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Scaling the Peaks of Global Communications

Fast Transition-Aware Reconfiguration of Liquid Crystal-based RISs

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Table of the content

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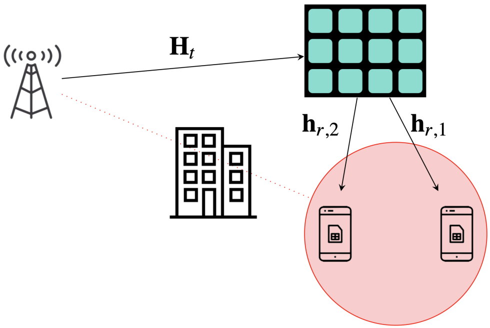
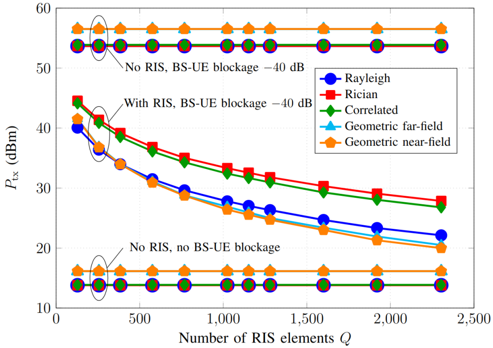
Introduction

RIS-Assisted wireless channel



How will it assist us? [1]

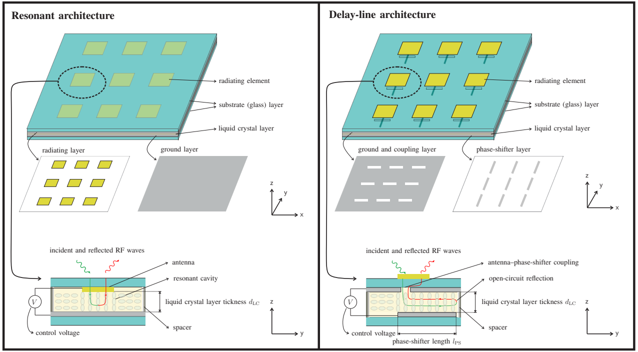


Impact of RIS [2]

LC phase-shift principle

	Varactor	PIN Diode	MEMS Switch	MEMS Mirror	LC
Tuning time	ns	ns	μs	100s of μs	$>$ 10 ms
Tunability	continuous	discrete (1 bit/diode)	discrete	discrete	continuous
Power consumption	medium	medium	low	low	low
Scalability	low (cost per diode)	low (cost per diode)	medium (encapsulation)	medium (cost per area)	high
Frequency range	few GHz	mm-Wave	mm-Wave	THz	$>$ 10 GHz
Cost	high	high	high	high	low

Feature's comparison [3]



2 models for LC phase shifter [3]

Communication-theoretic modelling

$$y_k = (\mathbf{h}_{d,k}^{\mathrm{H}} + \mathbf{h}_{r,k}^{\mathrm{H}}\mathbf{\Gamma}\mathbf{H}_t)\mathbf{q}_k s + n_k, \quad k = 1, \ldots, K,$$

$\mathbf{q} \in \mathbb{C}^{N_t}$:	beamforming vector,
$s \in \mathbb{C}$:	data symbol,
$y_k \in \mathbb{C}$:	received signal vector at the kth UE,
$n_k \in \mathbb{C} \sim \mathcal{CN}(0, \sigma_n^2)$:	additive white Gaussian noise (AWGN) at the kth UE,
$\mathbf{\Gamma} \in \mathbb{C}^{N \times N}$:	diagonal matrix with main diagonal entries $[\mathbf{\Gamma}]_n = [\mathbf{\Omega}]_n e^{j[\omega]_n}$.

$$\mathbf{H} = \sqrt{\frac{K_f}{K_f + 1}}\mathbf{H}^{\mathrm{LOS}} + \sqrt{\frac{1}{K_f + 1}}\mathbf{H}^{\mathrm{nLOS}},$$

where K_f denotes the K-factor and determines the relative power of the LOS component to the non-LOS components of the channel. $\mathbf{H}^{\mathrm{LOS}}$ and $\mathbf{H}^{\mathrm{nLOS}}$ are given by

$$\mathbf{H}^{\mathrm{LOS}} = c\,\mathbf{a}_{\mathrm{rx}}(\mathbf{\Psi}_{\mathrm{rx}})\mathbf{a}_{\mathrm{tx}}^{\mathrm{H}}(\mathbf{\Psi}_{\mathrm{tx}}),$$

$$[\mathbf{H}^{\mathrm{nLOS}}]_{n,m} \sim \mathcal{CN}(0, \sigma_{\mathrm{nLOS}}^2).$$

Fig. (a): Side view of the measurement setup with a picture of the RIS embedded in its supporting structure.

Fig. (b): Top view of the measurement setup.

Fig. (c): Heat maps, illustrating the measured normalized broadband response of the RIS for desired steering angles between -60° to -20°, and 20° to 60°, respectively.

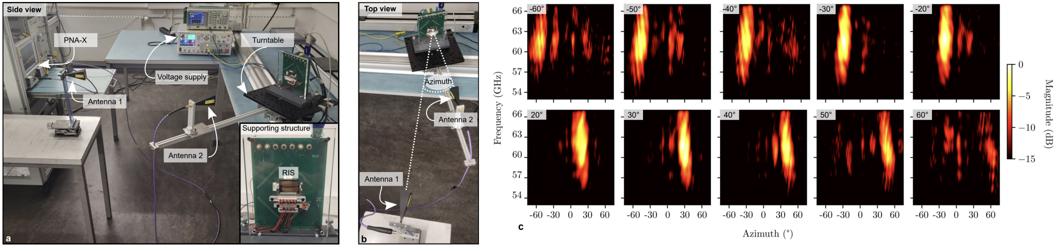
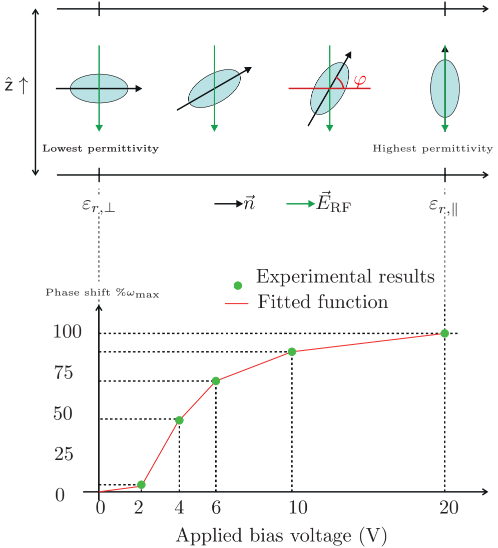


Figure: Implementation of the LC-RIS [4].

LC phase shifter



$$\Delta\omega_{\max} = 2\pi l \Delta n_{\varepsilon} \frac{f}{c},$$

$\Delta n_{\varepsilon} \triangleq \sqrt{\varepsilon_{r,\parallel}} - \sqrt{\varepsilon_{r,\perp}},$
l is the phase-shifter length,
f is the frequency,
c is the speed of light.

$\lambda = \frac{c}{f\sqrt{\varepsilon_r \mu_r}}$, where λ denotes the wavelength and the relative permeability μ_r of LC is typically one [5].

Transition-Aware LC-RIS Phase-Shift Design

The Erickson-Leslie differential equation [6, 7]:

$$\underbrace{(K_{11}\cos^2\varphi + K_{33}\sin^2\varphi)}_{K_{11}}\frac{\partial^2\varphi}{\partial z^2} + \underbrace{(K_{33} - K_{11})\sin\varphi\times\cos\varphi\left(\frac{\partial\varphi}{\partial z}\right)^2}_{0}$$

$$+\varepsilon_0\Delta\varepsilon E^2\sin\varphi\cos\varphi = \gamma_1\left(\frac{\partial\varphi}{\partial t}\right).$$

γ_1:	The LC's rotational viscosity,
K_{11} and K_{33}:	The LC splay and bend elastic constants, respectively,
$\varepsilon_0\Delta\varepsilon E^2$:	The electric field energy density,
ε_0:	Vacuum permittivity,
$\Delta\varepsilon$:	The LC dielectric anisotropy.

Assumptions:

1- $K_{11} \approx K_{33}$

2- $\sin\varphi\cos\varphi \approx \varphi(1-\frac{\varphi^2}{2})$:

$$E=0: \quad \varphi(z,t) \approx \varphi_0 \sin\left(\frac{\pi z}{l_g}\right)\exp\left\{(-\frac{t}{\tau_0})\right\},$$

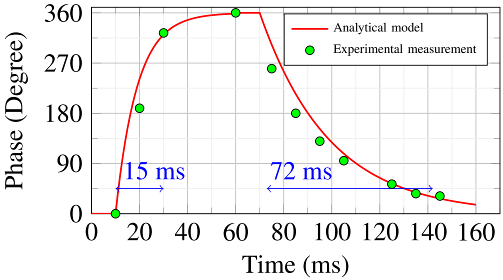
$E \neq 0$: Again exponential! [8, 9].

$$[\omega(t)]_n = [\omega_d]_n + ([\omega_0]_n - [\omega_d]_n)e^{\frac{-t}{[\tau c]_n}}.$$

Over-and undershooting technique:

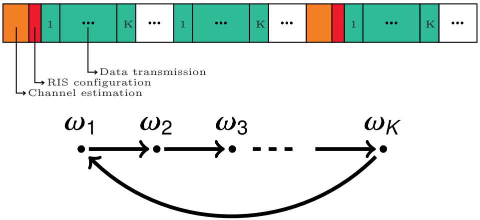
$$[\mathbf{t}_r]_n = \tau_c^+ \ln\left(1+\frac{[\omega_d]_n-[\omega_0]_n}{\omega_{\max}-[\omega_d]_n}\right),$$

$$[\mathbf{t}_r]_n = \tau_c^- \ln\left(1+\frac{[\omega_0]_n-[\omega_d]_n}{[\omega_d]_n}\right).$$



Experimental result of an LC phase shifter response time (green points) [4, Fig. 4a], analytical model (red line).

$$\text{P1:} \quad \min_{\boldsymbol{\omega}_k, \mathbf{q}_k, \forall k} \sum_{k=1}^{K} \|\mathbf{c}_k \circ \Delta\boldsymbol{\omega}_k\|_2^2$$
$$\text{s.t.} \quad \mathrm{SNR}_k(\mathbf{W}, \mathbf{q}_k) \geq \gamma_k^{\text{thr}}, \ \forall k$$
$$0 \leq [\boldsymbol{\omega}_k]_n < \omega_{\max}, \forall n, k,$$
$$\|\mathbf{q}_k\|_2^2 \leq P_t, \forall k.$$



Beamformer design:

$$\mathbf{q}_k \approx \frac{\sqrt{P_t}}{\|\mathbf{a}_{\mathrm{BS}}(\boldsymbol{\Psi}_{\mathrm{BS}})\|} \mathbf{a}_{\mathrm{BS}}(\boldsymbol{\Psi}_{\mathrm{BS}}),$$

is valid when direct channel is blocked ($\mathbf{h}_{d,k} \approx \mathbf{0}_{N_t}$) and LOS link is dominant.

RIS design:

$$\text{P2:} \quad \min_{\omega_k,\ \forall k} \sum_{k=1}^{K} \|\mathbf{c}_k \circ \Delta\omega_k\|_2^2$$
$$\text{s.t.} \quad \text{SNR}_k \geq \gamma_k^{\text{thr}}, \ \forall k$$
$$0 \leq [\omega_k]_n < 2\pi, \forall n, k,$$

$$\Delta\omega_k \triangleq \begin{cases} \omega_k - \omega_{k-1}, & \text{if } k \neq 1 \\ \omega_1 - \omega_K, & \text{if } k = 1. \end{cases}$$

Lagrangian duality: $L(\mathbf{W}, \lambda) \triangleq \sum_{k=1}^{K} \left(\|\mathbf{c}_k \circ \Delta\omega_k\|_2^2 + \lambda_k (\gamma_k^{\text{thr}} - \text{SNR}_k(\mathbf{W}, \mathbf{q}_k)) \right),$

The proposed decoupled dual problem:

$$\text{P3:} \quad \max_{\lambda} \min_{\mathbf{W} \in \mathcal{W}^{N \times K}} \sum_{k=1}^{K} \sum_{n=1}^{N} L_n([\omega_k]_n, \lambda_k),$$

Solved via an iterative algorithm (see [1])

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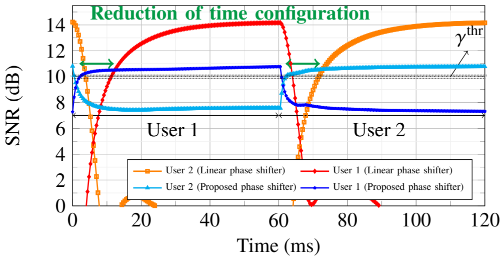
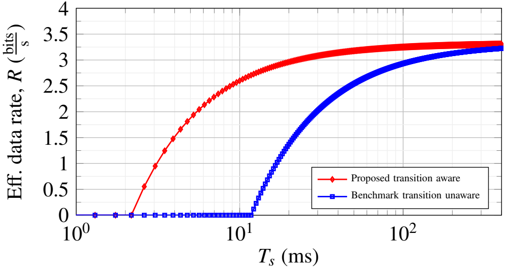
Performance Comparison

Simulation results





Conclusion and future works

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Conclusion

Extremely large RISs (ELRISs) are required.

Despite being good candidates to implement ELRISs, LC's response time is slower than other technologies.

We have reduced the effect of this disadvantage in the TDMA application.

Future works

LC-RISs' performance diminishes if changes in temperature and frequency are neglected. These problems should be investigated.

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Thank you for your attention

Should you have any questions, please send me via email:
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Link to the paper: