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 the system

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:

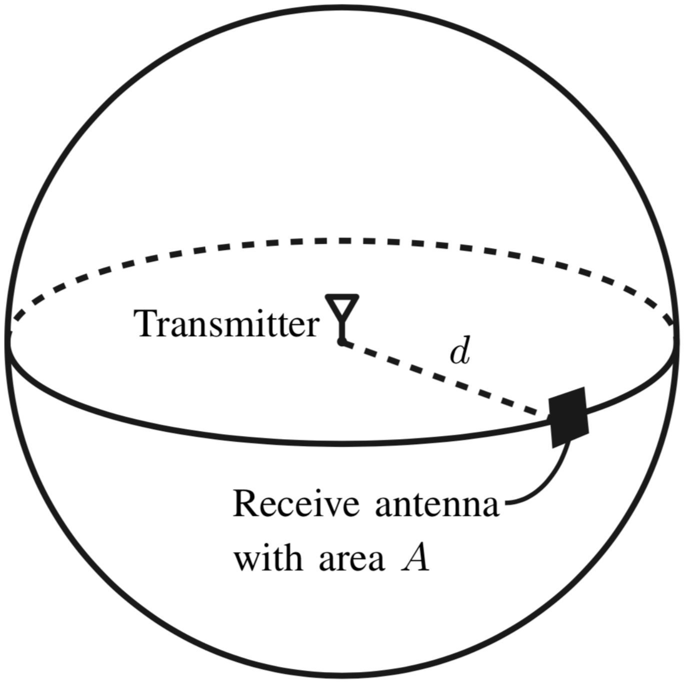
Channel gain

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

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

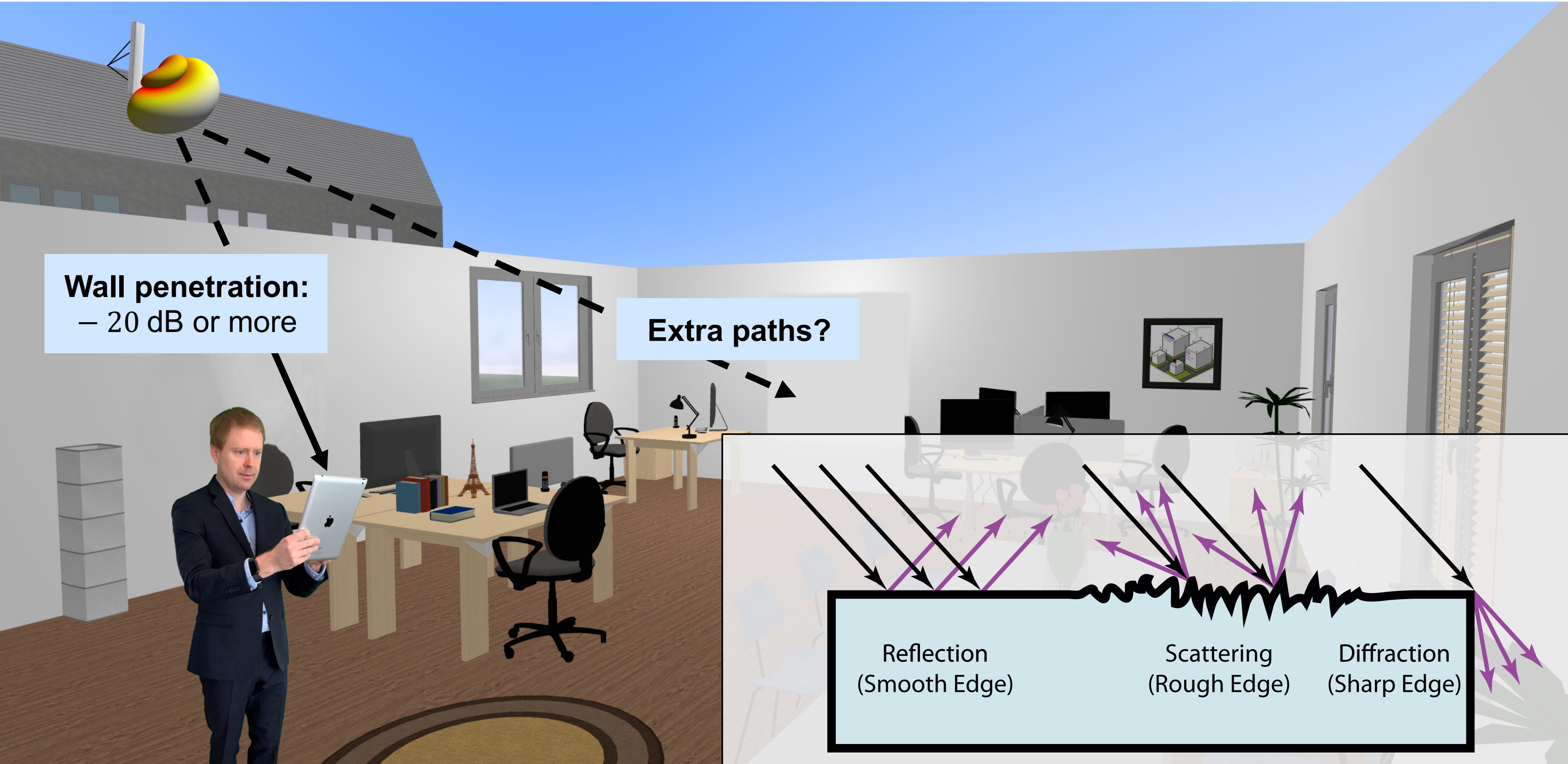
0.005% received at 1 m (−43 dB)
0.00005% received at 10 m (−63 dB)

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 big data to manage assets, resources and services efficiently

Internet-of-things (IoT) devices

- Mobile phones, base stations
- Various sensors

Monitor and manage

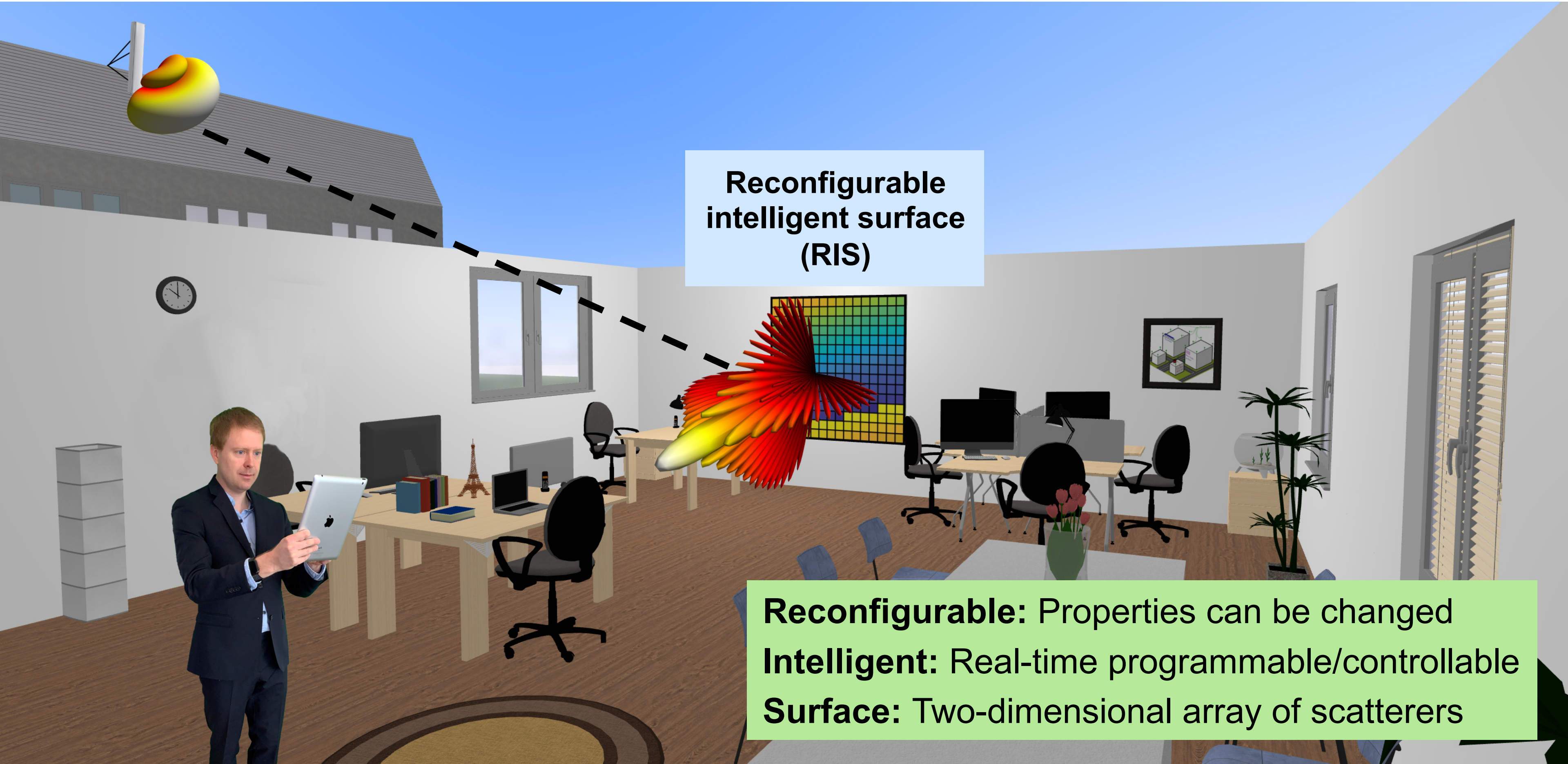
- Traffic and transportation
- Public utilities and services
- Crime prevention

Control and programmability

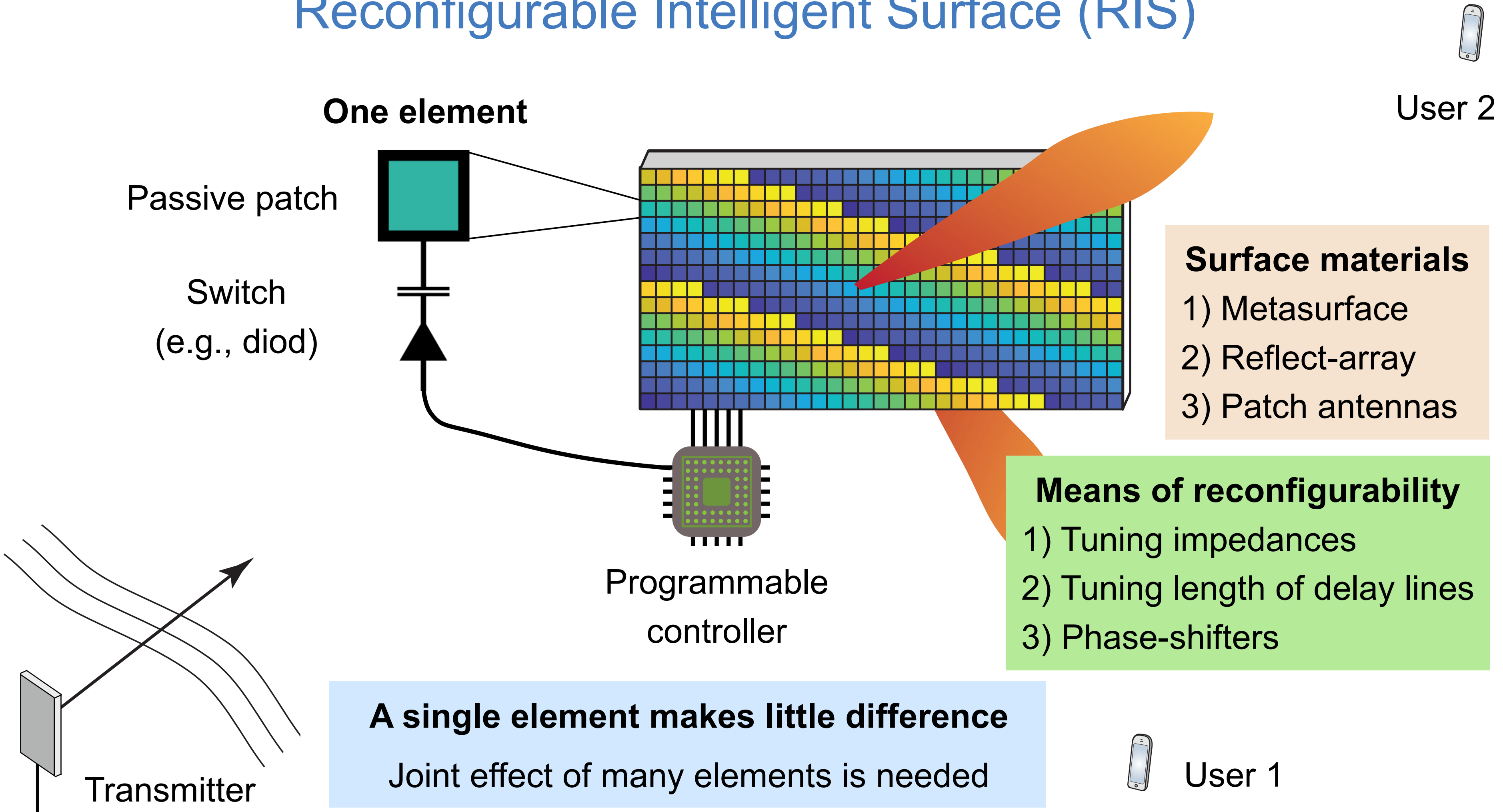
- Signal processing
- Machine learning

Can we also control the wireless propagation?

Shaping the Signal Scattering Towards the Receiver



Reconfigurable Intelligent Surface (RIS)



Surface materials
1) Metasurface
2) Reflect-array
3) Patch antennas

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 Wireless World

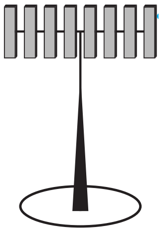
RIS **as a whole** can control

- Directivity of scattered signal
- Signal absorption
- Polarization

Improved indoor coverage

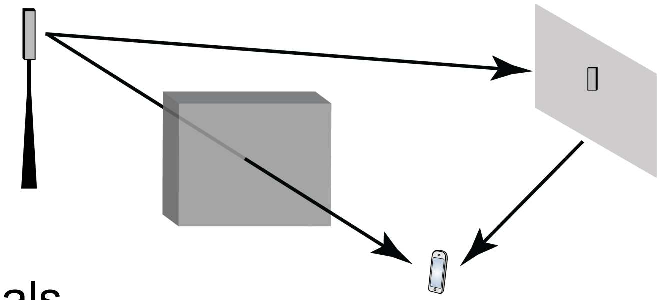
Alternative Approaches

Deploy more base stations



- Require infrastructure for power and backhaul
- Inter-cell interference

Utilize conventional relays



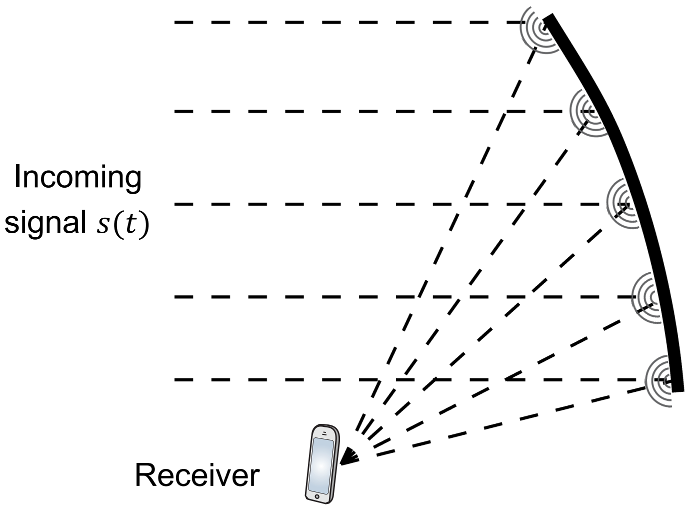
- Half-duplex operation
- RIS is a new type of semi-passive relay

Use building materials that are not blocking signals

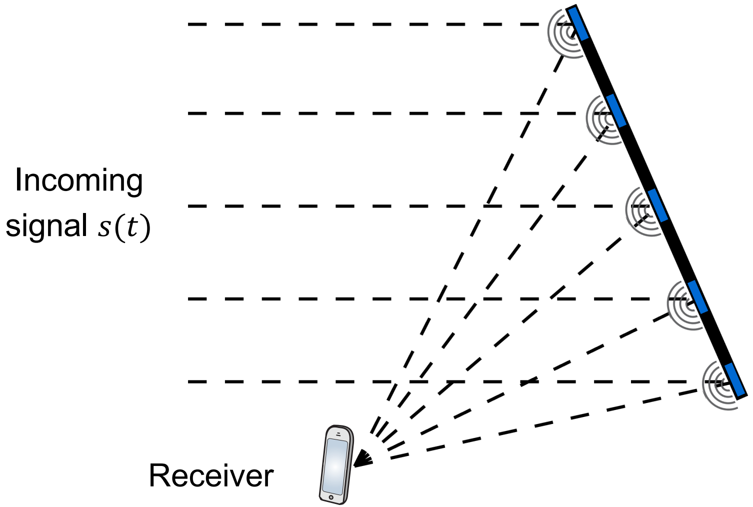
- Thermal insulation leads to signal attentuation
- Passive materials will not beamform in right direction

Signal Focusing in a Nutshell

Curved metal surface



Reconfigurable intelligent surface



Radio waves are not rays!

Every surface point “scatters” a spherical wave (Huygens–Fresnel principle)

Beamforming: Waves arrive in phase at receiver

Received signal:

$$c \cdot \sum_{\text{Element } n} s(t - \tau_n - \Delta_n)$$

Channel gain (c); Propagation delay (τ_n); Delay in surface (Δ_n)

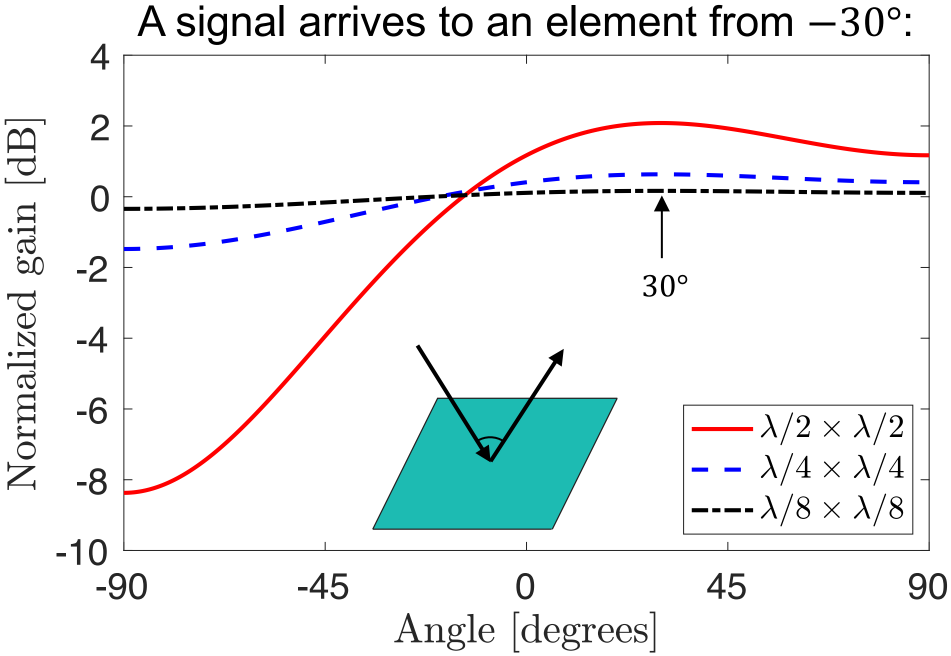
Synthesize curved surface:

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

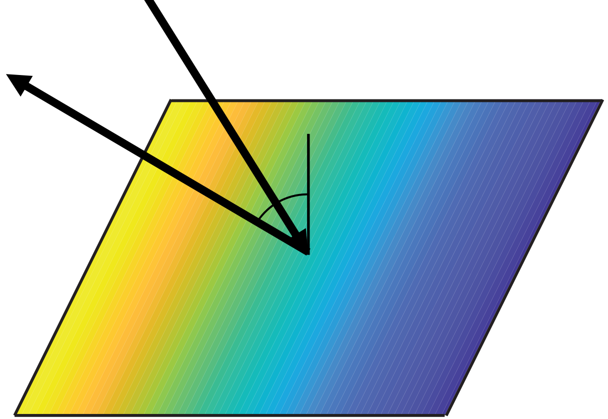
Causal solution:

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

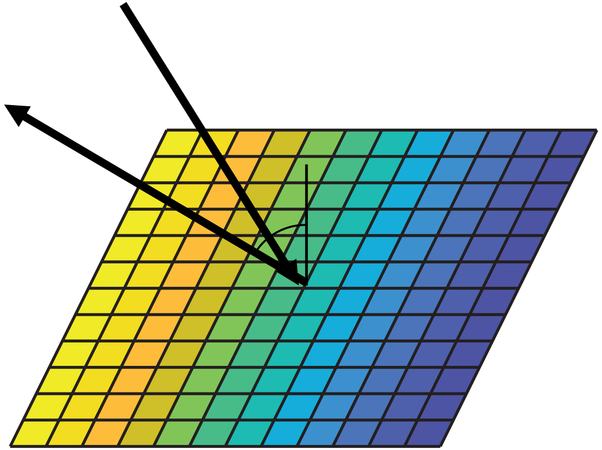
How Large are the Elements?



Each element should scatter signals almost uniformly



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.

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.

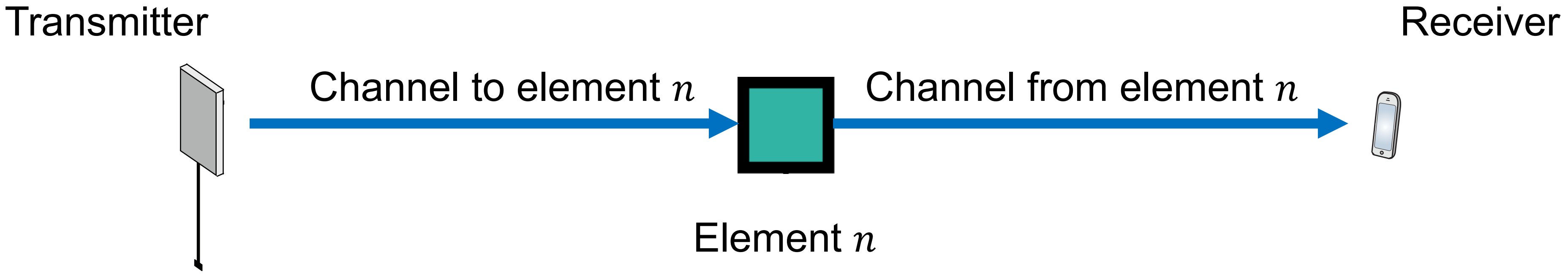
M. Di Renzo *et al.*, “Smart radio environments empowered by **reconfigurable AI meta-surfaces**: an idea whose time has come,” *EURASIP Journal on Wireless Commun. and Networking*, vol. 2019:129, 2019.

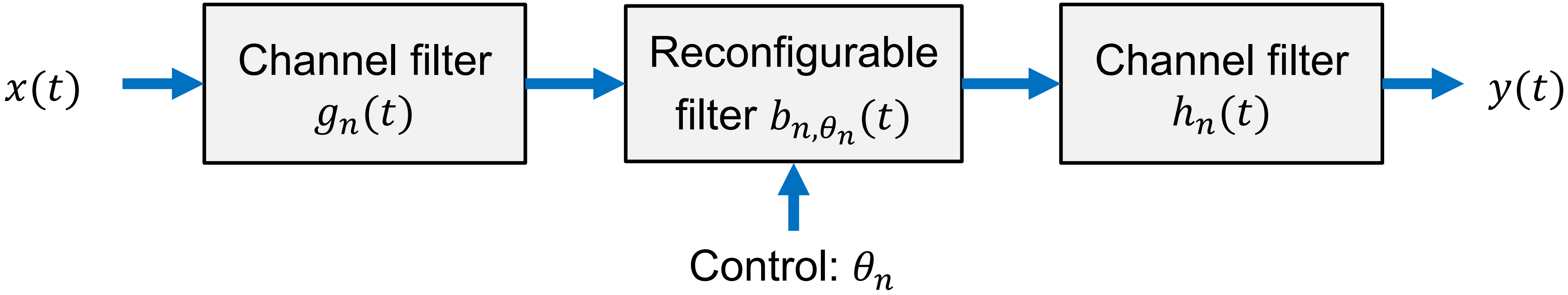
Q. Wu and R. Zhang, “Towards smart and reconfigurable environment: **Intelligent reflecting surface** aided wireless network,” IEEE Communications Magazine, 2020.

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

Basic Signals and Systems Description





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

Narrowband System Model

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

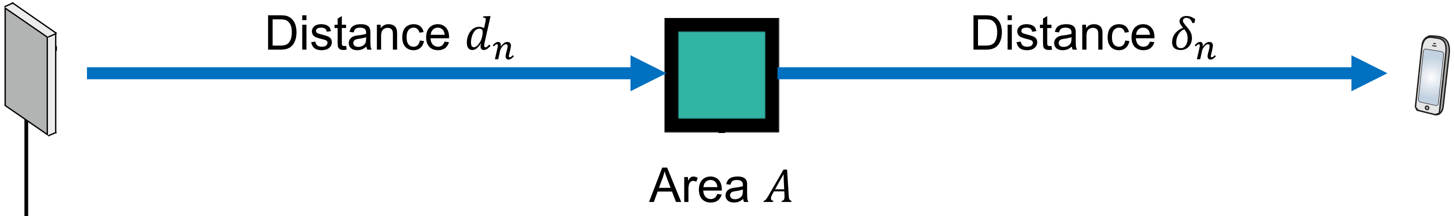
$$y(t) = \int_{-\infty}^{\infty} g(\tau)\, e^{j2\pi f_c (t-\tau)} d\tau$$
$$= G(f_c) e^{j2\pi f_c t}$$
$$= \underbrace{|G(f_c)|}_{\text{Amplitude change}} e^{j2\pi f_c \left(t + \underbrace{\frac{\arg(G(f_c))}{2\pi f_c}}_{\text{Phase shift}}\right)}$$

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

Narrowband input-output relation:

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

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



$x(t)$ → LoS channel → Reconfigurable filter → LoS channel → $y(t)$

$$G_n(f_c) = \sqrt{\frac{A}{4\pi d_n^2}}\, e^{\underbrace{-j2\pi f_c \frac{d_n}{c}}_{\phi_n}}$$

$$B_{n,\theta_n}(f_c) = \mu_n e^{-j\theta_n}$$

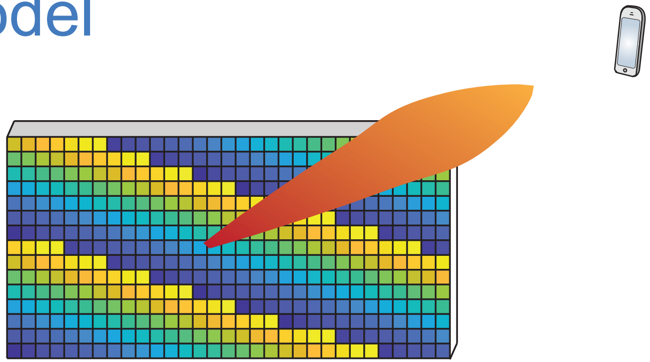
$$H_n(f_c) = \sqrt{\frac{A}{4\pi \delta_n^2}}\, e^{\underbrace{-j2\pi f_c \frac{\delta_n}{c}}_{\varphi_n}}$$

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

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:

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

Signal processing problem:

Maximize the signal-to-noise ratio

Channel gain:

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

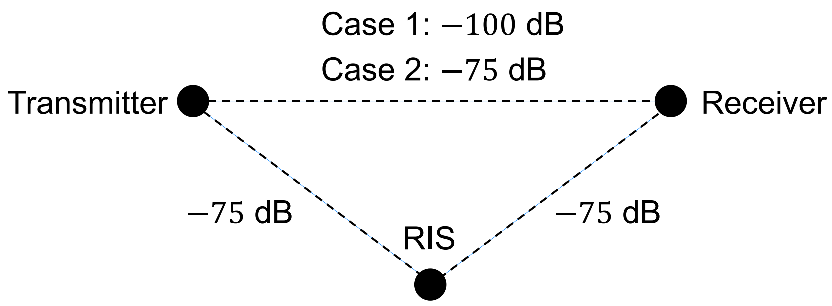
Cauchy–Schwarz inequality + set $\mu_n = 1$

Achieved when:

$\phi_n + \theta_n + \varphi_n$

$= \text{constant}$

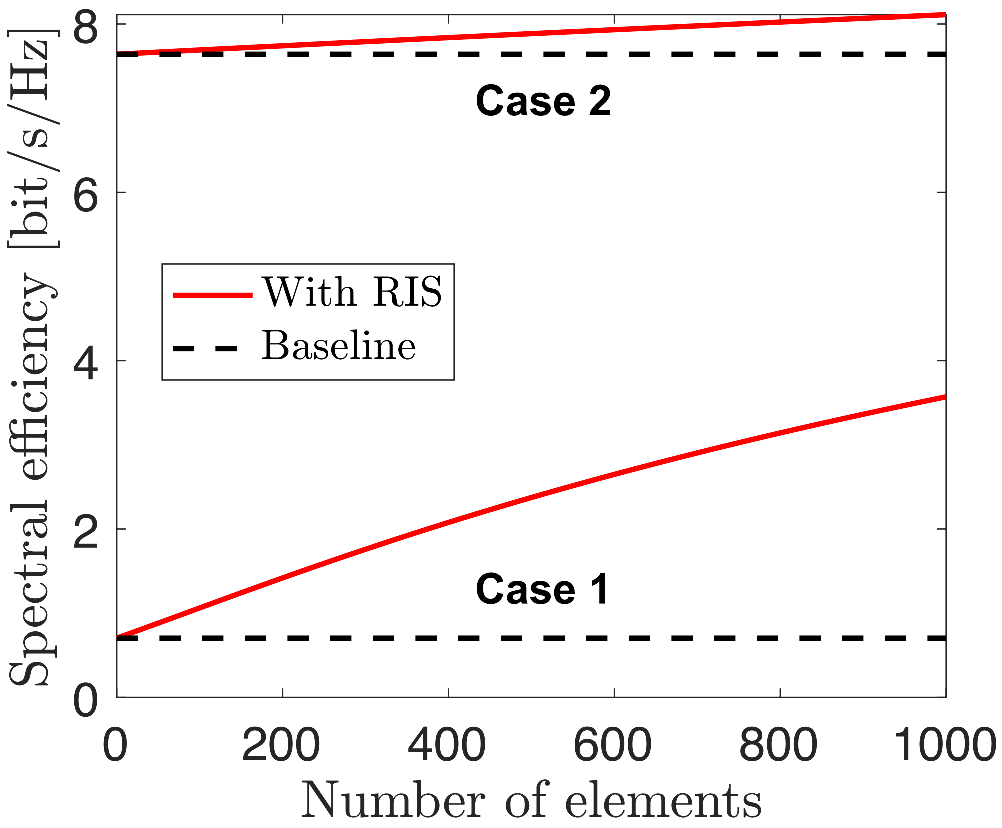
Basic Performance Benefit



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

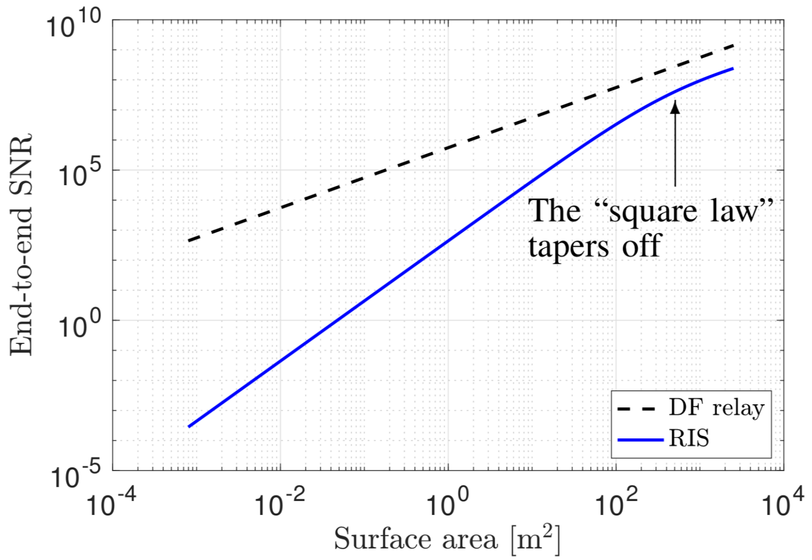
- Truth: Relaying is supported since 3G. RIS is a type of relay with unique properties.

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, scaling laws disappear 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.

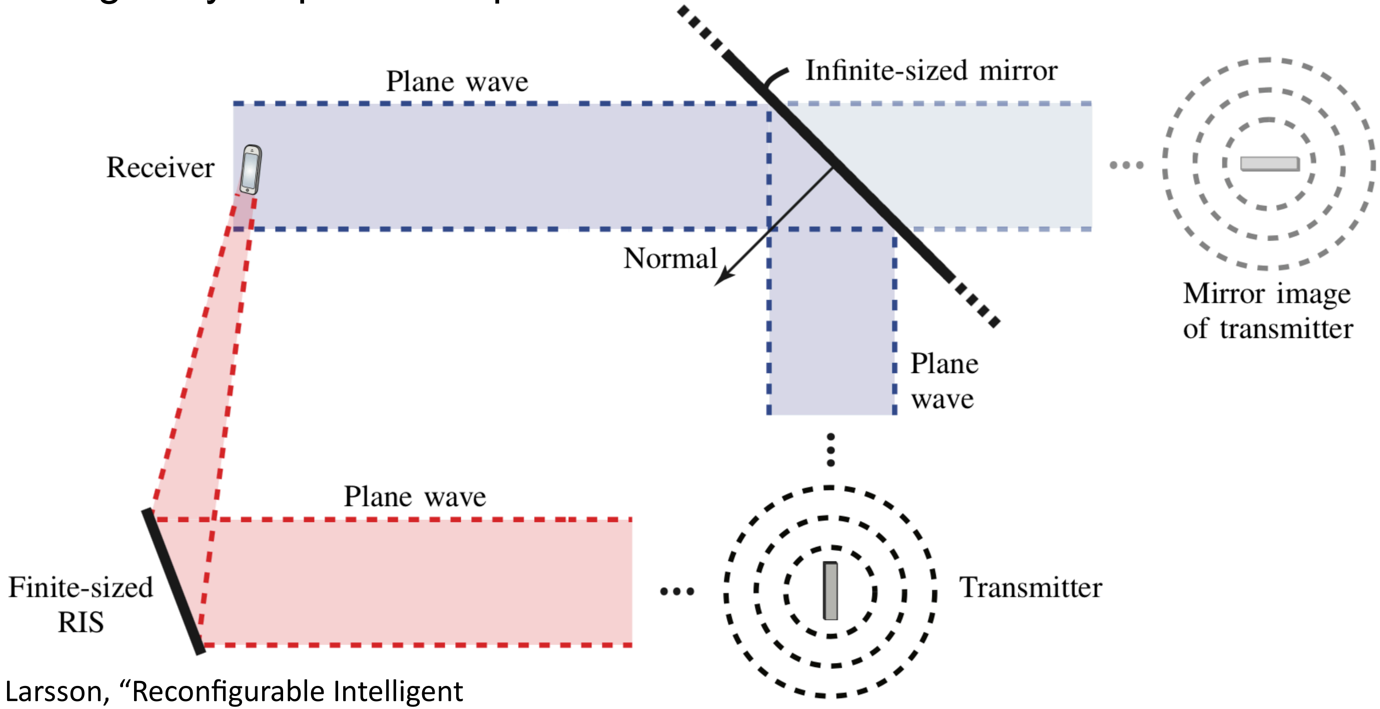
Three Misconceptions in the Literature

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?

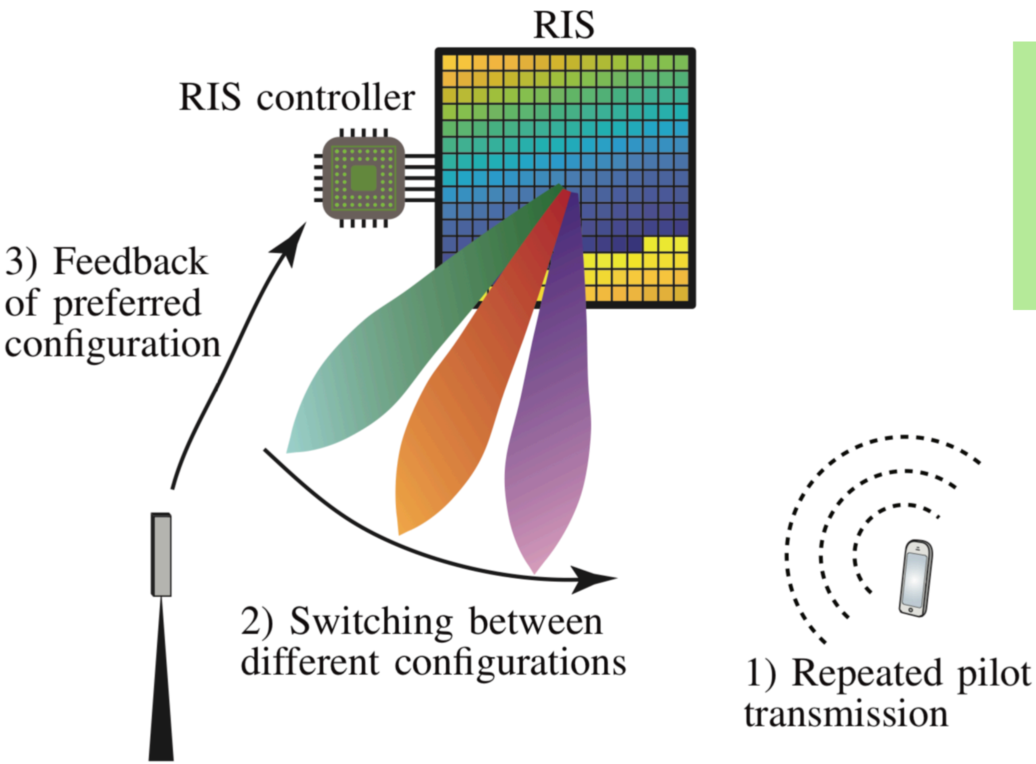
What can be improved by 10x over competing technologies?

No good answer yet, but some thoughts:

- Enable operation with very sparse channels
  (above 100 GHz, huge bandwidths → huge data rates)
- 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 parametric models?

Estimate position or angle to the user

Aided with machine learning?

Have a few active RIS elements?

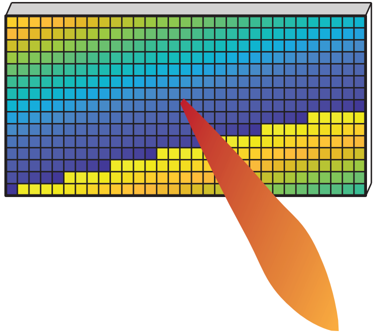
Anyway convenient for control channel

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



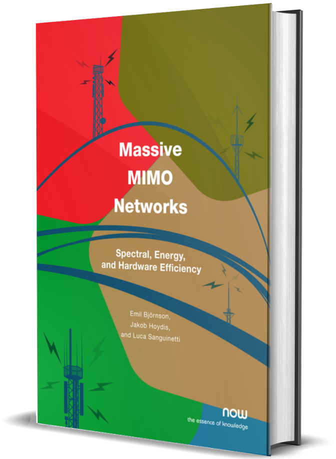
An active MIMO array can do anything that an RIS can do!

The hope and vision:

RIS can make a real difference for wireless propagation

More cost and energy efficient to use RIS instead massivemimobook.com

How Can You Contribute?



Good to learn in advance:

- Basic multi-antenna communications (Sec. 1-4)
- Physical channel and array modeling (Sec. 7.3-7.5)

Papers to read:

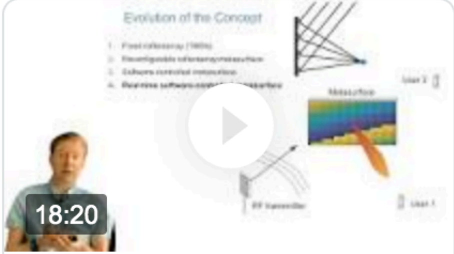
1. E. Björnson, Ö. Özdogan, E. G. Larsson, "Reconfigurable Intelligent Surfaces: Three Myths and Two Critical Questions," arXiv:2006.03377.
2. Ö. Özdogan, E. Björnson, E. G. Larsson, "Intelligent Reflecting Surfaces: Physics, Propagation, and Pathloss Modeling," IEEE Wireless Commun. Letters, 2020.
3. E. Björnson, L. Sanguinetti, "Power Scaling Laws and Near-Field Behaviors of Massive MIMO and Intelligent Reflecting Surfaces," arXiv:2002.04960.
4. B. Matthiesen, E. Björnson, E. De Carvalho, P. Popovski, "Intelligent Reflecting Surfaces that Track a Mobile Receiver: A Continuous Time Propagation Model" arXiv:2006.06991.

Overview (1)

Channel model (2–4)

Look beyond the hype: Focus on the two open questions

YouTube 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

Questions?