



Jammer Mitigation in Absorptive RIS-Assisted Uplink NOMA

Downloaded from: <https://research.chalmers.se>, 2026-04-22 03:11 UTC

Citation for the original published paper (version of record):

Tabeshnezhad, A., Zhu, Y., Vilenskiy, A. et al (2026). Jammer Mitigation in Absorptive RIS-Assisted Uplink NOMA. IEEE Transactions on Communications, 74: 7199-7212.
<http://dx.doi.org/10.1109/TCOMM.2026.3681624>

N.B. When citing this work, cite the original published paper.

© 2026 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, or reuse of any copyrighted component of this work in other works.

Jammer Mitigation in Absorptive RIS-Assisted Uplink NOMA

Azadeh Tabeshnezhad¹, Member, IEEE, Yuqing Zhu², Member, IEEE,
 Artem R. Vilenskiy³, Senior Member, IEEE, Van Ly Nguyen⁴, Member, IEEE,
 Arnold Lee Swindlehurst⁵, Life Fellow, IEEE, and Tommy Svensson⁶, Senior Member, IEEE

Abstract—Non-orthogonal multiple access (NOMA) is a promising technology for next-generation wireless communication systems due to its enhanced spectral efficiency. However, wireless communication is facing increasing requirements for security. To that end, jamming mitigation using multi-antennas has emerged as an important research topic. In this paper, we consider an uplink NOMA system with a reconfigurable intelligent surface (RIS) that assists the uplink users and, at the same time, mitigates the jammer. Our goal is to minimize the total users' transmitted power under signal-to-interference-plus-noise ratio constraints at the base station. To be effective, typically a high-dimensional RIS is needed, leading to a large optimization problem, which in general faces convergence problems. We propose an iterative algorithm for this high-dimensional non-convex optimization problem that converges with a jammer comprising as many as 64 antennas, and an RIS with 128 elements. More specifically, we introduce a design and optimize the performance of an absorptive RIS (A-RIS). Compared to a standard RIS, we show that an A-RIS can dramatically reduce the users' required transmit power and successfully mitigate the jammer. The A-RIS is in particular useful in cases when the number of jammer antennas is of the same order as the number of A-RIS elements.

Index Terms—A-RIS, NOMA, phase shift, non-convex optimization, SDR, Dinkelbach algorithm, absorptive, interference, jammer.

I. INTRODUCTION

NON-ORTHOGONAL multiple access (NOMA) is a promising technique for next-generation radio access. In contrast to conventional orthogonal multiple access (OMA) schemes, where each user is served using a single orthogonal resource block, NOMA is of particular interest because it allows multiple users to share the same orthogonal time,

Received 15 September 2025; revised 17 January 2026 and 12 March 2026; accepted 24 March 2026. Date of publication 7 April 2026; date of current version 16 April 2026. This work has been supported by the project SEMANTIC, funded from EU's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 861165, as well as by the U.S. National Science Foundation under grants CNS-2107182 and ECCS-2030029. The associate editor coordinating the review of this article and approving it for publication was K. Cao. (*Corresponding author: Azadeh Tabeshnezhad.*)

Azadeh Tabeshnezhad, Yuqing Zhu, Artem R. Vilenskiy, and Tommy Svensson are with the Department of Electrical Engineering, Chalmers University of Technology, 412 96 Gothenburg, Sweden (e-mail: azadeh.tabeshnezhad@chalmers.se; yuqingz@chalmers.se; artem.vilenskiy@chalmers.se; tommy.svensson@chalmers.se).

Van Ly Nguyen is with the Department of Electrical Engineering and Computer Science, The University of Kansas (KU), Lawrence, KS 66045 USA (e-mail: vanly.nguyen@ku.edu).

Arnold Lee Swindlehurst is with the Department of Electrical Engineering and Computer Science, University of California, Irvine, CA 92697 USA (e-mail: swindle@uci.edu).

Digital Object Identifier 10.1109/TCOMM.2026.3681624

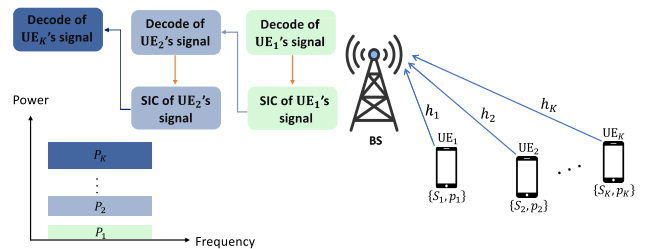


Fig. 1. Illustration of uplink power-domain NOMA with K users sending messages S_1, S_2, \dots , and S_K with power p_1, p_2, \dots , and p_K respectively.

frequency, spatial, and code-domain resource blocks. NOMA has significant advantages over traditional OMA schemes, with higher effective bandwidth, support for massive connectivity, and reduced transmission latency [1].

Generally, NOMA is divided into two main classes: power-domain and code-domain [2]. Power-domain NOMA exploits situations where the users have different path loss levels. The idea behind power-domain NOMA is that the users nearer the base station (BS) can employ successive interference cancellation (SIC) to remove the strong signals destined for the remote users before decoding their own signal [3].

In uplink NOMA, which is the focus of this paper, the BS can similarly employ SIC to remove stronger user signals before decoding a given signal of interest. However, as illustrated in Fig. 1, the SIC condition needs to include both the individual users' transmit powers, as well as the channel gain of the individual users' channels sharing the same NOMA resource. Thus, to effectively implement SIC, the transmit power levels of the uplink users are important. There is still substantially less work on uplink NOMA compared to the downlink case, and there is also a lack of work addressing the reliability of NOMA in the presence of active jamming. For either downlink or uplink NOMA, when the users and the BS only have one antenna, dealing with jammers is a challenge since neither the users (for the downlink) nor the BS (for the uplink) may have sufficient spatial degrees of freedom (DoFs) to cancel the jamming [4]. In such cases, the jamming can severely degrade the NOMA performance even when decoding is performed by or for the strongest user.

Recently, the use of RIS has emerged as a unique technology for improving both the spectral and energy efficiency of

wireless networks. An RIS consists of an array of elements whose reflective properties can be individually controlled, enabling some degree of control of the wireless propagation environment. In wireless communications, RIS can be easily deployed on various outdoor and indoor structures, including walls, vehicle windows, advertising billboards, etc., due to their use of small, low-cost, and lightweight elements [5]. RIS can provide additional channel paths to construct stronger combined channels with significant differences in strength [6].

In contrast to active amplify-and-forward relays that usually operate in half-duplex mode, the RIS functions in full-duplex mode and only reflects the received signals as a passive array, without the expenditure of any radio-frequency energy, which enables spectrum-efficient and cost-effective communications [7], [8], [9]. An RIS can increase the strength of received signals through beamforming gain and constructive interference, eliminate interfering signals through destructive interference or null-steering, and provide virtual line-of-sight paths to overcome blockages. For single-antenna NOMA systems in the presence of a jammer, an RIS has the potential to provide a large number of spatial DoFs that could allow the network to cancel the jamming signal, potentially creating a null channel from the jammer to either the single-antenna BS or single-antenna users. This is the key RIS capability that will be studied in this paper in the context of jamming mitigation in uplink NOMA.

In a conventional RIS implementation, it is the phase shift of the reflection coefficient of each element that is adjusted in order to achieve the desired effect on the wireless channels. More recently, researchers have also studied RIS architectures where both the phase shift and the attenuation or absorption of the reflection coefficient of each element can be controlled individually, referred to as absorptive RIS (A-RIS) [10], providing additional DoF for jamming signal cancellation. In this latter case, the energy absorbed by the A-RIS can be refracted to directions on the other side of the surface [11], [12] sampled using an active RF receiver for channel estimation or sensing [13], [14], [15] or simply dissipated. In [16], the interference mitigation problem using A-RIS in two spectrum sharing scenarios is investigated: under spectral coexistence of radar and communication systems, and spectrum sharing in device-to-device (D2D) communications. The results show that A-RIS significantly outperforms non-absorptive RIS for interference suppression scenarios. Similarly, the interference cancellation ability of A-RIS was exploited to support joint D2D and cellular communications in [17].

RIS technology has been applied in many different types of wireless communications scenarios, including NOMA. However, while the use of conventional phase-shift-only RIS has been proposed for NOMA applications with the goal of improving spectral efficiency, to the best of our knowledge, there is no prior work reported on using A-RIS with NOMA, nor on using RIS to mitigate the impact of external interference (e.g., jamming) on NOMA performance. NOMA is a vulnerable technology due to the use of shared resources since the decoding performance depends on sufficient differences in the users' received power levels, which in the uplink involves adapting the transmit power levels to the channel conditions.

In addition, jamming can reduce the efficiency of NOMA due to the severe loss of signal-to-noise ratio (SNR) [18].

A. Related Works

Several recent works have studied the use of RIS in NOMA applications. For example, an RIS-assisted NOMA system was investigated in [19] to achieve a tradeoff between sum rate and power consumption. In [20], joint power allocation, hybrid beamforming, and phase shift optimization for downlink multi-user RIS-assisted mm-wave NOMA were designed to maximize the sum rate using alternating manifold optimization (AMO) and successive convex approximation (SCA) methods. In [21], the maximum sum rate achieved by optimizing the RIS phase shifts subject to the user power constraints was studied for NOMA. In [22], NOMA was implemented in a multi-cell scenario assisted by multiple RISs to minimize the transmit power in the uplink. An RIS-aided multi-autonomous aerial vehicle (AAV) system with NOMA was studied in [23], with the goal of minimizing the system's power consumption. In [24], RIS-aided multi-cell NOMA was shown to improve the coverage probability using stochastic geometry methods and two different channel models. Furthermore, many other research problems in the context of RIS-assisted NOMA have been studied using different optimization methods in [25] and [26].

Relatively little work has been done on optimizing NOMA performance in the presence of a jammer. In [27], optimal user grouping for NOMA was proposed to overcome the impact of jamming and improve the sum rate. In [28], a mobile access point or a UAV was exploited together with joint power control to mitigate the effect of a jamming attack and increase the reliability of the communication. Furthermore, anti-jamming precoding was proposed in [29] to minimize the total transmit power in an uplink MIMO-NOMA system. In [30], transmit beamforming together with the use of an RIS and artificial noise was proposed to enhance the secrecy of a NOMA system. Several works have studied the use of RIS for anti-jamming in [31], [32], and [33]. It was shown in [34] that jamming can critically degrade the performance of communication systems by reducing data rates, communication reliability, and increasing packet loss. To address these challenges, the authors proposed a jamming-aware, fairness-driven design that employs RIS to enhance resilience against jamming attacks. In addition, [35] presented an RIS-aided MIMO-NOMA cellular network design aimed to reduce the inter-cell and inter-cluster interference to improve the data rates in cellular networks. These studies highlight the capability of RIS to improve the wireless interference environment and jamming mitigation. However, except for some initial work in [25], [36], and [37], none of the previous works cited above have considered the use of an RIS for mitigating jamming for an uplink NOMA system.

B. Motivations and Contributions

As already mentioned above, the focus of this paper is on the use of RIS, and in particular A-RIS, to mitigate the influence of a jammer on an uplink NOMA system. Our objective is

to minimize the sum transmit power of the uplink NOMA users under quality of service (QoS) constraints in the presence of a jammer. This problem formulation is well aligned with 6G key requirements on sustainability, trustworthiness, and digital inclusion [38]. The main contributions of our work are summarized as follows:

- We show that an uplink power-domain NOMA system assisted by an A-RIS can play a key role in mitigating interference from a sophisticated multi-antenna jammer. Compared to an uplink NOMA system without A-RIS assistance, we show a gain of more than 28 dB in the required sum transmit power by the uplink users. These gains come from the combined capability of an A-RIS to not only mitigate the jammer interference but also enable substantial beamforming and interference coordination gains for the uplink NOMA users. Unlike conventional RIS, we show that the nature of A-RIS introduces additional new important degrees of freedom in optimizing the system performance while keeping power consumption low.
- We propose a novel joint optimization problem formulation that minimizes the total transmit power of user terminals under constraints on the A-RIS response and the individual signal-to-interference-plus-noise ratio (SINR) at the BS for each of the users. This problem has not been studied in the literature before, and it turns out to be a highly complex non-convex optimization problem due to the strong coupling between user power control and the A-RIS phase-shift and gain design.
- To efficiently solve this problem, we develop an iterative algorithm that combines Linear Programming (LP) to find the user powers, ensuring optimal power allocation in each iteration and sequential convex relaxation via Dinkelbach's algorithm [39] to efficiently optimize the A-RIS response, leveraging fractional programming principles. The proposed algorithm does not rely on conventional convex approximations such as SDR (Semidefinite Relaxation), making it more computationally scalable and adaptable to large-scale A-RIS, which is a key enabler for realistic A-RIS deployments. Our approach effectively balances power minimization and interference mitigation.
- We present the results of several simulations that demonstrate the convergence of the algorithm and the effectiveness of the A-RIS in mitigating the jammer and controlling the multi-user interference, enabling the system to operate with relatively low sum transmit power. These results show that the proposed algorithm converges very well and can handle A-RIS with a large number of elements and a jammer with many antenna elements. This is very important since the passive nature of A-RIS implies that more elements are typically needed compared to conventional relays or APs.

Organization: The rest of the paper includes the following sections. In Section II, we detail the targeted scenario and the A-RIS-assisted NOMA system model, and we define the resulting optimization problem. In Section III, we provide details on the implementation of the A-RIS, which motivates

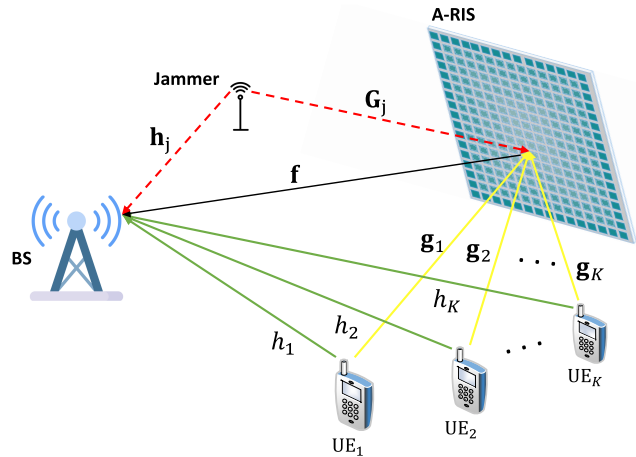


Fig. 2. Illustration of an A-RIS-aided uplink NOMA system with K users and a jammer.

our system model and simulation assumptions. Section IV then provides details for our proposed optimization algorithm that alternates between LP and the Dinkelbach algorithm combined with semi-definite relaxation (SDR) to minimize the total power transmitted from the users to the BS. Section V then presents numerical results that validate the performance of the algorithm in challenging scenarios, followed by a discussion on the relevance of the results for a corresponding downlink scenario. Finally, we summarize our findings in Section VI.

Notation: Scalars, vectors, and matrices are respectively written with italic, bold lowercase, and bold uppercase characters (e.g., h , \mathbf{h} , \mathbf{H}). The conjugate and transpose of vectors and matrices are respectively expressed by the superscripts $*$, \top (e.g., \mathbf{z}^* , \mathbf{Z}^* , \mathbf{z}^\top , \mathbf{Z}^\top). In addition, $\text{diag}(\mathbf{f})$ denotes the diagonal matrix whose diagonal elements are taken from the vector \mathbf{f} , $\|\cdot\|$ returns the norm of a vector, and $|\cdot|$ provides the magnitude of a complex number. The operator $\text{tr}(\mathbf{Z})$ yields the trace of a matrix, and \mathbb{C} denotes the space of complex numbers.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we first describe the system and signal model for our considered A-RIS-aided NOMA system and provide assumptions regarding the channel state information (CSI) available to the BS and the jammer.

A. System Model

We consider an A-RIS-aided uplink NOMA system with a BS equipped with a single-antenna, an A-RIS with N elements, a jammer with M antennas, and K single-antenna users employing power-domain NOMA, as shown in Fig. 2. For this scenario, the received signal at the BS can be written as

$$r = \sum_{i=1}^K (h_i + \mathbf{f}^\top \Phi \mathbf{g}_i) x_i + (\mathbf{h}_j^\top + \mathbf{f}^\top \Phi \mathbf{G}_j) \mathbf{x}_j + n_r, \quad (1)$$

where $h_i \in \mathbb{C}^{1 \times 1}$ denotes the direct channels between the users and the BS, x_i is the symbol transmitted by user i ,

$\mathbf{f} \in \mathbb{C}^{N \times 1}$ denotes the channel vector between the A-RIS and the BS, $\mathbf{g}_i \in \mathbb{C}^{N \times 1}$ is the channel vector between user i and the A-RIS, $\mathbf{h}_j \in \mathbb{C}^{M \times 1}$ represents the channel vector between the jammer and the BS, $\mathbf{G}_j \in \mathbb{C}^{N \times M}$ denotes the channel matrix between the jammer and A-RIS, $\mathbf{x}_j \in \mathbb{C}^{M \times 1}$ is the signal transmitted by the jammer, and $n_r \sim \mathcal{CN}(0, \sigma^2)$ is additive white Gaussian noise (AWGN). The matrix $\Phi = \text{diag}\{\beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, \dots, \beta_N e^{j\theta_N}\} \in \mathbb{C}^{N \times N}$ is a diagonal matrix consisting of the adjustable reflection coefficients of the A-RIS, where for the n -th element of an A-RIS we have an adjustable phase $\theta_n \in [0, 2\pi]$ and an adjustable amplitude $\beta_n \leq \beta_{\max} \leq 1$. We define the transmit power of each user as $p_i = E(|x_i|^2)$. We assume that the BS has the CSI for all the channels in (1).

Assume the K users are indexed in the order of declining channel gains, and $p_1|h_1|^2 \geq p_2|h_2|^2 \geq \dots \geq p_K|h_K|^2$, consistent with the situation illustrated in Fig. 1. The BS then first decodes the signal for UE₁, treating the multi-user interference of the signal from the other users as noise, and then subtracts it from the received signal r when decoding the signal from UE₂. Thus, the SINR for decoding UE₁ is given by

$$\gamma_1 = \frac{p_1|h_1 + \mathbf{f}^\top \Phi \mathbf{g}_1|^2}{\sum_{i=2}^K p_i|h_i + \mathbf{f}^\top \Phi \mathbf{g}_i|^2 + \sigma_j^2 + \sigma^2}, \quad (2)$$

where we let σ_j^2 denote the power of the jammer signal received by the BS. This term will be derived in Section II-B below. Under the assumption of perfect SIC of UE₁'s signal, i.e., without error propagation, the SINR for UE₂ can be written as

$$\gamma_2 = \frac{p_2|h_2 + \mathbf{f}^\top \Phi \mathbf{g}_2|^2}{\sum_{i=3}^K p_i|h_i + \mathbf{f}^\top \Phi \mathbf{g}_i|^2 + \sigma_j^2 + \sigma^2}. \quad (3)$$

Continuing to assume a perfect SIC for UE₂ and each of the subsequent user's signals with no error propagation, the SINR for the last user, UE _{K} , can be written as

$$\gamma_K = \frac{p_K|h_K + \mathbf{f}^\top \Phi \mathbf{g}_K|^2}{\sigma_j^2 + \sigma^2}. \quad (4)$$

The goal to be addressed is the design of the A-RIS response Φ to minimize the sum of the users' transmit powers $\sum_i p_i$ while satisfying constraints on the SINRs $\gamma_i, i = 1, \dots, K$.

B. Jammer Modeling

We assume an intelligent jammer that is aware of Φ and the CSI of all the channels affected by the jammer, i.e. $\{\mathbf{h}_j, \mathbf{f}, \mathbf{G}_j\}$. The objective of the jammer is to choose \mathbf{x}_j such that the interference power received at the BS is maximized. In other words, the jammer designs \mathbf{x}_j based on the following criterion:

$$\begin{aligned} \sigma_j^2 &= \max_{\mathbf{x}_j} \|(\mathbf{h}_j^\top + \mathbf{f}^\top \Phi \mathbf{G}_j) \mathbf{x}_j\|^2 \\ \text{s.t. } E(\|\mathbf{x}_j\|^2) &\leq P_j, \end{aligned} \quad (5)$$

where P_j is the jammer's maximum transmit power. The solution to this problem is simply

$\mathbf{x}_j = (\sqrt{P_j}/\rho) (\mathbf{h}_j^\top + \mathbf{f}^\top \Phi \mathbf{G}_j)^H$, where $\rho = \|\mathbf{h}_j^\top + \mathbf{f}^\top \Phi \mathbf{G}_j\|$. Thus, the term due to jamming in the denominator of the SINR expressions in (2)-(4) becomes:

$$\sigma_j^2 = P_j \|\mathbf{h}_j^\top + \mathbf{f}^\top \Phi \mathbf{G}_j\|^2. \quad (6)$$

Note that the jammer transmit power is fixed at P_j , and thus the power transmitted per jammer antenna decreases as the number of jammer antennas M increases. However, the amount of jamming power that reaches the BS will, in general, increase with M due to the coherent beamforming gain, thus the need for the intervention of the A-RIS. We also note that our subsequent analysis and algorithm development are relevant to the case where the jammer does not possess CSI. For example, suppose the jammer simply broadcasts spatially white Gaussian noise, i.e., $\mathbf{x}_j \sim \mathcal{CN}(0, \frac{P_j}{M} \mathbf{I})$. In this case, the power received at the BS becomes $\sigma_j^2 = (P_j/M) \|\mathbf{h}_j^\top + \mathbf{f}^\top \Phi \mathbf{G}_j\|^2$, or simply $1/M$ the power in the case of coherent jamming. Thus, results obtained for an intelligent jammer with a given P_j will be the same as those for a "dumb" jammer with M times more power.

III. ABSORPTIVE RIS

As discussed above, recent work has considered RIS implementations in which not all energy is reflected from the surface. In prior work, the non-reflected energy is either transmitted or "refracted" to the other side of the RIS, or it is demodulated and sampled for channel estimation or sensing purposes. Here we simply assume that the RIS absorbs an adjustable fraction of the incoming energy at each element, without assuming that the absorbed energy is used for any other purpose. From a sustainable 6G perspective, our numerical results demonstrate that an A-RIS can reduce the transmit power required at the user devices to satisfy QoS constraints, which translates into lower communication-user power consumption.

In Section V, we show that the ability to adjust the magnitude of the reflected power at each RIS element provides additional DoFs that are particularly useful in situations like the one we consider in this work, in which interference mitigation is required.

A. Discussion on RIS Implementation With Both Amplitude and Phase Control

As already introduced in Section II, the A-RIS model assumes that the reflection coefficient of each RIS element can be described as $\beta_n e^{j\theta_n}$, where $0 \leq \beta_n \leq 1$ describes the amplitude of the reflected signal component, whereas, in the conventional RIS, it is assumed that $\beta_n = 1$. In practice, depending on the update rate of the A-RIS, due to the limited capacity of the BS to A-RIS control channel, the values of $\{\beta_n\}$, and $\{\theta_n\}$, may have to be quantized. However, in this work, we assume the possibility of continuously controlling both and ignoring the impact of quantization. Such control information with a high sampling rate and quantization accuracy is feasible in less dynamic scenarios. The reason is twofold; the constraint $0 \leq \beta_n \leq 1$ has numerical advantages as it is convex, and as we show below, it is possible to

independently adjust phase and amplitude in a practical design of the A-RIS elements.

B. Practical Design of A-RIS

Compared to widely studied phase-controlled RIS designs, A-RIS designs with concurrent amplitude and phase reconfigurability are less prevalent due to the challenges in physical implementation and availability of tunable components [40]. Nevertheless, in recent years, the higher flexibility and versatility provided by combined amplitude-phase control have sparked growing research interest in this technology in the antenna, optics, and materials communities [42]. As an example, take the reconfiguration mechanism based on using semiconductor *p-i-n* and varactor diodes. A *p-i-n* diode can not only function as a microwave switch to generate a discrete phase shift but can also operate as a variable resistor by applying a forward current to bias the diode's junction to the transition state. In this case, the junction resistance can vary by several orders of magnitude [42]. When an RIS unit cell (UC) combines a *p-i-n* diode with a varactor diode, exploiting the control of the reverse-biased junction capacitance, a variable amplitude-phase RIS reflection response can be engineered. Recently, such a reconfigurable RIS UC was experimentally demonstrated, allowing independent and continuous amplitude-phase control [41].

In most cases, an RIS UC is implemented as a scattering metal topology distributed on a grounded dielectric substrate and carrying controllable components (i.e., diodes). The UC typically has polarization axes, e.g., x -axis in the local RIS coordinate system, defining the E -field orientation for which the UC can control reflection. Omitting technical details, a conceptual circuit diagram of a single-polarized, amplitude-and-phase controllable RIS UC is illustrated in Fig. 3(a). For a plane wave illuminating the RIS from the free-space side, the UC can be seen as a single-port network with some complex input impedance Z_{UC} , also known as the opaque surface impedance [43]. The latter can be decomposed into an equivalent sheet impedance (controllable by diode biasing) on the air-dielectric interface Z_{sh} and a substrate input impedance Z_{sub} , connected in parallel, i.e., $Z_{UC} = Z_{sh} || Z_{sub}$. The sheet impedance is modeled as a circuit containing *RLC* elements, representing passive metal parts of the topology, *p-i-n* and varactor diodes, which are connected to the input UC nodes through an impedance transformer with a turns ratio $\sqrt{N_T}$ Fig. 3(a). A value for N_T is defined by a sheet current distribution. At the same time, Z_{sub} can be regarded as the impedance of a short-circuited transmission line segment. This way, the UC reflection property can be described by a single scalar reflection coefficient $\beta = (Z_{UC} - Z_s)/(Z_{UC} + Z_s)$, where Z_s is the wave impedance of the incident plane wave.

C. Maximum Reflection Versus Phase of A-RIS

By continuously applying a forward bias current to the *p-i-n* diode and a reverse bias voltage to the varactor diode, values for β for all operating states can be mapped onto the complex plane, forming an effective UC coverage region, having area A_{cov} Fig. 3(b). The coverage region represents

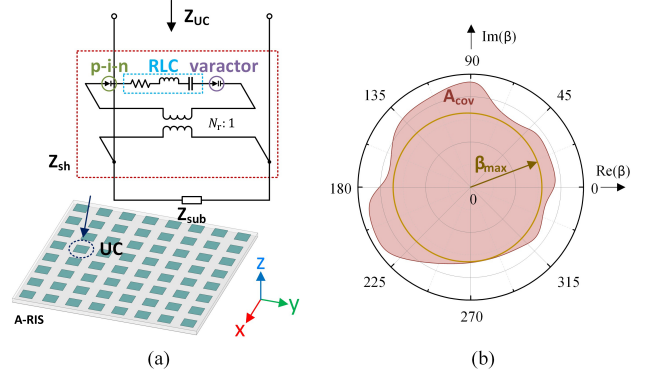


Fig. 3. A-RIS with both amplitude and phase control. (a) Equivalent circuit model of the UC. (b) UC reflection coefficient coverage in the complex plane.

the achievable UC β range, thus characterizing its reflection control capability over both amplitude and phase. In particular, a circle with a maximum radius β_{max} fully contained inside the coverage region can be introduced for quantitative analysis. Within this circular region, the A-RIS provides a full phase range of $(0-360)^\circ$ and an amplitude range of $(0-\beta_{max})$. Note that the β_{max} is typically less than 1, due to inherent losses in the UC. These losses include ohmic losses of a copper UC topology, substrate dielectric losses, and additional losses caused by the junction resistance and parasitic parameters of the diodes employed.

IV. OPTIMIZATION METHOD

Based on the UC design outlined in the previous section, here we address optimization of the A-RIS response in order to mitigate the impact of a jammer in an uplink NOMA system. We will assume A-RIS elements that are independently tunable within the disk of radius β_{max} depicted in Fig. 3(b). Clearly, there are additional β values greater than β_{max} that can be achieved for certain phase values θ , but we ignore this possibility in the discussion below to maintain a convex set of parameters.

A. Problem Formulation for K NOMA Uplink Users

There are several ways to illustrate the benefit of the A-RIS in the problem under consideration. Here we study the problem of minimizing the total transmit power of the users, such that given SINR QoS constraints of the users are met in the presence of a jammer. The optimization problem for K users can be written as follows:

$$\min_{\{p_k\}, \Phi} \sum_{k=1}^K p_k \quad (7a)$$

$$\text{s.t. C1: } p_k \geq 0, \quad k = 1, \dots, K \quad (7b)$$

$$\text{C2: } \frac{p_k |h_k + \mathbf{f}^\top \Phi \mathbf{g}_k|^2}{\sum_{i=k+1}^K p_i |h_i + \mathbf{f}^\top \Phi \mathbf{g}_i|^2 + \sigma_j^2 + \sigma^2} \geq T_k, \quad (7c)$$

$$k = 1, \dots, K$$

$$\text{C3: } |\Phi(n, n)| \leq \beta_{max}, \quad n = 1, \dots, N. \quad (7d)$$

Constraint **C1** ensures that each of the transmit powers is non-negative, constraint **C2** corresponds to the desired individual SINR constraint for each user UE_k, $k = 1, \dots, K$, where T_k denotes the SINR threshold for the k -th user and constraint **C3** indicates that the configuration of each A-RIS element $\{\beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, \dots, \beta_N e^{j\theta_N}\}$ should lie within a circle of maximum radius β_{\max} in the complex plane.

Note that in our optimization problem formulation above, we ensure robust SIC by incorporating SINR constraints into the optimization problem, which enforce a minimum threshold to guarantee the required QoS for each user. T_k is chosen such that the corresponding Shannon capacity is strictly above the target rate, ensuring that the desired QoS (in terms of both rate and error performance) is met with high reliability. By setting these constraints appropriately, the system automatically achieves the conditions necessary for successful SIC. Therefore, even without explicitly defining SIC constraints, our approach inherently ensures their fulfillment.

We see from (7) that the problem of interest is non-linear, non-convex, and high-dimensional, and cannot be solved directly. Therefore, we take the steps outlined below to transform it into a more tractable form that is amenable to optimization. We begin by noting that the weakest user must satisfy constraint **C2** with equality, otherwise p_K could be further reduced to achieve a lower value of the criterion function. Thus, we have

$$p_K |h_K + \mathbf{f}^\top \Phi \mathbf{g}_K|^2 = T_K (P_j \|\mathbf{h}_j^\top + \mathbf{f}^\top \Phi \mathbf{G}_j\|^2 + \sigma^2). \quad (8)$$

Substituting (8) into (7a) and after some simple modifications, the original optimization problem in (7) becomes

$$\min_{p_1, p_2, \dots, p_{K-1}, \bar{\Phi}} p_1 + \dots + \frac{T_K (P_j \|\mathbf{h}_j^\top + \mathbf{f}^\top \Phi \mathbf{G}_j\|^2 + \sigma^2)}{|h_K + \mathbf{f}^\top \Phi \mathbf{g}_K|^2} \quad (9a)$$

$$\text{s.t. } p_k \geq 0, \quad k = 1, \dots, K \quad (9b)$$

$$p_k |h_k + \mathbf{f}^\top \Phi \mathbf{g}_k|^2 \geq T_k (P_j \|\mathbf{h}_j^\top + \mathbf{f}^\top \Phi \mathbf{G}_j\|^2 + \sum_{i=k+1}^K p_i |h_i + \mathbf{f}^\top \Phi \mathbf{g}_i|^2 + \sigma^2), \quad k = 1, \dots, K-1 \quad (9c)$$

$$|\Phi(n, n)| \leq \beta_{\max}, \quad n = 1, \dots, N. \quad (9d)$$

Next, we convert the squared magnitude terms in the SINR constraints to quadratic forms involving the diagonal elements $\phi = [\beta_1 e^{j\theta_1} \beta_2 e^{j\theta_2} \dots \beta_N e^{j\theta_N}]^T$ of Φ :

$$|h_k + \mathbf{f}^\top \Phi \mathbf{g}_k|^2 = \bar{\phi}^H \mathbf{F}_k \bar{\phi}, \quad (10a)$$

$$\|\mathbf{h}_j^\top + \mathbf{f}^\top \Phi \mathbf{G}_j\|^2 = \bar{\phi}^H \mathbf{F}_j \bar{\phi}, \quad (10b)$$

where $\bar{\phi} = [\phi^\top \ 1]^T$,

$$\mathbf{F}_k = \begin{bmatrix} \mathbf{z}_k^* \mathbf{z}_k^\top & \mathbf{z}_k^* h_k \\ h_k^* \mathbf{z}_k^\top & |h_k|^2 \end{bmatrix}, \quad \mathbf{F}_j = \begin{bmatrix} \mathbf{Z}^* \mathbf{Z}^\top & \mathbf{Z}^* \mathbf{h}_j \\ \mathbf{h}_j^H \mathbf{Z}^\top & \|\mathbf{h}_j\|^2 \end{bmatrix}, \quad (11)$$

$\mathbf{z}_k = (\mathbf{f} \odot \mathbf{g}_k)$, and $\mathbf{Z} = \text{diag}(\mathbf{f}) \mathbf{G}_j$. Note that $\mathbf{F}_k \in \mathbb{C}^{N+1 \times N+1}$, $\mathbf{F}_j \in \mathbb{C}^{N+1 \times N+1}$, $\mathbf{z}_i \in \mathbb{C}^{N \times 1}$ and $\mathbf{Z} \in \mathbb{C}^{N \times 1}$.

With the above definitions, the optimization problem in (9) can be rewritten as

$$\min_{p_1, p_2, \dots, p_{K-1}, \bar{\Phi}} p_1 + \dots + \frac{T_K (P_j \bar{\phi}^H \mathbf{F}_j \bar{\phi} + \sigma^2)}{\bar{\phi}^H \mathbf{F}_K \bar{\phi}} \quad (12a)$$

$$\text{s.t. } p_k \geq 0, \quad k = 1, \dots, K$$

$$p_k \bar{\phi}^H \mathbf{F}_k \bar{\phi} \geq T_k \left(P_j \bar{\phi}^H \mathbf{F}_j \bar{\phi} + \sum_{i=k+1}^K p_i \bar{\phi}^H \mathbf{F}_i \bar{\phi} + \sigma^2 \right), \quad (12b)$$

$$k = 1, \dots, K-1 \quad (12c)$$

$$|\bar{\phi}(n)| \leq \beta_{\max}, \quad n = 1, \dots, N \quad (12d)$$

$$|\bar{\phi}(N+1)| = 1. \quad (12e)$$

B. Proposed Solution

We see from (12) that if the user powers $\{p_k\}$ are known, the optimization requires solving a fractional quadratically constrained quadratic programming (QCQP) problem. Thus, to solve (12), we propose an algorithm that iterates between (1) the use of LP to find the users' transmit powers, and (2) the Dinkelbach algorithm together with SDR [44] to solve for the optimal A-RIS response. We first introduce a new variable, $\bar{\Phi} = \bar{\phi} \bar{\phi}^H$, which is a rank-one Hermitian semidefinite matrix. Using the SDR approach, we convert the quadratic constraints into linear matrix inequalities, and we relax the rank-one constraint as follows:

$$\min_{p_1, p_2, \dots, p_{K-1}, \bar{\Phi}} p_1 + \dots + \frac{T_K (P_j \text{tr}(\mathbf{F}_j \bar{\Phi}) + \sigma^2)}{\text{tr}(\mathbf{F}_K \bar{\Phi})} \quad (13a)$$

$$\text{s.t. } p_k \geq 0, \quad k = 1, \dots, K \quad (13b)$$

$$p_k \text{tr}(\mathbf{F}_k \bar{\Phi}) \geq T_k (P_j \text{tr}(\mathbf{F}_j \bar{\Phi}) + \sum_{i=k+1}^K p_i \text{tr}(\mathbf{F}_i \bar{\Phi}) + \sigma^2), \quad k = 1, \dots, K-1 \quad (13c)$$

$$|\bar{\Phi}(n, n)| \leq \beta_{\max}, \quad n = 1, \dots, N \quad (13d)$$

$$|\bar{\Phi}(N+1, N+1)| = 1. \quad (13e)$$

With $\bar{\Phi}$ fixed, the $\{p_k\}$ can be found directly using LP:

$$\min \mathbf{1}^\top \mathbf{p} \quad (14a)$$

$$\text{s.t. } \mathbf{A} \mathbf{p} \leq \mathbf{b} \quad (14b)$$

$$\mathbf{p} \geq \mathbf{0} \quad (14c)$$

where $\mathbf{p} = [p_1, \dots, p_K]^T$, and (15a) and (15b), as shown at the bottom of the next page.

Next, (13) is solved assuming \mathbf{p} is fixed. Eliminating terms from the objective function that do not depend on $\bar{\Phi}$, we have

$$\min_{\bar{\Phi}} \frac{T_K (P_j \text{tr}(\mathbf{F}_j \bar{\Phi}) + \sigma^2)}{\text{tr}(\mathbf{F}_K \bar{\Phi})} \quad (16a)$$

$$\text{s.t. } p_k \text{tr}(\mathbf{F}_k \bar{\Phi}) \geq T_k (P_j \text{tr}(\mathbf{F}_j \bar{\Phi}) + \sum_{i=k+1}^K p_i \text{tr}(\mathbf{F}_i \bar{\Phi}) + \sigma^2), \quad k = 1, \dots, K-1 \quad (16b)$$

$$|\bar{\Phi}(n, n)| \leq \beta_{\max}, \quad n = 1, \dots, N \quad (16c)$$

$$|\bar{\Phi}(N+1, N+1)| = 1. \quad (16d)$$

Thanks to the relaxation, what remains is a fractional programming problem with linear inequality constraints, so we turn to the Dinkelbach algorithm to optimize over $\bar{\Phi}$. To do so, we introduce a slack variable λ and rewrite problem (16) as

$$\min_{\lambda, \bar{\Phi}} T_K(P_j \text{tr}(\mathbf{F}_j \bar{\Phi}) + \sigma^2) - \lambda \text{tr}(\mathbf{F}_K \bar{\Phi}) \quad (17a)$$

$$\text{s.t. } p_k \text{tr}(\mathbf{F}_k \bar{\Phi}) \geq T_k(P_j \text{tr}(\mathbf{F}_j \bar{\Phi}) +$$

$$\sum_{i=k+1}^K p_i \text{tr}(\mathbf{F}_i \bar{\Phi}) + \sigma^2), \quad k = 1, \dots, K-1 \quad (17b)$$

$$|\bar{\Phi}(n, n)| \leq \beta_{\max}, \quad n = 1, \dots, N \quad (17c)$$

$$|\bar{\Phi}(N+1, N+1)| = 1. \quad (17d)$$

The Dinkelbach procedure operates by iteratively solving for λ and $\bar{\Phi}$. For fixed $\bar{\Phi}$, the solution for λ can be obtained in closed form:

$$\lambda = \frac{T_K(P_j \text{tr}(\mathbf{F}_j \bar{\Phi}) + \sigma^2)}{\text{tr}(\mathbf{F}_K \bar{\Phi})}. \quad (18)$$

Once λ is found, the optimization for $\bar{\Phi}$ is convex. This inner iteration between λ and $\bar{\Phi}$ continues until a convergence criterion is met. As a final step, the rank of the solution must be examined as a result of the SDR. Let $\bar{\Phi}^*$ denote the solution after convergence. If the rank of $\bar{\Phi}^*$ is 1, the optimal solution for $\bar{\phi}$ is obtained directly using an eigenvalue decomposition. Otherwise, a rank-one approximation or Gaussian randomization must be employed to find $\bar{\phi}^*$. The optimal A-RIS response ϕ^* is found via the normalization $\phi^* = \bar{\phi}^*(1:N)/\bar{\phi}^*(N+1)$.

C. Algorithm Initialization

Our empirical results indicate that the procedure outlined above critically depends on proper initialization. We have found that the following initialization procedure works well, based on the observation that, for sufficiently large N , the optimal $\bar{\Phi}$ tends to eliminate the contribution of the jammer at the BS:

- 1) Solve the following convex problem to find a $\bar{\Phi}^{(-1)}$ that minimizes the jammer power at the BS:

$$\bar{\Phi}^{(-1)} = \arg \min_{\bar{\Phi}} \text{tr}(\mathbf{F}_j \bar{\Phi}) \quad (19a)$$

$$\text{s.t. } |\bar{\Phi}(n, n)| \leq \beta_{\max}, \quad n = 1, \dots, N \quad (19b)$$

$$|\bar{\Phi}(N+1, N+1)| = 1. \quad (19c)$$

The solution to (19) is typically not unique.

- 2) Use $\bar{\Phi}^{(-1)}$ in (14) to compute the initial set of user powers \mathbf{p}^0 .
- 3) Find the initial A-RIS response $\bar{\Phi}^{(0)}$ as the one that minimizes the jammer power at the BS, and satisfies the SINR constraints based on $\mathbf{p}^{(0)}$:

$$\bar{\Phi}^{(0)} = \arg \min_{\bar{\Phi}} \text{tr}(\mathbf{F}_j \bar{\Phi}) \quad (20a)$$

$$\text{s.t. } p_k^{(0)} \text{tr}(\mathbf{F}_k \bar{\Phi}) \geq T_k(P_j \text{tr}(\mathbf{F}_j \bar{\Phi}) +$$

$$+ \sum_{i=k+1}^K p_i^{(0)} \text{tr}(\mathbf{F}_i \bar{\Phi}) + \sigma^2),$$

$$k = 1, \dots, K-1 \quad (20b)$$

$$|\bar{\Phi}(n, n)| \leq \beta_{\max}, \quad n = 1, \dots, N \quad (20c)$$

$$|\bar{\Phi}(N+1, N+1)| = 1. \quad (20d)$$

This is also a convex problem and is easily solvable.

With the initialization procedure defined above, the overall algorithm is summarized as Algorithm 1 below.

V. PERFORMANCE ANALYSIS

In this section, we analyze the optimized performance of the A-RIS-assisted uplink NOMA system in Fig. 2 using Algorithm 1 in various scenarios.

A. Performance for Various Number of Users With Fixed A-RIS Location

Here we study the performance of the proposed algorithm in terms of the sum total uplink transmit power for $K = 2$, $K = 3$, and $K = 4$ users, for various numbers of jammer antennas and A-RIS elements, assuming a fixed location of the A-RIS. We also assess the benefit and characterize the optimized behavior of the absorption capability of the A-RIS in terms of the average reflection coefficients of the A-RIS elements.

In Table I we show our simulation parameters. Here we assume a fixed network, whereas in Section V-B we relax this by studying the performance for various A-RIS locations. We focus on a scenario with static rather than random channel gains to ensure that the near-far relationship between the users remains the same throughout the simulation trials, which (together with the SINR constraints in the optimization) enables us to fix the decoding order rather than adding this as

$$\mathbf{A} = \begin{bmatrix} -\text{tr}(\mathbf{F}_1 \bar{\Phi}) & T_1 \text{tr}(\mathbf{F}_2 \bar{\Phi}) & T_1 \text{tr}(\mathbf{F}_3 \bar{\Phi}) & \dots & T_1 \text{tr}(\mathbf{F}_K \bar{\Phi}) \\ 0 & -\text{tr}(\mathbf{F}_2 \bar{\Phi}) & T_2 \text{tr}(\mathbf{F}_3 \bar{\Phi}) & \dots & T_2 \text{tr}(\mathbf{F}_K \bar{\Phi}) \\ 0 & 0 & -\text{tr}(\mathbf{F}_3 \bar{\Phi}) & \dots & T_3 \text{tr}(\mathbf{F}_K \bar{\Phi}) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & -\text{tr}(\mathbf{F}_K \bar{\Phi}) \end{bmatrix} \quad (15a)$$

$$\mathbf{b} = \begin{bmatrix} -T_1(P_j \text{tr}(\mathbf{F}_1 \bar{\Phi}) - \sigma^2) \\ -T_2(P_j \text{tr}(\mathbf{F}_2 \bar{\Phi}) - \sigma^2) \\ -T_3(P_j \text{tr}(\mathbf{F}_3 \bar{\Phi}) - \sigma^2) \\ \vdots \\ -T_K(P_j \text{tr}(\mathbf{F}_K \bar{\Phi}) - \sigma^2) \end{bmatrix}. \quad (15b)$$

Algorithm 1 LP + Dinkelbach Approach

Require: Channel state information, P_j , σ^2 , thresholds $\{T_k\}$, β_{\max} , convergence thresholds ϵ_1, ϵ_2
Ensure: Optimal A-RIS configuration ϕ^* , minimum user transmit powers $\{p_k^*\}$

- 1: **Initialization**
- 2: Solve (19) to find $\bar{\Phi}^{(-1)}$
- 3: Compute \mathbf{p}^0 using $\bar{\Phi}^{(-1)}$ in (14)
- 4: Compute $\bar{\Phi}^{(0)}$ using \mathbf{p}^0 in (20)
- 5: $q = 1$
- 6: **repeat**
- 7: Compute $\mathbf{p}^{(q)}$ using $\bar{\Phi}^{(q-1)}$ in (14)
- 8: $\text{diff1}(q) = \mathbf{p}^{(q)} - \mathbf{p}^{(q-1)}$
- 9: Initialize $\lambda^{(0)}$ using $\bar{\Phi}^{(q-1)}$ in (18)
- 10: $\ell = 1$
- 11: **repeat**
- 12: Compute $\bar{\Phi}^{(q,\ell)}$ using $\mathbf{p}^{(q)}$ and $\lambda^{(\ell-1)}$ in (17)
- 13: Compute $\lambda^{(\ell)}$ using $\bar{\Phi}^{(q,\ell)}$ in (18)
- 14: $\text{diff2}(\ell) = \lambda^{(\ell)} - \lambda^{(\ell-1)}$
- 15: $\ell \leftarrow \ell + 1$
- 16: **until** $\text{diff2}(\ell - 1) < \epsilon_2$
- 17: $\bar{\Phi}^{(q)} = \bar{\Phi}^{(q,\ell-1)}$
- 18: $q \leftarrow q + 1$
- 19: **until** $\text{diff1}(q - 1) < \epsilon_1$
- 20: Set $\mathbf{p}^* = \mathbf{p}^{(q-1)}$
- 21: Set $\bar{\Phi}^* = \bar{\Phi}^{(q)}$
- 22: Perform a rank-one decomposition or Gaussian randomization on $\bar{\Phi}^*$ to find $\bar{\phi}^*$, then set $\phi^* = \bar{\phi}^*(1 : N)/\bar{\phi}^*(N + 1)$.
- 23: **return**

TABLE I
SUMMARY OF SIMULATION PARAMETERS

Variable	Description	Value
P_j	Normalized jammer antenna power (Watt)	10
T_1	Targeted SINR threshold for UE ₁	5
T_2	Targeted SINR threshold for UE ₂	5
T_3	Targeted SINR threshold for UE ₃	5
σ^2	AWGN power at BS receiver	1
β_{\max}	Maximum A-RIS reflection coefficient	1
$\mathbb{E} h_1 $	Gain between UE ₁ & BS	5
$\mathbb{E} h_2 $	Gain between UE ₂ & BS	2
$\mathbb{E} h_3 $	Gain between UE ₃ & BS	1
$\mathbb{E} f(n) $	Gain between A-RIS & BS	2
$\mathbb{E} g_1(n) $	Gain between UE ₁ & A-RIS	1
$\mathbb{E} g_2(n) $	Gain between UE ₂ & A-RIS	1
$\mathbb{E} g_3(n) $	Gain between UE ₃ & A-RIS	0.2
$\mathbb{E} h_i(n) $	Gain between jammer & BS	1
$\mathbb{E} G_i(n, m) $	Gain between jammer & A-RIS	0.2

an additional complication to the simulation. The benefit of the A-RIS in mitigating the jamming for the NOMA system is ultimately independent of this assumption, so the purpose is mainly to simplify our experiments. Note that for numerical stability in the optimization, we normalize the noise at the BS as $\sigma^2 = 1$ and scale the path losses correspondingly. The chosen path loss values are representative for a network with

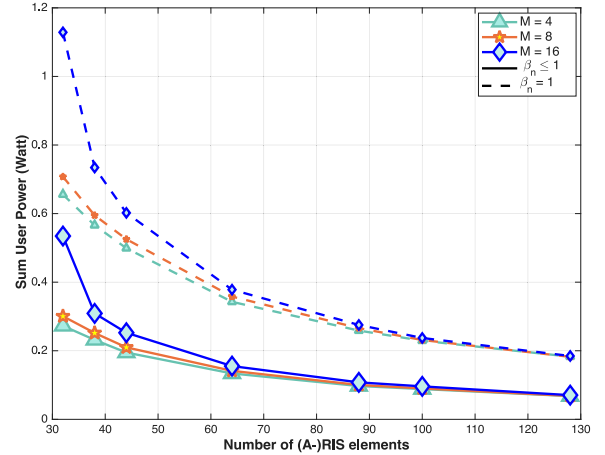


Fig. 4. Total transmit power required to meet the user quality of service constraints in the presence of a jammer with $M = 4, 8, 16$ antennas, as a function of the number of (A-)RIS elements $N = 32, 38, 44, 64, 88, 100, 128$ for $K = 2$ users.

inter-node distances of a few tens of meters, assuming path loss exponent $\alpha = 3$.

We choose to focus on a jammer with a rather large number of antennas M and also an A-RIS with a large number of elements N . This is an interesting case in practice, since in mm-wave systems a rather large number of antennas/elements would be needed, and we want to show the capability of Algorithm 1 to find a solution for such large optimization problems. This is in contrast to our initial work in [25] using the Matlab *fmincon* tool, in which we could not find an optimal solution for a jammer larger than $M = 16$ in combination with A-RIS larger than $N = 32$. Note that we assume a maximum A-RIS reflection coefficient $\beta_{\max} = 1$, despite our discussions in Section III. The reason is that in our considered evaluation scenarios, a value of $\beta_{\max} < 1$ can simply be included in the assumed path losses to the A-RIS.

In Fig. 4 we show the total user transmit power required to meet the user QoS requirements in the presence of a jammer with $M = 4, 8, 16$ antennas, as a function of the number of A-RIS and conventional RIS elements $N = 32, 38, 44, 64, 88, 100, 128$ for $K = 2$ users. We see that a large A-RIS is very beneficial in mitigating the jammer's interference. The required sum transmit power drops from 0.28 W (24.5 dBm) to 0.07 W (18.5 dBm) when increasing the number of A-RIS elements from $N = 4$ to 128 for a jammer with $M = 4$ antenna elements. Doubling the number of jammer antennas to $M = 8$ does not significantly change the required total transmit power. However, with $M = 16$ there is a significant increase in the required sum user power for an A-RIS with 32 elements, increasing to 0.54 W (27.3 dBm), whereas for a large A-RIS the increase in sum user power is still small. As a result, the advantage of A-RIS over conventional passive RIS is most pronounced when N is small, or the jammer is strong (large M). Since a conventional RIS has fewer spatial degrees of freedom to mitigate interference, the users must transmit with increased power to overcome the additional interference.

As seen in Fig. 5, the reason for this is that absorption starts to be needed to mitigate the jammer: In the case of $N = 32$

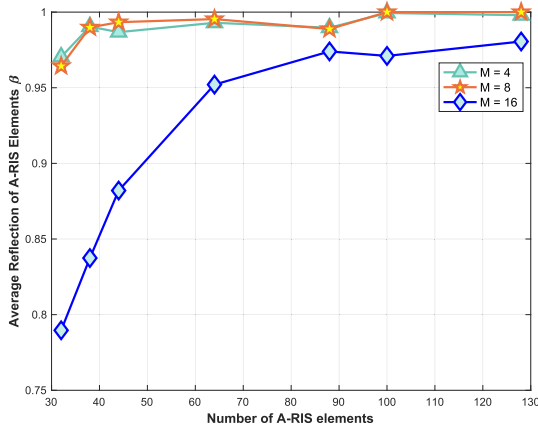


Fig. 5. Resulting average reflection as a function of the number of A-RIS elements $N = 32, 38, 44, 64, 88, 100, 128$ for $K = 2$ users in the presence of a jammer with $M = 4, 8, 16$ antennas.

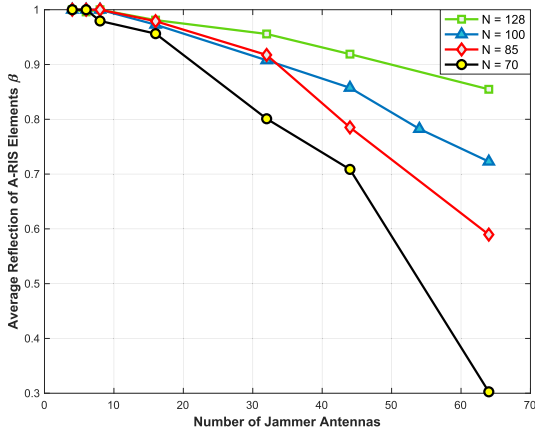


Fig. 6. Resulting average reflection level for jammers $M = 4, 6, 8, 16, 32, 44, 54, 64$ antennas for $70, 85, 100, 128$ A-RIS elements in case of $K = 2$ users.

and $M = 4, 8$ there is almost no absorption by the A-RIS with an average reflection close to $\bar{\beta} \approx 1$, whereas with $M = 16$ the average reflection gain drops to $\bar{\beta} = 0.8$ for $N = 32$, and then gradually increases to $\bar{\beta} \approx 1$ as N increases.

In Fig. 6, we further investigate the absorption behavior of the A-RIS as a function of the number of jammer antennas M and A-RIS elements N . Here we investigate larger M and N compared to Fig. 5, but the behavior of the A-RIS is the same. This also shows that Algorithm 1 converges well also for large M and N . In general, for the investigated deployment and propagation scenario here, it seems that with $N/M \approx 5$, absorption is not needed, whereas for $N/M \ll 5$, absorption is very useful. This can be explained by the required number of DoFs for the A-RIS to cancel the jammer signal.

In Fig. 7, we investigate the performance of the A-RIS compared with conventional passive RIS as a function of the number of A-RIS and conventional RIS elements for $K = 3$ users, and in Fig. 8, we investigate the performance and behavior of the A-RIS only in the case of $K = 3$ users. Algorithm 1 also converges very well in this case, and the overall behavior

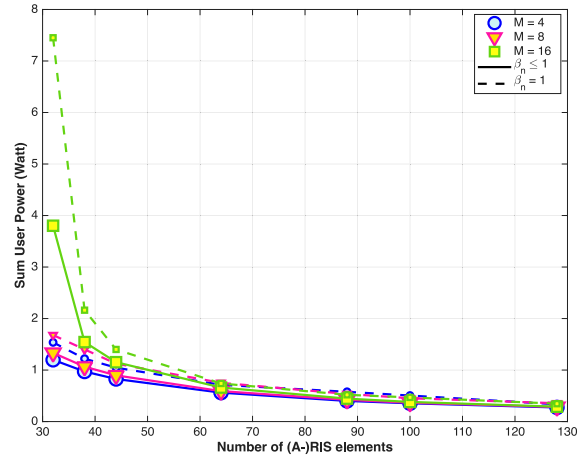


Fig. 7. Total transmit power required to meet the user quality of service constraints in the presence of a jammer with $M = 4, 8, 16$ antennas, as a function of the number of (A-)RIS elements $N = 32, 38, 44, 64, 88, 100, 128$ for $K = 3$ users.

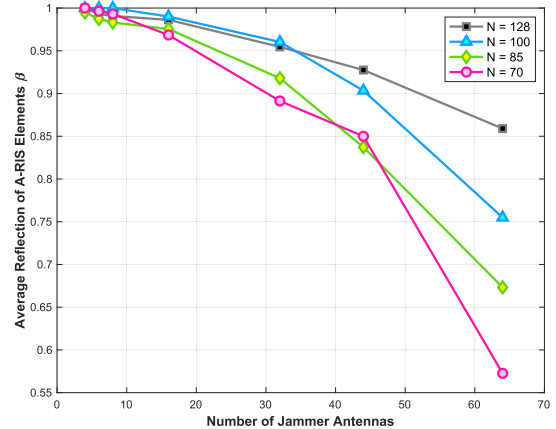


Fig. 8. Resulting average reflection of A-RIS for jammers with $M = 4, 6, 8, 16, 32, 44, 64$ antennas for $70, 85, 100, 128$ A-RIS elements in case of $K = 3$ users.

is the same as in the $K = 2$ users case. One difference comparing Fig. 7 with Fig. 4 is that the total required transmit power by the users is larger for $K = 3$ compared to $K = 2$, due to the residual NOMA multi-user interference for the users $k < K$ that is not canceled at the BS. Comparing Fig. 6 and Fig. 8 shows that the A-RIS absorption *decreases* for the larger number of users with increased multiuser interference (MUI). This is interesting since absorption *increases* when the jammer interference increases. The difference can be explained by the fact that the A-RIS is attempting to entirely cancel the jammer, while combating the MUI still requires the individual user signals to be received with a strong SNR.

In Table II we present a comparison of the total required transmit power in the presence of a jammer with different numbers of antennas $M = 4, 8, 16$ for $K = 2, K = 3$ and $K = 4$ users, with and without the assistance of an A-RIS. As shown, there is a very large gain with the A-RIS, up to more than a 28 dB gain in the required total transmit power. The results also clearly show that as the number

TABLE II

COMPARISON OF REQUIRED TOTAL POWER IN THE PRESENCE OF A JAMMER WITH $M = 4, 8, 16$ ANTENNAS FOR $K = 2, 3, 4$ USERS, WITH ($N = 32$) AND WITHOUT A-RIS

Num. of M	Num. of UE	No-RIS baseline	With A-RIS
$M = 4$	2 Users	0.27×10^3	0.27
	3 Users	0.51×10^4	1.19
	4 Users	1.65×10^4	10.68
$M = 8$	2 Users	0.59×10^3	0.30
	3 Users	0.89×10^4	1.33
	4 Users	1.35×10^4	11.90
$M = 16$	2 Users	1.07×10^3	0.54
	3 Users	1.90×10^4	3.80
	4 Users	2.72×10^4	36.53

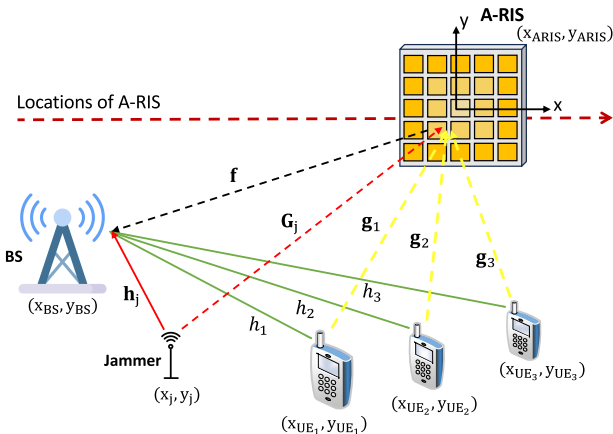


Fig. 9. Illustration of an A-RIS deployment with gradually larger distance to the BS compared to the jammer and the K users.

of jammer antennas M increases, the total power consumption increases more without an A-RIS than with an A-RIS. The reason for these gains is that the proposed A-RIS not only introduces an additional reflected link but also provides additional spatial degrees of freedom for shaping the effective channel. This enables more effective suppression of jammer-induced interference while enhancing the useful signal reception at the BS. Consequently, the system requires much less total user transmit power to satisfy the same QoS/SINR constraints. By contrast, in the no-RIS baseline, the users rely solely on the direct non-RIS-assisted links while still being affected by the jammer. Under the same QoS/SINR requirements, the optimization with no-RIS must therefore allocate much higher user transmit power. When increasing the number of users K from $K = 3$ to $K = 4$, there is a larger increase in the required total transmit power than going from $K = 2$ to $K = 3$ users, indicating that using the A-RIS degrees of freedom to simultaneously mitigate the jammer and control the multi-user interference is getting more challenging. However, the gain compared to the case with no-RIS is still substantial.

B. Performance for Various A-RIS Locations

In order to understand the optimal behavior of the A-RIS under various propagation conditions, we analyze the

TABLE III

SUMMARY OF DEPLOYMENT PARAMETERS WITH MOVING A-RIS

Variable	Description	Value
K_0	Path loss factor	$3e5$
α_1	Path loss exponent for h_1, h_2, h_3	3
α_2	Path loss exponent for $h_j, G_j, f, g_1, g_2, g_3$	2
x_{BS}, y_{BS}	Location of BS (m)	0, 0
x_{ARIS}, y_{ARIS}	Locations of A-RIS (m)	10-200, 65
x_j, y_j	Location of jammer (m)	50, -80
x_{UE1}, y_{UE1}	Location of UE ₁ (m)	30, -15
x_{UE2}, y_{UE2}	Location of UE ₂ (m)	50, -30
x_{UE3}, y_{UE3}	Location of UE ₃ (m)	80, -45

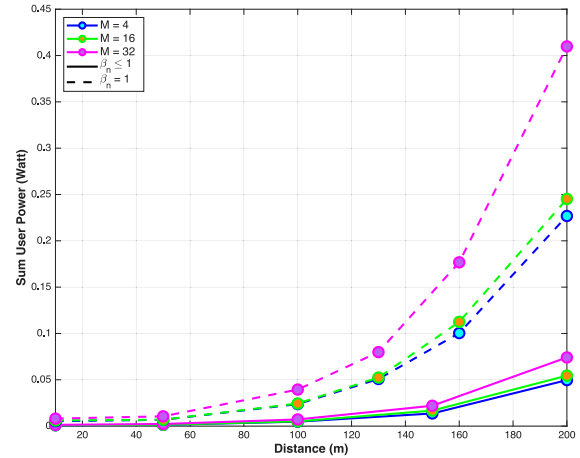


Fig. 10. Total transmit power required as a function of distance when moving an (A-)RIS with $N = 64$ elements away from the BS for a jammer having $M = 4, 16, 32$ antennas and $K = 3$ users. Distance refers to the coordinate along the x -axis.

performance of a range of A-RIS locations, as illustrated in Fig. 9. By changing the locations of the A-RIS, the path loss for all the channels to/from the A-RIS changes. We initially locate the A-RIS closer to the BS than any of the K users, and also closer than the jammer. Then we gradually move the A-RIS further away from the BS towards the jammer and the users, until the distance to the BS becomes larger compared to the distance to the BS for the jammer and any of the K users.

We adopt a two-dimensional deployment model described by the (x, y) positions of the nodes, as defined in Fig. 9. We then position the A-RIS at various locations along the x -axis, with the BS at the origin, and the jammer and users at the fixed locations given in Table III. The related path losses are then calculated for all the channel components.

We use the path loss model $P_r/P_t = K_0/d^\alpha$, in which we assume path loss exponent $\alpha_1 = 3$ for all UE-BS channels, and free space path loss, $\alpha_2 = 2$, for all other channels. These path loss exponents can be motivated by assuming the A-RIS is positioned in a location with favorable propagation conditions, and assuming the jammer also would strive for favorable propagation conditions. For numerical stability in the optimization, we normalize the noise at the BS as $\sigma^2 = 1$ and scale the path loss factor K_0 correspondingly. All other non-channel related parameters are the same as in Table I.

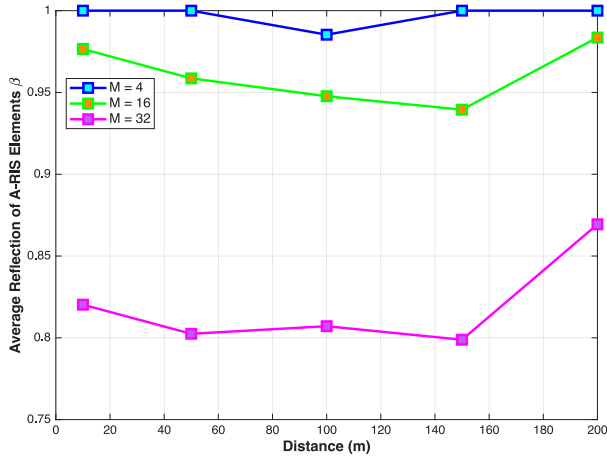


Fig. 11. Average amplitude of the A-RIS reflection coefficients as the A-RIS moves away from the BS for a case with $K = 3$ users, $N = 64$ A-RIS elements, $M = 4, 16, 32$ jammer antennas. Distance refers to the coordinate along the x -axis.

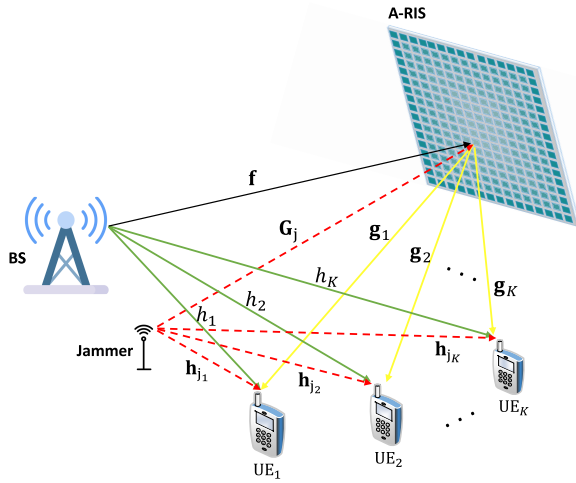


Fig. 12. Illustration of an A-RIS-aided downlink NOMA system with K users and a jammer.

In Fig. 10, we show the resulting total transmit power required as a function of the distance of the (A-)RIS from the BS in the presence of a jammer. We assume $N = 64$ (A-)RIS elements and a jammer with $M = 4, 16, 32$ antennas. As can be seen, the required total transmit power monotonically increases when the A-RIS is moving away from the BS. Moreover, for all distances and numbers of jammer antennas, the conventional passive RIS requires higher transmit power than the proposed A-RIS.

Fig. 11 plots the average amplitude of the optimal A-RIS as a function of the distance of the A-RIS from the BS. As in Fig. 10, we assume $N = 64$ A-RIS elements and the three curves are for a jammer with $M = 4, 16, 32$ antennas, respectively. As can be seen, the absorption is larger when the A-RIS is closer to the jammer and decreases as the A-RIS moves further away from the jammer and the users. We also see the effect discussed in the previous section, in which the absorption by the A-RIS increases with an increase in the dimension of the jammer array M . Specifically, for a

weak jammer $M = 4$, the interference is relatively limited, and the optimizer therefore selects β close to one (nearly full reflection) for all A-RIS locations. When the jammer array is larger, $M = 8$ and $M = 16$, the jamming component becomes more dominant, and the optimizer reduces β (i.e., increases absorption) to better suppress the jammer's impact.

C. Relevance of the Results for Downlink Scenario

Here we discuss the relevance of the results above for a corresponding downlink scenario, as illustrated in Fig. 12. We discuss an initial system model as a starting point for possible future work on A-RIS optimization. In general, the downlink problem is quite different, since in the downlink, the jammer has more than one potential target, more precisely, all K users. Thus, to analyze the downlink problem, we would need to define the objective of the jammer:

- Case 1: Select only one victim user,
- Case 2: Attack the users with some kind of priority,
- Case 3: Attack all the users with equal importance.

In Case 1, the jammer will optimize its signal to focus on attacking only a selected victim receiver. This case is similar to the uplink case, in which the jammer focuses on optimizing its attack only on the BS. However, a key difference is that in our uplink model, there is only one receiver, the BS, whereas in the downlink, there are still $K - 1$ other active receivers besides the one under attack that would still experience the jammer interference. Without loss of generality, assume that the jammer attacks user k_v . Furthermore, assume a typical power domain downlink NOMA system, in which the users' path losses are ordered with the strongest channel from user $k = 1$, and the weakest channel for the last user $k = K$. Then, unless the target downlink SINRs T_k are very different for the users, the BS will allocate more power to users with weaker channels. This enables each user to perform SIC for all other users with weaker path loss, i.e., higher user index k , before decoding its own signal. Under these assumptions, and assuming equal AWGN power σ^2 for all users with perfect SIC, the resulting SINR expressions are as follows, where $\sigma_j^2(k_v, k)$ denotes the jammer power at user k optimized to attack user k_v :

$$\gamma_1 = \frac{p_1 |h_1 + \mathbf{g}_1^\top \Phi \mathbf{f}|^2}{\sigma_j^2(k_v, 1) + \sigma^2}, \quad (21)$$

$$\gamma_2 = \frac{p_2 |h_2 + \mathbf{g}_2^\top \Phi \mathbf{f}|^2}{p_1 |h_2 + \mathbf{g}_2^\top \Phi \mathbf{f}|^2 + \sigma_j^2(k_v, 2) + \sigma^2}, \quad (22)$$

$$\gamma_3 = \frac{p_3 |h_3 + \mathbf{g}_3^\top \Phi \mathbf{f}|^2}{(p_1 + p_2) |h_3 + \mathbf{g}_3^\top \Phi \mathbf{f}|^2 + \sigma_j^2(k_v, 3) + \sigma^2}, \quad (23)$$

and in general for user $k = 1, \dots, K$

$$\gamma_k = \frac{p_k |h_k + \mathbf{g}_k^\top \Phi \mathbf{f}|^2}{\sum_{i=1}^{k-1} p_i |h_k + \mathbf{g}_k^\top \Phi \mathbf{f}|^2 + \sigma_j^2(k_v, k) + \sigma^2}. \quad (24)$$

In Case 1, with a single-antenna victim receiver, the intelligent jammer would optimize its jamming signal \mathbf{x}_j as in the

uplink case described in Section II-B. Thus, it is straightforward to obtain an expression for the resulting received jammer power at user k optimized for jamming user k_v , as follows:

$$\sigma_j^2(k_v, k) = P_j \frac{\|(\mathbf{h}_{j,k}^\top + \mathbf{g}_k^\top \Phi \mathbf{G}_j)(\mathbf{h}_{j,k_v}^\top + \mathbf{g}_{k_v}^\top \Phi \mathbf{G}_j)^H\|^2}{\|\mathbf{h}_{j,k_v}^\top + \mathbf{g}_{k_v}^\top \Phi \mathbf{G}_j\|^2}, \quad (25)$$

which for the victim UE k_v becomes

$$\sigma_j^2(k_v, k_v) = P_j \|\mathbf{h}_{j,k_v}^\top + \mathbf{g}_{k_v}^\top \Phi \mathbf{G}_j\|^2, \quad k_v = 1, \dots, K. \quad (26)$$

This is an expression similar to the one when the jammer attacks the BS in the uplink case. If it is desired to optimize the total sum transmit power in this downlink case, we observe that, similar to the uplink case, γ_1 should equal T_1 , allowing us to eliminate one optimization parameter as in (9) (in the uplink, we eliminate p_K). However, since in general the path losses $\|\mathbf{h}_{j,k}\|$ are different between the jammer and the K different users, there is no straightforward way to map the power minimization problem in the downlink to Algorithm 1 due to point-to-multipoint channels from the jammer to the users, resulting in a user-dependent jammer power $\sigma_j^2(k_v, k)$.

In Case 2, one could define the jamming signal as a weighted sum of the jamming signals targeting each user, i.e. $\bar{\mathbf{x}}_j = (\sqrt{P_j}/\bar{\rho}) (\bar{\mathbf{h}}_j^\top + \bar{\mathbf{g}}^\top \Phi \mathbf{G}_j)^H$, where $\bar{\rho} = \|\bar{\mathbf{h}}_j^\top + \bar{\mathbf{g}}^\top \Phi \mathbf{G}_j\|$, $\bar{\mathbf{h}}_j = \sum_{i=1}^K \eta_i \mathbf{h}_{j,i}$, and $\bar{\mathbf{g}} = \sum_{i=1}^K \eta_i \mathbf{g}_i$, for some user weights $\{\eta_k\}, k = 1, \dots, K$ chosen by the jammer. In that case, it is straightforward to show that the jamming power at user k depends only on k ,

$$\sigma_j^2(k) = P_j \frac{\|(\mathbf{h}_{j,k}^\top + \mathbf{g}_k^\top \Phi \mathbf{G}_j)(\bar{\mathbf{h}}_j^\top + \bar{\mathbf{g}}^\top \Phi \mathbf{G}_j)^H\|^2}{\|\bar{\mathbf{h}}_j^\top + \bar{\mathbf{g}}^\top \Phi \mathbf{G}_j\|^2}. \quad (27)$$

In Case 3, one could define the objective of the jammer to maximize $\sigma_j^2(k_v, k) = \sigma_{j,0}^2$, i.e., a constant received jammer power for all users, independent of k . For propagation conditions in which there is a feasible solution for the jammer to meet this objective, one would end up with an optimization problem that could potentially be solved using Algorithm 1.

VI. CONCLUSION

In this paper, we have considered an uplink power-domain NOMA system assisted by an A-RIS in the presence of an intelligent jammer. An A-RIS can adaptively adjust both the amplitude and phase shift of its elements, providing more control of the surface, particularly for interference mitigation scenarios. A realistic model for constructing an A-RIS with independently tunable amplitude and phase was presented, together with important hardware characteristics that should be considered in realistic implementations.

An optimization problem was formulated whose goal is to minimize the total transmit power of the users under constraints on the SINR that the users achieve at the base station. The optimization is non-convex and of high dimension, so we reformulate it and employ an iterative approach that alternates between using linear programming to estimate the user powers and the Dinkelbach algorithm to determine the A-RIS coefficients.

Our simulation results demonstrate that A-RIS elements provide dramatic reductions in required total transmit power due to their ability to enhance the signals of interest and cancel the effects of the interference. We also demonstrated that if the number of elements in the intelligent surface is large, the A-RIS can provide additional degrees of freedom that enable increased signal enhancement and interference mitigation. We showed that the influence of the absorption is most important when the ratio of A-RIS elements to jammer antennas is not too large, i.e., when the extra degrees of freedom offered by the variable element amplitudes become crucial. Finally, we briefly discussed the relevance of our results for a corresponding downlink scenario.

VII. MONOTONICITY CONDITIONS

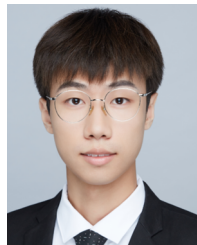
REFERENCES

- [1] L. Dai, B. Wang, Y. Yuan, S. Han, I. Chih-lin, and Z. Wang, "Non-orthogonal multiple access for 5G: Solutions, challenges, opportunities, and future research trends," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 74–81, Sep. 2015.
- [2] H. Sadia, M. Zeeshan, and S. A. Sheikh, "Performance analysis of downlink power domain NOMA under fading channels," in *Proc. ELEKTRO*, Mikulov, Czech Republic, May 2018, pp. 1–6.
- [3] T. M. Cover and J. A. Thomas, *Elements of Information Theory* (Wiley Series in Telecommunications and Signal Processing). Hoboken, NJ, USA: Wiley, 2006.
- [4] L. Xiao, Y. Li, C. Dai, H. Dai, and H. V. Poor, "Reinforcement learning-based NOMA power allocation in the presence of smart jamming," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 3377–3389, Apr. 2018.
- [5] Y. Liu et al., "Reconfigurable intelligent surfaces: Principles and opportunities," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 3, pp. 1546–1577, 3rd Quart., 2021.
- [6] G. Yang, X. Xu, Y.-C. Liang, and M. D. Renzo, "Reconfigurable intelligent surface-assisted non-orthogonal multiple access," *IEEE Trans. Wireless Commun.*, vol. 20, no. 5, pp. 3137–3151, May 2021.
- [7] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Trans. Wireless Commun.*, vol. 18, no. 11, pp. 5394–5409, Nov. 2019.
- [8] C. Huang et al., "Holographic MIMO surfaces for 6G wireless networks: Opportunities, challenges, and trends," *IEEE Wireless Commun.*, vol. 27, no. 5, pp. 118–125, Oct. 2020.
- [9] Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 106–112, Jan. 2020.
- [10] F. Wang and A. L. Swindlehurst, "Applications of absorptive reconfigurable intelligent surfaces in interference mitigation and physical layer security," *IEEE Trans. Wireless Commun.*, vol. 23, no. 5, pp. 3918–3931, May 2024.
- [11] Y. Liu et al., "STAR: Simultaneous transmission and reflection for 360° coverage by intelligent surfaces," *IEEE Wireless Commun.*, vol. 28, no. 6, pp. 102–109, Dec. 2021.
- [12] S. Zhang et al., "Intelligent omni-surfaces: Ubiquitous wireless transmission by reflective-refractive metasurfaces," *IEEE Trans. Wireless Commun.*, vol. 21, no. 1, pp. 219–233, Jan. 2022.
- [13] X. Hu, R. Zhang, and C. Zhong, "Semi-passive elements assisted channel estimation for intelligent reflecting surface-aided communications," *IEEE Trans. Wireless Commun.*, vol. 21, no. 2, pp. 1132–1142, Feb. 2022.
- [14] A. Albanese, F. Devoti, V. Sciancalepore, M. Di Renzo, and X. Costa-Pérez, "MARISA: A self-configuring metasurfaces absorption and reflection solution towards 6G," in *Proc. IEEE Conf. Comput. Commun.*, London, United Kingdom, May 2022, pp. 250–259.
- [15] L. V. Nguyen and A. Lee Swindlehurst, "Decision-directed hybrid RIS channel estimation with minimal pilot overhead," *IEEE Trans. Commun.*, vol. 72, no. 10, pp. 6505–6519, Oct. 2024.
- [16] F. Wang and A. L. Swindlehurst, "Hybrid RIS-assisted interference mitigation for spectrum sharing," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, Rhodes Island, Greece, Jun. 2023, pp. 1–5.

- [17] L. V. Nguyen and A. L. Swindlehurst, "RIS-aided interference cancellation for joint device-to-device and cellular communications," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, Denver, CO, USA, Jun. 2024, pp. 602–607.
- [18] Y. Bi, Y. Wu, C. Hua, and F. Zou, "Evolutionary anti-jamming game in non-orthogonal multiple access system," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Waikoloa, HI, USA, Dec. 2019, pp. 1–6.
- [19] T. Wang, F. Fang, and Z. Ding, "An SCA and relaxation based energy efficiency optimization for multi-user RIS-assisted NOMA networks," *IEEE Trans. Veh. Technol.*, vol. 71, no. 6, pp. 6843–6847, Jun. 2022.
- [20] Y. Xiu et al., "Reconfigurable intelligent surfaces aided mmWave NOMA: Joint power allocation, phase shifts, and hybrid beamforming optimization," *IEEE Trans. Wireless Commun.*, vol. 20, no. 12, pp. 8393–8409, Dec. 2021.
- [21] X. Li, Z. Xie, G. Huang, J. Zhang, M. Zeng, and Z. Chu, "Sum rate maximization for RIS-aided NOMA with direct links," *IEEE Netw. Lett.*, vol. 4, no. 2, pp. 55–58, Jun. 2022.
- [22] L. Liu, H. Wang, and R. Song, "Optimization for multi-cell NOMA systems assisted by multi-RIS with inter-RIS reflection," *IEEE Commun. Lett.*, vol. 28, no. 1, pp. 123–127, Jan. 2024.
- [23] W. Feng et al., "Resource allocation for power minimization in RIS-assisted multi-UAV networks with NOMA," *IEEE Trans. Commun.*, vol. 71, no. 11, pp. 6662–6676, Nov. 2023.
- [24] C. Zhang, W. Yi, Y. Liu, Z. Ma, and X. Zhang, "NOMA for multi-cell RIS networks: A stochastic geometry model," *IEEE Trans. Wireless Commun.*, vol. 23, no. 8, pp. 10398–10413, Aug. 2024.
- [25] A. Tabeshnezhad, A. L. Swindlehurst, and T. Svensson, "RIS-assisted interference mitigation for uplink NOMA," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Glasgow, U.K., Mar. 2023, pp. 1–5.
- [26] W. U. Khan et al., "Integration of NOMA with reflecting intelligent surfaces: A multi-cell optimization with SIC decoding errors," *IEEE Trans. Green Commun. Netw.*, vol. 7, no. 3, pp. 1554–1565, Sep. 2023.
- [27] C. Han, A. Liu, Z. Gao, K. An, G. Zheng, and S. Chatzinotas, "Anti-jamming transmission in NOMA-based satellite-enabled IoT: A game-theoretic framework in hostile environments," *IEEE Internet Things J.*, vol. 10, no. 23, pp. 20311–20322, Dec. 2023.
- [28] V.-L. Dao, L.-N. Hoang, S. Girs, and E. Uhlemann, "Defeating jamming using outage performance aware joint power allocation and access point placement in uplink pairwise NOMA," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 1957–1979, 2021.
- [29] H. Wang, Y. Fu, R. Song, Z. Shi, and X. Sun, "Power minimization precoding in uplink multi-antenna NOMA systems with jamming," *IEEE Trans. Green Commun. Netw.*, vol. 3, no. 3, pp. 591–602, Sep. 2019.
- [30] W. Wang et al., "Beamforming and jamming optimization for IRS-aided secure NOMA networks," *IEEE Trans. Wireless Commun.*, vol. 21, no. 3, pp. 1557–1569, Mar. 2022.
- [31] X. Tang, D. Wang, R. Zhang, Z. Chu, and Z. Han, "Jamming mitigation via aerial reconfigurable intelligent surface: Passive beamforming and deployment optimization," *IEEE Trans. Veh. Technol.*, vol. 70, no. 6, pp. 6232–6237, Jun. 2021.
- [32] Y. Sun et al., "RIS-assisted robust hybrid beamforming against simultaneous jamming and eavesdropping attacks," *IEEE Trans. Wireless Commun.*, vol. 21, no. 11, pp. 9212–9231, Nov. 2022.
- [33] M. Ji, J. Chen, L. Lv, Q. Wu, Z. Ding, and N. Al-Dhahir, "Secure NOMA systems with a dual-functional RIS: Simultaneous information relaying and jamming," *IEEE Trans. Commun.*, vol. 71, no. 11, pp. 6514–6528, Nov. 2023.
- [34] H. Al-Obiedollah, H. A. Bany Salameh, and E. Benkhelifa, "Jamming-resilient fairness-oriented resource allocation technique for IRS-assisted NOMA 6G-enabled IoT networks," *IEEE Trans. Consum. Electron.*, vol. 70, no. 3, pp. 5796–5803, Aug. 2024.
- [35] J. Li, Z. Song, T. Hou, J. Gao, A. Li, and Z. Tang, "An RIS-aided interference mitigation-based design for MIMO-NOMA in cellular networks," *IEEE Trans. Green Commun. Netw.*, vol. 8, no. 1, pp. 317–329, Mar. 2024.
- [36] G. Asemian, M. Amini, and B. Kantarci, "Active RIS-NOMA uplink in URLLC, jamming mitigation via surrogate and deep learning," *IEEE Open J. Commun. Soc.*, vol. 6, pp. 690–707, 2025.
- [37] X. Kang, H. Lei, L. Yang, G. Pan, T. A. Tsiftsis, and H. Liu, "Active-RIS-aided covert communications in NOMA systems with cooperative jamming," *IEEE Trans. Veh. Technol.*, vol. 73, no. 5, pp. 7436–7440, May 2024.
- [38] M. A. Uusitalo et al., "6G vision, value, use cases and technologies from European 6G flagship project Hexa-X," *IEEE Access*, vol. 9, pp. 160004–160020, 2021.
- [39] W. Dinkelbach, "On nonlinear fractional programming," *Manage. Sci.*, vol. 13, no. 7, pp. 492–498, Mar. 1967.
- [40] Y. Saifullah, Y. He, A. Boag, G.-M. Yang, and F. Xu, "Recent progress in reconfigurable and intelligent metasurfaces: A comprehensive review of tuning mechanisms, hardware designs, and applications," *Adv. Sci.*, vol. 9, no. 33, Nov. 2022, Art. no. 2203747.
- [41] Y. Zhu et al., "Millimeter-wave reconfigurable intelligent surface with independent and continuous amplitude-phase control: Unit cell design and circuit model," *IEEE Trans. Antennas Propag.*, vol. 73, no. 10, pp. 7627–7641, Oct. 2025.
- [42] J. Liao, S. Guo, L. Yuan, C. Ji, C. Huang, and X. Luo, "Independent manipulation of reflection amplitude and phase by a single-layer reconfigurable metasurface," *Adv. Opt. Mater.*, vol. 10, no. 4, Feb. 2022, Art. no. 2101551.
- [43] G. Minatti, F. Caminita, E. Martini, and S. Maci, "Flat optics for leaky-waves on modulated metasurfaces: Adiabatic floquet-wave analysis," *IEEE Trans. Antennas Propag.*, vol. 64, no. 9, pp. 3896–3906, Sep. 2016.
- [44] Z.-Q. Luo, W.-K. Ma, A. M. So, Y. Ye, and S. Zhang, "Semidefinite relaxation of quadratic optimization problems," *IEEE Signal Process. Mag.*, vol. 27, no. 3, pp. 20–34, May 2010.



Azadeh Tabeshnezhad (Member, IEEE) received the M.Sc. degree in communication systems from the Science and Research Branch, Tehran, Iran, in 2018. She is currently pursuing the Ph.D. degree with Chalmers University of Technology, Sweden. She was a Visiting Researcher with the University of California, Irvine, USA, in 2022, 2024, and 2025, under the co-supervision of Prof. Arnold Lee Swindlehurst. Her research interests include non-orthogonal multiple access, (non-)convex optimization, reconfigurable intelligent surfaces, and integrated sensing and communications.



Yuqing Zhu (Member, IEEE) received the B.S. degree in electronic information engineering and the M.S. degree in electronics science and technology from Beijing Institute of Technology, Beijing, China, in 2019 and 2022, respectively. He is currently pursuing the Ph.D. degree with the Antenna Systems Group, Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden. His current research interests include millimeter-wave antennas and arrays, phased array antennas, 5G/6G mobile terminal antennas, reconfigurable intelligent surfaces, and over-the-air testing techniques. He was a recipient of the Oral Best Paper Award at ICEICT 2020, the Best Student Paper Award at ICMMT 2022, and the Student Travel Grant at AP-S/URSI 2024 from the IEEE Antennas and Propagation Society. He serves as a Reviewer for IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION.



Artem R. Vilenskiy (Senior Member, IEEE) received the Specialist degree (summa cum laude) in radio engineering and the Ph.D. degree in antennas and microwave devices from Bauman Moscow State Technical University, Moscow, Russia, in 2011 and 2014, respectively. From 2011 to 2019, he was with Samsung Research Institute Russia, Moscow, where he had the role of a Researcher, an Expert Engineer, and the Project Leader with the Electromagnetics Group and RF Sensor Part. From 2015 to 2019, he was an Associate Professor with the Radio-Electronic Systems and Devices Department of Bauman Moscow State Technical University. Since 2019, he has been a Researcher with Antenna Systems Group, Chalmers University of Technology, Gothenburg, Sweden. His current research interests include array antennas, periodic structures, integrated circuit design, and controllable high-frequency materials and devices, as well as computational electromagnetics.



Van Ly Nguyen (Member, IEEE) received the M.Sc. degree in wireless communications from Centrale-Supélec, Paris-Saclay University, France, in 2016, and the Ph.D. degree in computational science from the University of California, Irvine (UCI) and San Diego State University (SDSU), USA, in 2022. Since August 2022, he has been a Post-Doctoral Researcher with the Department of Electrical Engineering and Computer Science, UCI. He is currently an Assistant Professor with the Electrical Engineering and Computer Science Department and the Institute of Information Sciences (I2S), The University of Kansas (KU), USA. His research interests include wireless communications, signal processing, and machine learning.



Arnold Lee Swindlehurst (Life Fellow, IEEE) received the B.S. and M.S. degrees in electrical engineering from Brigham Young University (BYU) in 1985 and 1986, respectively, and the Ph.D. degree in electrical engineering from Stanford University in 1991. He was with the Department of Electrical and Computer Engineering, BYU, from 1990 to 2007, where he was the Department Chair from 2003 to 2006. From 1996 to 1997, he held a joint appointment as a Visiting Scholar with Uppsala University and the Royal Institute of Technology, Sweden. From 2006 to 2007, he was on leave working as the Vice President of Research with ArrayComm LLC, San Jose, CA, USA. Since 2007, he has been with the Electrical Engineering and Computer Science (EECS) Department, University of California, Irvine, where he is currently a Distinguished Professor and the Department Chair. His research focuses on array signal processing for radar, wireless communications, and biomedical applications. He was also a Hans Fischer Senior Fellow of the Institute for Advanced Studies, Technical University of Munich, and in 2016, he was elected as a Foreign Member of the Royal Swedish Academy of Engineering Sciences (IVA). He received the 2000 IEEE W. R. G. Baker Prize Paper Award, the 2006 IEEE Communications Society Stephen O. Rice Prize in the Field of Communication Theory, the 2006, 2010, and 2021 IEEE Signal Processing Society's Best Paper Awards, the 2017 IEEE Signal Processing Society Donald G. Fink Overview Paper Award, a Best Paper award at the 2020 and 2024 IEEE International Conferences on Communications, the 2022 Claude Shannon-Harry Nyquist Technical Achievement Award from the IEEE Signal Processing Society, and the 2024 Fred W. Ellersick Prize from the IEEE Communications Society.



Tommy Svensson (Senior Member, IEEE) received the Ph.D. degree in information theory from Chalmers in 2003. He is currently a Full Professor in communication systems at Chalmers University of Technology, leading the Wireless Systems research on air interface and wireless backhaul networking technologies. He has worked at Ericsson AB with core, radio access, and microwave networks. He was active in European WINNER I/II/+ and ARTIST4G projects with important contributions to the 3GPP LTE standards, the EU METIS and mmMAGIC and 5GCar projects towards 5G and the EU Hexa-X and Hexa-X-II, RISE-6G, SEMANTIC, and newly started ROBUST-6G and ECO-eNET projects towards 6G, and in Chase/ChaseOn and newly started WiTECH antenna systems excellence centers at Chalmers targeting mm-wave and (sub)-THz solutions for access, backhaul/ fronthaul and V2X scenarios. His main research interests include design and analysis of mobile communication systems, physical layer algorithms, multiple access, resource allocation, cooperative/ context-aided/ secure communications, mm-wave/ sub-THz communications, C-V2X, JCAS, satellite networks, sustainable design, and end-to-end architecture. He has co-authored six books, 115 journal articles, 156 conference papers, and more than 80 public EU projects' deliverables. He is a founding member/editor of IEEE JSAC Series on Machine Learning in Communications and Networks, and a board member of Swedish Post and Telecom Authority (PTS). He has been Chair of the awards winning IEEE Sweden Vehicular Technology/ Communications/ Information Theory Societies Chapter, editor of IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, IEEE WIRELESS COMMUNICATIONS LETTERS, a Guest Editor of top journals, organized tutorials and workshops at top IEEE conferences, Led local organizer of EuCNC and 6G Summit 2023, and coordinator of the Communication Engineering Master's Program at Chalmers.