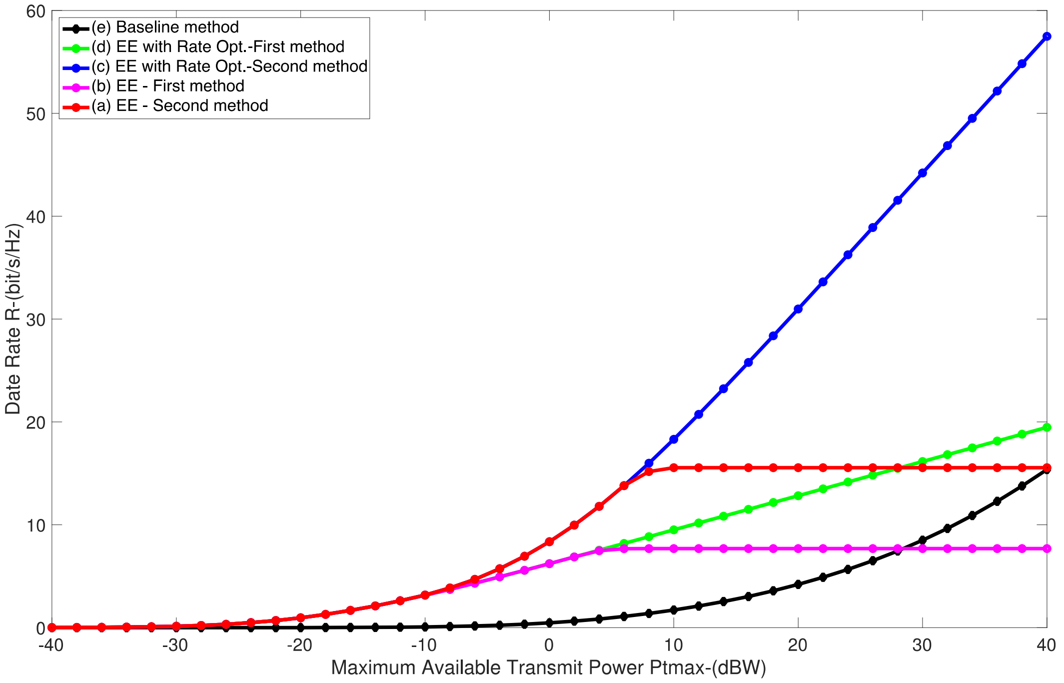
(a) maximizing the achievable rate by the first developed optimization method.

(b) maximizing the achievable rate by the second developed optimization method.

(c) the resource allocation obtained by maximizing the system energy efficiency by the first developed optimization method.

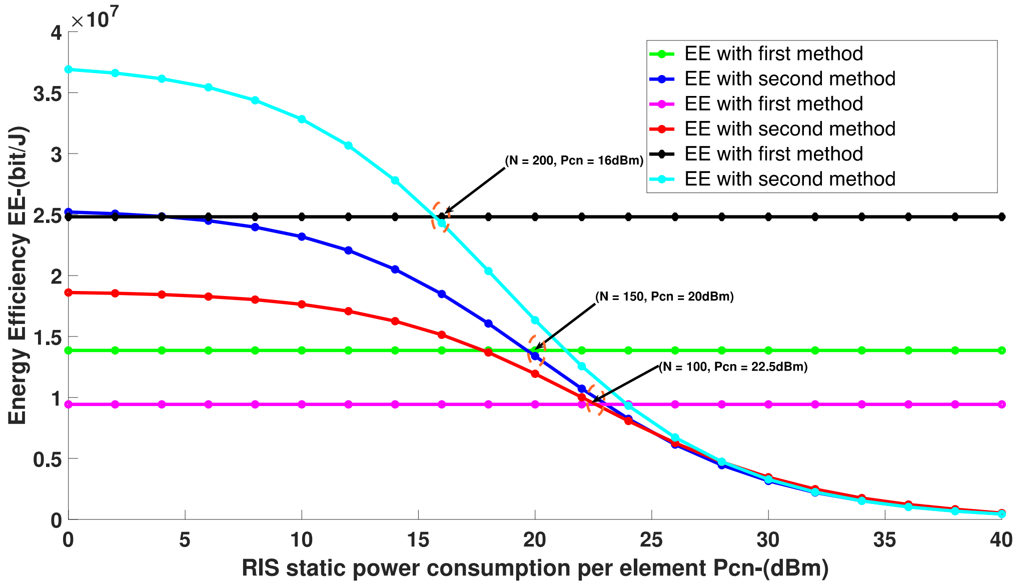
(d) the resource allocation obtained by maximizing the system energy efficiency by the second developed optimization method.

(e) uniform power allocation and random reconfigurable intelligent surface phases, i.e. the baseline achievable rate that can be obtained without the developed optimization algorithms.

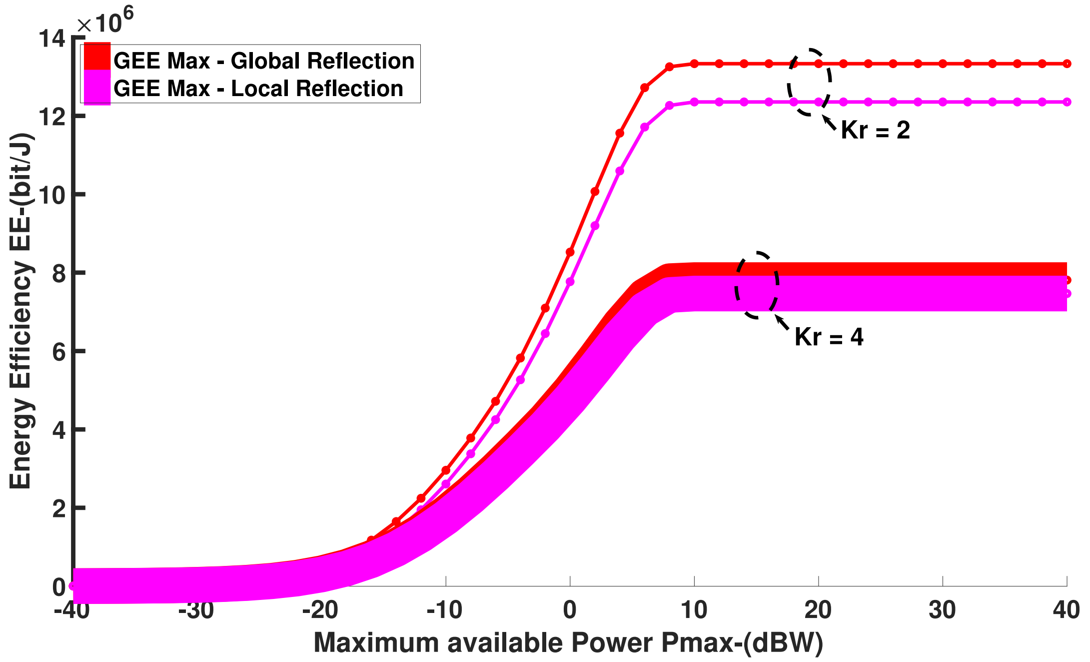


As for the previous figure, the developed methods largely outperform the baseline scenario, which shows the gains provided by the novel designs developed by CNIT-1. Moreover, again it is observed that the second optimization method performs better than the first one.

Finally, the figure below compares the energy efficiency obtained by considering active and passive surfaces. In both cases, the second algorithm has been considered, and then the resource allocation problems has been solved by considering a maximum power amplification of the intelligent surface of P_R=1 (for the passive case) or P_R>1 (for the active case). The illustrations report the energy efficiency versus the static power consumption $P_{c,n}$ of each reflecting element of the active intelligent surface, while a static power consumption of 0 dBm has been considered for each element of the passive surface. Thus, the results show by how much the power consumption of an active reconfigurable intelligent surfaces can increase, with respect to a passive surface, before it is no longer convenient to employ an active surface from an energy-efficient point-of-view. Indeed, eventually, as $P_{c,n}$ increases, the passive reconfigurable intelligent surfaces becomes more energy-efficient than the active one. Moreover, the crossing point is encountered for lower values of $P_{c,n}$ when the intelligent surface is equipped with more active elements N. Thus, as expected, there is a trade-off between the system energy efficiency and the number of elements of the active intelligent surface.



With reference to the second line of work, the same optimization algorithms described above have been shown to be able to handle the case of reconfigurable intelligent surfaces with global reflection constraints with global reflections, too. They have been tested in the same numerical setup described above, to assess the energy efficiency and achievable rate that can be provided. The figure below compares the system energy efficiency obtained by the second developed optimization method with local and global reflection constraints. The comparison is made for two different values of the Ricean factor K_r, which shows that global reflection provides better gains when a weaker line-of-sight is present.



The research activities of CNIT-1 have led to the following publications:

- A. Zappone, M. Di Renzo, R. Fotock, *Surface-Based Techniques for IoT Networks:Opportunities and Challenges*, IEEE IoT Magazine, 2022, in press.

- R. Fotock, A. Zappone, M. Di Renzo, *Energy Efficiency in RIS-Aided Wireless Networks: Active or Passive RIS?*, submitted to IEEE ICC 2023.

- R. Fotock, A. Zappone, M. Di Renzo, *Energy Efficiency Maximization in RIS-Aided Networks with Global Reflection Constraints*, submitted to IEEE ICASSP 2023.

2.3 Contribution of CNRS-1 – Overcoming Gap 2.3

The research project of CNRS-1 is meant to address the research Gap 2.3 identified in the technical annex of the grant agreement. Specifically, the performance and design of wireless networks is currently based on the Shannonian "mathematical theory of communications". In metasurface-based networks this is not enough anymore. It is necessary, in particular, to take into account how the radio waves interact with metasurface-coated objects, and with their specific electromagnetic properties. New electromagnetic-compliant theoretical paradigms are needed to overcome these fundamental limitations. To overcome Gap 2.3, a new mathematical and physics-compliant theory of communications is to be developed, generalizing Shannon's theory of communications to account for Kirchhoff's theory of diffraction. The considered approach consists of modeling transmitters and receivers as distributed sources of electrical/magnetic charges that emit waves, which interact with the objects, and are reflected, refracted, and scattered. By using the tool of Kirchhoff's theory of diffraction based on Green's functions, the objective of this research activity is to devise new mathematical models for estimating the electromagnetic field scattered by large-size and small-size reconfigurable intelligent surfaces. The objective is to identify so far unknown operating conditions under which reconfigurable intelligent surfaces act as anomalous mirrors or diffusers, for multiple applications (e.g. beamforming, broadcasting). Exact analytical frameworks that can be efficiently computed numerically by system-level simulators, and closed-form approximations that are tractable for mathematical optimization will be devised. To this end, the stationary-phase methodology based on physics and geometric optics will be employed [24].

Given challenges and limitations in 5th generation (5G) networks, novel and innovative technologies are needed in 6th generation (6G). Reconfigurable intelligent surfaces represent one of the essential paradigms, for their ability to provide high capacity, low cost, low energy expenditure, and low complexity. Above all, reconfigurable intelligent surfaces are capable of handling the randomness of the wireless channel. Various coding, diversity, and beamforming approaches are applied to cope with this problem. Thus, the barrier of high data rate, energy-efficient, and demand for massive connectivity motivated researchers to investigate the idea of using reconfigurable intelligent surfaces in communication systems. Deploying reconfigurable intelligent surfaces on a vast scale in future wireless networks will help increase the capacity growth of the system. Integration of reconfigurable intelligent surfaces in existing wireless network make a novel hybrid architecture consisting of both active and passive units.

Currently, wireless networks designs based on reconfigurable intelligent surfaces mostly disregard the peculiar electromagnetic characteristics of the surfaces, which are instead key, and thus need to be optimized. The research activity of CNRS-1 is focusing on developing a new framework consisting of both mathematics and physics theory applied to metasurface-based wireless networks, while keeping in mind Shannon's theory of communication and incorporating Kirchhoff's theory of diffraction. The proposed approach comprises designing transmitter and receiver as a distributed source of electric/magnetic charges that emit electromagnetic waves, further interacting with the wireless communication environment by reflecting, refracting, and scattering incoming electromagnetic signals.

This research activity is developing a new electromagnetically consistent mathematical model to estimate the fields scattered by small and large size reconfigurable intelligent surfaces. The conditions upon which a metasurface behaves as a mirror or a diffuser are identified, while improving different applications such as beamforming, multicasting. Furthermore, tractable, closed-form mathematical expressions that approximate the exact analytical framework are being developed, which will enable practical mathematical optimization of the major performance metrics of wireless networks. To this end, a stationary phase-based methodology based on the principle of physics and geometric optics is being employed.

To elaborate, two main optimization approaches are being investigated [25], [26]:

1. Global design
2. Approximated Global Design – Purely Reactive

In the global design the average power flow in term of Surface Poynting Vector is taken as an objective function while fulfilling the Helmholtz constraint. So, the optimization variable in Global design problem is surface impedances corresponding to each reflecting element of the reconfigurable intelligent surface.

The second approach operates in synergy with the first one. A purely reactive surface is considered, which is closer to the practical operation of reconfigurable intelligent surfaces. The real part of surface is enforced to be zero and the surface impedances that are adopted are taken from the global design problem. Both global and approximated design problems are subject to Helmholtz's condition to check the feasibility. In agreement to Floquet's theorem, both the Global and approximated designs show that practical metasurfaces reflect an incoming wave not only in the intended direction that is designed, but also towards different, spurious directions. The inclusion of additional constraints in the design problem of the radiation pattern of the reconfigurable intelligent surface is being investigated to suppress these spurious reflections.

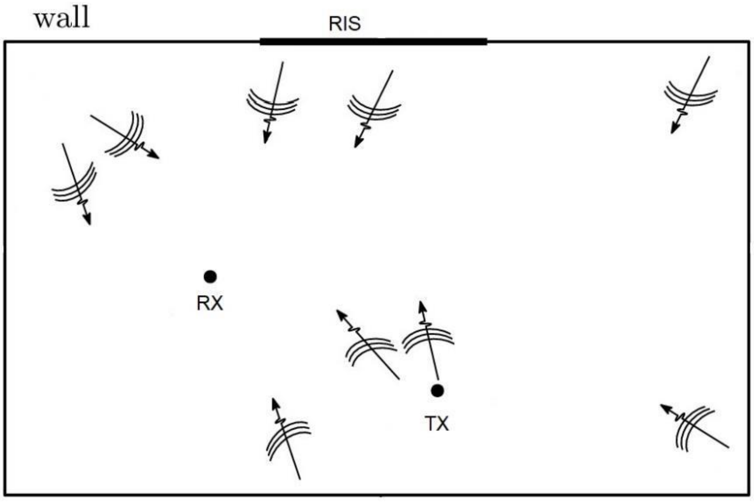
As far as the details of the adopted optimization methods are concerned, the current approach is based on the development of mathematical optimization algorithms, base on the framework of the augmented Lagrangian multiplier. The method under investigation consists of two steps [27], [28]:

1. The minimization of the augmented Lagrangian function given by optimizing the surfaces impedance.
2. Update of Lagrangian multiplier and penalty parameter to ensure the feasibility of the derived solution.

2.4 Contribution of UPF-1 – Overcoming Gap 2.4

The research project of UPF-1 is meant to address the research Gap 2.4 identified in the technical annex of the grant agreement. Specifically, since reconfigurable intelligent surfaces enable the customization of the propagation channels, the traditional Shannon information theory based on channel transition probabilities does not apply anymore, because not only the input distribution, but also the channels can be optimized. This requires extending the traditional notion of channel capacity by developing new information-theoretic tools specifically conceived to account for the possibility of optimizing wireless channels. To overcome Gap 2.4, the research activity of UPF-1 is focused on unveiling the ultimate performance limits of wireless networks empowered by reconfigurable intelligent surfaces, in which data can be encoded into the state of the reconfigurable intelligent surfaces (besides the transmitters). This innovative use of reconfigurable intelligent surfaces cannot be tackled with conventional information-theoretic tools. To this end, the considered approach consists on employing a new information-theoretic formulation that models the reconfigurable intelligent surfaces as systems with action-dependent states, since their configuration determines the state of the system itself. The ultimate objective of this research is to unveil the ultimate performance limits of wireless networks empowered by reconfigurable intelligent surfaces and to understand the potential gain of using reconfigurable intelligent surfaces for encoding information under practical operating conditions (e.g. under finite-rate control channels and finite-bandwidth feedback links).

Within this context, at present, the research activity of UPF-1 is focusing on formulating and analyzing theoretical tools that are capable of modeling indoor wireless environments empowered by reconfigurable intelligent surfaces. The main objective is to understand the potential gains and to unveil the ultimate performance that can be obtained by controlling the electromagnetic properties of the wireless environment through the design of the reflection coefficients applied by the reconfigurable intelligent surfaces. The current approach is based on deriving electromagnetic-compliant expressions of the signal-to-noise-ratio (SNR) for indoor wireless networks in which the reconfigurable intelligent surfaces are embedded in the walls. Deriving an electromagnetic-compliant expression of the SNR allows deriving corresponding expressions of all major performance metrics of commonly used in wireless communications, e.g. achievable rate, energy efficiency, latency, and reliability. To this end, the adopted approach is to assume a wave propagation in a 2D medium with an inhomogeneity created by an enclosed rectangular shape. The rectangular room represents a material with a complex refractive index. One side of the room partially embeds a reconfigurable intelligent surface. There is one transmitter and one receiver in the room, as shown in the figure below. Also, the effects of the diffraction occurring at the corners of the room are negligible as long as we assume the room dimensions are much larger than the wavelength.



In a free-space environment, wave propagation is described by a linear and space-invariant system that is fully described by its impulse response. In a 2D medium, a cylindrical wave generated at the transmitter and measured at the receiver is the first kind of zero order Hankel function. The classical approach for computing the received power is to formulate boundary conditions. Boundary conditions are described by the image theorem, which states that the reflection elicited by an infinite planar surface may be reproduced precisely by a mirrored image of the source concerning the surface. The image theorem yields an infinite number of image sources for the rectangular room. Despite the infinite imaginary sources being of mathematical relevance, a loss is inherently introduced at each step of the image-forming process in a realistic setting, which allows truncating the series up to a specific order.

The main difficulty about modeling the scenario in the figure above is that it is not possible to replace the imaginary transmitters from the top wall for computing the received power as long as a partial part of this wall is covered by the reconfigurable intelligent surface. While retaining the result on the essential number of image sources, an electromagnetic tool that can evaluate the effect of the top wall on the received power accurately is required. Due to the linearity of wave propagation, the wave field generated by all added images can be studied separately for all possible orders. Hence, the considered approach focuses on the first-order image, while the remaining images follow similarly by symmetry. Only the reflection produced by the wall as if no reconfigurable intelligent surface were involved is considered and it is assumed that the wall is infinitely long.

Next, the previous study is extended to the practical case in which the reflection happens either off a wall with finite dimension, or the reconfigurable intelligent surface generates the electromagnetic field. The aim is to replace the imaginary sources with secondary currents impressed on the top border of the room to formulate the received power from the top wall and extend it to all imaginary sources. Both the transmitter and receiver are assumed to have a single omnidirectional antenna, and a narrow-band system with flat-fading channels is considered. Using the reconfigurable intelligent surface on the top wall, the goal is to maximize the signal-to-noise ratio by optimizing the phase shifts applied by the passive elements of the reconfigurable intelligent surface.

The channel between the transmitter and the receiver contains two terms. The first term is the part of the channel that can not be controlled, which is the signal from the direct link and the impinging signal from the walls covered by a material. The second term is the effect of the reconfigurable intelligent surface that can be controlled to affect the phase of the received signal. There are different optimization methods that are being investigated to maximize the received power. In particular, the phases of the reflecting elements of the metasurface are designed in a way that all received signals from the elements of the reconfigurable intelligent surface have the same phase as the first coefficient of the channel, so as to maximize the received power.

3. Conclusions

The research activities concerning Task 1.2 are progressing as planned. All 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:

AAL-2 has developed novel electromagnetic-compliant models for wireless networks employing reconfigurable intelligent surfaces. According to what is outlined in the technical annex of the grant agreement, the considered approach is based on the introduction of equivalent surface impedance, assuming the reconfigurable intelligent surface can be considered a bi-dimensional object. Initial theoretical models are already available and corresponding research articles are in preparation. In the second half of the project, the research activities of AAL-2 will focus on the refinement of the developed models, and on the derivation of suitable approximation to enable mathematical analysis and optimization with reduced complexity.

CNIT-1 has developed novel radio resource optimization techniques for the maximization of the achievable rate and energy efficiency of wireless networks employing reconfigurable intelligent surfaces. These novel results have led to an accepted journal publication and two submitted conference publication. One more journal publication is in preparation based on the contributions of the two conference articles. The achieved results have provided the optimized energy efficiency and rate that can be attained in wireless networks thanks to the use of reconfigurable intelligent surfaces. This is in line with the objective of Task 1.2 of WP1. In the second half of the project, the research activities of CNIT-1 will focus on the optimization of networks employing reconfigurable intelligent surfaces, assuming only partial knowledge of the propagation channels.

CNRS-1 has developed novel electromagnetic model for signal propagation in the presence of reconfigurable intelligent surfaces. According to what is outlined in the technical annex of the grant agreement, the considered approach leverages Kirchhoff's theory of diffraction, overcoming the traditional Shannon theory. Transmitters and receivers are modeled as distributed sources of electrical/magnetic charges that emit waves, which electromagnetically interact with the surrounding objects. Initial theoretical models are already available and corresponding research articles are in preparation. In the second half of the project, the research activities of CNRS-1 will focus on the refinement of the developed models, and on the derivation of low-complexity approaches to solve the optimization problems formulated so far.

UPF – 1 has developed novel SNR models that are tailored to the presence of reconfigurable intelligent surfaces in a wireless environment. This represents the basis for the derivation of a mathematical expression of achievable rate, energy efficiency, latency, and reliability in networks employing reconfigurable intelligent surfaces, and allows for the characterization of the ultimate performance bounds of networks with reconfigurable intelligent surfaces. In the second half of the project, the research activities of UPF-1 will focus on the refinement of the developed SNR models, also considering the presence of multi-user interference.

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