Received SNR Comparison of Hybrid RIS Phase Shift Methods Based on Channel and DOA Estimations

1st Jaehong Kim, 2nd Taehee Choi, 3rd Jingon Joung

School of Electrical and Electronics Engineering, Chung-Ang University, Seoul 06974, South Korea

{kjhct9606; chlxogml00; jgjoung}@cau.ac.kr

***Abstract*—A hybrid reconfigurable intelligent surface (HRIS) is an emerging technology that combines sensors with the reflecting element of a conventional reconfigurable intelligent surface. Because of the hybrid element's receiving (or sensing) capability, the HRIS can estimate the channel or the direction of arrival (DOA), thereby adjusting the optimal phase-shift values to maximize the downlink signal-to-noise ratio (SNR). This study compares the SNR performance of the HRIS phase-shift methods utilizing the estimated channel and the DOA. Numerical simulations verified that the superiority of the two HRIS phase-shift methods depends on the communication channel and system parameters. Specifically, the received SNR of the HRIS phase-shift method with DOA estimation is advantageous over channel estimation for the line-of-sight-dominant channel when the number of pilot symbols and the uplink transmit power are low.**

***Index Terms*—Hybrid reconfigurable intelligent surface (HRIS), channel estimation, direction of arrival (DOA) estimation.**

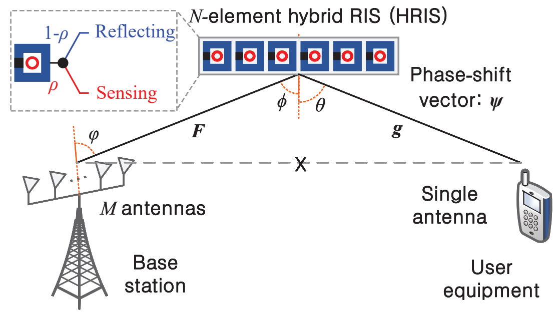

Fig. 1. HRIS-aided downlink communication systems between an M-antenna equipped base station and a single antenna user equipment. HRIS has N hybrid phase-shift elements, each receiving ρ of the incident signal power and reflecting the remaining $1-\rho$.

I. Introduction

A reconfigurable intelligent surface (RIS) is a promising technology that cost-effectively mitigates high path loss in various wireless communication systems [1]–[5]. However, RIS-aided communication systems should handle the substantial RIS control signaling overhead, as the phase-shift design is unavailable at the RIS. To alleviate excessive signaling overhead, a hybrid RIS (HRIS) has recently been proposed [6]. Each element of the HRIS can adjust the power of the received and reflected signals by a certain ratio, called the sensing factor. The HIRS enables channel or direction-of-arrival (DOA) estimation of the received signal and can compute the optimal phase-shift vector based on these estimates. In [7], an optimal design of the sensing factor for DOA-based HRIS systems has been studied. However, the performance comparisons of channel- and DOA-based HRIS systems with their optimal sensing factors have not been investigated.

This study compares the received signal-to-noise ratio (SNR) performance of channel-based and DOA-based HRIS phase-shift methods across various parameters, including the Rician factor, the number of pilot symbols, and the uplink transmit power. Simulation results verify that, in a wireless channel where line-of-sight (LoS) components dominate, the DOA-based HRIS achieves a higher received SNR than the channel-based HRIS systems. Furthermore, the received SNR from the channel-based HRIS with the optimal sensing factor increases with the number of pilot symbols.

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II. HRIS-Aided System and Channel Models

This study considers an HRIS-aided wireless communication in which an M-antenna-equipped base station (BS) supports a single-antenna user equipment (UE). When the direct channel between the BS and UE is blocked, as shown in Fig. 1, downlink data transmission can be maintained using the HRIS with N hybrid elements. Here, each hybrid element receives ρ and reflects the remainder $1-\rho$ of the incident signal power, where $\rho \in [0,1]$ is the sensing factor determined by its hardware structure [6]. Moreover, the phase of the incident signal is shifted by $\chi_n \in [0, 2\pi)$ in the nth hybrid element. Thus, the HRIS phase-shift vector can be written as $\boldsymbol{\psi} = [\psi_1 \cdots \psi_n \cdots \psi_N]^T \in \mathbb{C}^{N\times 1}$ where $\psi_n = e^{j\chi_n}$.

The channel between the BS and HRIS $\boldsymbol{F} \in \mathbb{C}^{N\times M}$, and the channel between the HRIS and the UE $\boldsymbol{g} \in \mathbb{C}^{N\times 1}$ can be modeled as Rician channel as follows:

$$\boldsymbol{F} = \sqrt{\eta_F}\left(\sqrt{\frac{\kappa_F}{1+\kappa_F}}\bar{\boldsymbol{F}} + \sqrt{\frac{1}{1+\kappa_F}}\hat{\boldsymbol{F}}\right), \tag{1a}$$

$$\boldsymbol{g} = \sqrt{\eta_g}\left(\sqrt{\frac{\kappa_g}{1+\kappa_g}}\bar{\boldsymbol{g}} + \sqrt{\frac{1}{1+\kappa_g}}\hat{\boldsymbol{g}}\right), \tag{1b}$$

where η_F and η_g are the large-scale fading coefficients of the channel $\boldsymbol{F}$ and $\boldsymbol{g}$, respectively; κ_F and κ_g are the Rician factor of $\boldsymbol{F}$ and $\boldsymbol{g}$, respectively; $\hat{\boldsymbol{F}} = \left[\hat{\boldsymbol{f}}_1 \cdots \hat{\boldsymbol{f}}_M\right]$ and $\hat{\boldsymbol{g}}$ are non-LoS (NLoS) components of the channel $\boldsymbol{F}$ and $\boldsymbol{g}$, respectively, where $\hat{\boldsymbol{f}}_m$ and $\hat{\boldsymbol{g}}$ follow the complex normal distribution with zero mean and $\boldsymbol{I}_N$. Here, $\bar{\boldsymbol{F}}$ is the LoS component of the channel $\boldsymbol{F}$ which is modeled as $\bar{\boldsymbol{F}} = \boldsymbol{a}_{\mathrm{R}}(\phi)\boldsymbol{a}_{\mathrm{B}}^H(\varphi)$, where $\boldsymbol{a}_{\mathrm{B}}(x) \in \mathbb{C}^{M\times 1}$ is the steering vector at the BS whose mth element is given by $e^{\frac{j2\pi d(m-1)}{\lambda}\sin x}$. $\boldsymbol{a}_{\mathrm{R}}(x) \in \mathbb{C}^{N\times 1}$ is the steering vector at the HRIS whose nth element is given by $e^{\frac{j2\pi d(n-1)}{\lambda}\sin x}$, where d and λ denote the antenna (or element) spacing of the BS (or HRIS) and signal wavelength, respectively. Similarly, the LoS component of the channel $\boldsymbol{g}$ is given as $\bar{\boldsymbol{g}} = \boldsymbol{a}_{\mathrm{R}}(\theta)$. As depicted in Fig. 1, the ϕ (or φ) denotes the DOA of the signal transmitted from BS to HRIS (or HRIS to BS); θ denotes the DOA of the signal transmitted from HRIS to UE. By using the maximum ratio transmission at the BS, the downlink received SNR at the UE can be written as follows [7]:

$$\mathrm{SNR}(\rho,\boldsymbol{\psi}) = (1-\rho)P_{\mathrm{B}}\sigma_n^{-2}\left\|\boldsymbol{F}\mathrm{diag}(\boldsymbol{\psi})\boldsymbol{g}^H\right\|^2, \quad (2)$$

where P_{B} and σ_n^2 are the transmit power at the BS and the noise power at the UE, respectively.

III. HRIS Phase-Shift Methods Using Channel and DOA Estimations

Typically, the LoS channel (i.e., $\bar{\boldsymbol{F}}$) and the DOAs (i.e., φ and ϕ) between the BS and the HRIS are available at the HRIS[1]. Therefore, the HRIS can calculate its own phase-shift values by estimating the channel $\boldsymbol{g}$ or the DOA θ. The channel $\boldsymbol{g}$ or the DOA θ can be estimated by using the uplink pilot symbols transmitted at the UE, which is denoted by $\boldsymbol{x} = [x_1^* \cdots x_Q^*]^H \in \mathbb{C}^{Q\times 1}$ where $\mathrm{E}[|x_q|^2] = P_{\mathrm{U}}$; P_{U} is the transmit power at the UE; Q is the number of pilot symbols. The received uplink pilot signal at the HRIS $\boldsymbol{Y} \in \mathbb{C}^{N\times Q}$ can be written as follows:

$$\boldsymbol{Y} = \sqrt{\rho}\boldsymbol{g}\boldsymbol{x}^H + \boldsymbol{Z}, \quad (3)$$

where $\boldsymbol{Z} \in \mathbb{C}^{N\times Q}$ is the additive white Gaussian noise whose element conforms to the complex normal distribution with zero mean and σ_z^2 variance.

A. Channel-Based HRIS Phase-Shift Method

By using the least squares (LS) estimation, the estimated channel $\tilde{\boldsymbol{g}}$ can be obtained at the HRIS as follows [8]:

$$\tilde{\boldsymbol{g}} = \boldsymbol{Y}\boldsymbol{x}\left(\sqrt{\rho}\|\boldsymbol{x}\|^2\right)^{-1}. \quad (4)$$

The optimal HRIS phase-shift vector that maximizes the received SNR in (2) can be designed by using the existing modified block coordinate descent method [9]. Specifically, the received SNR (2) can be written in quadratic form as $\mathrm{SNR}(\rho,\boldsymbol{\psi}) = (1-\rho)P_{\mathrm{B}}\sigma_n^{-2}\boldsymbol{\psi}^H\tilde{\boldsymbol{M}}\boldsymbol{\psi}$, where $\tilde{\boldsymbol{M}} = \left(\mathrm{diag}(\tilde{\boldsymbol{g}})^H\boldsymbol{F}\boldsymbol{F}^H\mathrm{diag}(\tilde{\boldsymbol{g}})\right)^*$. Therefore, the optimal HRIS phase-shift vector can be obtained by solving the problem as follows [9]:

$$\boldsymbol{\psi}_{\mathrm{c}} = \arg\max_{\boldsymbol{\psi}\in\mathbb{C}^{N\times 1}} \ \boldsymbol{\psi}^H\tilde{\boldsymbol{M}}\boldsymbol{\psi} \quad (5a)$$

$$\text{s.t.} \quad |\psi_n| = 1. \quad (5b)$$

According to [9], the $\boldsymbol{\psi}_{\mathrm{c}}$ can be found by iteratively computing the $\bar{\boldsymbol{\psi}}^{(i)} = \tilde{\boldsymbol{M}}\hat{\boldsymbol{\psi}}^{(i-1)}$ and $\hat{\psi}_n^{(i)} = \bar{\psi}_n^{(i)}/|\bar{\psi}_n^{(i)}|$, where i denotes the iteration index. The optimal solution is set to $\boldsymbol{\psi}_{\mathrm{c}} = [\hat{\psi}_1^{(I)} \cdots \hat{\psi}_N^{(I)}]^T$, where I is the maximum iteration number.

B. DOA-Based HRIS Phase-Shift Method

The DOA θ can be estimated by using the multiple signal classification (MUSIC) algorithm, which is one of the widely used subspace-based DOA estimation algorithms [10]. In the MUSIC algorithm, the noise subspace of the sample covariance matrix $\boldsymbol{R}_y = \frac{1}{Q}\boldsymbol{Y}\boldsymbol{Y}^H$ is used to generate the MUSIC spectrum as follows [10]:

$$S(\theta) = \left(\boldsymbol{a}_{\mathrm{R}}^H(\theta)\boldsymbol{V}_z\boldsymbol{V}_z^H\boldsymbol{a}_{\mathrm{R}}(\theta)\right)^{-1}, \quad (6)$$

where $\boldsymbol{V}_z = [\boldsymbol{v}_1 \cdots \boldsymbol{v}_{N-1}] \in \mathbb{C}^{N\times(N-1)}$ is the noise subspace matrix, where $\boldsymbol{v}_n \in \mathbb{C}^{N\times 1}$ is the column vector corresponding to the n-smallest eigenvalue of the $\boldsymbol{R}_y$. Then, the estimated DOA $\tilde{\theta}$ is obtained by searching θ that provides maximum value of $S(\theta)$, as follows:

$$\tilde{\theta} = \max_{\theta\in[-\pi/2,\pi/2]} \ S(\theta). \quad (7)$$

By using $\tilde{\theta}$, the optimal HRIS phase-shift vector can be obtained as $\boldsymbol{\psi}_{\mathrm{a}} = \boldsymbol{a}_{\mathrm{R}}(\tilde{\theta}) \odot \boldsymbol{a}_{\mathrm{R}}^*(\phi)$, where $\odot$ denotes the element-wise multiplication operator [7].

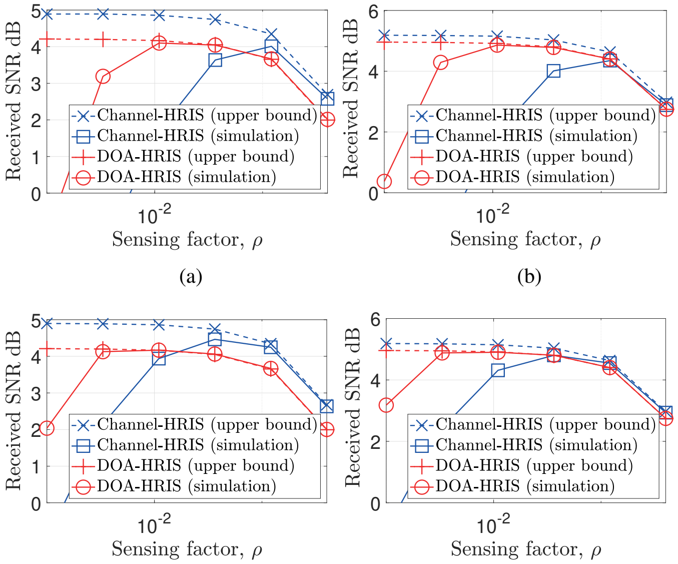
IV. SNR Performance Comparisons

This section evaluates the SNR performance of the HRIS phase-shift methods using the channel and DOA estimates described in Section III. The simulation parameters are listed as follows: the number of BS antennas $M = 32$; the number of HRIS elements $N = 40$; carrier frequency $f_c = 5$ GHz; signal wavelength $\lambda = 0.06$ m; antenna (or element) spacing $d = \lambda/2 = 0.03$ m; $P_{\mathrm{B}} = 43$ dBm; $P_{\mathrm{U}} = 15$ dBm; $\sigma_z^2 = \sigma_n^2 = -107$ dBm. The path loss model is given as $\eta_{\mathrm{a}} = -28 - 20\log_{10}(f_c) - 22\log_{10}(d_{\mathrm{a}})$ for a $\in \{F, g\}$, following [11]; $d_F = 1000$ m and $d_g = 200$ m denotes the signal propagation distance of channel $\boldsymbol{F}$ and $\boldsymbol{g}$, respectively. The DOAs are set to $\varphi = 50°$, $\phi = 40°$, and $\theta = 10°$. The maximum iteration number in solving (5) is set to $I = 5$.

In Fig. 2, the average received SNR performance is compared by varying the sensing factor ρ under various numbers of pilot symbols Q and Rician factor. The upper bound of the channel-based HRIS phase-shift method is numerically obtained from (5) by assuming that the channel is perfectly estimated, i.e., $\tilde{\boldsymbol{g}} = \boldsymbol{g}$. Similarly, the upper bound of the DOA-based HRIS phase-shift method is obtained by assuming that the DOA is perfectly estimated, i.e., $\tilde{\theta} = \theta$.

Figs. 2(a) and 2(b) evaluated the received SNR performance when the number of the uplink pilot symbols is relatively

[1]The HRIS is initially deployed to guarantee the LoS link between the BS and the HRIS. Therefore, it is practical to assume that the LoS channel and DOAs between the BS and the HRIS are known at the HRIS.

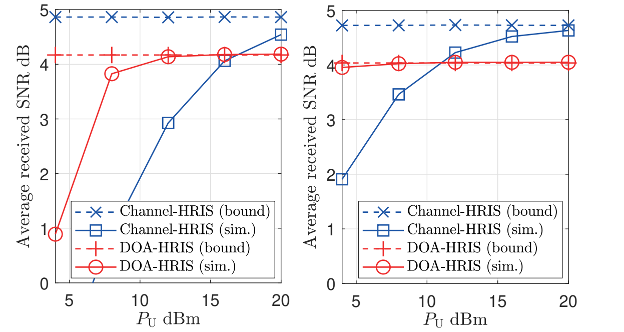


(a) (b) (c) (d)

Fig. 2. Average received SNR versus sensing factor ρ for $\kappa_F = 5$ dB. (a) When $Q = 1$ and $\kappa_g = 5$ dB. (b) When $Q = 1$ and $\kappa_g = 10$ dB. (c) When $Q = 4$ and $\kappa_g = 5$ dB. (d) When $Q = 4$ and $\kappa_g = 10$ dB.

small, i.e., $Q = 1$. As shown in Fig. 2(a), the upper bound of the channel-based HRIS phase-shift method is higher than that of the DOA-based HRIS phase-shift method, when $\kappa_g = 5$ dB. This is because the channel-based HRIS phase-shift method utilizes both LoS and NLoS components of the channel $\boldsymbol{g}$, while the DOA-based HRIS phase-shift method only utilizes the LoS components of $\boldsymbol{g}$. However, since the estimated channel is inaccurate for $Q = 1$, the gap between the actual performance and its upper bound is large, especially when ρ is small. Consequently, the maximum average received SNR using optimal ρ is comparable to each other. In Fig. 2(b), the received SNR is evaluated for a higher Rician factor, i.e., $\kappa_g = 10$ dB. It is verified that the HRIS phase-shift method using DOA estimation outperforms the channel-based HRIS phase-shift method, as the LoS component dominates as the Rician factor increases. In Figs. 2(c) and 2(d), the SNR performance under $Q = 4$ is evaluated. Since the increase in Q improves the accuracy of the LS channel estimation, the channel-based HRIS phase-shift method outperforms the other in Fig. 2(c). On the other hand, when the Rician factor increases to $\kappa_g = 10$ dB as shown in Fig. 2(d), the performance gap between the two methods becomes negligible.

The impact of the UE's uplink transmit power, P_{U}, is evaluated in Fig. 3. It can be verified that the channel-based HRIS phase-shift method achieves a higher received SNR than the DOA-based HRIS phase-shift method as P_{U} increases. On the other hand, it is shown that the DOA-based HRIS phase-shift method is more robust in the low P_{U} region compared to the channel-based HRIS phase-shift method. Consequently, it is beneficial for HRIS to use the HRIS phase-shift method based on DOA estimation, especially when the UE's uplink pilot signal power is relatively weak.



(a) (b)

Fig. 3. Average received SNR evaluation by varying the uplink transmit power at the UE, P_{U}. (a) When $\rho = 10^{-2}$. (b) When $\rho = 4 \times 10^{-2}$.

V. Conclusion

In this study, the received SNR performance of the HRIS phase-shift methods based on channel and DOA estimations is compared. Using the received pilot symbols at the HRIS, the channel or the DOA between the HRIS and the UE can be estimated. Then, the channel or the DOA is utilized to design the optimal HRIS phase-shift vector. Numerical results verified that the DOA-based HRIS phase-shift method is advantageous over the channel-based HRIS phase-shift method when the LoS component is dominant, the number of pilot symbols is low, and the UE's transmit power is low.

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