Reconfigurable intelligent surfaces: Myths and realities

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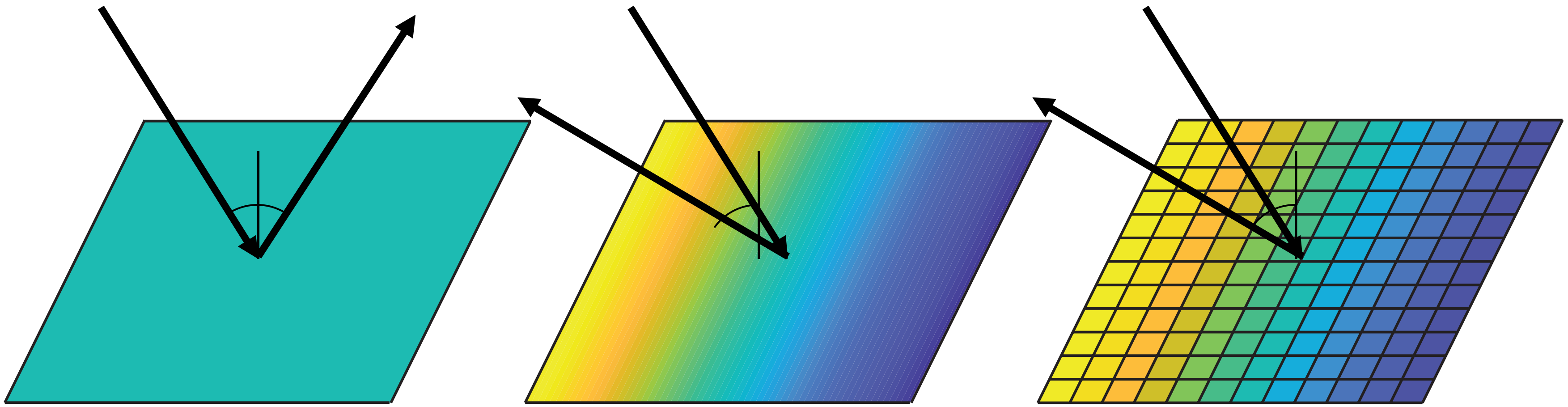
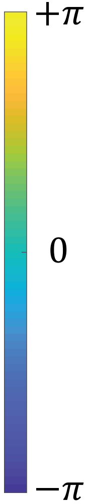
What is a Reconfigurable Intelligent Surface?





Metal plate

(Snell's law)

Ideal Metasurface

(Generalized Snell's law)

Practical Metasurface

(Discretization)

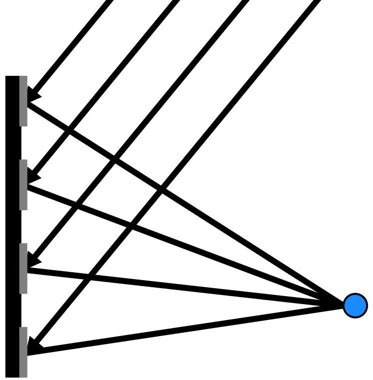
Constant surface impedance

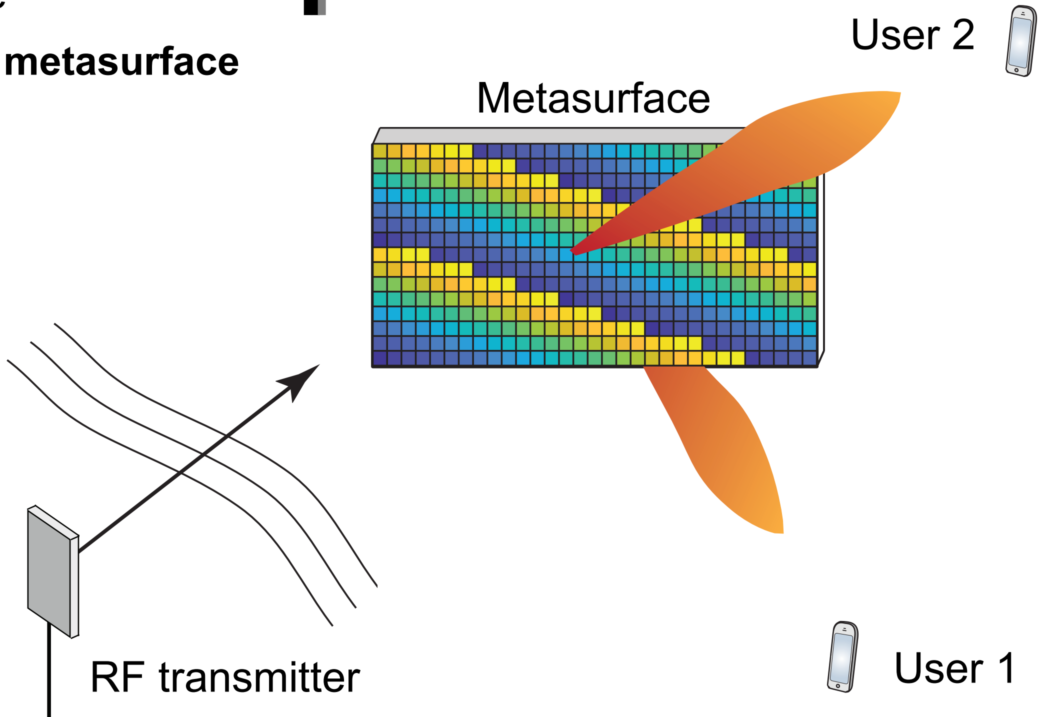
Altering surface impedance to phase-shift reflection

Approximation with discrete elements, e.g., $\frac{\lambda}{5} \times \frac{\lambda}{5}$

Evolution of the Concept

1. Fixed reflectarray (1960s)
2. Reconfigurable reflectarray/metasurface
3. Software-controlled metasurface
4. **Real-time software-controlled metasurface**





People Cannot Stop Making Up New Names…

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.

E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, “Wireless communications through **reconfigurable intelligent surfaces**,” *IEEE Access*, 2019.

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

Exciting Idea: Intelligent Propagation Environments

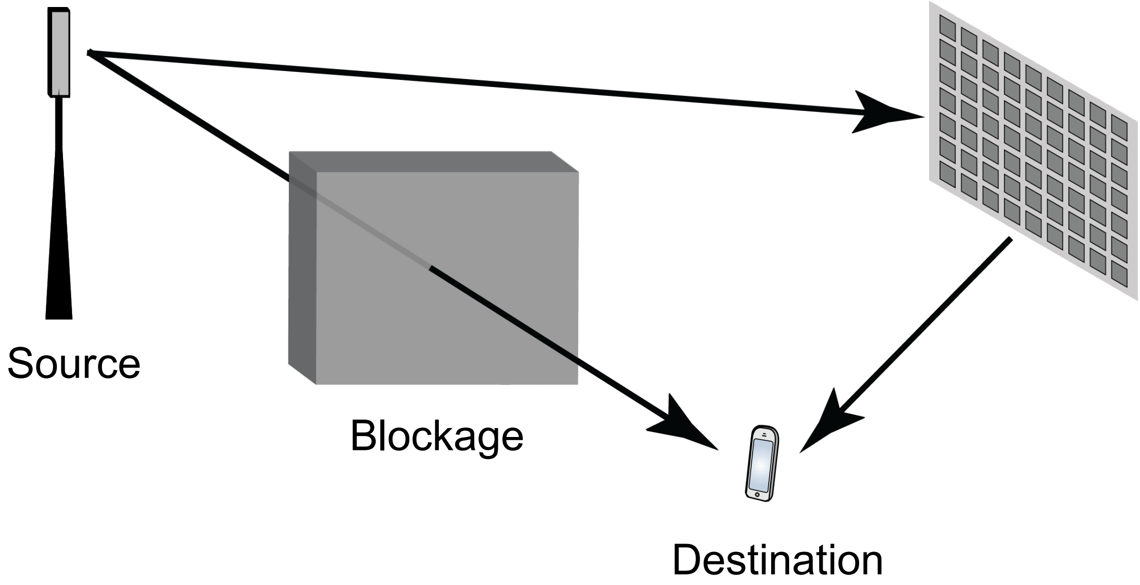
We conventionally control

1) Transmitter
2) Receiver

Now we can control the channel!

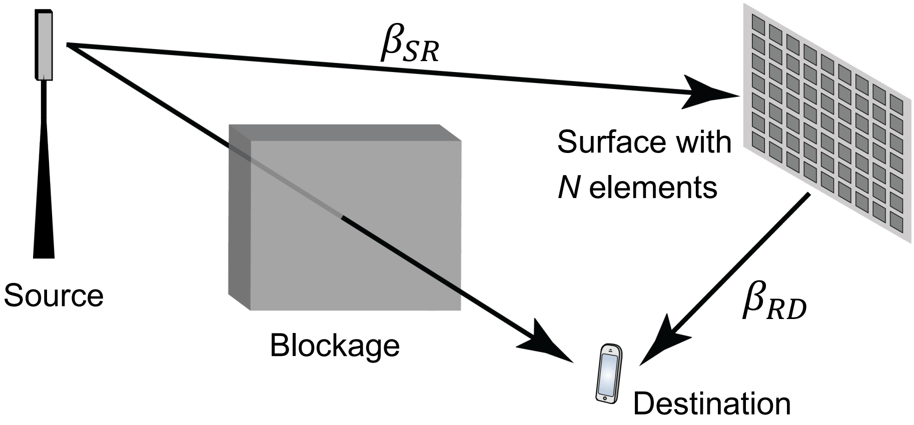
Is this a game changer?

Several myths exist!



Myth 1: The First Technology That can Control the Channel

Using intelligent reflecting surface (IRS)

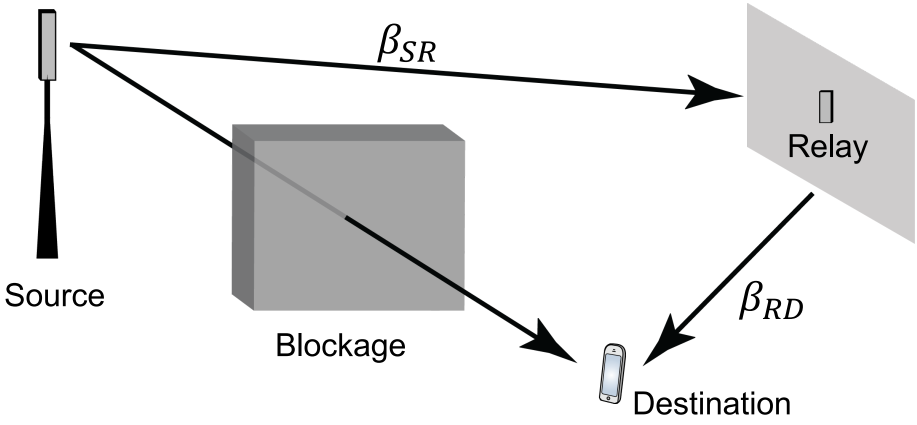


Spectral efficiency:

$$\log_2(1 + \rho N^2 \beta_{SR}\beta_{RD})$$

+ No pre-log penalty
– Multiplication of channel gains

Classical solution: Relay

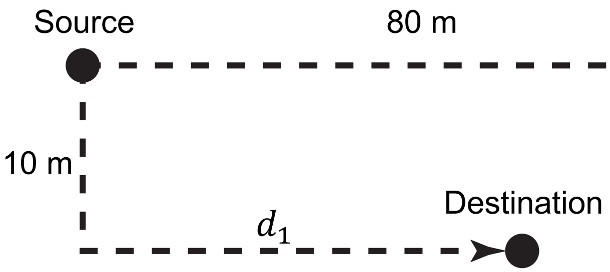


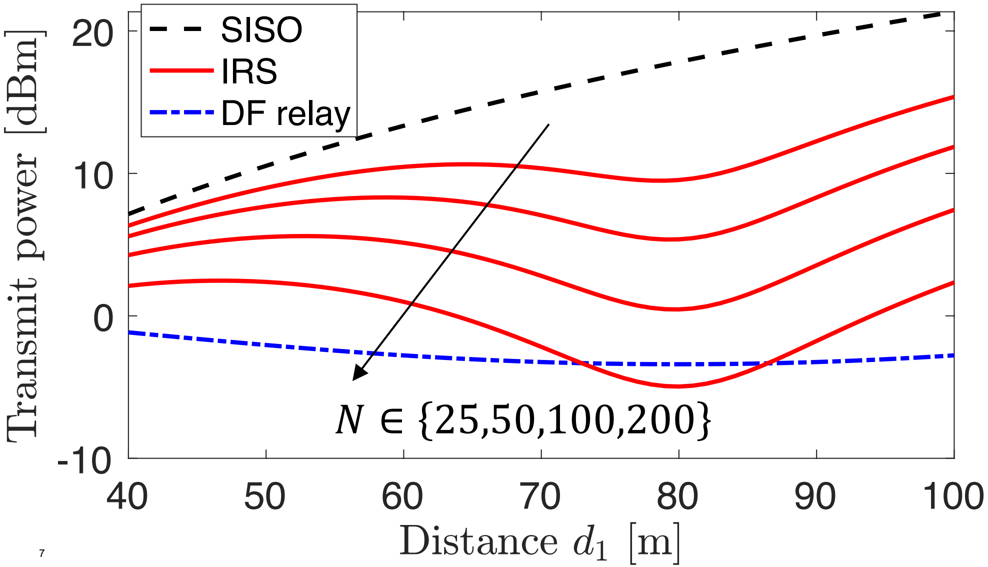
Spectral efficiency (decode-and-forward):

$$\frac{1}{2}\log_2(1 + \rho \min(\beta_{SR}, \beta_{RD}))$$

+ Signal amplification at relay
– Pre-log penalty: ½

A Large Surface is Needed to Beat Relays





Goal: Achieve 4 bit/s/Hz

Channel gain: 3GPP Urban Micro (NLOS direct path, LOS otherwise)

Bandwidth: 10 MHz

Metasurface

Outperforms SISO case

200 elements needed to beat relay

But fits into $1{\times}0.5\ \mathrm{m}^2$ at 3 GHz carrier

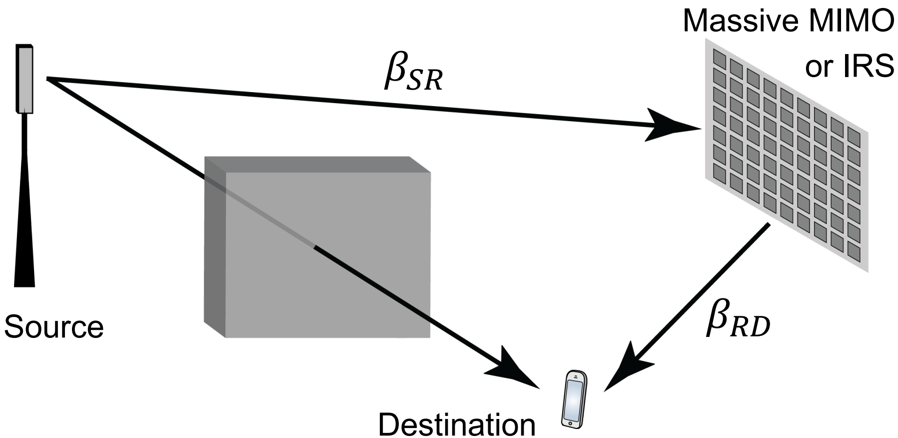
Reference: E. Björnson, Ö. Özdogan, E. G. Larsson, "Intelligent Reflecting Surface vs. Decode-and-Forward: How Large Surfaces Are Needed to Beat Relaying?," IEEE Wireless Commun. Letters, vol. 9, no. 2, pp. 244-248, February 2020.

Myth 2: Beamforming Gains are Better than in Massive MIMO

Spectral efficiency: $\log_2(1 + \rho N^2 \beta_{SR}\beta_{RD})$

Claim: Received power increases as N^2, thus it is better than Massive MIMO where it grows as N

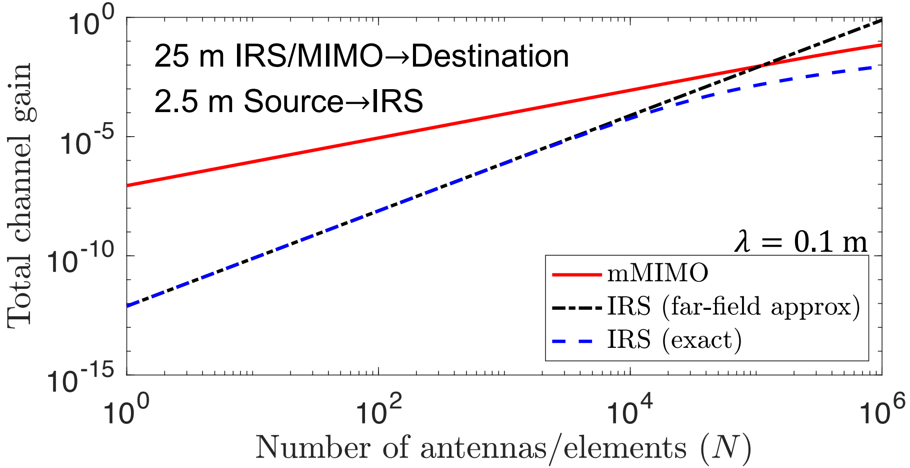
Reality: An IRS always has worse SNR. The gap reduces but remains as $N \to \infty$



$$\rho N^2 \beta_{SR}\beta_{RD} = \rho N \beta_{RD} \cdot N\beta_{SR}$$

SNR with Massive MIMO instead of IRS

Fraction of source's power that is reflected (≤ 1)

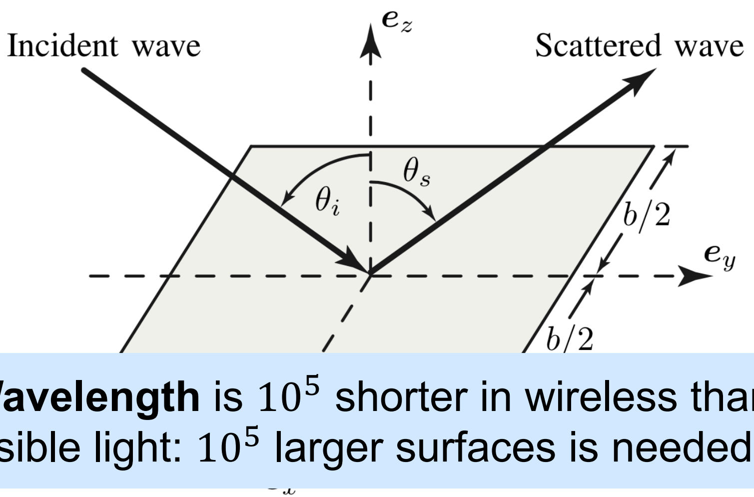


Reference: E. Björnson, L. Sanguinetti, "Power Scaling Laws and Near-Field Behaviors of Massive MIMO and Intelligent Reflecting Surfaces," arXiv:2002.04960.

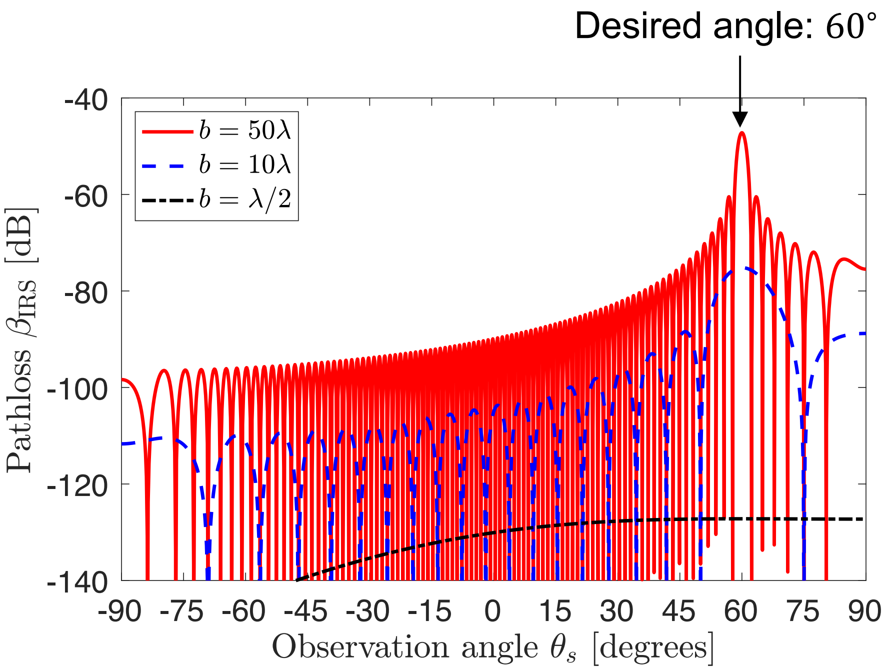
Myth 3: An IRS is a Specular Reflector (“Anomalous Mirror”)

Claim: A surface of size $10\lambda \times 10\lambda$ behaves as a specular reflector (plane wave in, plane wave out)

Reality: A plane wave is scattered with a main beam of $2\lambda/b$ radians. ($b = 10\lambda$ gives 36 degrees)

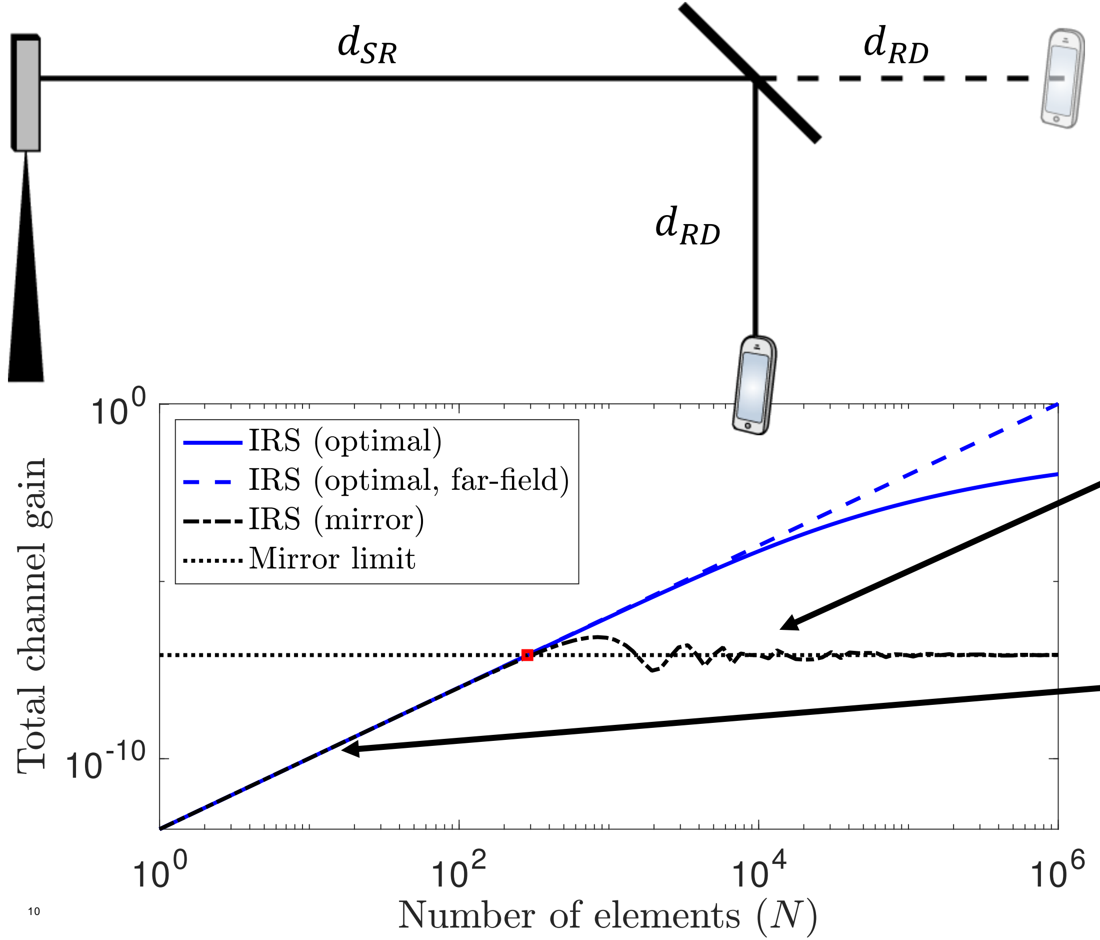


Wavelength is 10^5 shorter in wireless than in visible light: 10^5 larger surfaces is needed!



Reference: Ö. Özdogan, E. Björnson, E. G. Larsson, “Intelligent Reflecting Surfaces: Physics, Propagation, and Pathloss Modeling,” IEEE Wireless Commun. Letters, to appear.

Is it Anyway be Helpful to Interpret it as a Mirror?



Channel gain (Mirror limit)

$$\left(\frac{\lambda}{4\pi(d_{SR}+d_{RD})}\right)^2$$

Near-field

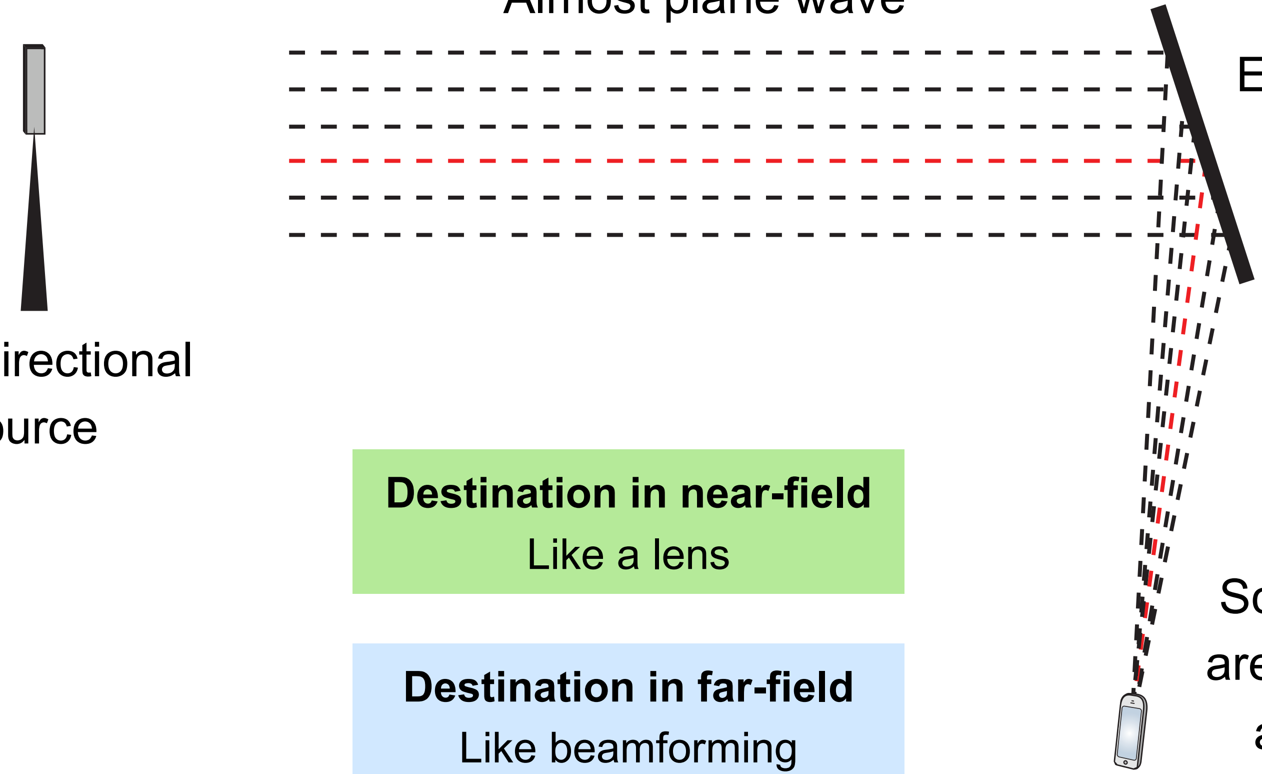
Can achieve the mirror limit, but it is grossly suboptimal

Far-field

Mimicking a mirror is optimal, but mirror limit is not reached

Reference: E. Björnson, L. Sanguinetti, "Power Scaling Laws and Near-Field Behaviors of Massive MIMO and Intelligent Reflecting Surfaces," arXiv:2002.04960.

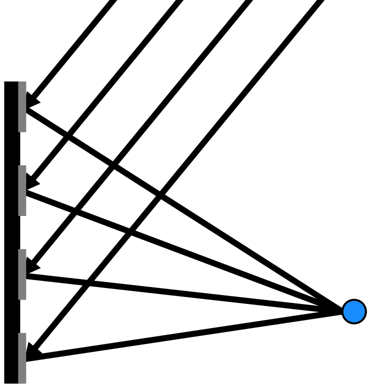
IRS is Not a Mirror But a Lens!



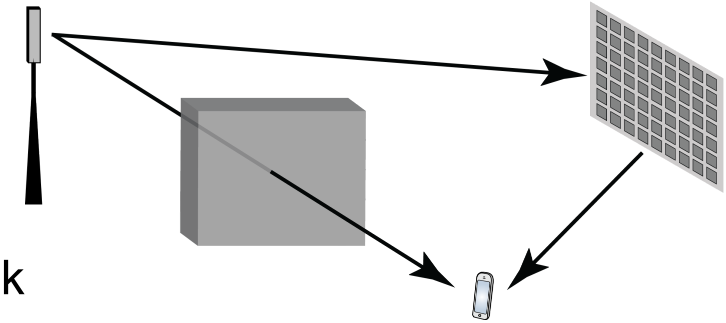
Destination in near-field
Like a lens

Destination in far-field
Like beamforming

Potential Use Cases and Open Problems



- **Lens-based array design**
  - Implement “hybrid” transceivers?
  - Holographic beamforming



- **Operation above 100 GHz**
  - Hard to build conventional arrays
  - Very sparse channels:
    Important to create new paths, even if weak

Open Problems:

Control interface
Channel estimation

Game-changing use case
10x improvement or more