Reconfigurable Intelligent Surfaces: A Signal Processing Perspective

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KTH VETENSKAP OCH KONST

Outline

Introduction

- Reconfigurable intelligent surface (RIS), vision of a reconfigurable world

Developing a system model

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

What are good use cases?

- Compared to alternative technologies

Summary

INTRODUCTION

Physics of Wireless Signal Propagation

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

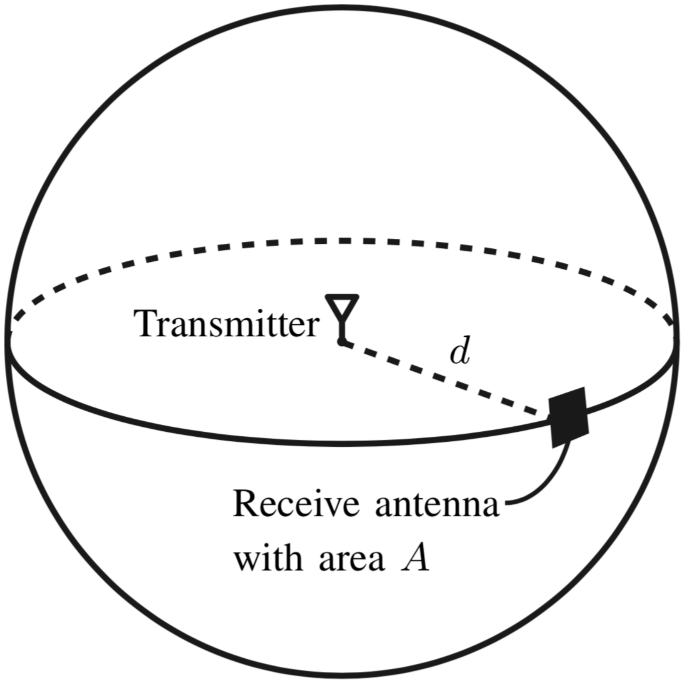
- Friis' propagation formula:

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

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

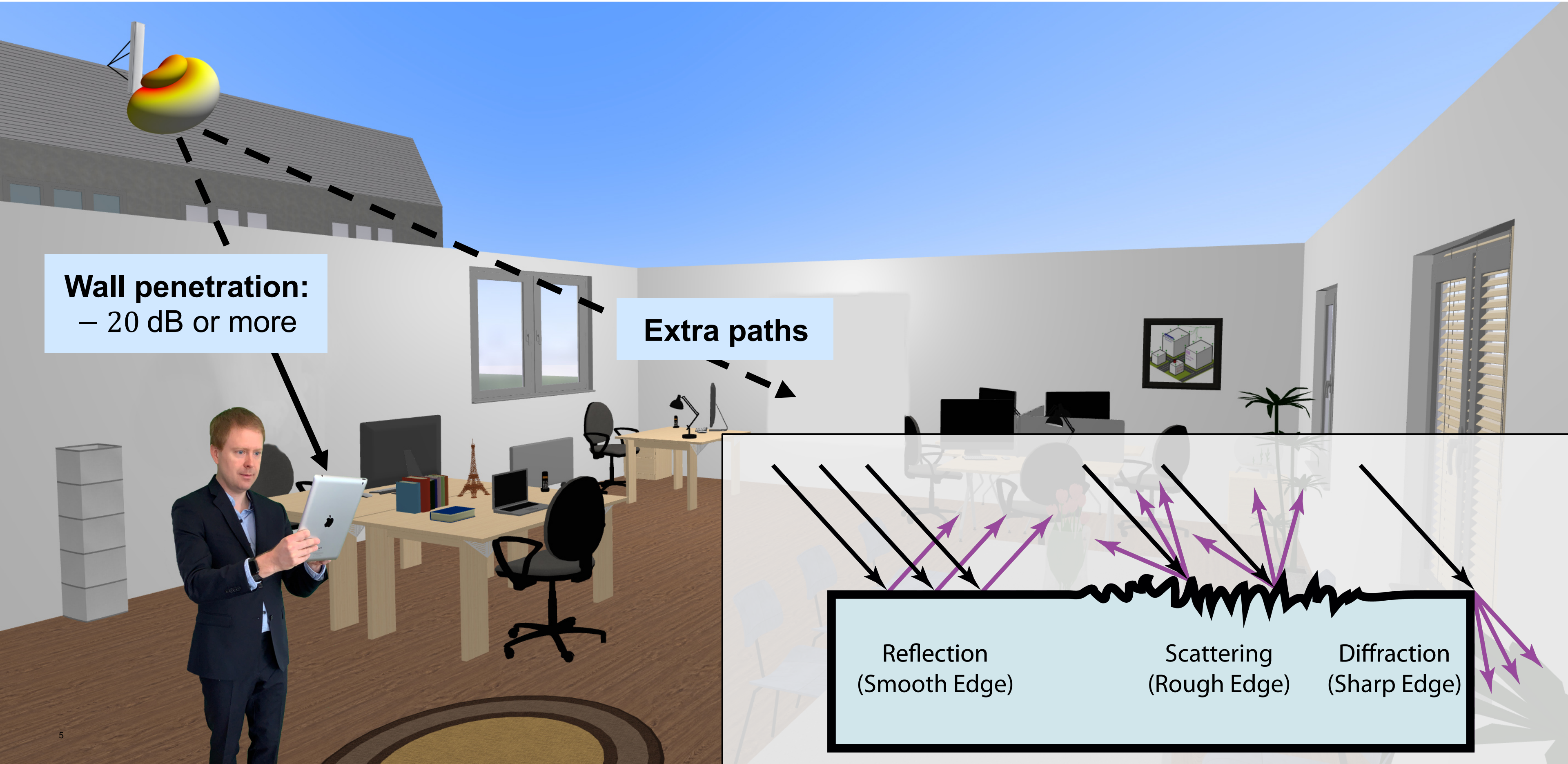
0.005% received at 1 m (−43 dB)
0.00005% received at 10 m (−63 dB)

Only a tiny fraction of transmit power is received!

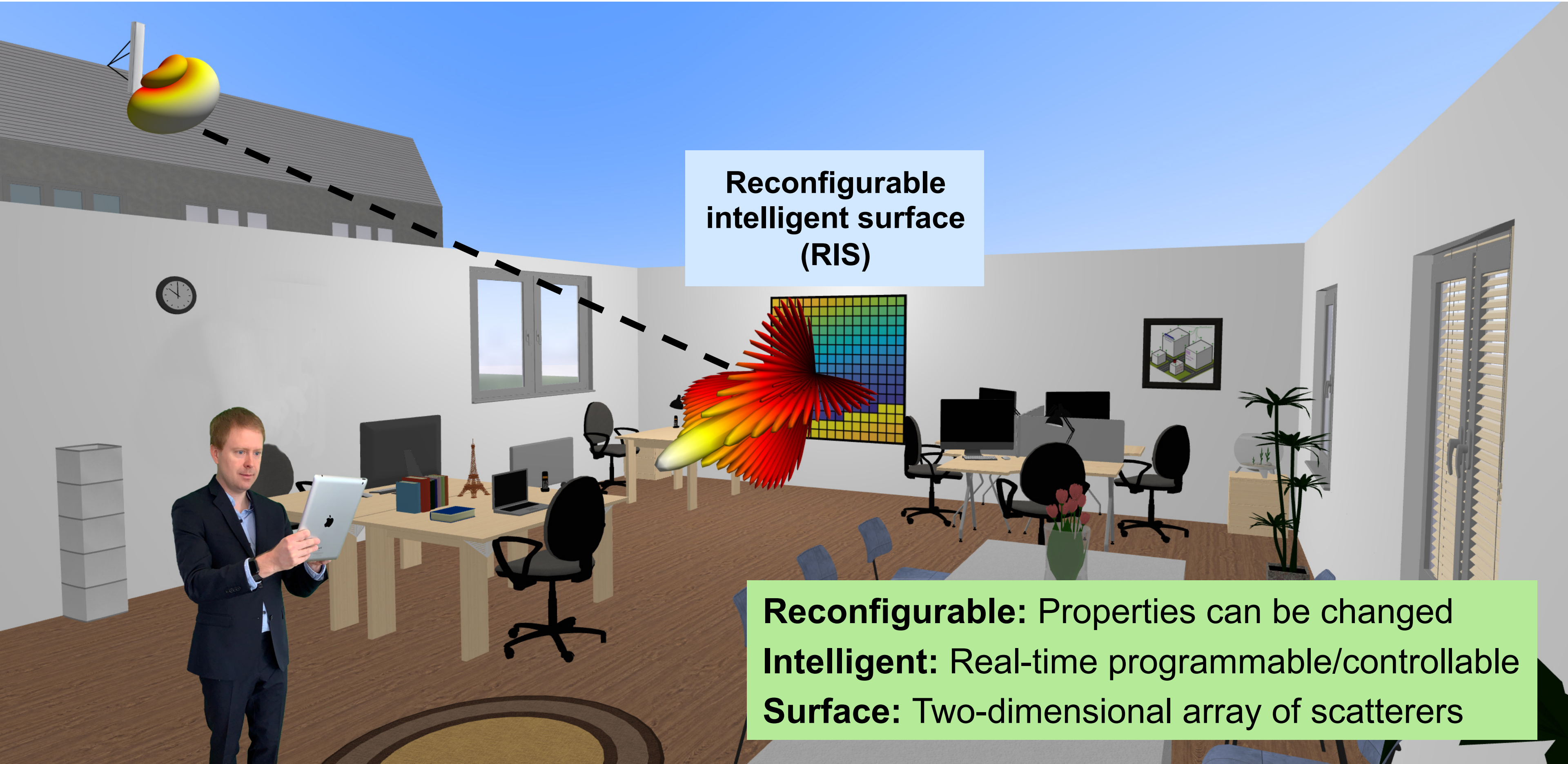


H. T. Friis, "A note on a simple transmission formula," IRE, vol. 34, no. 5, pp. 254–256, 1946

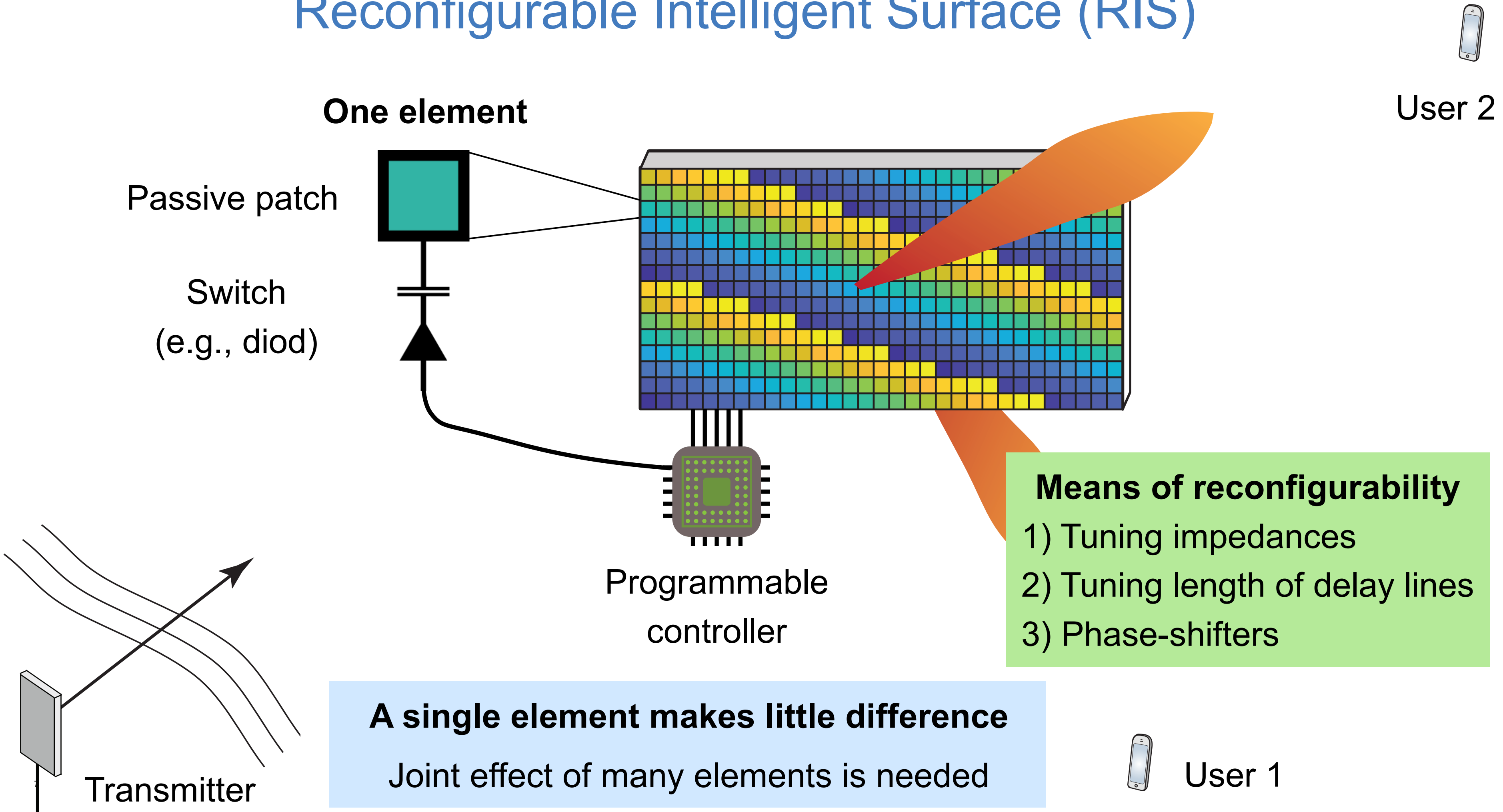
No Direct Path: Even Larger Propagation Losses



Shaping the Signal Scattering Towards the Receiver



Reconfigurable Intelligent Surface (RIS)



Means of reconfigurability

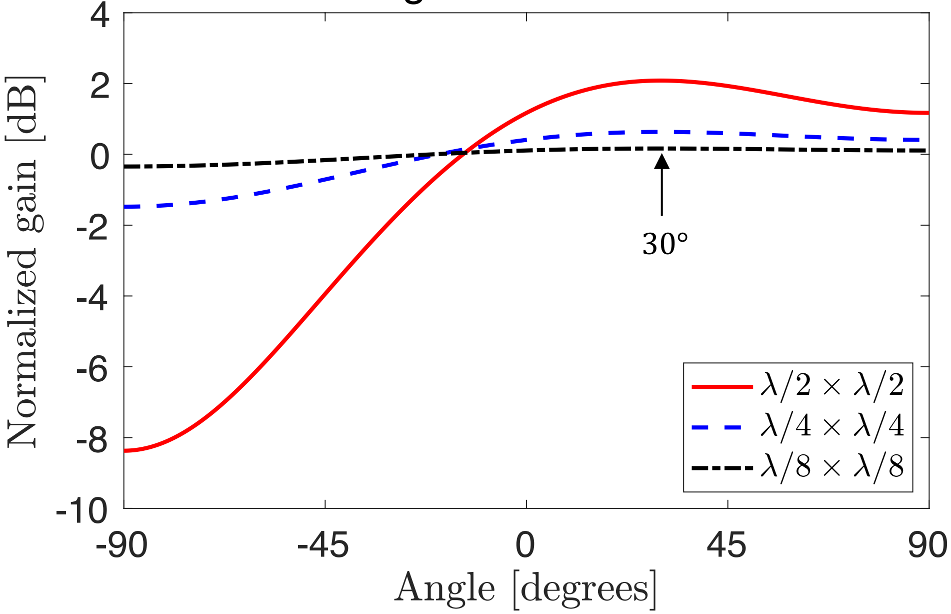
1) Tuning impedances
2) Tuning length of delay lines
3) Phase-shifters

A single element makes little difference

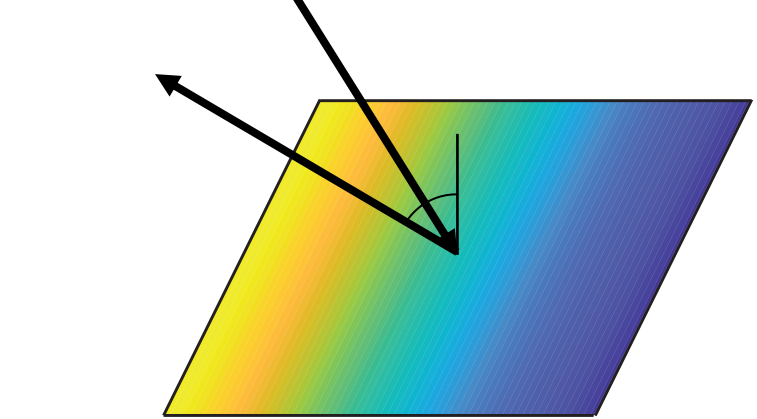
Joint effect of many elements is needed

How Large are the Elements?

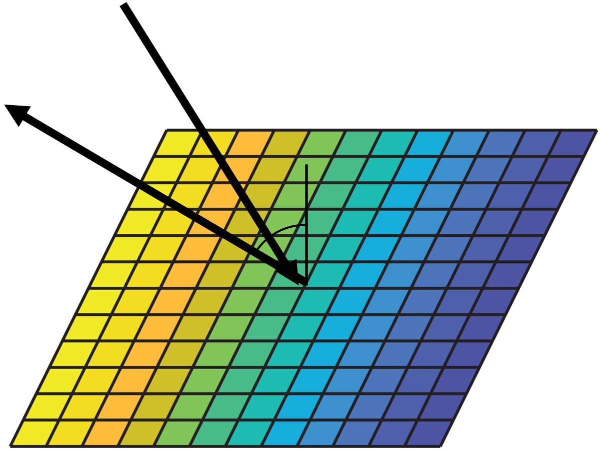
When a signal arrives from $-30°$:



Each element should scatter signals almost isotropically



Ideal continuous reconfiguration



Discretized reconfiguration

A Reconfigurable World

RIS **as a whole** can control

- Directivity of scattered signal
- Signal absorption
- Polarization

Improved indoor coverage

Different People Use Different Terminology

L. Subrt and P. Pechac, “**Intelligent walls** as autonomous parts of smart indoor environments,” IET Communications, vol. 6, no. 8, pp. 1004–1010, 2012.

C. Liaskos, S. Nie, A. Tsioliaridou, A. Pitsillides, S. Ioannidis, and I. Akyildiz, “A new wireless communication paradigm through **software-controlled metasurfaces**,” IEEE Commun. Mag., vol. 56, no. 9, pp. 162–169, 2018.

C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, C. Yuen, “**Reconfigurable Intelligent Surfaces** for Energy Efficiency in Wireless Communication,” *IEEE Transactions on Wireless Communications, vol. 18, no. 8, pp.* 4157–4170, 2019.

M. Di Renzo *et al.*, “Smart radio environments empowered by **reconfigurable AI meta-surfaces**: an idea whose time has come,” *EURASIP Journal on Wireless Commun. and Networking*, vol. 2019:129, 2019.

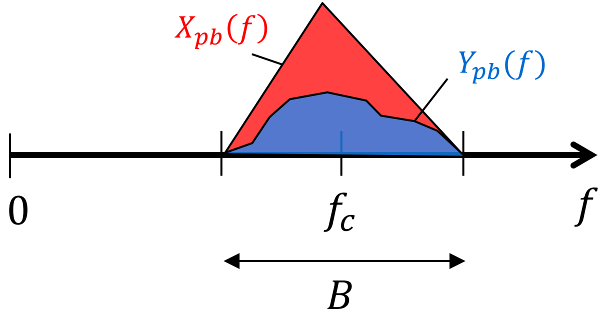
Q. Wu and R. Zhang, “Towards smart and reconfigurable environment: **Intelligent reflecting surface** aided wireless network,” IEEE Communications Magazine, 2020.

E. Björnson, L. Sanguinetti, H. Wymeersch, J. Hoydis, and T. L. Marzetta, “Massive MIMO is a reality—What is next? Five promising research directions for antenna arrays,” Digital Signal Processing, vol. 94, pp. 3–20, Nov. 2019.

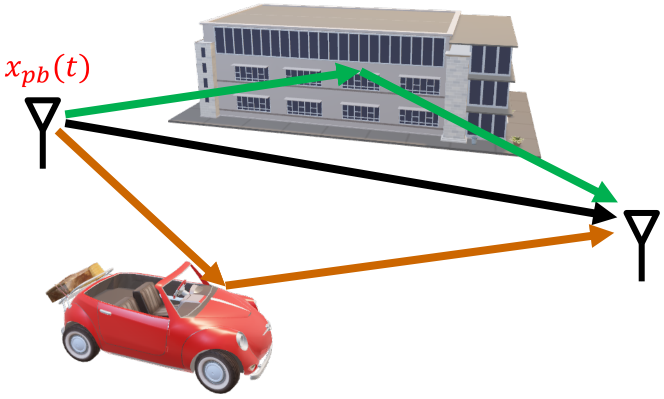
DEVELOPING A SYSTEM MODEL

Introduction to Signals and Systems

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



- Communication channels are systems/filters:

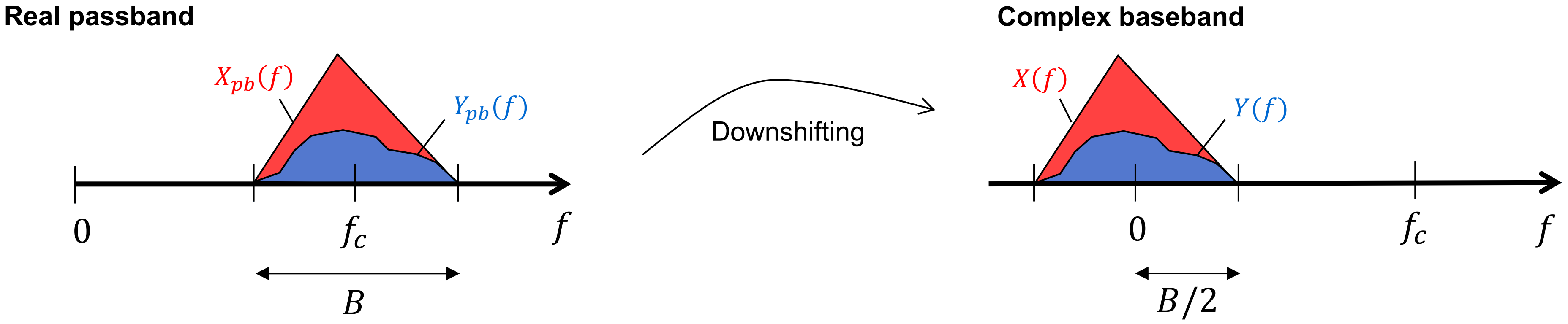


$$y_{pb}(t) = \sqrt{\rho_1}x_{pb}(t-\tau_1) + \sqrt{\rho_2}x_{pb}(t-\tau_2) + \sqrt{\rho_3}x_{pb}(t-\tau_3)$$

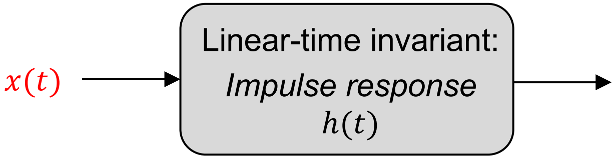
Impulse response: $h_{bp}(t) = \sqrt{\rho_1}\delta(t-\tau_1) + \sqrt{\rho_2}\delta(t-\tau_2) + \sqrt{\rho_3}\delta(t-\tau_3)$

Complex Baseband Representation

- Communication theory is developed for the baseband



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

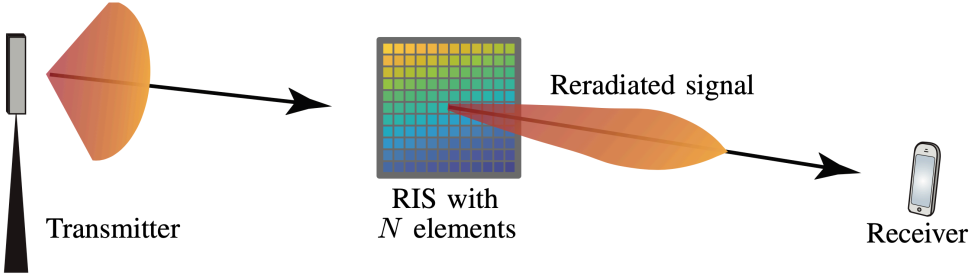


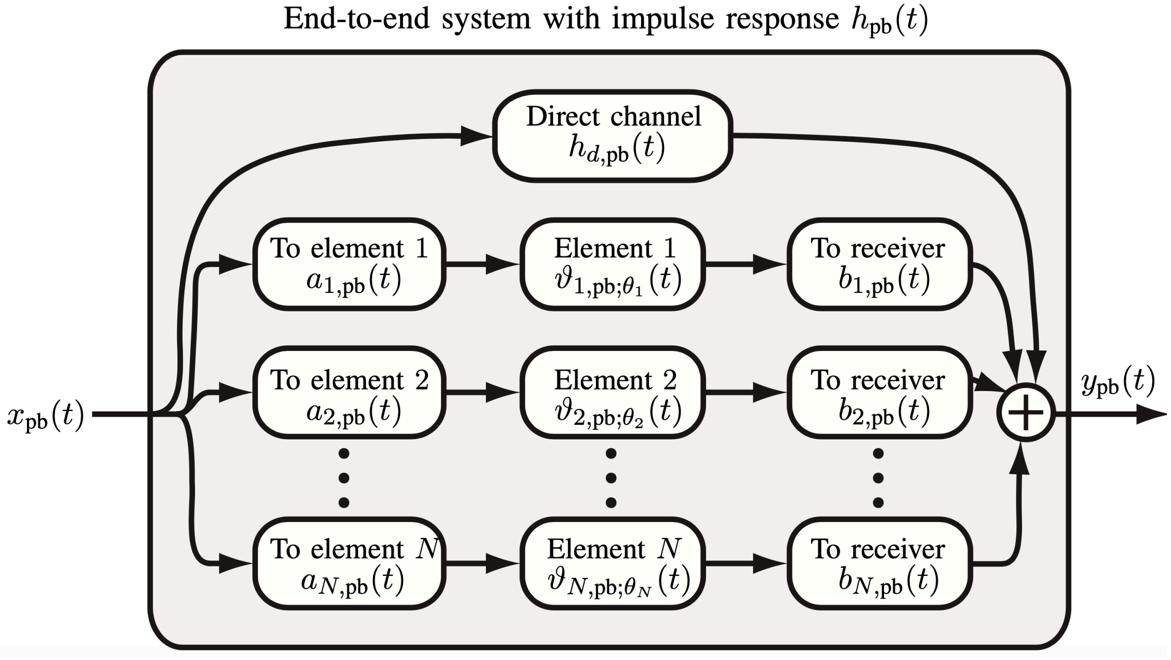
$y(t) = \int_{\infty}^{-\infty} h(u)x(t-u)du$

Down-shifted channel:

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

Analyzing Reconfigurable Intelligent Surface





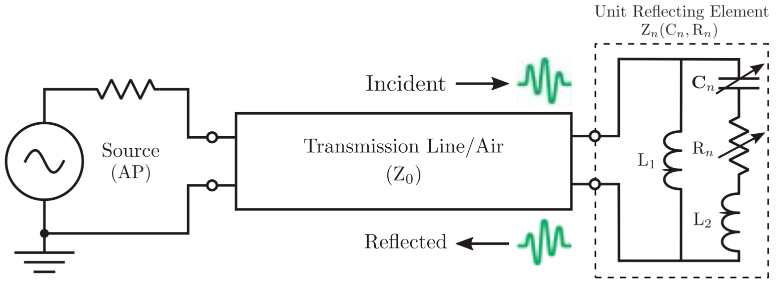
End-to-end impulse response:

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

Conventional channel models for $a_{n,pb}, b_{n,pb}, h_{d,pb}$

RIS control variables $\theta_1, \dots, \theta_N$ in $\vartheta_{n,pn;\theta_n}$

How Will an RIS Element Filter the Signal?

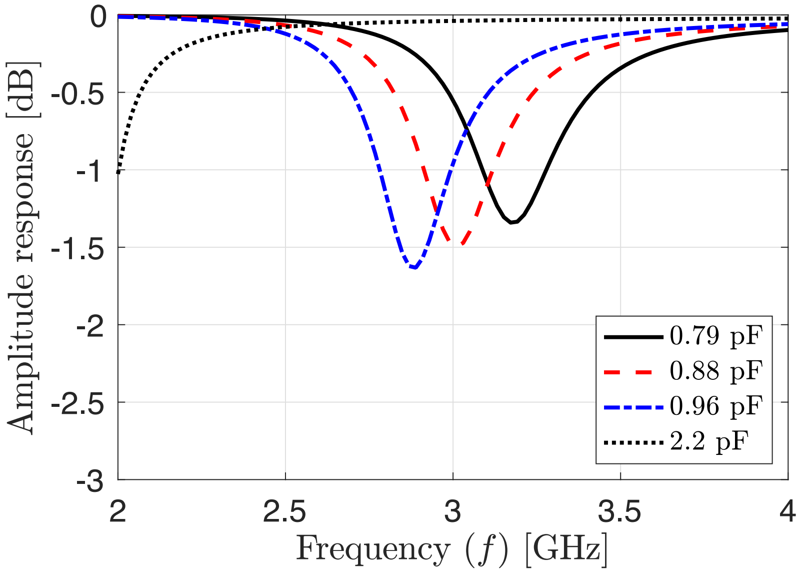


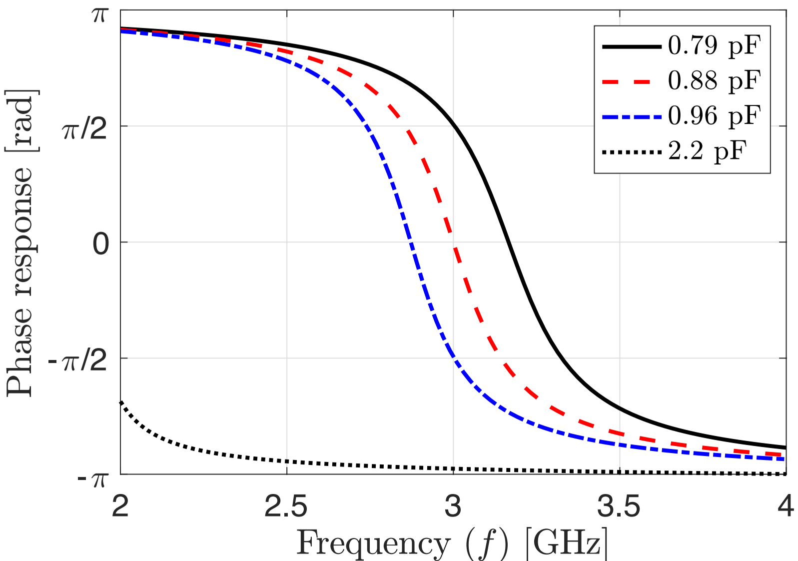
Example: Metal patch with tunable capacitance C_n

Reflection coefficient:

$$\frac{Z_n(C_n, R_n) - Z_0}{Z_n(C_n, R_n) + Z_0}$$

Reference: S. Abeywickrama, R. Zhang, Q. Wu, and C. Yuen, "Intelligent reflecting surface: Practical phase shift model and beamforming optimization," IEEE Trans. Commun., 2020.





How To Transmit Data?

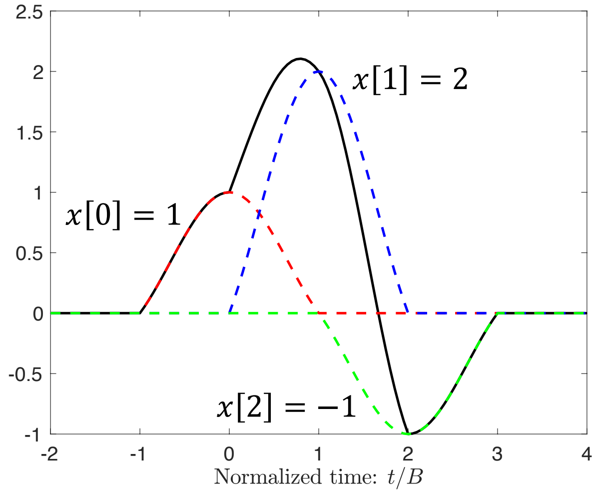
- Pulse amplitude modulation:

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

  - 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:

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

Call it $z[k]$ | Effective pulse function | 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:

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

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

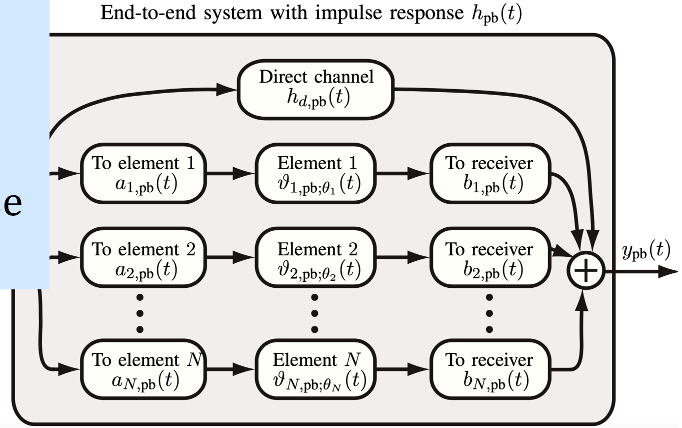
$$b_{n,pb}(t) = \sqrt{\beta_n}\delta(t-\tau_{n,b}) \rightarrow b_n(t) = \sqrt{\beta_n}e^{-j2\pi f_c t}\delta(t-\tau_{n,b})$$

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!

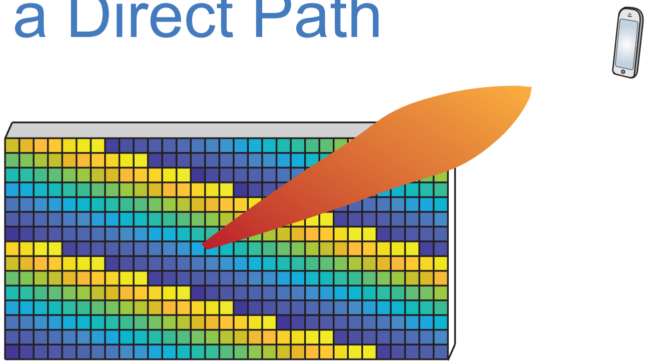


OPTIMIZING COMMUNICATION PERFORMANCE

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

Channel gain:

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

Cauchy–Schwarz inequality

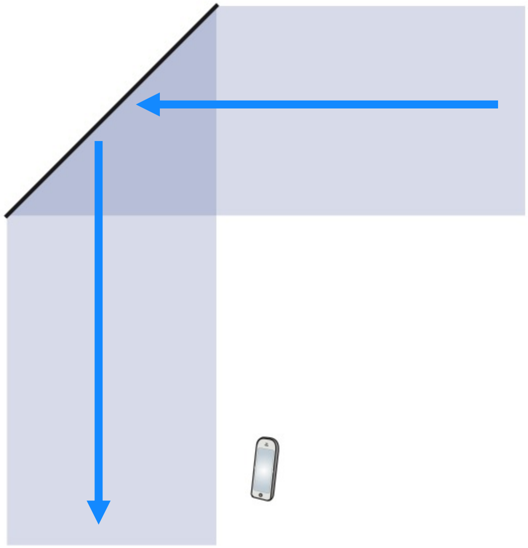
Achieved when:

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

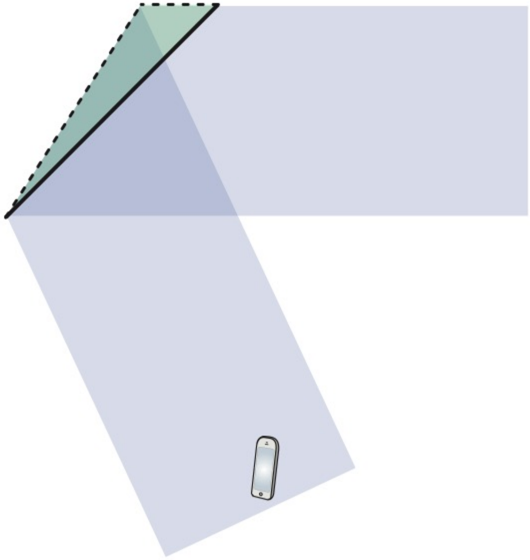
Minimum positive delay solution:

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

Example: Synthesizing Surface Shapes



1: Normal reflection



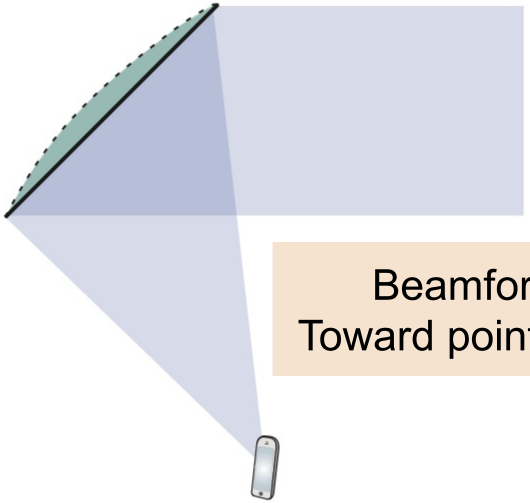
2: Anamolous reflection

(focus at infinity)

Varying phase delay profile along the surface

3: Signal focusing

(closer than infinity)



Beamforming:
Toward point/direction

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:

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

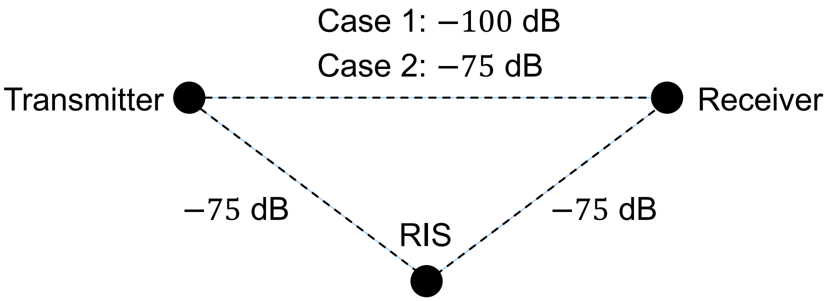
Achieved when:

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

Minimum positive delay solution:

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

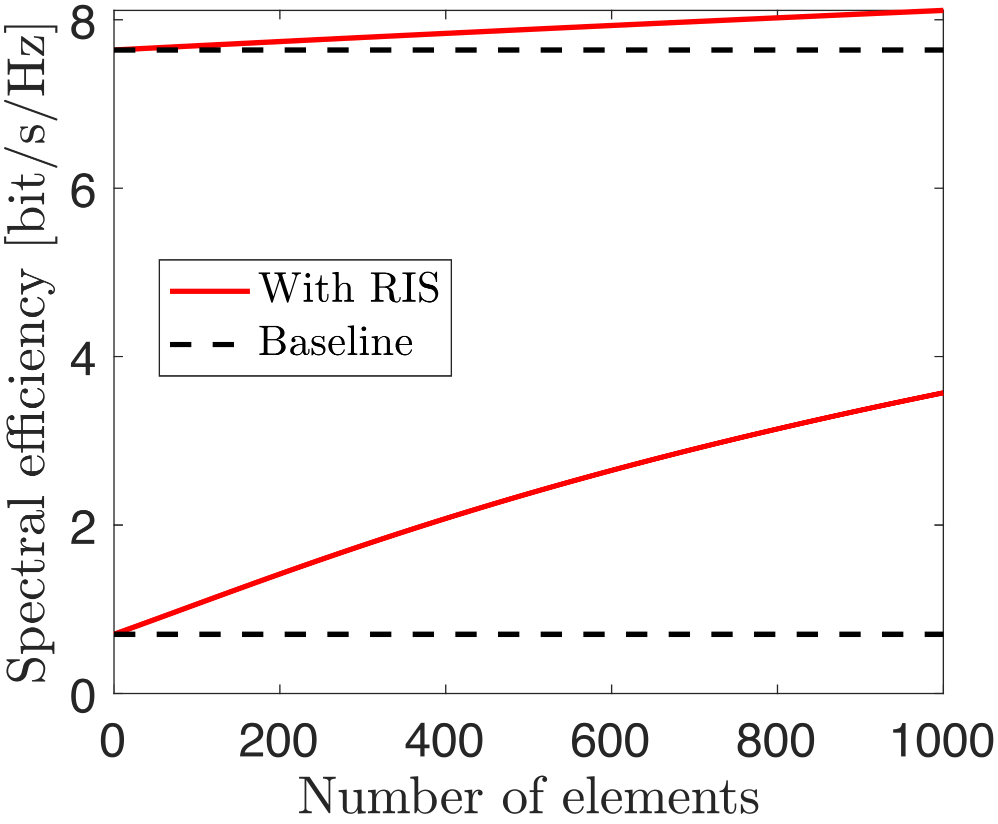
Basic Performance Benefit



Transmit power: 10 mW per 20 MHz

RIS is Particularly Helpful

When direct path is relatively weak

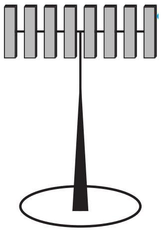


WHAT ARE GOOD USE CASES?

Alternative Technologies

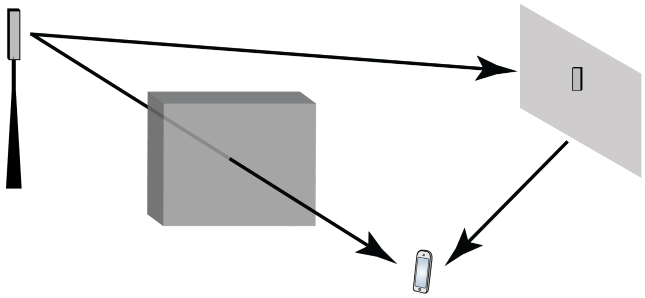
Deploy more base stations

- Require power and backhaul infrastructure
- Inter-cell interference



Utilize conventional relays

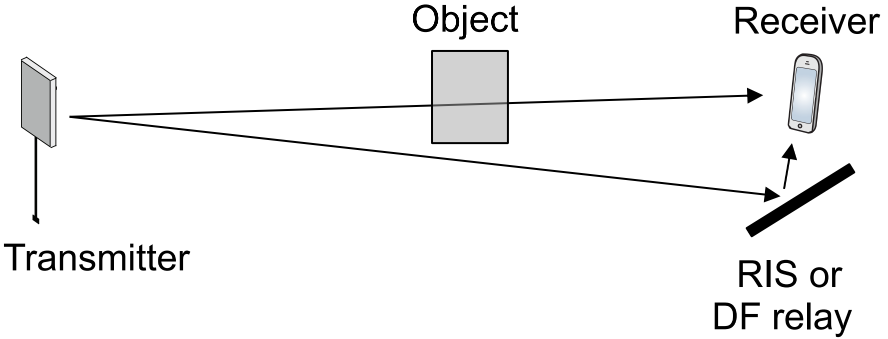
- Half-duplex operation, involve higher layers
- Example: Decode-and-forward

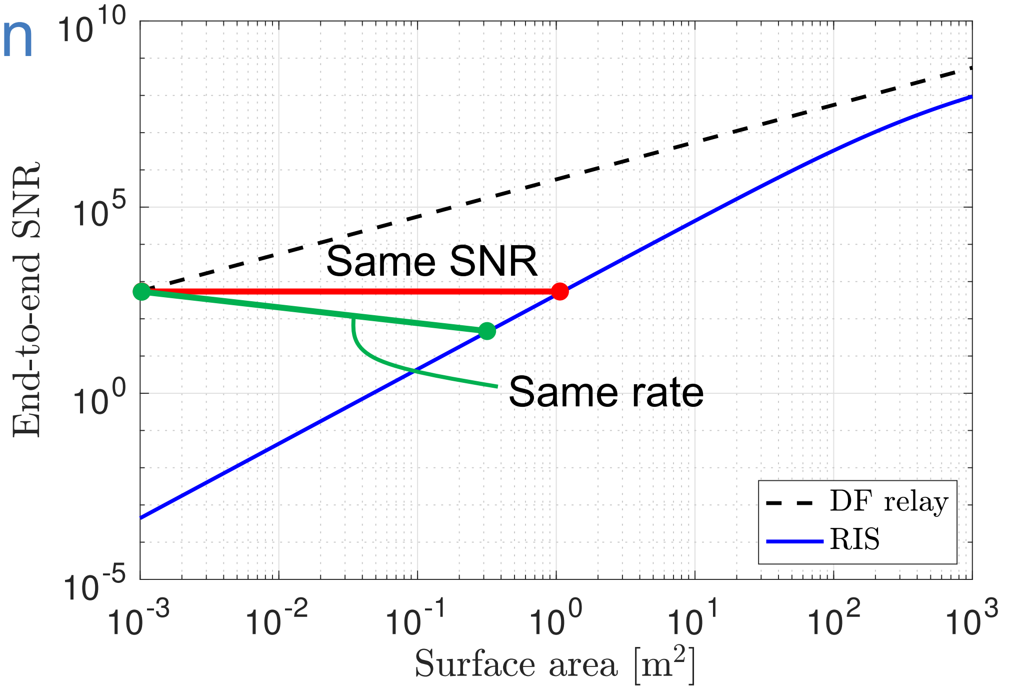


Use new building materials

- Thermal insulation is primary goal
- Passive materials will not beamform in right direction

Comparison: SNR Maximization



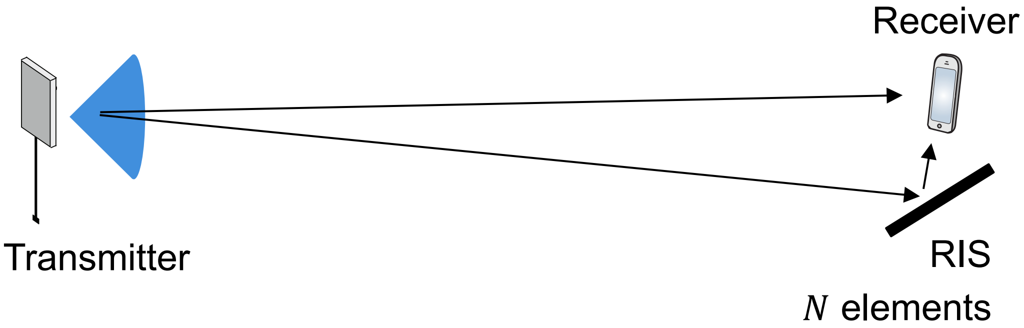


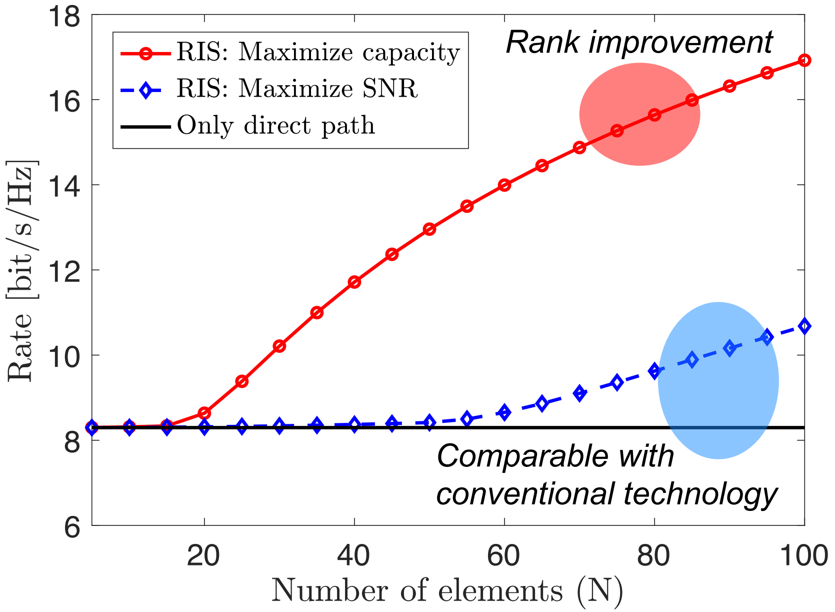
Large surfaces are needed
to beat an elementary DF relay

Reference:

[R1] Ö. Özdogan, E. Björnson, E. G. Larsson, “Reconfigurable Intelligent Surfaces: Three Myths and Two Critical Questions”

Improving Channel Properties





Two antennas at each device

Line-of-sight channels: Rank 1

Improve propagation conditions

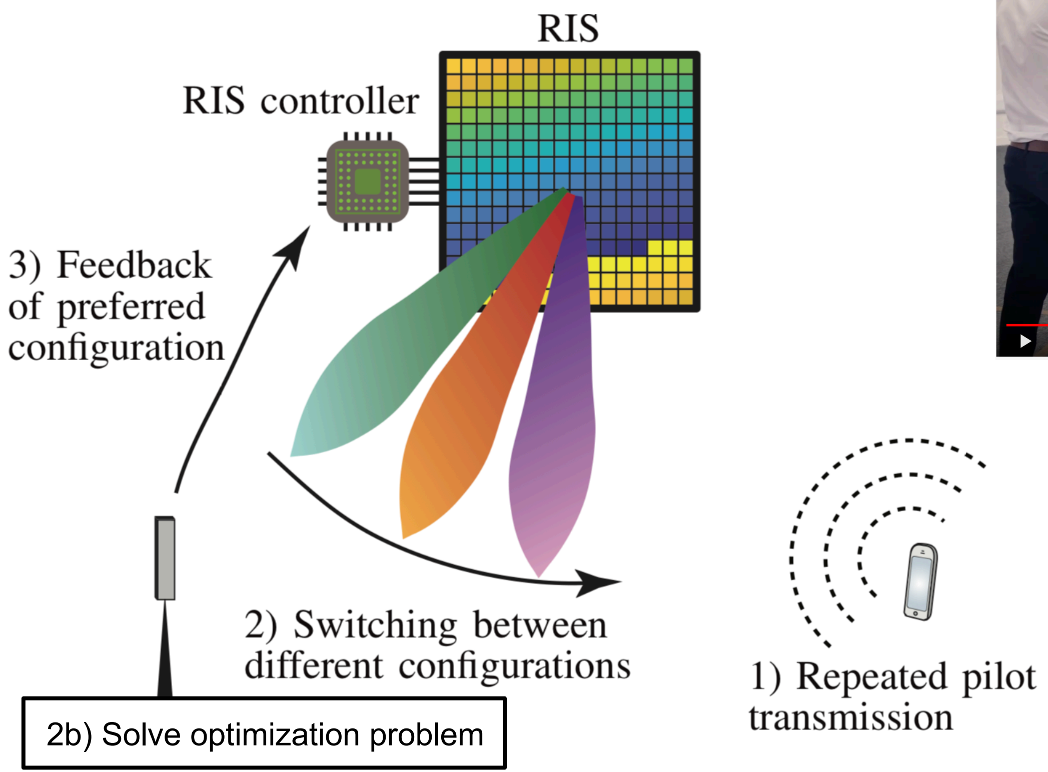
More than just SNR gain!

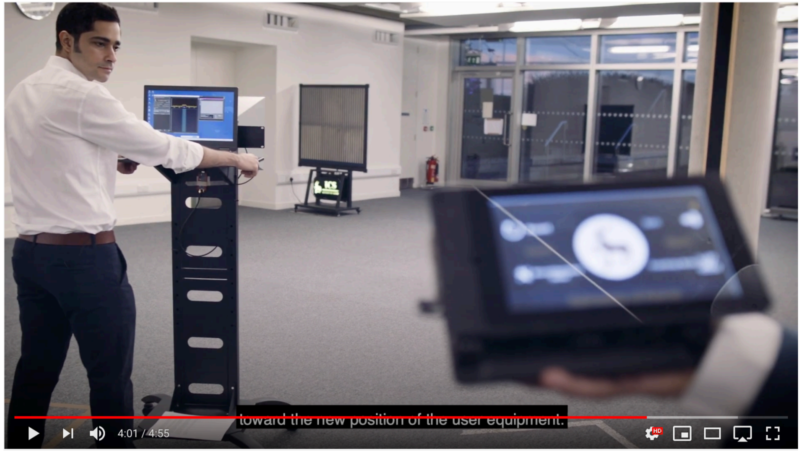
Reference:

[R2] Ö. Özdogan, E. Björnson, E. G. Larsson, "Using Intelligent Reflecting Surfaces For Rank Improvement in MIMO Communications"

Reconfigurability is Complicated But Doable

An RIS is blind!





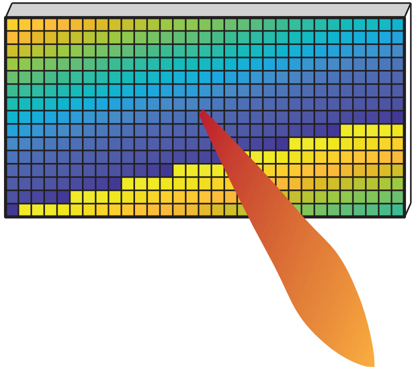
YouTube video from University of Surrey

Is a Reconfigurable Wireless World Possible?

Easy to say:

- Conventional technology:
  Only control transmitter and receiver
- RIS controls ~~the entire~~ propagation

some minor parts of the



An active MIMO array can do anything that an RIS can do!

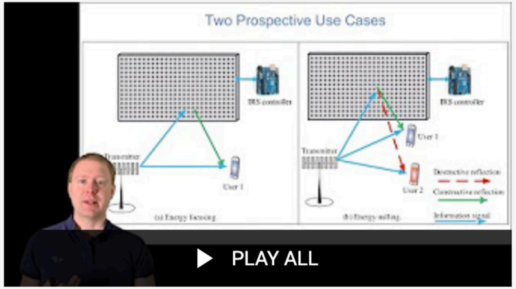
RIS characteristics

- Maybe a cost and energy efficient alternative
- Well suited to improve channel properties:
  - Increased MIMO rank
  - Macro diversity (large surface)
  - …?
- Particularly useful above 100 GHz?
- Great research topic in academia!

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

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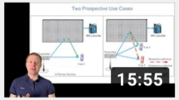
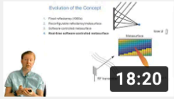
1 

Fundamentals of Intelligent Reflecting Surfaces

Wireless Future / Communication Systems

2 

Reconfigurable intelligent surfaces: Myths and realities

Wireless Future / Communication Systems

3 

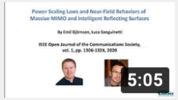
A Programmable Wireless World With Reconfigurable Intelligent Surfaces

Wireless Future / Communication Systems

4 

Communication Using Reconfigurable Intelligent Surfaces: Fundamentals and Recent Insights

Wireless Future / Communication Systems

5 

Power Scaling Laws and Near-Field Behaviors of Massive MIMO and Intelligent Reflecting Surfaces

IEEEComSoc

Key References

Overview papers

1. Upcoming paper on “A Signal Processing Perspective on Reconfigurable Intelligent Surfaces With Wireless Applications”, Available on arXiv.org in Feb. 2021.
2. E. Björnson, L. Sanguinetti, H. Wymeersch, J. Hoydis, and T. L. Marzetta, “Massive MIMO is a reality—What is next? Five promising research directions for antenna arrays,” Digital Signal Processing, 2019.
3. 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,” 2020.

Questions?