Study on the Reflection of the IRS in the Presence of Misaligned Incident Angles

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***Abstract*—Intelligent reflecting surface (IRS) has recently emerged as a cost-effective solution to overcome the deep fading and uncontrollable wireless environment. The anomalous reflection on the IRS has been characterized using the theory of scattering. This paper investigates this anomalous reflection in a more general case where there is a misalignment in incident angles between the IRS's configuration and the actual field. The obtained results show that the IRS can perform a reflection in this general case. Moreover, the angle range of the actual incident/reflecting field for an acceptable reflection efficiency is narrow enough to ensure the highly directional connection but is large enough for implementing the multiple-antenna applications.**

***Index Terms*—Intelligent reflecting surface, squared magnitude, scattering field, physic optic technique.**

I. Introduction

RECENTLY, the intelligent reflecting surface (IRS) which can passively perform anomalous reflection, phase shifting, and even polarization control, has emerged as an effective solution to overcome the issues of the current network and assist the wireless systems to satisfy the requirements of the fifth generation (5G) and beyond [1]. The IRS has quickly attracted much interest from the research community. Numerous studies on the IRS showed that it allows a remarkable improvement in both performance and security capability. The reflection's properties on the surface is a key to accessing the performance of the IRS-aided system. The recent approach presented in [2] used the theory of the scattered field and the physical optics techniques to develop the far-field path-loss model for the reflection on the RT. However, this work is limited to the case of perfect alignment in the incident angles between the IRS and the actual field, it is impossible to model the path loss for the more general scenario where the configuration on the IRS does not match with the actual incident field. In this study, we investigate this general scenario. The obtained results indicate that the actual incident angle can vary within an angle range to guarantee an acceptable signal's strength at an observation position. This angle range is narrow enough to enable highly directional connections but it is sufficiently wide enough to reflect the signal from antennas of the multiple-antenna transmitter to a receiver.

This work was supported in part by the Basic Science Research Program under Grant 2020R1I1A3057142, in part by the Priority Research Center Program through the National Research Foundation under Grant 2019R1A6A1A03032988, and in part by the Underground City of the Future Program funded by the Ministry of Science and ICT.

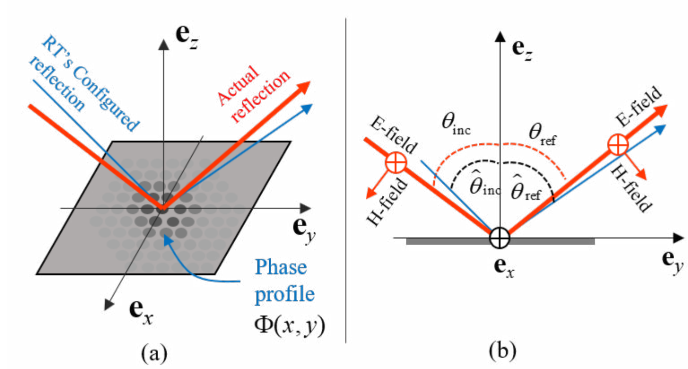

Fig. 1. (a) The reflection on the IRS and (b) the side view of the reflection.

Notation: We use $\mathrm{REF}(\theta_1, \theta_2, \varphi)$ to denote the reflection on the IRS of a wave field hitting the IRS at an angle θ_1 and departing at angle θ_2 with the phase shift φ; $\arcsin(\cdot)$ is the inverse sine function; $\angle(r)$ returns the angle of a complex number r in polar form; $\mathrm{sinc}(x) = 1$ if $x = 0$, otherwise $\mathrm{sinc}(x) = \sin(x)/x$; $\mathbf{u}\cdot\mathbf{v}$ is the dot product of the two vectors $\mathbf{u}$ and $\mathbf{v}$.

II. IRS's Scattered Field Characterization with Misaligned Incident Angles

We characterize the scattered field of an $a \times b$ rectangle IRS as illustrated in Fig. 1 as shown that there is a slight misalignment in the incident angle between the IRS and the actual incident field, i.e., the configured incident angle at the IRS, $\hat{\theta}_{\rm inc}$, may differ a bit from the actual incident angle, $\theta_{\rm inc} = \hat{\theta}_{\rm inc} + \Delta\theta$, where $\Delta\theta$ is small and it represents the difference in angle between $\theta_{\rm inc}$ and $\hat{\theta}_{\rm inc}$. The formulas for the electric field (E-field) and the magnetic field (H-field) of a general incident field hitting the IRS at an angle θ are given in [2] as $\mathbf{E}_{\rm inc}(\theta) = \mathbf{e}_x E_{\rm inc} e^{-j\boldsymbol{\beta}_{\rm inc}(\theta)\cdot\mathbf{r}}, \mathbf{H}_{\rm inc}(\theta) = \mathbf{e}_{\rm inc}(t)\frac{E_{\rm inc}}{\eta} e^{-j\boldsymbol{\beta}_{\rm inc}(\theta)\cdot\mathbf{r}}$, and the formulas for E-field and

H-field of a general reflected field departing at angle θ are given as $\mathbf{E}_{\text{ref}}(\theta) = \mathbf{e}_x E_{\text{ref}} e^{-j\boldsymbol{\beta}_{\text{ref}}(\theta)\cdot\mathbf{r}+j\varphi_0}, \mathbf{H}_{\text{ref}}(\theta) = \mathbf{e}_{\text{ref}}(\theta)\frac{E_{\text{ref}}}{\eta} e^{-j\boldsymbol{\beta}_{\text{ref}}(\theta)\cdot\mathbf{r}+j\varphi_0}$ where $E_{\text{inc/ref}}$ is the magnitude of the incident/reflected E-field, $\beta = 2\pi/\lambda_0$ is the phase constant, λ_0 is the wavelength, η is the characteristic impedance of the medium, $\boldsymbol{\beta}_{\text{inc}}(\theta) \triangleq \beta(\sin(\theta)\mathbf{e}_y - \cos(\theta)\mathbf{e}_z)$ and $\boldsymbol{\beta}_{\text{ref}}(\theta) \triangleq \beta(\sin(\theta)\mathbf{e}_y + \cos(\theta)\mathbf{e}_z)$ are respectively the phase constant vector which also indicates the propagation direction of the incident and reflected wave plane, $\mathbf{r}$ is the position vector in rectangular coordinates, and $\mathbf{e}_{\text{inc}}(\theta) \triangleq -\cos(\theta)\,\mathbf{e}_y - \sin(\theta)\,\mathbf{e}_z$ and $\mathbf{e}_{\text{ref}}(\theta) \triangleq \cos(\theta)\mathbf{e}_y - \sin(\theta)\mathbf{e}_z$ are respectively the direction of the incident and reflected H-field, φ_0 is the IRS's phase shift achieved via adjusting the phase profile of the IRS $\Phi(x,y)$, Assume that the IRS is configured to perform a reflection $\text{REF}(\hat{\theta}_{\text{inc}}, \hat{\theta}_{\text{ref}}, \varphi_0)$. Examining incident/reflected waves at the surface $(z=0)$ and using the fact $\Phi(x,y) = \angle\left(\mathbf{E}_{\text{ref}}^{z=0}\left(\hat{\theta}_{\text{ref}}\right)/\mathbf{E}_{\text{inc}}^{z=0}\left(\hat{\theta}_{\text{inc}}\right)\right)$, the phase profile $\Phi(x,y)$ is determined as

$$\Phi(x,y) = \beta\left(\sin\left(\hat{\theta}_{\text{inc}}\right)y - \sin\left(\hat{\theta}_{\text{ref}}\right)\right)y + \varphi_0. \quad (1)$$

The phase of actual reflected E-field is determined as $\angle(\mathbf{E}_{\text{ref}}|_{z=0}) = \Phi(x,y) + \angle(\mathbf{E}_{\text{inc}}(\theta_{\text{inc}})) = -\beta\sin(\theta_{\text{ref}})y + \varphi_0$ where $\theta_{\text{ref}} = \arcsin\left(\sin\left(\hat{\theta}_{\text{ref}}\right) + \sin(\theta_{\text{inc}}) - \sin\left(\hat{\theta}_{\text{inc}}\right)\right)$ is the actual reflected angle.

Lemma 1. *Consider a reflection on perpendicular a plane of the IRS consisting of the vectors $\mathbf{e_z}$ and $\mathbf{r}$. The static phase profile given in (1) for performing a configured anomalous reflection $\text{REF}(\hat{\theta}_{\text{inc}}, \hat{\theta}_{\text{ref}}, \varphi_0)$ can also perform an anomalous reflection $\text{REF}(\theta_{\text{inc}}, \theta_{\text{ref}}, \varphi_0)$*

At an arbitrary observation angle θ_s, we have the follows.

Lemma 2. *The squared magnitude of the scattered field yielded from the reflection of an incident field $(\mathbf{E}_{\text{inc}}(\theta_{\text{inc}}), \mathbf{H}_{\text{inc}}(\theta_{\text{inc}}))$ on a RT, which is purposely configured for a reflection $\text{REF}(\hat{\theta}_{\text{inc}}, \hat{\theta}_{\text{ref}}, \varphi_0)$, is calculated as $S\left(\theta_s; E_{\text{inc}}^2, d\right) = \left(\frac{ab}{\lambda_0}\right)^2 \frac{E_{\text{inc}}^2}{d^2}\cos(\theta_{\text{inc}})\cos(\theta_{\text{ref}}) \times \text{sinc}^2\left(\frac{1}{2}b\beta\left(\sin(\theta_s) - \sin(\theta_{\text{ref}})\right)\right)$, where d is the distance from the center of the IRS to the observer's position.*

Proof. The electric current density at $z=0$ is approximated as $J_S \approx 2\mathbf{e}_z \times \mathbf{H}_{\text{ref}} = -2\mathbf{e}_x \frac{E_{\text{inc}}\cos(\theta_{\text{ref}})}{\eta} e^{-j\beta\sin(\theta_{\text{ref}})y+j\varphi_0}$. Assuming the loss-less reflection on the surface, i.e., $E_{\text{inc}}^2\cos(\hat{\theta}_{\text{inc}}) = E_{\text{ref}}^2\cos(\hat{\theta}_{\text{ref}})$, then following the similar steps as in [2], we can prove Lemma 2. □

In Fig. 2, the normalized squared magnitude $|\theta_s - \theta_{\text{ref}}| \gg 0°$, $S(\theta_s)$ receives great values around the configured reflection angle $\theta_{\text{ref}} = \hat{\theta}_{\text{ref}} = 30°$. At other observation angles $|\theta_s - \theta_{\text{ref}}| \gg 0°$, $S(\theta_s)$ receives very small values. Due to the misalignment in the incident angle, the peaks of the normalized squared magnitudes for different fields are varied

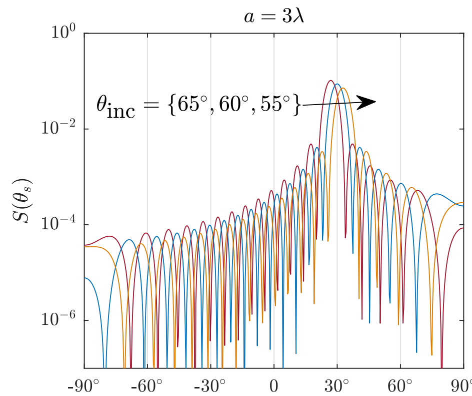

Fig. 2. The normalized squared magnitude of the scattered field at $\theta_s \in (-90°, 90°)$ for the reflection $\text{REF}(\hat{\theta}_{\text{inc}} = 60°, \hat{\theta}_{\text{ref}} = 30°, -)$.

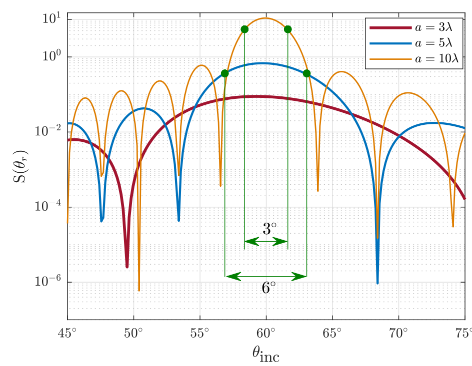

Fig. 3. The normalized squared magnitude of the scattered field at a fixed observation angle $\theta_s = \hat{\theta}_{\text{ref}} = 30°$ with different actual incident angles $\theta_{\text{inc}} \in (45°, 75°)$ for the reflection $\text{REF}(\hat{\theta}_{\text{inc}} = 60°, \hat{\theta}_{\text{ref}} = 30°, -)$.

$\theta_{\text{ref}} \in \{26.6°, 30°, 33.1°\}$. In Fig. 3, the results for the 3-dB angle-range, denoted by $\Delta_{3\,\text{dB}}$, show that it is possible to reflect the signal from several sources or antennas to the receiver. For example, $a = 10\lambda_0$ yields $\Delta_{3\,\text{dB}} = 3°$, equivalently at a distance 20 meters far from the RT, a maximum position variation is $20 \times \tan(3°) \approx 1.05$ meters. This range is wide enough to facilitate applications of IRS-aided multiple-antenna systems.

III. Conclusions

Our studies have revealed some important properties of the reflection on the IRS that allow accessing the realistic performance of IRS-aided wireless system. Moreover, these results allow further study on the channel modeling for IRS-aided multiple-antenna systems.

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