Reconfigurable Intelligent Surfaces for Wideband Communications

Challenges and Possible Solutions

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Swedish Research Council

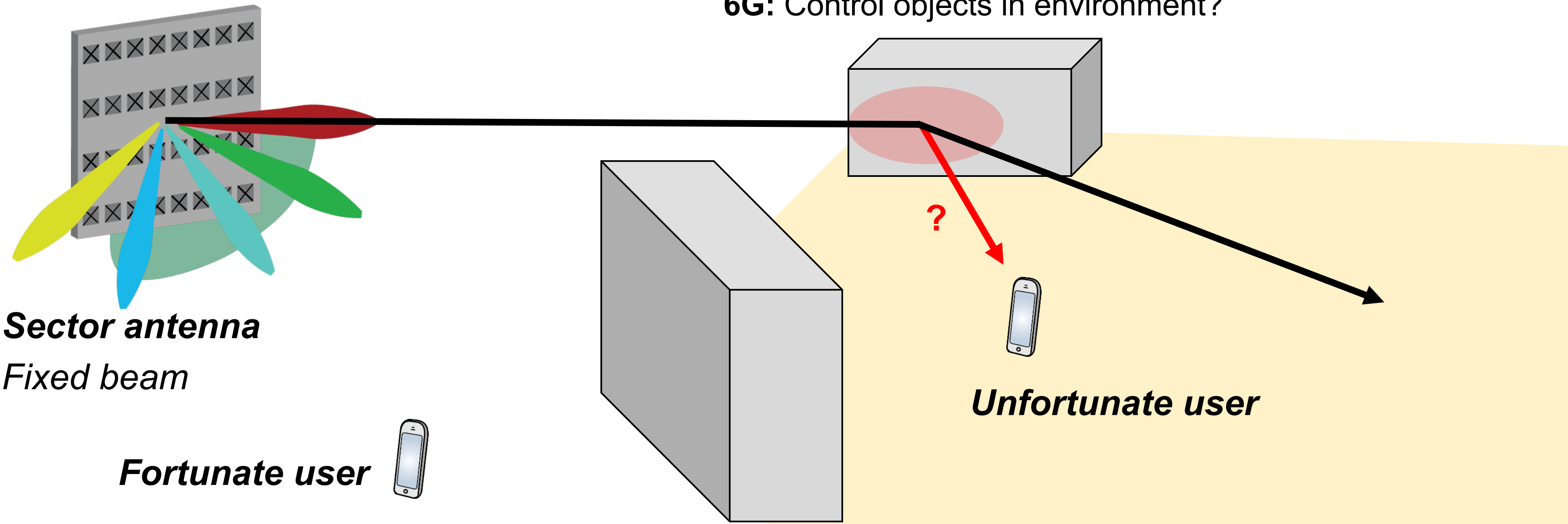
Project Grant

INTRODUCTION

Evolution of Wireless Infrastructure

5G: Adaptive multi-user beamforming

6G: Control objects in environment?

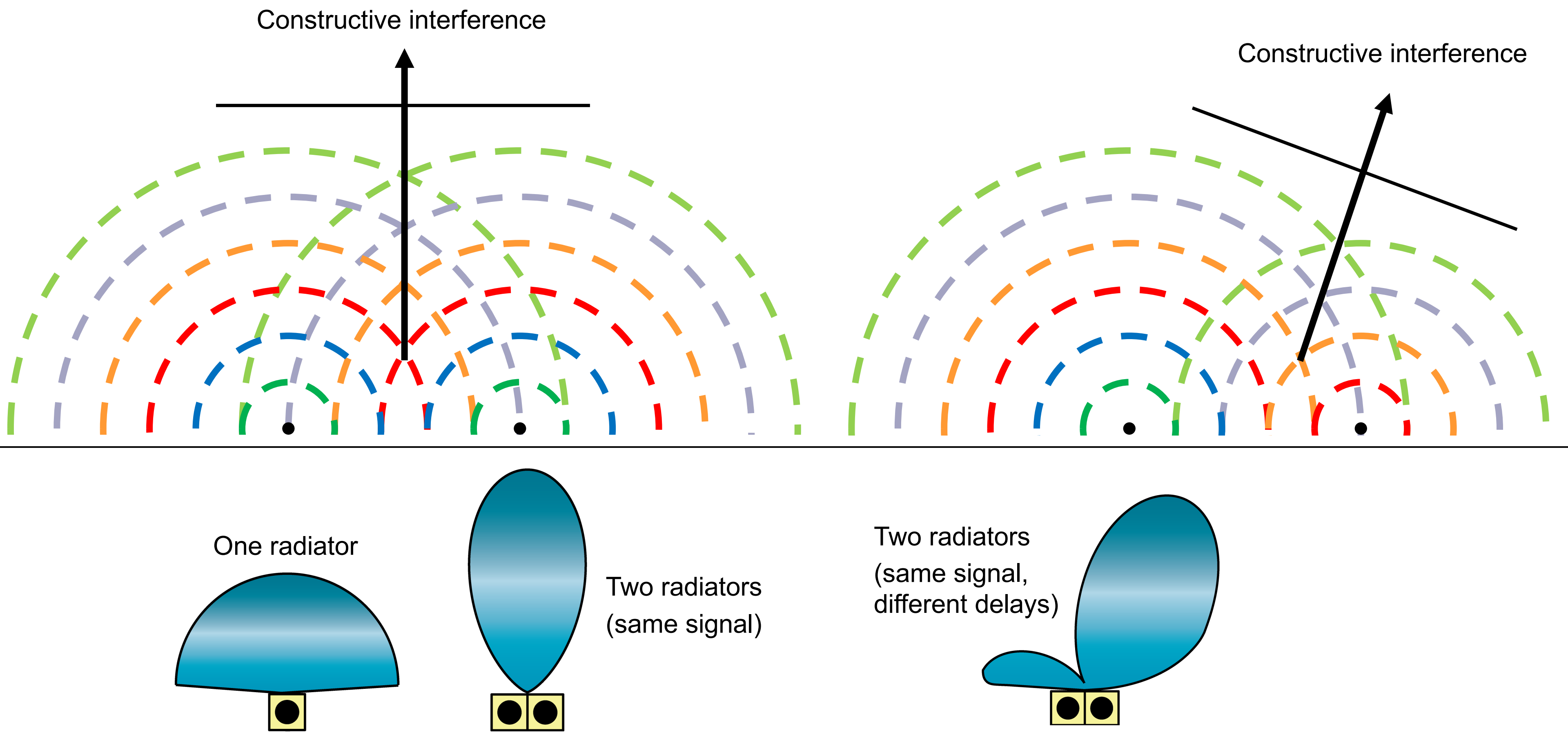


Reconfigurable metasurfaces

Reconfigurable intelligent surface (RIS)

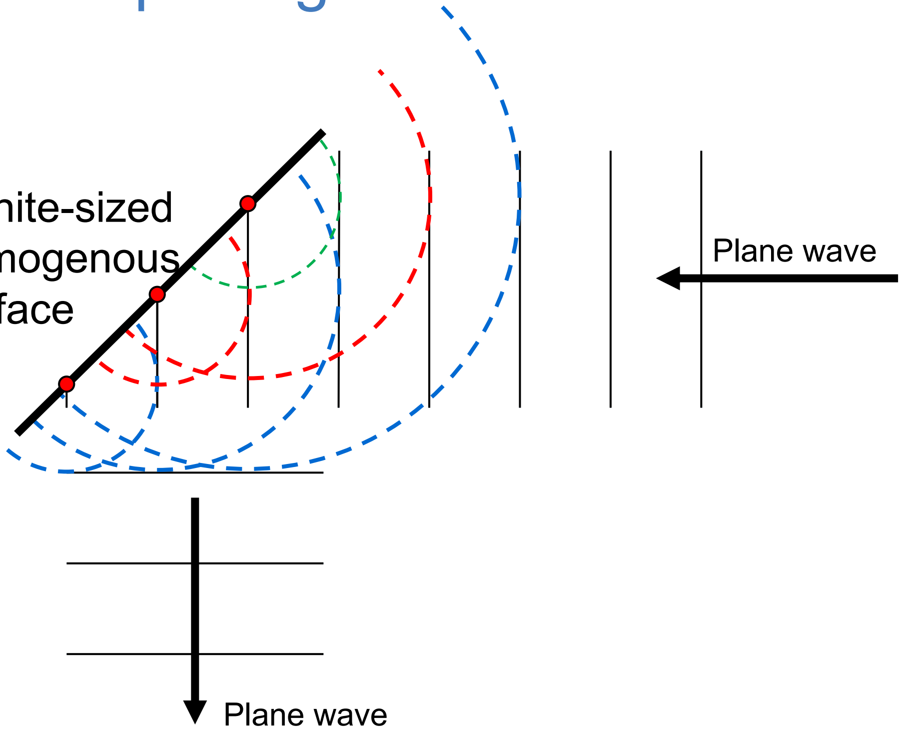
Intelligent reflecting surface (IRS)

Beamforming: Directivity by Constructive Interference

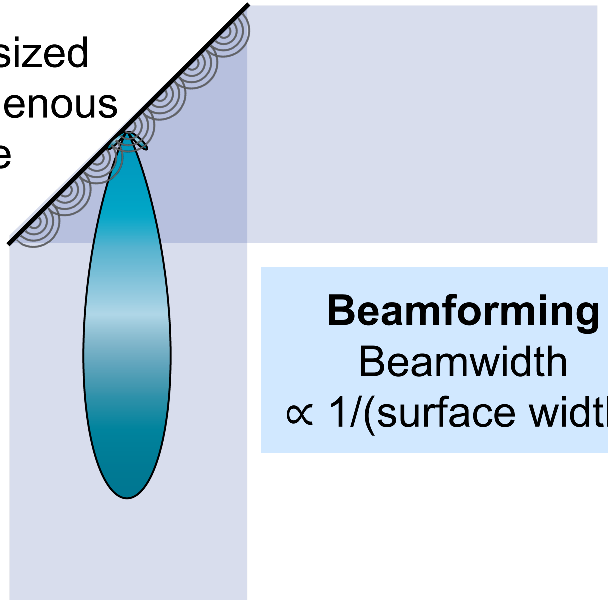


Interpreting Reflection via the Huygens-Fresnel Principle

Infinite-sized homogenous surface



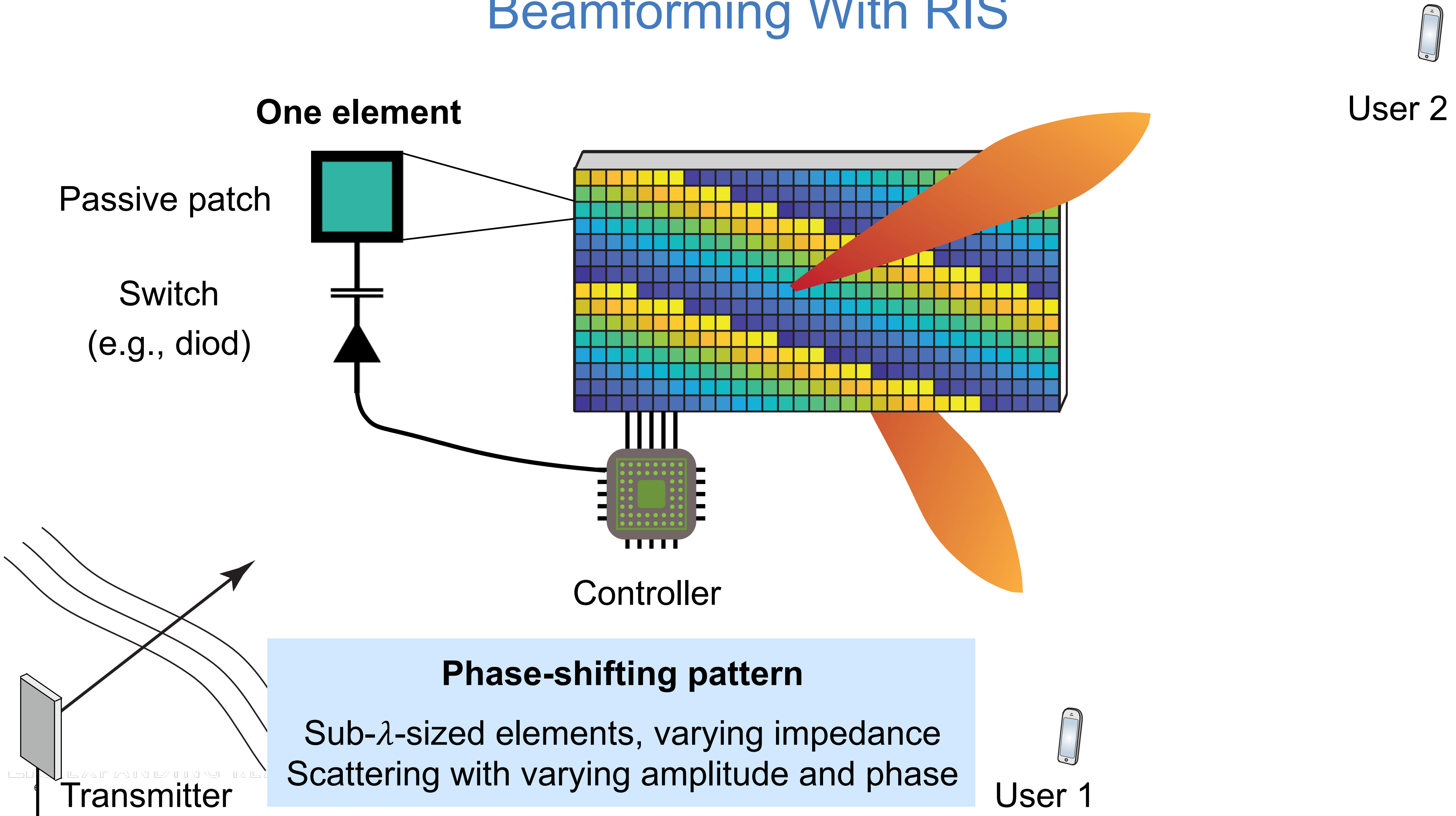
Finite-sized homogenous surface



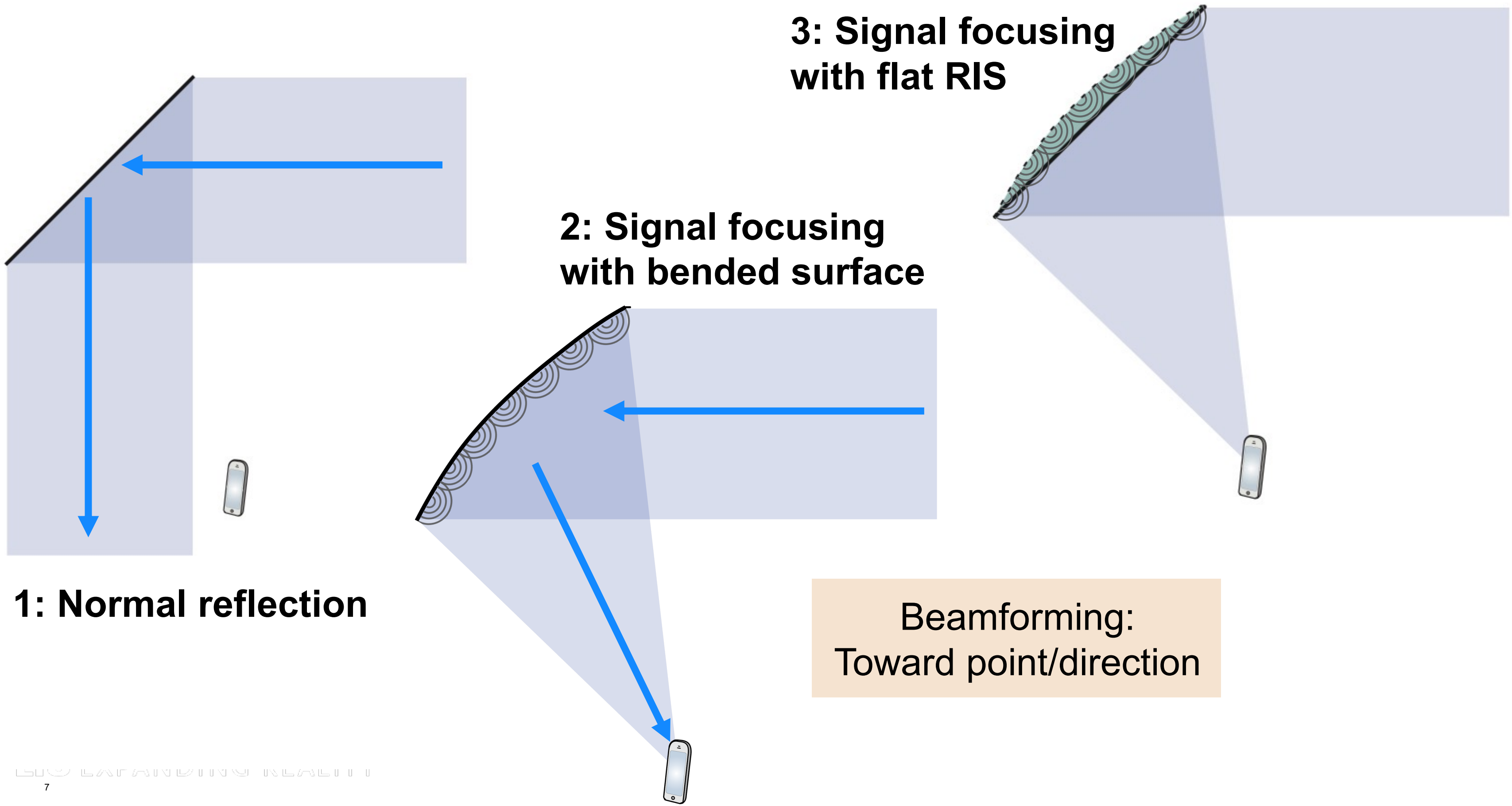
Beamforming
Beamwidth
∝ 1/(surface width)

Every point ”scatters” a spherical wave:
Constructive interference determines direction

Beamforming With RIS



Geometrical Interpretation at the Global Level

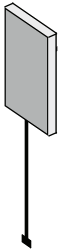


Beamforming:
Toward point/direction

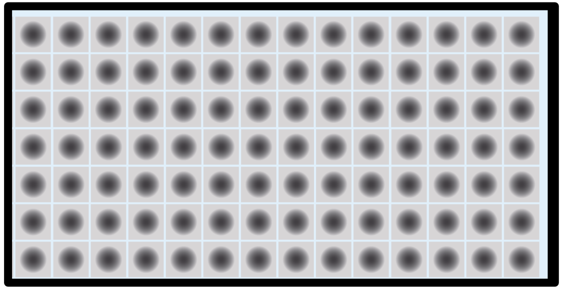
SYSTEM MODELING

Narrowband System Modelling: N RIS elements

Transmitter



$$\boldsymbol{h} = \begin{bmatrix} h_1 \\ \vdots \\ h_N \end{bmatrix}$$



Phase-shifts: $\boldsymbol{\omega}_\theta = \begin{bmatrix} e^{-j\theta_1} \\ \vdots \\ e^{-j\theta_N} \end{bmatrix}$

Receiver

$$\boldsymbol{g} = \begin{bmatrix} g_1 \\ \vdots \\ g_N \end{bmatrix}$$

End-to-end-channel

$$\rho = \sum_{n=1}^{N} h_n e^{-j\theta_n} g_n = (\boldsymbol{h} \odot \boldsymbol{g})^T \boldsymbol{\omega}_\theta$$

Element-wise product

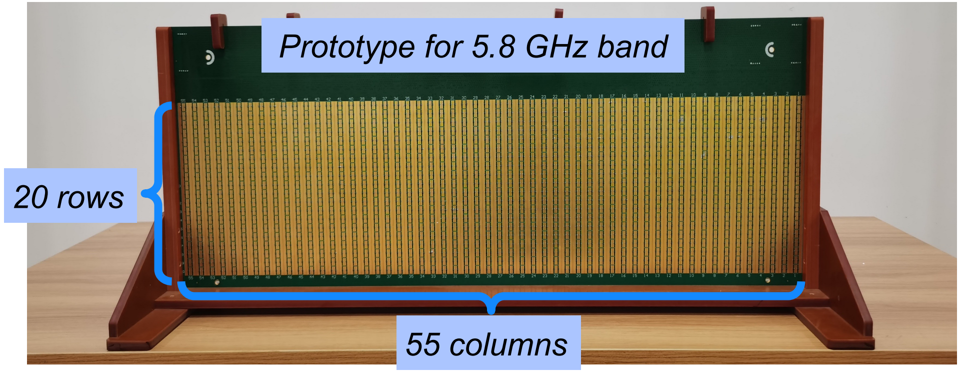
Configure RIS to maximize $|\rho|^2$:

Opposite phases in $\boldsymbol{\omega}_\theta$ and $\boldsymbol{h} \odot \boldsymbol{g}$:

$$\theta_n = \arg(h_n g_n)$$

$$|\rho|^2 = \left| \sum_{n=1}^{N} h_n e^{-j\theta_n} g_n \right|^2 \leq \left| \sum_{n=1}^{N} |h_n|\,|g_n| \right|^2 = \|\boldsymbol{h} \odot \boldsymbol{g}\|_1^2$$

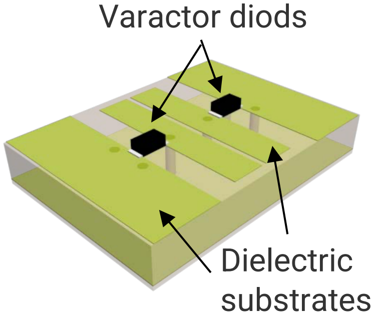
How Will an RIS Element Filter the Signal?



Example: Patch with bias voltage V

Reflection coefficient:

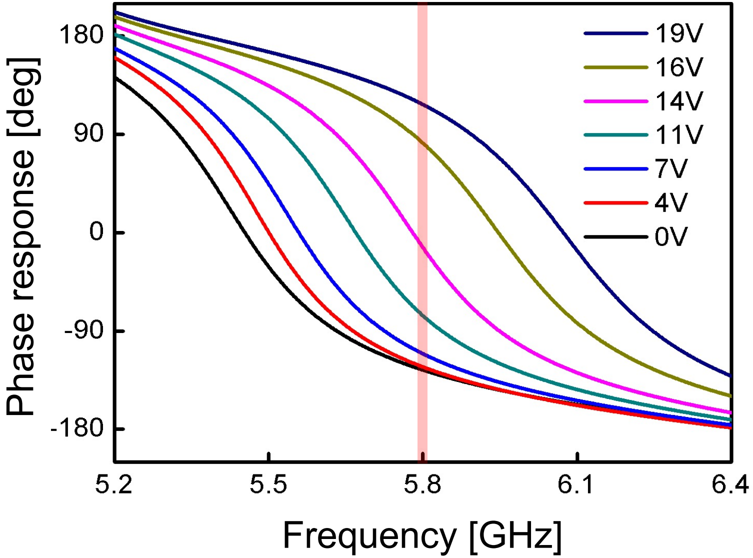
$$\frac{Z_n(V) - Z_0}{Z_n(V) + Z_0}$$



Reference: X. Pei, H. Yin, L. Tan, L. Cao, Z. Li, K. Wang, K. Zhang, E. Björnson, “RIS-Aided Wireless Communications: Prototyping, Adaptive Beamforming, and Indoor/Outdoor Field Trials,” arXiv:2103.00534

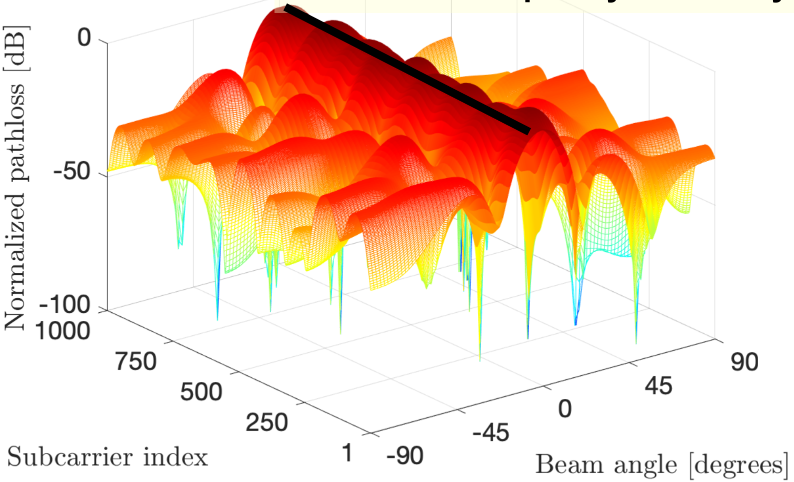
Roughly constant for 20 MHz

What about the channels?

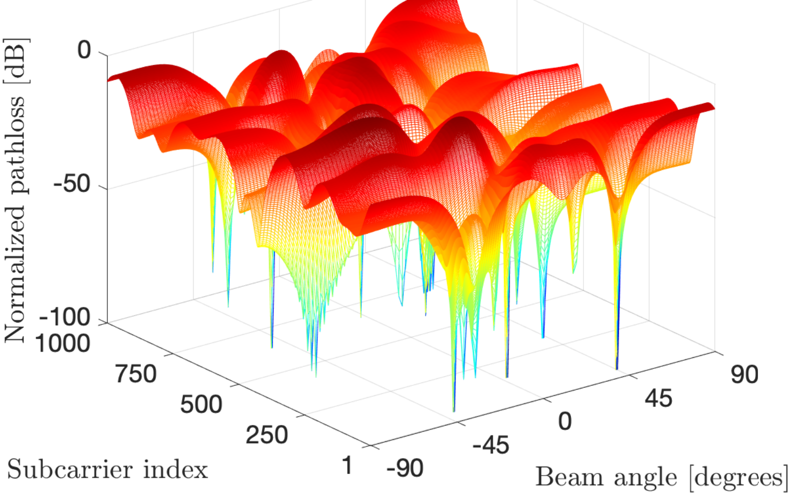


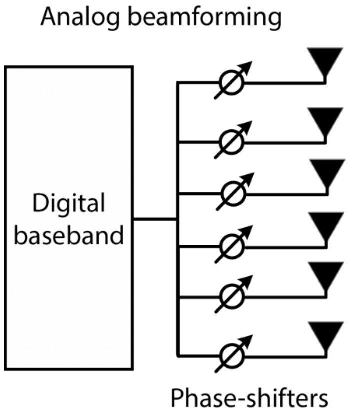
Frequency selective fading

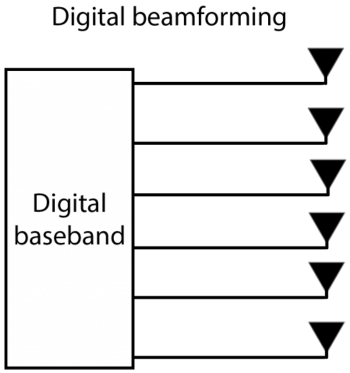
LOS: Weak frequency-selectivity



NLOS: Strong frequency-selectivity







One *angular* beam

Same on all subcarriers

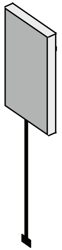
Sum of many beams

Different over subcarriers

Same principle as for RIS

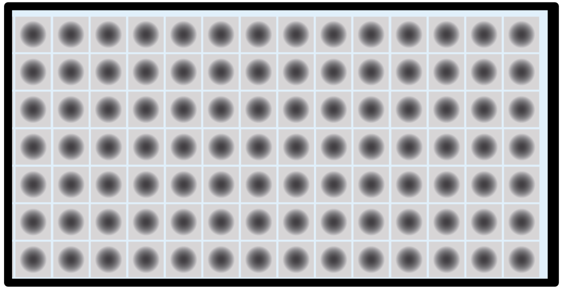
OFDM System Modeling

Transmitter



Distinct paths:

$\boldsymbol{h}_1, \dots, \boldsymbol{h}_{L_h}$



Phase-shifts: $\boldsymbol{\omega}_\theta = \begin{bmatrix} e^{-j\theta_1} \\ \vdots \\ e^{-j\theta_N} \end{bmatrix}$

Receiver

Distinct paths:

$\boldsymbol{g}_1, \dots, \boldsymbol{g}_{L_g}$

K subcarrier channels:

$$\boldsymbol{\rho} = \begin{bmatrix} \rho_1 \\ \vdots \\ \rho_K \end{bmatrix} = \boldsymbol{F}\boldsymbol{V}^T\boldsymbol{\omega}_\theta$$

DFT matrix $(K \times M)$

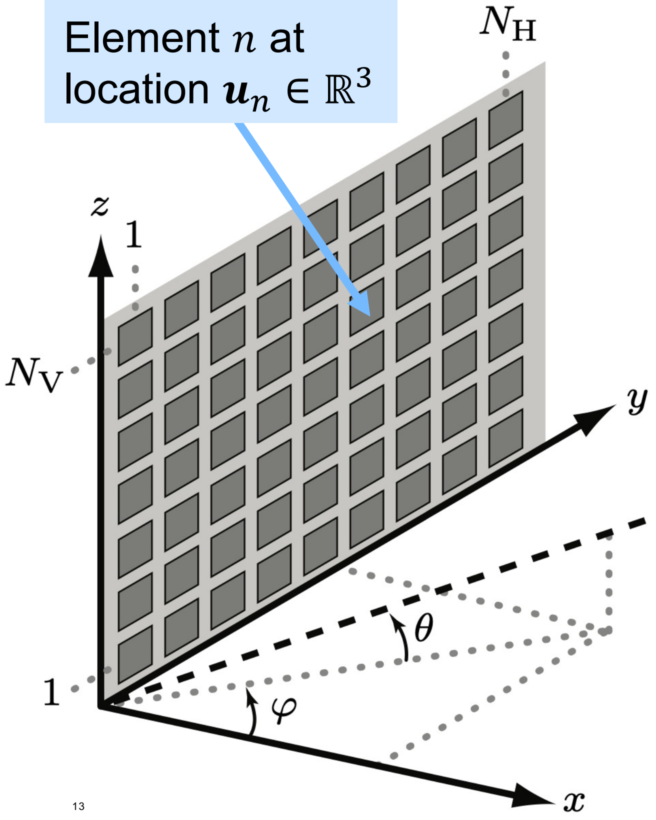
Time-domain end-to-end channel matrix (M taps)

$$\boldsymbol{V} = \sum_{l=1}^{L_h}\sum_{i=1}^{L_g}(\boldsymbol{h}_l \odot \boldsymbol{g}_i)\left[\delta[\tau_{h,l} + \tau_{g,i}] \dots \delta[\tau_{h,l} + \tau_{g,i} - (M-1)]\right]$$

Integer delays

Channel Modeling Using Array Response Vector

Element n at location $\boldsymbol{u}_n \in \mathbb{R}^3$



Far-field: Incoming/outgoing plane wave determined by

- Azimuth angle $\varphi \in [-\pi, \pi]$
- Elevation angle $\theta \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$

Channels $\boldsymbol{h}_l$ and $\boldsymbol{g}_i$ for cluster in direction (φ, θ)

$$\text{constant} \cdot \boldsymbol{a}(\varphi, \theta)$$

Array response vector:

$$\boldsymbol{a}(\varphi, \theta) = \begin{bmatrix} e^{j\boldsymbol{k}(\varphi,\theta)^T \boldsymbol{u}_1} \\ \vdots \\ e^{j\boldsymbol{k}(\varphi,\theta)^T \boldsymbol{u}_N} \end{bmatrix}$$

$$\boldsymbol{k}(\varphi, \theta) = \frac{2\pi}{\lambda} \begin{bmatrix} \cos(\theta)\cos(\varphi) \\ \cos(\theta)\sin(\varphi) \\ \sin(\theta) \end{bmatrix}$$

RIS Optimization for OFDM system

Sum rate expression:

$$R = \frac{B}{K+M-1}\sum_{k=1}^{K}\log_2\left(1+\frac{P}{\sigma^2}|\rho_k|^2\right) = \frac{B}{K+M-1}\sum_{k=1}^{K}\log_2\left(1+\frac{P}{\sigma^2}|\boldsymbol{f}_k^H\boldsymbol{V}^T\boldsymbol{\omega}_\theta|^2\right)$$

Row k of $\boldsymbol{F}$

Upper bound: Optimize $\boldsymbol{\omega}_\theta$ for each subcarrier:

$$\left|\boldsymbol{f}_k^H\boldsymbol{V}^T\boldsymbol{\omega}_\theta\right|^2 \leq \|\boldsymbol{f}_k^H\boldsymbol{V}^T\|_1^2$$

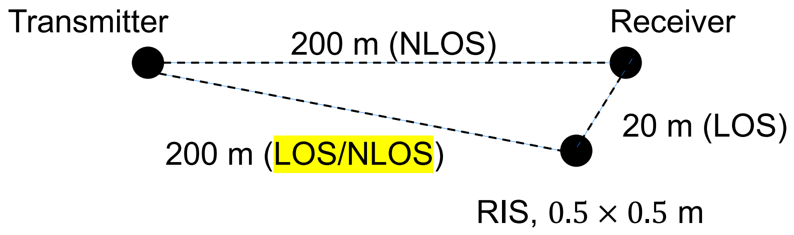
Heuristic solution: Strongest-path maximization (STM),

$$m = \arg\max_i \|\boldsymbol{v}_i\|_1^2 \;\; \text{where } \boldsymbol{V} = [\boldsymbol{v}_1 \; \dots \boldsymbol{v}_M]$$

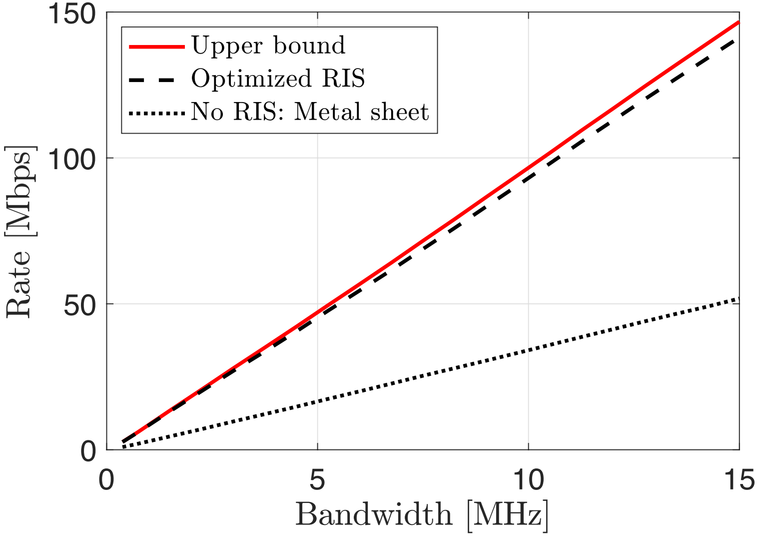
$$\boldsymbol{\omega}_\theta = \arg\max_{\boldsymbol{\omega}} |\boldsymbol{v}_m^T\boldsymbol{\omega}|^2$$

RIS in Frequency Selective Channels

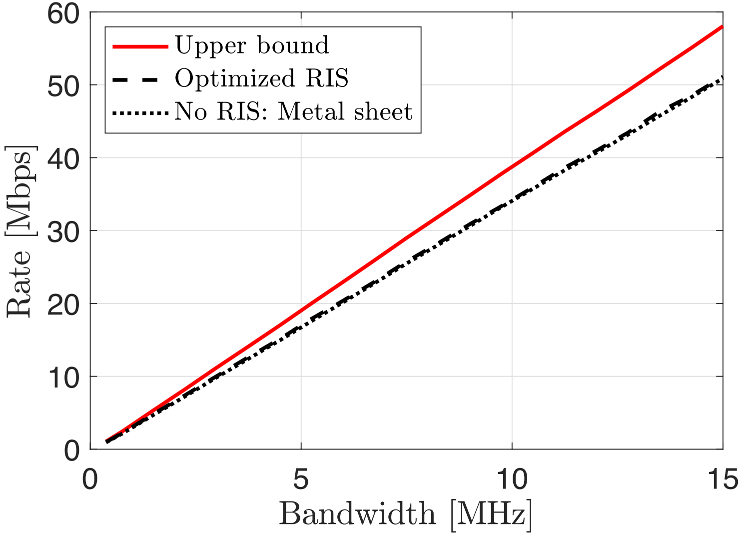
RIS only effective with LOS to transmitter and receiver!



LOS: Weakly frequency-selective

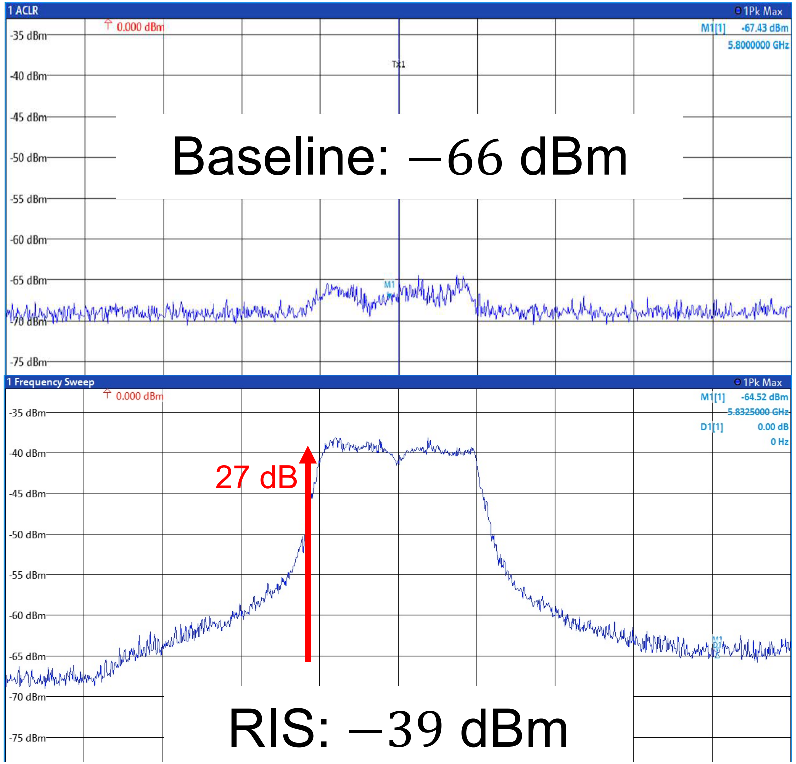


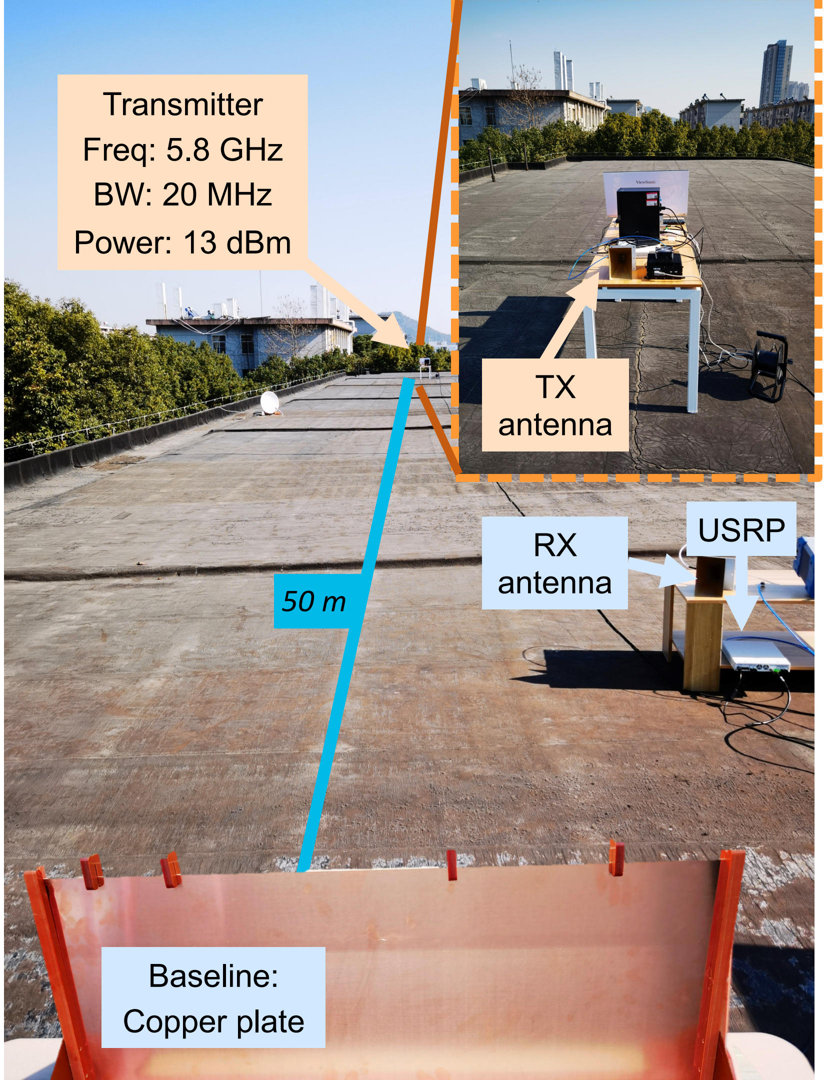
NLOS: Strongly frequency-selective



Reference: *E. Björnson, et al.,* "Reconfigurable Intelligent Surfaces: A Signal Processing Perspective With Wireless Applications"*, Available on arXiv:2102.00742.*

Experimental Validation





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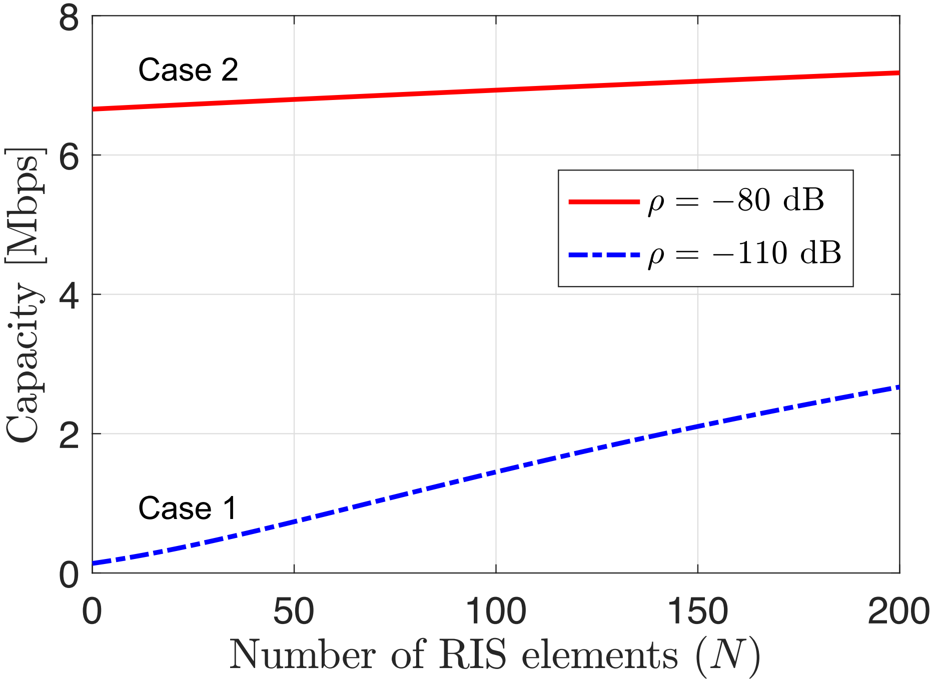
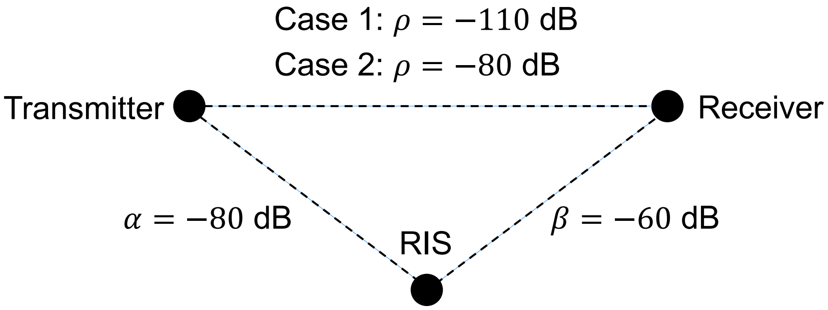
IDENTIFYING THE BEST USE CASE

Importance of the Direct Path





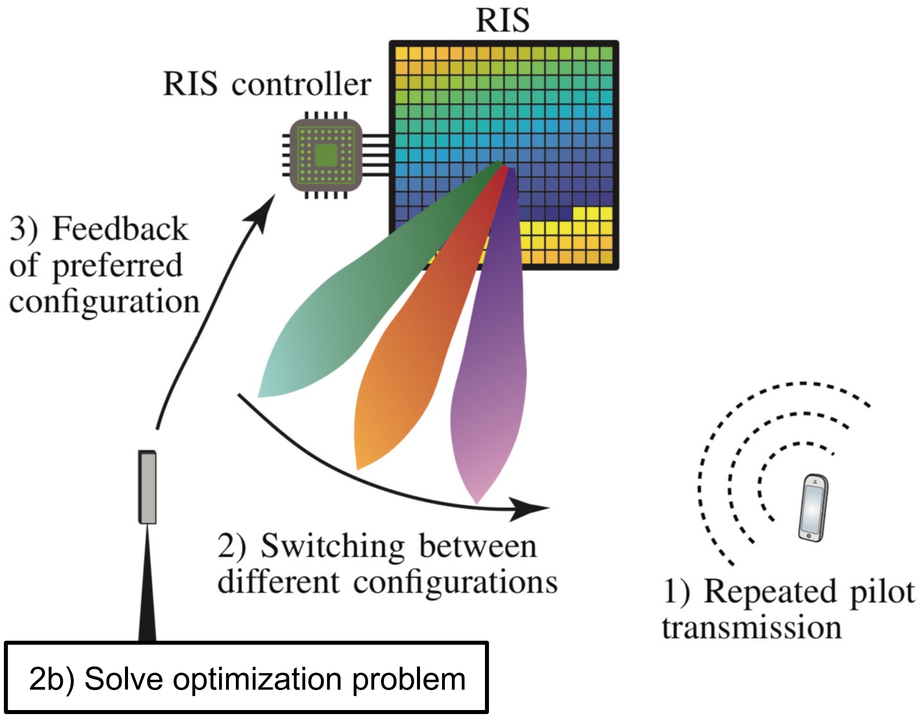
Bandwidth: $B = 1$ MHz

Transmit SNR: 100 dB

RIS only effective if direct path is weak

How Difficult is Channel Estimation?

The RIS is blind!



How Many Parameters to Estimate?

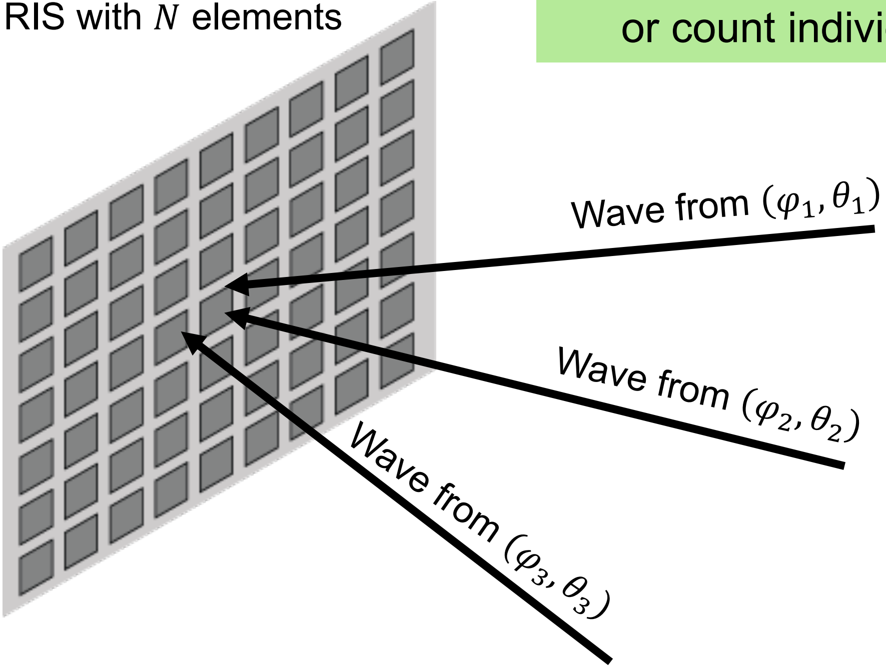
L_h **channel vectors**

$\boldsymbol{h}_l = c_l \boldsymbol{a}(\varphi_l, \theta_l)$

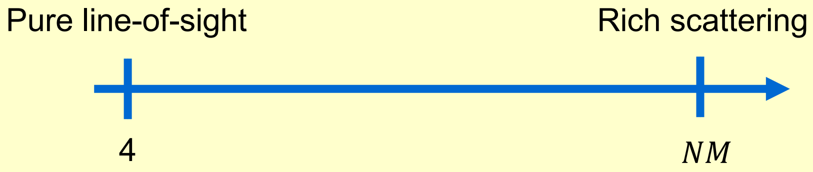
NM complex parameters in $\boldsymbol{V}$

or count individual parameters

RIS with N elements



Parameters to estimate:



E. Björnson, L. Sanguinetti, "Rayleigh Fading Modeling and Channel Hardening for Reconfigurable Intelligent Surfaces," IEEE Wireless Communications Letters, 2021.

Summary

<table>
<tr><td></td><td>NLOS to/from RIS</td><td>LOS to/from RIS</td></tr>
<tr><td>Strong direct path</td><td rowspan="2">RIS not effective in OFDM

Difficult to estimate</td><td>RIS adds little to direct path</td></tr>
<tr><td>Weak direct path</td><td>Large gains in OFDM
Few parameters to estimate</td></tr>
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OPEN PROBLEMS

Much *Deeper* Research is Needed!

- Efficient RIS configuration for OFDM

  With amplitude variations and limited resolution

  "*Optimizing a Binary Intelligent Reflecting Surface for OFDM Communications under Mutual Coupling*" arXiv:2106.04280

- Effective estimation algorithm

  Utilize spatial correlation

  "*Rayleigh Fading Modeling and Channel Hardening for Reconfigurable Intelligent Surfaces*" arXiv:2009.04723

- Further system modeling
  - What if we the RIS is also frequency selective?

Conclusion: OFDM Works in One Particular Use Case