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Opportunities and Challenges of IRS-based Wireless Communication systems

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Outline

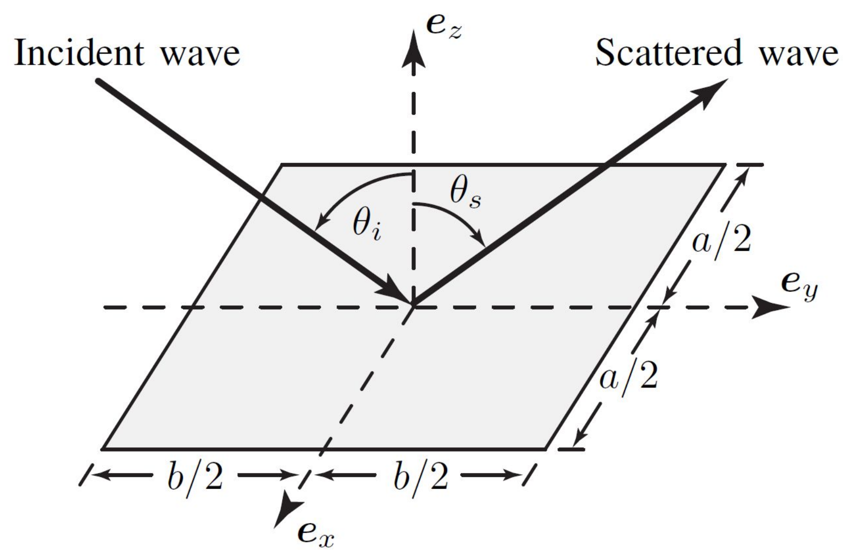
- Introduction of Intelligent Reflecting Surface (IRS)
  - Motivation
  - Hardware architecture
  - Reflection and channel models
  - Main functions and applications
  - Comparison with existing wireless technologies
- Communication Design Challenges
  - IRS reflection optimization
  - IRS channel estimation
  - IRS deployment
- Other Applications/Extensions

Have We Reached Shannon's Capacity Limit?

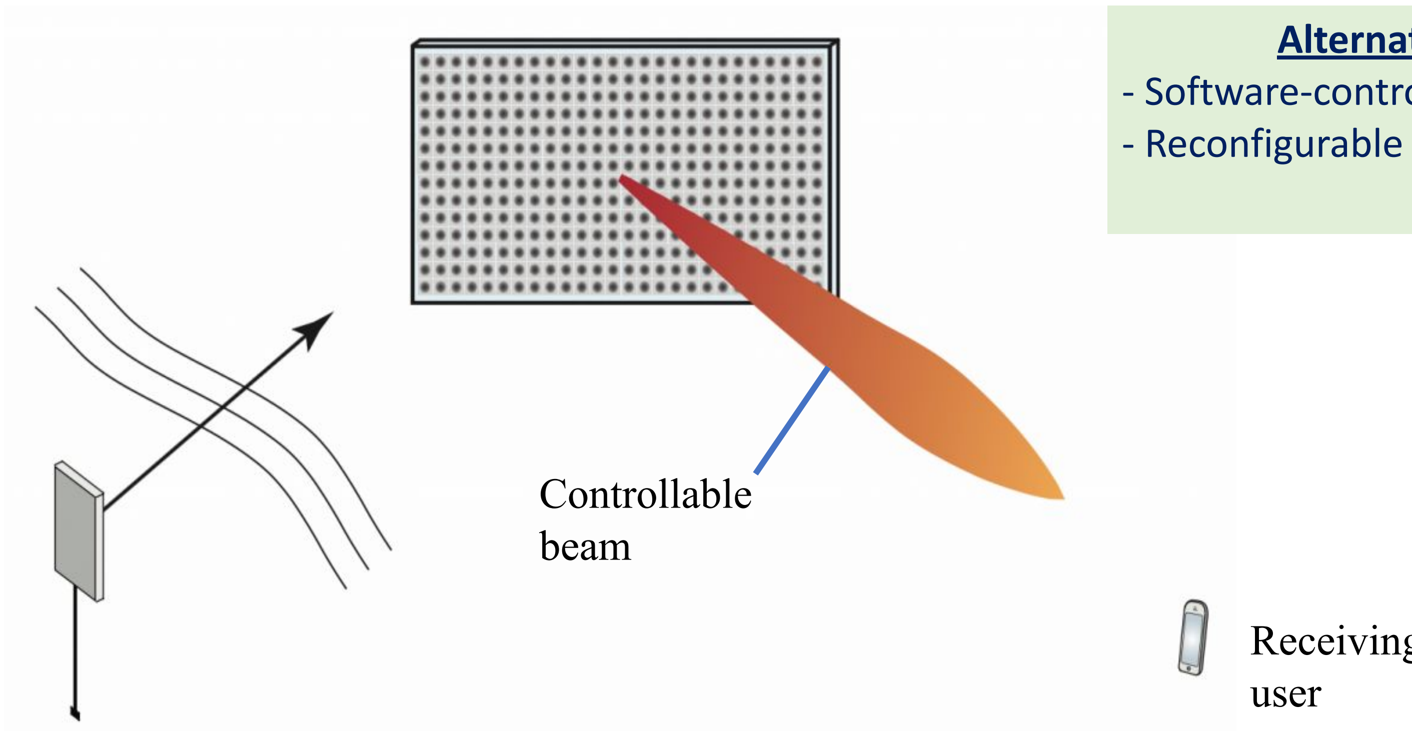
$$C = \log\left(1 + \frac{HP}{\sigma^2}\right)$$

- ❑ Yes, also No (as wireless channel *H* is still random and uncontrolled)
  - ✓ Can we make *H* arbitrarily large, say from H<<1 to H→1?
  - ✓ Can we make *H* less random, e.g., from Rayleigh fading to Rician fading?
  - ✓ Existing wireless technologies (beamforming, power control, adaptive modulation, etc.) only adapt to *H*, but have no control over it
  - ✓ How to break this ultimate barrier to achieving ultra-high capacity and ultra-high reliability in future wireless communications (e.g., 6G)?
- ❑ Promising new paradigm: Smart and Reconfigurable Wireless Environment
- ❑ Key enabling technology: Intelligent Reflecting Surface (IRS)
  - ➢ Other nomenclature: reconfigurable intelligent surface (RIS), software controlled metasurface, passive intelligent mirror, smart reflect array, ….

What is a Reflecting Surface?

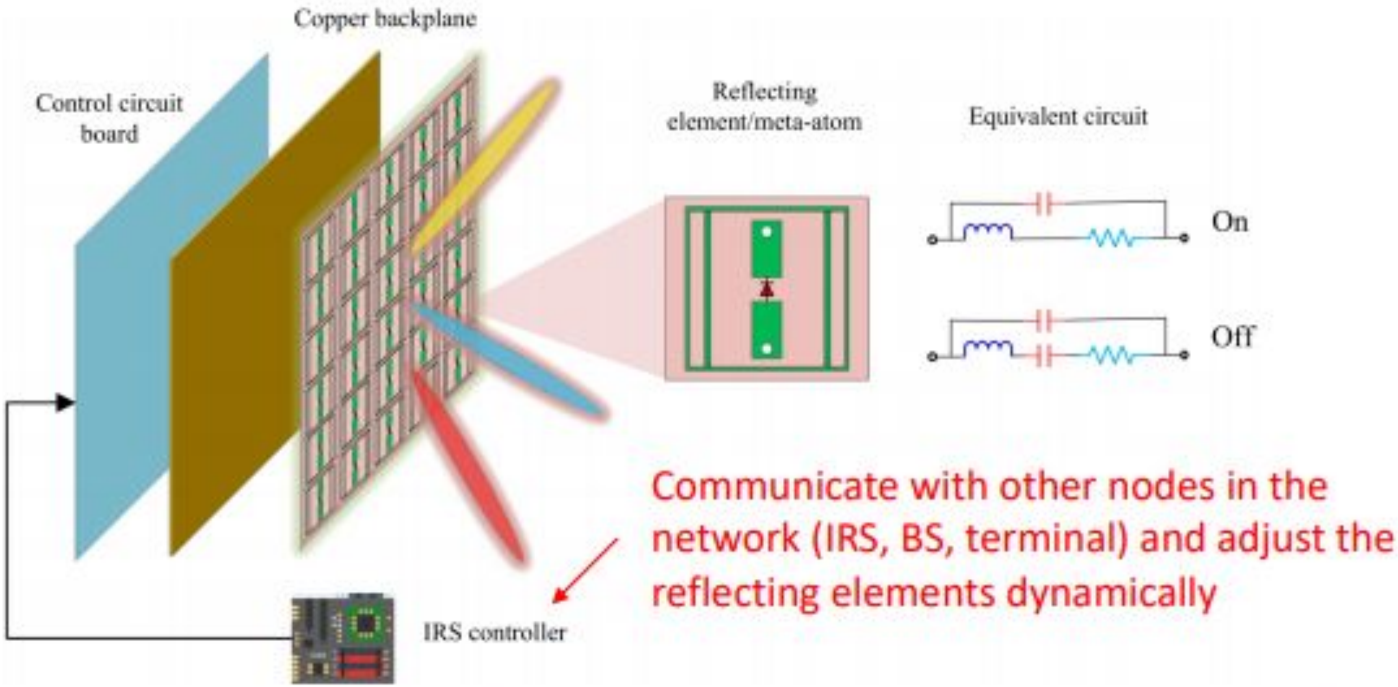


Intelligent Reflecting Surface (IRS)



RF
transmitter

Alternative names
- Software-controlled metasurface
- Reconfigurable intelligent surface



- A digitally-controlled metasurface with massive low-cost passive reflecting elements (each able to induce an amplitude/phase change in the incident signal)
- Low energy consumption (without the use of any transmit RF chains), high spectral efficiency (full-duplex, noiseless reflection)

IRS: Reflection Model

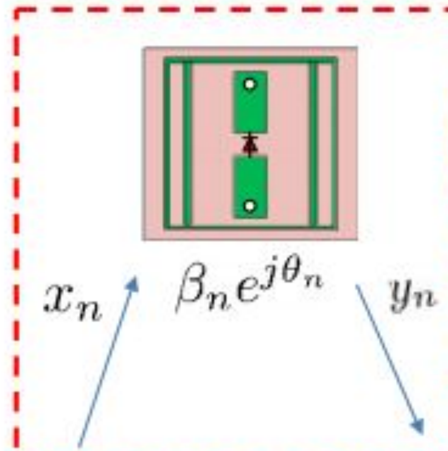
- Baseband equivalent signal model at each IRS element

$$y_n = \beta_n e^{j\theta_n} x_n, \quad n = 1, \ldots, N$$

where $\beta_n \in [0,1]$: reflection amplitude

$\theta_n \in [0, 2\pi)$: phase shift

N : No. of elements



$\beta_n = 0$:	Absorption
$\beta_n = 1$:	Full reflection

- In practice, both amplitude and phase shift need to be discretized

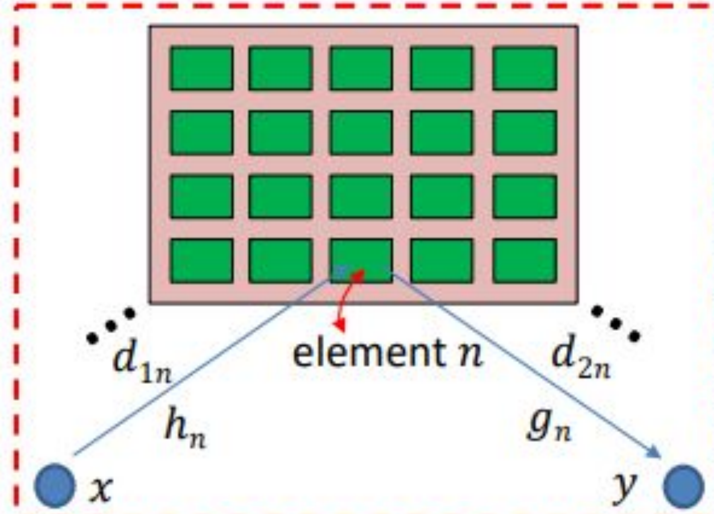
IRS: Channel Model

- Baseband equivalent channel model (narrow-band)
  - ✓ Assume isotropic reflection, and no mutual coupling among reflecting elements

$$y = \left(\sum_{n=1}^{N} h_n g_n \beta_n e^{j\theta_n} \right) x + z$$

$h_n g_n$ → complex channel coefficients

$\beta_n e^{j\theta_n}$ → complex reflection coefficient



- x: transmitted signal
- y: received signal
- h_n: first link channel
- g_n: second link channel

- Product-distance path loss model

$$|h_n|^2 \propto c_1 d_{1n}^{-\alpha_1}$$

$$|g_n|^2 \propto c_2 d_{2n}^{-\alpha_2}$$

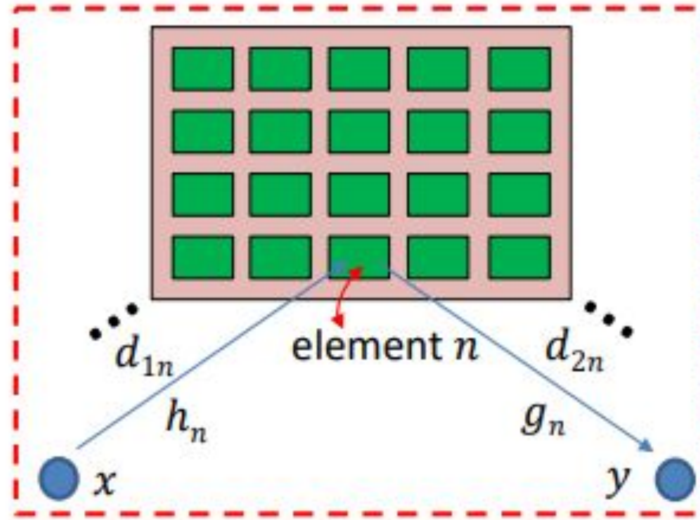
- Extendible to wide-band channel, with IRS frequency-flat reflection only

IRS Path Loss Model: Product Distance or Sum Distance?

- **Product-distance path loss** model

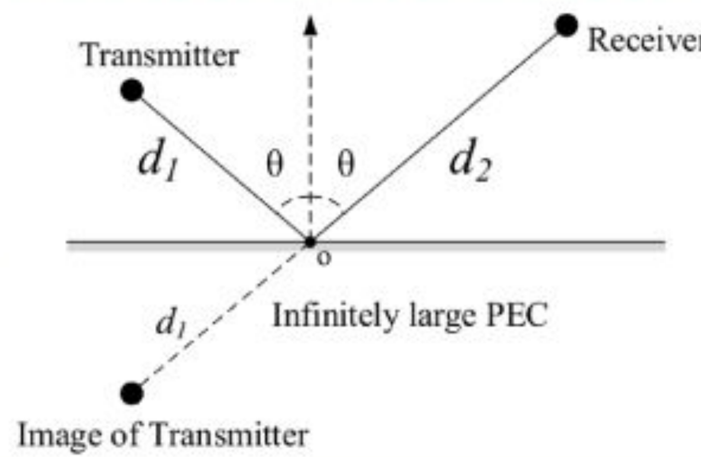
$$|h_n|^2 \propto c_1 d_{1n}^{-\alpha_1}$$

$$|g_n|^2 \propto c_2 d_{2n}^{-\alpha_2}$$



- **Sum-distance path loss** model

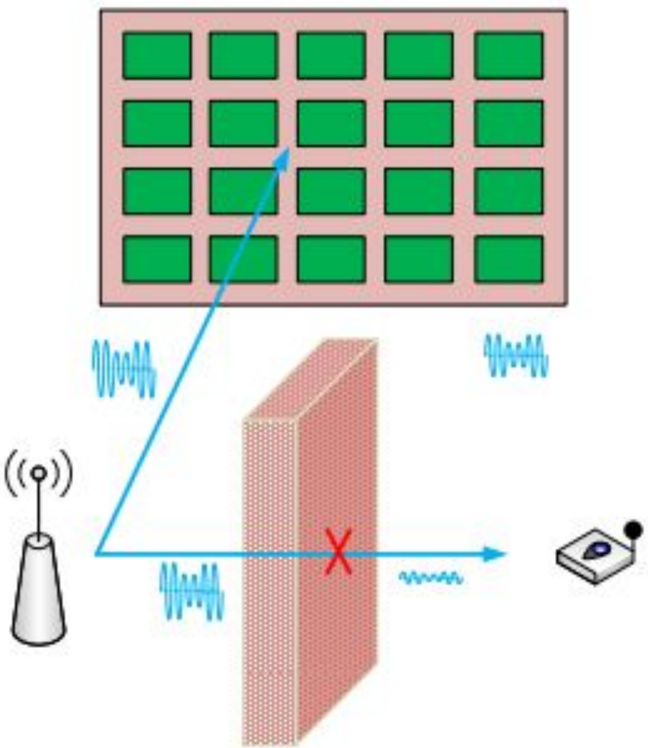
$$P_r \propto \frac{1}{(d_1 + d_2)^2}$$



✓ Applies to free-space propagation and infinitely large perfect electric conductor (PEC) only

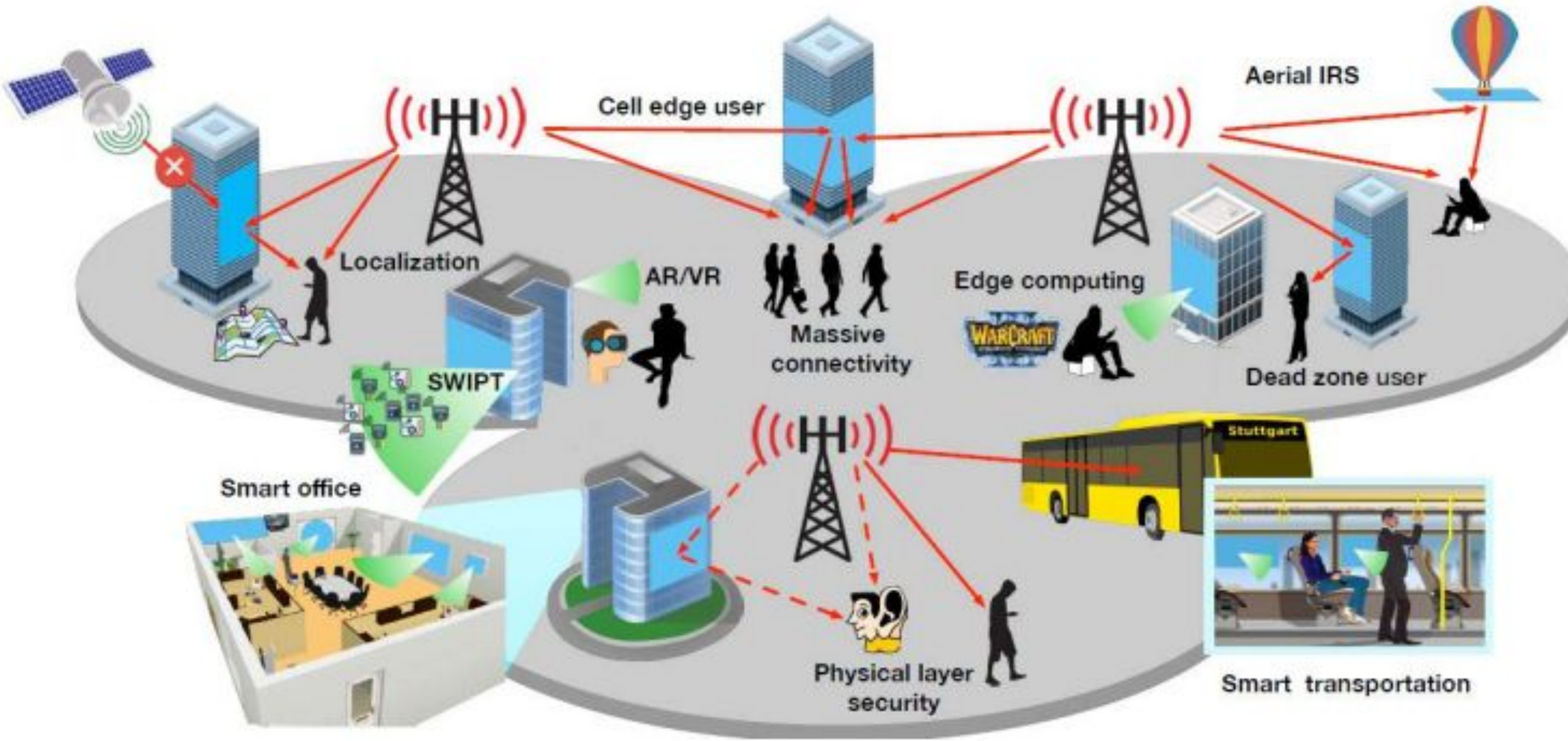
✓ Not applicable to IRS with finite-size elements

IRS for Channel Reconfiguration

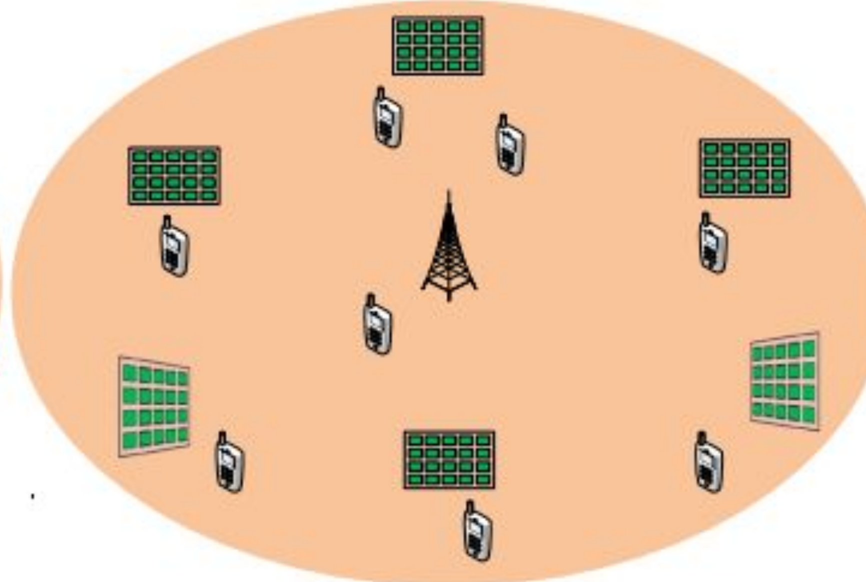


- Create virtual LoS link by smart reflection to bypass obstacle
  - Coverage extension for mmWave
- Add extra signal path toward desired direction
  - Improve channel rank and thus spatial multiplexing gain
- Refine channel statistics/distribution
  - Transform Rayleigh/fast fading to Rician/slow fading for ultra-high reliability

IRS Applications for 5G/6G



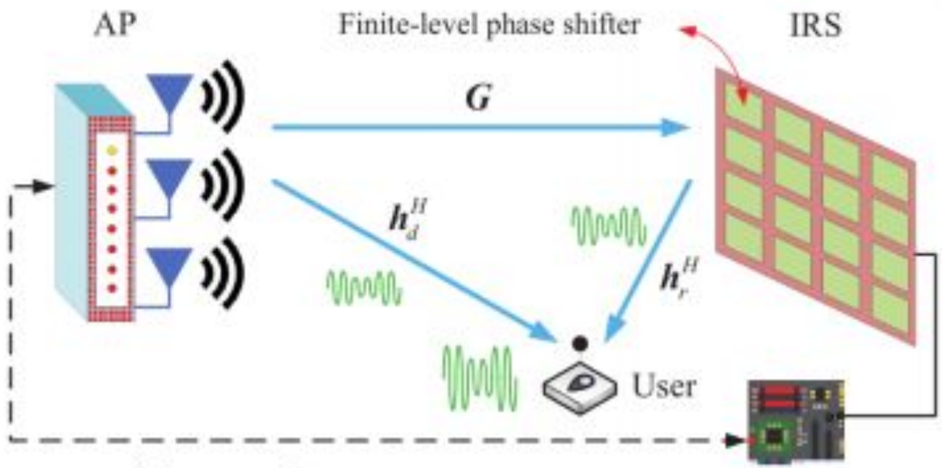
IRS vs Active Relay/Small Cell/DAS/Cell-free MIMO



- Network with active BS/AP/relay only
- High cost, high energy consumption
- Backhaul issue
- Complicated interference management
- Low spectral efficiency due to half duplex (full-duplex radio needs costly self-interference cancelation)

- Hybrid active-passive network: fewer BSs with many passive IRSs
- Low cost, low energy consumption
- Low-rate wireless backhaul suffices (for control link only)
- Local coverage only without the need of inter-IRS interference management
- Full duplex without self-interference

Joint Active and Passive Beamforming: Single-user Case



- AP: active (transmit) beamforming
- IRS: passive (reflect) beamforming with maximum reflection amplitude ($\beta_n = 1$)
- Objective: maximize the received signal power via joint transmit and reflect beamforming optimization
- Establish a local "signal hotspot" in the vicinity of IRS
- Received SNR scaling order: ***$O(N^2)$***
  - Thanks to the dual role of "receive" and "reflect" (full-duplex, noise-free), in contrast to *O(N)* of massive MIMO (limited by sum-power constraint at Tx), and *O(N)* of MIMO AF relay (due to relay noise)
  - Hold even for practical IRS with discrete phase shifts

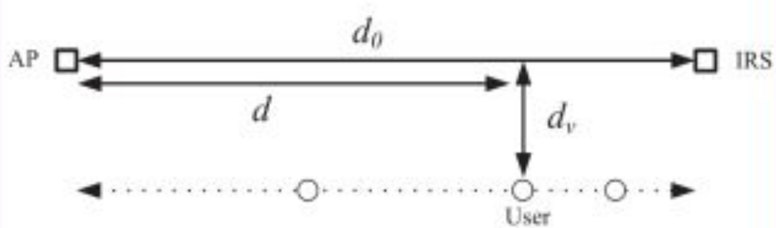
Minimum AP transmit Power vs AP-user Distance

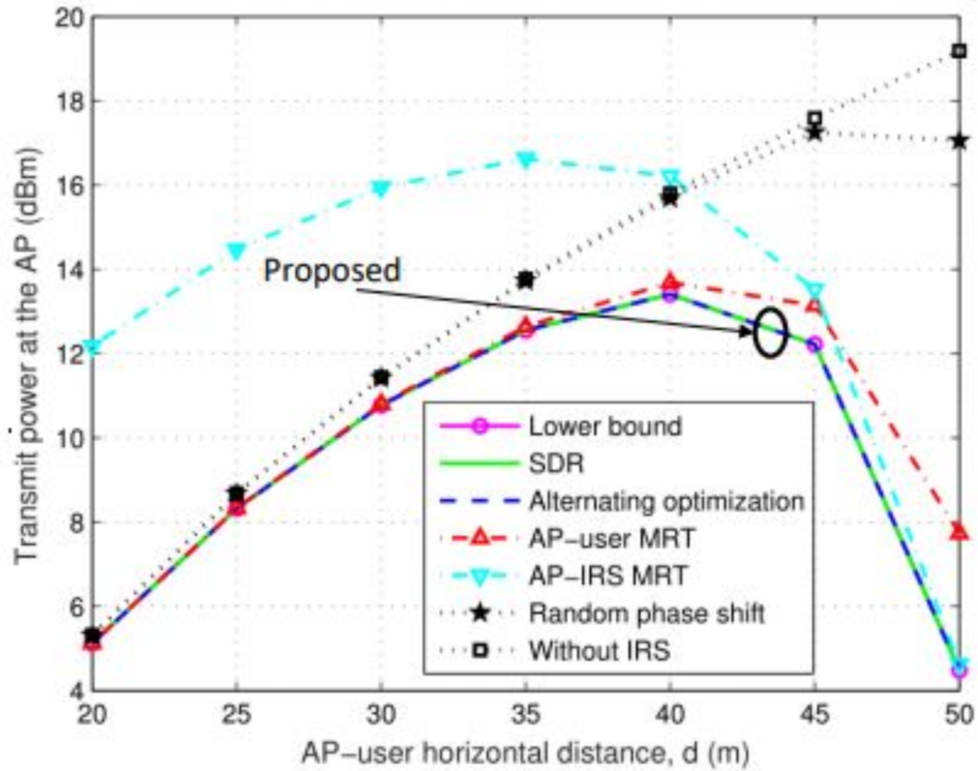
- ❑ Transmit beamforming: $\boldsymbol{w}$
- ❑ Reflect beamforming: $\boldsymbol{\Theta}$

Problem formulation (suboptimal solutions obtained via SDR or alternating optimization)

$$\begin{aligned} \min_{\boldsymbol{w},\boldsymbol{\theta}} \quad & \|\boldsymbol{w}\|^2 \\ \text{s.t.} \quad & |(\boldsymbol{h}_r^H \boldsymbol{\Theta} \boldsymbol{G} + \boldsymbol{h}_d^H)\boldsymbol{w}|^2 \geq \gamma\sigma^2, \\ & 0 \leq \theta_n \leq 2\pi, \forall n = 1, \cdots, N. \end{aligned}$$

Simulation setup

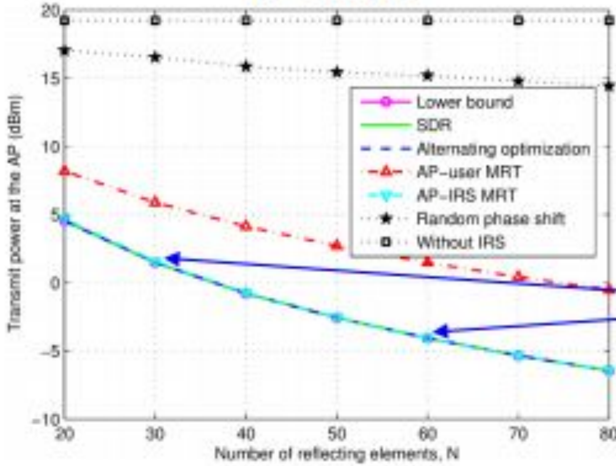




- ❑ Significant power saving with IRS (vs w/o IRS)
- ❑ Performance gain of joint transmit and reflect beamforming design (vs AP-user MRT or AP-IRS MRT benchmarks)

Minimum AP transmit Power vs No. of IRS Elements (1)

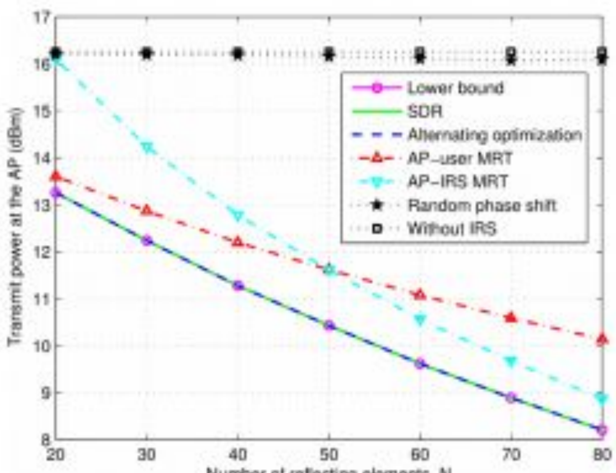
d = 50 m



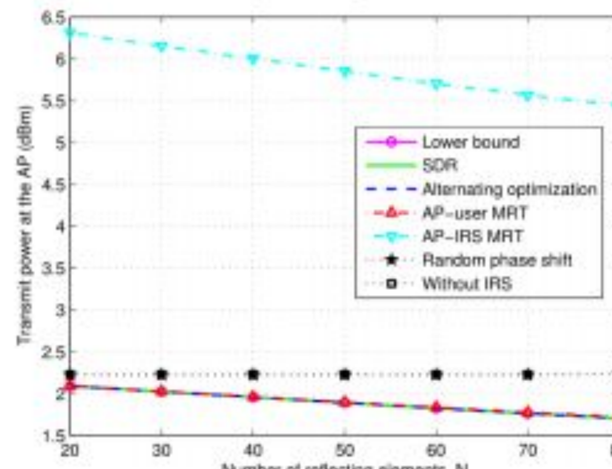
- ❑ SNR scaling law $O(N^2)$ for sufficiently large *N,* near IRS

Increasing *N* from 30 to 60 results in 6 dB power gain/saving

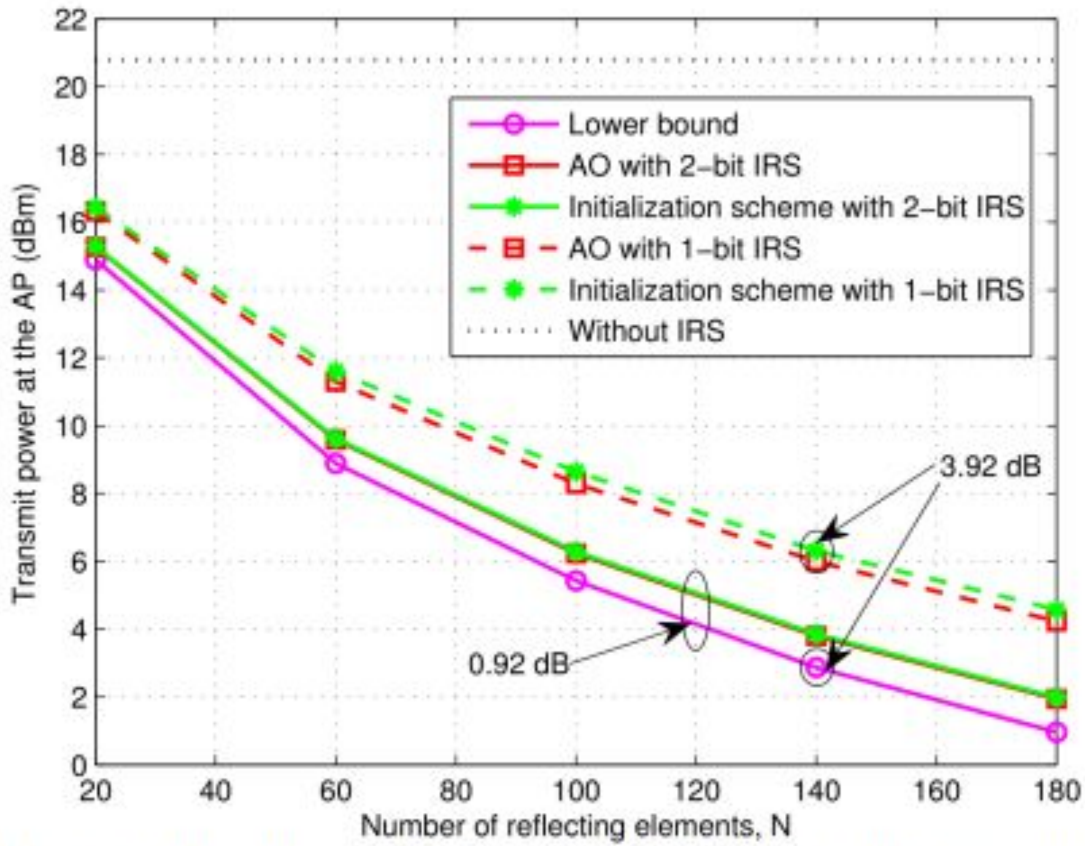
d = 41 m



d = 15 m



Minimum AP transmit Power vs No. of IRS Elements (2)



- Finite number of levels of phase-shift: 2^b
  - b: No. of phase-control bits

- Power loss of using b phase-control bits

$$\eta(b) \triangleq \frac{P_r(b)}{P_r(\infty)} = \left(\frac{2^b}{\pi}\sin\left(\frac{\pi}{2^b}\right)\right)^2$$

- Suboptimal solution obtained via uniformly quantizing the continuous-phase solution
- SNR scaling law, i.e., $O(N^2)$, still holds with finite-level phase shifters
- IRS with 1-bit (2-bit) phase-shifters suffers a power loss of 3.9 dB (0.9 dB)

Promising Directions for Future Work

- ❑ IRS hardware design/prototype
- ❑ IRS reflection/channel modeling
- ❑ IRS reflection optimization for more general setups (e.g., with partial/imperfect CSI, under hardware imperfections) and other applications (spatial modulation, localization, etc.)
- ❑ Capacity and performance analysis of IRS-aided system/network
- ❑ Practical IRS channel estimation and low-complexity passive beamforming designs
- ❑ IRS deployment/association/multiple access in multi-cell network
- ❑ IRS meets massive MIMO, mmWave/THz, energy harvesting, UAV, security, wireless power transfer, etc.
- ❑ IRS integration to WiFi/Cellular
- ❑ ……

Thanks for your listening