Advances in the Design of Reconfigurable Intelligent Surfaces using the Composite Vortex Theory

Mirko Barbuto* (1), Alessio Monti(1), Stefano Vellucci(2), Andrea Alù(3),
Filiberto Bilotti(1), and Alessandro Toscano(1)
(1) Department of Industrial, Electronic and Mechanical Engineering, "Roma Tre" University, Rome, Italy
(mirko.barbuto@uniroma3.it)
(2) Department of Engineering, "Niccolò Cusano" University, Rome, Italy
(3) Photonics Initiative, Advanced Science Research Center, City University of New York, New York, USA

Abstract

Reconfigurable Intelligent Surfaces (RIS) represent a groundbreaking technology in wireless communication, with applications in both reflective and transmitting configurations. Recent studies have proposed the use of Composite Vortex Theory (CVT) to simplify the reconfiguration process of RIS, albeit at the cost of reducing the degrees of freedom in the design space. In this contribution, we extend this approach by investigating how the degrees of freedom can be restored through the strategic selection of the order of the overlapping modes, tailored to specific application requirements. This offers a balance between simplified reconfiguration and enhanced flexibility, enabling optimized performance for diverse use cases. Numerical results and theoretical insights illustrate the viability of the proposed method.

1. Introduction

Reconfigurable Intelligent Surfaces (RIS) have emerged as a pivotal innovation in the evolution of wireless communication technologies [1]-[2]. By enabling dynamic manipulation of electromagnetic waves, RIS offer a powerful means to enhance signal quality, improve energy efficiency, and address the increasing demands for capacity and connectivity in next-generation wireless networks. Traditionally, RIS configurations have focused on reflective designs, with substantial research dedicated to modelling and optimizing their operation [3]-[4]. However, transmitting RIS have recently gained attention for their ability to further expand the versatility of this technology by enabling the controlled transmission of electromagnetic waves through the surface [5].

A critical challenge in deploying RIS, whether reflective or transmitting, lies in their reconfiguration. The ability to reconfigure RIS with minimal computational and physical complexity is essential for their practical implementation, especially in scenarios with dynamic environmental conditions or stringent latency requirements. Recent advances, including our previous work, have shown that the Composite Vortex Theory (CVT) provides a promising approach to simplifying RIS reconfiguration [6]-[8]. CVT exploits overlapping vortex modes to control the overall field behavior, significantly reducing the complexity of the reconfiguration process. However, this simplicity comes at the cost of reduced degrees of freedom, which may limit the flexibility and adaptability of RIS in certain applications.

In this contribution, we investigate the foundations of CVT to address this limitation. Specifically, we propose to restore the degrees of freedom in RIS design by strategically selecting the number or order of overlapping modes based on application-specific requirements. This extended approach balances the trade-off between simplified reconfiguration and enhanced flexibility, allowing RIS to achieve optimized performance across a range of use cases.

The remainder of this contribution is organized as follows. Section II briefly reviews the fundamentals of the Composite Vortex Theory and its role in RIS design. Section III introduces the proposed approach, detailing the methodology for restoring degrees of freedom and presenting preliminary numerical results to validate the approach. Finally, Section IV concludes the paper and outlines directions for future research.

2. Fundamental of Composite Vortex Theory for RIS Design

The CVT provides a novel approach for analyzing and controlling electromagnetic wave interactions, offering a promising solution to RIS design and reconfiguration. At its core, CVT utilizes the concept of vortex modes, which are electromagnetic fields characterized by their helical phase fronts and inherent angular momentum properties. By overlapping multiple vortex modes with different orders or phase shifts, a structured electromagnetic field is generated, which can be tailored to achieve specific wave propagation characteristics [9].

In the context of RIS, CVT enables the design of reflective or transmitting surfaces capable of dynamically shaping and directing electromagnetic waves with reduced complexity. This is achieved by dividing the RIS structure in two concentric regions, each one with the associated parameters of the vortex modes, such as the mode order and relative phase shift, as shown in Figure 1. The resulting electromagnetic field distributions are highly controllable, making it possible to achieve desired functionalities like beamforming, steering, and focusing. Moreover, a notable property is the possibility to analytically calculate the overall scattering pattern, simplifying the design phase [10].

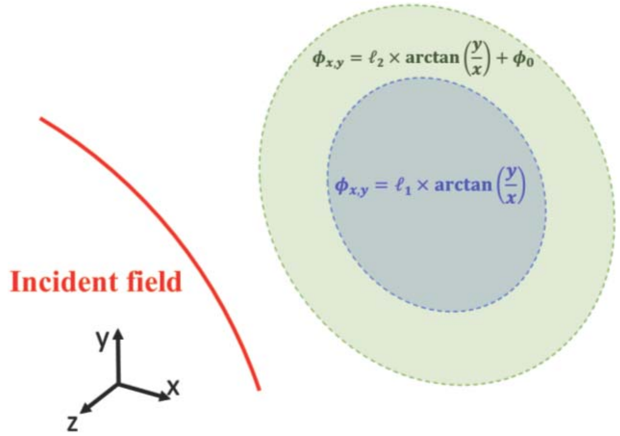

Figure 1. Schematic representation of a RIS structure divided in two concentric regions, each one imparting a different helical phase profile ($\varphi_{x,y}$) to the impinging beam.

As an example, we have recently proposed to use CVT to control the angle of reflection of the RIS by adopting a simplified 1-bit reconfiguration scheme [7]. This approach exploits the overlapping vortex modes to achieve precise wavefront manipulation despite the binary control constraints, offering a cost-effective and energy-efficient solution for dynamic beam steering. Another possible configuration involves the use of a statically configured surface, where the reconfiguration of the reflected beam is achieved by adjusting the illuminated area of the incident beam [8]. In this setup, the interaction between the incident wave and the RIS is complemented by reflections from the supporting wall, effectively expanding the reconfiguration capabilities.

However, in both cases, the use of CVT introduces a reduction in the degrees of freedom: once the order of the modes is fixed, the shape of the scattering pattern or the maximum angle of reflection becomes inherently constrained. This trade-off highlights the need for further exploration of methods to restore flexibility while maintaining the benefits of simplified reconfiguration.

3. Extending the Degrees of Freedom through Mode Selection

While the CVT simplifies the reconfiguration process of RIS, the choice of vortex modes plays a critical role in determining the resulting scattering patterns and operational flexibility. In this section, we present two illustrative examples that demonstrate how the strategic selection of overlapping modes can unlock additional configurations, expanding the applicability of RIS for diverse communication scenarios.

3.1 Generating Sectorial, Saddle-Shaped, and Flower-Shaped Scattering Patterns

Scattering pattern design is a key aspect of RIS functionality, as it determines how electromagnetic waves are distributed in space. By combining a vortex-free mode with a second-order vortex mode, it is possible to create scattering patterns characterized by two distinct nulls [11]. These nulls can be exploited to generate sectorial or saddle-shaped patterns [11], which are particularly advantageous for applications such as mobile communications or satellite systems. In this design, the RIS surface is divided into two distinct regions: an inner region that imparts a constant phase shift, corresponding to the vortex-free mode, and an outer region that imparts a helical phase profile of the second order. The balance between these two regions controls the relative amplitude of the modes and determines whether the resulting scattering pattern takes on a sectorial or saddle-shaped form.
A flower-shaped pattern, on the other hand, is generated by exploiting the increasing number of scattering nulls introduced by higher-order modes combined with a vortex mode of the first order. This design similarly relies on dividing the RIS surface into regions with distinct phase profiles but uses higher-order modes to create multiple nulls. These nulls create multiple lobes in the scattering distribution, which can be tailored for scenarios requiring simultaneous multi-directional coverage, such as multi-user communications.
Figure 1 illustrates the analytically derived scattering pattern for this configurations, highlighting their corresponding peculiar shapes. It is important to note that this analysis assumes ideal sheets able of perfectly imparting the required phase profile to the impinging field. In practical implementations, however, a realistic RIS with a finite number of discrete elements can be employed (see, for instance, [7]).

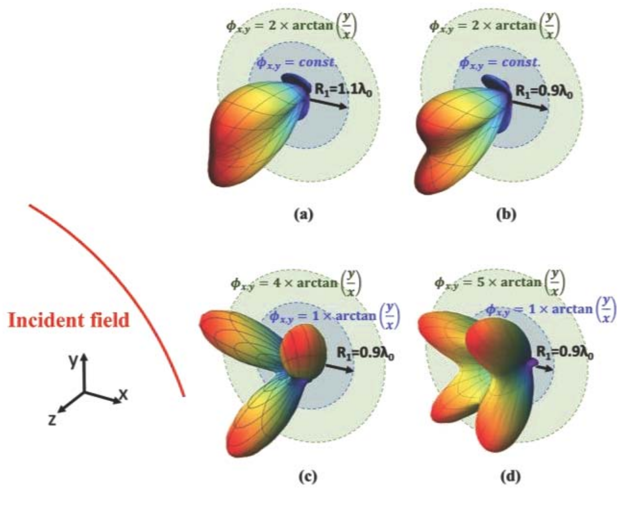

Figure 2. Examples of scattering patterns generated using a combination of vortex modes: (a) sectorial-shaped pattern; (b) saddle-shaped pattern; (c) flower-shaped pattern. In all the cases, $R_2 = 1.5\lambda_0$.

3.2 Extending the Maximum Steering Angle

According to the CVT, achieving a single null requires the inner region of the RIS to be designed with a vortex mode whose order is one lower than that of the outer region [11]. This specific configuration creates the desired interference pattern with a single null, which is critical for tilting the beam effectively. The maximum steering angle is determined by the divergence angle introduced by the higher-order vortex modes [7]. Therefore, to increasingly tilt the beam, both the inner and outer regions must have their respective vortex mode orders increased while maintaining the one-order difference between them.
As shown in Figure 2, by appropriately selecting the order of the vortex modes, the scattering pattern can be shaped to achieve larger steering angles without compromising the overall energy efficiency. This capability is particularly valuable in scenarios requiring wide-area coverage.

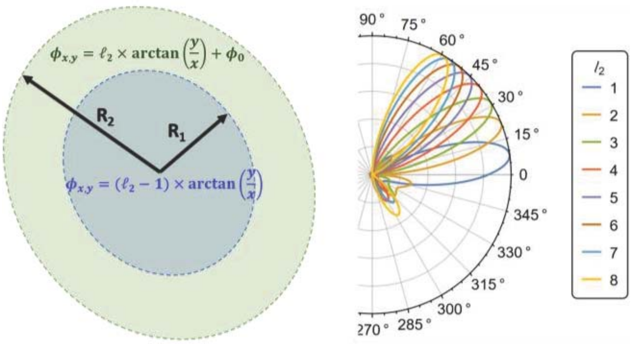

Figure 3. Scattering patterns illustrating the extended maximum steering angle achieved by increasing the vortex mode orders in the RIS design. The inner region employs a vortex mode with an order one lower than the outer region, generating a single null that steers the beam in the opposite direction (here $R_1 = \lambda_0$ and $R_2 = 1.3\lambda_0$).

4. Conclusions

In this work, we extended the CVT to enhance the flexibility of RIS by restoring degrees of freedom through strategic mode selection. Two examples were presented: the combination of vortex-free and vortex modes to generate sectorial, saddle-shaped or flower shaped scattering patterns, and the use of higher-order modes to extend the maximum beam steering angle. These results demonstrate the potential of CVT to balance simplicity in reconfiguration with enhanced versatility, making it suitable for applications such as mobile and satellite communications. More details about the different designs will be provided at the conference, including some practical implementations of the RIS structures.

5. Acknowledgements

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