Faster, Smarter, Greener: Intelligent Reflecting Surface for 6G Communications

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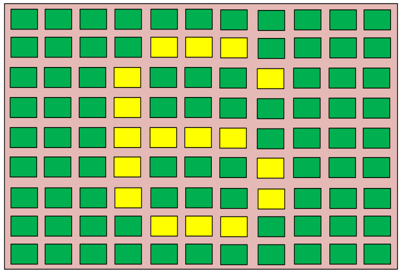

FASTER, SMARTER, GREENER

Oct. 13, 2020

Outline

- Part 1: Introduction of Intelligent Reflecting Surface (IRS)
  - Motivation
  - Hardware architecture
  - Reflection and channel models
  - Applications and industry initiatives
  - Comparison with existing technologies
- Part 2: Major Challenges
  - IRS reflection optimization
  - IRS channel estimation
  - IRS deployment
- Part 3: Conclusions and Future Work Directions

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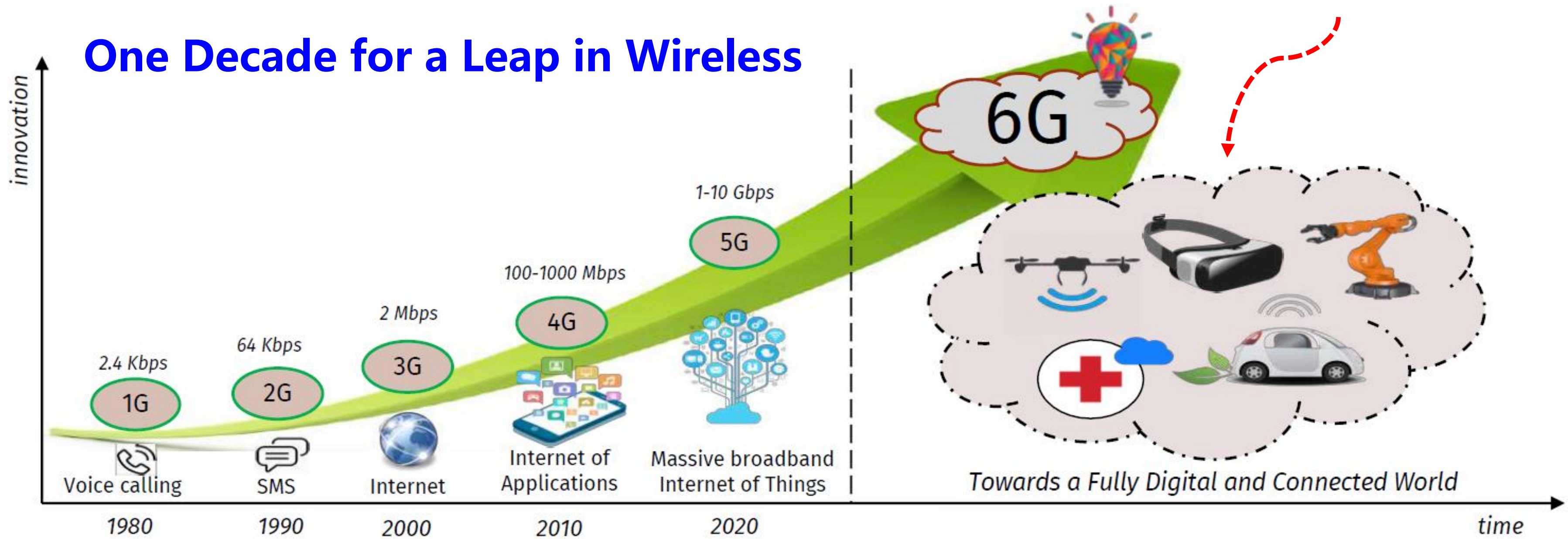
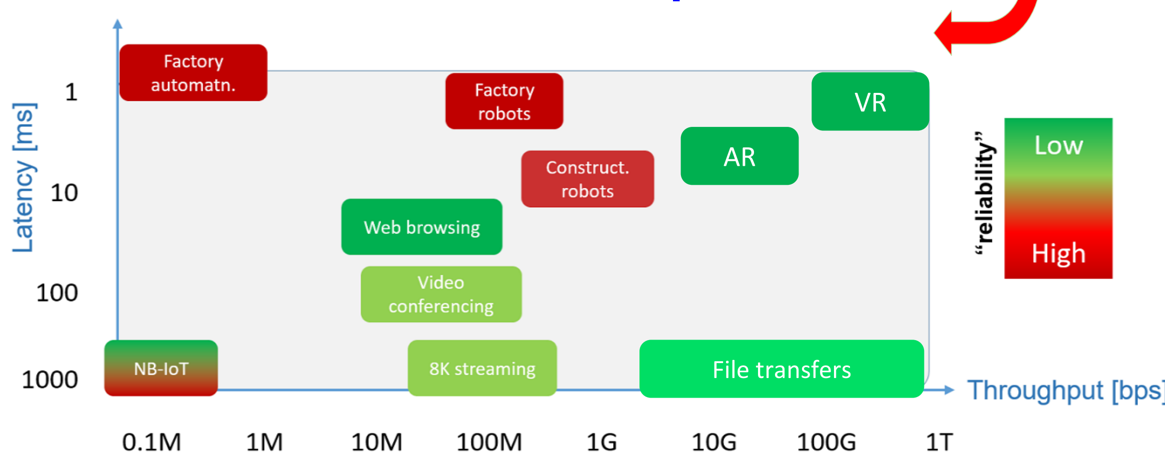
Why 6G?

One Decade for a Leap in Wireless

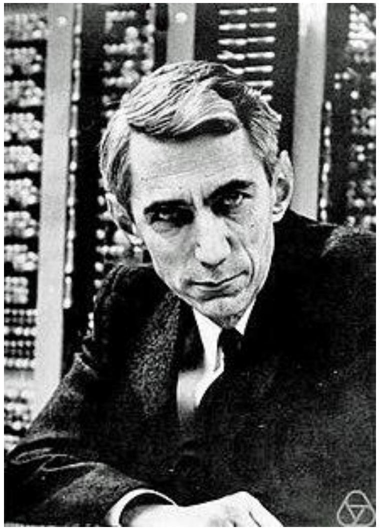


Cost, Energy, Complexity

New Communication Requirements

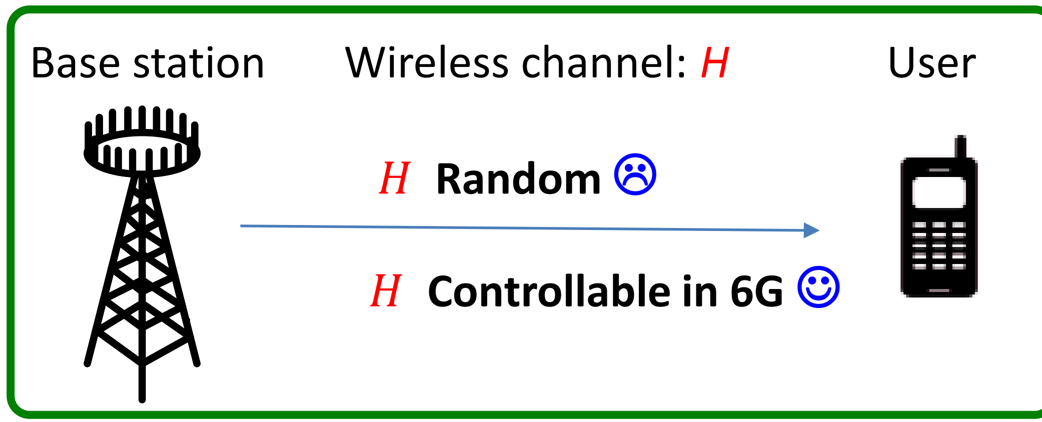


What's New in 6G?



Claude Shannon（1916-2001）
“the father of information theory”

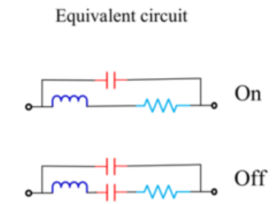
$$C = \log\left(1 + \frac{HP}{\sigma^2}\right)$$

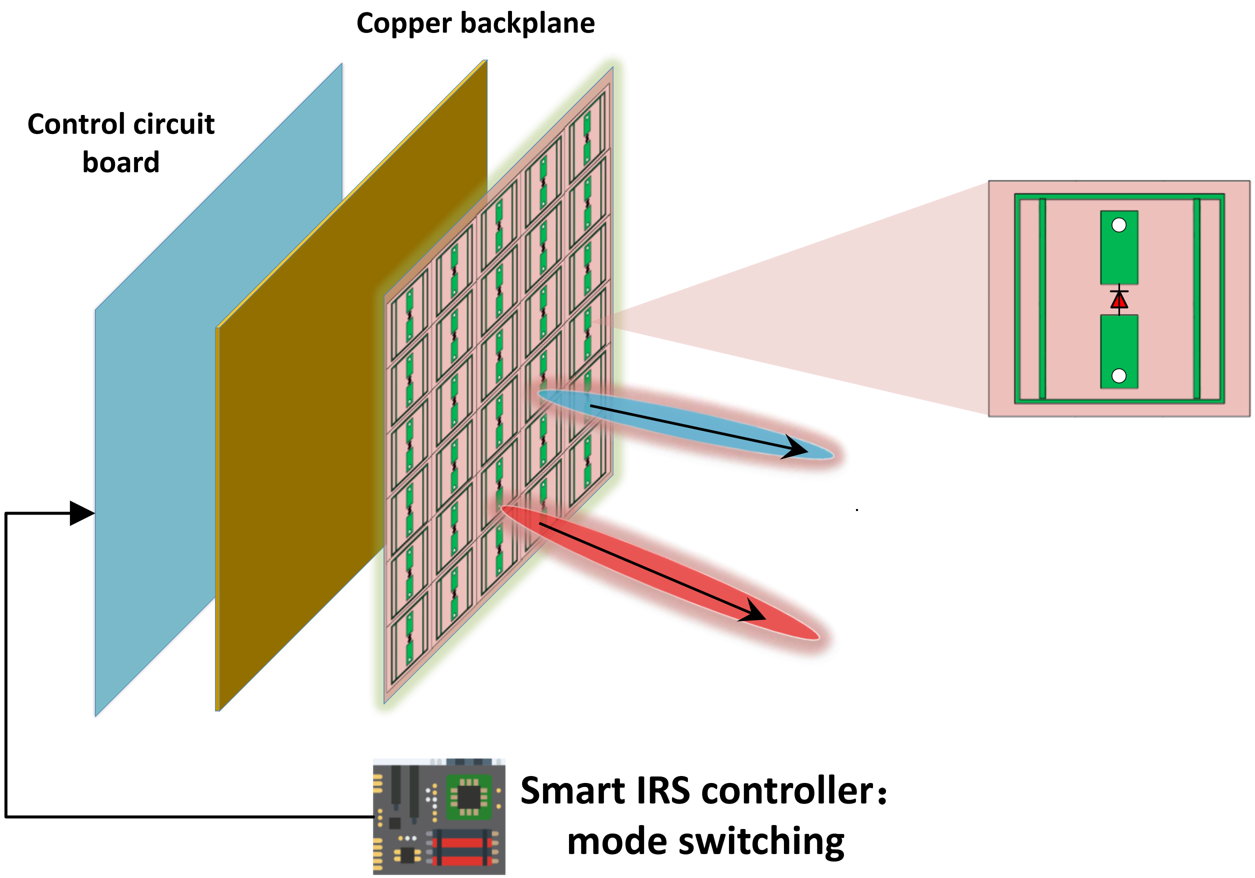


- ❑ Past decades: wireless channel *H* is only treated random and uncontrollable!
- ❑ Promising 6G paradigm: Smart and Reconfigurable Wireless Environment
  - ➢ 6G: Highly controllable wireless channel
- ❑ Key enabling technology: Intelligent Reflecting Surface (IRS)

Qingqing Wu, University of Macau

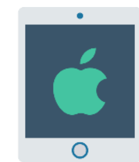
What is IRS?





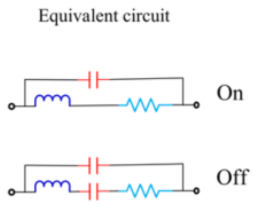
Reflecting element/meta-atom

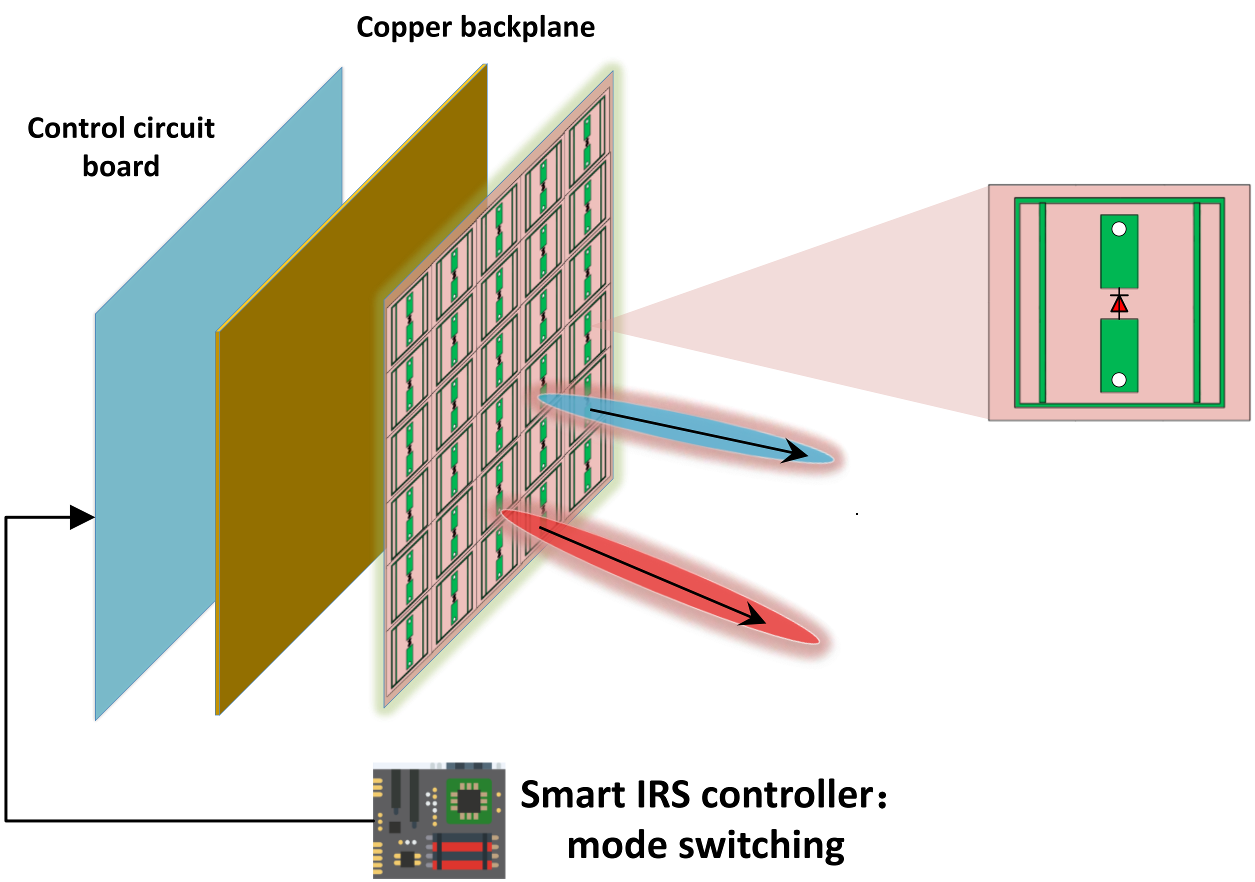
Controllable reflection amplitude and phase shift!



- ❑ **Intelligent:** Reconfigurable element, software
- ❑ **Reflecting:** Passive, not active transmit/emit
- ❑ **Surface:** Massive elements, Conformal

What is IRS?





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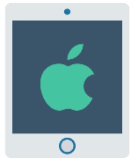

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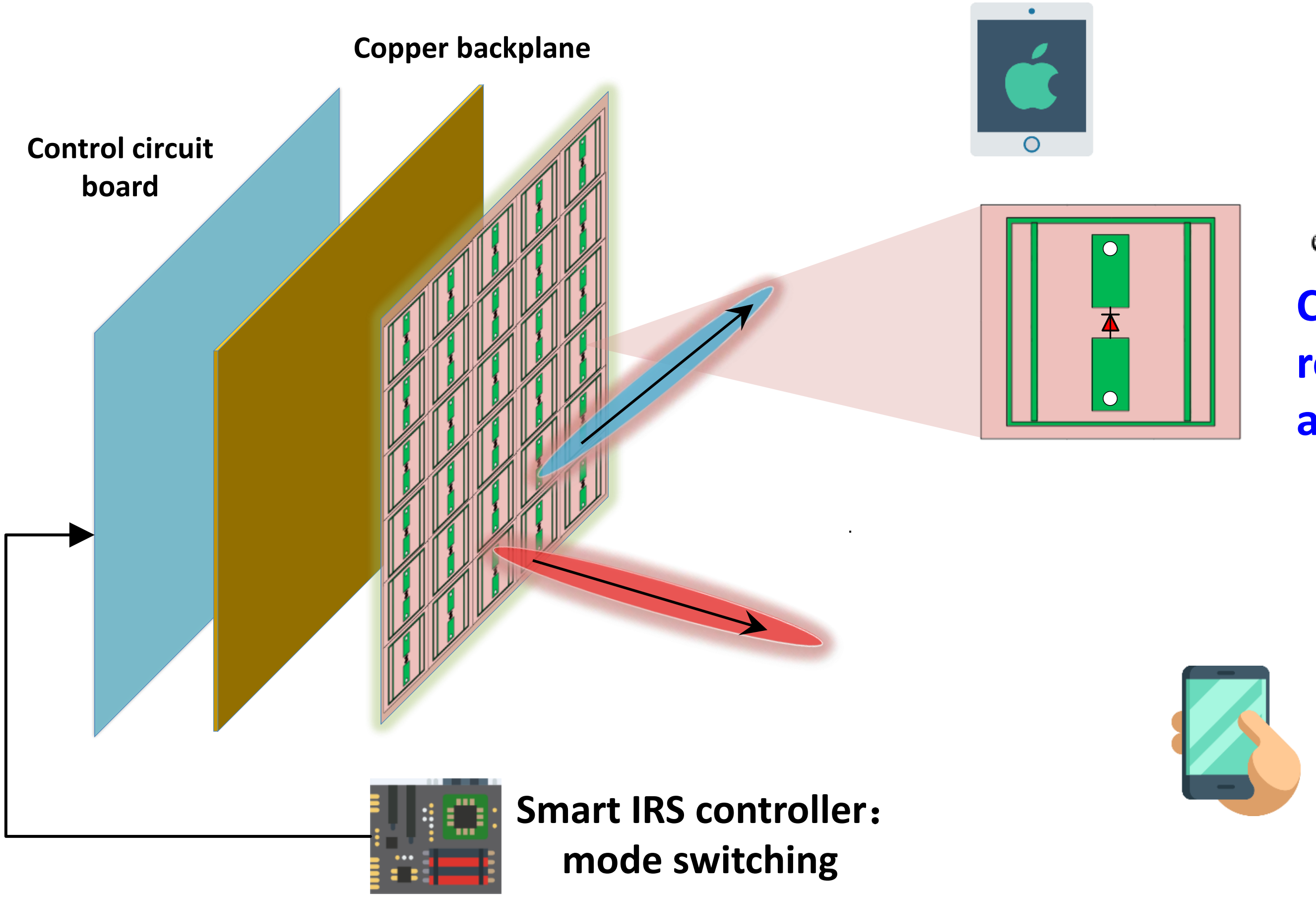

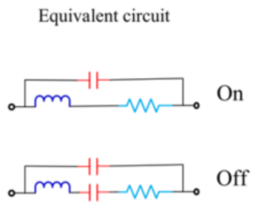

Reflecting element/meta-atom

Controllable reflection amplitude and phase shift!

- ❑ **Intelligent:** Reconfigurable element, software
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Energy Harvesting, Fully passive

[S. Hu2017TSP]
Large intelligent surface

IRS: Reflection Model

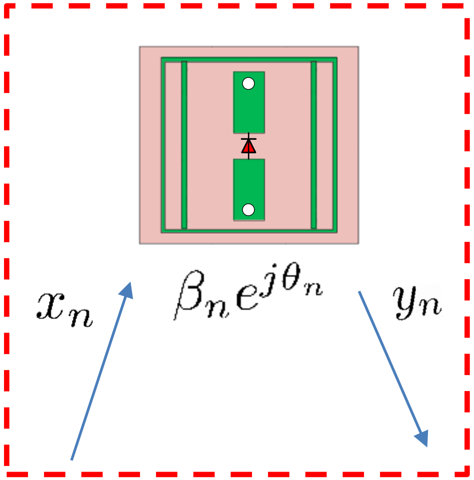
- Baseband equivalent signal model at each IRS element

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

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

- Vector form with *N* reflecting elements

$\boldsymbol{\Theta}$: diagonal reflecting matrix

$$\boldsymbol{y} = \boldsymbol{\Theta}\boldsymbol{x} = \mathrm{diag}(\beta_1 e^{j\theta_1}, \cdots, \beta_2 e^{j\theta_n}, \cdots, \beta_N e^{j\theta_N})\boldsymbol{x}$$

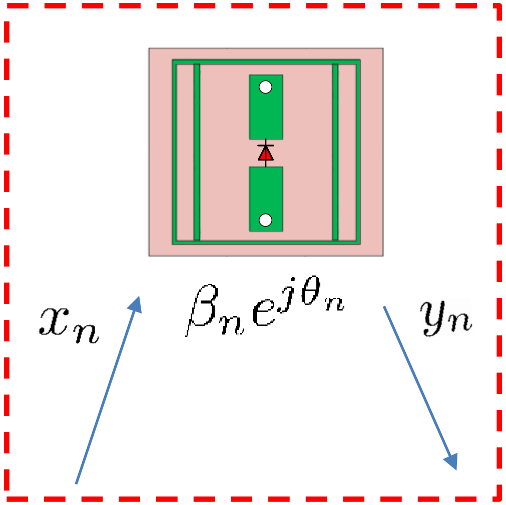
Q. Wu and R. Zhang, "Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Networks," IEEE Communications Magazine, January 2020.

Practical Model: Discrete Amplitude and Phase Shift

- Discrete values available at each element

$$\mathcal{F}'_\beta = \{\bar\beta_1, \cdots, \bar\beta_{K_\beta}\}, \qquad 0 \le \bar\beta_m < \bar\beta_{m'} \le 1$$

$$\mathcal{F}'_\theta = \{\bar\theta_1, \cdots, \bar\theta_{K_\theta}\}, \qquad 0 \le \bar\theta_l < \bar\theta_{l'} < 2\pi$$



- Uniformly quantize [0, 1] and [0, 2π]

$$\mathcal{F}'_\beta = \{0, \Delta\beta, \cdots, (K_\beta - 1)\Delta\beta\},$$

{0, 1} or {0.5, 1}?

$$\mathcal{F}'_\theta = \{0, \Delta\theta, \cdots, (K_\theta - 1)\Delta\theta\},$$

$$\Delta\beta = 1/(K_\beta - 1),\ \Delta\theta = 2\pi/K_\theta$$

- Special cases:
  - phase-shift control only: $\mathcal{F}'_\beta = \{\beta | \beta = 1\}$ and $\mathcal{F}'_\theta = \{0, \Delta\theta, \cdots, (K_\theta - 1)\Delta\theta\}$
  - amplitude control only: $\mathcal{F}'_\beta = \{0, \Delta\beta, \cdots, (K_\beta - 1)\Delta\beta\}$ and $\mathcal{F}'_\theta = \{\theta | \theta = 0\}$

Q. Wu and R. Zhang, "Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Networks," IEEE Communications Magazine, January 2020.
V. Arun and H. Balakrishnan, "RFocus: Beamforming Using Thousands of Passive," arXiv:1905.05130, 2019.

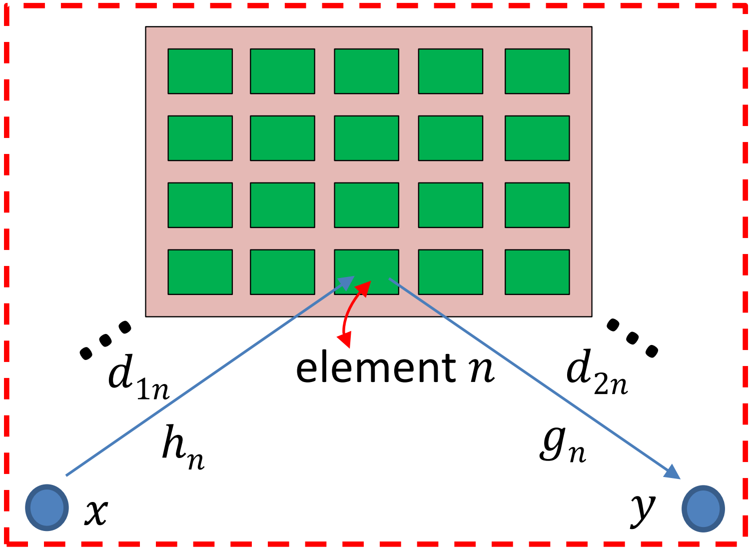
IRS: Channel Model

- Baseband equivalent channel model (narrow band)

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

$h_n g_n$: complex channel coefficients

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



- Product-distance path loss model

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

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

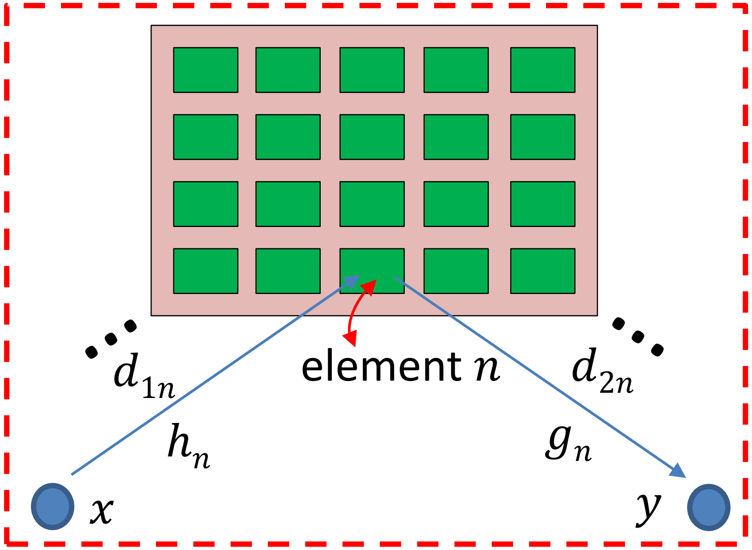
- x: transmitted signal
- y: received signal
- h_n: first link channel
- g_n: second link channel

Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," IEEE Transactions on Wireless Communications, November 2019.

IRS Path Loss Model: Product Distance or Sum Distance?

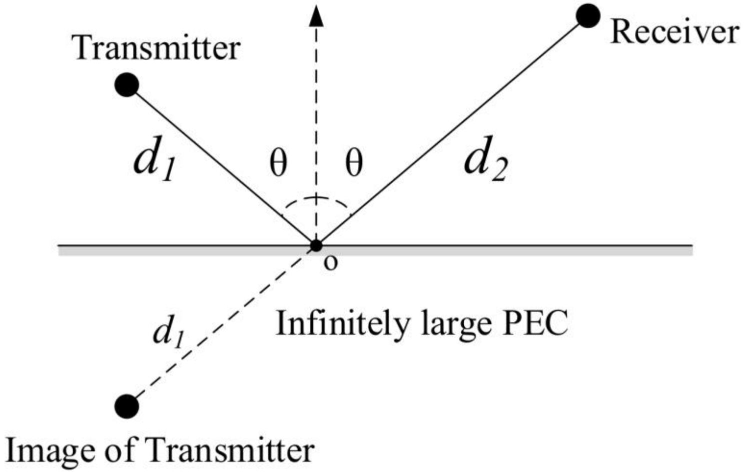
- ❑ Product-distance path loss model

$$|h_n|^2|g_n|^2 \propto c_1 c_2 d_{1n}^{-\alpha_1} d_{2n}^{-\alpha_2}$$



- ❑ Sum-distance path loss model

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



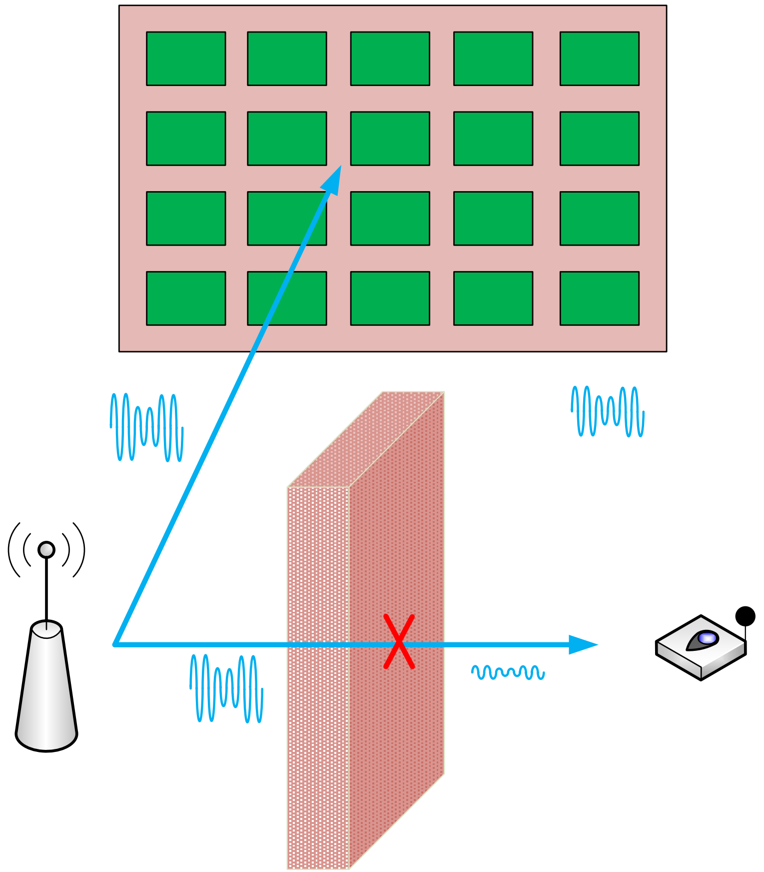
- ✓ Applies to free-space propagation and infinitely large perfect conductor only
- ✓ Not applicable to IRS element-wise amplitude/phase shift control

IRS Applications in Wireless Network

- ❑ IRS-enhanced coverage
- ❑ IRS-enhanced network throughput
- ❑ IRS-assisted interference cancelation
- ❑ IRS-aided secure communication
- ❑ IRS-aided SWIPT

Q. Wu and R. Zhang, "Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Networks," IEEE Communications Magazine, January 2020.

IRS-enhanced Coverage

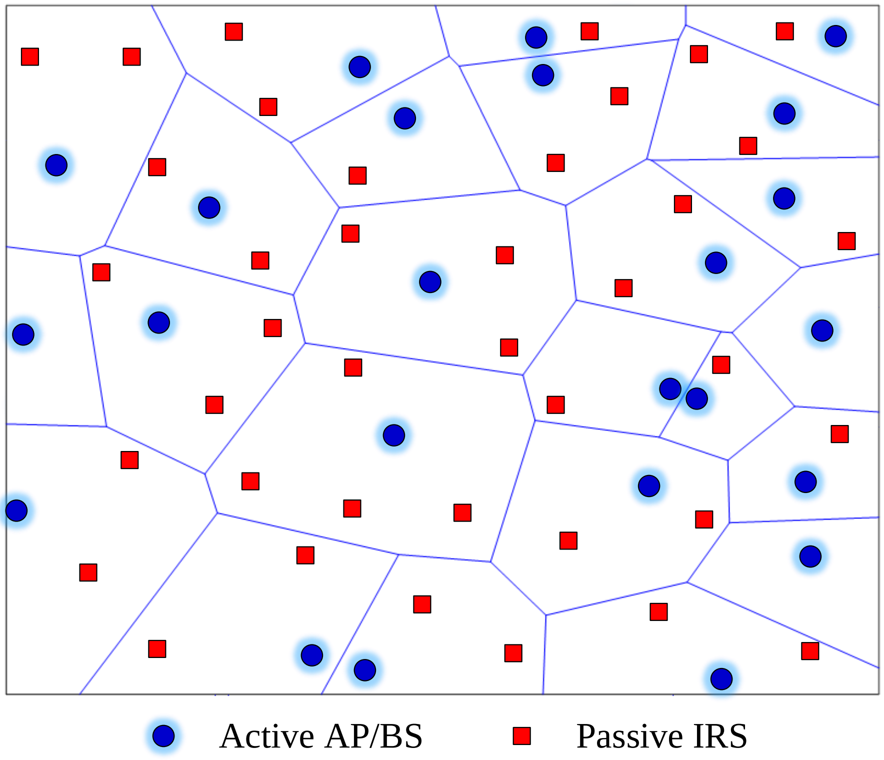


- Create LoS link by smart reflection to bypass obstacle
- Solve the "dead zone" problem in mmWave indoor coverage

Prof. Erik G. Larsson: https://ma-mimo.ellintech.se/2020/01/09/intelligent-reflecting-surfaces-on-use-cases-and-path-loss-models/

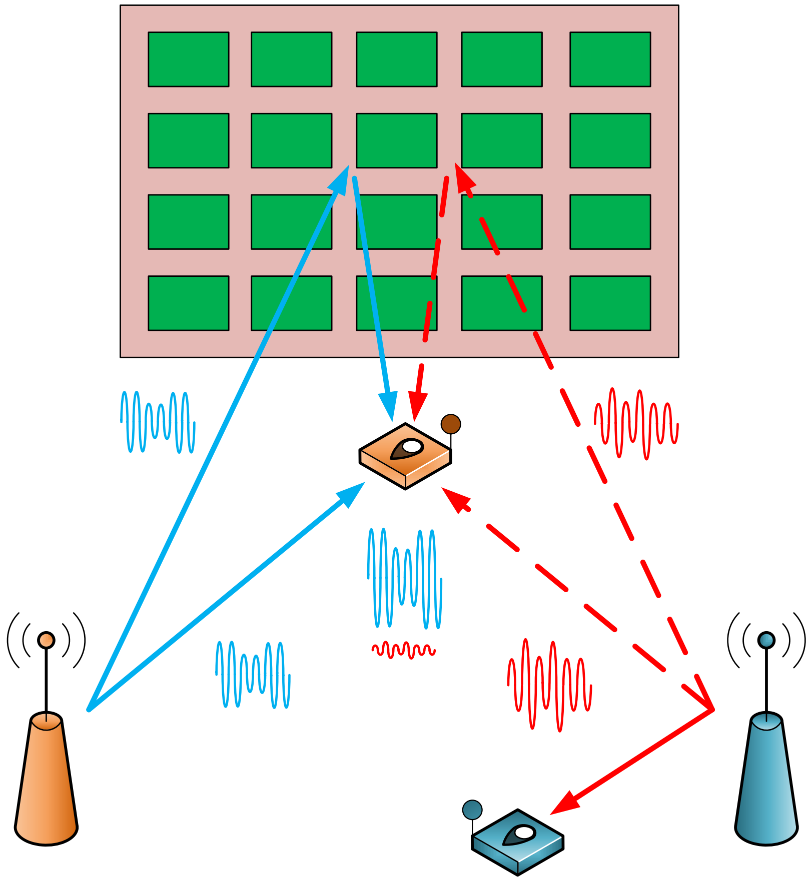
Qingqing Wu, University of Macau

IRS-enhanced Network Throughput



- A new hybrid network with active BSs/APs and passive IRSs
- Enhance signal power at "cell edge" or "hot spot"
- Boost network capacity without additional energy consumption
- Application scenario: eMBB for dense population areas (airport, stadium, shopping mall, etc.)

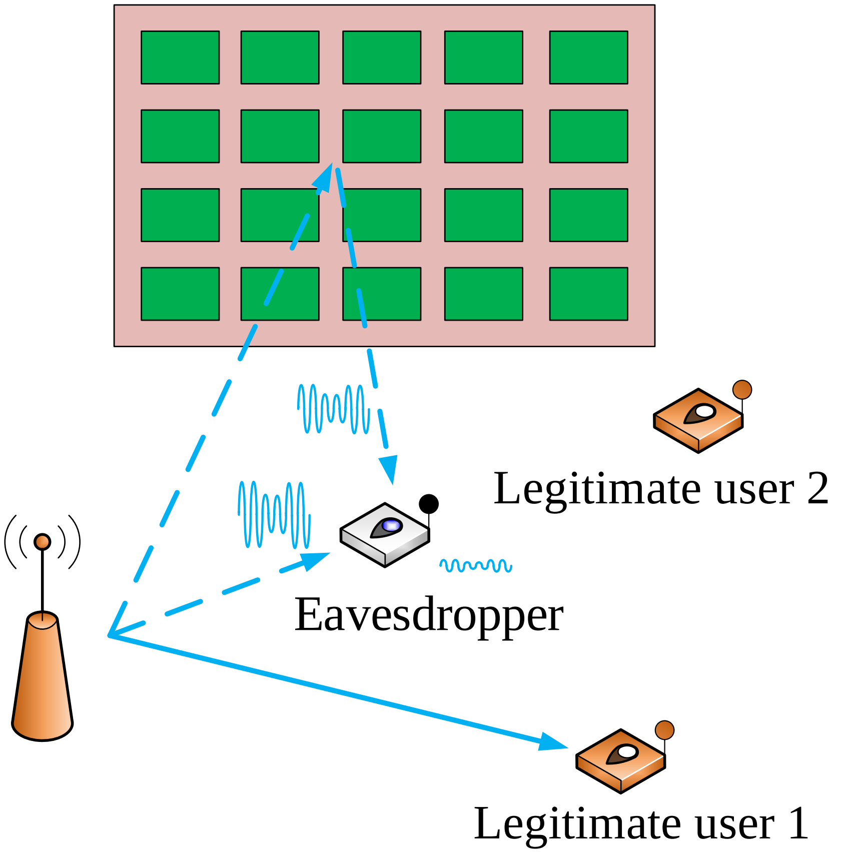
IRS-assisted Interference Cancelation



- Improve cell-edge user's SINR by enhancing desired signal and suppressing interference at the same time
- Create a "signal hotspot" and "interference-free zone" in the vicinity of IRS

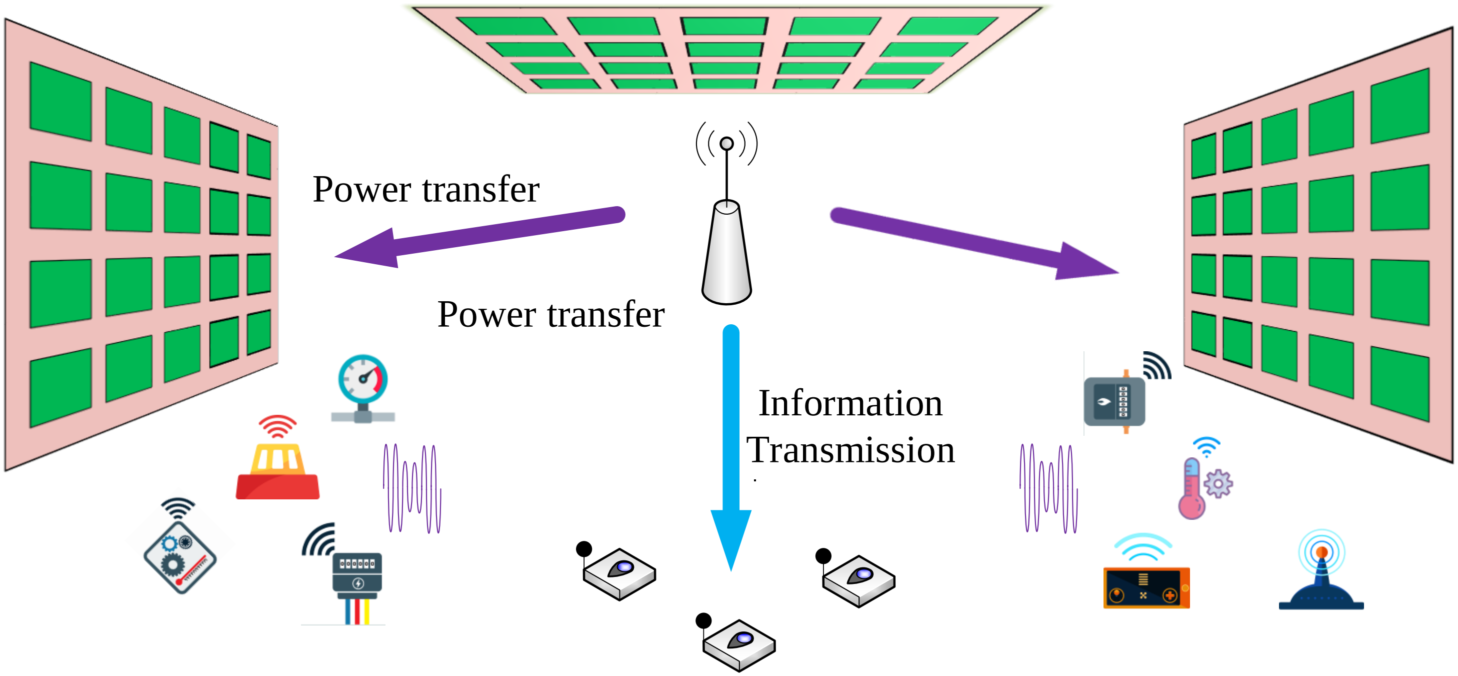
Conventional Scheme: Coordination, low frequency factor

IRS-aided Secure Communication



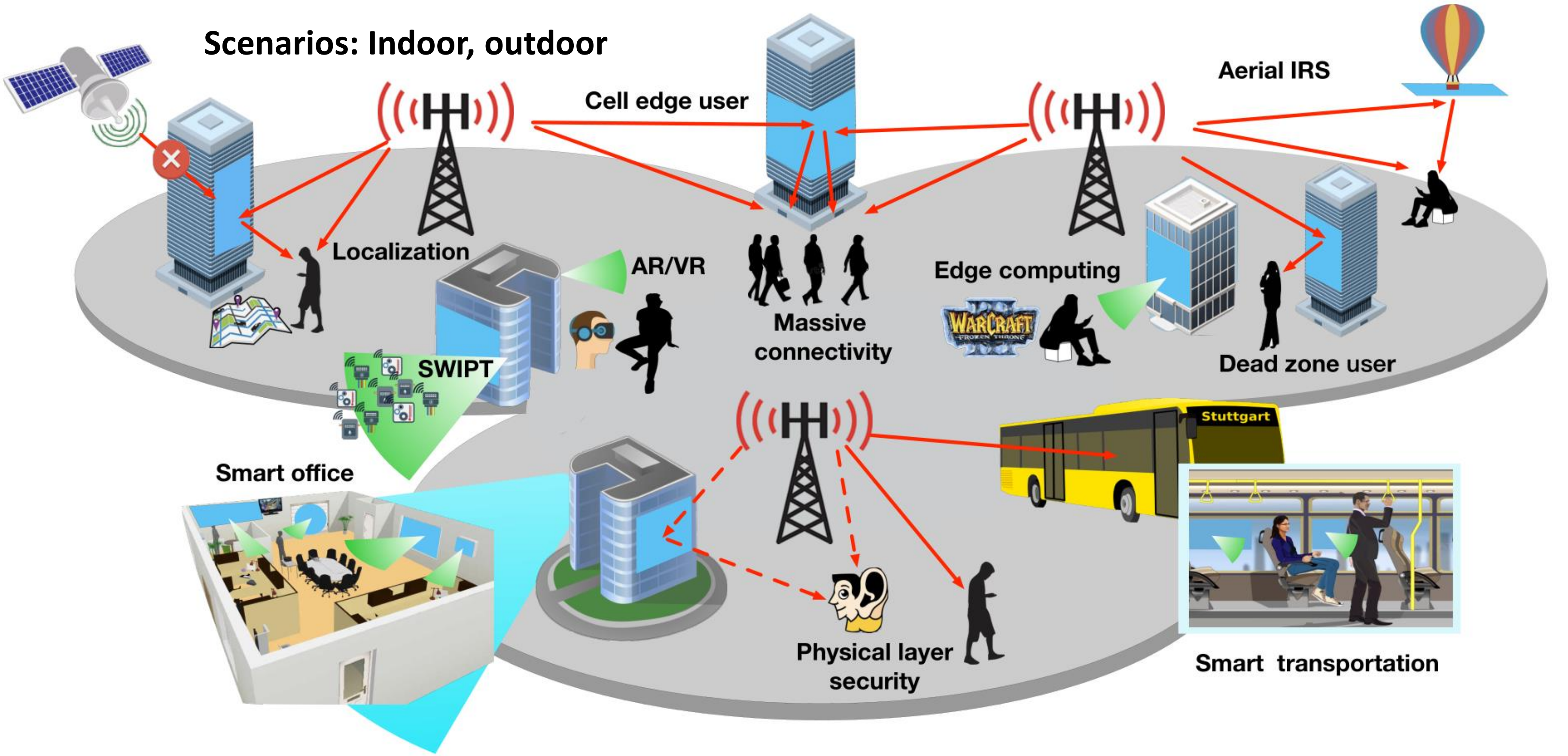
- Enhance physical layer security by canceling the signal at Eve receiver

IRS-aided SWIPT



- SWIPT: Simultaneous Wireless Information Power Transfer
- Performance bottleneck in SWIPT: Low energy efficiency of wireless power transfer (WPT) over long distance
- Enhance the WPT efficiency by creating an IRS-aided charging zone
- Application scenario: smart home/office, smart warehouse, and so on

Smart Radio Environment achieved by IRS



Making Our Infrastructure Intelligent for 6G Communications!

Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface aided wireless communications: A tutorial," submitted to IEEE Trans. on Commun., Invited Paper, available on arXiv

Industry Initiatives

New startups

➢ Metawave

Automotive radar, 5G wireless and AI, active repeaters (TURBO) and passive relays (ECHO)

➢ Greenerwave

4D imaging radar, millimeter wave 5G to broadband satellite communications, IoT solutions and RFID

➢ Pivotal Commware

5G mmWave technologies, systems and applications using holographic beam forming

Industry Initiatives

TABLE I

LIST OF MAIN INDUSTRY PROGRESS, PROTOTYPES, AND PROJECTS RELATED TO IRS.

Company	**Year**	**Main activity and achievement**
NTT DOCOMO and Metawave	2018	Demonstrate 28 GHz-band 5G using the first meta-structure reflectarray [21].
Lumotive and TowerJazz	2019	Demonstrate the first true solid-state beam steering using liquid crystal metasurface [22].
Pivotal Commware	2019	Demonstrate holographic beamforming technology using software-defined antennas [23].
NTT DOCOMO and AGC Inc.	2020	Demonstrate the first prototype transparent dynamic metasurface for 5G [24].
Greenerwave	–	Develop physics-inspired algorithms for reconfigurable metasurfaces [25].
Research project	**Start year**	**Main objective**
VisorSurf	2017	Develop a hardware platform for software-driven functional metasurface [26].
ARIADE	2019	Design metasurface integrated with new radio and artificial intelligence (AI) techniques [27].
PathFinder	2021	Establish the theoretical and algorithmic foundations for intelligent metasurface enabled wireless 2.0 networks [28].

Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface aided wireless communications: A tutorial," submitted to IEEE Trans. on Commun., Invited Paper, available on arXiv

❑ 6G White paper, published online in June 2020

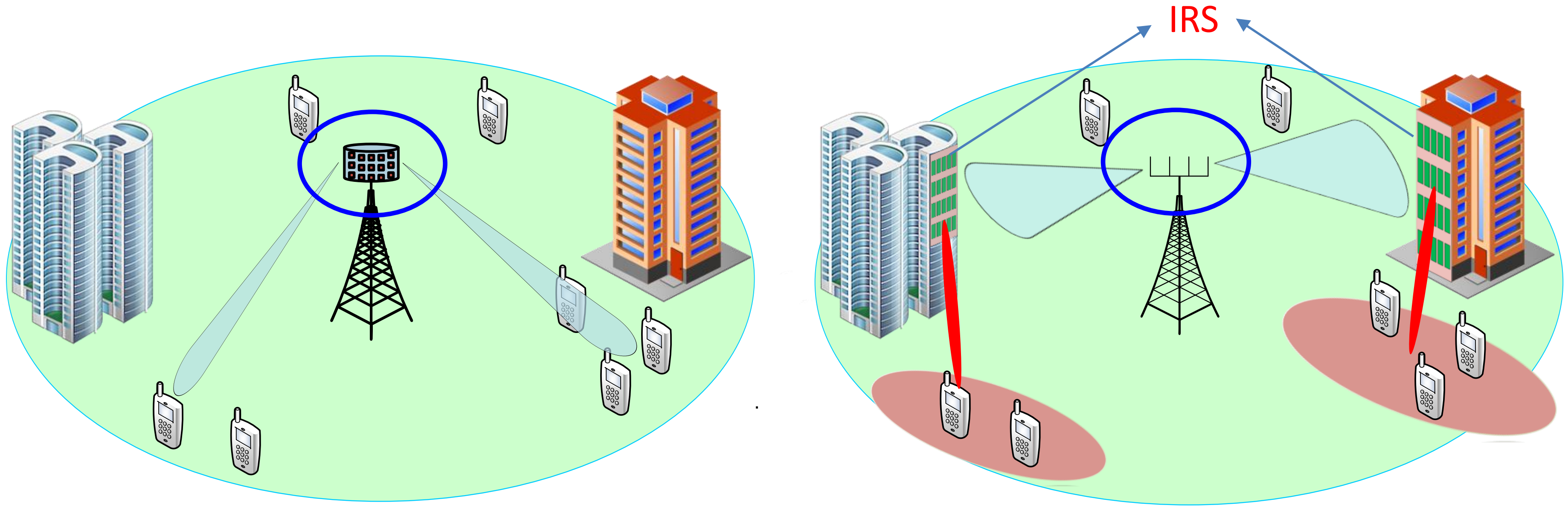
White Paper on Broadband Connectivity in 6G

Table of Contents

6G White Paper Author Distribution: Finland, Sweden, China, USA, Australia, Germany, UK, France, …

Nov. 4, 2020: 6G Research Visions Webinar Series: Deep Dive into the White Paper on Broadband Connectivity in 6G

IRS vs Massive MIMO/Large Intelligent Surface (LIS)



Massive MIMO

(Non-scalable with increased frequency)

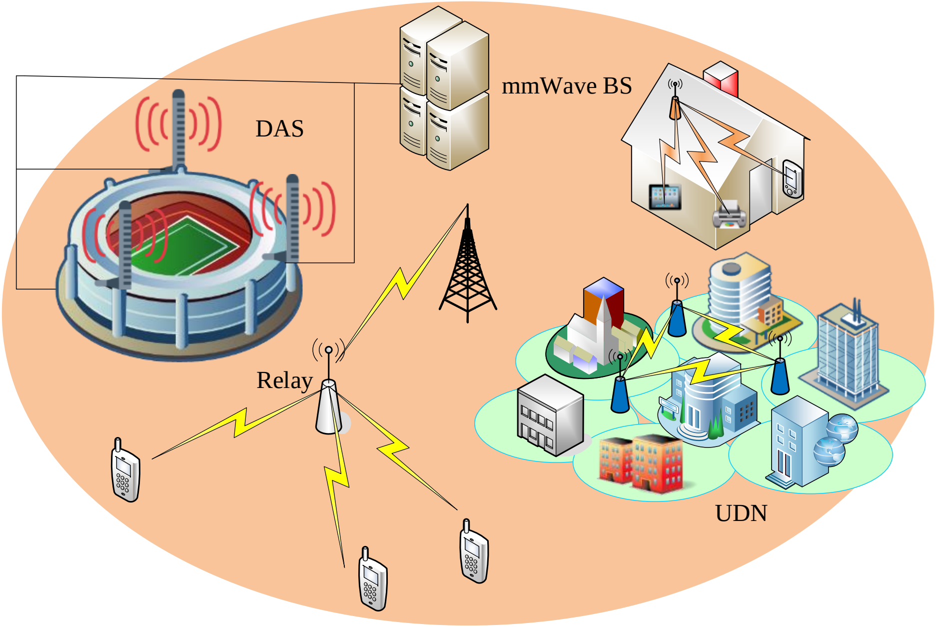
- Need large # of RF chains due to large # of active elements
- Increased energy consumption, hardware cost, and processing complexity at higher frequencies (e.g., mmWave)

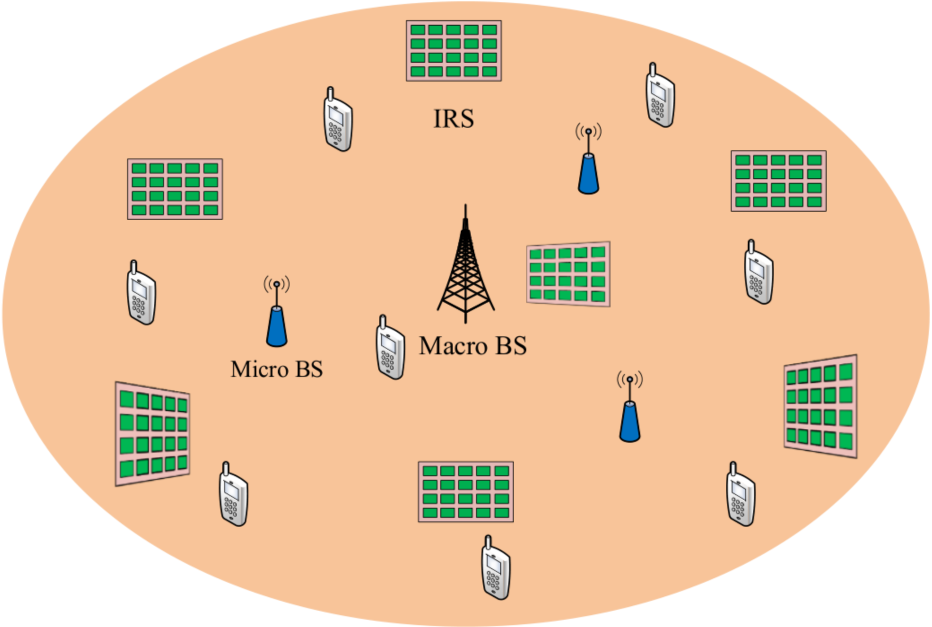
IRS-aided Small MIMO

(Scalable at any frequency)

- No RF chains needed for IRS due to passive reflection only
- Low energy consumption and scalable cost
- Compatible with cellular/WiFi and can be densely deployed

IRS vs Active Relay/Small Cell/DAS





- Network with active components only
- High cost and high energy consumption
- Backhaul bottleneck
- Complicated interference management
- Low spectrum efficiency due to half-duplex (full-duplex radio suffers severe self-interference)

Is this sustainable?

- Hybrid network: active BS with many passive IRSs
- Low cost and low energy consumption
- Wireless backhaul suffices (for control signaling only)
- Local coverage only without the need of inter-IRS interference management
- Full duplex without self-interference

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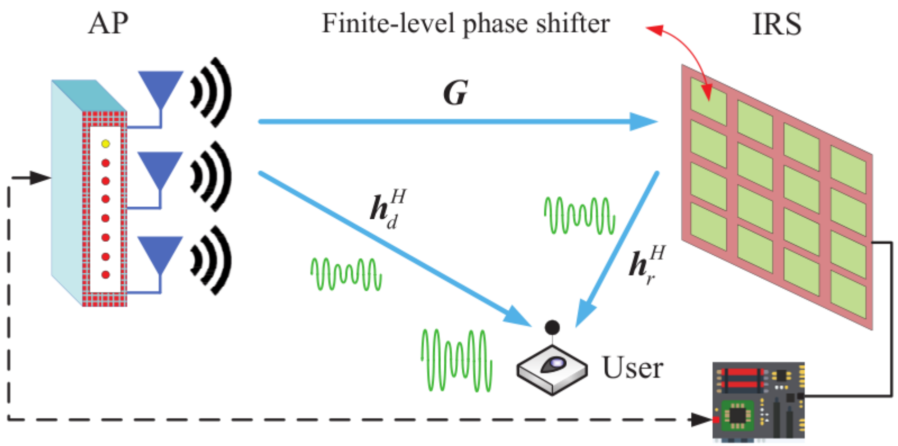
Joint Active and Passive Beamforming: Single-user Case



- AP: active (transmit) beamforming
- IRS: passive (reflect) beamforming with maximum reflection amplitude ($\beta_n = 1$)
- Objective: minimize the transmit power at the AP via joint transmit and reflect beamforming optimization subject to the given SNR target
- Establish a local "signal hotspot" in the vicinity of IRS
- Power scaling law: ***O(N²)***
  - **Thanks to the dual role of "receive" and "reflect" (full-duplex and noise-free), in contrast to O(N) by conventional massive MIMO and MIMO relay**
  - **Hold even by using IRS with 1-bit/binary phase shifters**

Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," IEEE Trans. Wireless Commun., vol. 18, no. 11, pp. 5394–5409, Nov. 2019.
Q. Wu and R. Zhang, "Beamforming optimization for wireless network aided by intelligent reflecting surface with discrete phase shifts," IEEE Trans. Commun., vol. 68, no. 3, pp. 1838–1851, Mar. 2020.

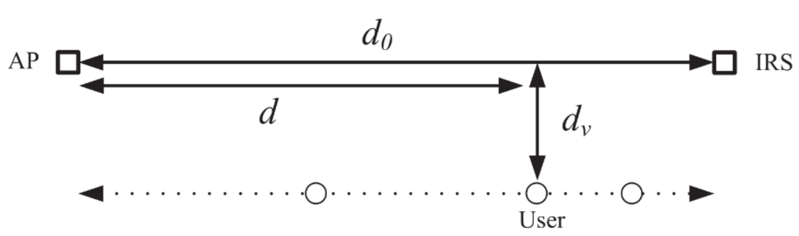
Benefit: Signal Hot Spot

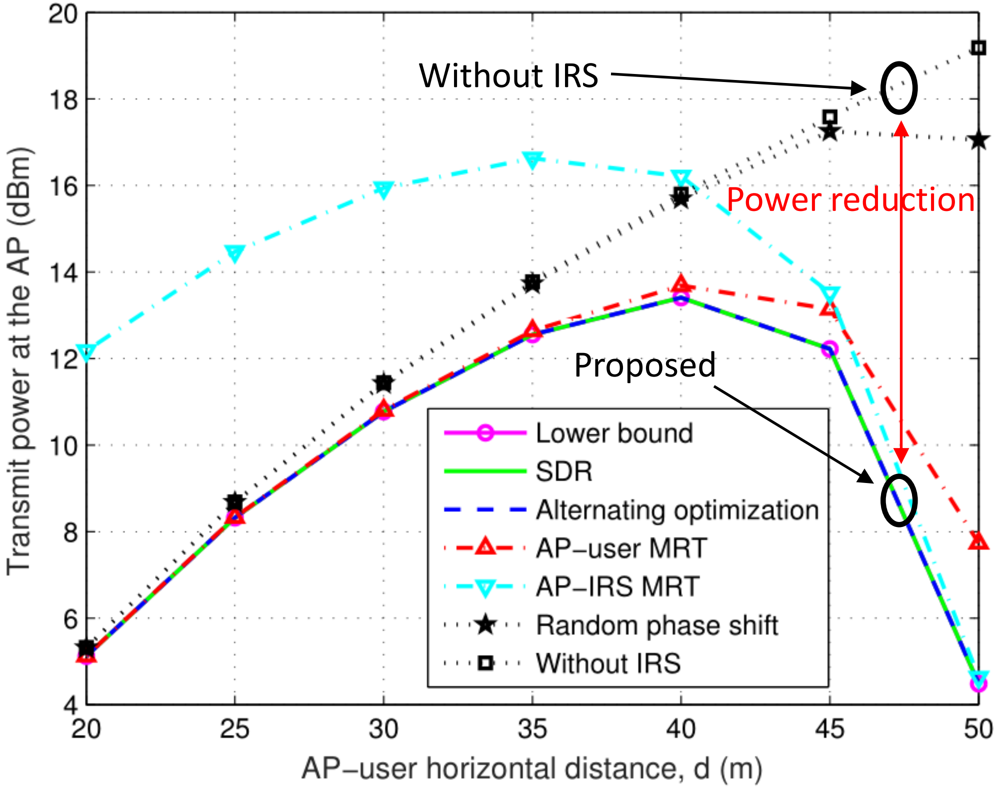
- ❑ Transmit beamforming: $\boldsymbol{w}$
- ❑ Reflect beamforming: $\boldsymbol{\Theta}$
- ❑ Problem formulation

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

- ❑ NP-hard in general
- ❑ Semidefinite relaxation (SDR) or alternating optimization (AO), near-optimal

Simulation setup





Minimum AP transmit Power vs AP-user Distance

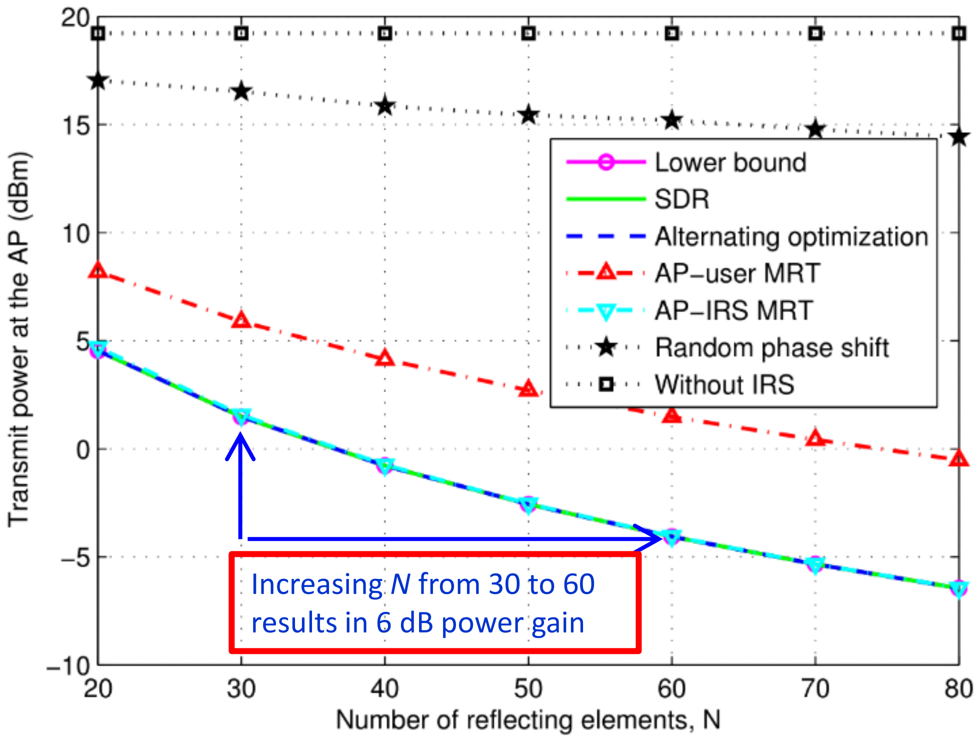
- ❑ Significant power saving with IRS (vs w/o IRS)
- ❑ Performance gain of joint transmit and reflect beamforming design (vs AP-user MRT or AP-IRS MRT benchmarks)

Squared Power Gain: Continuous Phase Shifts

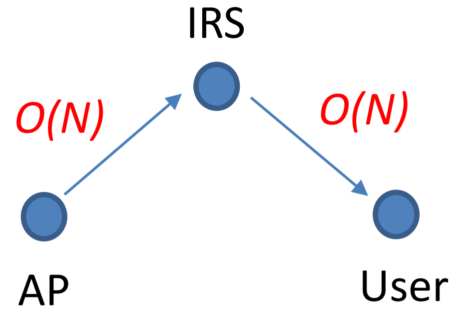
❑ What is the fundamental performance limit of using IRS?

Proposition 1. *Assume* $\boldsymbol{h}_r^H \sim \mathcal{CN}(\boldsymbol{0}, \varrho_h^2 \boldsymbol{I})$ *and* $\boldsymbol{g} \sim \mathcal{CN}(\boldsymbol{0}, \varrho_g^2 \boldsymbol{I})$*. As* $N \to \infty$*, it holds that*

$$P_u \to \begin{cases} NP\varrho_h^2\varrho_g^2, & \text{for } \boldsymbol{\Theta} = \boldsymbol{I} \text{ or random } \boldsymbol{\Theta}, \\ N^2 \dfrac{P\pi^2\varrho_h^2\varrho_g^2}{16}, & \text{for optimal } \boldsymbol{\Theta}. \end{cases} \quad (29)$$



d = 50 m

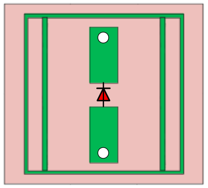


- ❑ Power scaling law $O(N^2)$ for large IRS
  - ➢ IRS aperture gain: $O(N)$
  - ➢ passive beamforming gain: $O(N)$
- ❑ Impact: decrease AP's power
- ❑ But requires continuous phase shifts $\theta_n \in [0, 2\pi)$

Squared Power Gain: Discrete Phase Shifts

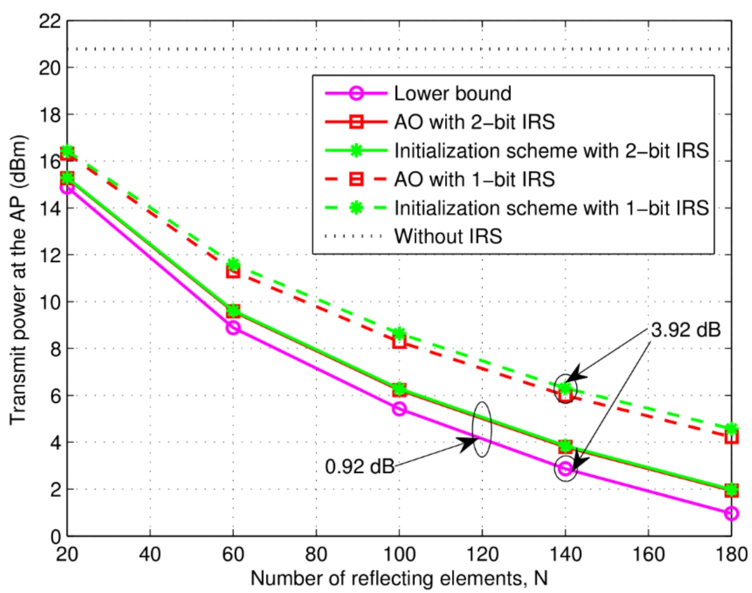
❑ Can we still achieve O(N²) by using IRS with discrete phase shifts?

Proposition 2. Assume $\boldsymbol{h}_r^H \sim \mathcal{CN}(\mathbf{0}, \varrho_h^2 \boldsymbol{I})$ and $\boldsymbol{g} \sim \mathcal{CN}(\mathbf{0}, \varrho_g^2 \boldsymbol{I})$. As $N \to \infty$, we have[3]



$$\eta(b) \triangleq \frac{P_r(b)}{P_r(\infty)} = \left(\frac{2^b}{\pi}\sin\left(\frac{\pi}{2^b}\right)\right)^2. \quad (31)$$

Number of control bits: b	$b=1$	$b=2$	$b=3$	$b = \infty$ (continuous phase shifts)
Power loss: $1/\left(\frac{2^b}{\pi}\sin\left(\frac{\pi}{2^b}\right)\right)^2$	3.9 dB	0.9 dB	0.2 dB	0 dB



- ❑ *b-bit phase shifts*
- ❑ *E.g., b*=1 → θ_n={0, π}
- ❑ Power loss: *η(b)*
  - ➢ regardless of N
  - ➢ depend only on b

- ❑ Power scaling law, i.e., *O(N²)*, still holds even with 1-bit phase shifters
  - ➢ IRS has a great potential in practice by using low-cost hardware!

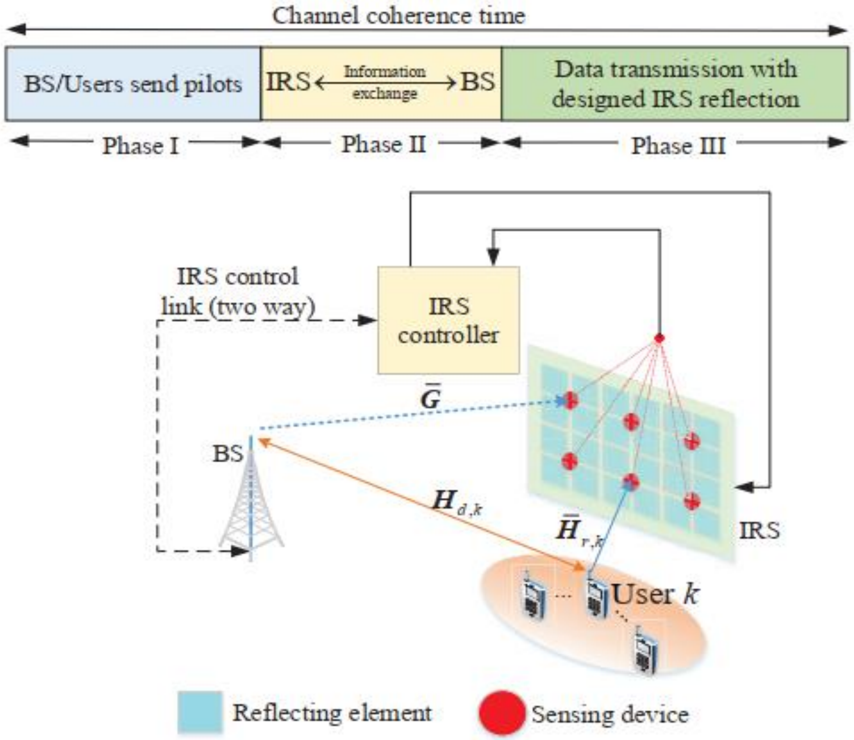
Q. Wu and R. Zhang, "Beamforming optimization for wireless network aided by intelligent reflecting surface with discrete phase shifts," IEEE Trans. Commun., vol. 68, no. 3, pp. 1838–1851, Mar. 2020.

IRS Channel Estimation

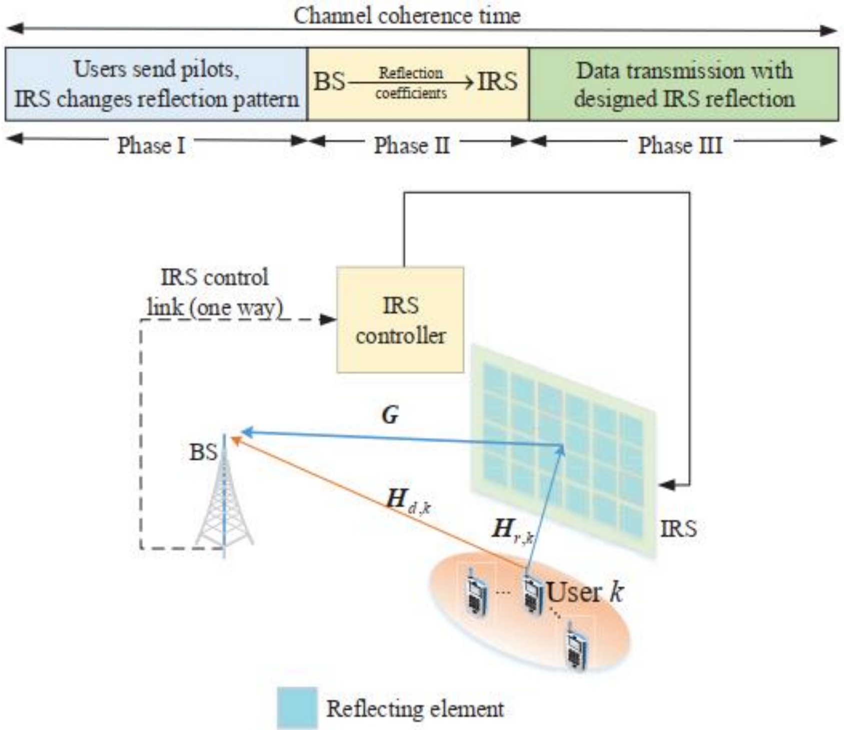
- Channel estimation
  - AP-user link: estimated by conventional method and switching off IRS
  - AP-IRS link: estimated periodically (offline) with static AP and IRS
  - IRS-user link: vary with user location, need to be estimated in real time
- Main difficulties in IRS channel acquisition
  - Passive (no Tx RF chain)
  - Large number of elements
- With Rx RF chains/sensors (semi-passive IRS)
  - Channels estimated by leveraging TDD and channel reciprocity
  - Low-cost sensors limit the estimation accuracy
  - Signal processing techniques for reducing the number of sensors/Rx chains
- Without Rx RF chains/sensors (fully-passive IRS)
  - More challenging case (as compared to semi-passive IRS)
  - Cascaded channel (AP-IRS-user) estimation via varying IRS reflection pattern
  - An active area of research!

Q. Wu and R. Zhang, "Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Networks," IEEE Communications Magazine, January 2020.

IRS Channel Estimation



- Semi-passive approach



- Fully passive approach

Q. Wu and R. Zhang, "Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Networks," IEEE Communications Magazine, January 2020.
Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface aided wireless communications: A tutorial," submitted to IEEE Trans. on Commun., Invited Paper, available on arXiv

IRS Deployment

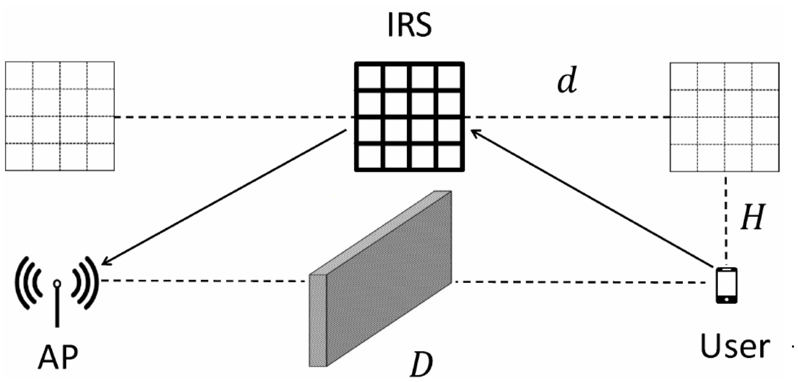
- Ray-tracing based method
  - Require site-specific information, complex and non-scalable
  - Costly

- Opportunity and Challenge
  - Short/local coverage of individual IRSs makes them free of mutual interference
  - Each IRS may associate with one or more (neighboring) APs

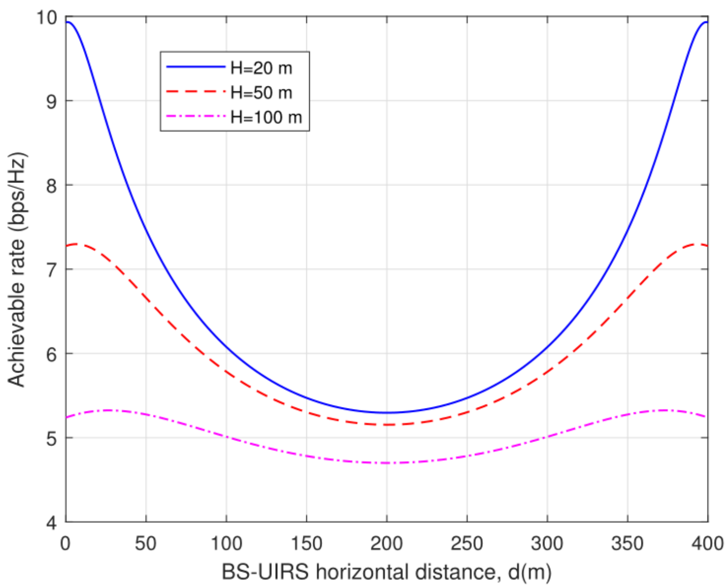
- Some useful guidelines for IRS deployment
  - Single-cell setup
    - Single-user IRS: deploy the IRS in strong LoS of both AP and user to achieve high BF gain
    - Multi-user IRS: deploy the IRS in LoS and yet rich-scattering environment to avoid low-rank AP-IRS channel and achieve spatial multiplexing gain
  - Multi-cell setup
    - Mild-interference scenario: deploy the IRS in hot-spot area to reduce the AP cost
    - Strong-interference scenario: deploy the IRS at cell edge to achieve interference mitigation

IRS Deployment: Single-User Case

- Where to place the IRS to maximize the SNR?
  - Near AP? Near User? Or In the middle as the relay?



$$\rho_S = \frac{P\beta_0^2 N^2}{(d^2 + H^2)((D-d)^2 + H^2)\sigma^2}$$

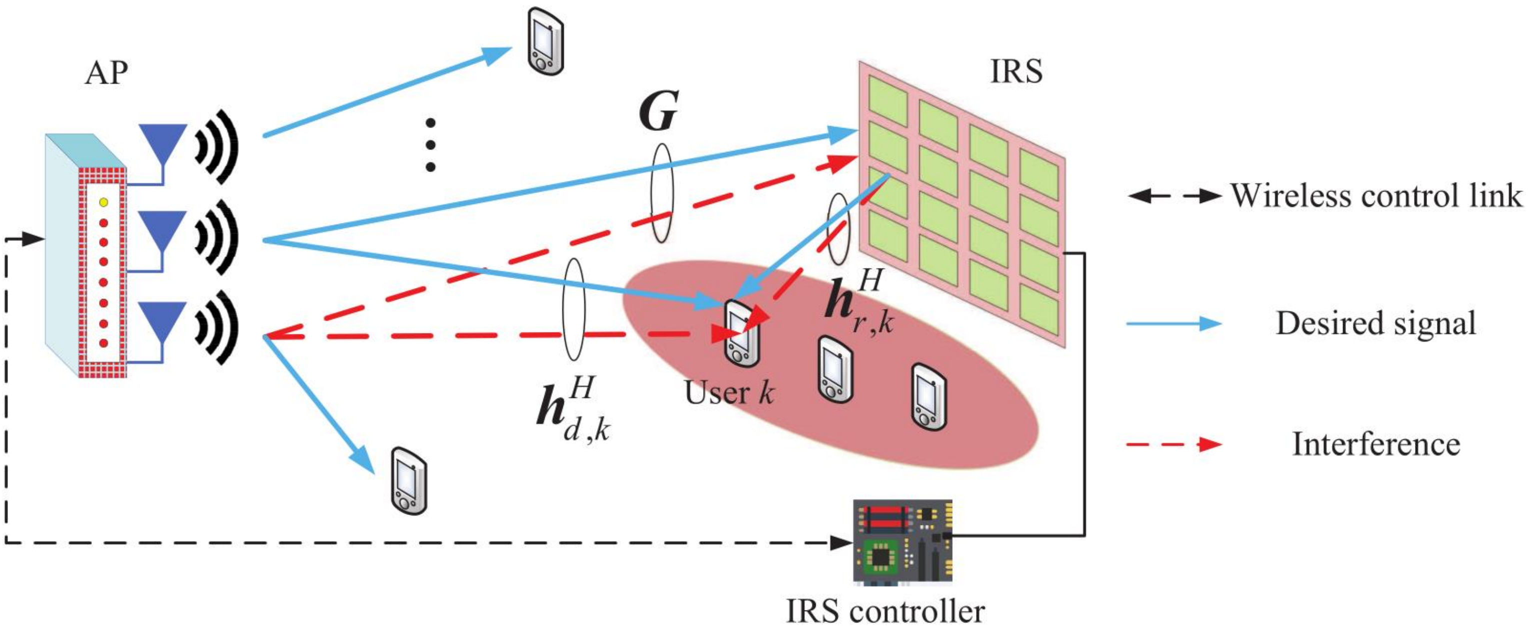


- IRS Deployment: Single IRS or Cooperative IRSs?

Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface aided wireless communications: A tutorial," submitted to IEEE Trans. on Commun., Invited Paper, available on arXiv

IRS Deployment: Multi-user Case

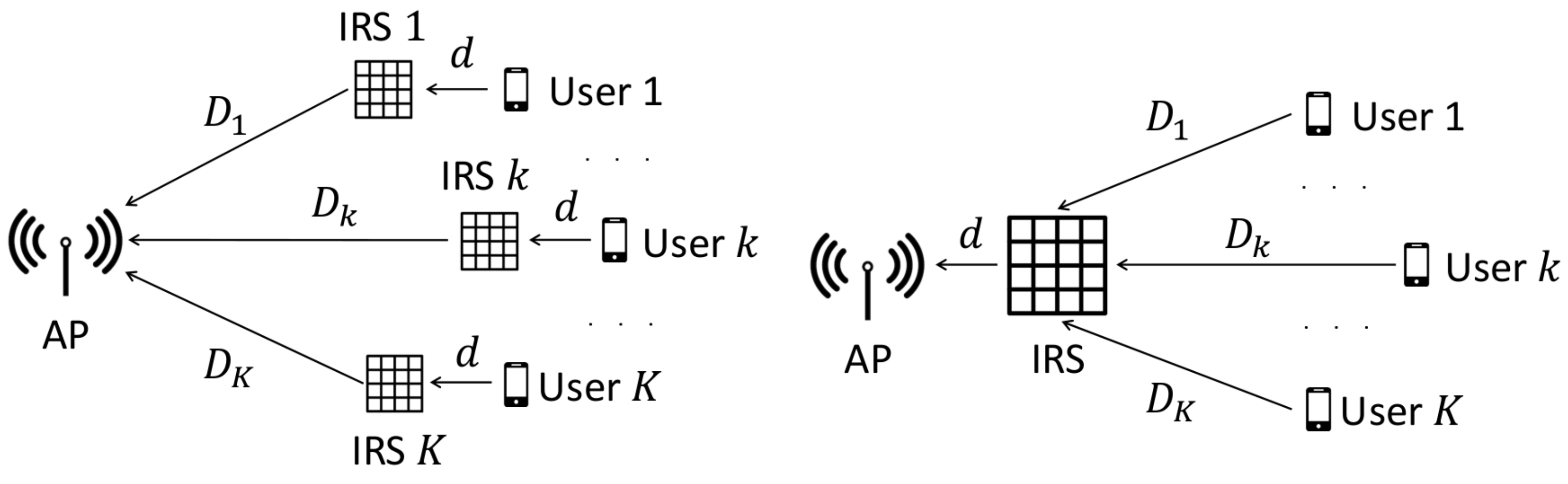
- LoS or Non-LoS?
  - high beamforming gain versus spatial multiplexing gain



Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," IEEE Transactions on Wireless Communications, November 2019.
Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface aided wireless communications: A tutorial," submitted to IEEE Trans. on Commun., Invited Paper, available on arXiv

IRS Deployment: Multi-user Case

❑ Centralized IRS or Distributed IRSs?



(a) Distributed IRS deployment (b) Centralized IRS deployment

Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface aided wireless communications: A tutorial," submitted to IEEE Trans. on Commun., Invited Paper, available on arXiv
S. Zhang and R. Zhang, "Intelligent reflecting surface aided multiple access: capacity region and deployment strategy," IEEE SPAWC, 2020.

Outline

- ❑ Part 1: Introduction of Intelligent Reflecting Surface (IRS)
  - ➢ Motivation
  - ➢ Hardware architecture
  - ➢ Reflection and channel models
  - ➢ Applications and industry initiatives
  - ➢ Comparison with existing technologies
- ❑ Part 2: Major Challenges
  - ➢ IRS reflection optimization
  - ➢ IRS channel estimation
  - ➢ IRS deployment
- ❑ **Part 3: Conclusions and Future Work Directions**

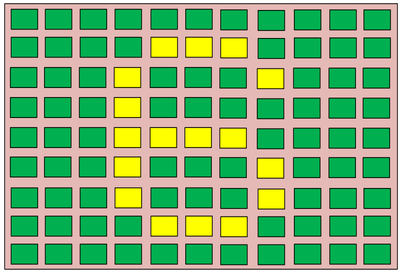
Conclusions

- IRS: a new and disruptive technology to achieve smart and reconfigurable propagation environment for future wireless network

- Achieve high spectral/energy efficiency with low-cost passive reflecting elements

- A paradigm shift of wireless communication from traditional "active component solely" to the new "active and passive" hybrid network

- Major challenges (from the communications perspective):
  - IRS reflection optimization
  - IRS channel estimation
  - IRS deployment



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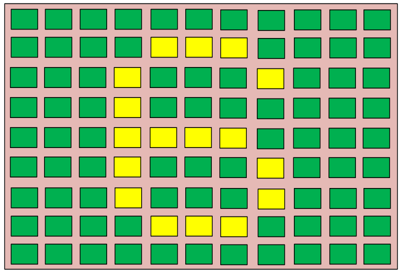
Promising Directions for Future Work

- 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 (mobile edge computing, localization, etc.)
- Capacity and performance analysis of IRS-aided system/network
- Practical IRS channel estimation and low-complexity passive beamforming designs
- IRS deployment/association in multi-cell network
- IRS meets massive MIMO, active relay, mmWave, energy harvesting, UAV, etc.
- IRS integration to WiFi/Cellular
- ......



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References (1)

- Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: intelligent reflecting surface aided wireless network," IEEE Communications Magazine, vol. 58, no. 1, pp. 106-112, January 2020.
- Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," IEEE Trans. Wireless Commun., vol. 18, no. 11, pp. 5394-5409, November 2019.
- Q. Wu and R. Zhang, "Beamforming optimization for wireless network aided by intelligent reflecting surface with discrete phase shifts," IEEE Transactions on Communications, vol. 68, no. 3, pp. 1838-1851, March 2020.
- S. Zhang and R. Zhang, "Capacity characterization for intelligent reflecting surface aided MIMO communication," to appear in IEEE JSAC. Available: https://arxiv.org/abs/1910.01573
- B. Zheng, Q. Wu, and R. Zhang, "Intelligent reflecting surface-assisted multiple access with user pairing: NOMA or OMA?" IEEE Communications Letters, vol. 24, no. 4, pp. 753-757, April 2020.
- X. Guan, Q. Wu, and R. Zhang, "Joint power control and passive beamforming in IRS-assisted spectrum sharing," IEEE Communications Letters, to appear.
- Y. Han, S. Zhang, L. Duan, and R. Zhang, "Cooperative double-IRS aided communication: beamforming design and power scaling," IEEE Wireless Communications Letters, to appear.
- S. Zhang and R. Zhang, "Intelligent reflecting surface aided multiple access: capacity region and deployment strategy," to appear in IEEE SPAWC, 2020. Available: https://arxiv.org/abs/2002.07091

References (2)

- Y. Yang, B. Zheng, S. Zhang, and R. Zhang, "Intelligent reflecting surface meets OFDM: protocol design and rate maximization," to appear in IEEE Trans. Commun. Available: https://arxiv.org/abs/1906.09956
- B. Zheng and R. Zhang, "Intelligent reflecting surface enhanced OFDM: channel estimation and reflection optimization," IEEE Wireless Communications Letters, vol. 9, no. 4, pp. 518-522, April 2020.
- Y. Yang, S. Zhang, and R. Zhang, "IRS-enhanced OFDMA: Joint resource allocation and passive beamforming optimization," to appear in IEEE Wireless Commun. Lett. Available: https://arxiv.org/abs/1912.01228
- B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface assisted multi-user OFDMA: channel estimation and training design," submitted to IEEE Transactions on Wireless Communications. Available: https://arxiv.org/abs/2003.00648
- S. Abeywickrama, R. Zhang, and C. Yuen, "Intelligent reflecting surface: practical phase shift model and beamforming optimization," to appear in IEEE ICC, 2020. Available: https://arxiv.org/abs/1907.06002
- M. M. Zhao, Q. Wu, M. J. Zhao, and R. Zhang, "Intelligent reflecting surface enhanced wireless network: two-timescale beamforming optimization," submitted to IEEE Transactions on Wireless Communications. Available: https://arxiv.org/abs/1912.01818
- C. You, B. Zheng, and R. Zhang, "Channel estimation and passive beamforming for intelligent reflecting surface: discrete phase shift and progressive refinement," to appear in IEEE JSAC. Available: https://arxiv.org/abs/1912.10646

References (3)

- J. Lyu and R. Zhang, "Spatial throughput characterization for intelligent reflecting surface aided multiuser system," IEEE Wireless Communications Letters, to appear.
- J. Lyu and R. Zhang, "Hybrid active/passive wireless network aided by intelligent reflecting surface: system modeling and performance analysis," submitted to IEEE Transactions on Wireless Communications. Available: https://arxiv.org/abs/2004.13318
- M. Cui, G. Zhang, and R. Zhang, "Secure wireless communication via intelligent reflecting surface," IEEE Wireless Commun. Letters, vol. 8, no. 5, pp. 1410-1414, October 2019.
- X. Guan, Q. Wu, and R. Zhang, "Intelligent reflecting surface assisted secrecy communication: is artificial noise helpful or not?," to appear in IEEE Wireless Communications Letters.
- Q. Wu and R. Zhang, "Weighted sum power maximization for intelligent reflecting surface aided SWIPT," to appear in IEEE Wireless Commun. Letters. Available: https://arxiv.org/abs/1907.05558
- Q. Wu and R. Zhang, "Joint active and passive beamforming optimization for intelligent reflecting surface assisted SWIPT under QoS constraints," to appear in IEEE JSAC. Available: https://arxiv.org/abs/1910.06220
- H. Lu, Y. Zeng, S. Jin, and R. Zhang, "Enabling panoramic full-angle reflection via aerial intelligent reflecting surface," to appear in IEEE ICC Workshop, 2020. Available: https://arxiv.org/abs/2001.07339

Thank You

Q & A ?