Binary Reconfigurable Intelligent Surfaces with Angle-Independent Reflection Phase

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Abstract – In this presentation we investigate the use of physical optics (PO) approximation in the design of binary reconfigurable intelligent surfaces (RISs). We show that PO may be used to design and study RIS operating in a wide sheer of incidence and deviation angles if the reflection phase is angularly stable for uniform settings of the RIS array realizing both required phase shifts of reflected plane waves.

I. INTRODUCTION

Reconfigurable Intelligent Surfaces (RISs) are passive structures that enable smart radio environments by adding an extra signal path between access points and dead-zone users in high-frequency wireless networks. RISs promise a qualitative improvement of 5G and 6G networks [1]. Many RISs are based on metasurfaces (MSs) with controllable deflection (anomalous reflection). As per [2], the most common approach to designing MSs with deflection is to linearly change the local reflection phase $\Phi_R$ with the coordinate $x$ in the incidence plane. In this approach, it is often assumed by default that $\Phi_R(x)$ at the point $x$ is the same as if the whole MS was uniform. This approximation offers a fast method to design RISs. The technique utilized in this approach is the physical optics (PO) approximation. When PO is applied in cases of large incident and deflection angles, significant errors can arise, even in the case of infinite periodically non-uniform metasurfaces, as explained in [3]. Thus, it is crucial to identify the conditions under which this approximation is valid. Initially, it may appear that this approximation is applicable to any incidence and deflection angles. However, based on the Floquet theory, the angle of the $m$-th diffraction channel $\theta_m$ is related to the incidence angle $\theta_i$ as:

$$\sin \theta_m = \sin \theta_i + m\lambda / D.$$  

In this context, $\lambda$ represents the free-space wavelength, while $m$ is the spatial harmonic number. When both the incidence angle $\theta_i$ and deviation angle $\theta_d = \theta_i - \theta_m$ are small, i.e., $D \gg |m|\lambda$, the phase gradient remains low. As a result, the difference in loads between adjacent unit cells is minimal, making PO a reasonable approximation. However, for larger values of $\theta_i$ or $\theta_d$, $D$ must be comparable to $\lambda$, casting doubt on the applicability of PO. Despite this limitation, RISs must function with substantial incidence angles of up to $(60 - 75)^\circ$ and large deviation angles. Is it possible to extend the standard approach to this case?

II. RESULTS AND DISCUSSION

In a prior study [4], we introduced a uniform metasurface that maintains angular stability in reflection phases. Now, we show that it would enable the use of the PO for its non-uniform analogue with any $D$ as long as the requirement $D > |m|\lambda$ was met. This means that the conventional approach to designing a metasurface-based reconfigurable intelligent surface (RIS) is applicable as long as the uniform metasurface maintains angular stability for a significant range of incident angles $\theta_i$. To achieve this, we constructed a metasurface composed of metal Jerusalem crosses on a metal-backed dielectric substrate with optimized thickness and low-loss permittivity. We achieved angular stability of the reflection phase $\Phi_R$ for both polarizations across a wide frequency band.
Fig. 1: Full-wave simulations of RIS diffraction pattern for multi-user scenarios (TM polarization): (a) and (b) – our RIS, (c) and (d) – mushroom MS.

5 GHz) within the range of incident angles \( \theta_i \leq \pi/4 \) using analytical methods. As per numerical simulations and experiments, this resulted in an angular stability range of \( \theta_i \leq \pi/3 \). [4].

In this work, we show that the angular stability of local reflection phases in uniform MS can be a suitable condition for applying PO to design finite-size binary RISs. We have modified the design from [4] to accommodate K/Ku band frequencies (15 – 22 GHz) as our experimental setup enabled us to assess the operational characteristics within this range. Although possible, engineering such a metamaterial surface in the mm-wave or even THz range would require feasible electrically controllable capacitances. Our experiment did not necessitate real-time variation of the deflected wave angle, and we created a binary version of the metamaterial surface by fabricating two uniform metasurfaces, A and B. The only difference between them was the structural capacitance between two adjacent Jerusalem crosses. The geometric parameters of grid A are as follows: \( a = 2.3 \text{ mm}, d = 0.5 \text{ mm}, w = 0.1 \text{ mm}, \) and \( g = 0.3 \text{ mm} \). For grid B, we have the same \( a, w \) with \( g = 0.1 \text{ mm} \), and \( d = 1.3 \text{ mm} \). The explanation for all these notations is available in [4]. The substrate is Meteorwave 8300 with the relative permittivity of \( \varepsilon = 3(1-j0.0025) \).

The physical limits for the metamaterial design were determined using analytical methods. As per numerical simulations and experiments, the specular reflection at \( \theta = 62^\circ \), the negative first-order reflection at \( \theta = -1^\circ \), and the negative second-order reflection at \( \theta = -2^\circ \) are negligible. From Fig. 1(a), it is evident that our MS matches these predictions, while the mushroom MS does not. As shown in Fig. 1(c), the harmonic with \( m = -2 \) is absent, resulting in User 1 not receiving the signal. It means that the PO fails to function for the mushroom MS. Note that Figs. 1(b) and (d) show the radar cross-sections of the MS against the scattering angle \( \theta \) in the vertical \((x,z)\) plane.

The NRL Arc setup was used in our experiment, employing two linearly polarized horn antennas as transmitters and receivers. The transmitting horn and RIS were positioned on a remotely controlled rotation stage, as depicted in Figs. 2(a-b). Post-processed data was used to reconstruct the scattered power density color map for two frequencies.
Fig. 2: (a) 3D view of the measurement setup, (b) the rotating platform with our RIS, (c) and (e) scattered intensity color map for TE polarized incident wave at 17 and 18 GHz, respectively. (d) and (f) show the same for the TM-polarized incident wave. Dot green lines – predictions of PO. White areas show blind spots.

(17 and 18 GHz) and both TE and TM polarizations, covering incidence angles ranging from $-75^\circ$ to $75^\circ$. The green dotted lines in Fig. 2(c-f) correspond to the PO approximation, where the straight dot line represents the specular reflection and the curved green lines represent $m = \pm 1$ and $m = \pm 2$. Notably, the scattering patterns agree perfectly with the analytical predictions.

III. CONCLUSION

We have successfully validated the suitability of the physical optics approximation for a finite binary RIS for large deviation angles when its uniform MS is angularly stable. Conversely, in the case of the strong dependence of the reflection phase on the incident angle, our attempt was unsuccessful, as demonstrated by the example of the optimized mushroom MS. Unfortunately, many researchers blindly apply the PO approximation in the context of the generalized reflection law. Our measurement results strongly support our numerical simulations and the underlying concept.

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REFERENCES


