A Programmable Wireless World With Reconfigurable Intelligent Surfaces

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Outline

Introduction

- Reconfigurable intelligent surface, programmable wireless world

Developing a system model

- Basic modeling
- Optimization of surface operation

Misconceptions and open problems

- Three misconceptions
- Two key open questions

INTRODUCTION

Physics of Wireless Signal Propagation

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

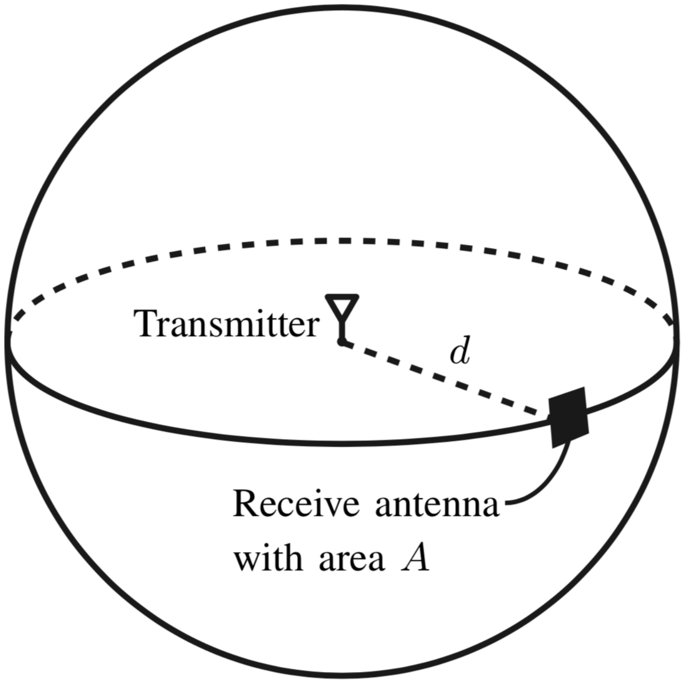
- Friis' propagation formula:

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

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

0.005% received at 1 m (−43 dB)

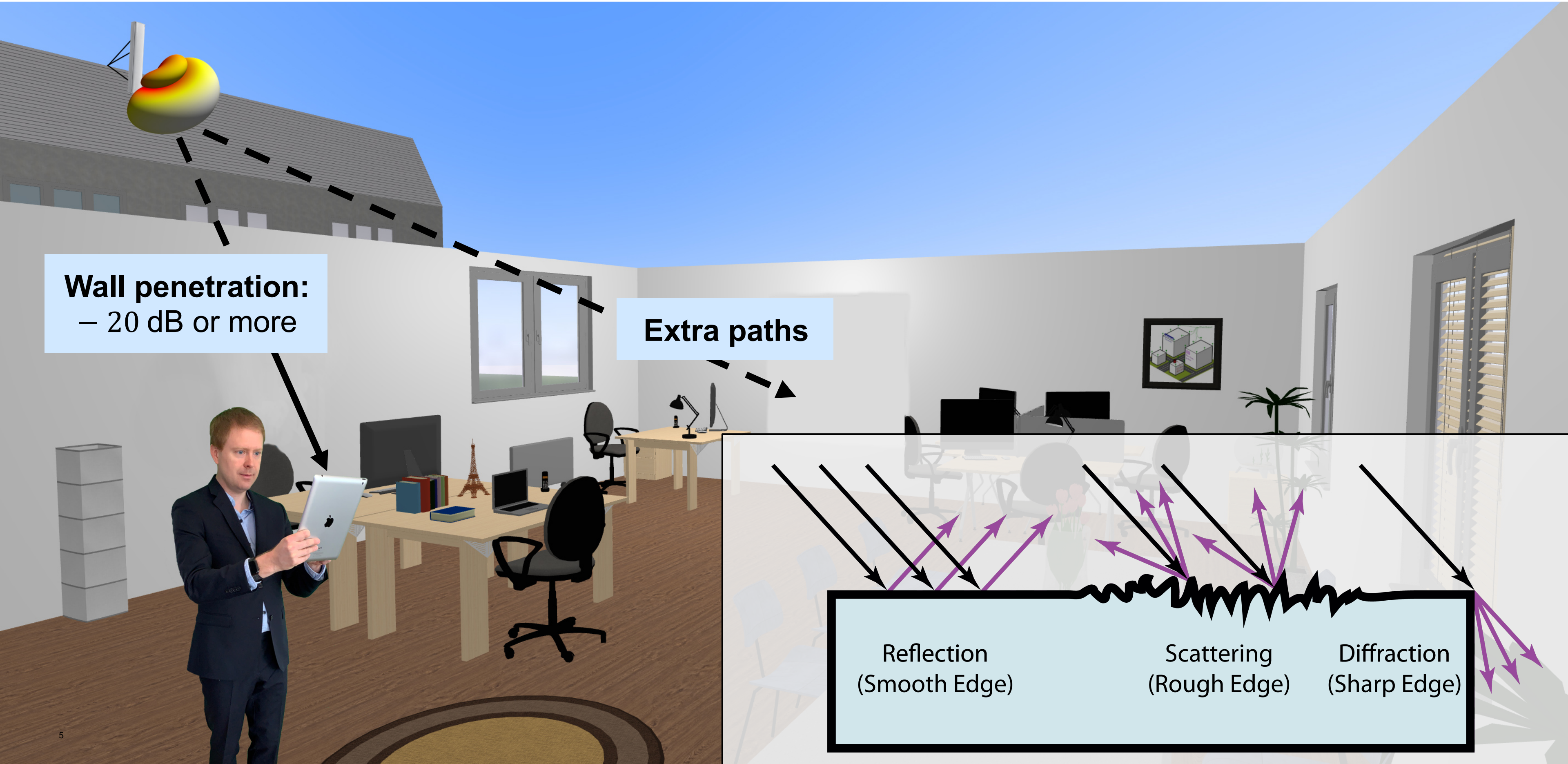
0.00005% received at 10 m (−63 dB)



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



Smart City Concept

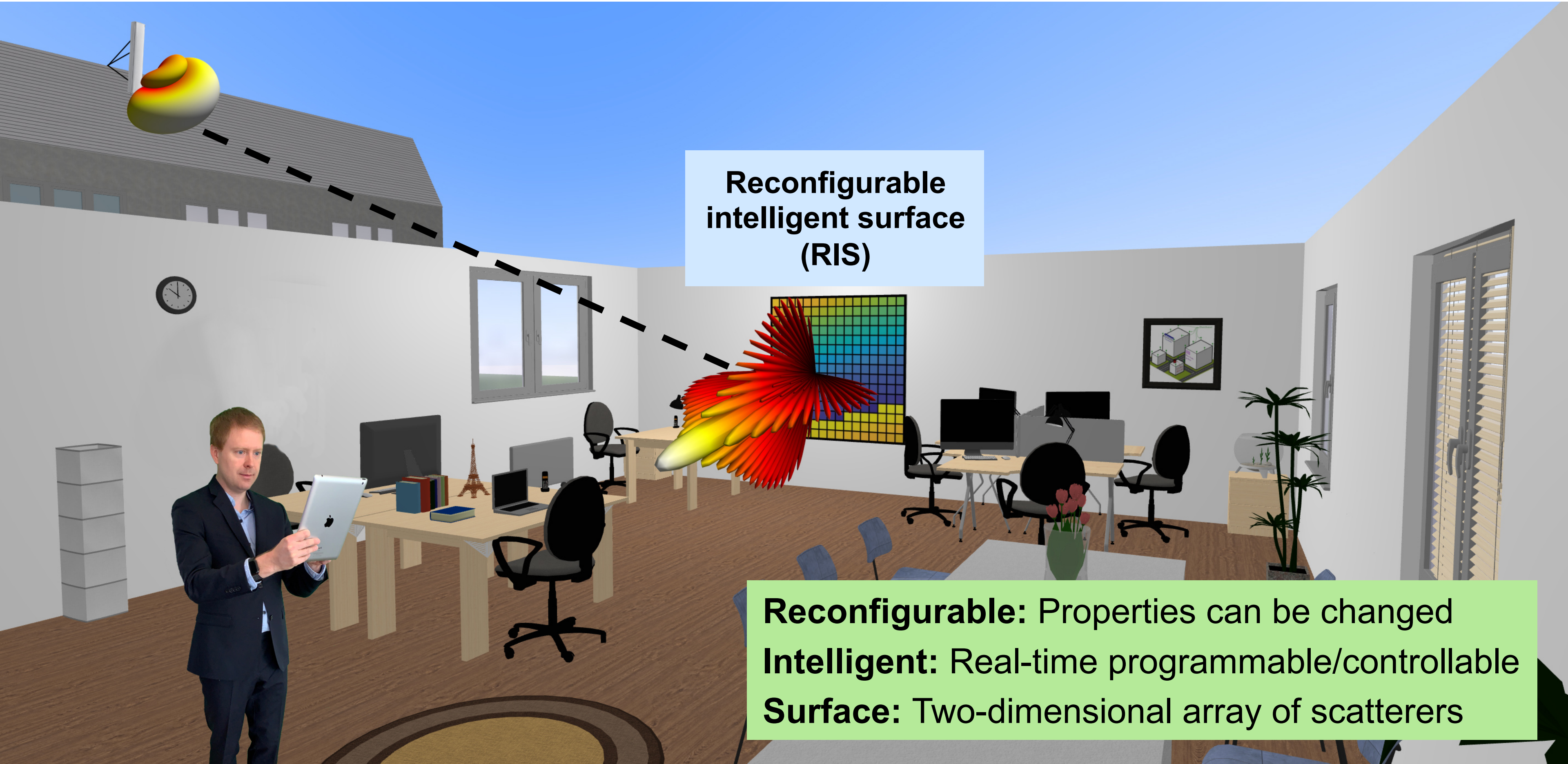
Collect data to manage assets, resources and services efficiently

Internet-of-things (IoT) devices
- Mobile phones, base stations
- Various sensors

Monitor and manage
- Traffic and transportation
- Public utilities and services
- Crime prevention

Control and programmability
- Signal processing
- Big data, machine learning

Shaping the Signal Scattering Towards the Receiver

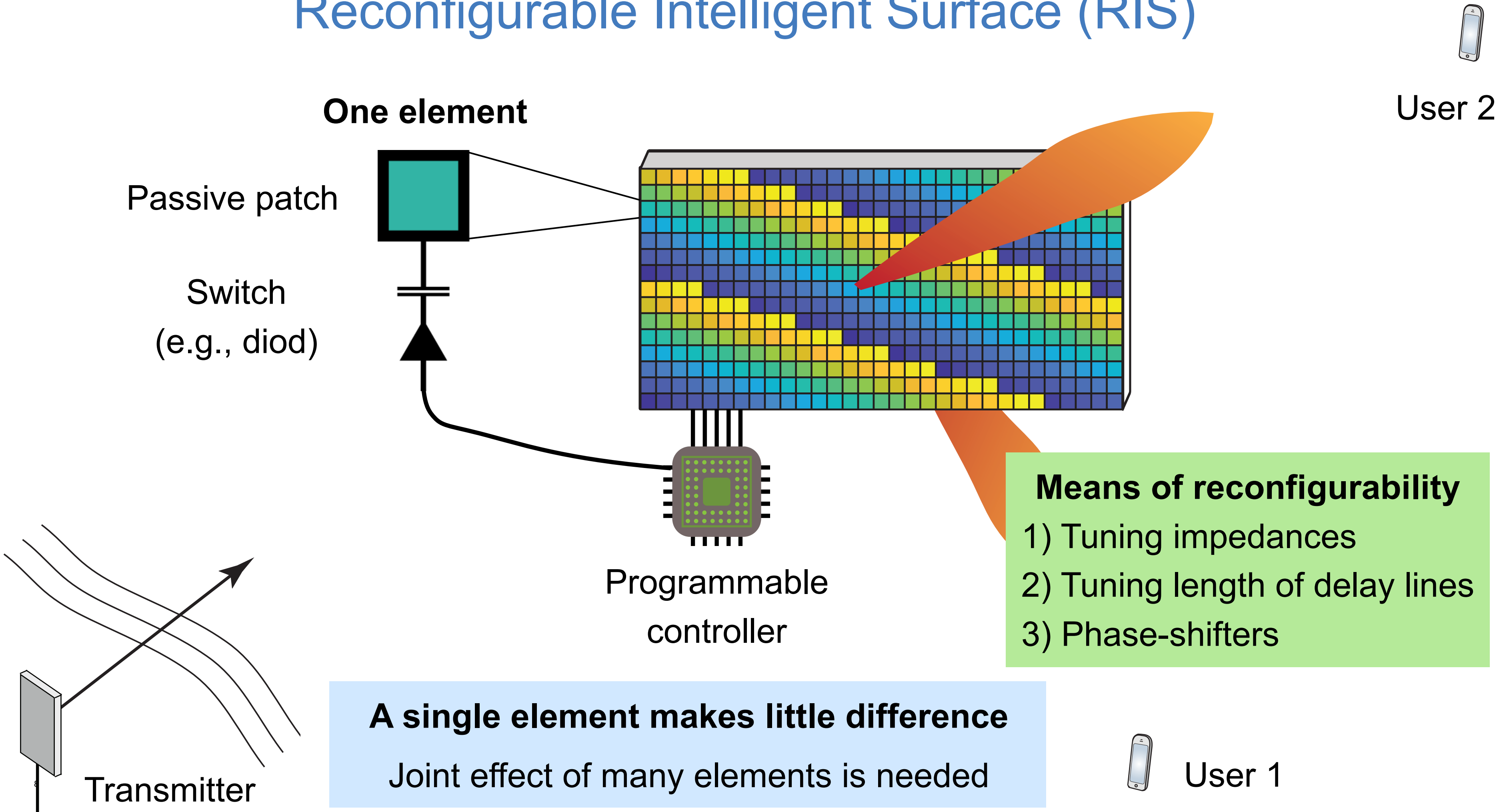


Reconfigurable: Properties can be changed

Intelligent: Real-time programmable/controllable

Surface: Two-dimensional array of scatterers

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

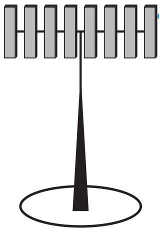
A Programmable World

RIS **as a whole** can control

- Directivity of scattered signal
- Signal absorption
- Polarization

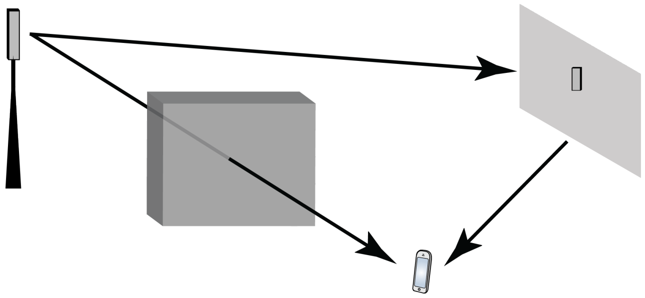
Improved indoor coverage

Alternative Approaches



Deploy more base stations

- Require power and backhaul infrastructure
- Inter-cell interference



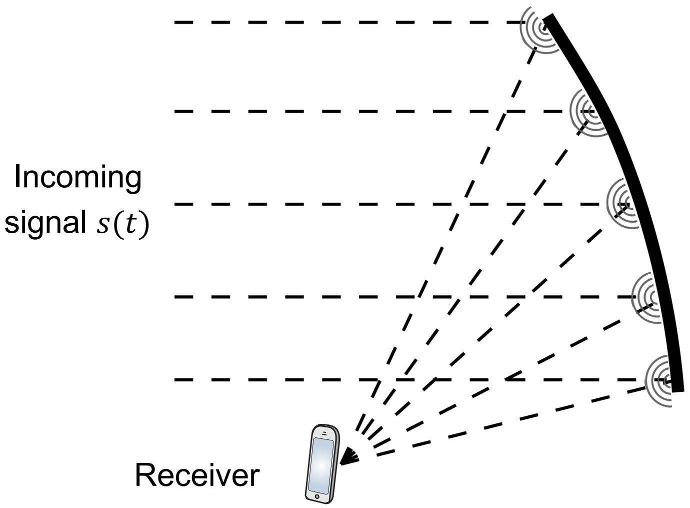
Utilize conventional relays

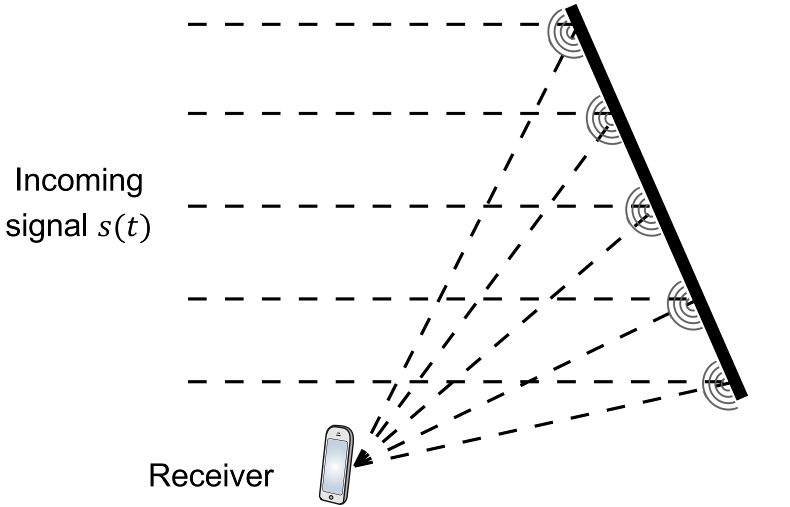
- Half-duplex operation
- RIS is a new type relay

Use new building materials

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

Signal Focusing in a Nutshell





Waves are not rays!

Every surface point ”scatters” a spherical wave

(Huygens–Fresnel principle)

Waves arrive in phase at receiver: Beamforming

Received signal:

$$\underbrace{c}_{\text{Pathloss}} \cdot \sum_{\text{Element } n} s(t - \underbrace{\tau_n}_{\text{Propagation delay}} - \underbrace{\Delta_n}_{\text{Delay in surface}})$$

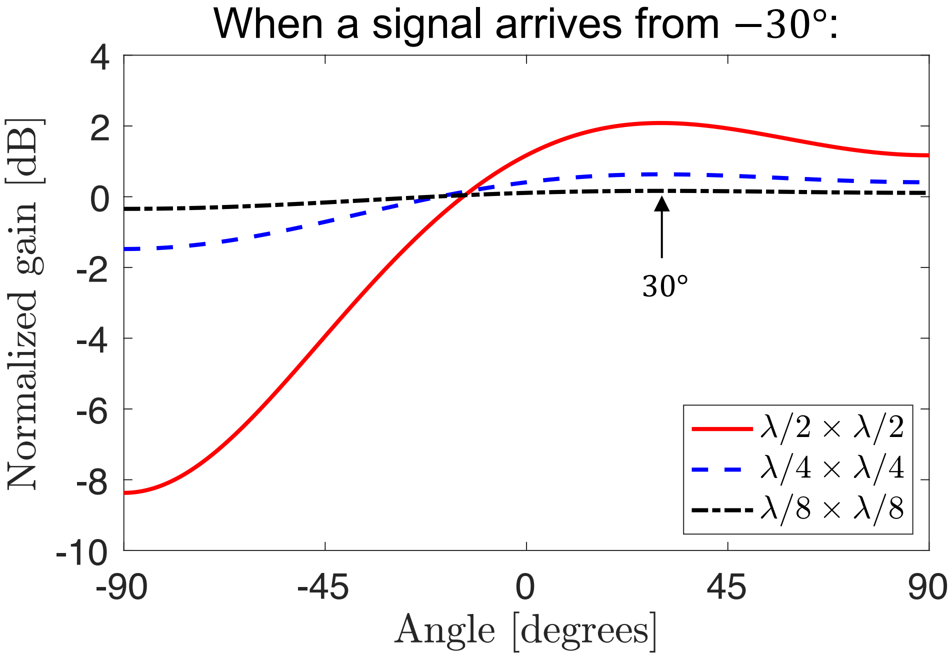
Synthesize curved surface:

Make $\tau_n + \Delta_n$ equal for all n!

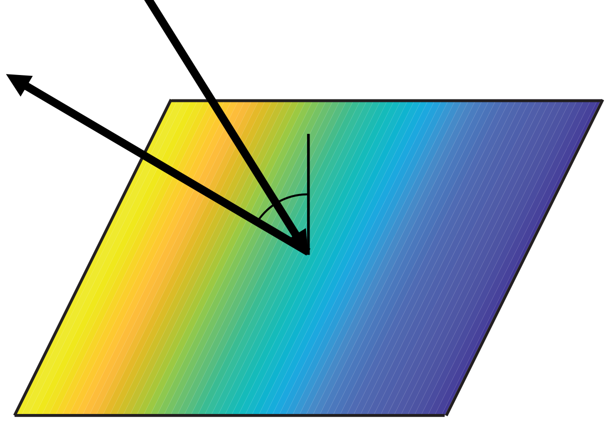
Causal solution:

$\tau_n + \Delta_n = \max_m \tau_m$

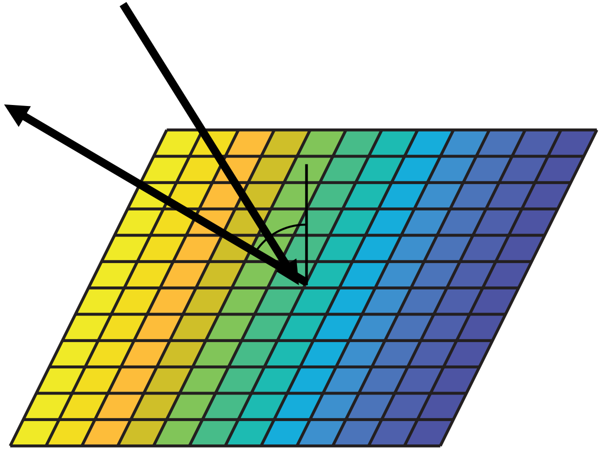
How Large are the Elements?



Each element should scatter signals almost isotropically



Ideal continuous reconfiguration



Discretized reconfiguration

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.

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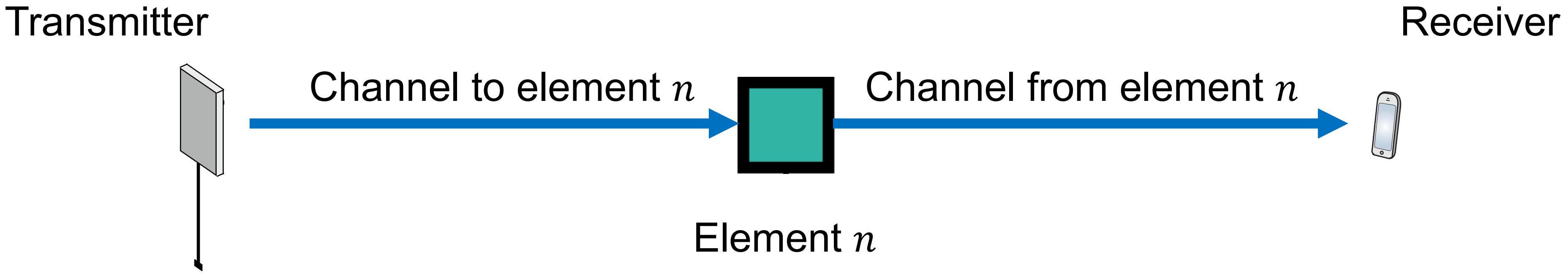
M. Di Renzo *et al.*, "Smart radio environments empowered by **reconfigurable AI meta-surfaces**: an idea whose time has come," *EURASIP Journal on Wireless Commun. and Networking*, vol. 2019:129, 2019.

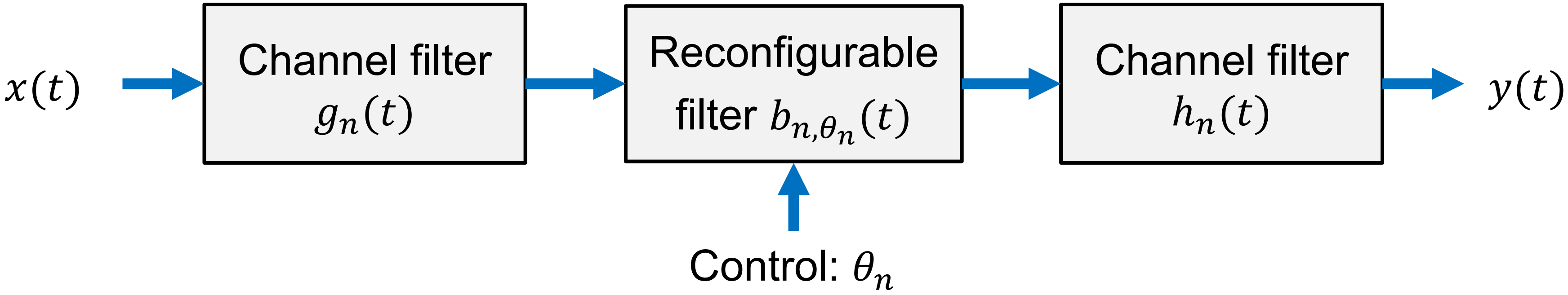
Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: **Intelligent reflecting surface** aided wireless network," IEEE Communications Magazine, 2020.

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

Basic Signals and Systems Description





Input−output relation: $y(t) = (g_n * b_{n,\theta_n} * h_n * x)(t)$

Narrowband Signal Processing Model

$x(t) = e^{j2\pi f_c t}$ → Impulse response: $g(t)$; Frequency response: $G(f)$ →

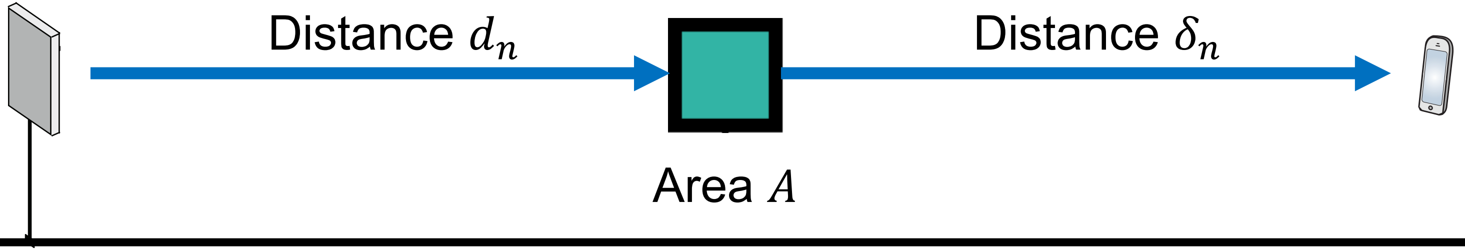
$$y(t) = \int_{-\infty}^{\infty} g(\tau)\, e^{j2\pi f_c (t-\tau)} d\tau$$
$$= G(f_c) e^{j2\pi f_c t}$$
$$= \underbrace{|G(f_c)|}_{\text{Amplitude change}} e^{j2\pi f_c \left(t + \underbrace{\frac{\arg(G(f_c))}{2\pi f_c}}_{\text{Phase shift}}\right)}$$

Recall: $y(t) = (g_n * b_{n,\theta_n} * h_n * x)(t)$

Narrowband input-output relation:

$$y(t) = \underbrace{|G_n(f_c)| \cdot \left|B_{n,\theta_n}(f_c)\right| \cdot |H_n(f_c)|}_{\text{Joint amplitude change (pathloss)}} \cdot x\left(t + \underbrace{\frac{\arg(G_n(f_c)) + \arg\left(B_{n,\theta_n}(f_c)\right) + \arg(H_n(f_c))}{2\pi f_c}}_{\text{Joint phase shift (delay)}}\right)$$

A Physical Model for Line-of-Sight (LoS) Setup



$x(t) \rightarrow$ LoS channel $\rightarrow$ Reconfigurable filter $\rightarrow$ LoS channel $\rightarrow y(t)$

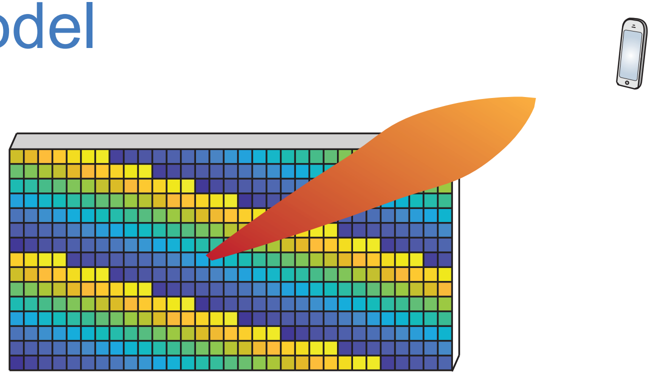
$$G_n(f_c) = \sqrt{\frac{A}{4\pi d_n^2}}\, e^{\underbrace{-j2\pi f_c \frac{d_n}{c}}_{\phi_n}} \qquad B_{n,\theta_n}(f_c) = \mu_n e^{-j\theta_n} \qquad H_n(f_c) = \sqrt{\frac{A}{4\pi \delta_n^2}}\, e^{\underbrace{-j2\pi f_c \frac{\delta_n}{c}}_{\varphi_n}}$$

Received signal: $y(t) = G_n(f_c) B_{n,\theta_n}(f_c) H_n(f_c) x(t) = \left(\frac{A}{4\pi d_n \delta_n}\right) \mu_n e^{-j(\phi_n + \theta_n + \varphi_n)}$

We can tune it by selecting:

Amplitude $\mu_n \in [0,1]$, Phase: $\theta_n \in [0,2\pi)$

End-to-End System Model



Received signal with N elements:

$$y = \sum_{n=1}^{N} \left(\frac{A}{4\pi d_n \delta_n} \right) \mu_n e^{-j(\phi_n + \theta_n + \varphi_n)} \cdot \text{signal} + \text{noise}$$

Signal processing problem:

Maximize the signal-to-noise ratio

Channel gain:

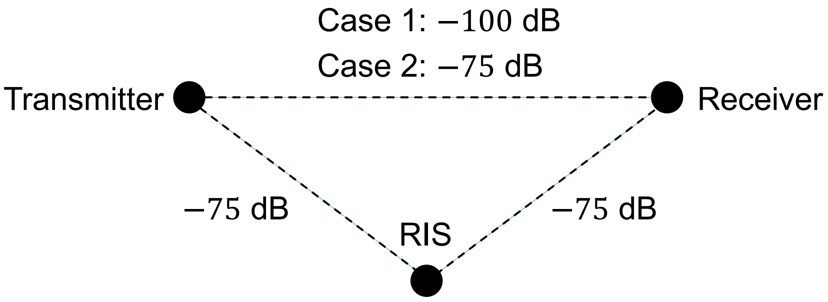
$$\left| \sum_{n=1}^{N} \left(\frac{A}{4\pi d_n \delta_n} \right) \mu_n e^{-j(\phi_n + \theta_n + \varphi_n)} \right|^2 \leq \left| \sum_{n=1}^{N} \frac{A}{4\pi d_n \delta_n} \right|^2 \approx N^2 \left(\frac{A}{4\pi d \delta} \right)^2$$

Achieved when:

$\phi_n + \theta_n + \varphi_n$
$= \text{constant}$

Cauchy–Schwarz inequality + set $\mu_n = 1$

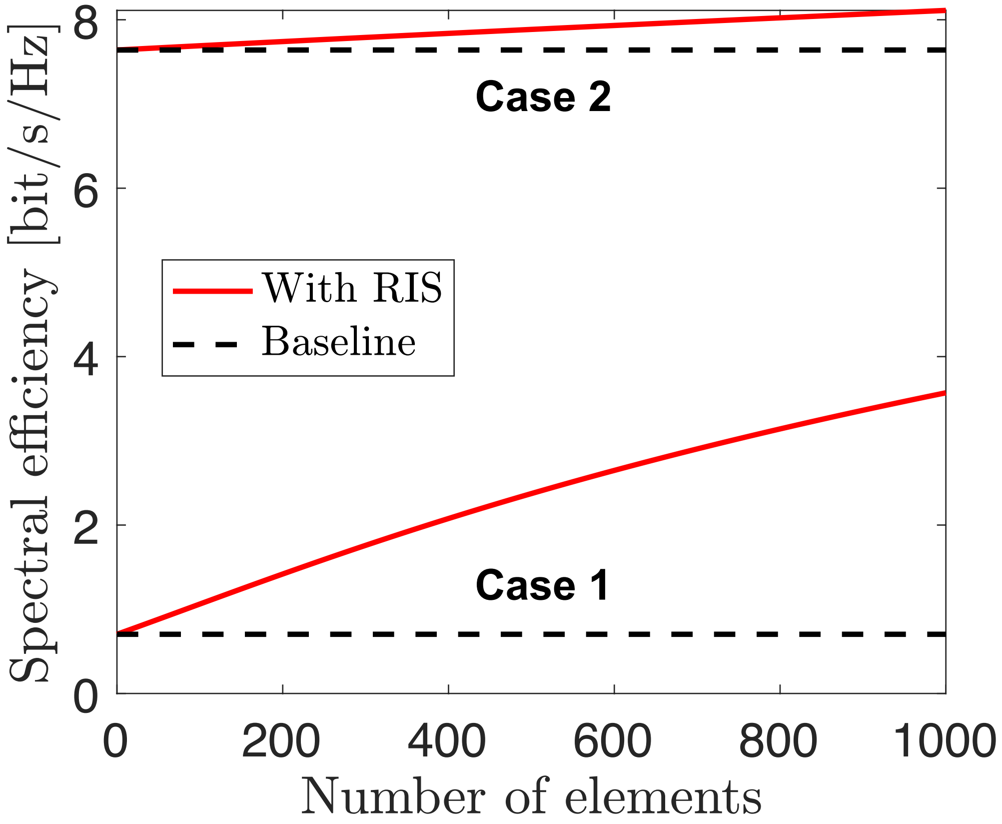
Basic Performance Benefit



Transmit power: 10 mW per 20 MHz

RIS is Particularly Helpful

When direct path is relatively weak



MISCONCEPTIONS AND OPEN PROBLEMS

Three Misconceptions in the Literature

Myth 1: Current network technology cannot control the propagation environment

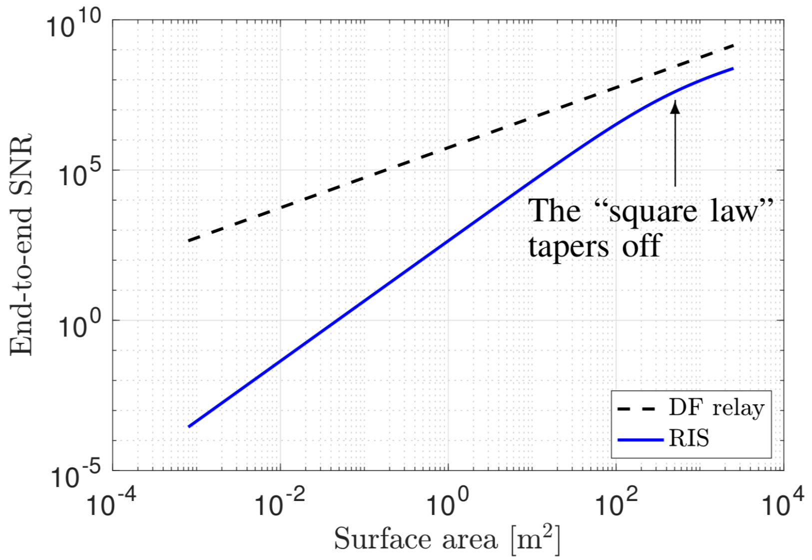
- Truth: Relaying has been supported since 3G. RIS is a new type of relay.

Myth 2: An RIS has a better asymptotic array gain than classical beamforming

- SNR grows as N^2 with RIS and N with classical beamforming (in far-field)
- Truth: The curves never cross, trend breaks down in near-field

When a RIS wins:

1×1 m RIS compared to single-antenna DF relay



E. Björnson, Ö. Özdogan, E. G. Larsson, "Reconfigurable Intelligent Surfaces: Three Myths and Two Critical Questions," arXiv:2006.03377.

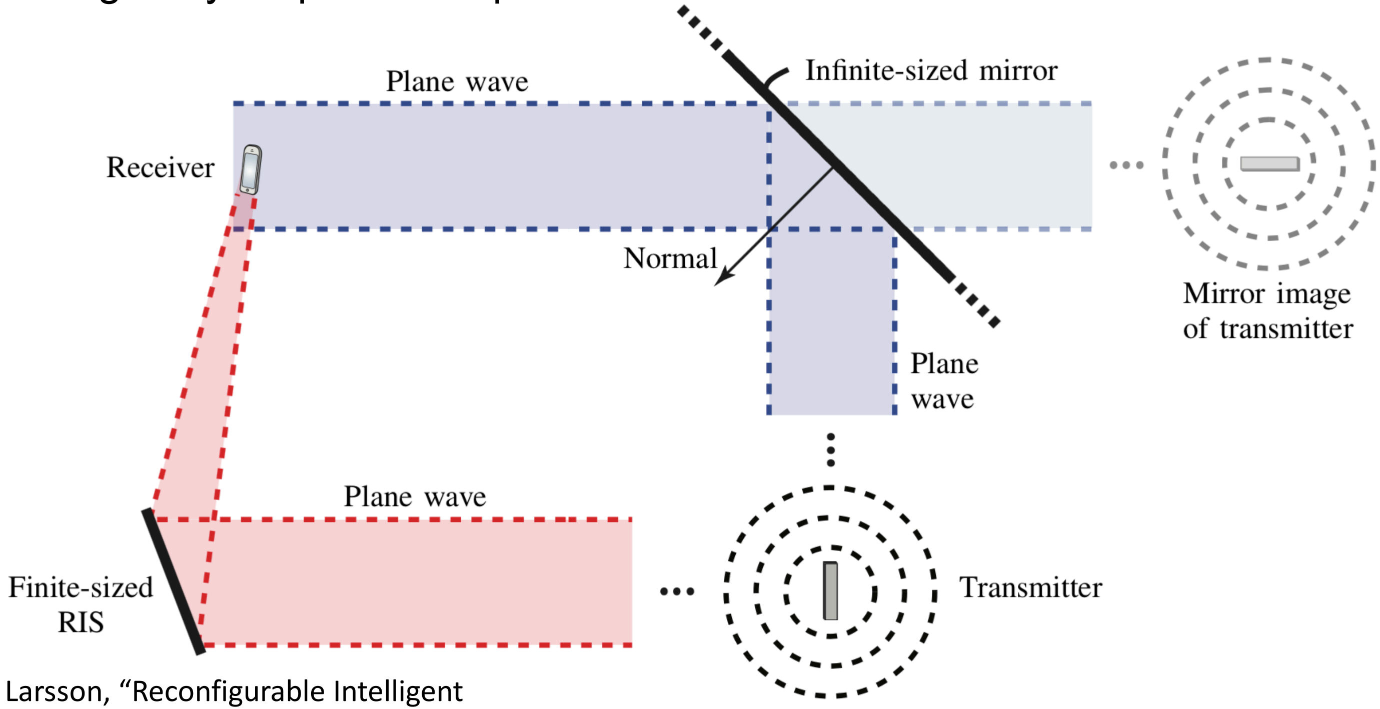
Three Misconceptions in the Literature

Myth 3: An RIS is an anomalous plane mirror

- Truth: An RIS can greatly outperform a plane mirror

RIS synthesizes a curved mirror

Makes use of the entire surface



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First Open Question: What is a Convincing Use Case?

What worked out in 5G?

- Massive MIMO: Increase spectral efficiency
- mmWave technology: Use more bandwidth

Less successful

NOMA, spatial modulation

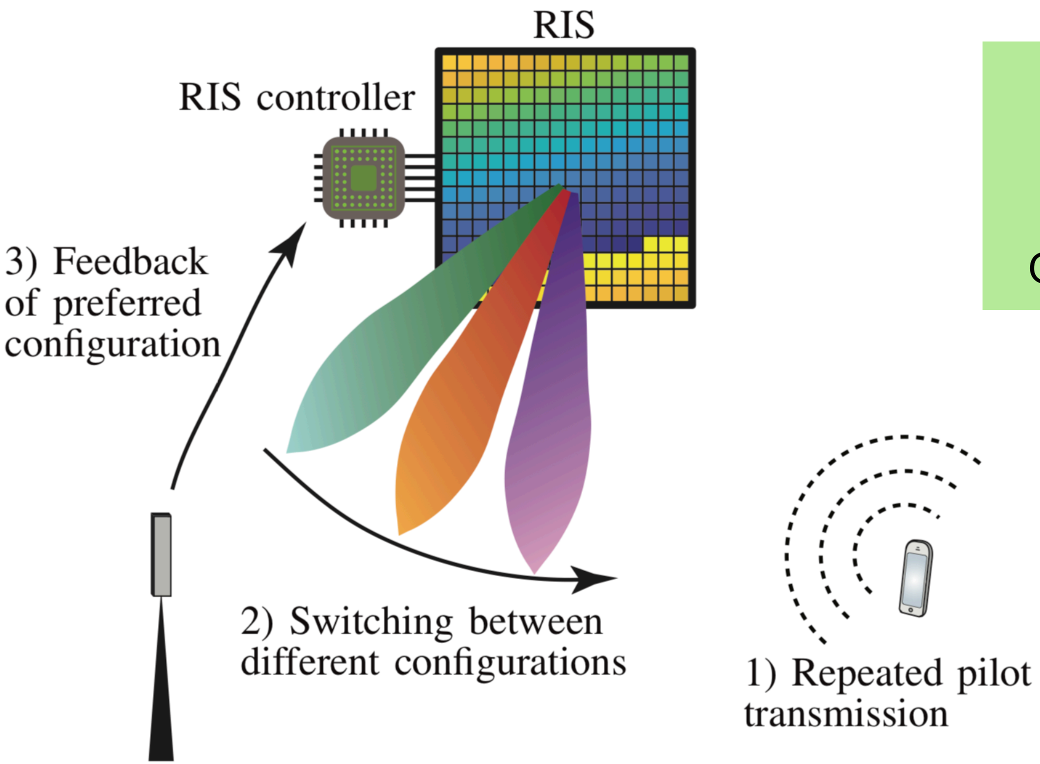
What are reconfigurable intelligent surfaces good at?

What can be improved by 10x over competing technologies?

- **No good answer yet,** but some thoughts:
  - Enable operation with very sparse channels (above 100 GHz)
  - Enable large arrays when active antennas are complicated

Second Open Question: How to Learn the Channel?

Hard: The surface is passive – no measurements



Codebook approach:

Send pilots and switch configuration

Select the best configuration in a set

Overhead grows with number of elements!

Use parameteric models?

Estimate position or angle to the user

Aided with machine learning?

Have a few active RIS elements?

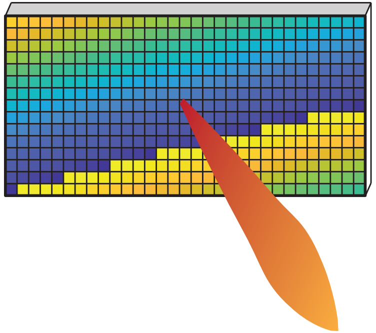
Anyway convenient for control channel

Is a Programmable Wireless World Possible?

Easy to say:

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

  some minor parts of the



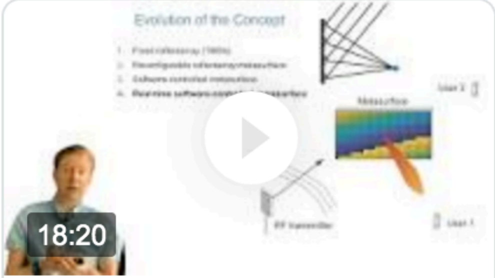
An active MIMO array can do anything that an RIS can do!

The hope:

More cost and energy efficient to use RIS instead

YouTube Videos

Check out my previous videos:



Reconfigurable intelligent surfaces: Myths and realities

Communication Systems...

YouTube - Mar 17, 2020

Fundamentals of Intelligent Reflecting Surfaces

Communication Systems...

YouTube - Mar 30, 2020

Towards 6G: Massive MIMO is a Reality—What is Next?

Communication Systems...

YouTube - Apr 23, 2020

Key References

Overview papers

1. 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.
2. E. Björnson, Ö. Özdogan, E. G. Larsson, “Reconfigurable Intelligent Surfaces: Three Myths and Two Critical Questions,” arXiv:2006.03377.

Channel modeling

3. Ö. Özdogan, E. Björnson, E. G. Larsson, “Intelligent Reflecting Surfaces: Physics, Propagation, and Pathloss Modeling,” IEEE Wireless Commun. Letters, to appear.
4. E. Björnson, L. Sanguinetti, “Power Scaling Laws and Near-Field Behaviors of Massive MIMO and Intelligent Reflecting Surfaces,” arXiv:2002.04960.

Questions?