Design and Operating Principles of a Wave-Controlled Holographic MIMO System

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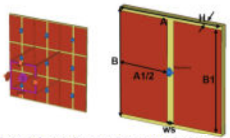
NSF Award 2030029

Our Implementation of RIS

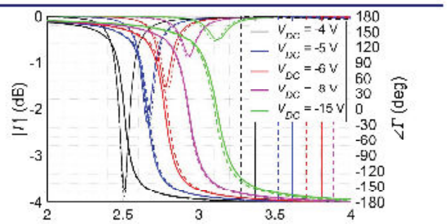


- Square-shaped metal patches on a grounded substrate, with varactors in the middle of the unit cell connected between adjacent patches separated by the gap
- Dielectric spacer substrate Rogers RT5880LZ is used with relative permittivity $\epsilon_r = 2$, $\tan\delta = 0.0021$ (Im[ϵ_r]/Re[ϵ_r], low loss if small)
- Dimensions in mm are A = B = 19, A1 = B1 = 17.8, H = 1.27, ws = 1.2
- Frequency response depends on the dimensions

RIS Model

- Equivalent model for RIS used to evaluate the reflection coefficient
- R_d, C_d, L_d are associated with the square-shaped unit cell element
- L_s is an equivalent element to account for the substrate. It may contain nonlinear terms in ω
- The varactor is represented by the series $R_v(V)$, $C_v(V)$, L_v where V is the varactor biasing voltage
- In order to determine R_d, C_d, L_d, a single full-wave simulation without including the varactor is performed and the phase reflection curve is determined
- L_s is determined analytically from the dielectric substrate height H and relative dielectric constant ϵ_r
- The varactor model in parallel with C_d is analytically calculated for various varactor voltages from the datasheet provided by the manufacturer

RIS Reflection Coefficient with the Varactor



$$\Gamma_{dev} = \frac{Z_{RIS} - Z_0}{Z_{RIS} + Z_0}$$

Mathematical Model

- Narrowband or flat fading scenario with a single-antenna transmitter, K single-antenna receivers, and an RIS with M elements
- No direct signal path between the TX and RX
- Signal at k-th receiver

$$y_k = \mathbf{h}_k^T \Phi \mathbf{g} s + n_k$$

- Where $\mathbf{h}_k$ and $\mathbf{g}$ are the Mx1 channels from the RIS to the k-th RX and the TX to the RIS, respectively
- RIS response is determined by a diagonal matrix with reflection coefficients of the RIS

$$\Phi = \mathrm{diag}\,[\phi_1 \ \cdots \ \phi_M]$$

- In a varactor-based implementation, the value of the m-th reflection coefficient ϕ_m is determined by a biasing voltage applied to the m-th RIS element
- Because RIS elements are passive, $|\phi_m| \le 1$ for all $m = 1, 2, \ldots, M$
- We will use

$$\boldsymbol{\phi} = [\phi_1 \ \cdots \ \phi_M]$$

to denote the vector with all RIS reflection coefficients, we assume $|\phi_m| = 1$ for all $m = 1, 2, \ldots, M$

Wave-Controlled RIS

- Biasing voltage composed of a sum of basis functions representing standing waves along the length of the RIS
- For example, with a sinusoidal basis, the biasing voltage $v(x)$ as a function of the position x in wavelengths along the linear RIS is

$$v(x) = \alpha_0 + \sum_{n=1}^{N} \alpha_n \sin\left(\frac{n\pi x}{(M-1)\Delta}\right)$$

where N is the number of modes and α_n is the amplitude of the n-th mode

- N is desired to be as small as possible to limit the variation in $v(x)$ with x, and to reduce the control signaling overhead
- Biasing voltage is sampled along the waveguide and applied as inputs to the RIS elements at positions $x = m\Delta$, $m = 0, 1, \ldots, M-1$ where Δ is the distance between the centers of each RIS element in wavelength

Algorithm 1, Update for [15, Algorithm 1]

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Algorithm 1 Update for [15, Algorithm 1]
Initialization: Compute $\lambda_{nk}$ = [illegible] for $n = 1, 2, \ldots, N$ and $k = 1, 2, \ldots, K$.
Eliminate duplicates among $\lambda_{nk}$ and sort to get $\lambda_\ell$ such that $0 \le \lambda_1 < \lambda_2 < \cdots < \lambda_L < 2\pi$.
Let, for $\ell = 1, 2, \ldots, L$, $\mathcal{N}(\lambda_\ell) = \{$[illegible]$ = \lambda_\ell\}$.
Set $\mu = 0$. For $n = 1, 2, \ldots, N$, calculate $\theta_n$ = [illegible] $\cos(\theta_n + \alpha_n - \mu)$.
Set $g_0 = h_0 + \sum_{n=1}^{N} h_n e^{j\theta_n}$, absgmax $= |g_0|$.
for $\ell = 1, 2, \ldots, L$ do
    For each $n \in \mathcal{N}(\lambda_\ell)$, let $\theta_n + \omega \to \theta_n$ mod $\Phi_K$.
    Let
    $g_\ell = g_{\ell-1} + \sum_{n \in \mathcal{N}(\lambda_\ell)} h_n (e^{j\theta_n} - e^{j(\theta_n - \omega) \bmod \Phi_K})$
    if $|g_\ell| >$ absgmax then
        Let absgmax $= |g_\ell|$
        Store $\theta_n$ for $n = 1, 2, \ldots, N$
    end if
end for
Read out $\theta_n^*$ as the stored $\theta_n$, $n = 1, 2, \ldots, N$.
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Periodicity of $|g_{c,\ell}|^2$

[illegible]

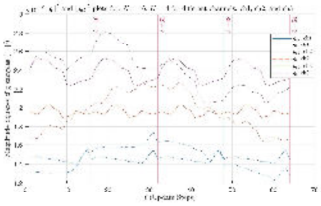

FIGURE 8. Variation of $|g_\ell|^2$ and $|g_{c,\ell}|^2$ with ℓ.

Algorithm 2

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Algorithm 2 Simplified Algorithm 1 with $|\mathcal{N}(\lambda_\ell)| = 1$ for all $\ell$
Initialization: Set [illegible]
Compute $\varphi_n = (\alpha_n - \alpha_0) \bmod \frac{2\pi}{K}$, $n = 1, 2, \ldots, N$
Sort $\varphi_n$ such that $0 \le \varphi_{n_1} \le \varphi_{n_2} \le \cdots \le \varphi_{n_N} < \frac{2\pi}{K}$
Set $\theta_n = \arg\max_{\theta'_n \in \Phi_K} \cos(\theta'_n - \alpha_n - \mu)$, store $\theta_n$, $n = 1, 2, \ldots, N$
Set $g_0 = h_0 + \sum_{n=1}^{N} h_n e^{j\theta_n}$, absgmax $= |g_0|$
for $\ell = 1, 2, \ldots, N$ do
    Let $(\theta_{n_\ell} + \omega \to \theta_{n_\ell})$ mod $\Phi_K$
    Let
    $g_\ell = g_{\ell-1} + h_{n_\ell}\left(e^{j\theta_{n_\ell}} - e^{j(\theta_{n_\ell} - \omega) \bmod \Phi_K}\right)$
    if $|g_\ell| >$ absgmax then
        Let absgmax $= |g_\ell|$
        Store updated $\theta_n$
    end if
end for
Read out $\theta_n^*$ as the stored $\theta_n$, $n = 1, 2, \ldots, N$.
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UPQ: Uniform Polar Quantization

- Problem (continuous-phase version)

$$\underset{\theta^{(c)}}{\text{maximize}} \; f_c(\theta^{(c)})$$
$$\text{subject to } \theta_n^{(c)} \in [0, 2\pi), \; n = 1, 2, \ldots, N$$

where

$$f_c(\theta) = \left|\beta_0 e^{j\alpha_0} + \sum_{n=1}^{N} \beta_n e^{j(\alpha_n + \theta_n)}\right|^2.$$

- Continuous-phase solution

$$\alpha_n + \theta_n^{(c)} = \alpha_0, \; \text{for } n = 1, 2, \ldots, N.$$

- Uniform polar quantization

$$\theta_n^{(UPQ)} = \left\lfloor \frac{\alpha_0 - \alpha_n}{\omega} \right\rceil \times \omega, \; \text{for } n = 1, 2, \ldots, N.$$

SNR Boost Performance, K = 2

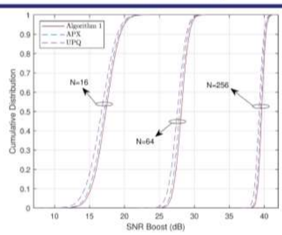

FIGURE 2. CDF plots for SNR Boost [15] with Uniform Polar Quantization (UPQ), Algorithm 1, and Approximation (APX) Algorithm [13], $K = 2$.

SNR Boost Performance, K = 4

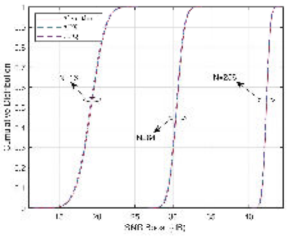

FIGURE 3. CDF plots for SNR Boost [15] with Uniform Polar Quantization (UPQ), Algorithm 1, and Approximation (APX) Algorithm [13], $K = 4$.

Comparison with Algorithms from the Literature

	Search Steps	Time Complexity	Optimality Guarantee
[13] APX	1	$\mathcal{O}(N)$	Local
[13] CPP	Projection of Each Phase Selection	—	Local
[13] Optimal	$2N + 2$, for $K = 2$	$\mathcal{O}(N)$ ($K = 2$ Only)	Global
[14] DaS	N, $K = 2$ KN, $K > 2$	$\mathcal{O}(N^2)$ (not elementwise)	Global
[15]	$2N$, $h_0 \neq 0$ KN, $h_0 = 0$	$\mathcal{O}(N)$ $\mathcal{O}(KN)$	Global
[20]	N, for $h_0 = 0$	$\mathcal{O}(N^2)$ (not elementwise)	Global
[21]	$2N + 1$, $K = 2$ $2N(K-1)$, $K > 2$	$\mathcal{O}(N^2)$ (not elementwise)	Global
[25] FPR	KN	$\mathcal{O}(N^2)$ (not elementwise)	Global
UPQ	Deterministic	—	Local
Algorithm 2	N, any h_0 $\mathcal{N}(\lambda_\ell) = 1$, all ℓ	$\mathcal{O}(N)$	Global
Algorithm 3	$< N$, any h_0 $\mathcal{N}(\lambda_\ell) > 1$, some ℓ	$\mathcal{O}(N)$	Global

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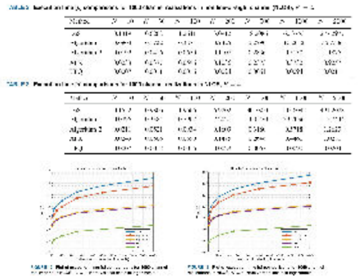
Execution Time Comparisons



Broader Impacts

- RISs are expected to form the basis of next-generation wireless MIMO systems. Our wave-controlled RIS structure will simplify the control of RISs and will likely change the way RISs are implemented in the future
- The project will provide access to users in a wireless network who may be blocked or may be in heavy fading. It will also provide coexistence by avoiding physical locations via reflections where those locations may have alternative wireless transmission
- Students involved have gained experience in cross-disciplinary research because the project involves electromagnetic system development, physical layer communications, reduced dimension control of RISs, and machine learning

Future Work

- Different RIS structures
- Development of models with different angles of incidence
- Investigation of discrete vs. continuous phase angles
- Investigation of the role of $|\phi_m| < 1$
- Effect of voltage and phase distribution