Reconfigurable Intelligent Surfaces

Through the Lens of Array Signal Processing

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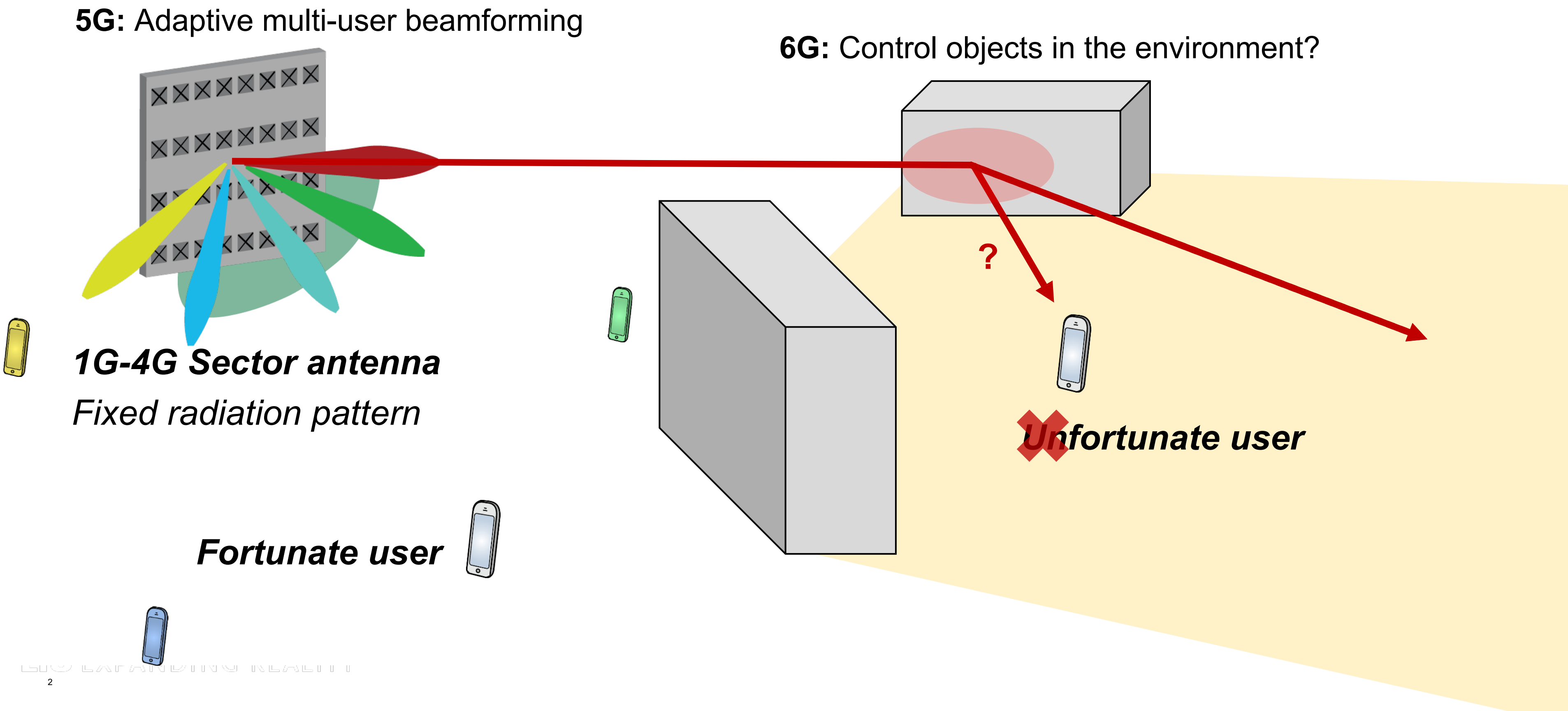
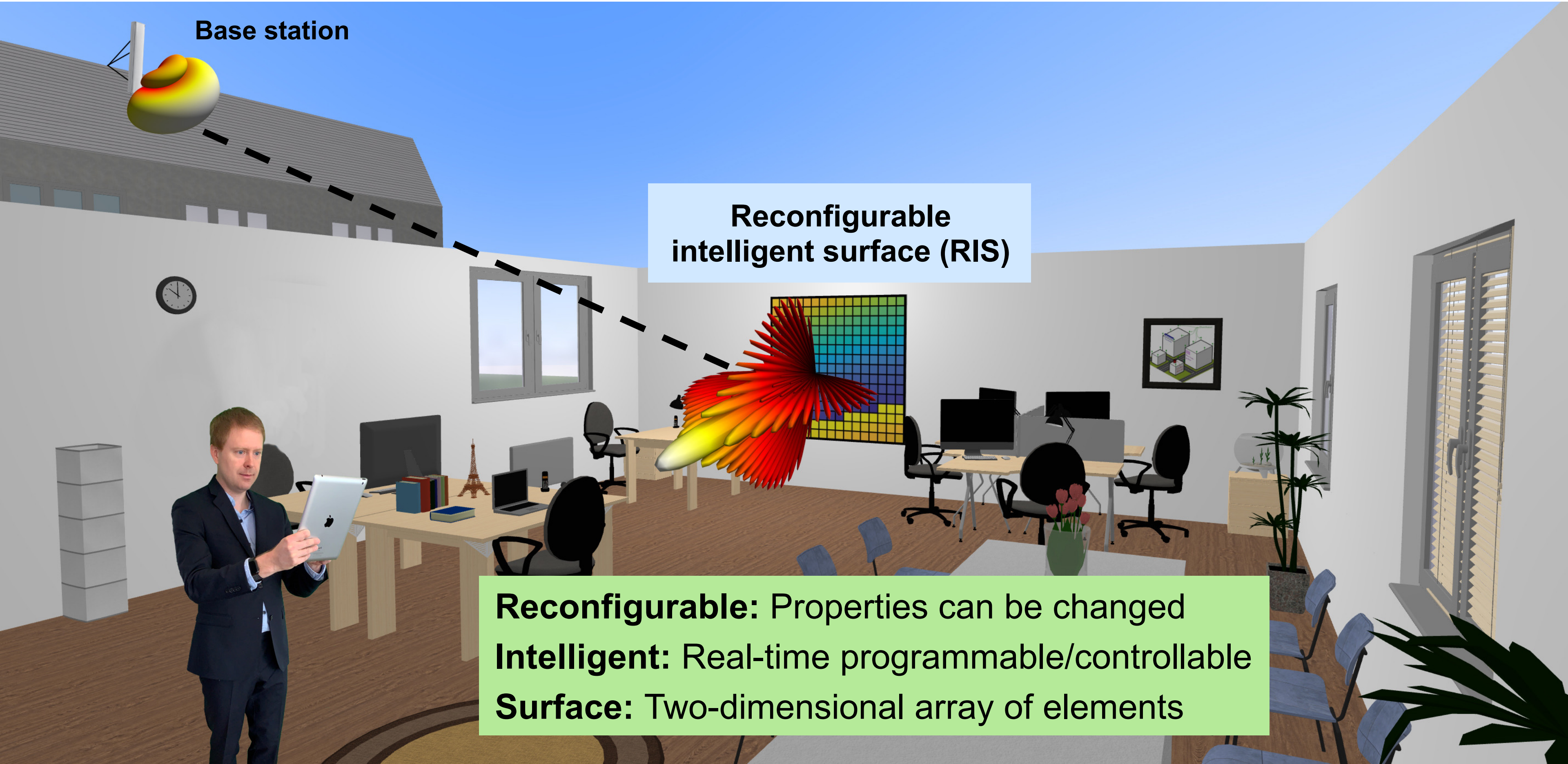
Evolution of Wireless Infrastructure

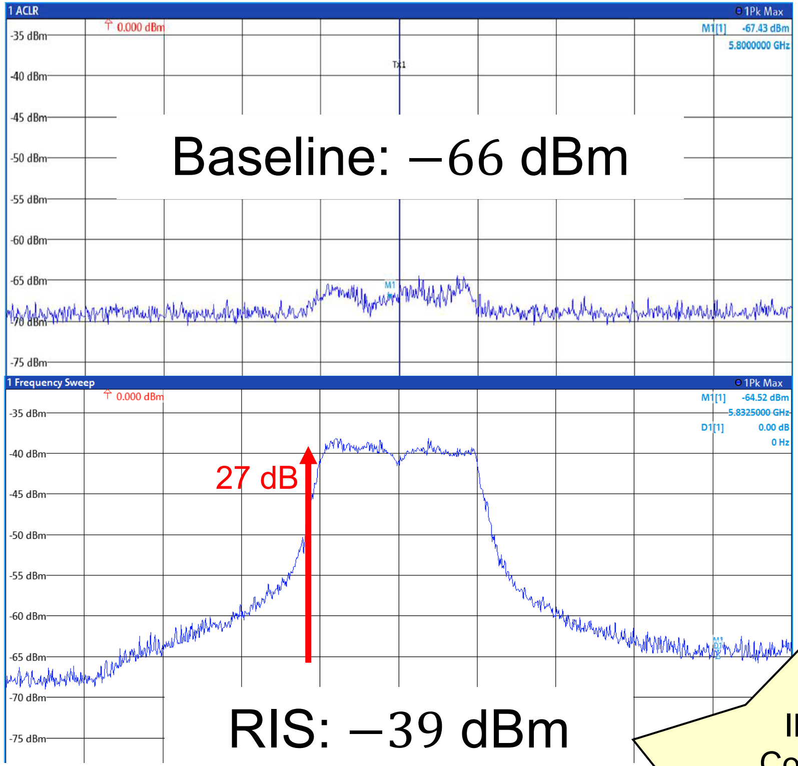


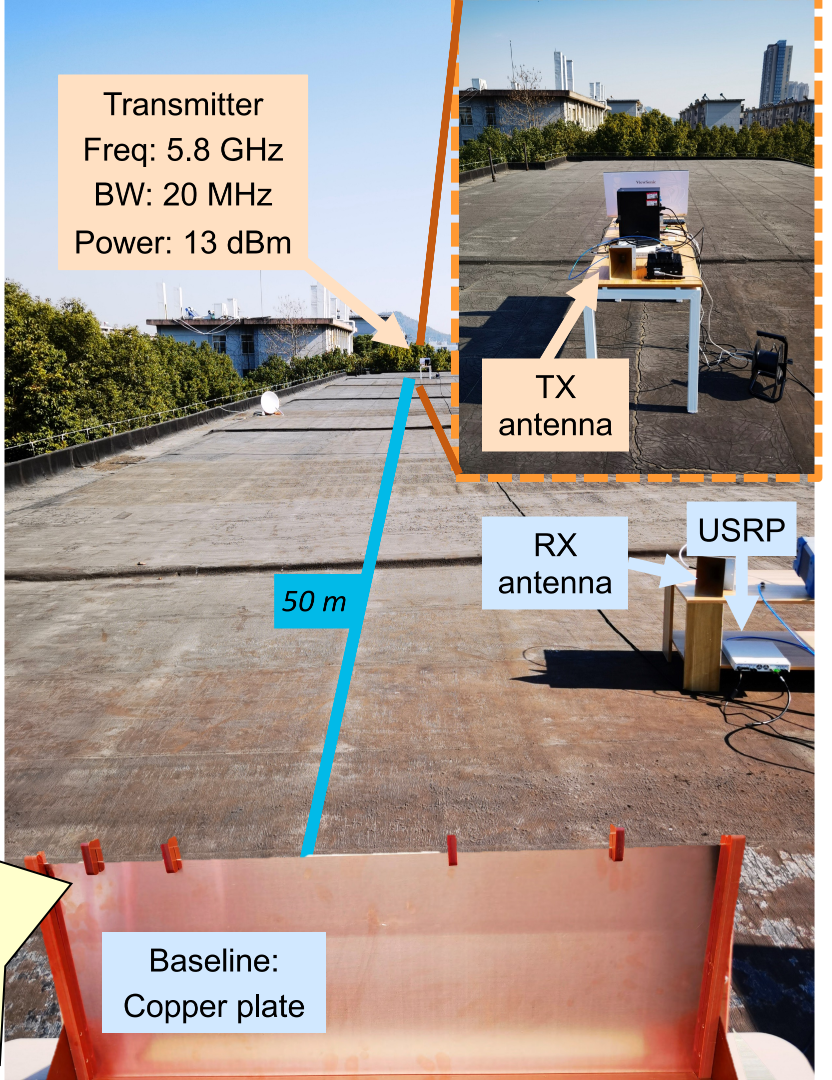

Base station
Wall penetration:
– 20 dB or more
Reflection

Virtual Line-of-Sight (LOS) Path



Experimental Demonstration





IEEE ComSoc Stephen O. Rice Prize 2024

Reference: X. Pei, H. Yin, L. Tan, L. Cao, Z. Li, K. Wang Björnson, "RIS-Aided Wireless Communications: Prototy Beamforming, and Indoor/Outdoor Field Trials," IEEE TC M, 2021

Technology Readiness Level

ACCEPTED FROM OPEN CALL

Reconfigurable Intelligent Surfaces: Three Myths and Two Critical Questions

Emil Björnson, Özgecan Özdogan, and Erik G. Larsson

The authors take a neutral look at the RIS technology. They review the fundamentals and then explain specific features that can be easily misinterpreted. They debunk three myths: 1) current network technology can only control the transmitter and receiver, not the environment in between; 2) a better asymptotic array gain is achieved than with conventional

ABSTRACT

The search for physical layer technologies that can play a key role in beyond 5G systems has started. One option is reconfigurable intelligent surfaces (RISs), which can collect wireless signals from a transmitter and passively beamform them toward the receiver. The technology has exciting prospects and is quickly gaining traction in the communication community, but in the current hype we have witnessed how several myths and overstatements are spreading in the literature.

In this article, we take a neutral look at the RIS technology. We first review the fundamentals and then explain specific features that can be easily misinterpreted. In particular, we debunk three myths: 1) current network technology can

riences minor losses. Inside the window, an RIS is deployed to capture signal energy proportional to its area and re-radiate it in the shape of a beam toward the receiver. To ensure the beam is focused toward the user device, wherever it is in the room, the RIS must be reconfigurable. By using an RIS in this setup, the signal-to-noise ratio (SNR) can be improved.

An RIS is a thin surface composed of N elements, each being a reconfigurable scatterer: a small antenna that receives and re-radiates without amplification, but with a configurable time delay [3]. For narrowband signals, this delay corresponds to a phase shift. Assuming the phase shifts are properly adjusted, the N scattered waves will add constructively at the receiver. This principle resembles traditional beamforming: each element

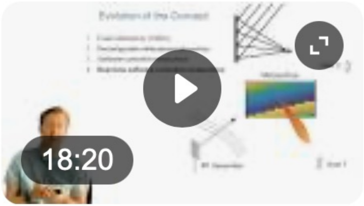
Myths

1. Relays are entirely different
2. RIS are more efficient than antenna arrays
3. Same pathloss as with mirrors

Critical Questions

1. What is a convincing use case?
2. Can we control a RIS in real-time?

Focus of today!



Reconfigurable intelligent surfaces: Myths and realities

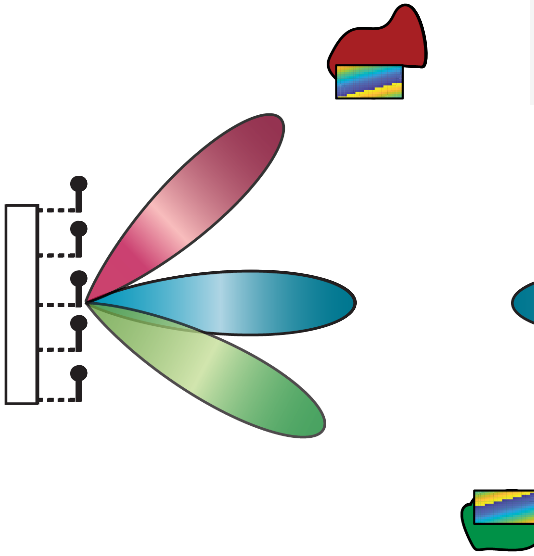
YouTube · Wireless Future

17 Mar 2020

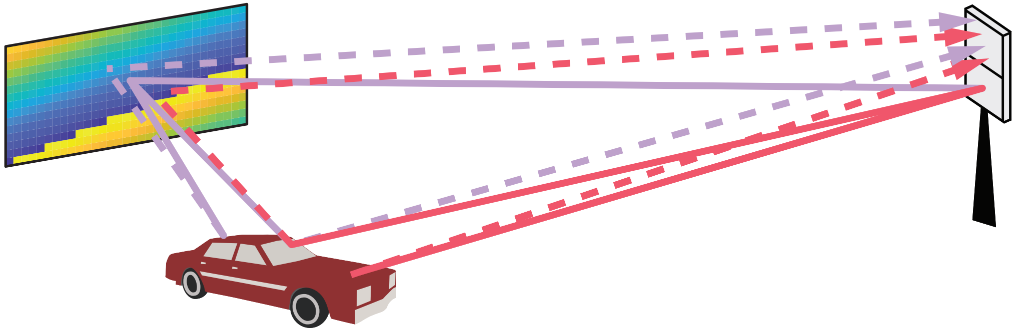
Many Possible Use Cases

1. Relay around blockages

2. Improved channel rank

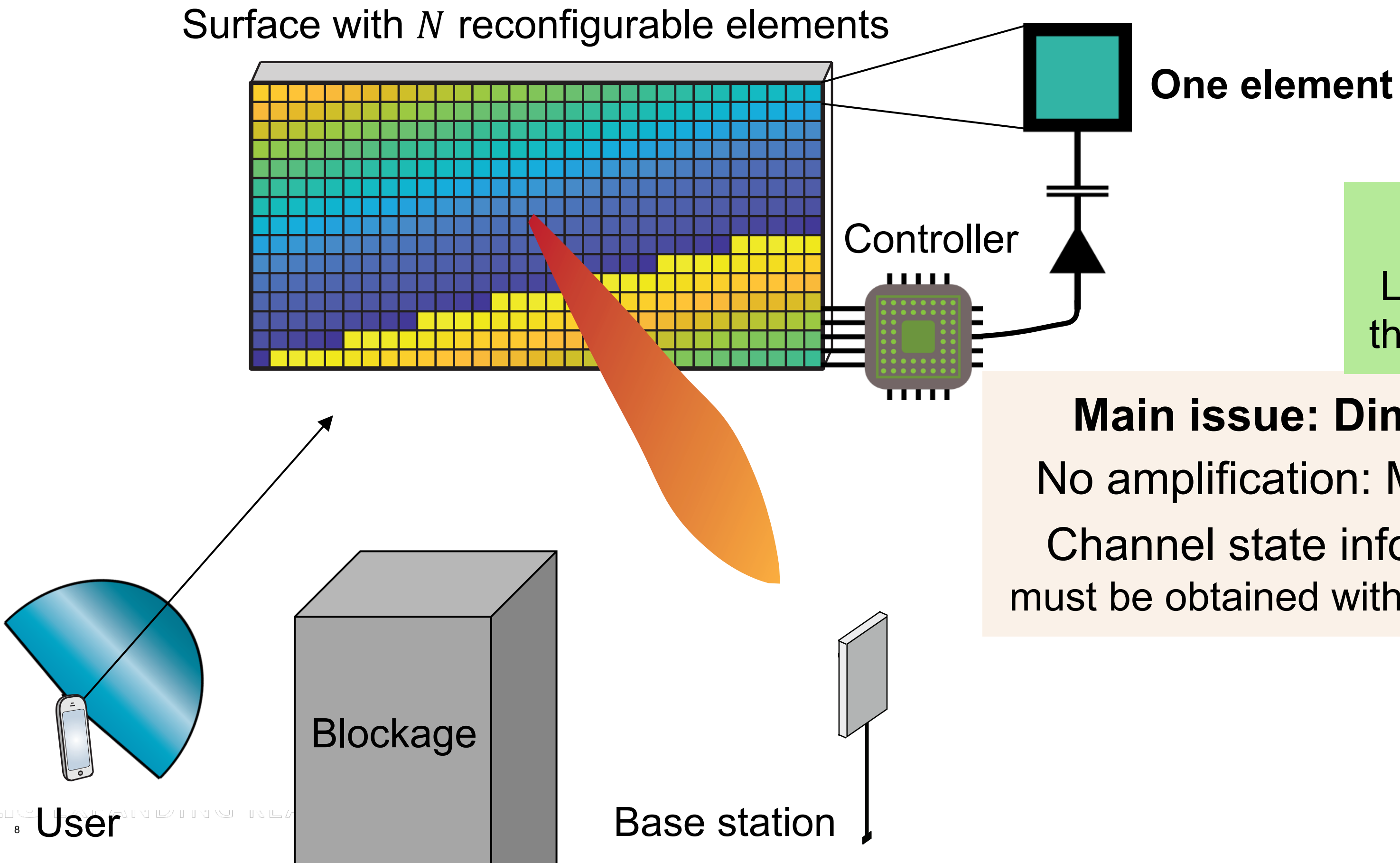


3. Improved localization and sensing



4. Physical layer security
5. Wireless power transfer
6. …

Basic Use Case: Relaying Around Blockages



Main benefit

Lower cost/energy than other solutions

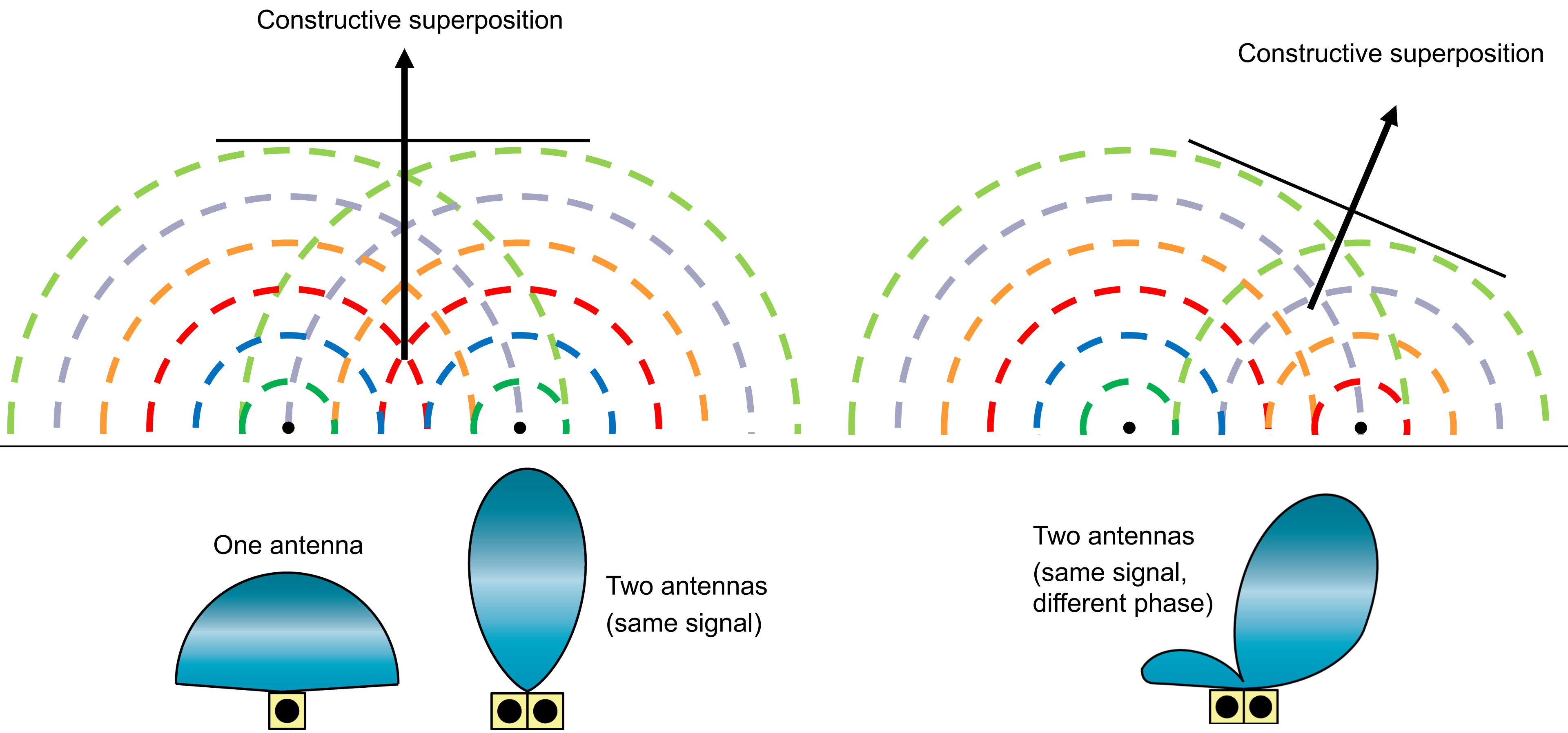
Main issue: Dimensionality

No amplification: Many elements

Channel state information (CSI) must be obtained with limited resources

THROUGH THE LENS OF ARRAY SIGNAL PROCESSING

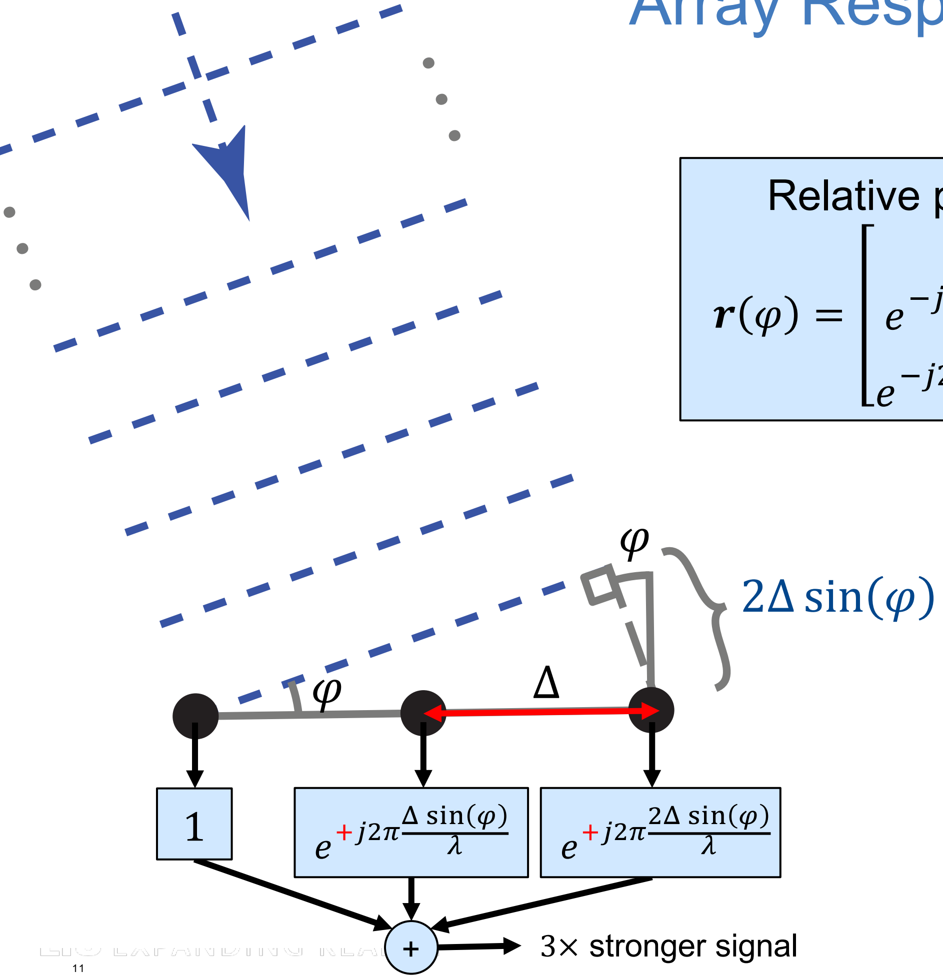
Adaptive Beamforming

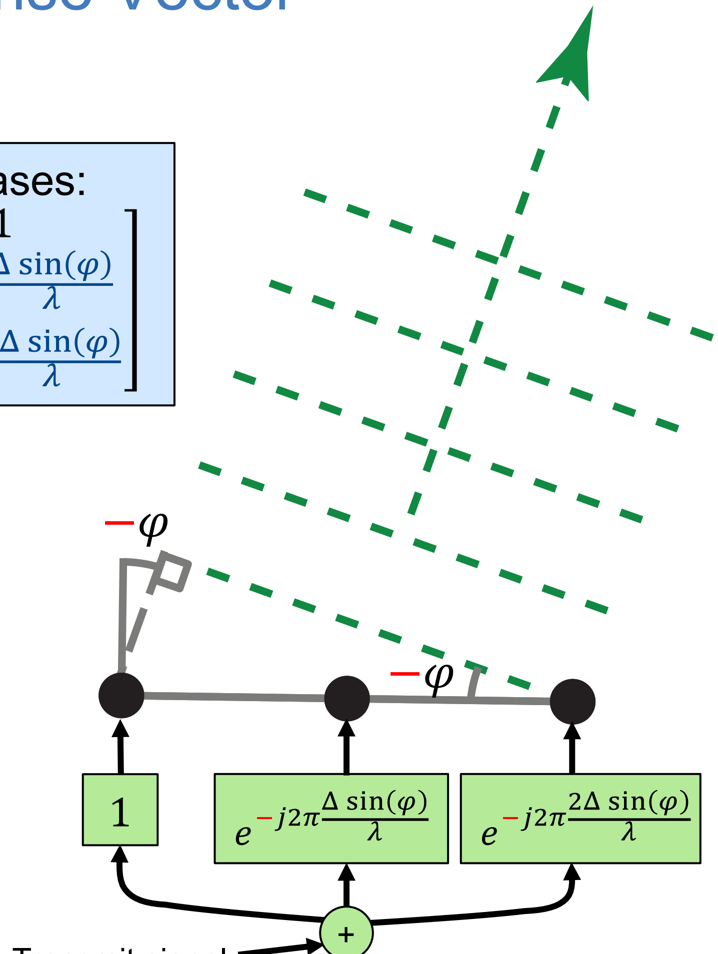


Array Response Vector

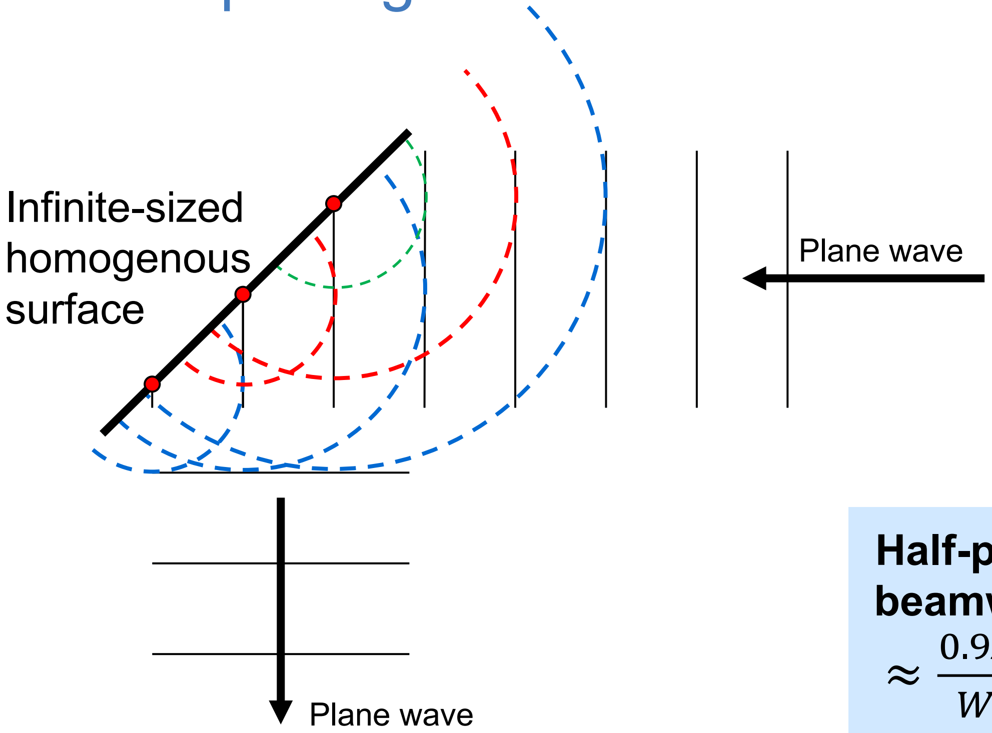
Relative phases:

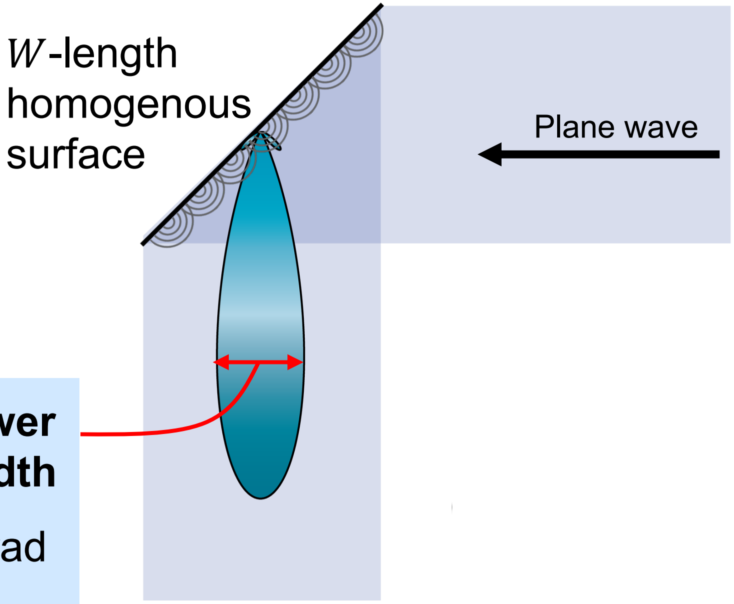
$$\boldsymbol{r}(\varphi) = \begin{bmatrix} 1 \\ e^{-j2\pi\frac{\Delta\sin(\varphi)}{\lambda}} \\ e^{-j2\pi\frac{2\Delta\sin(\varphi)}{\lambda}} \end{bmatrix}$$





Interpreting Reflection via the Huygens-Fresnel Principle





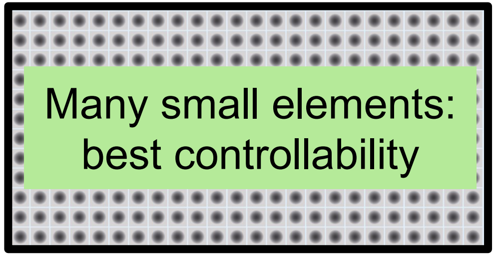
Half-power beamwidth

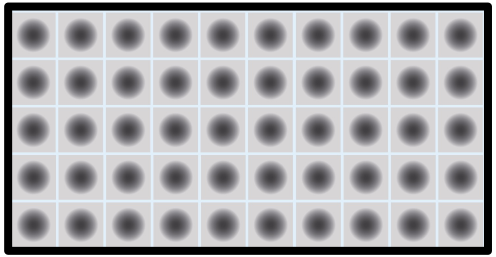
$$\approx \frac{0.9\lambda}{W} \text{ rad}$$

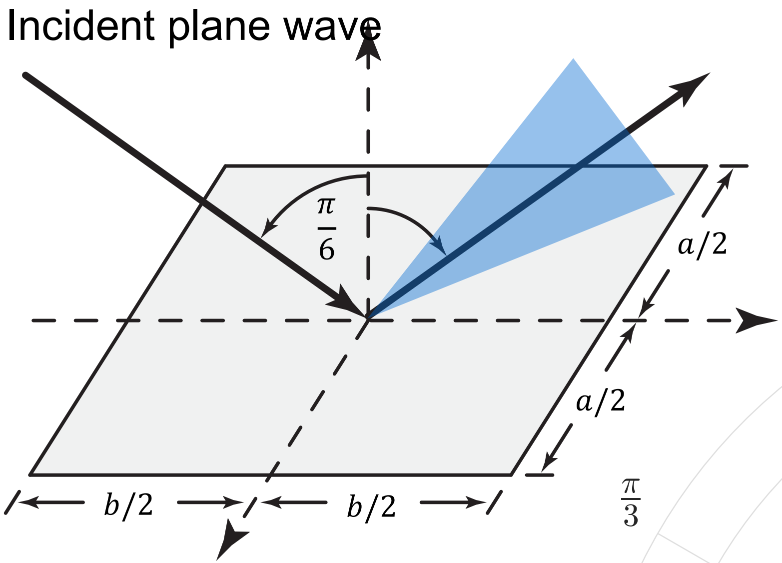
Every point “scatters” a spherical wave

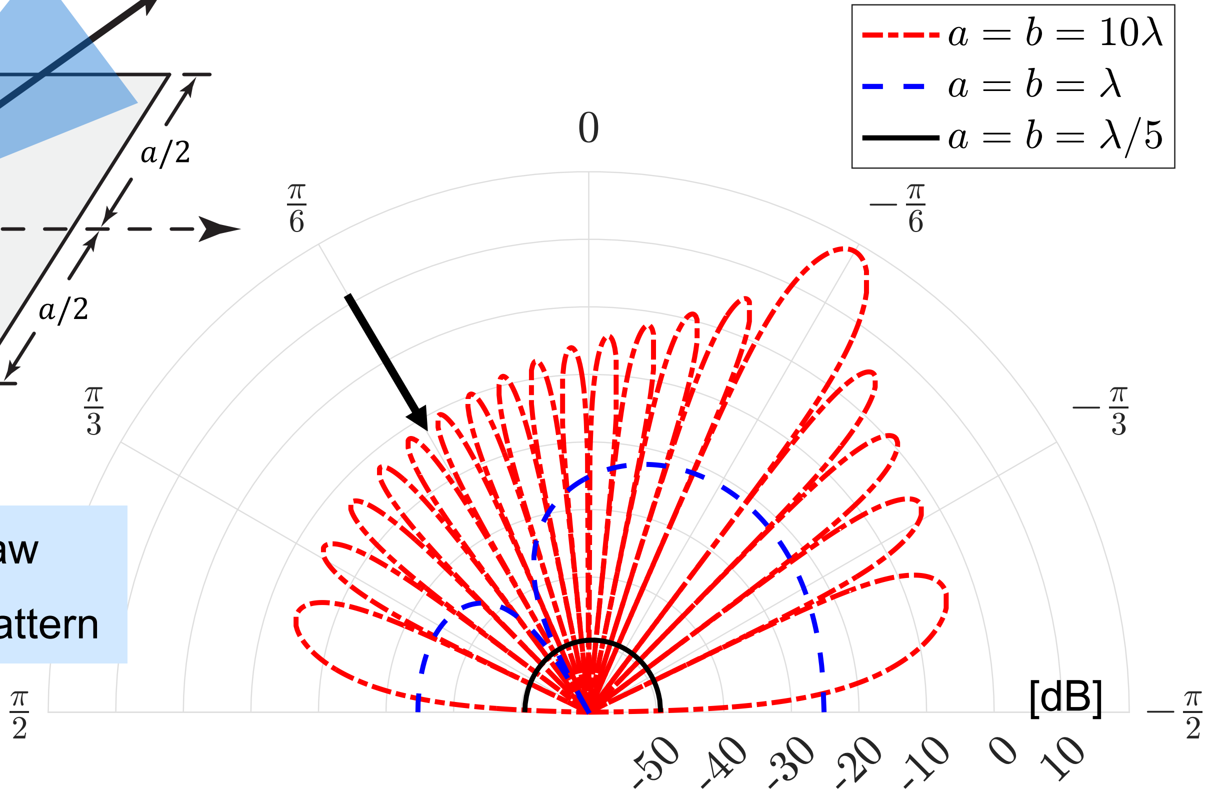
Constructive superposition determines direction

What Element Size?





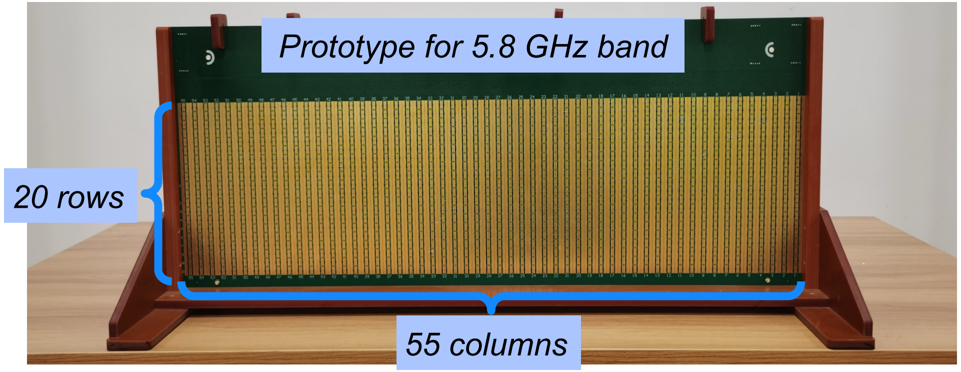


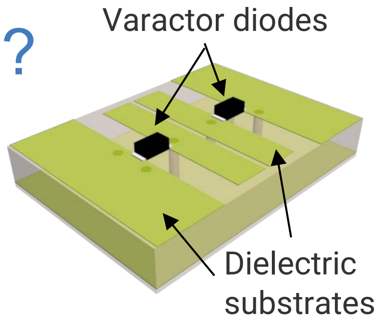


Large element: ≈ Snell's law

Small element: Isotropic pattern

How Does an Element Phase-Shift the Signal?



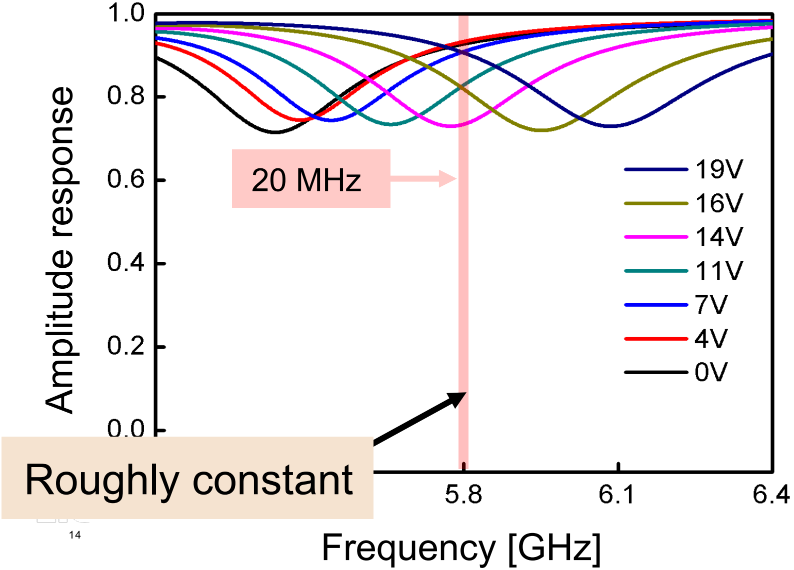


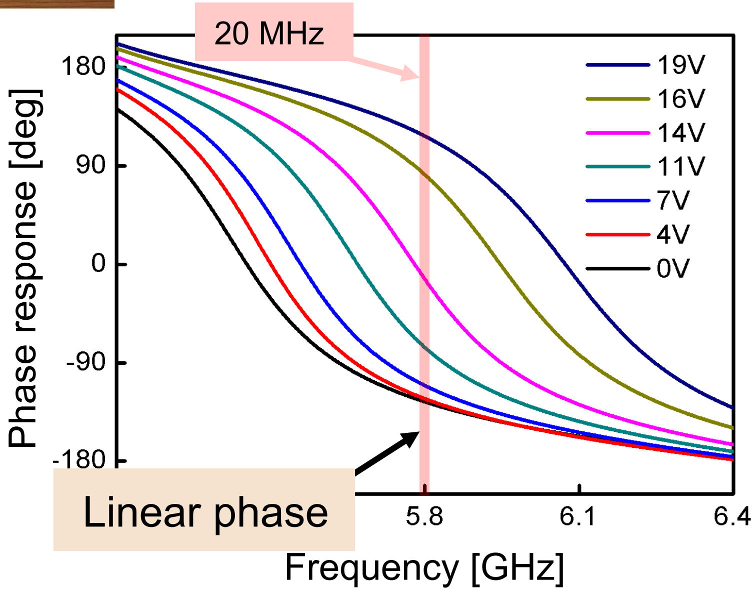
Example: Patch with bias voltage V

Reflection coefficient:

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

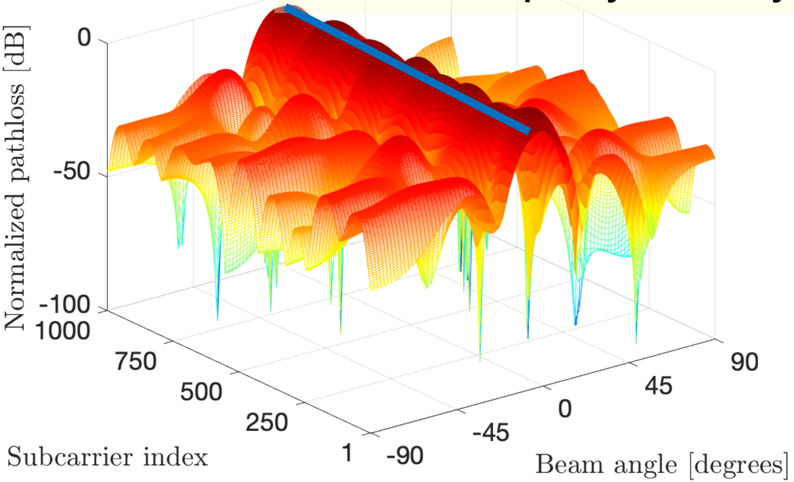
Reference: X. Pei, H. Yin, L. Tan, L. Cao, Z. Li, K. Wang, K. Zhang, E. Björnson, “RIS-Aided Wireless Communications: Prototyping, Adaptive Beamforming, and Indoor/Outdoor Field Trials,” IEEE TCOM 2021.



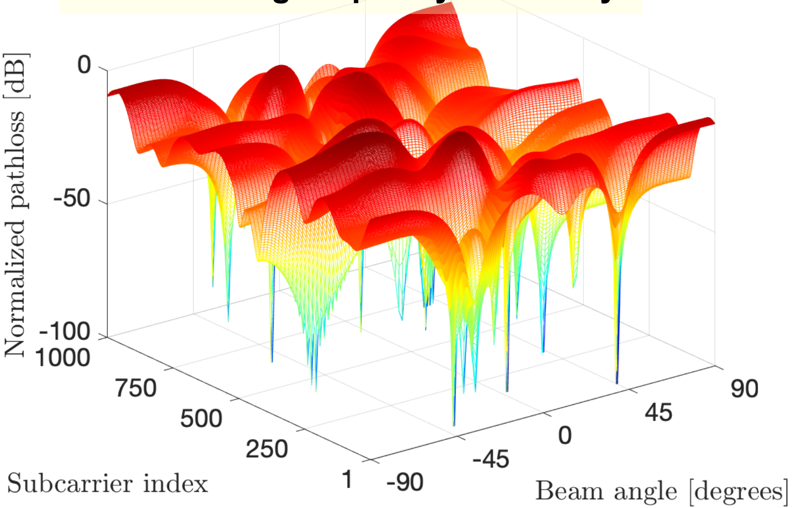


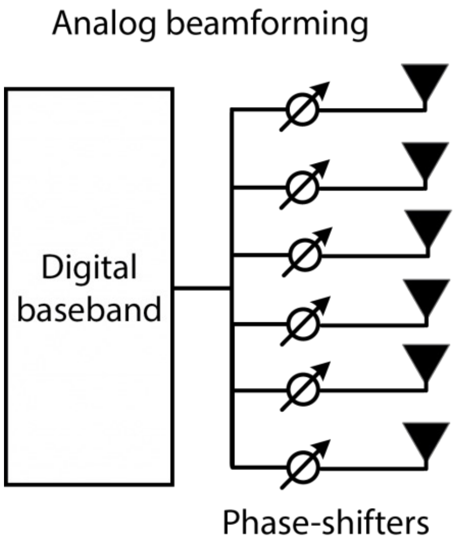
Beamforming & Multipath Channels

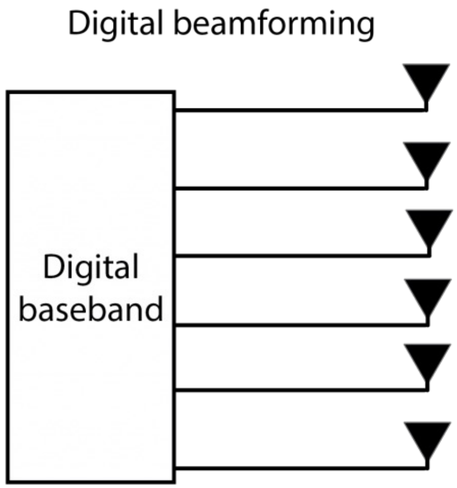
LOS: Weak frequency-selectivity



NLOS: Strong frequency-selectivity







One *angular* beam

Same on all subcarriers

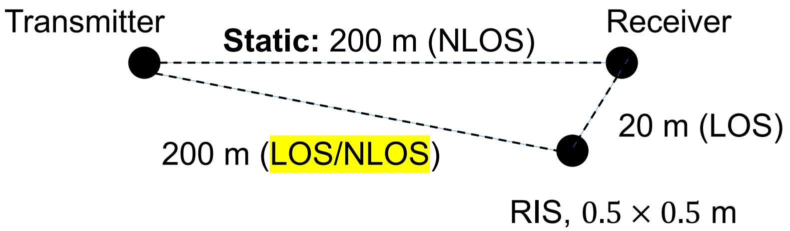
Same principle as for RIS

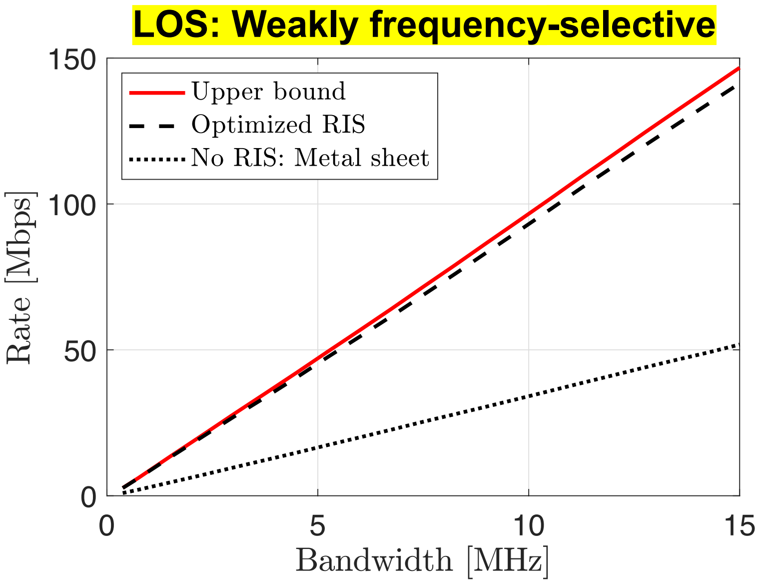
Sum of many beams

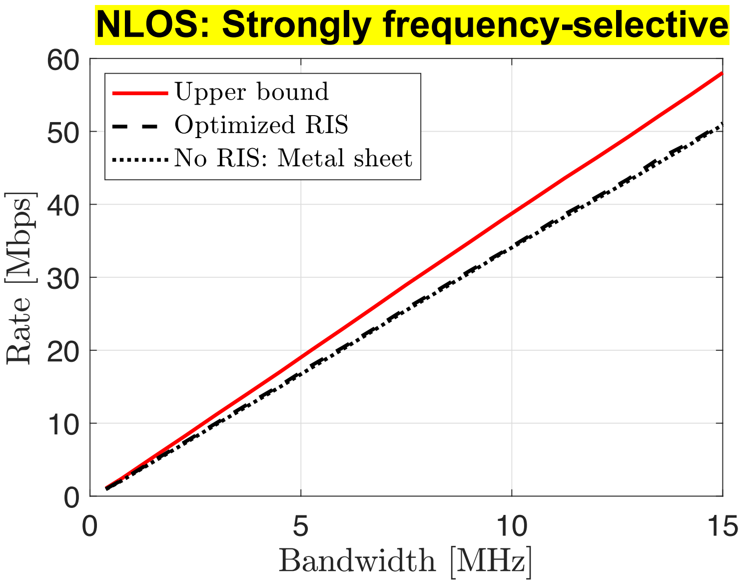
Different over subcarriers

Simulation: RIS in Frequency-Selective Channels

RIS mostly effective with LOS to transmitter and receiver!



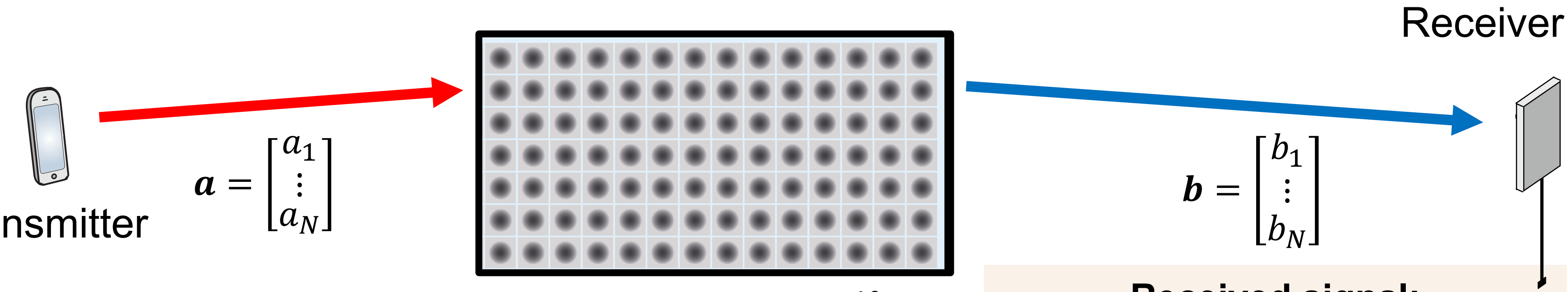




Reference: E. Björnson, H. Wymeersch, B. Matthiesen, P. Popovski, L. Sanguinetti, E. de Carvalho, "Reconfigurable Intelligent Surfaces: A Signal Processing Perspective With Wireless Applications", IEEE SPM, 2022

RIS OPTIMIZATION AND CHANNEL ESTIMATION

System Model and Achievable Rate



$$\boldsymbol{a} = \begin{bmatrix} a_1 \\ \vdots \\ a_N \end{bmatrix}$$

$$\boldsymbol{b} = \begin{bmatrix} b_1 \\ \vdots \\ b_N \end{bmatrix}$$

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

Received signal:

$$y = \sum_{n=1}^{N} a_n e^{-j\theta_n} b_n \, x + w$$

Signal, power P_d

Noise, power σ^2

Achievable rate: $\log_2\left(1 + G\,\frac{P_d}{\sigma^2}\right)$

$$G = \left|\sum_{n=1}^{N} a_n e^{-j\theta_n} b_n\right|^2 = |\boldsymbol{\theta}^T(\boldsymbol{a} \odot \boldsymbol{b})|^2 \leq \|\boldsymbol{a} \odot \boldsymbol{b}\|_1^2$$

Element-wise product

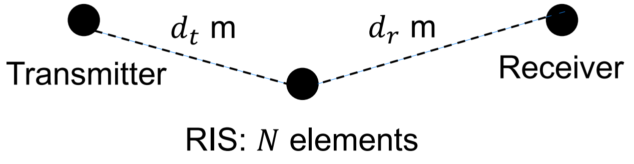
Upper bound achieved by $\theta_n = \arg(a_n b_n)$

Essential CSI

Phases in

cascaded channel $\boldsymbol{a} \odot \boldsymbol{b}$

End-to-End Channel Gain



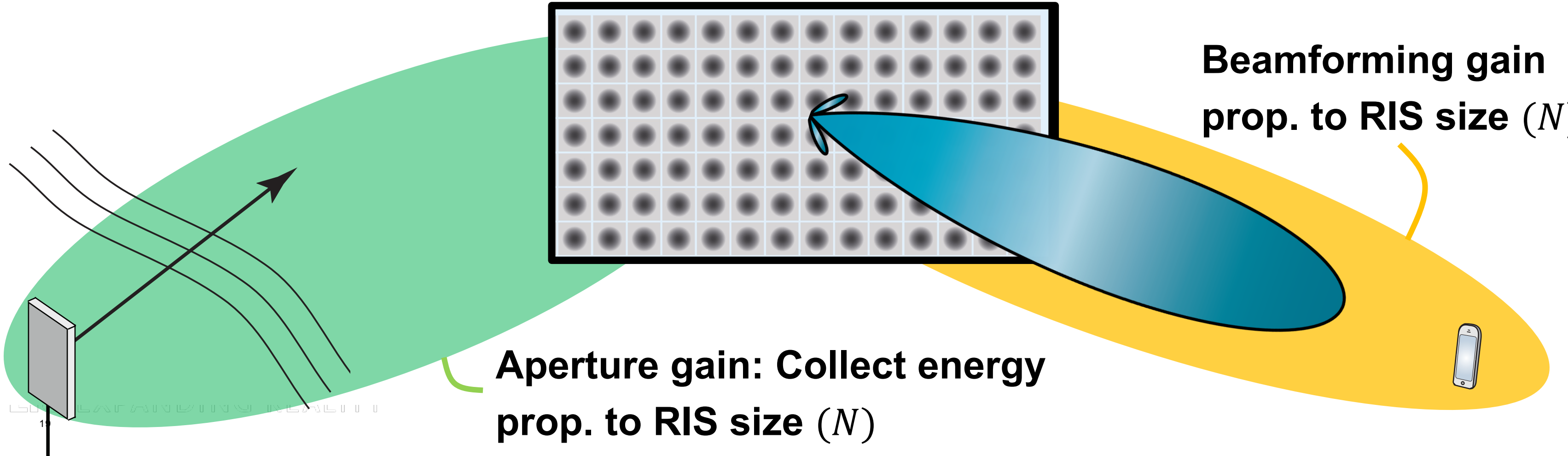
Line-of-sight channels (element area A):

- $|a_n|^2 = \frac{\lambda^2}{(4\pi d_t)^2} A, \quad |b_n|^2 = \frac{\lambda^2}{(4\pi d_r)^2} A$ for all n
- Optimized channel gain: $G = \|\boldsymbol{a} \odot \boldsymbol{b}\|_1^2 = N^2 |a_n|^2 |b_n|^2 = (NA)^2 \frac{\lambda^4}{(4\pi)^4 (d_t d_r)^2}$

"Squaring law"

N at the order of 100s?

Why is the SNR Proportional to N^2?



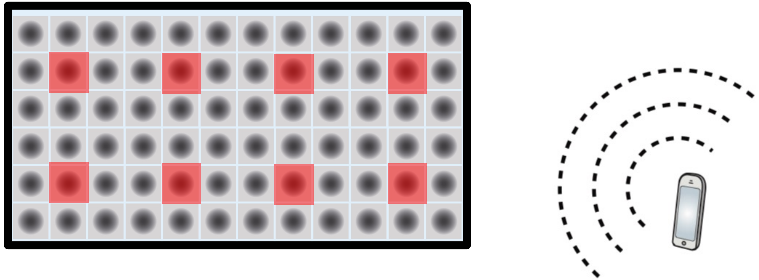
Two Approaches to RIS Channel Estimation

The RIS is blind!

~~**Approach 1: Have a fraction of active RIS elements**~~

~~Use multi-antenna estimation methods~~

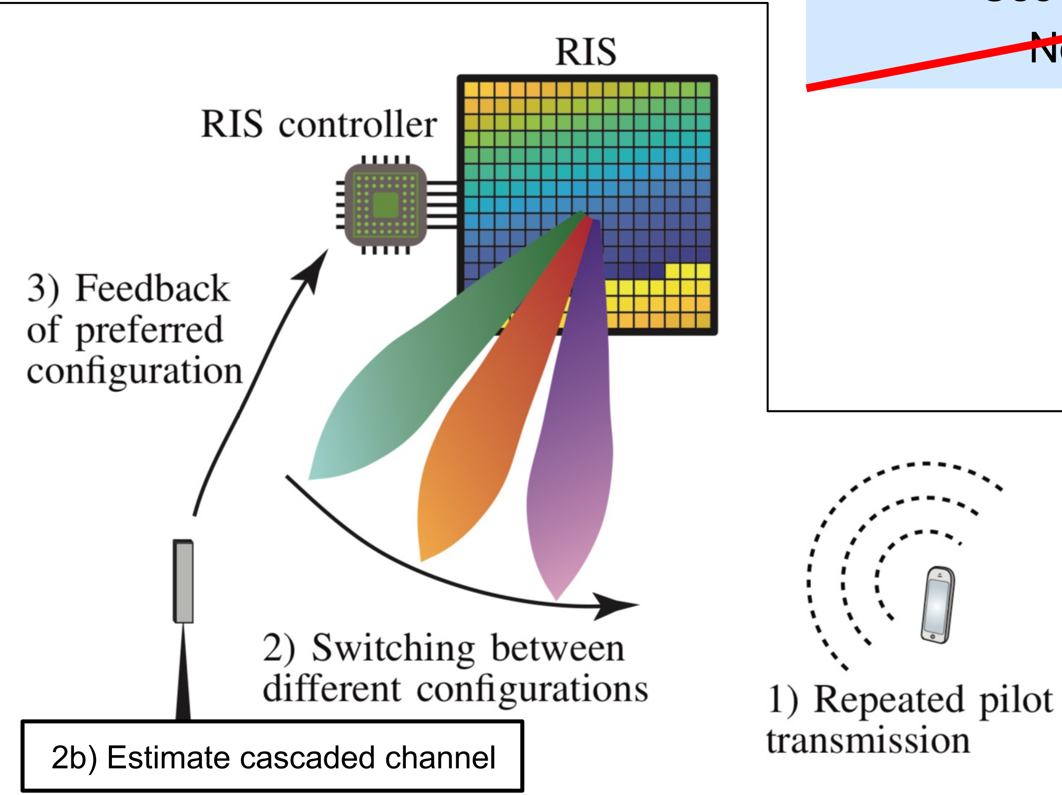
~~Not a “low-cost” surface anymore~~



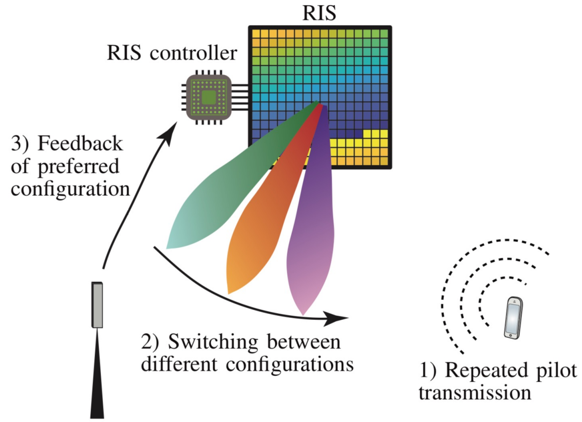
Approach 2: Codebook approach

Send pilots and switch configuration $\boldsymbol{\theta}$

Compute the preferred $\boldsymbol{\theta}$



Basic Codebook-Based Channel Estimation



Received signal: $y_l = \boldsymbol{\theta}_l^T (\boldsymbol{a} \odot \boldsymbol{b}) x_l + w_l$

Repeat a pilot signal L times: $x_l = \sqrt{P_p}, \; l = 1, \dots, L$

- Use different configurations: $[\boldsymbol{\theta}_1, \dots, \boldsymbol{\theta}_L] = \boldsymbol{B}^T \in \mathbb{C}^{N \times L}$

- Received signal: $$\underbrace{\begin{bmatrix} y_1 \\ \vdots \\ y_L \end{bmatrix}}_{\boldsymbol{y} \in \mathbb{C}^L} = \boldsymbol{B} \underbrace{(\boldsymbol{a} \odot \boldsymbol{b})}_{\boldsymbol{c} \in \mathbb{C}^N} \sqrt{P_p} + \underbrace{\begin{bmatrix} w_1 \\ \vdots \\ w_L \end{bmatrix}}_{\boldsymbol{w} \in \mathbb{C}^L} \longrightarrow \boldsymbol{y} = \boldsymbol{B}\boldsymbol{c}\sqrt{P_p} + \boldsymbol{w}$$

To be estimated

Problem: Estimate $\boldsymbol{c}$ from $\boldsymbol{y}$ with a small L

Classical *Maximum Likelihood Estimation*

Recall the received signal:

$$\underbrace{\begin{bmatrix} y_1 \\ \vdots \\ y_L \end{bmatrix}}_{\boldsymbol{y} \in \mathbb{C}^L} = \boldsymbol{B} \underbrace{(\boldsymbol{a} \odot \boldsymbol{b})}_{\boldsymbol{c} \in \mathbb{C}^N} \sqrt{P_p} + \underbrace{\begin{bmatrix} w_1 \\ \vdots \\ w_L \end{bmatrix}}_{\boldsymbol{w} \sim CN(\boldsymbol{0}, \sigma^2 \boldsymbol{I})}$$

Probability density function for a given $\boldsymbol{c}$:

$$f(\boldsymbol{y}; \boldsymbol{c}) = \frac{1}{(\pi\sigma^2)^L} e^{-\left\|\boldsymbol{y} - \boldsymbol{B}\boldsymbol{c}\sqrt{P_p}\right\|^2 / \sigma^2}$$

Maximum likelihood estimator (MLE)

$$\hat{\boldsymbol{c}} = \mathrm{argmax}_{\boldsymbol{c} \in \mathbb{C}^N} f(\boldsymbol{y}; \boldsymbol{c}) = \mathrm{argmin}_{\boldsymbol{c} \in \mathbb{C}^N} \left\|\boldsymbol{y} - \boldsymbol{B}\boldsymbol{c}\sqrt{P_p}\right\|^2 = \boldsymbol{B}^{\dagger} \boldsymbol{y} / \sqrt{P_p}$$

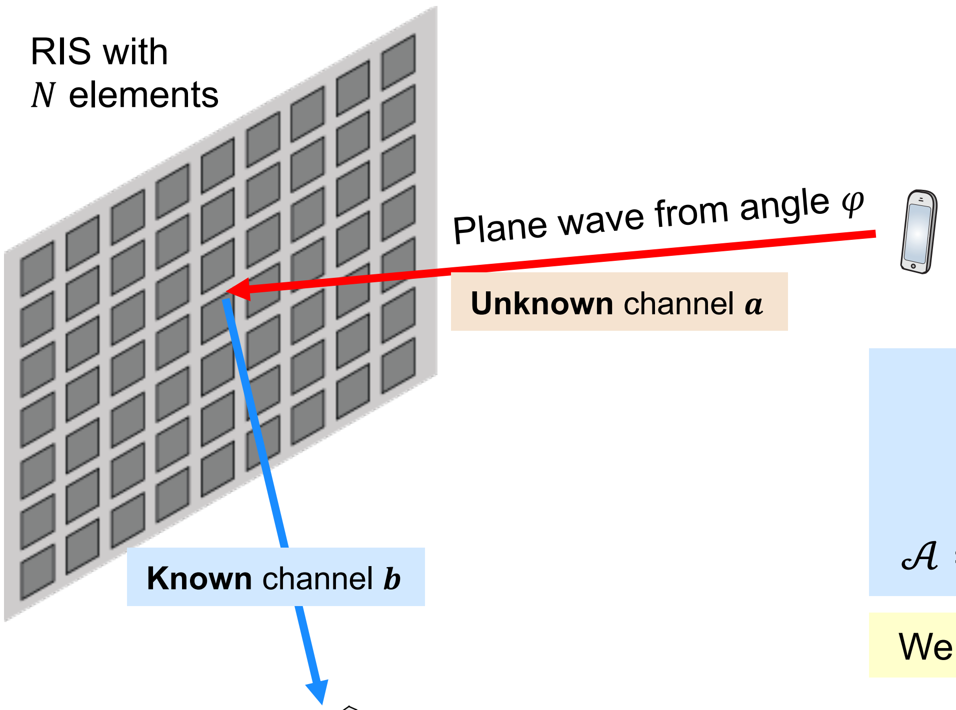
Pseudo-inverse

We will call it: **Least-squares (LS)** estimator

Only works well if $L \geq N$:
Requires ***many*** pilots

Can we reduce it?

Estimation of Parametrized LOS Channels



LOS channel vector

$$\boldsymbol{a} = \sqrt{\alpha} e^{j\omega} \boldsymbol{r}(\varphi)$$

Channel gain — Phase shift — Array response vector

Channel parametrization

$$\boldsymbol{a} \in \mathcal{A} \subset \mathbb{C}^N$$

$$\mathcal{A} = \left\{ \sqrt{\alpha} e^{j\omega} \boldsymbol{r}(\varphi) : \alpha \geq 0, \omega \in \mathbb{R}, \varphi \in \Phi \right\}$$

We should find the most likely channel in $\mathcal{A}$!

Received signal:

$$\boldsymbol{y} = \boldsymbol{B}(\boldsymbol{a} \odot \boldsymbol{b})\sqrt{P_p} + \boldsymbol{w} = \boldsymbol{B}\boldsymbol{D}_{\boldsymbol{b}}\boldsymbol{a}\sqrt{P_p} + \boldsymbol{w}$$

$\mathrm{diag}(b_1, \dots, b_N)$

Maximum Likelihood Estimator (MLE) for LOS Channels

Maximum likelihood estimate

$$\hat{\boldsymbol{a}} = \text{argmax}_{\boldsymbol{a}\in\mathcal{A}}\, f(\boldsymbol{y};\boldsymbol{a}) = \text{argmin}_{\boldsymbol{a}\in\mathcal{A}} \left\|\boldsymbol{y} - \boldsymbol{B}\boldsymbol{D}_{\boldsymbol{b}}\boldsymbol{a}\sqrt{P_p}\right\|^2$$

$$\mathcal{A} = \left\{\sqrt{\alpha}e^{j\omega}\boldsymbol{r}(\varphi): \alpha \geq 0, \omega \in \mathbb{R}, \varphi \in \Phi\right\}$$

Solution: $\hat{\boldsymbol{a}} = \sqrt{\hat{\alpha}}e^{j\hat{\omega}}\boldsymbol{r}(\hat{\varphi})$:

$$\hat{\varphi} = \text{argmax}_{\varphi\in\Phi} \frac{|\boldsymbol{y}^H\boldsymbol{B}\boldsymbol{D}_{\boldsymbol{b}}\boldsymbol{r}(\varphi)|^2}{\|\boldsymbol{B}\boldsymbol{D}_{\boldsymbol{b}}\boldsymbol{r}(\varphi)\|^2}$$

Solve by a numerical search

$$\hat{\alpha} = \frac{|\boldsymbol{y}^H\boldsymbol{B}\boldsymbol{D}_{\boldsymbol{b}}\boldsymbol{r}(\hat{\varphi})|^2}{P_p\|\boldsymbol{B}\boldsymbol{D}_{\boldsymbol{b}}\boldsymbol{r}(\hat{\varphi})\|^4} \quad \text{and} \quad \hat{\omega} = -\arg\left(\boldsymbol{y}^H\boldsymbol{B}\boldsymbol{D}_{\boldsymbol{b}}\boldsymbol{r}(\hat{\varphi})\right)$$

Achievable rate:

$$\log_2\left(1 + \left|\sum_{n=1}^{N} a_n e^{-j\theta_n} b_n\right|^2 \frac{P_d}{\sigma^2}\right)$$

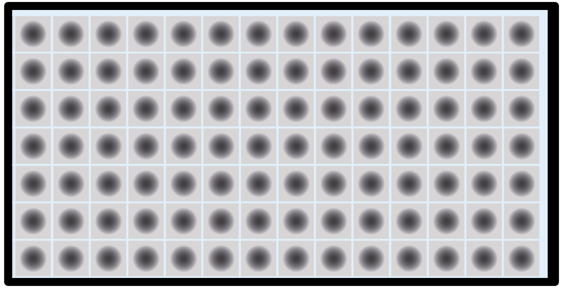
using $\theta_n = \arg(\hat{a}_n b_n)$

Useful with any array response vector

Can restrict angle interval, 1-2 angles, depth in near-field

Reference: M. Haghshenas, P. Ramezani, M. Magarini, E. Björnson, "Parametric Channel Estimation with Short Pilots in RIS-Assisted Near- and Far-Field Communications," IEEE TWC, 2024

Simulation of LOS Channel Estimation



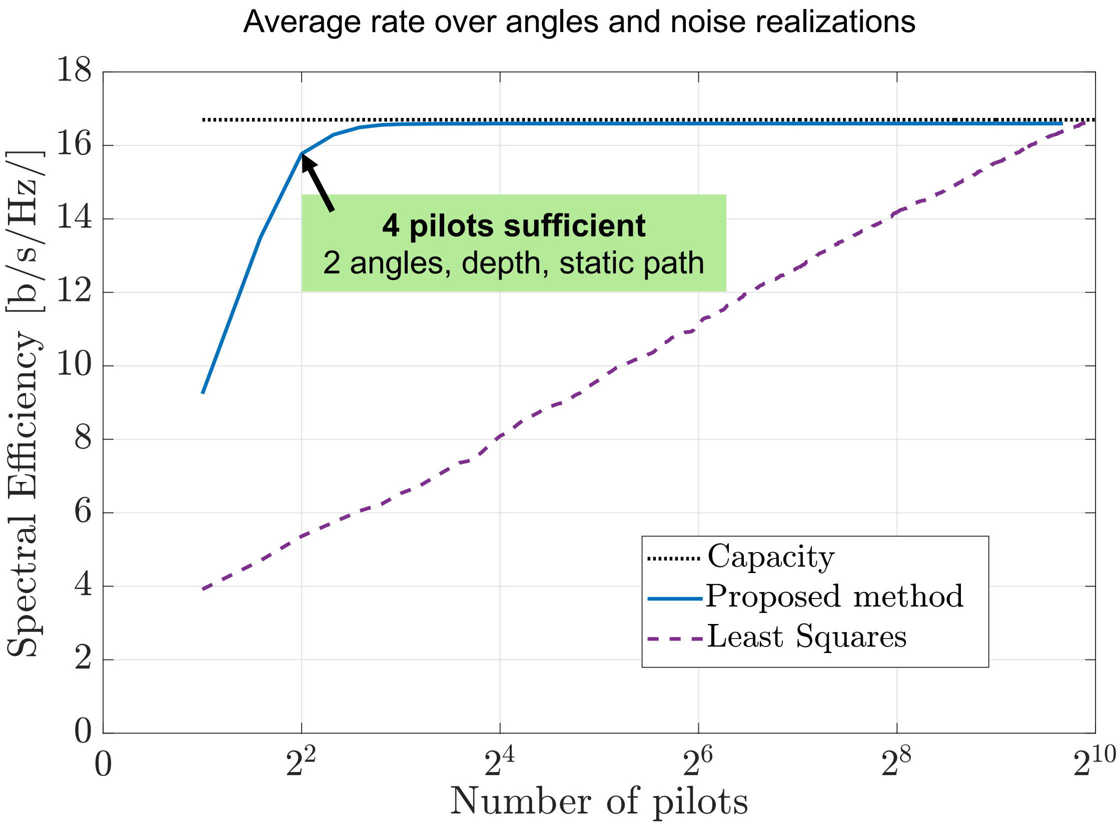
$N = 1024$ elements ($\lambda/2$ spacing)

Data SNR: $\frac{P_d}{\sigma^2}|a_n b_n|^2 = -10$ dB

10 times larger pilot SNR

Estimation

Pilot transmission with one configuration



Reference: M. Haghshenas, P. Ramezani, M. Magarini, E. Björnson, “Parametric Channel Estimation with Short Pilots in RIS-Assisted Near- and Far-Field Communications,” IEEE TWC, 2024

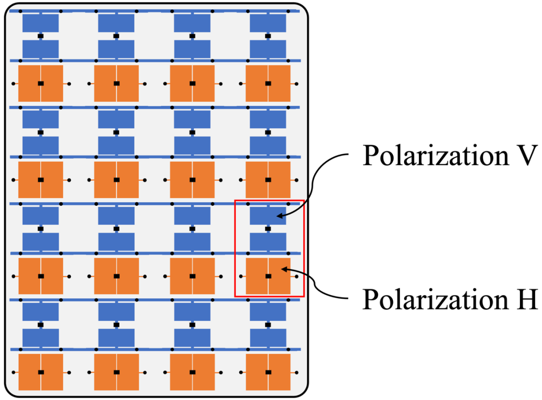
Another Example: Broad Beamforming

Method

DFT of received power in different angles (array factor)

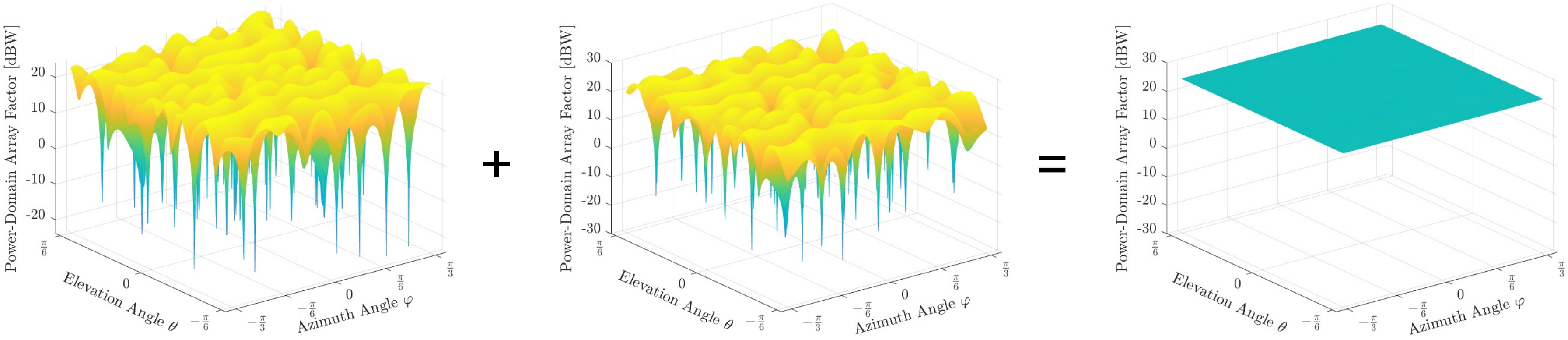
Find phase-shifts that make it flat (Golay sequences)

Dual-polarized RIS



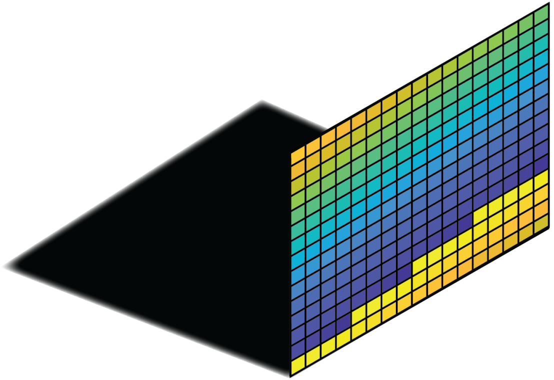
Horizontal polarization

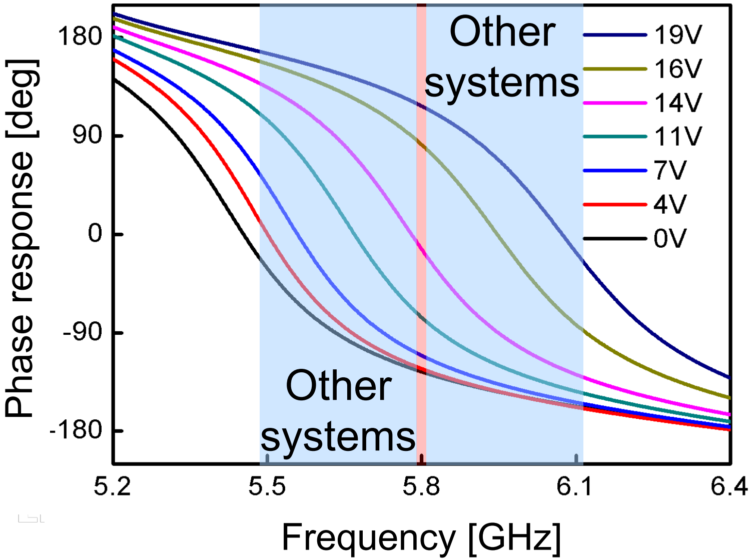
Vertical polarization



Reference: P. Ramezani, M. Girnyk, E. Björnson, "Broad Beam Reflection for RIS-Assisted MIMO Systems with Planar Arrays," Asilomar SSC, 2023.

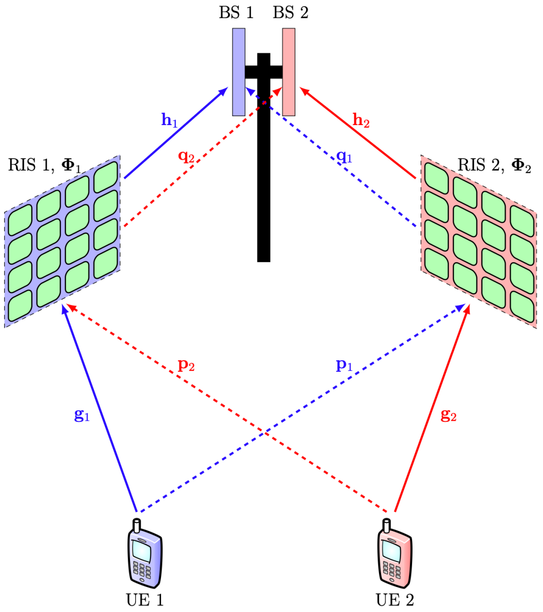
The Dark Side of RIS





Best case:
Increased small-scale fading

Worst case:
"Pilot contamination"



RIS is not a passband filter!
Modifies channels for neighboring systems

Reference: D. Gürgünoglu, E. Björnson, G. Fodor, "Combating Inter-Operator Pilot Contamination in Reconfigurable Intelligent Surfaces Assisted Multi-Operator Networks," arXiv:2311.01151

Conclusion:
Array Signal Processing Makes RIS Operation Efficient

Can we control a RIS in real-time?

- Yes, using geometry-based estimators
- Not for arbitrary models or data-driven

What is a *convincing* use case?

- Still unclear, telecom operators are exploring
- 3GPP studies smart repeaters

<u>Learn the basics:</u>

Chapter 9 of our book
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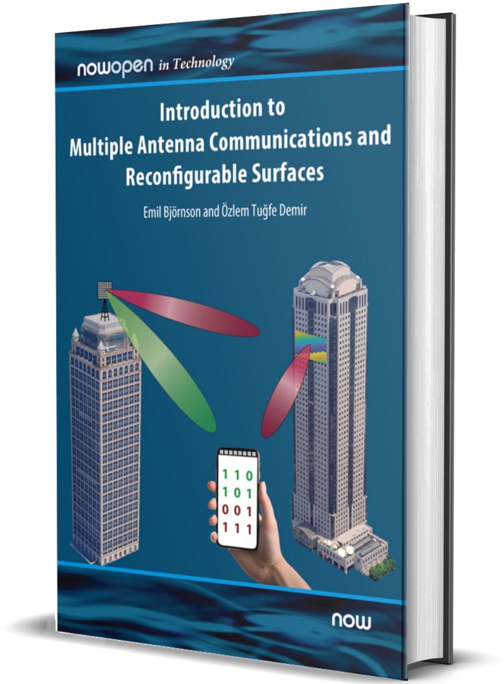
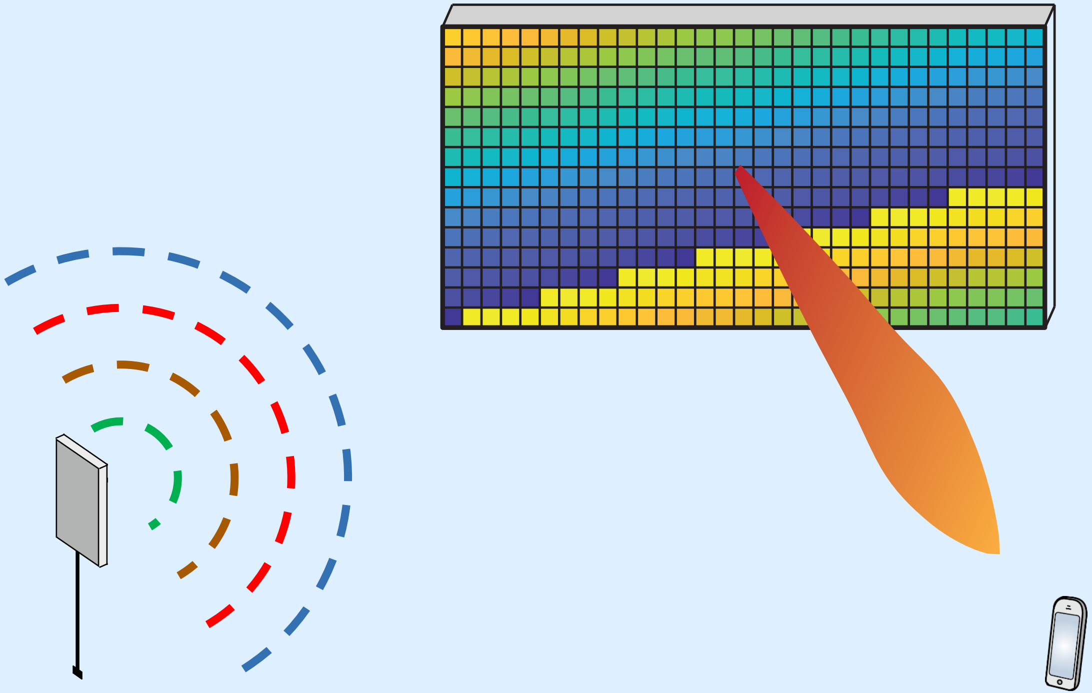


Reconfigurable Intelligent Surfaces

Through the Lens of Array Signal Processing



Keynote speech from

CAMSAP 2023 and **SITB 2024**