Reconfigurable Intelligent Surfaces:
A Signal Processing Perspective

Emil Björnson

Visiting professor, KTH, Sweden

Associate professor, Linköping
University, Sweden

Outline

Introduction

- Reconfigurable intelligent surface (RIS)
- Vision for how to improve wireless communications

Developing a system model

- Basic signals and systems theory
- Application to model RIS systems
- Optimization of RIS for communication

Spatial channel structure

- Reduce number of parameters to learn

Summary

INTRODUCTION

Physics of Wireless Signal Propagation

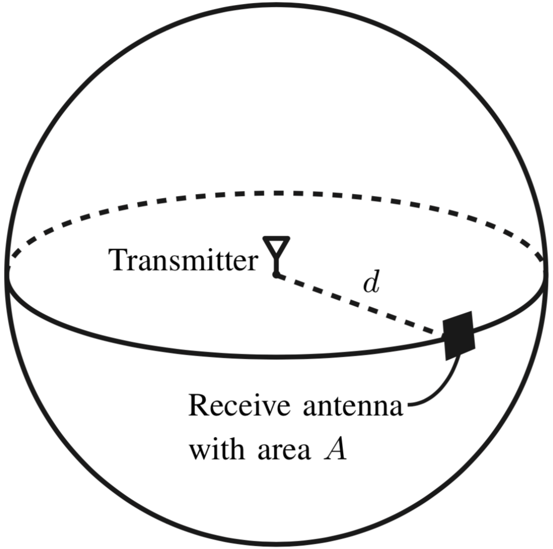
- Electromagnetic travel at speed of light
  - Spreads out in all directions

- Friis' propagation formula:

$$\text{Receive power} = \text{Transmit power} \cdot \frac{A}{4\pi d^2}$$

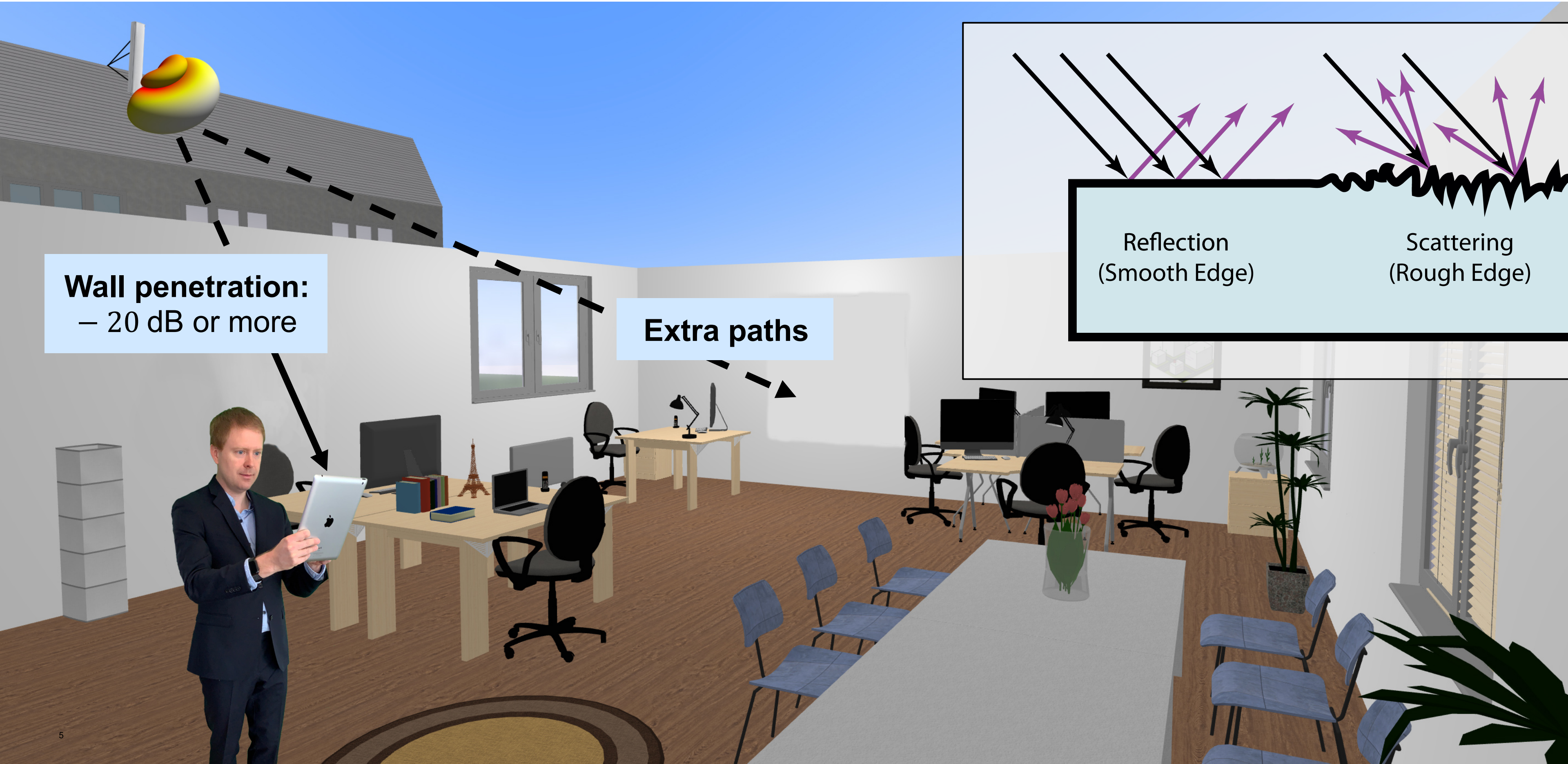
Example: $A = \left(\frac{\lambda}{4}\right)^2, \lambda = 0.1$ m (3 GHz)

0.005% received at 1 m $(-43$ dB)
0.00005% received at 10 m $(-63$ dB)

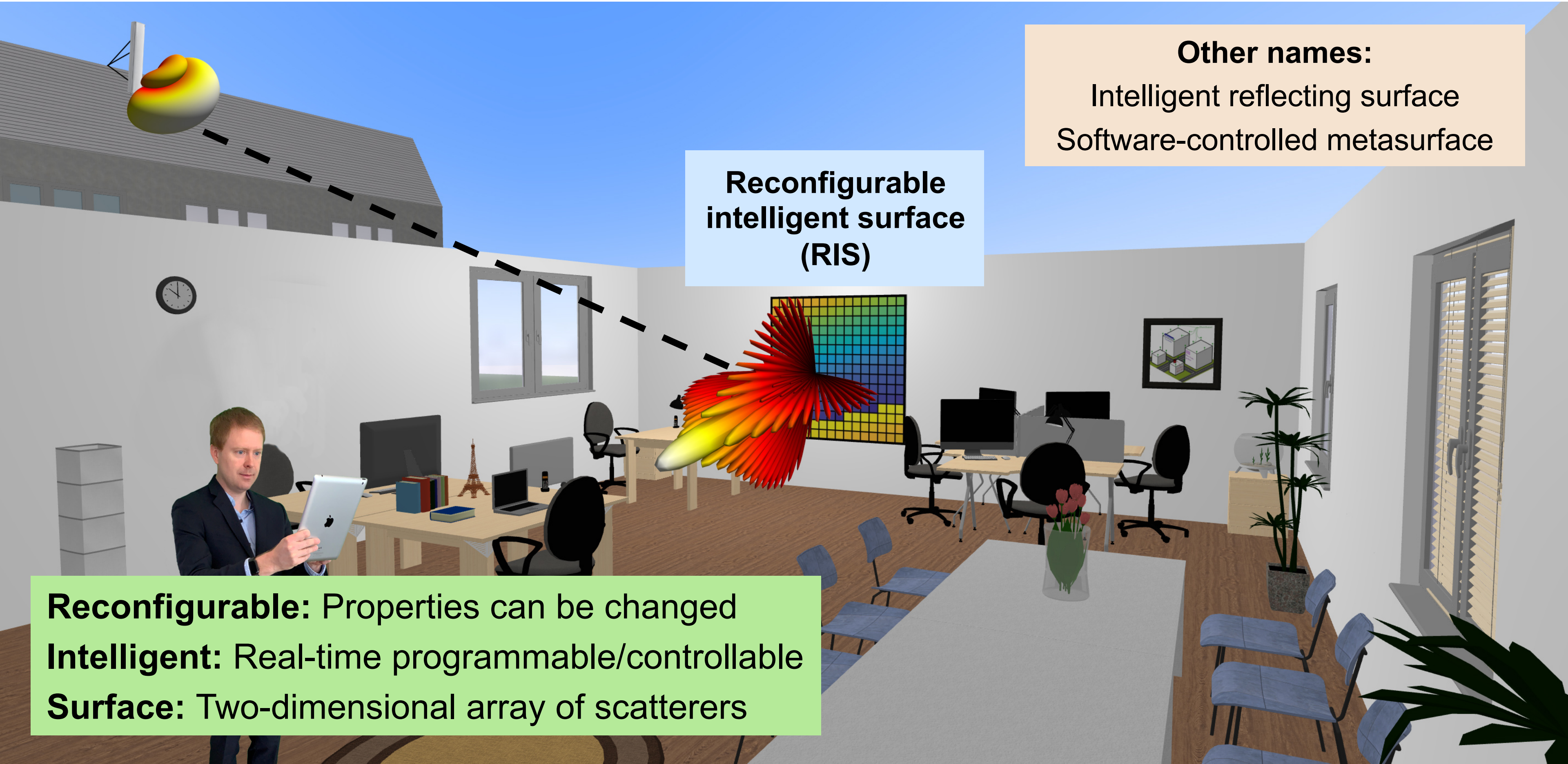


Only a tiny fraction of transmit power is received!

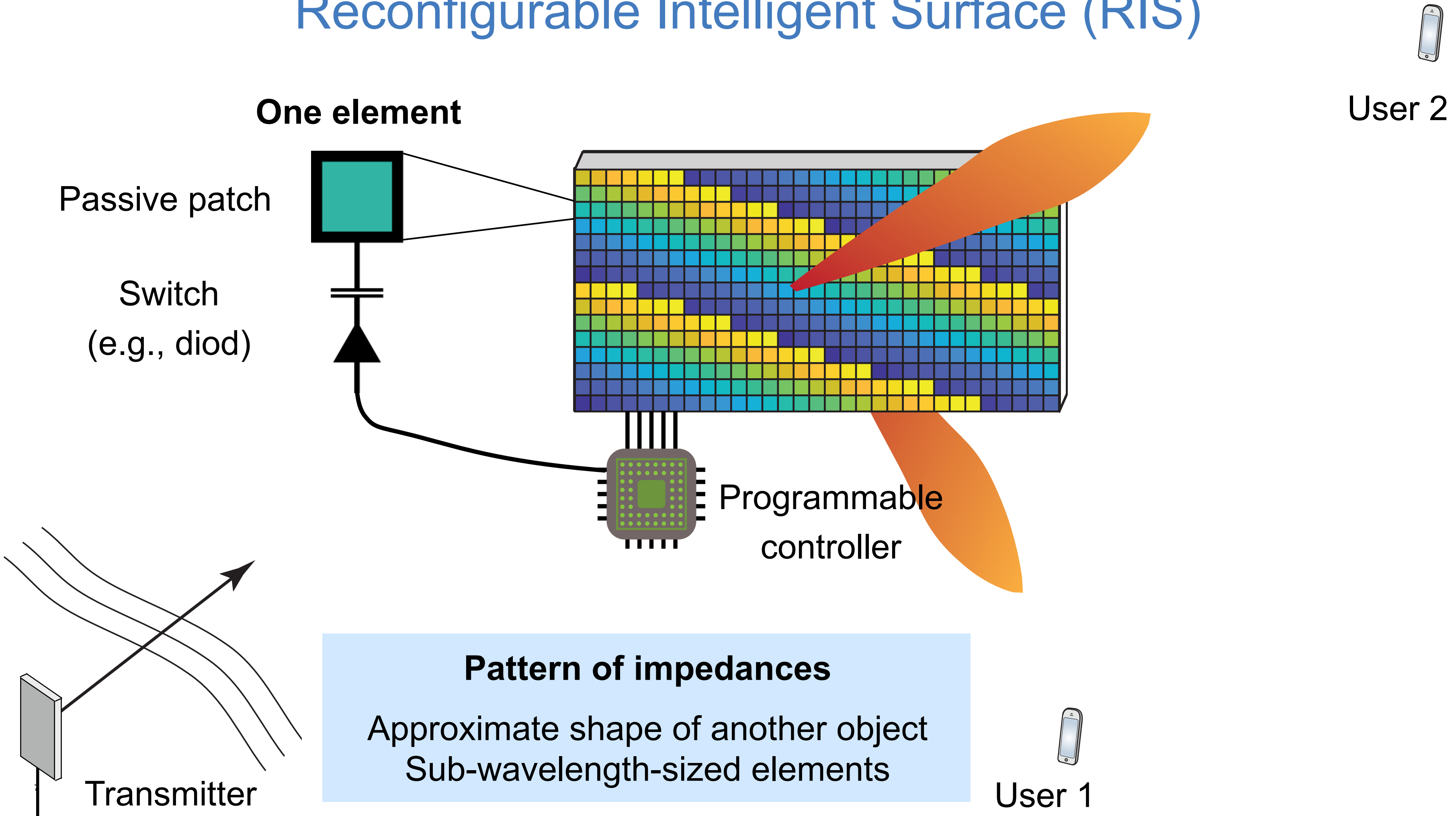
No Direct Path: Even Larger Propagation Losses



Shaping the Signal Scattering Towards the Receiver



Reconfigurable Intelligent Surface (RIS)



Pattern of impedances

Approximate shape of another object
Sub-wavelength-sized elements

Vision: Controllable propagation

RIS ***as a whole*** can control

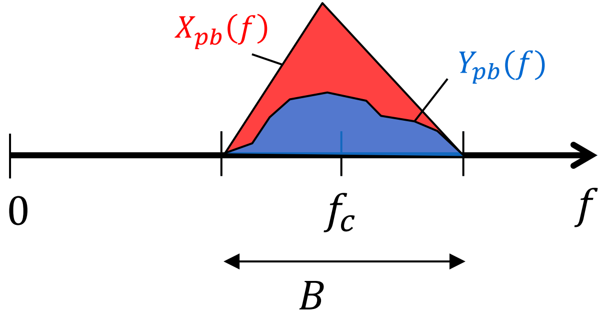
- Directivity of scattered signal
- Signal absorption
- Change polarization

Improved indoor coverage

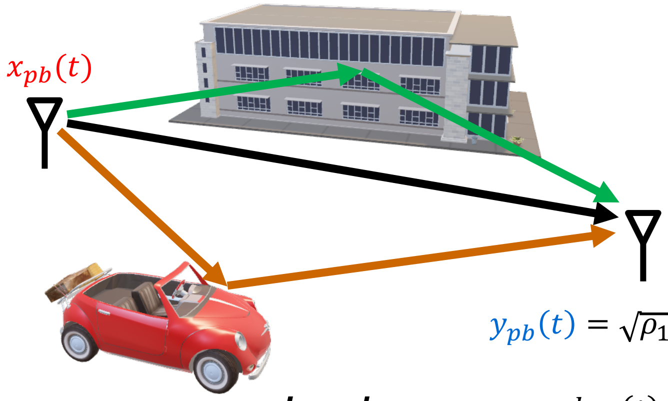
DEVELOPING A SYSTEM MODEL

Introduction to Signals and Systems

$x_{pb}(t) \rightarrow$ **Linear-time invariant:** *Impulse response* $h_{bp}(t)$ $\rightarrow$ $y_{pb}(t) = (h_{pb} * x_{pb})(t) = \int_{\infty}^{-\infty} h_{pb}(u) x_{pb}(t-u)\,du$



- Communication channels are systems/filters:



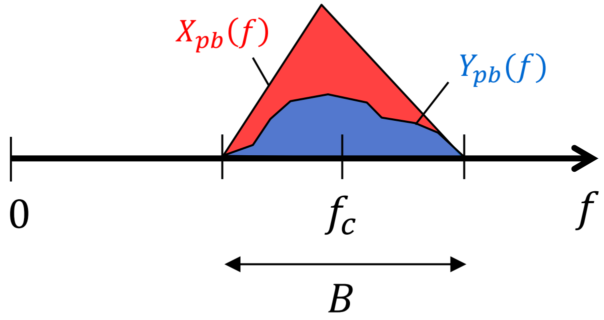
$$y_{pb}(t) = \sqrt{\rho_1} x_{pb}(t-\tau_1) + \sqrt{\rho_2} x_{pb}(t-\tau_2) + \sqrt{\rho_3} x_{pb}(t-\tau_3)$$

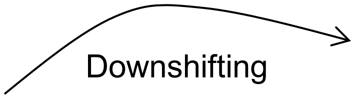
Impulse response: $h_{bp}(t) = \sqrt{\rho_1}\delta(t-\tau_1) + \sqrt{\rho_2}\delta(t-\tau_2) + \sqrt{\rho_3}\delta(t-\tau_3)$

Complex Baseband Representation

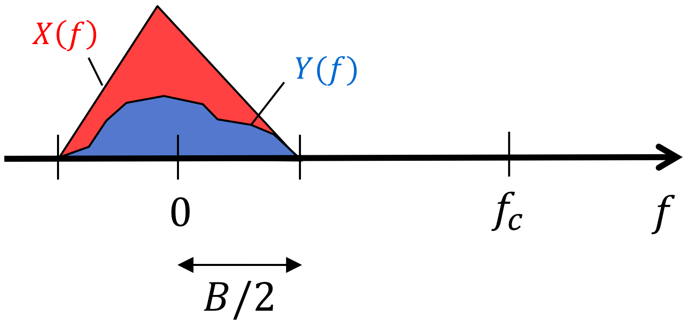
- Communication theory is developed for the baseband

Real passband

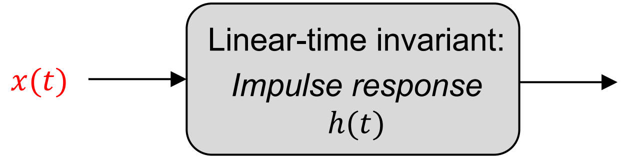




Complex baseband



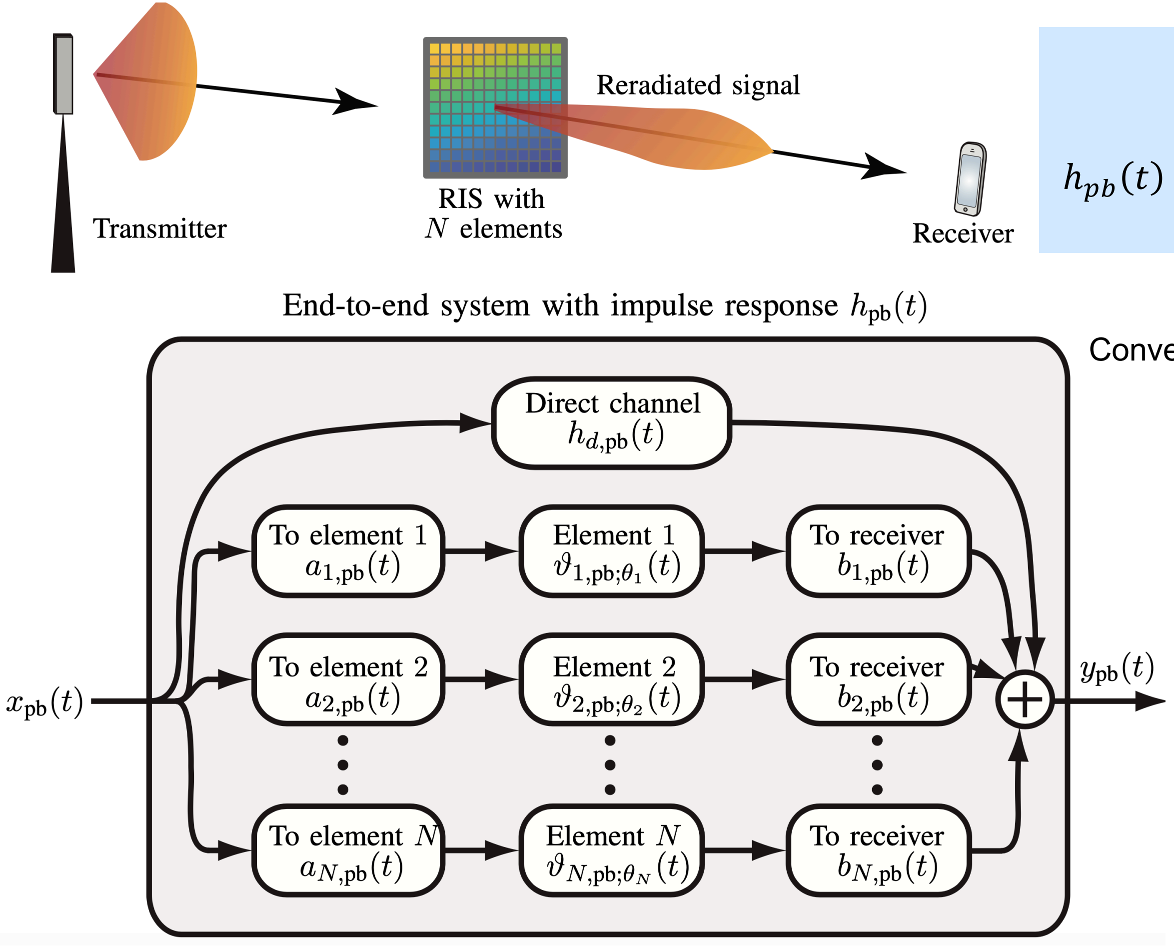
- Connection: $X_{pb}(f) = \frac{X(f-f_c)+X^*(-f-f_c)}{\sqrt{2}}$, $Y_{pb}(f) = \frac{Y(f-f_c)+Y^*(-f-f_c)}{\sqrt{2}}$



$y(t) = \int_{\infty}^{-\infty} h(u)x(t-u)du$

Downshifted channel: $h(t) = h_{pb}(t)e^{-j2\pi f_c t}$

Analyzing Reconfigurable Intelligent Surface



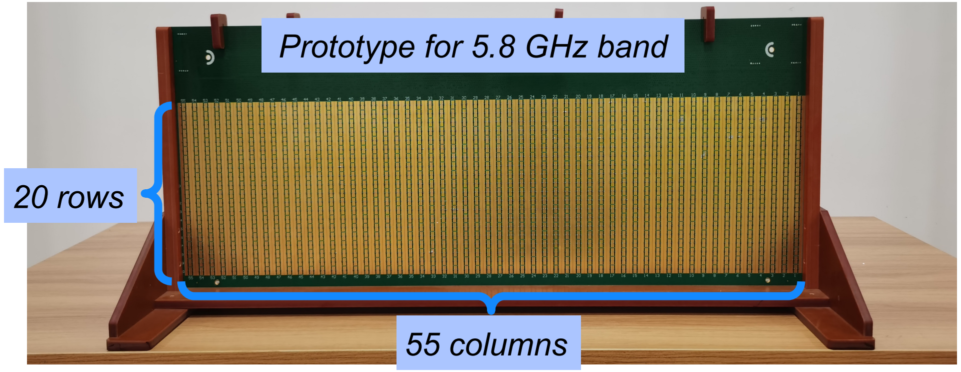
End-to-end impulse response:

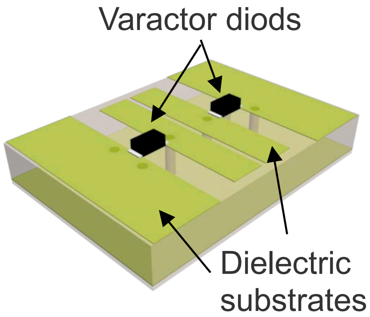
$$h_{pb}(t) = h_{d,pb}(t) + \sum_{n=1}^{N} \left(b_{n,pb} * \vartheta_{n,pb;\theta_n} * a_{n,pb}\right)(t)$$

Conventional channel models

Controlled by RIS using $\theta_1, \dots, \theta_N$

How Will an RIS Element Filter the Signal?



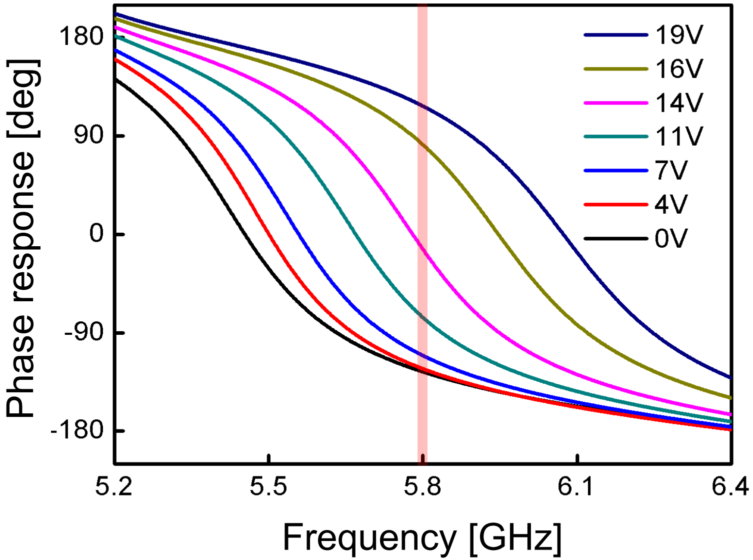


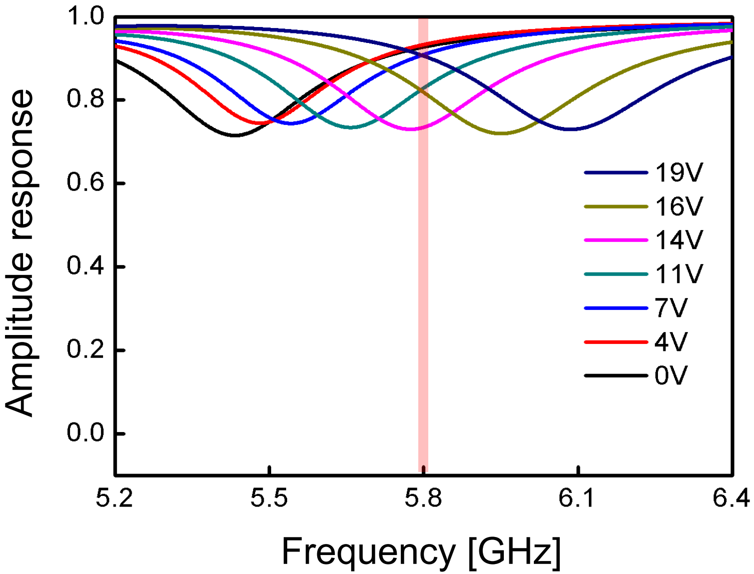
Example: Patch with bias voltage V

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





How To Transmit Data?

- Pulse amplitude modulation:

$$x(t) = \sum_m x[m]p\left(t - \frac{m}{B}\right)$$

  - Transmit discrete sequence: $x[m],\ m = \text{integer}$

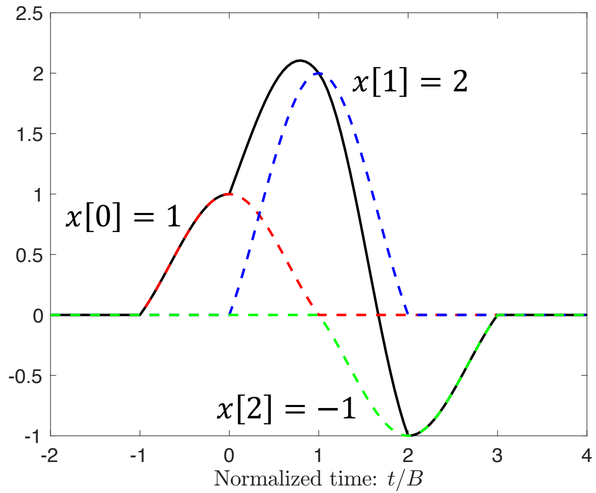
Use a pulse-form $p(t)$ satisfying the Nyquist criterion:

$p\left(\frac{m}{B}\right) = 0$ for integer $m \neq 0$ and non-zero for $m = 0$

  - **Example:** $p(t) = \sqrt{B}\,\text{sinc}(Bt)$

Sampling of received signal $y(t) = x(t)$:

$$y\left(\frac{k}{B}\right) = x\left(\frac{k}{B}\right) = \sum_m x[m]p\left(\frac{k-m}{B}\right) = x[k]$$



Reception with Channel and Noise

- Received signal (with Gaussian noise):

$$y(t) = (h * x)(t) + w(t)$$

1. Filter using $p(t) = \sqrt{B}\,\mathrm{sinc}(Bt)$:

$$z(t) = (p * y)(t) = \sum_m x[m]\,(p * h * p)\left(t - \frac{m}{B}\right) + (p * w)(t)$$

2. Sample received signal:

$$\underbrace{z\left(\frac{k}{B}\right)}_{\text{Call it } z[k]} = \sum_m x[m]\,\underbrace{(p * h * p)}_{\text{Effective pulse function}}\left(\frac{k-m}{B}\right) + \underbrace{(p * w)\left(\frac{k}{B}\right)}_{\text{Complex Gaussian noise } CN(0, N_0)}$$

Narrowband channel: $h \approx \mathrm{constant} \cdot \delta(t-\tau)$ in the band, Nyquist criterion satisfied

$$z[k] = \mathrm{constant} \cdot\ x[k] + \text{Gaussian noise}$$

Putting the Pieces Together: Narrowband Channels

- Direct channel: $h_{d,pb}(t) = \sqrt{\rho}\delta(t-\tau_d) \quad \rightarrow h_d(t) = \sqrt{\rho}e^{-j2\pi f_c t}\delta(t-\tau_d)$

- Related to element n: $a_{n,pb}(t) = \sqrt{\alpha_n}\delta(t-\tau_{n,a}) \quad \rightarrow a_n(t) = \sqrt{\alpha_n}e^{-j2\pi f_c t}\delta(t-\tau_{n,a})$

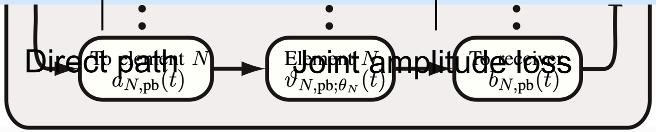
$$\vartheta_{n,pb;\theta_n}(t) = \sqrt{\gamma_n}\delta(t-\tau_{\theta_n}) \quad \rightarrow \vartheta_{n;\theta_n}(t) = \sqrt{\gamma_n}e^{-j2\pi f_c t}\delta(t-\tau_{\theta_n})$$

$$b_{n,pb}(t) = \sqrt{\beta_n}\delta(t-\tau_{n,b}) \quad \rightarrow b_n(t) = \sqrt{\beta_n}e^{-j2\pi f_c t}\delta(t-\tau_{n,b})$$

End-to-end system with impulse response $h_{\mathrm{pb}}(t)$

End-to-end discrete-time system model:

$$z[k] = \left(\sqrt{\rho}e^{-j2\pi f_c \tau_d} + \sum_{n=1}^{N}\sqrt{\alpha_n\beta_n\gamma_n}e^{-j2\pi f_c(\tau_{n,a}+\tau_{\theta_n}+\tau_{n,b})}\right)x[k] + \text{Noise}$$



Direct path

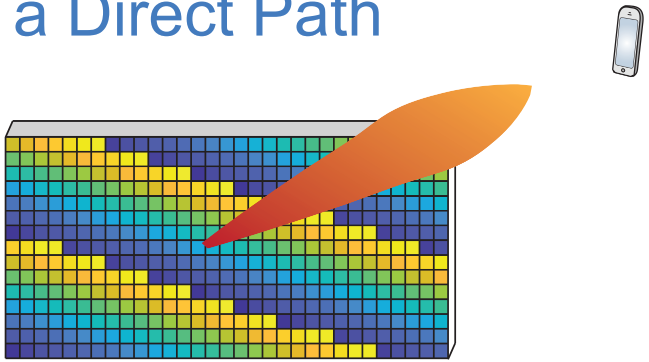
Joint amplitude loss

Joint delay

Tunable!

OPTIMIZING COMMUNICATION PERFORMANCE

Maximizing Performance Without a Direct Path



Received signal without direct path:

$$y = \sum_{n=1}^{N} \sqrt{\alpha_n \beta_n \gamma_n} e^{-j2\pi f_c(\tau_{n,a}+\tau_{\theta_n}+\tau_{n,b})} \cdot \text{signal} + \text{noise}$$

Signal processing problem:

Maximize the signal-to-noise ratio

Minimum positive delay solution:

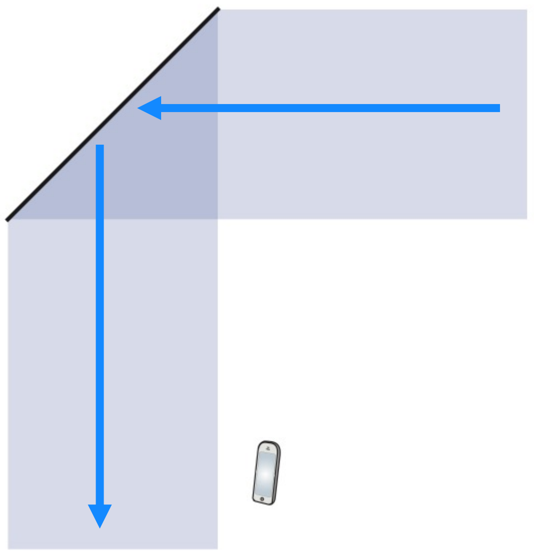
$$\tau_{\theta_n} = \max_m(\tau_{m,a} + \tau_{m,b}) - (\tau_{n,a} + \tau_{n,b})$$

$$\left| \sum_{n=1}^{N} \sqrt{\alpha_n \beta_n \gamma_n} e^{-j2\pi f_c(\tau_{n,a}+\tau_{\theta_n}+\tau_{n,b})} \right|^2 \leq \left| \sum_{n=1}^{N} \sqrt{\alpha_n \beta_n \gamma_n} \right|^2 \approx N^2 \alpha\beta\gamma$$

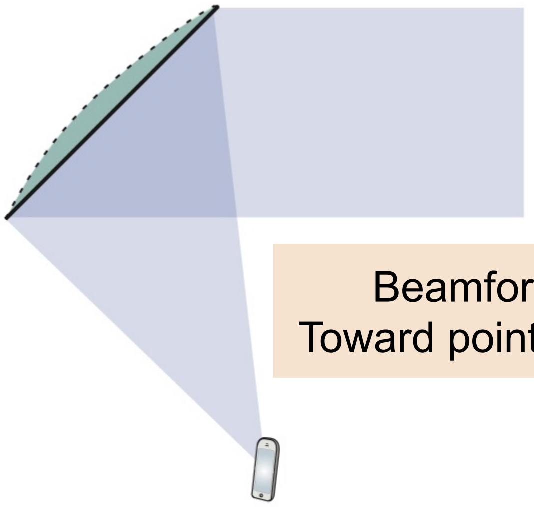
Cauchy–Schwarz inequality

$$(\tau_{n,a} + \tau_{\theta_n} + \tau_{n,b} = \text{constant})$$

Example: Synthesizing Surface Shapes



1: Normal reflection



Beamforming:
Toward point/direction

2: Signal focusing

Maximizing Performance With a Direct Path

Received signal with direct path:

$$y = \left(\sqrt{\rho} e^{-j2\pi f_c \tau_d} + \sum_{n=1}^{N} \sqrt{\alpha_n \beta_n \gamma_n} e^{-j2\pi f_c (\tau_{n,a} + \tau_{\theta_n} + \tau_{n,b})} \right) \cdot \text{signal} + \text{noise}$$

Maximize channel gain:

$$\left| \sqrt{\rho} e^{-j2\pi f_c \tau_d} + \sum_{n=1}^{N} \sqrt{\alpha_n \beta_n \gamma_n} e^{-j2\pi f_c (\tau_{n,a} + \tau_{\theta_n} + \tau_{n,b})} \right|^2 \leq \left| \sqrt{\rho} + \sum_{n=1}^{N} \sqrt{\alpha_n \beta_n \gamma_n} \right|^2$$

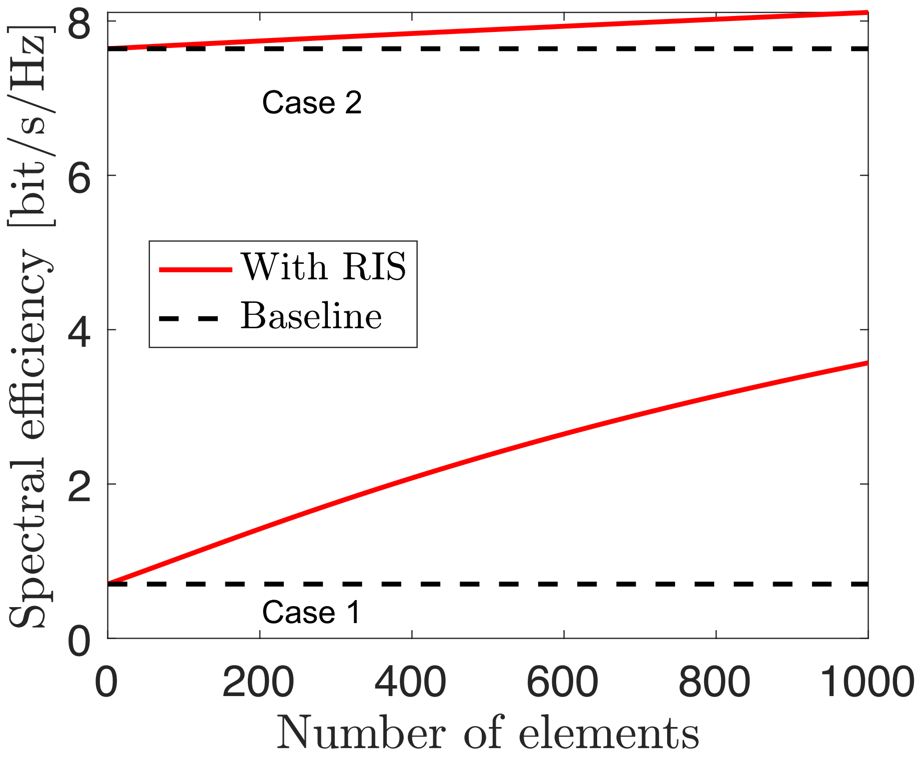
Achieved when:

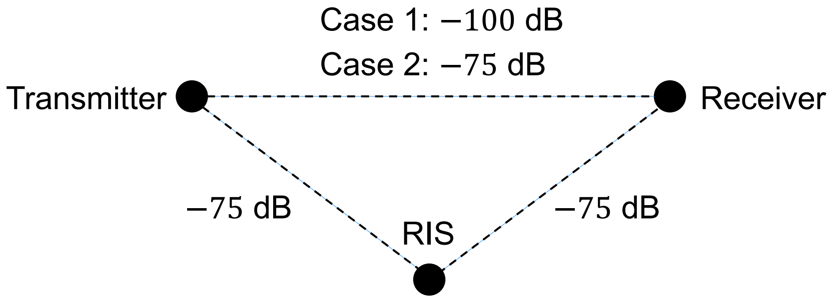
$$\tau_{n,a} + \tau_{\theta_n} + \tau_{n,b} = \tau_d$$

Minimum positive delay solution:

$$\tau_{\theta_n} = \tau_d - (\tau_{n,a} + \tau_{n,b}) + \frac{\text{integer}}{f_c}$$

Basic Performance Benefit



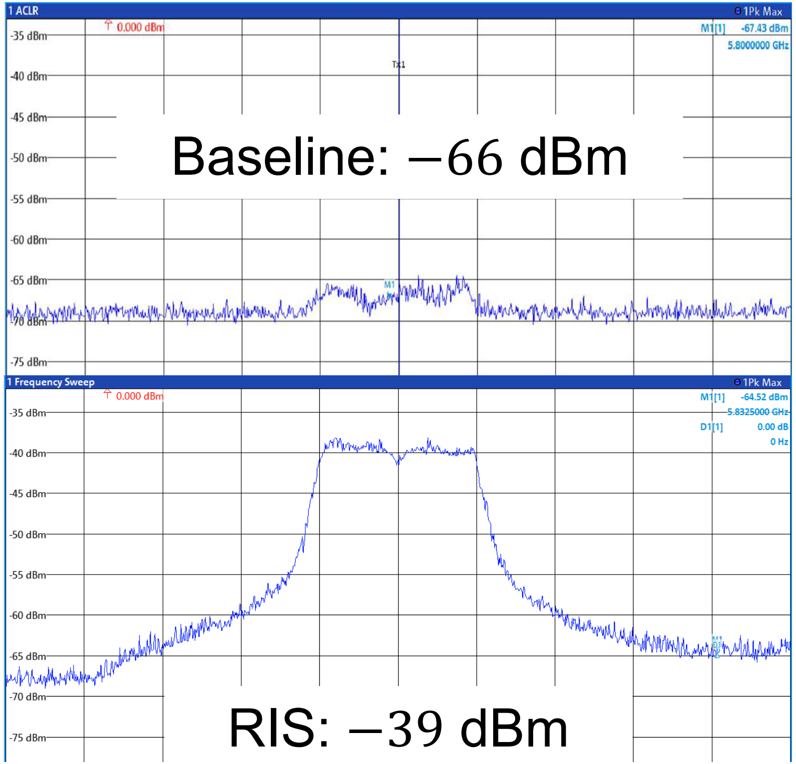


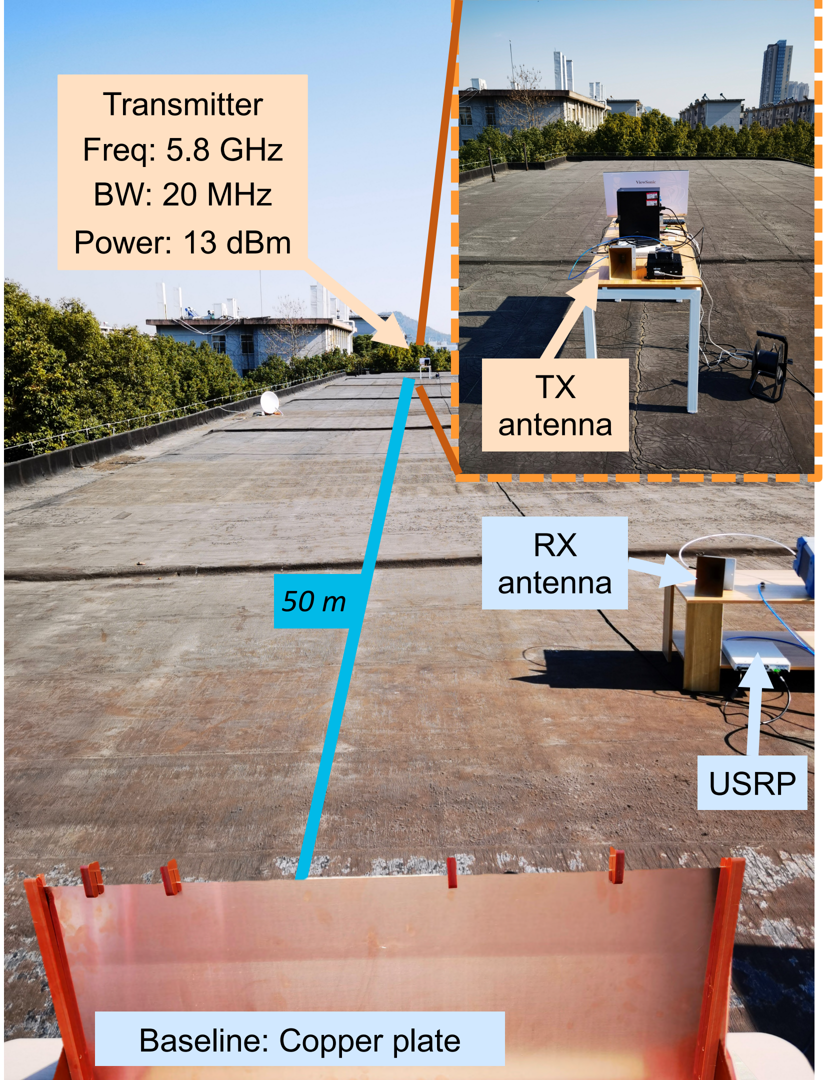
Transmit power: 10 mW per 20 MHz

RIS is particularly helpful

when direct path is relatively weak

Experimental Validation

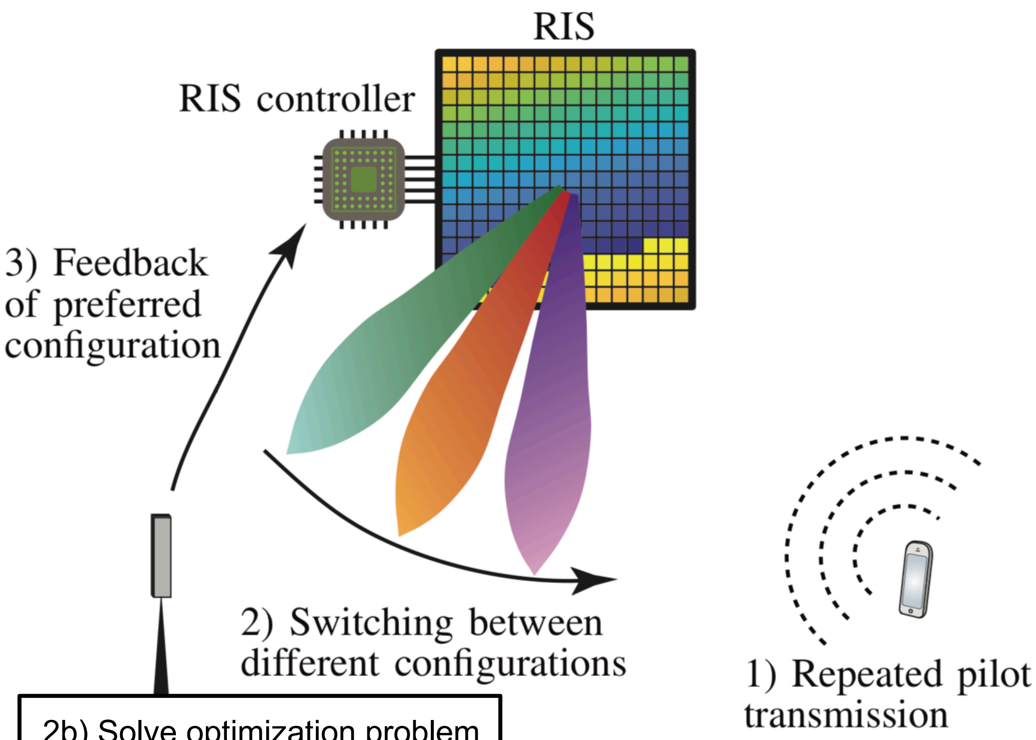




Reference: X. Pei, H. Yin, L. Tan, L. Cao, Z. Li, K. Wang, K. Zhang, E. Björnson, “RIS-Aided Wireless Communications: Prototyping, Adaptive Beamforming, and Indoor/Outdoor Field Trials,” arXiv:2103.00534

Reconfigurability is Complicated?

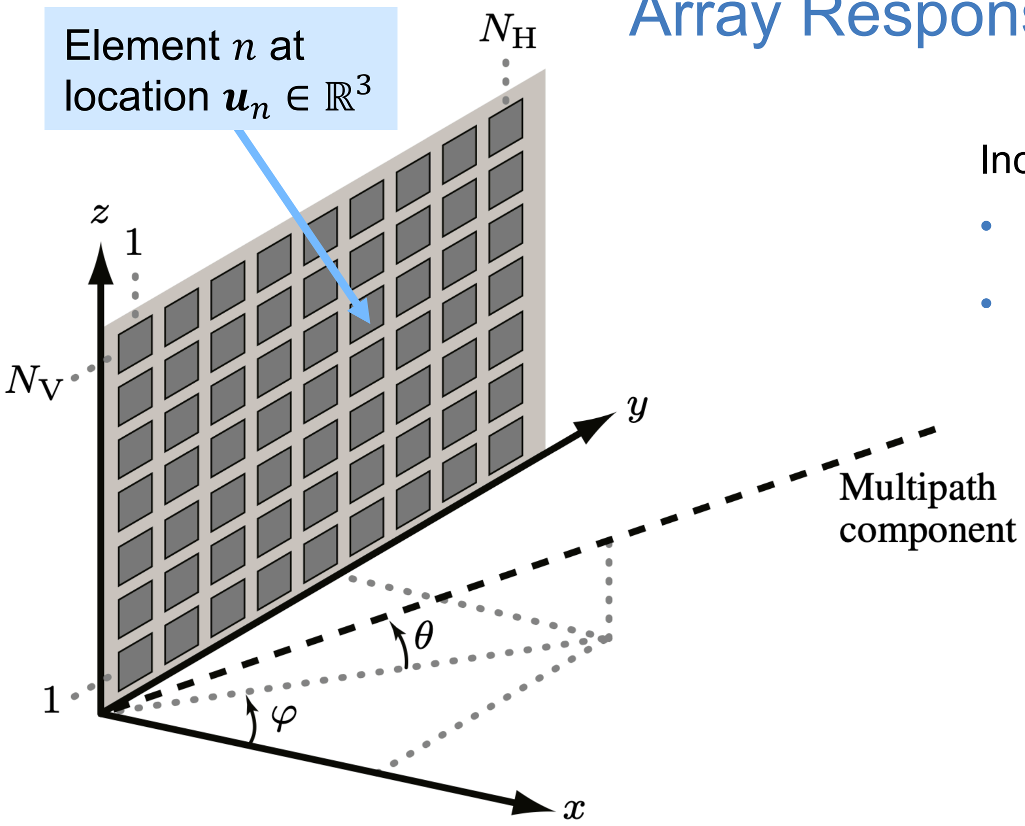
The RIS is blind!



2b) Solve optimization problem

SPATIAL CHANNEL STRUCTURE

Array Response Vector



Incoming/outgoing plane wave determined by

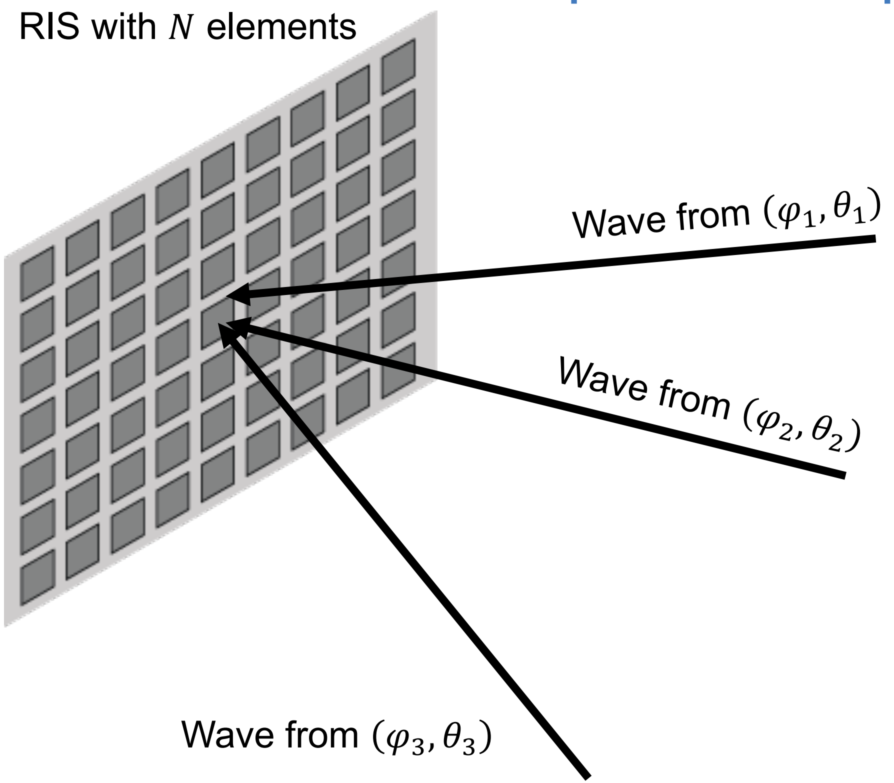
- Azimuth angle $\varphi \in [-\pi, \pi]$
- Elevation angle $\theta \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$

Channel vector for one plane wave

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

$$a(\varphi,\theta) = \begin{bmatrix} e^{j\boldsymbol{k}(\varphi,\theta)^T \boldsymbol{u}_1} \\ \vdots \\ e^{j\boldsymbol{k}(\varphi,\theta)^T \boldsymbol{u}_N} \end{bmatrix}, \quad \boldsymbol{k}(\varphi,\theta) = \frac{2\pi}{\lambda} \begin{bmatrix} \cos(\theta)\cos(\varphi) \\ \cos(\theta)\sin(\varphi) \\ \sin(\theta) \end{bmatrix}$$

Sparse Multipath Channel



Channel vector for L plane wave

$$\boldsymbol{h} = \sum_{l=1}^{L} c_l \cdot a(\varphi_l, \theta_l)$$

Number of parameters

N complex parameters in $\boldsymbol{h}$

or $3L$ real parameters

Sparse channels

L is small or one path is much stronger than all other

Sparse Channels with RIS

Recall the channel gain:

Element-wise multiplication

$$\sqrt{\rho}e^{-j2\pi f_c\tau_d} + \sum_{n=1}^{N} \sqrt{\alpha_n\beta_n\gamma_n}e^{-j2\pi f_c(\tau_{n,a}+\tau_{\theta_n}+\tau_{n,b})}$$

$$= \sqrt{\rho}e^{-j2\pi f_c\tau_d} + \Bigg(\underbrace{\begin{bmatrix} \sqrt{\beta_1}e^{-j2\pi f_c\tau_{1,b}} \\ \vdots \\ \sqrt{\beta_N}e^{-j2\pi f_c\tau_{N,b}} \end{bmatrix}}_{\text{Sparse channel from RIS?}} \odot \underbrace{\begin{bmatrix} \sqrt{\alpha_1}e^{-j2\pi f_c\tau_{1,a}} \\ \vdots \\ \sqrt{\alpha_N}e^{-j2\pi f_c\tau_{N,a}} \end{bmatrix}}_{\text{Sparse channel to RIS?}}\Bigg)^T \underbrace{\begin{bmatrix} \sqrt{\gamma_1}e^{-j2\pi f_c\tau_{\theta_1}} \\ \vdots \\ \sqrt{\gamma_N}e^{-j2\pi f_c\tau_{\theta_N}} \end{bmatrix}}_{\text{Controllable vector}}$$

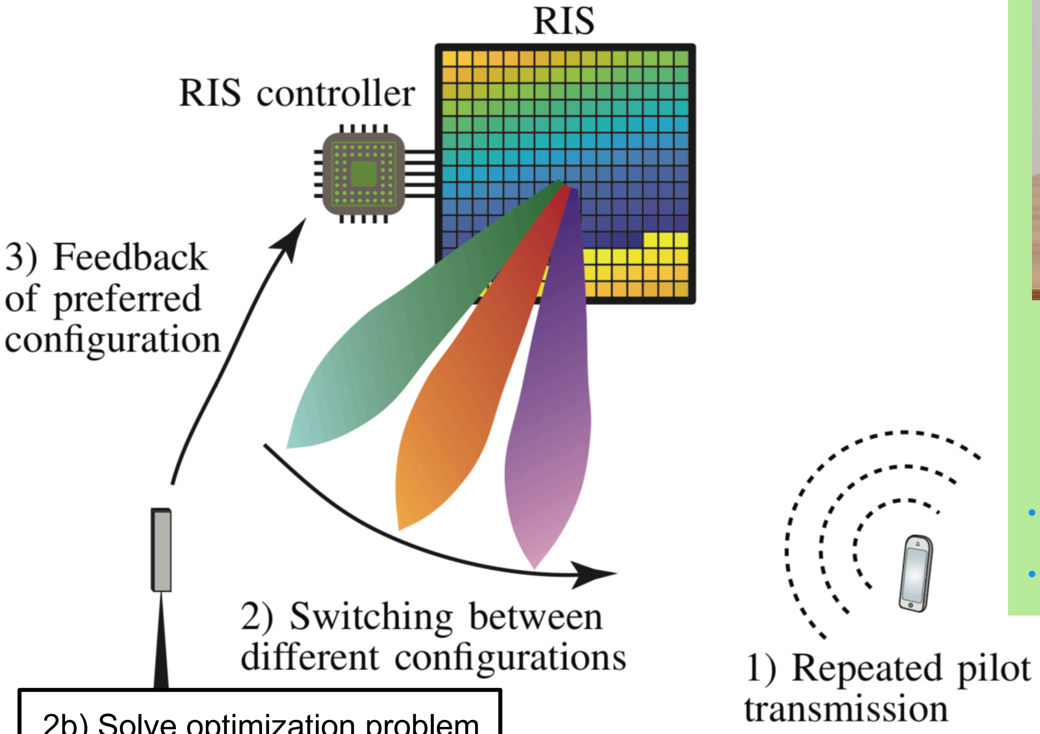
Unknowns *without* sparsity: $N + 1$

Unknowns *with* sparsity: Much fewer?

Slow variations for adjacent elements:

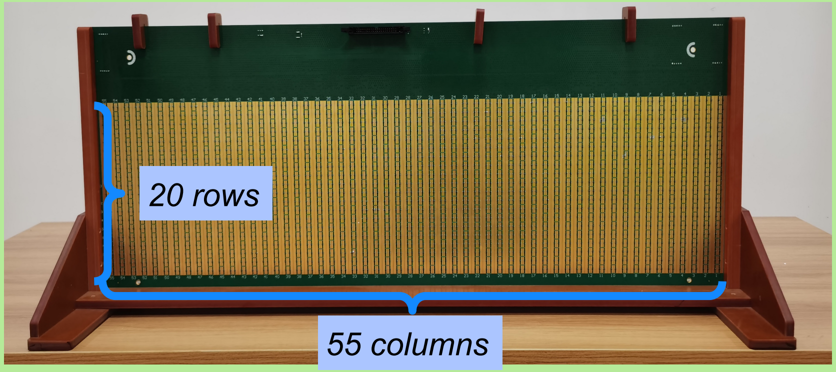
Similar phase shifts in RIS

Reconfigure RIS by Exploiting Channel Sparsity



2b) Solve optimization problem

Basic configuration algorithm

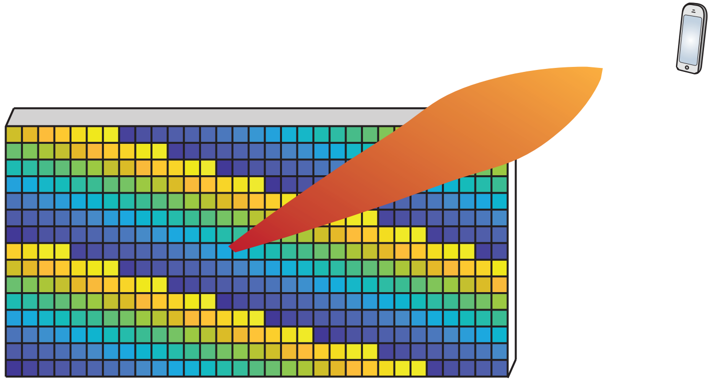


Two states per element: ±90 degrees

- Flip one row or column, pick best option
- Sweep horizontally, then vertically

SUMMARY

Reconfigurable Intelligent Surfaces for Wireless Communications



Use RIS technology to:

- Control propagation environment
- Example: Improve signal-to-noise ratio

A signal processing problem

- Learn propagation channels
- Determine how to configure the RIS

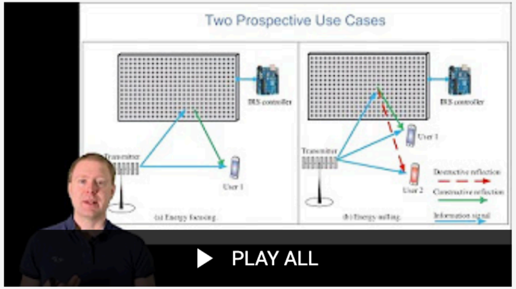
Speculations about the future

- A cost and energy efficient relay?
- Suitable when there is sparsity
  - “Easier” to channel estimate
  - Sensitive propagation
- Particularly useful above 100 GHz?

Podcast:

WIRELESS FUTURE

YouTube Videos



Intelligent reflecting surfaces for 6G

5 videos • 1,361 views • Last updated on Jan 4, 2021

Wireless Future / Communication Systems

SUBSCRIBE

1. **Fundamentals of Intelligent Reflecting Surfaces** (15:55)
   Wireless Future / Communication Systems
2. **Reconfigurable intelligent surfaces: Myths and realities** (18:20)
   Wireless Future / Communication Systems
3. **A Programmable Wireless World With Reconfigurable Intelligent Surfaces** (47:36)
   Wireless Future / Communication Systems
4. **Communication Using Reconfigurable Intelligent Surfaces: Fundamentals and Recent Insights** (27:23)
   Wireless Future / Communication Systems
5. **Power Scaling Laws and Near-Field Behaviors of Massive MIMO and Intelligent Reflecting Surfaces** (5:05)
   IEEEComSoc

Key References

Overview papers

1. E. Björnson, H. Wymeersch, B. Matthiesen, P. Popovski, L. Sanguinetti, E. de Carvalho, “A Signal Processing Perspective on Reconfigurable Intelligent Surfaces With Wireless Applications”, Available on arXiv:2102.00742.
2. E. Björnson, Ö. Özdogan, E. G. Larsson, “Reconfigurable Intelligent Surfaces: Three Myths and Two Critical Questions,” IEEE Communications Magazine, 2020.

Channel modeling

3. Ö. Özdogan, E. Björnson, E. G. Larsson, “Intelligent Reflecting Surfaces: Physics, Propagation, and Pathloss Modeling,” IEEE Wireless Commun. Letters, 2020.
4. E. Björnson, L. Sanguinetti, “Power Scaling Laws and Near-Field Behaviors of Massive MIMO and Intelligent Reflecting Surfaces,” IEEE O. J. Commun. Soc. 2020.

Prototyping and field trials

5. 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,” Available on arXiv:2102.00742

Questions?