ARIADNE

ARIADNE Project Results on RIS

Tailoring Application of Reconfigurable Intelligent Meta-Surfaces in future Beyond 5G Networks

Newsletter 02/2022

The ARIADNE PROJECT

Artificial Intelligence Aided D-band Network for 5G Long Term Evolution

https://www.ict-ariadne.eu

Editorial

In recent three years of its life time, the ARIADNE project investigated various aspects of application of the Reconfigurable Intelligent meta-Surfaces (RIS) in future beyond 5G wireless telecommunications networks. The project considered channel modelling issues related to the RIS application, established a new corresponding framework "beyond Shannon" to characterize RIS aided networks, investigated application of Artificial Intelligence and Machine Learning enabling control of such complex systems as well as proper positioning of the RIS elements across network coverage areas, and much more.

In this publication, we summarize the main achieved project results proposing solutions for future deployment of the RIS aided wireless network and refer also to detailed related project deliverables and publications.

Halid Hrasnica, Eurescom

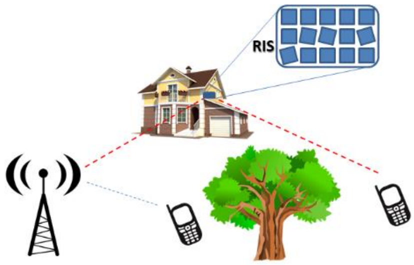
Introduction and background

Reconfigurable Currently used 6 GHz bands in the mobile communications are reaching their limits to respond to always more demanding services and applications as well as continuously increasing number of served end users and devices. Therefore, the new communications networks are being designed to utilize higher frequency bands and with it increase the overall network capacity and data rates, such as the D band (130 – 174.8 GHz) mainly used for wireless backhaul and fronthaul which are also considered for short range communications in radio access networks and, as such, are investigated in the scope of the ARIADNE project "Artificial Intelligence Aided D-band Network for 5G Long Term Evolution", funded by the European Horizon 2020 research and innovation program.

The D bands enable LOS (Line of Sight) communications in outdoor environments, where NLOS (Non-Line of Sight) communications, where no direct radio link can be established between a sender and a receiver, are possible in indoor environments, due to in some cases convenient signal reflections. On the other side, the outdoor NLOS communications is difficult to achieve, due to changing propagation characteristics caused by weather conditions (e.g. rain, fog), or unpredictable signal reflections. A kind of conventional NLOS communications can be ensured by deploying so-called relay nodes, which are actively repeating received signal, so that certain areas can be covered, enabling the NLOS communications scenarios. However, the relays as active network elements need power supply leading to increased power consumption of the overall communications system as well as some signal processing capabilities contributing to higher costs of implementation of the relays-based solutions.

This is one of the reasons to look for passive elements serving as specular reflectors, e.g. dielectric mirrors, which do not need (significant) power supply and the processing capabilities. However, such passive reflectors are non-reconfigurable, which means that directions they are reflecting the radio signals are not dynamically adaptable, so that dynamic beam shaping is not possible. To ensure it, the reflectors must be able to change angels of their positions, so that the radio beams can be directed as needed. This requirement can be fulfilled by application of so-called Reconfigurable Intelligent Surfaces (RIS), which are made of materials with appropriate characteristics to arbitrarily shape electro-magnetic wave front, to reflect, refract, or absorb the waves as needed, which can be dynamically controlled to support specific communications requirements. Thus, the RIS can be attached at an appropriate point (see figure below), to ensure communication for the case where a direct link does not exist, e.g. due a natural obstacle, moving objects, etc.

The future communications services and applications will have very high requirements on the networks, demanding also a highly dynamic control of the RIS based wireless network infrastructure. A full optimization for dynamic control of the RIS based networks could be achieved by accurate mathematical models, which are however very complex and therefore not feasible to be efficiently used for the purpose. On the other hand, Artificial Intelligence (AI) technologies, in particular Machine-Learning (ML) techniques learning from a large amount of data, without being explicitly programmed, might be able to ensure network respond to current data traffic situations, where the RIS structure is configured as needed as well as dynamically adapted in accordance with the changing demand of currently used communications services and applications. Furthermore, AI/ML should also be able to predict overall situation in a network or a network segment and react accordingly by configuring dynamically the RIS infrastructure.



RIS attached to a house enabling communications avoiding obstacles

Thus, the main advantage of the RIS usage is that they are so-called almost passive elements involving very low-power electronics, representing an environment friendly and low-cost solution which can be easily deployed at walls, ceilings, billboards, lampposts, event vehicles, etc. On the other hand, the absence of power amplifiers and digital signal processing capabilities at RIS naturally pose some design challenges and a trade-off consideration between the coverage range of the surface, its size, and number of RIS elements that need to be deployed on it. Furthermore, research on channel modelling and characterization, related signal processing aspects, physical RIS design, etc., is still in progress. Finally, the RIS Control and Management remain a big challenge in front of related research and innovation activities, where the ARIADNE project is well positioned to provide significant results and outcomes, presented along the following sections.

The RIS Design

The RISs can be realized in different ways, for instance, by utilizing large phased antenna arrays or applying surfaces made of metamaterials. The both solutions aim at the same goal, to modulate the incoming and thereafter reflected electromagnetic waves in order to steer the reflected wave. The wanted reflection properties are obtained by individually controlling the RIS elements or the entire metasurface substructures. Knowing their behavior exactly, RIS steering algorithms can ensure maximum beamforming gain and give the best possible transmission conditions.

From observing the rising interest in Artificial Intelligence, it is also anticipated that radio technologies will be impacted by this trend at the physical layer in future. This is motivated by the idea that link level information may improve or enhance AI predictions on reliability, outage and performance of wireless communication networks further. For this reason, cognitive functions and reconfiguration possibilities become more and more important, which have been neglected at THz frequencies so far. The development of metasurfaces for THz frequencies beyond 100 GHz is an open research field so far and the physical layer implementation is in its childhood. ARIADNE has started to classify and screen candidates that are attractive from the functional and fabrication point of view. Prototypes for planar and corrugated structures were studied with focus on their frequency selective properties. The frequency selective aspect aligns with research on multi-band / broadband radio technologies covering multiple channels from 130 – 175 GHz.

Novel reflecting surfaces – metasurfaces - can be implied for dramatic enhancement of new generations network coverage. Known methods for theoretical characterization and design of such reflectors are based on a so-called conventional phase-gradient reflectors (reflect-arrays) approach. However, this approach has a number of limitations, leading to reduced reflection efficiency and overestimations of the channel characteristics. In ARIADNE, we apply a novel method of nonlocal optimization for metasurface reflectors, that allows us to obtain theoretically perfect reflection for the desired functionality. Using this method we develop and investigate reflection from finite-sized reflectors mounted on walls with realistic scenarios of prospective indoor communications.

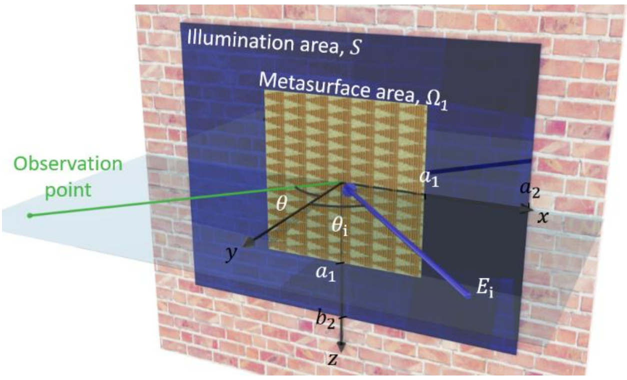


Figure: Schematic representation of a finite-size reflective metasurface mounted over an impenetrable wall. The incident signal, created by a directive antenna, is reflected towards the desired direction

As a particular example, we have developed an analytical model of far-field scattering from anomalously reflecting metasurfaces of a finite size and discussed the features of reflected fields that cannot be found using existing models. Another analysis was focused on clear physical understanding of scattering from these metasurfaces illuminated from different directions. Our analytical results are supported by full-wave simulations.

As a final goal within this project, our work is targeted on an indoor demonstration of the developed and experimentally realized metasurfaces for the next generations of wireless communications systems, as presented above.

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Beyond Shannon Framework

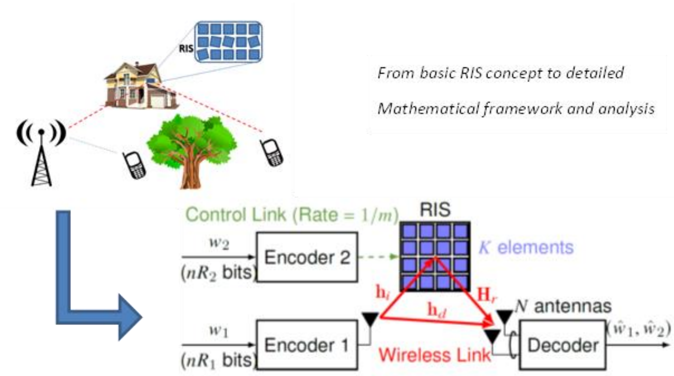
The ARIADNE project has been transforming the conventional networking system concept of a universal resources manager into a fully adaptive connectivity provider, in accordance with transmission channel and environmental characteristics, dynamic user and application requirements, and the users' mobility patterns. Here, the RIS implementation provides a possibility to modify the propagation environment and differently from the conventional networking approach, to consider the environment as a dynamic variable, in order to provide good signal quality also in NLOS situations.

However, the RIS-aided communications require a joint optimization of the entire considered wireless communications environment, which includes not only modeling and optimization of input signals, but also the entire changing and adaptive communications environment. The main challenges for establishing the novel communications framework – beyond Shannon – are to ensure appropriate and accurate channel characterization and modelling, explore wave/beam-forming system capabilities, estimate blockage in the system, and more. This requires new approaches for system optimization and evaluation involving Artificial Intelligence and Machine Learning techniques to ensure programmable system design.

The ARIADNE project considers passive RIS structures with the possibly adjustable elements. The investigations have confirmed that with adequately sized RIS elements, it is possible to outperform relay-aided systems in terms of data rates and energy efficiency. The initial theoretical analysis showed that a significant capacity gain can be achieved by introducing a novel signaling approach. It is based on joint information encoding for transmitted and RIS reflected signals, including their joint optimization. However, more accurate channel estimation is needed to ensure the needed capacity gain.

A first system coverage evaluation was carried out to extract an end-to-end path gain formula, assuming a full knowledge of the system parameters at Access Points (AP) and RIS, to find out the optimal phase shift of each of the Reflection Units (RU) at RIS, estimate minimum AP transmission power ensuring full coverage, including elaboration on losses caused by molecular absorption in the system environment.

Furthermore, the optimal RIS placement with respect to the position of the transmitter and receiver has been investigated. To answer this, we firstly computed the end-to-end received power and SNR under an RIS of arbitrary size. Subsequently, we provided closed-form approximate expressions for the cases of the RIS being either much smaller or larger than the transmit beam footprint at the RIS plane. Finally, based on the resulting SNR expressions, we analytically derived the optimal horizontal RIS placement that maximizes the end-to-end SNR. The analytical outcomes, which have been validated by Monte-Carlo simulations in various scenarios, reveal that:



1)When the transmission beam footprint at the RIS plane is much larger than the RIS size, the optimal RIS placement is either close to the TX, RX, or the middle of the TX-RX horizontal distance, depending on the system parameters;

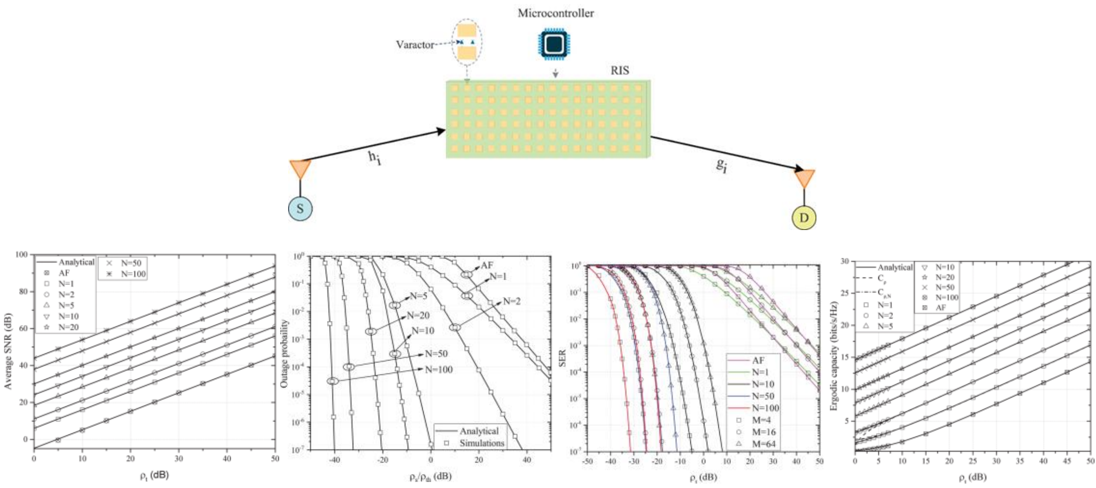
2)When the footprint is equal to or smaller than the RIS size, the optimal RIS placement is close to the RX. Such outcomes can be readily used by the system designer to properly deploy RISs in a way that the system performance is maximized.

In addition, a line of works has started targeting the possibility of supplying the energy consumption needs of the RIS through wireless energy harvesting from information signals. Towards this, we first identified the main RIS power-consuming components and then proposed an energy harvesting and power consumption model. Furthermore, we formulated and solved the problem of the optimal RIS placement together with the amplitude and phase response adjustment of its elements in order to maximize the signal-to-noise ratio (SNR) while harvesting sufficient energy for its operation. Finally, numerical results validated the autonomous operation potential and reveal the range of power consumption values that enables it. The results from this study can help the system designer identify the design requirements of future ultra-low power components in order to materialize the vision of autonomous RIS operation.

A theoretical framework to analyze the performance of RIS-assisted wireless systems

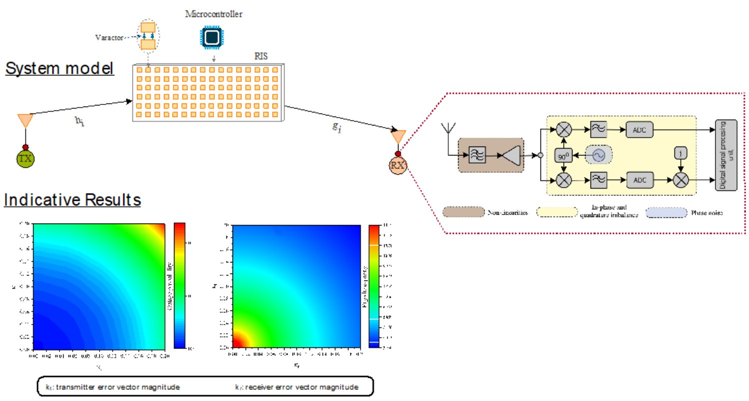
Despite of the paramount importance that RIS-assisted wireless systems are expected to play in B5G setups, their performance has been only assessed in terms of symbol error rate (SER) lower-bounds. Likewise, regardless of their similarities with the amplify and forward (AF)-relaying systems, no analytical comparison between RIS-assisted and conventional AF-relaying wireless systems has been conducted. Motivated by this, ARIADNE focused on presenting the theoretical framework that quantifies the performance of the RIS-assisted wireless system. Moreover, an analytic comparison between the aforementioned wireless systems, in terms of average signal-to-noise-ratio (SNR), outage probability (OP), SER, and ergodic capacity EC was conducted.

As depicted in the following figure, for the RIS-assisted wireless system, we consider a scenario, in which a single-antenna source (S) node communicates with a single-antenna desitnation (D) node through a RIS, that consists of N meta-atoms. Our results revealed that as the number of MSs increases, the diversity gain and order also increase; hence, the performance of the RIS-assisted wireless systems improves. Additionally, interesting design observations were extracted. For example, it was reported that as the number of MSs, from which a RIS consists, doubles, the average e2e SNR increases for approximately 6 dB, and the EC by about 2 bits/s/Hz. Finally, it became evident that, in general, realistic RIS-assisted wireless systems clearly outperform the corresponding AF-relaying ones in terms of average SNR, OP, SER, and EC.



On the impact of transceiver hardware imperfections on the performance of RIS-assisted wireless systems

Scanning the technical literature, we can easily observe that most of the published contributions in the area of RISs neglect the impact of hardware imperfections. This motivated ARIADNE to present a general model to accommodate the impact of transceiver impairments on RIS-assisted systems. This model also takes into account the effect of fading as well as the RIS size. Building upon this model, we extracted the instantaneous signal-to-noise-plus-distortion-ratio (SNDR), and we derived novel closed-form expressions for the outage probability of RIS-assisted wireless systems. These expressions can quantify the outage performance degradation due to hardware imperfections and reveal that in order to achieve an acceptable outage probability, the spectral efficiency of the transmission scheme should be constrained by a hardware imperfection-dependent limit. As a benchmark, we revisit the outage probability for the special case in which both the TX and the RX are equipped with ideal RF front-ends. Moreover, we provide a diversity order analysis that reveals that the diversity order of RIS-assisted wireless systems depends only from the number of RIS's RUs. Additionally, we present a low-complexity closed-form upper bound for the ergodic capacity of RIS-assisted wireless systems. Finally, ergodic capacity ceilings are extracted for the cases in which the signal-to-noise-ratio (SNR) and/or the number of RIS's RUs tend to infinity.



As illustrated in the previous figure, we considered a scenario in which a single-antenna TX node communicates with a single-antenna RX node through a RIS, which consists of N MAs. It was assumed that, due to blockage, no-direct link between TX and RX can be established. Our results manifested the detrimental impact of transceiver hardware imperfections on the outage and ergodic capacity performance of these systems. In more detail, they revealed that there exists a specific spectral efficiency limit, which sorely depends on the level of transceiver hardware imperfections, after with the outage probability becomes 1. Moreover, the importance of accurately modeling the level of transceiver hardware imperfections when evaluating the performance of such systems is reported. Likewise, it is highlighted that there exists a capacity ceiling that is independent of the number of RIS's MAs; however, it is determined by the TX and RX error vector magnitudes (EVMs). This ceiling cannot be crossed by increasing the transmission SNR or altering the propagation medium characteristics. This is an RIS-assisted wireless system constraint that is expected to influence future designs.

Impact of beam size on the performance of RIS-aided links

In a conventional LoS link, the beam travels from the Access Point (AP) directly to the User Equipment (UE) with increasing width (subject to free-space propagation) and therefore with decreasing power density, which can be further reduced by possible atmospheric absorption and scattering. As a result, for certain emitted beam power, the narrower the beam-width at the UE, the higher the power density and the more the power that can be received by the UE. However, when an intermediate re-radiating element, such as a RIS, comes into play, this intuitive picture can change entirely. The reason is that the RIS is effectively a secondary antenna; it is driven by the incident field from the AP and is re-emitting a secondary beam (towards the UE), the propagation characteristics of which depend on both the incident power density on the RIS and the illuminated area. In this context, the size of the incident beam footprint relative to the RIS size plays crucial role on the RIS performance. For low AP antenna gain, the incident beam is relatively wide and can illuminate the entire RIS; therefore, the incident power residing beyond the RIS surface cannot be captured by the RIS, leading effectively to power loss. Intuitively, to compensate for the lost power, the AP antenna gain must be increased, in order to reduce the area of the AP beam footprint on the RIS and achieve the utilization of the entire AP beam. Simultaneously, the power density of the beam will increase, as now the same incident power will be concentrated in a smaller region on the RIS, and more power is expected to be received by the UE. However, a smaller AP footprint will lead the secondary beam (from the RIS to the UE) to undergo stronger spreading in air, subsequently reducing its power density and possibly leading to the opposite result.

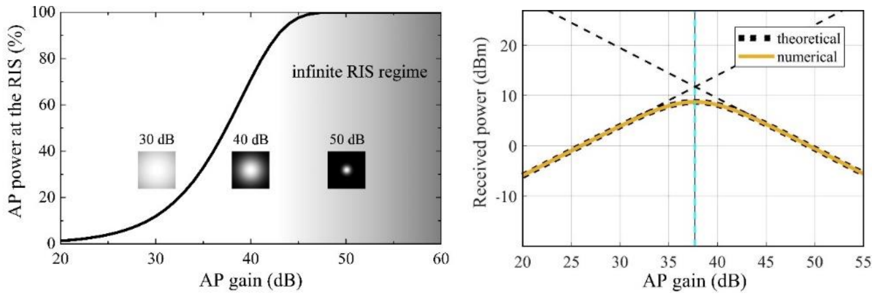


Figure: Power captured by the RIS (left) and power received by the UE (right), as a function of the AP antenna gain

The insets on the left show the AP beam footprint on the RIS for 30 dB, 40 dB and 50 dB AP antenna gain. With increasing AP gain more power is captured by the RIS and the power received by the UE increases. For very narrow AP beam footprint, however, it is possible that higher AP antenna gain leads to the opposite outcome.

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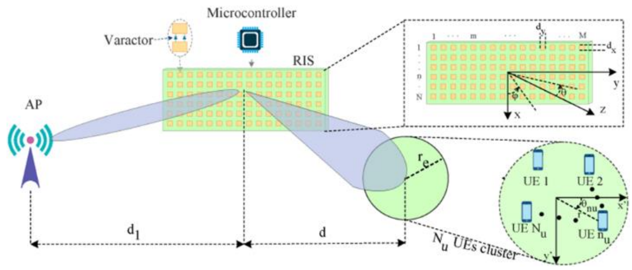
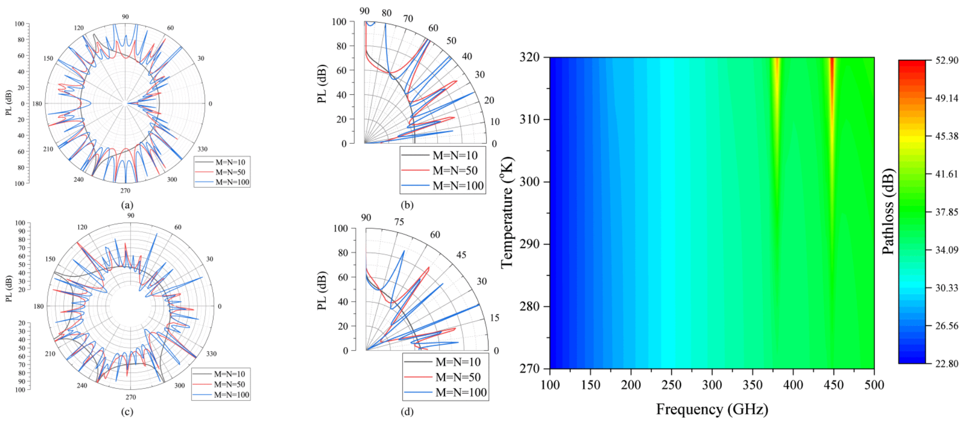
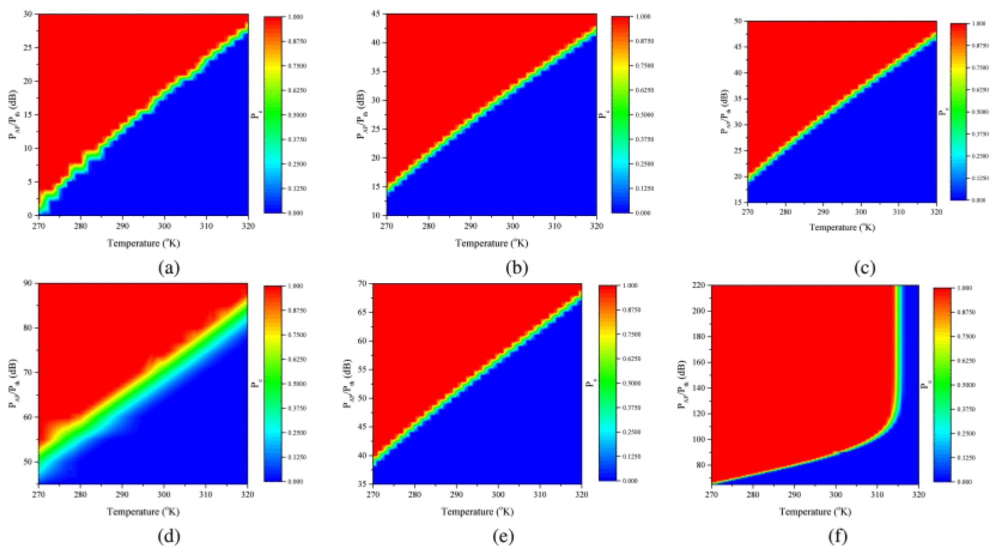
Coverage analysis of RIS-assisted THz wireless systems

According to the international telecommunication union (ITU), the global mobile traffic is expected to continue its exponential growth, reaching 5 zettabytes per month by 2020. This increase is driven by emerging data rate hungry applications, like virtual, augmented and extended reality, virtual presence by means of holographic projection, autonomous vehicles, and others. Looking forward to the sixth generation (6G) era, two main approaches have been identified as candidate technology enabler to support these unprecedented traffic demands. The first one is to exploit higher-frequency bands, with emphasis to the terahertz (THz), while the second one lies to the use of reconfigurable intelligent surfaces (RISs) capable of alternating their electromagnetic properties and thus devising a beneficial wireless propagation environment.

Scanning the open technical literature, we were able to identify only a few published works that examine the use of RIS in THz wireless systems The main reason behind this is the lack of tractable channel model for RIS-assisted systems operating in the THz band that accommodates both the building blocks of such systems and the particularities of the THz band. In more detail, this model should take into account the transceivers' antenna gains as well as their position in respect to the RIS position, the transmission frequency, the characteristics of the reflection units (RUS), namely number and dimensions of reflection elements, reflection coefficients, antenna patterns and phase shifts of each one of the RU, as well as the environmental conditions, while being tractable in order to become a useful tool for analyzing the performance of such systems. Motivated by this, ARIADNE focused on covering this gap by providing a low-complexity channel model that takes into account the particularities of the THz propagation medium as well as the physical characteristic of the RIS. Building upon this model, we presented a comprehensive system model for RIS-assisted THz wireless systems that support broadcasting and we conduct coverage analysis that reveals their limitations.







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RIS-assisted UAV wireless systems

By setting the stage for a range of novel use cases, such as remote sensing, monitoring and surveillance, ad-hoc and rapid connectivity as well as network augmentation, unmanned aerial vehicles (UAVs) have been widely recognized as a key technology for the beyond the fifth generation (B5G) era. From a communications perspective, all UAV-based applications have two common requirements: i) ultra-reliable connectivity to ensure a high quality of experience, and ii) high-energy efficiency to guarantee acceptable hover time. These requirements can be technically translated into the need to create a favorable and reconfigurable electromagnetic environment without increasing the UAV's energy consumption.

In response to the above need, the ARIADNE project has recently turned its attention on combining UAVs and RIS. In more detail, we examined the interesting scenario in which the RIS is attached to a fixed position, such as a wall, and has a clear line of sight (LOS) to the RIS. In this case, after scanning the technical literature, we identified the following important research gaps:

•No generalized channel model has yet been presented that captures the specifics of RIS-assisted UAV wireless systems and enables performance evaluation in different propagation environments.

•Most of published contributions assume that the RIS-UAV link is not directional. As a result, the adverse effects of UAV disorientation and/or misalignment of the RIS-UAV beam have been neglected. However, as we move toward next-generation wireless systems, both the operating frequency and thus the directionality of links are expected to increase. Therefore, even small disorientations and/or misalignments may adversely affect the performance of the RIS-assisted UAV wireless system.

Motivated by the above observations, we focused on presenting a comprehensive system model, which is graphically illustrated in Fig. 1, deriving a generalized framework for evaluating the outage performance of RIS-assisted UAV wireless systems that takes into account the effects of various fading conditions, disorientation, misalignment, and/or hardware imperfections.

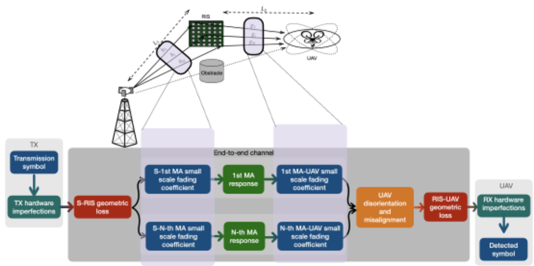
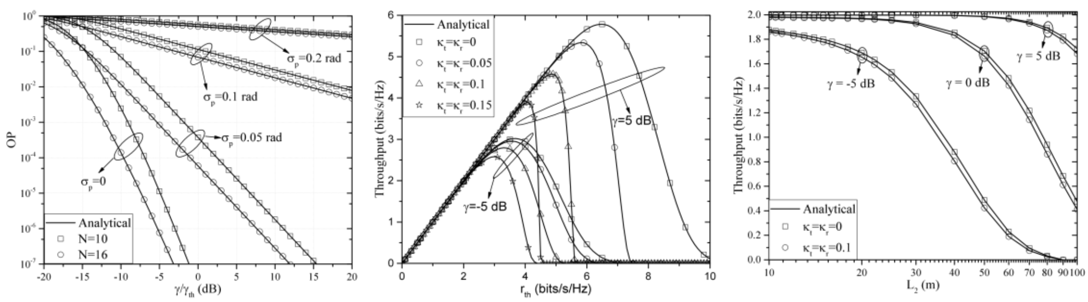


Figure: UAV-RIS system model



The presented theoretical framework gave birth to a number of interesting insights and results that are summarized in the following figures. Most importantly the results revealed the detrimental effect of disorientation and misalignment in the outage and throughput performance of the system. Moreover, it become evident that an optimal family of transmission schemes can be defined as a solution to the throughput maximization problem. In other words, for a given set of transceivers, propagation environment, level of disorientation and misalignment, transmission distance and frequency, an optimal transmission scheme spectral efficiency exists for which the throughput is maximized.

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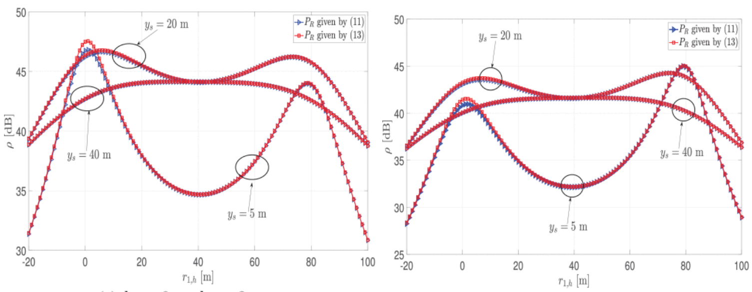
RIS optimal placement

Most of the published RIS-related works consider the case of the entire RIS area being illuminated by the transmitted beam. However, due to the highly directional transmissions in mmWave/THz networks and the low manufacturing cost of RISs, which make them suitable, as it is envisioned, to cover a big portion of the facades of large structures, such as buildings, it is expected that in many cases only a part of the total RIS area is going to be illuminated. Based on this, in ARIADNE, we are aim to answer the question of what the optimal RIS placement policy is, which can be seen as a network planning question, in the two cases of the RIS area being smaller and larger than the transmitted beam footprint. In this direction, we presented a system model for RIS-aided highly directional mmWave/THz links of fixed topology, such as wireless backhaul/fronthaul links, and use electromagnetic theory to evaluate the received power in the general case of an RIS of arbitrary size. Based on the resulting received-power expression, we provided approximate closed-form expressions for the cases in which the transmission footprint at the RIS plane is either much larger or smaller than the RIS. According to the expressions, we evaluated the end-to-end SNR for both cases. We used the closed-form SNR expressions to analytically extract the policies for the optimum RIS placement that results in SNR maximization. Finally, we provided an extensive simulation campaign in various scenarios in order to validate the analytical results and, furthermore, to provide design guidelines to the system designer from a practical point of view.



(a) $h_t = 6$ m, $h_r = 3$ m. (b) $h_t = 3$ m, $h_r = 6$ m.

The analytical outcomes have been validated by an extensive simulation campaign in various scenarios, which reveal that: i) when the transmission beam footprint at the RIS plane is much larger than the RIS size, the optimal RIS placement is either close to the TX, RX, or the middle of the TX-RX horizontal distance, depending on the system parameters; ii) when the footrpint is equal to or smaller than the RIS size, the optimal RIS placement is close to the RX. Such outcomes can be readily used by the system designer to properly deploy RISs in a way that the system performance is maximized.

Annex

Annex I - ARIADNE Guest Editorial

Special issue of the IEEE Journal on Selected Areas in Communications (IEEE J-SAC) on the topic "Beyond Shannon Communications: A Paradigm Shift to Catalyze 6G.

The members of the ARIADNE team are guest editors of a special issue of the IEEE Journal on Selected Areas in Communications (IEEE J-SAC) on the topic "Beyond Shannon Communications: A Paradigm Shift to Catalyze 6G", which will be published in the second quarter of 2023. Topics of interest of the journal include but are not limited to the following:

•Reconfigurable Intelligent Surfaces in wireless systems: channel models, fundamental performance, algorithm and protocol design

•Holographic MIMO communication systems: physics-based modeling, signal processing, network optimization and emerging applications

•3D connectivity and intelligence support wireless systems

•Semantics-native and goal-oriented communication systems: critical components modeling and validation, mathematical frameworks, fundamental trade-offs and limits

•Artificial Intelligence/Machine Learning for wireless systems modeling, analysis, design and optimization

•System architecture and HW design implications for Beyond Shannon 6G paradigms

Annex II – related ARIADNE project publications

Beside a number of project deliverables elaborating on various aspects of RIS aided systems characterization and development and presenting the ARIADNE project results in details, which are available on the project website at https://www.ict-ariadne.eu/deliverables/, the consortium members provided significant number of related publications at various journals and magazines as well as at conferences, as indicated below.

•A.-A. A. Boulogeorgos, and A. Alexiou, "Reconfigurable Intelligent Surfaces for Beyond Shannon Wireless Systems Design," in Statistical Modeling of Reliability Structures and Industrial Processes, to be published by CRC Press, 2021.

•A. -A. A. Boulogeorgos and A. Alexiou, "Performance Analysis of Reconfigurable Intelligent Surface-Assisted Wireless Systems and Comparison With Relaying," in IEEE Access, vol. 8, pp. 94463-94483, May 2020, doi: 10.1109/ACCESS.2020.2995435.

•A.-A. A. Boulogeorgos, and A. Alexiou, "How much do hardware imperfections affect the performance of reconfigurable intelligent surface-assisted systems?" IEEE Open Journal of the Communications Society, July 2020.

•A.-A. A. Boulogeorgos and A. Alexiou, "Coverage Analysis of Reconfigurable Intelligent Surface Assisted THz Wireless Systems," in IEEE Open Journal of Vehicular Technology, vol. 2, pp. 94-110, Jan. 2021, doi: 10.1109/OJVT.2021.3051209.

•K. Ntontin, A. -A. A. Boulogeorgos, D. G. Selimis, F. I. Lazarakis, A. Alexiou and S. Chatzinotas, "Reconfigurable Intelligent Surface Optimal Placement in Millimeter-Wave Networks," in IEEE Open Journal of the Communications Society, vol. 2, pp. 704-718, March 2021, doi: 10.1109/OJCOMS.2021.3068790.

•A.-A. A. Boulogeorgos, E. Yaqub, M. Di Renzo, A. Alexiou, R. Desai, and R. Klinkenberg, "Machine Learning: A Catalyst for THz Wireless Networks," Frontiers in Communications and Networks, July 2021.

•A.-A. A. Boulogeorgos, J. M. Jornet and A. Alexiou, "Directional Terahertz Communication Systems for 6G: Fact Check," in IEEE Vehicular Technology Magazine, vol. 16, no. 4, pp. 68-77, Dec. 2021, doi: 10.1109/MVT.2021.3113883.

•A.-A. A. Boulogeorgos, N. D. Chatzidiamantis, H. G. Sandalidis, A. Alexiou and M. D. Renzo, "Cascaded Composite Turbulence and Misalignment: Statistical Characterization and Applications to Reconfigurable Intelligent Surface-Empowered Wireless Systems," in IEEE Transactions on Vehicular Technology, vol. 71, no. 4, pp. 3821-3836, April 2022, doi: 10.1109/TVT.2021.3140084.

•A.-A. A. Boulogeorgos, A. Alexiou and M. D. Renzo, "Outage performance analysis of RIS-assisted UAV wireless systems under disorientation and misalignment," in IEEE Transactions on Vehicular Technology, June 2022, doi: 10.1109/TVT.2022.3187050.

•A. Chrysologou, A.-A. A. Boulogeorgos, N. Chatzidiamantis, and A. Alexiou, "Outage Analysis of Holographic Surface Assisted Downlink TeraHertz NOMA," IEEE Global Communications Conference (Globecom), Dec. 2022

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All ARIADNE project publications can be found at https://www.ict-ariadne.eu/scientific-publications/.

Annex III – related workshops organized by ARIADNE

•Network Management workshop at EUCNC 2021 – with other B5G projects of 5G PPP

•IEEE MeditCom, 7-10 September 2021, Athens, Greece – ARIADNE Workshop on Reconfigurable Intelligent Surfaces: A Technology Enabler to catalyze 6G

•IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 13-16 September 2021, Helsinki – workshop with RISE-6G and AIMM projects - Workshop on Reconfigurable Intelligent Surfaces for B5G/6G

•IEEE Global Communications Conference (GLOBECOM 2021), 7-11 December 2021, Madrid - WS-19: Workshop on Reconfigurable Intelligent Surfaces for Future Wireless Communications

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