Intelligent Reflecting Surface (IRS) for Wireless Communications and Sensing

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IEEE ICC 2022 Workshop on
Synergies of communication, localization, and sensing towards 6G

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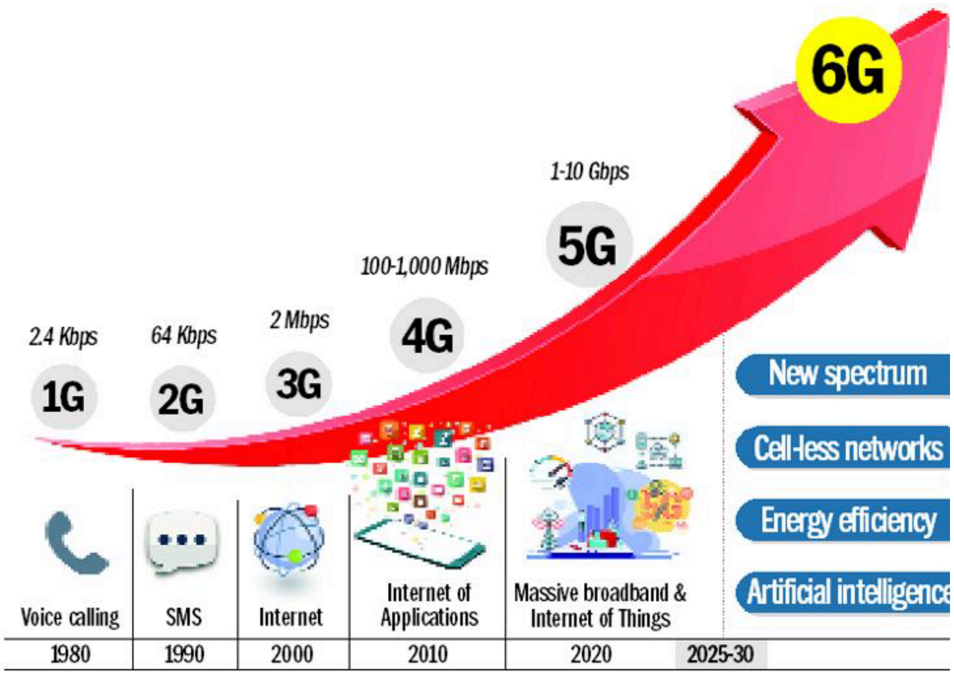
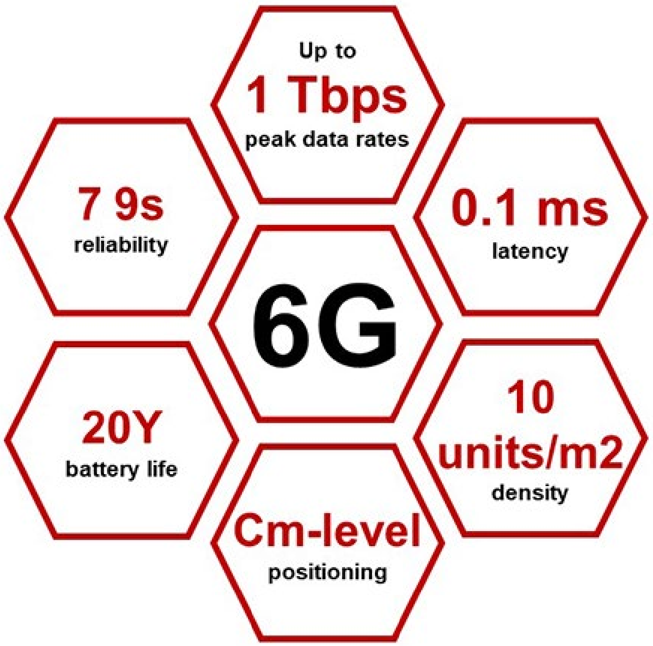
Outline

- ❑ Intelligent Reflecting Surfaces (IRS): Motivation and Applications
- ❑ IRS-aided Wireless Communications
- ❑ IRS-aided Sensing
- ❑ Conclusions

Wireless Network Evolution: From 1G to 6G



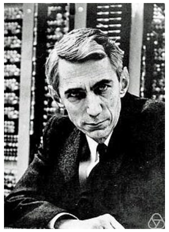


Key Features of 6G Wireless Networks

- ❑ From “connected wold” to “connected intelligence”
- ❑ Unprecedentedly high data rate (up to 1Tbps), reliability (99.99999%), low latency (0.1ms), and massive connectivity (10 devices/m^2)
- ❑ Extremely high energy/spectral efficiency
- ❑ Multi-functional (integrated communication-sensing), space-air-ground integrated

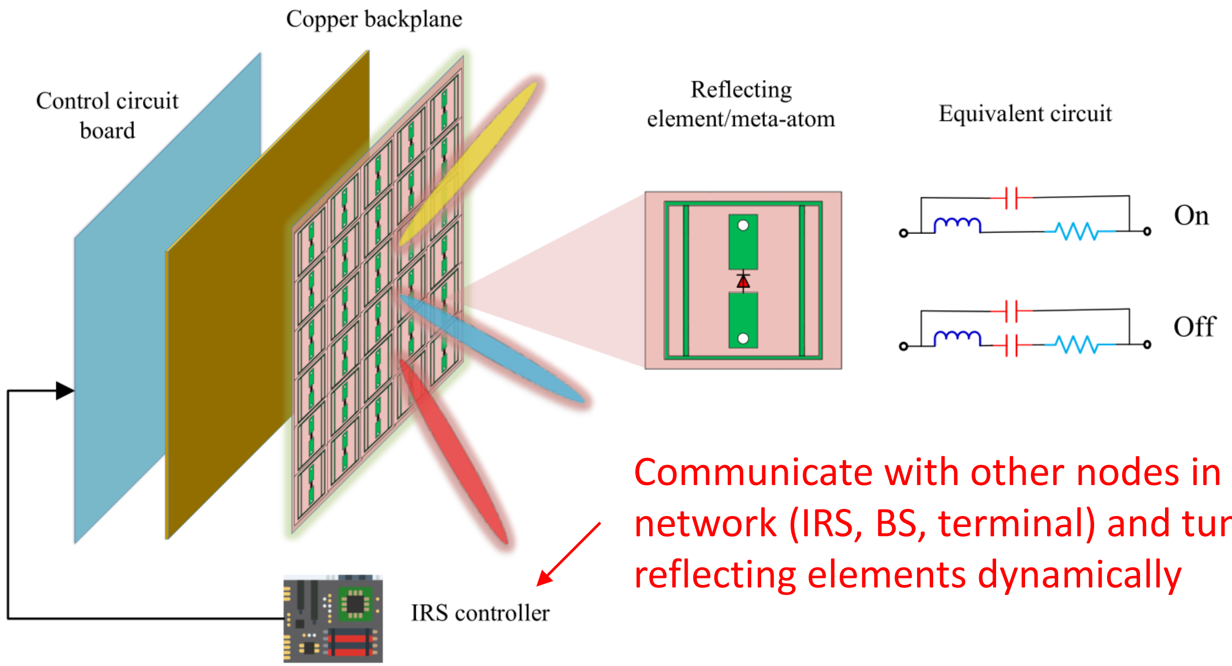
Have We Reached Shannon's Capacity Limit?

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



- Yes, also No (as wireless channel *H* is still random and uncontrolled)
  - ✓ Can we make *H* arbitrarily large, say from $H<<1$ to $H \rightarrow 1$?
  - ✓ 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 Programmable Wireless Environment
- Key enabling technology: Intelligent Reflecting Surface (IRS)
  - ➢ Other similar terms: reconfigurable intelligent surface (RIS), software controlled metasurface, passive intelligent mirror, smart reflect array, ….

What is IRS?

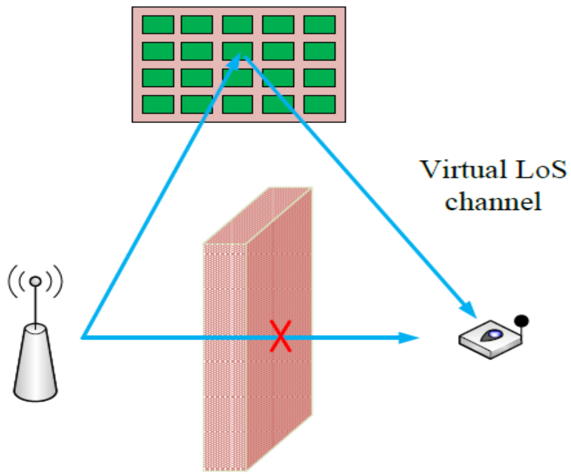


Communicate with other nodes in the network (IRS, BS, terminal) and tune the reflecting elements dynamically

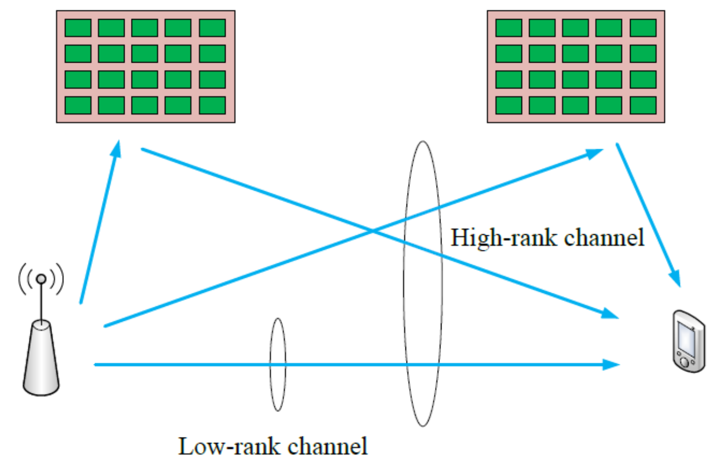
- IRS (Intelligent Reflecting Surface): Digitally-controlled metasurface (hardware) + smart controller (software)
- Passive reflection only, low energy consumption (without transmit/receive RF chains), high spectral efficiency (full-duplex, noise-free)

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

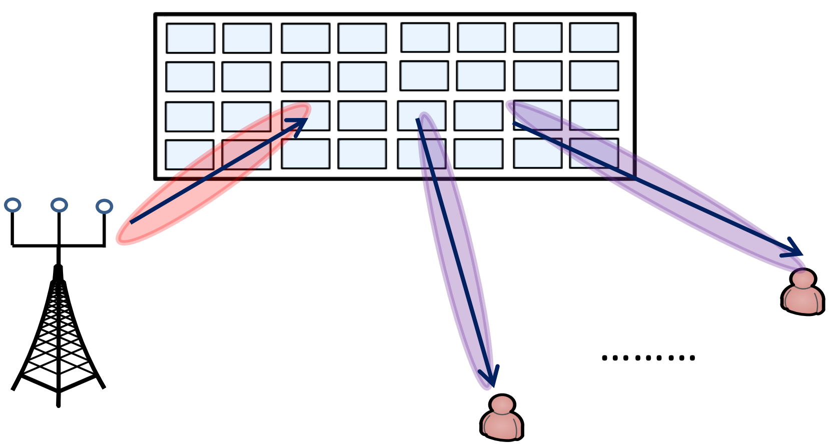
IRS Applications for Wireless Communications



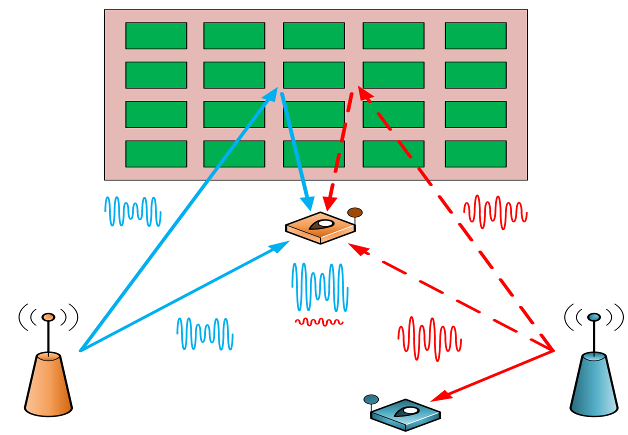
(a) Bypass obstruction



(b) Enhance MIMO channel rank



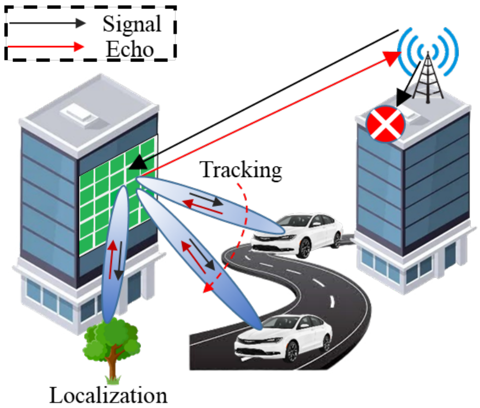
(c) Passive relaying/beamforming



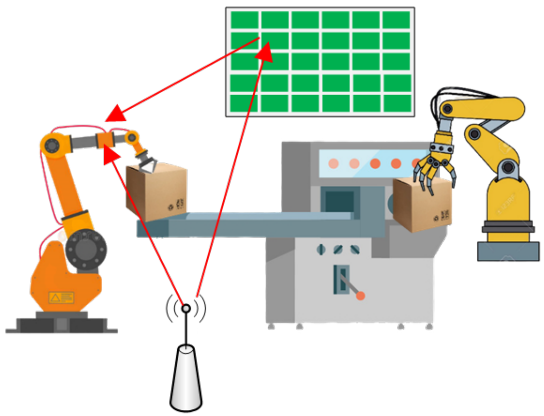
(d) Passive Interference Cancelation

Rui Zhang, National University of Singapore

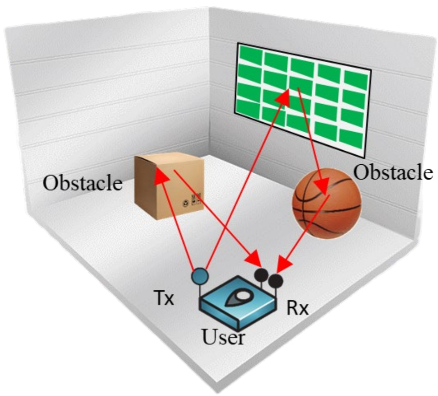
IRS Applications for Wireless "Sensing"



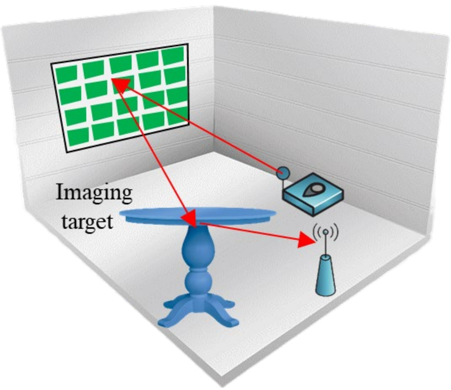
(a) Radar sensing (device-free sensing)



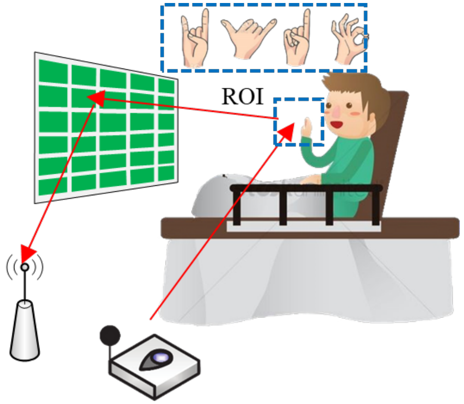
(b) Wireless localization (device-based sensing)



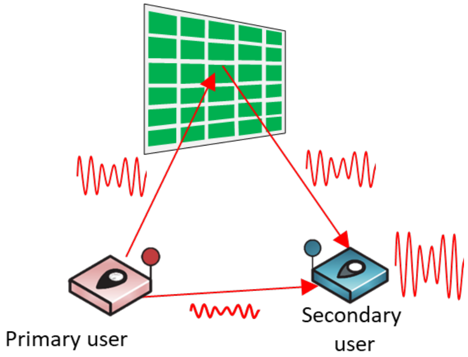
(c) Simultaneous localization and mapping



(d) Imaging

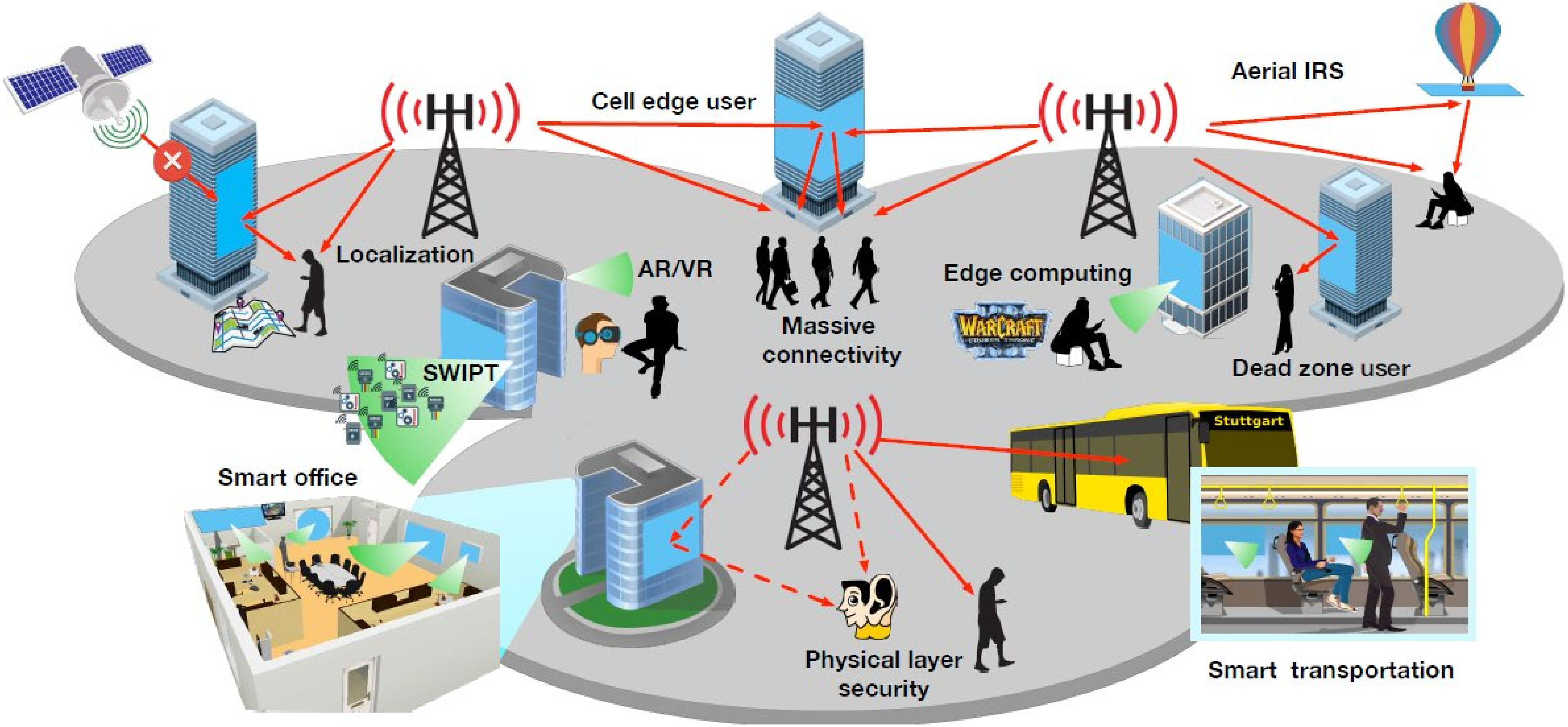


(e) Human activity recognition



(f) Spectrum sensing

IRS Applications for B5G/6G



Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface aided wireless communications: a tutorial," IEEE Transactions on Communications (Invited Paper), May 2021.

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- IRS-aided Wireless Communications
  - Overview of IRS-aided communications
  - Review of IRS-aided communication design and optimization with single-IRS-refection links
  - Recent progress:
    - Communication design with multi-IRS-reflection links
    - New IRS architectures
- IRS-aided Sensing
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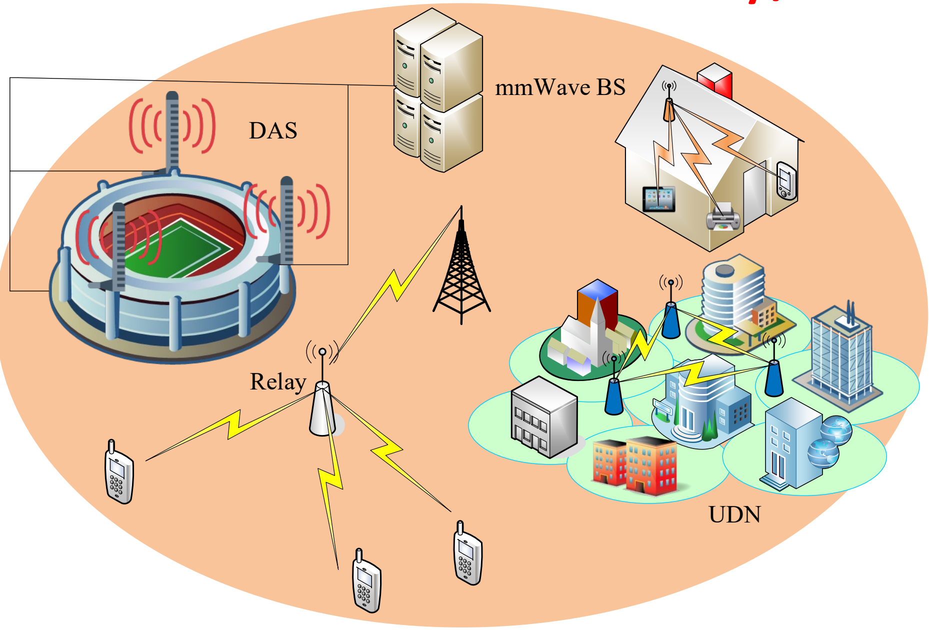
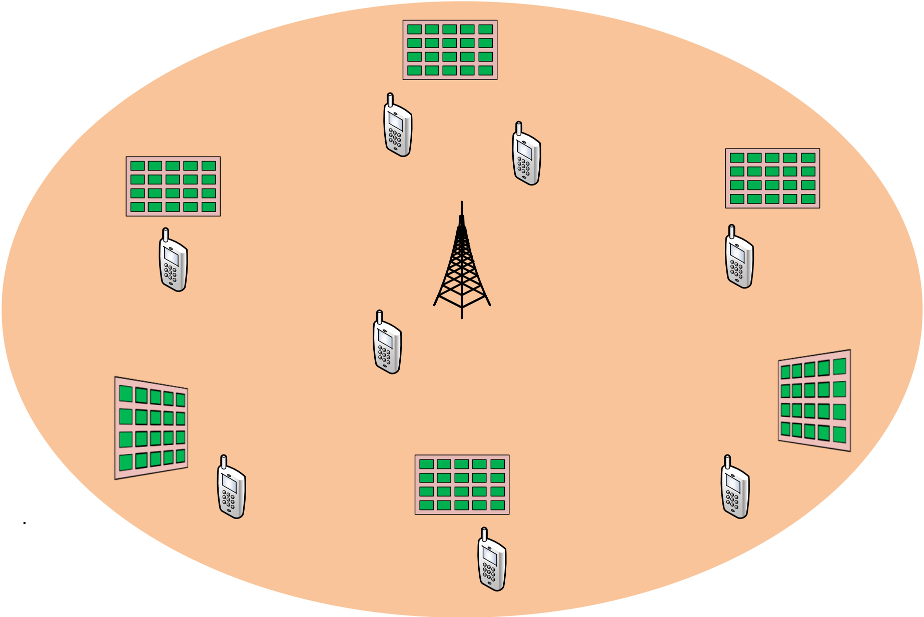
IRS vs Active Relay/Small Cell/DAS/Cell-free MIMO

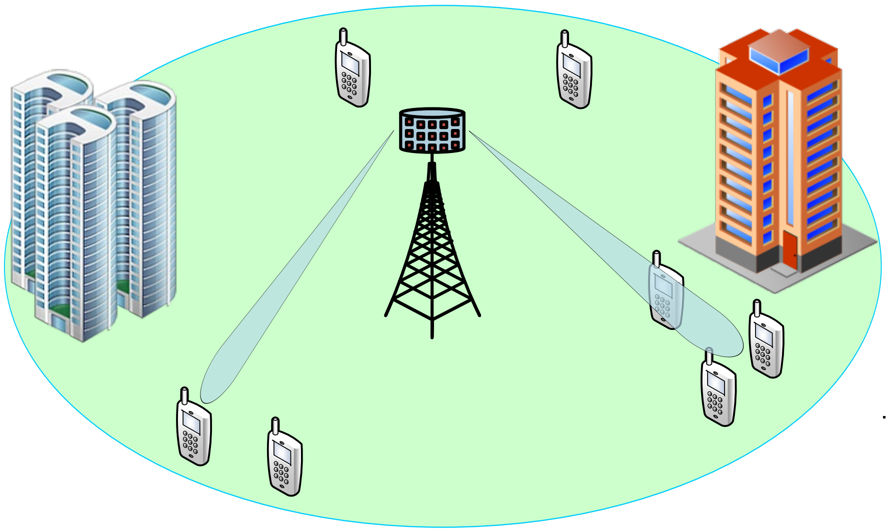




- Network with active BS/AP/relay only
- High cost, high energy consumption
- Backhaul issue
- Complicated interference management
- Low spectral efficiency due to half duplex (full-duplex radio needs costly self-interference cancelation)

- 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

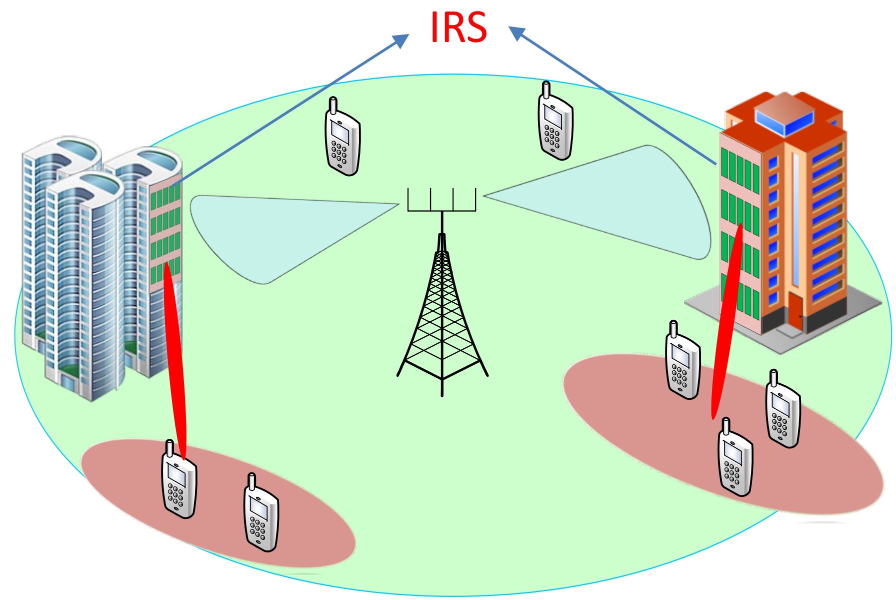
IRS vs Massive MIMO/Active Large Surface



Massive MIMO

(Non-scalable with increased frequency)

- More RF chains needed for more active elements used
- Increased energy consumption, hardware cost, and processing complexity at higher frequencies (mmWave, THz)

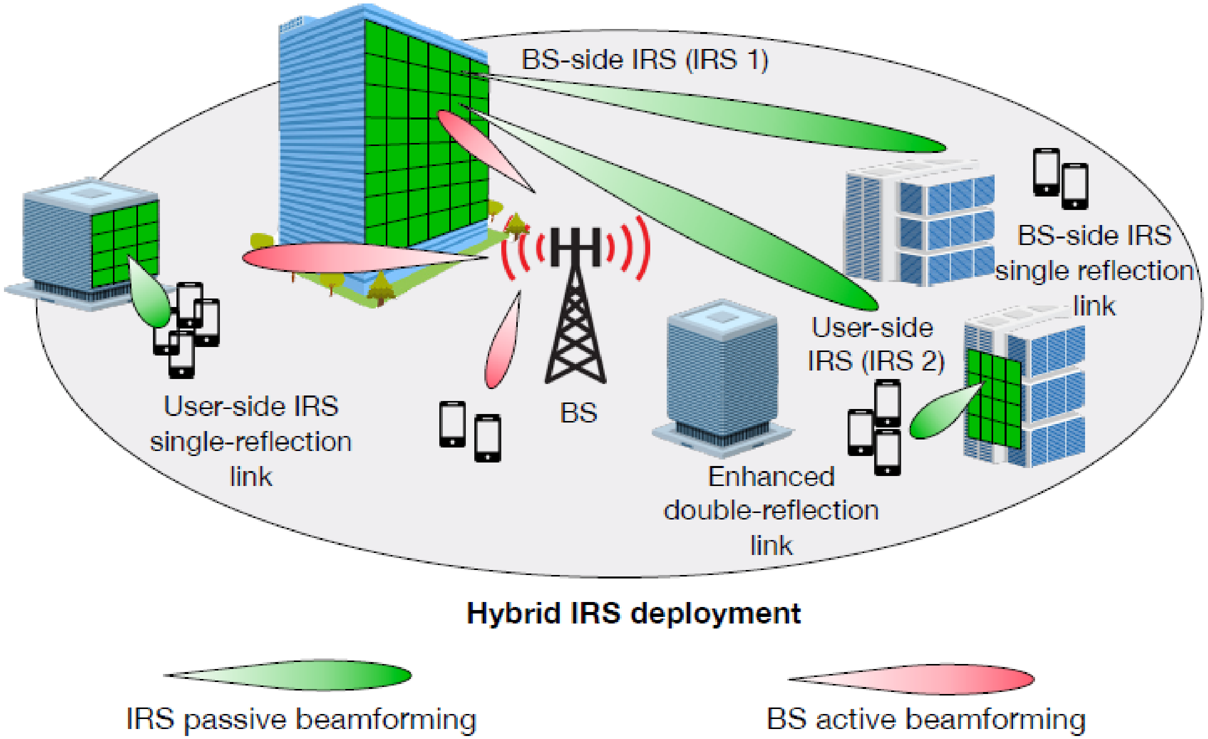


IRS-aided Small MIMO

(Scalable at any frequency)

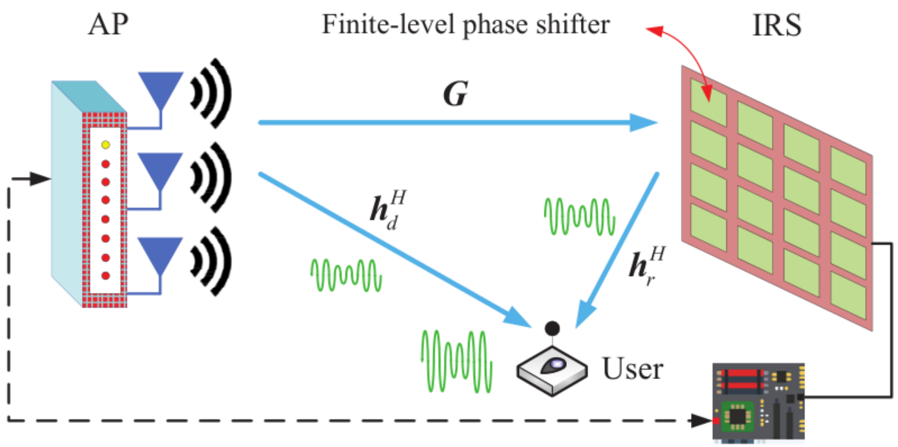
- No RF chains needed for IRS due to passive reflection only
- Low energy consumption, scalable cost/complexity
- Compatible with cellular/WiFi and can be densely deployed

IRS: New Communication Design Challenges



- ❑ Passive reflection optimization (single-reflection, multi-reflection, jointly with active beamforming/relaying)
- ❑ Channel acquisition (with/without sensors on IRS, passive beam training)
- ❑ IRS deployment (BS-side/user-side, centralized/distributed)

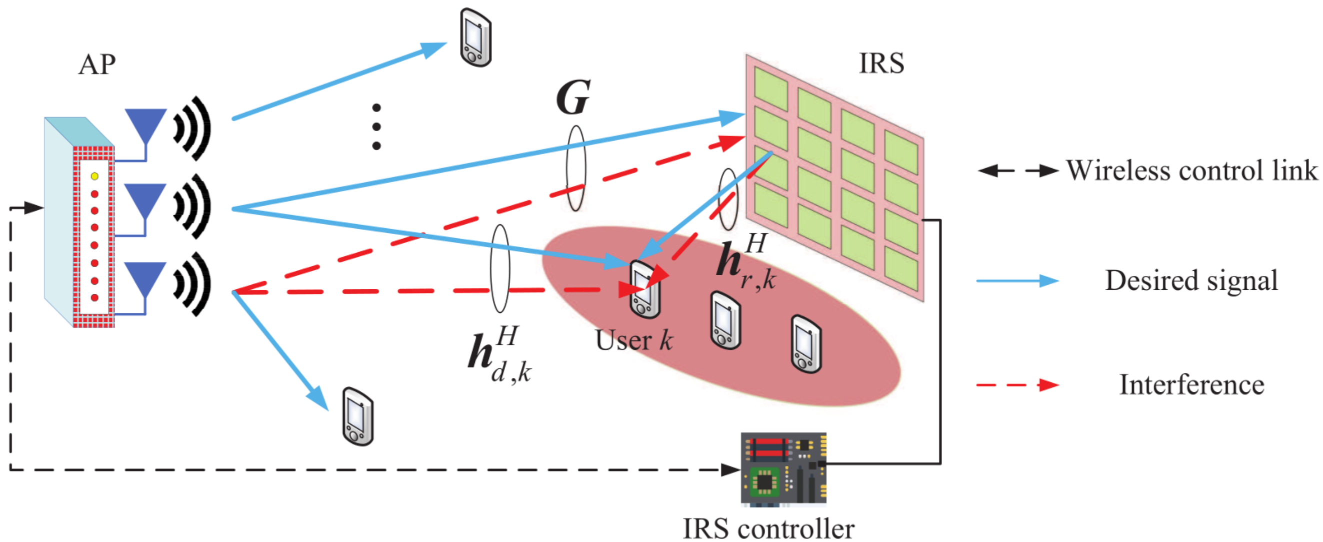
Joint Active and Passive Beamforming: Single-user Case



- 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

Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network: joint active and passive beamforming design," in Proc. IEEE GLOBECOM, 2018.
Q. Wu and R. Zhang, "Beamforming optimization for intelligent reflecting surface with discrete phase shifts," in Proc. IEEE ICASSP, 2019.

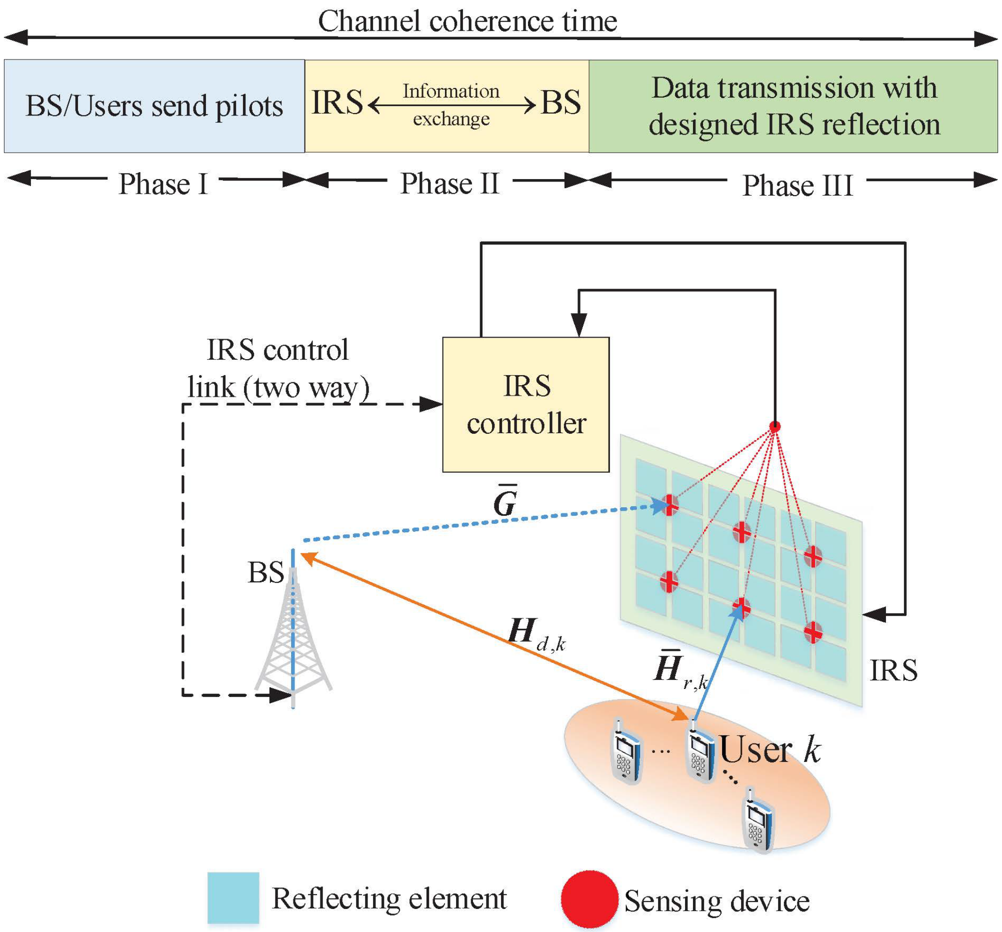
Joint Active and Passive Beamforming: Multi-user Case



- Objective: minimize total transmit power at the AP subject to individual user SINR constraints via joint transmit and reflect beamforming optimization
- Establish a "signal hotspot" as well as an "interference-free zone" near IRS
- Reflect beamforming by IRS
  - help enhance SINR of the users near IRS
  - Enable more flexible AP transmit beamforming toward users outside IRS coverage
  - Thereby improve the overall network SINR performance

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

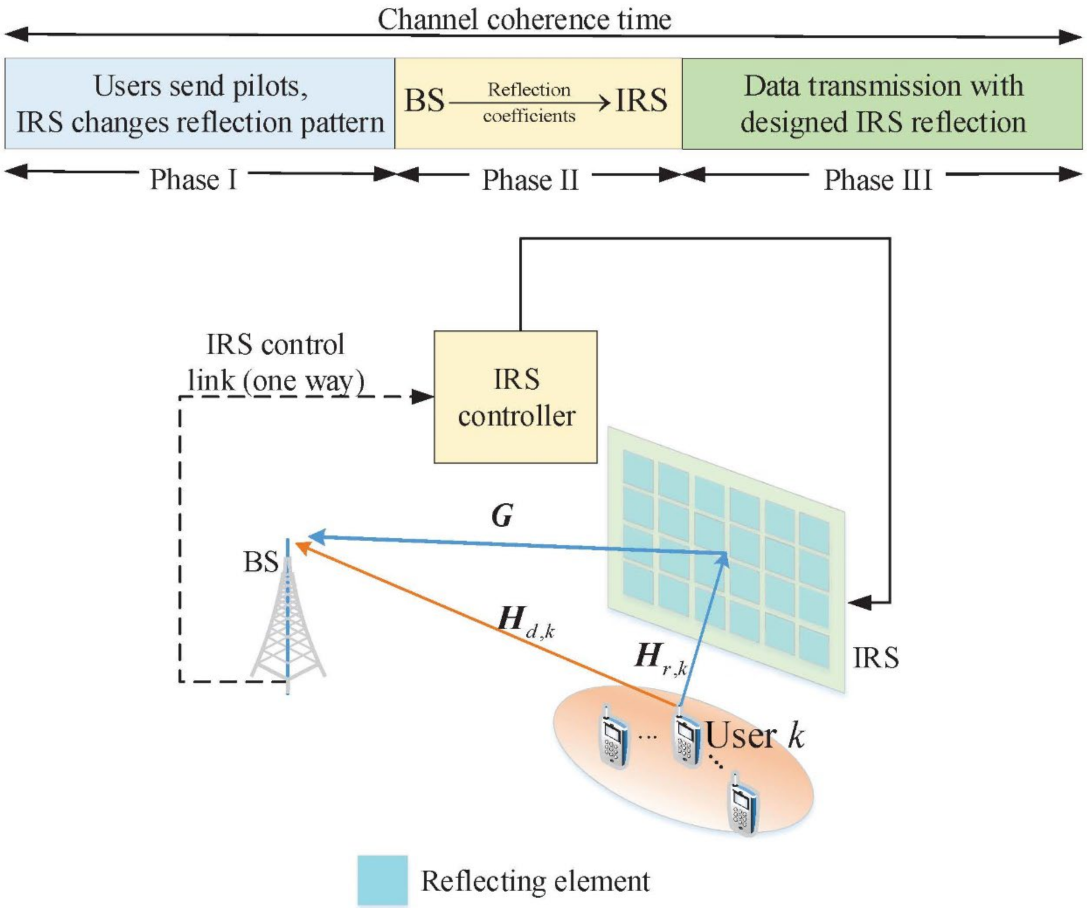
Channel Estimation with Semi-Passive IRS



- IRS with active elements /sensing devices
  - Channels estimated by IRS leveraging TDD and channel reciprocity
  - Signal processing required for reconstructing the IRS-BS/user channels with limited/low-cost sensors

Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface aided wireless communications: a tutorial," IEEE Transactions on Communications (Invited Paper), May 2021.

Channel Estimation with Fully-Passive IRS



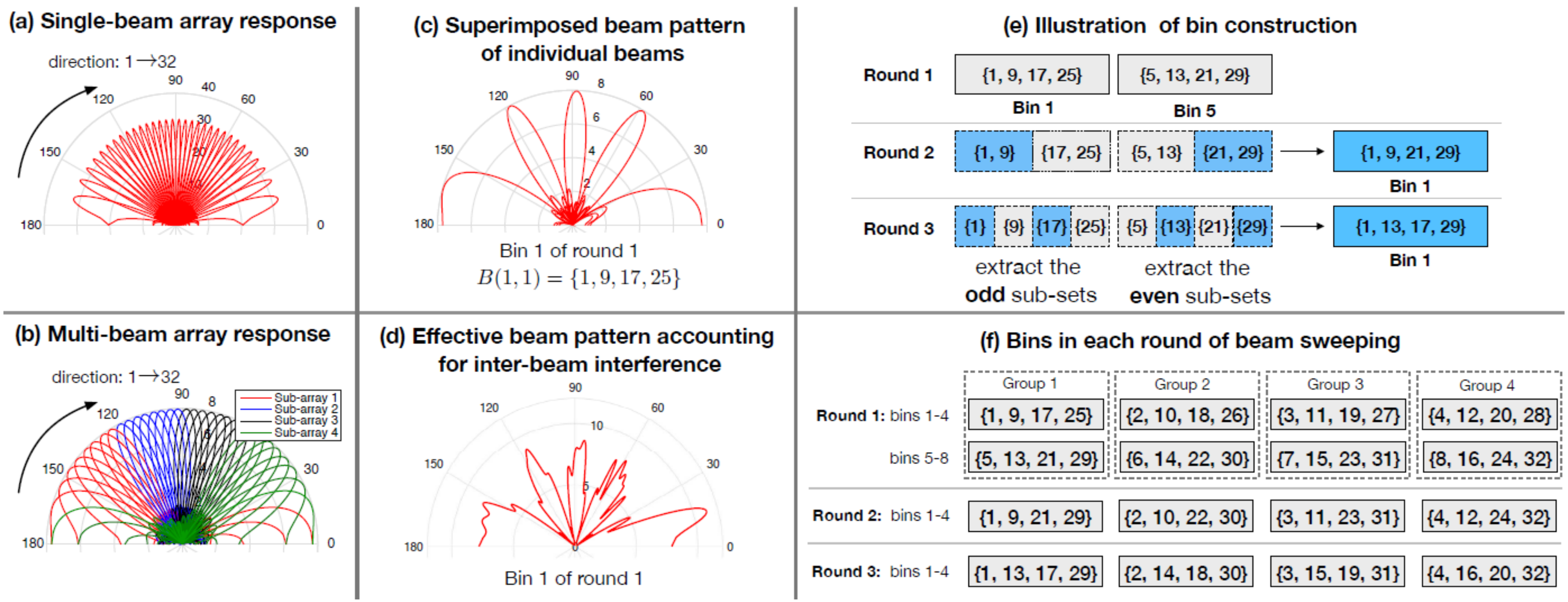
- IRS w/o active elements and sensing devices
  - More challenging case (as compared to semi-passive IRS)
  - Cascaded channel (BS-IRS-user) estimation by varying IRS reflection and exploiting the static/sparse BS-IRS channel (common for all users): an active area of research!

Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface aided wireless communications: a tutorial," IEEE Transactions on Communications (Invited Paper), May 2021.

Beam Searching without Explicit Channel Estimation

❑ Codebook-based IRS beam searching

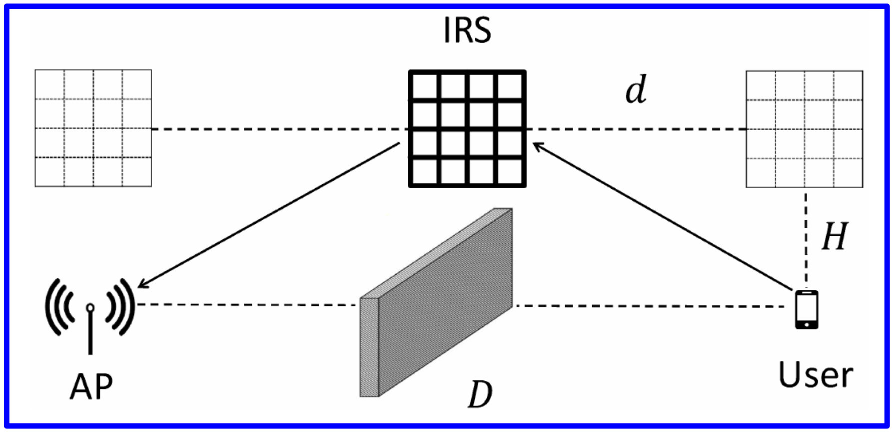
- Multi-beam training (new): divide IRS reflecting elements into sub-arrays and design their simultaneous multi-beam steering over time
- More efficient than conventional single-beam training

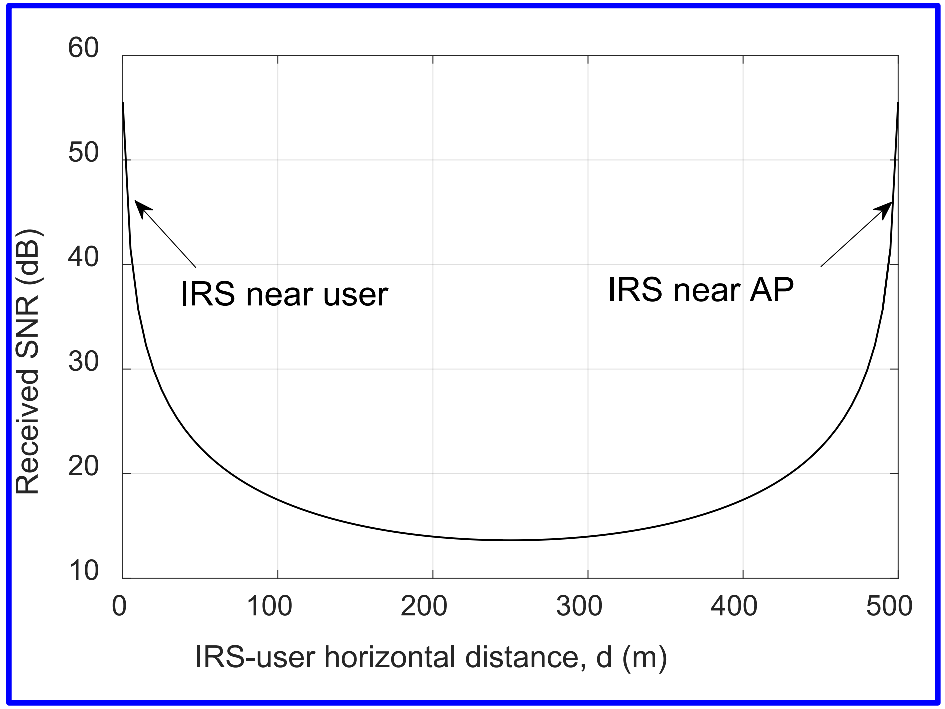


C. You, B. Zheng, and R. Zhang, "Fast beam training for IRS-assisted multiuser communications," IEEE Wireless Communications Letters, November 2020.

IRS Deployment: Single IRS

- Consider one single IRS with N reflecting elements, assume no direct link





- Double path loss (product distance)
  - Received SNR:

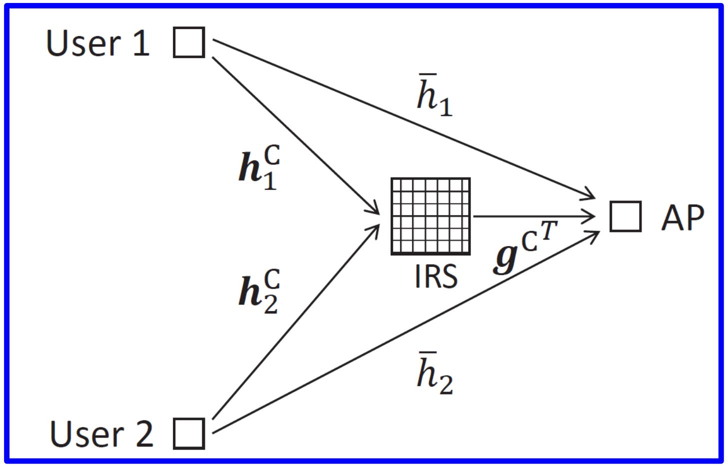
$$\rho_{\text{S}} = \frac{P\beta_0^2 N^2}{(d^2 + H^2)((D-d)^2 + H^2)\sigma^2}$$

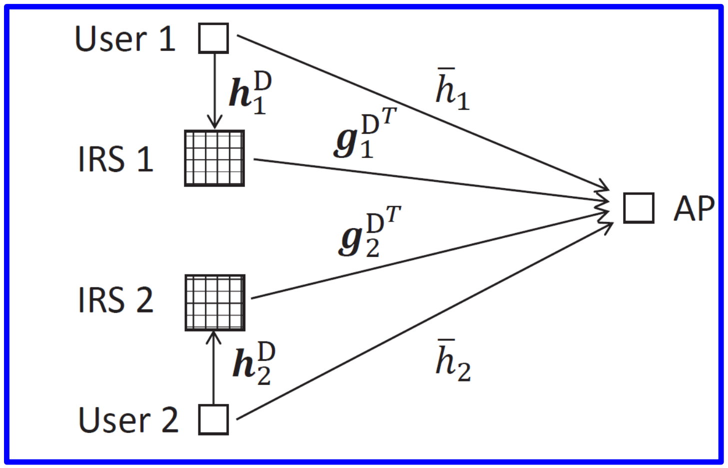
  - IRS-AP distance generally increases as the user-IRS distance decreases
- Optimal deployment strategy to maximize received SNR (minimize product distance): $d = 0$ (IRS near user) or $d = D$ (IRS near AP), different from active relay (d=D/2)
  - Maximum received SNR:

$$\rho_{\text{S}}^{\star} = \frac{P\beta_0^2 N^2}{H^2(D^2+H^2)\sigma^2} \approx \frac{P\beta_0^2 N^2}{H^2 D^2 \sigma^2}$$

IRS Deployment: BS-side or User-side IRS?

- **BS-side IRS:** Deploy all N reflecting elements near the AP
- **User-side IRS:** Deploy N_k elements near each user k, $\sum_{k=1}^{K} N_k = N$





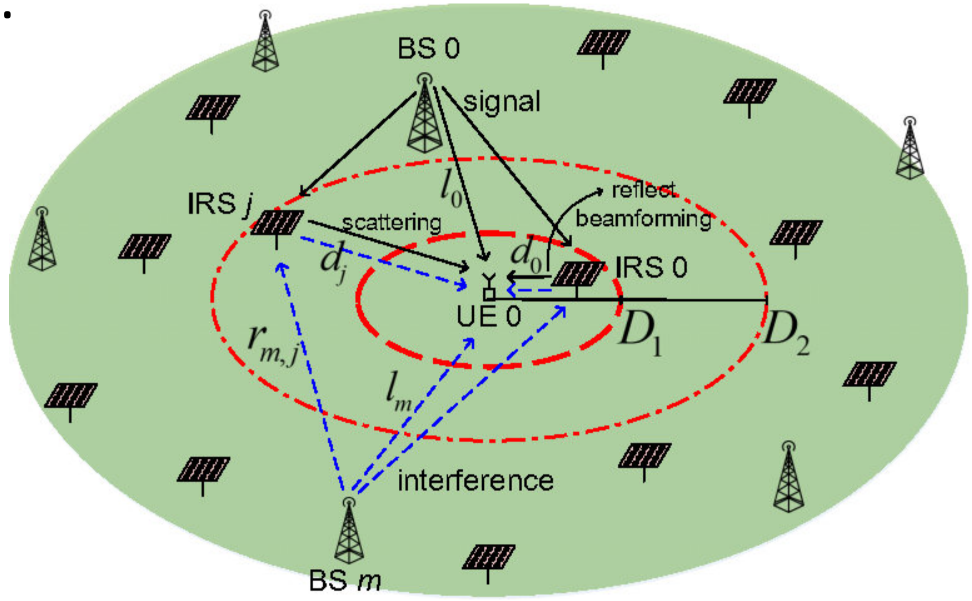
- Both users are served by the centralized IRS with N elements
  - Pros: Larger beamforming gain $\mathcal{O}(N^2)$
  - Cons: Beamforming gain needs to be shared by the two users

- Each user is only served by its nearby IRS with N_k ($N_k < N$) elements
  - Pros: Beamforming gain is maximized for each user
  - Cons: Only $\mathcal{O}(N_k^2)$ beamforming gain for each user

S. Zhang and R. Zhang, "Intelligent reflecting surface aided multi-user communication: capacity region and deployment strategy," IEEE Transactions on Communications, Sept. 2021.

Wireless Future: Hybrid Active/Passive Network with IRS

- A fundamental question for IRS:
  - Can large-scale deployment of IRSs provide cost-effective & sustainable capacity growth in wireless network?



- New hybrid active/passive network with IRS
  - Randomly distributed active BSs and passive IRSs subjected to inter-cell interference
  - Characterize network coverage probability and spatial throughput in terms of key system parameters including BS/IRS densities and network loading factor
- Analytical framework based on stochastic geometry

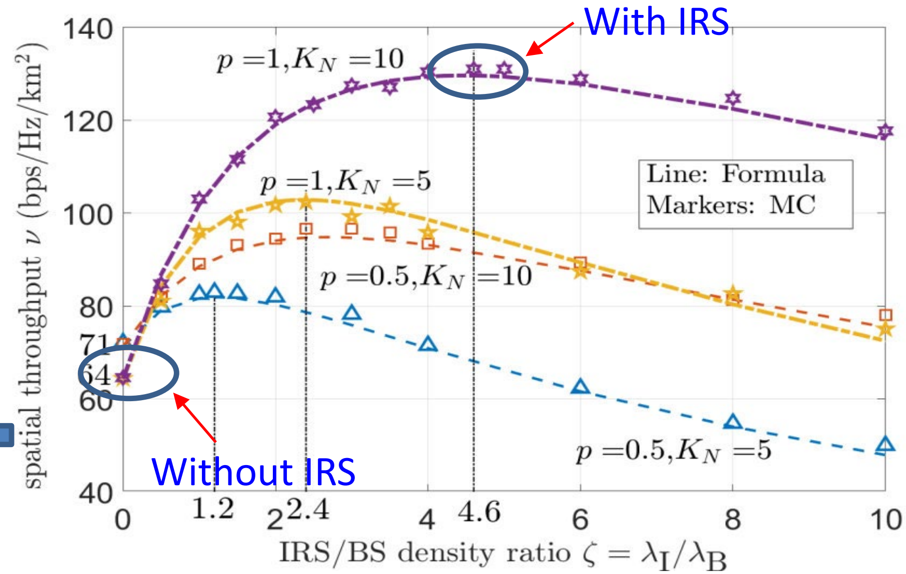
J. Lyu and R. Zhang, "Hybrid active/passive wireless network aided by intelligent reflecting surface: System modelling and performance analysis," IEEE Transactions on Wireless Communications, Nov. 2021.

Wireless Network Capacity With IRS vs W/o IRS

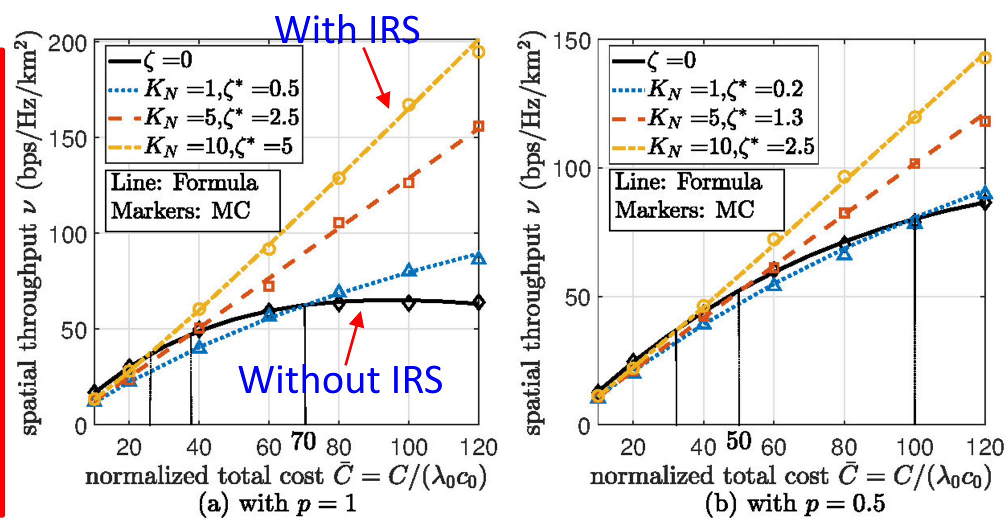
- Spatial throughput ν subject to total BS/IRS cost C
  - IRS/BS density ratio: $\zeta \triangleq \lambda_{\mathrm{I}}/\lambda_{\mathrm{B}}$
  - Cost of each BS: c_0 , BS/IRS cost ratio: K_N
  - Total cost C per m² in the hybrid network:

$$C \triangleq \lambda_{\mathrm{B}} c_0 + \lambda_{\mathrm{I}} c_0 / K_N = \lambda_{\mathrm{B}} c_0 (1 + \zeta / K_N)$$

- ν versus ζ under given total cost C:
  - Optimal ratio ζ^* to achieve maximum ν^* exists
  - Significantly outperforms BS-only network (ζ=0)
  - ζ too large: no enough signal power for effective IRS reflection and beamforming



- ν versus C under given density ratio ζ :
  - BS-only network: ν first increases then decreases due to more severe interference than improved signal power
  - Hybrid network with optimal ζ^* : maximum ν^* increases almost linearly with C → cost-effective and sustainable capacity growth



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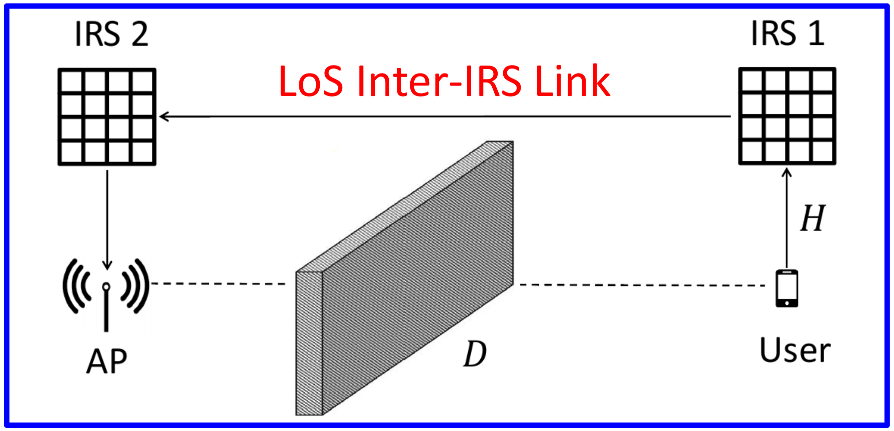
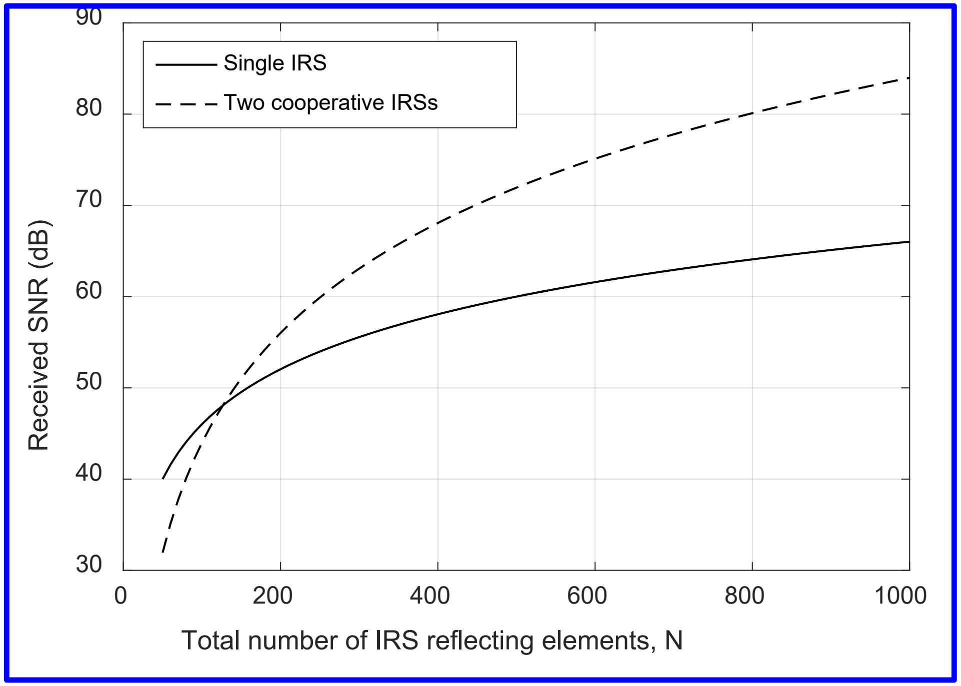
IRS Deployment: Double IRS

- Given N IRS reflecting elements, forming them as two cooperative IRSs



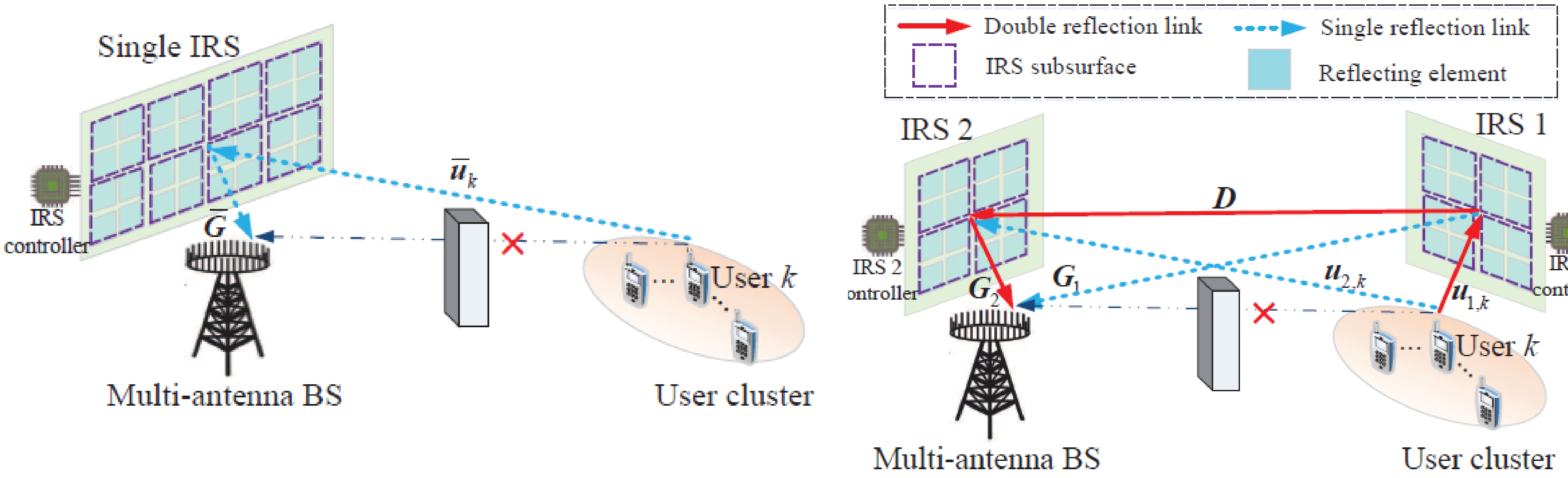


- Pros: Cooperative beamforming gain with order $\mathcal{O}((N/2)^4)$ (vs. $\mathcal{O}(N^2)$ for single-IRS case)
- Cons: Double reflection, more path loss
- Received SNR: $$\rho_{\mathrm{D}} = \frac{P\beta_0^3 N^4}{16H^4D^2\sigma^2}$$
- Two cooperative IRSs outperform one single IRS if $N > \frac{4H}{\sqrt{\beta_0}}$

Y. Han, S. Zhang, L. Duan, and R. Zhang, "Cooperative double-IRS aided communication: beamforming design and power scaling," IEEE Wireless Communications Letters, August 2020.

General Channel Case: Single-IRS or Double-IRS?

- Consider multi-antenna BS, all single- and double-reflection links



- Double IRS generally outperforms single IRS at any SNR (theoretically proved if K=1 or single-user case)
- Double IRS also provides larger effective channel rank than single IRS (thus, higher spatial multiplexing gain)

B. Zheng, C. You, and R. Zhang, "Double-IRS assisted multi-user MIMO: cooperative passive beamforming design," IEEE Transactions on Wireless Communications, July 2021.

Double-IRS Channel Estimation

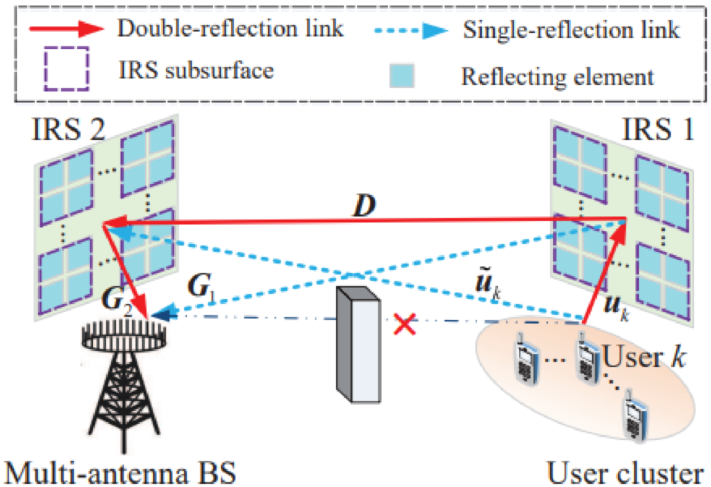
- C. You, B. Zheng, and R. Zhang, “Wireless communication via double IRS: channel estimation and passive beamforming designs,” IEEE Wireless Communications Letters, vol. 10, no. 2, pp. 431-435, February 2021.
- B. Zheng, C. You, and R. Zhang, “Efficient channel estimation for double-IRS aided multi-user MIMO system,” IEEE Transactions on Communications, vol. 9, no. 6, pp. 3818-3832, June 2021.

Double-IRS Channel Estimation

- ✓ K: Number of users in the cluster
- ✓ N: Number of antennas at the BS
- ✓ M_1: Number of reflecting units at IRS 1
- ✓ M_2: Number of reflecting units at IRS 2

- Effective channel from user *k* to the BS

$$\boldsymbol{h}_k = \underbrace{\boldsymbol{G}_2\boldsymbol{\Phi}_2\boldsymbol{D}\boldsymbol{\Phi}_1\boldsymbol{u}_k}_{\text{One double-reflection link}} + \underbrace{\boldsymbol{G}_2\boldsymbol{\Phi}_2\tilde{\boldsymbol{u}}_k + \boldsymbol{G}_1\boldsymbol{\Phi}_1\boldsymbol{u}_k}_{\text{two single-reflection links}}$$



- For fully passive IRSs without any receiving/transmitting capability, it is infeasible to acquire the CSI between the two IRSs as well as that with the BS/users separately

- With some transformations, the channel model can be equivalently expressed as (in terms of cascaded CSI)

$$\boldsymbol{h}_k = \sum_{m=1}^{M_1} \underbrace{\boldsymbol{G}_2 \operatorname{diag}\left(\tilde{\boldsymbol{d}}_{k,m}\right)}_{\boldsymbol{Q}_{k,m}} \boldsymbol{\theta}_2 \theta_{1,m} + \tilde{\boldsymbol{R}}_k \boldsymbol{\theta}_2 + \boldsymbol{R}_k \boldsymbol{\theta}_1$$

- Number of channel coefficients $K \times NM_1M_2 \gg K \times N(M_1 + M_2)$

Much higher-order!!!

- **Challenge:** Double-IRS channel may require significantly more training overhead that renders much less or even no time for data transmission

Double-IRS Channel Estimation

☐ Channel relationship

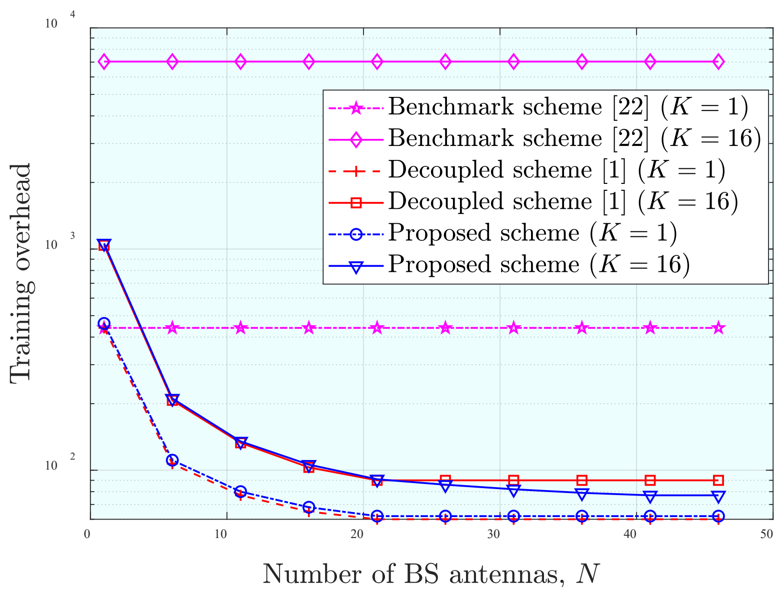
➢ Single-user case

(High-dimensional) Double-reflection channel:

$$\boldsymbol{Q}_m = \underbrace{\boldsymbol{G}_2 \operatorname{diag}(\tilde{\boldsymbol{u}})}_{\tilde{\boldsymbol{R}}} \cdot \underbrace{\operatorname{diag}(\tilde{\boldsymbol{u}})^{-1} \operatorname{diag}\left(\tilde{\boldsymbol{d}}_m\right)}_{\operatorname{diag}(\boldsymbol{a}_m)}$$

⇩ Single-reflection channel

⇩ **(Low-dimensional)** Scaling vector



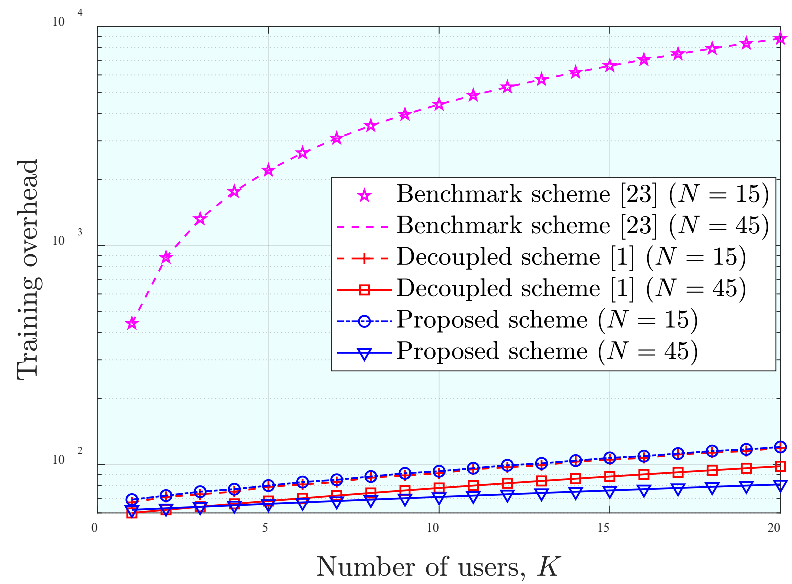
➢ Multi-user case

$$\boldsymbol{R}_k = \boldsymbol{G}_1 \operatorname{diag}(\boldsymbol{u}_1) \cdot \operatorname{diag}(\boldsymbol{u}_1)^{-1} \boldsymbol{u}_k = \boldsymbol{R}_1 \operatorname{diag}(\boldsymbol{b}_k)$$

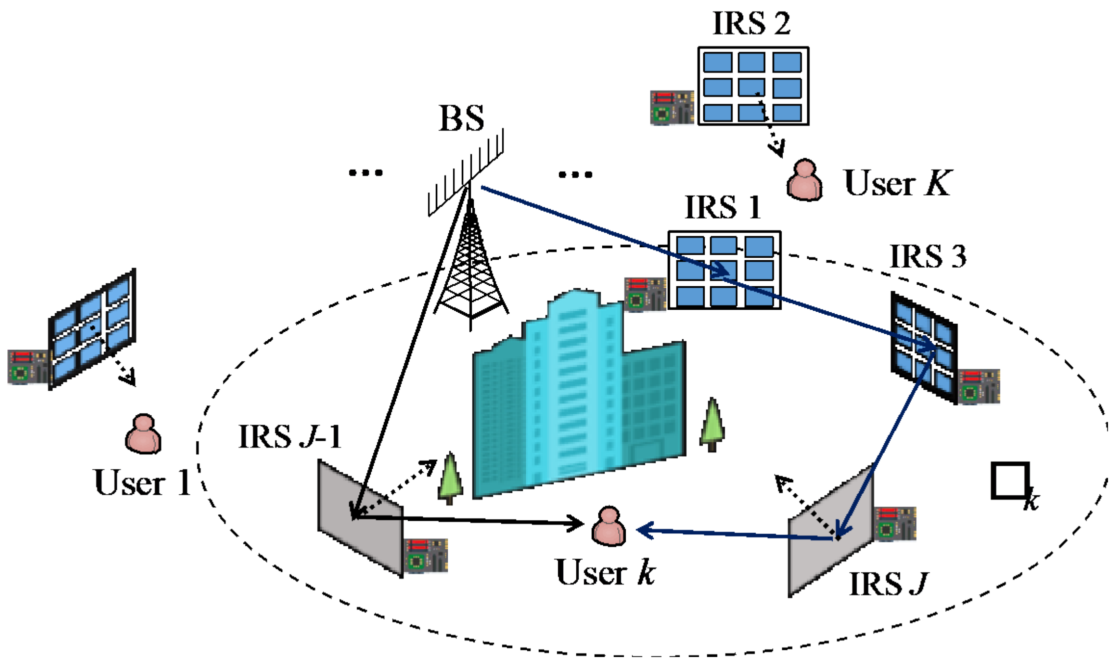
$$\tilde{\boldsymbol{R}}_k = \boldsymbol{G}_2 \operatorname{diag}(\tilde{\boldsymbol{u}}_1) \cdot \operatorname{diag}(\tilde{\boldsymbol{u}}_1)^{-1} \tilde{\boldsymbol{u}}_k = \tilde{\boldsymbol{R}}_1 \operatorname{diag}\left(\tilde{\boldsymbol{b}}_k\right)$$

$$Q_{k,m} = G_2 \operatorname{diag}(d_m u_{1,m}) \cdot u_{1,m}^{-1} u_{k,m} = Q_{1,m} b_{k,m}$$

⇩ Reference CSI (user 1)



Dense-IRS Aided Wireless Network: Beam Routing Approach

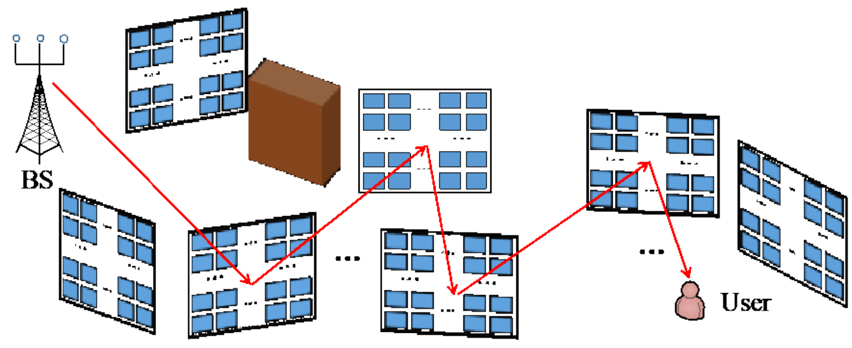


- The multi-IRS aided multi-reflection system provides more pronounced cooperative passive beamforming (CPB) and LoS path diversity gains for each user as compared to single-/double-reflection systems
- The inter-IRS CPB gain can compensate for their (higher) multiplicative path loss
- The LoS path diversity can help create multiple blockage-free links for each user

W. Mei, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface aided wireless networks: from single-reflection to multi-reflection design and optimization," to appear in Proceedings of the IEEE (Invited Paper)

Multi-IRS Cooperative Beam Routing: Single-User Case

- Cooperative beam routing problem
  - ✓ Jointly optimize LoS path selection and active/passive beamforming at the BS/selected IRSs



- Maximum end-to-end channel power gain for a given multi-reflection link Ω by the optimal BS/IRS beamforming

CPB gain
"product" path loss

$$|h_{0,J+1}(\Omega)|^2 = \frac{M^{2K} N \beta^{K+1}}{d_{0,a_1}^2 d_{a_K,J+1}^2 \prod_{k=1}^{K-1} d_{a_k,a_{k+1}}^2}$$

- Fundamental trade-off
  - ✓ Cooperative passive beamforming gain (which increases with the number of reflections, K)
  - ✓ End-to-end "product-distance" path loss (which also increases with K)

- LoS path selection problem

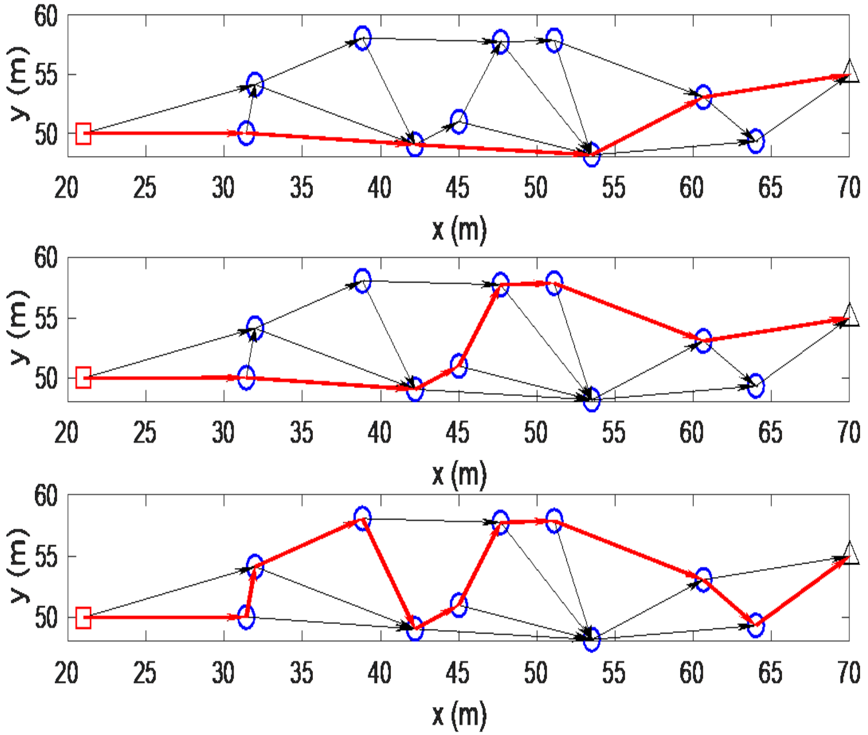
$$\max_{\Omega} |h_{0,J+1}(\Omega)|^2, \quad \text{s.t. } u_{a_i,a_{i+1}} = 1, 0 \le i \le K$$

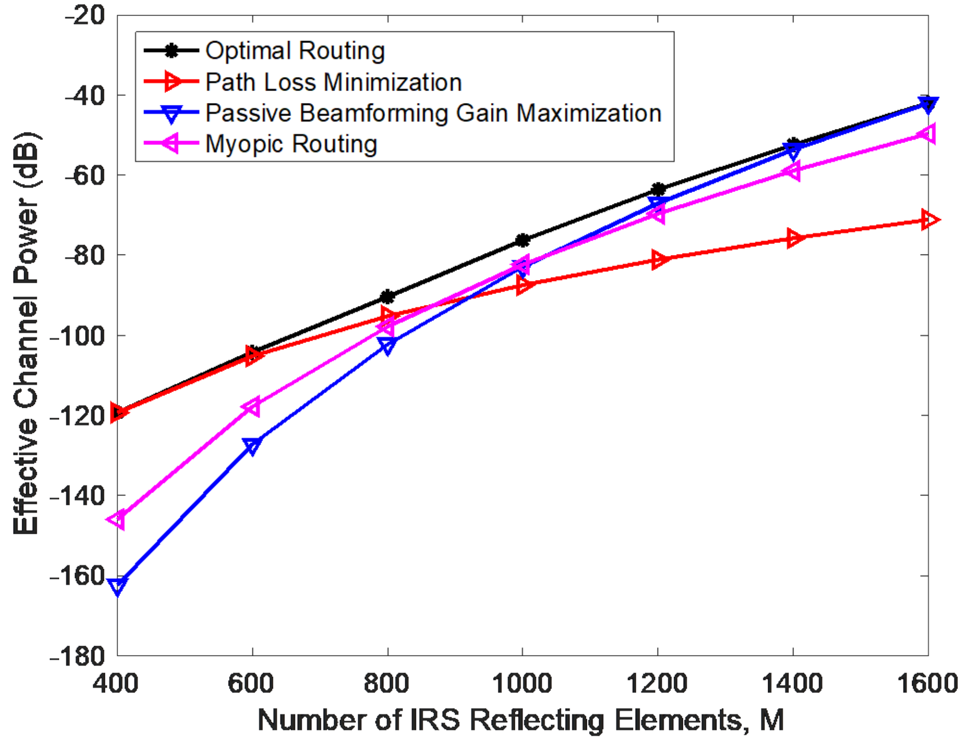
Each constituent link of Ω has an LoS path

  - ✓ Select the best LoS path among all paths
  - ✓ Equivalent to the shortest path problem in graph theory

W. Mei and R. Zhang, "Cooperative beam routing for multi-IRS aided communication," IEEE Wireless Communications Letters, February 2021.

Effective Channel Power vs No. of IRS Elements



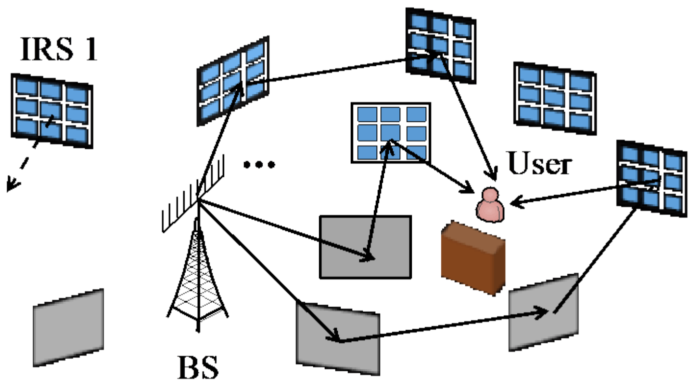


No. of IRS elements: 400, 700, 1500 (top to bottom)

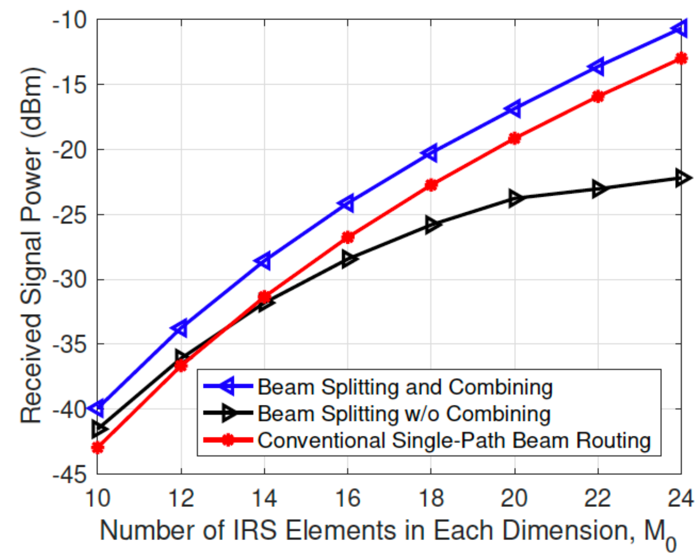
- Small No. of IRS elements: Minimizing end-to-end path-loss is optimal
- Large No. of IRS elements: Maximizing the cooperative passive beamforming gain is optimal
- In general, need to optimally balance the above two objectives

Multi-IRS Beam Routing: Beam Splitting and Combining

- Conventional single-path beam routing
  - ✓ Fail to leverage all available IRSs and their LoS path diversity
- General multi-path beam routing
  - ✓ Active beam splitting: The BS sends the user's information signal via multiple active beams pointing to different IRSs
  - ✓ Passive beam combining: The beamed signals are reflected by selected IRSs in different paths, and finally coherently combined at the user's receiver



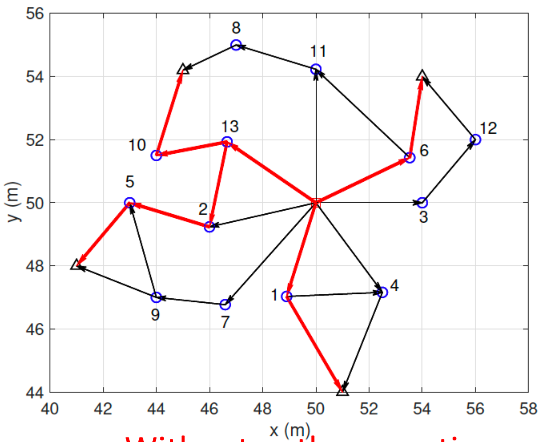
- Problem formulation
  - ✓ Jointly optimize the number of IRS reflection paths, the selected IRSs for each path, the BS/IRS beamforming, and the BS's power allocation over different active beams, to maximize the user's received signal power
- The optimized multi-path beam routing outperforms its single-path special case



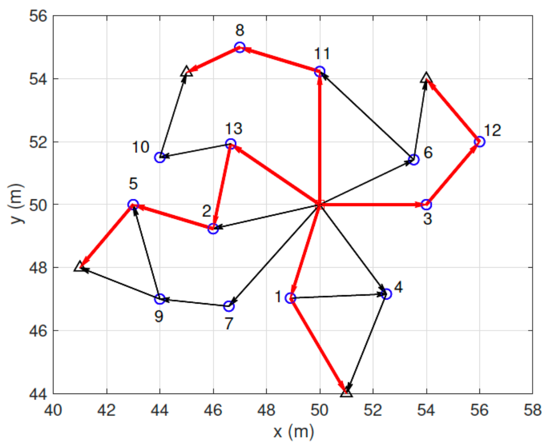
W. Mei and R. Zhang, "Intelligent reflecting surface for multi-path beam routing with active/passive beam splitting and combining," to appear in IEEE Communications Letters.

Multi-IRS Cooperative Beam Routing: Multi-User Case

- Multi-beam routing for multiple users
  - ✓ In contrast to single-user beam routing, a new challenge is how to avoid the inter-user/inter-beam interference due to IRSs' undesired scattering
  - ✓ Path separation constraints: the IRSs selected for different users/paths should avoid having strong/LoS channels with each other
  - ✓ Then the optimal BS/IRS beamforming is similarly designed as in the single-user beam routing



Without path separation



With path separation

- Problem formulation

$$\max_{\{\Omega^{(k)}\}_{k\in\mathcal{K}}} \min_{k\in\mathcal{K}} |h_{0,J+k}(\Omega^{(k)})|^2,$$

$$\text{s.t. } u_{a_i^{(k)},a_{i+1}^{(k)}} = 1, 1 \le i \le n_k, k \in \mathcal{K},$$ (Each constituent link of Ω has an LoS path)

$$u_{a_i^{(k)},a_{i'}^{(k')}} = 0,\ a_i^{(k)} \neq a_{i'}^{(k')}, \forall i, i' \neq 0, k, k' \in \mathcal{K}, k \neq k'.$$

(Path separation constraints)

- ✓ An NP-complete problem
- ✓ Solved by the graph theoretic clique-based approach

W. Mei and R. Zhang, "Multi-beam multi-hop routing for intelligent reflecting surfaces aided massive MIMO," IEEE Transactions on Wireless Communications, March 2022.

Distributed Beam Training for Multi-IRS-Reflection System

- W. Mei and R. Zhang, "Distributed beam training for intelligent reflecting surface enabled multi-hop routing," IEEE Wireless Communications Letters, Nov. 2021.

Distributed Beam Training for Dense/Multi-IRS System

- ❑ Channel estimation for the general multi-IRS system becomes more challenging
  - ➢ An excessively large number of IRS-associated channel coefficients (BS-IRS, inter-IRS, and IRS-user channels) to be estimated
  - ➢ Existing cascaded channel estimation techniques are inapplicable to the multi-reflection channels
- ❑ Beam training becomes more practical
  - ➢ Real-time optimal beam training may still incur practically prohibitive training time
- ❑ Distributed beam training
  - ➢ Leverage the offline cooperative beam training among the BS and IRSs' controllers
  - ➢ The BS and all IRSs create local beam training tables and exchange them with each other to facilitate the optimal BS/IRS beamforming and LoS path selection design

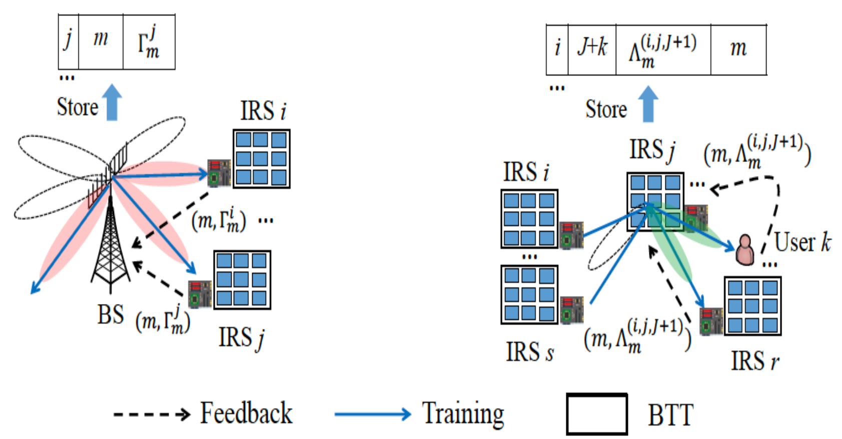
Next node (IRS)	Active beamforming index	Channel gain
1	1	$\Gamma_1^1 = -40$ dBm
1	3	$\Gamma_3^1 = -35$ dBm
…	…	…
1	D_B	$\Gamma_{D_B}^1 = -33$ dBm
…	…	…
15	1	$\Gamma_1^{15} = -34$ dBm
…	…	…
15	D_B-1	$\Gamma_{D_B-1}^{15} = -36$ dBm

(a) Local BTT at the BS

Previous node (BS/IRS)	Next node (IRS/user)	Channel gain	Passive beamforming index
0	3	$\Lambda_1^{0,j,3} = -40$ dBm	1
…	…	…	…
0	3	$\Lambda_{D_I}^{0,j,3} = -46$ dBm	D_I
…	…	…	…
5	8	$\Lambda_2^{5,j,8} = -48$ dBm	2
…	…	…	…
5	8	$\Lambda_{D_I}^{5,j,8} = -50$ dBm	D_I

Offline (with BS/IRS) Online (with user)

(b) Local BTT at IRS j



(c) Active beam training

(d) Passive beam training

Outline

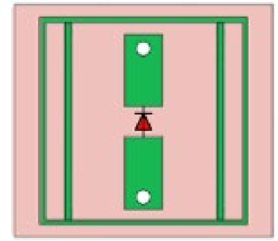
- ❑ Intelligent Reflecting Surfaces (IRS): Motivation and Applications
- ❑ IRS-aided Wireless Communications
  - ❑ Overview of IRS-aided communications
  - ❑ Review of IRS-aided communication design and optimization with single-IRS-refection links
  - ❑ Recent progress:
    - ❑ Communication design with multi-IRS-reflection links
    - ❑ New IRS architectures
- ❑ IRS-aided Sensing
- ❑ Conclusions

Active IRS

- C. You and R. Zhang, "Wireless communication aided by intelligent reflecting surface: active or passive?" IEEE Wireless Communications Letters, Dec. 2021.

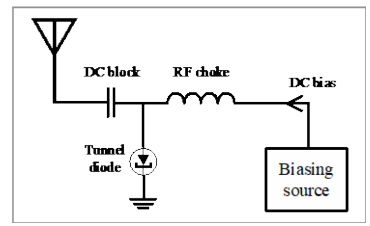
Active IRS

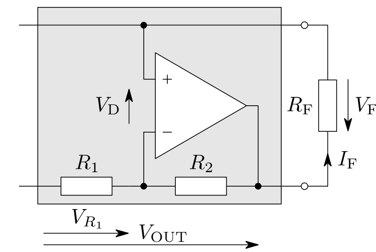
- Passive IRS
  - Reflection only, positive resistance
  - Limitation: low reflection gain
  - Solution: more reflecting elements, proper IRS deployment



- New active IRS (reflection-type amplifier)
  - Negative resistance: tunnel diode and negative impedance converter (NIC)
  - New function: reflection power amplification

$$\mathbf{\Psi} = \mathrm{drag}(\eta_1 e^{j\phi_1}, \cdots, \eta_N e^{j\phi_N}) \quad \eta_n \geq 1, \forall n.$$





	Operation mechanism	Amplification factor	Duplex	Hardware cost	Energy consumption
Active IRS	Active, reflect and amplify	Relatively low	Full duplex	Low	Moderate
Passive IRS	Passive, reflect	–	Full duplex	Very low	Very low
AF Relay	Active, receive and amplify	High	Full/half duplex	High	High

Active IRS vs. Passive IRS

- New design considerations for active IRS:
  - Amplification factor per element
  - Limited amplification power
- Joint deployment, reflection amplitude and phase optimization for active IRS:

$$\max_{\boldsymbol{\Theta},\eta,x_{\mathrm{AI}},x_{\mathrm{IU}}} \log_2\left(1+\frac{P_{\mathrm{A}}|\boldsymbol{h}_{\mathrm{IU}}^H\eta\boldsymbol{\Theta}\boldsymbol{h}_{\mathrm{AI}}|^2}{\|\boldsymbol{h}_{\mathrm{IU}}^H\eta\boldsymbol{\Theta}\|^2\sigma_{\mathrm{F}}^2+\sigma^2}\right)$$

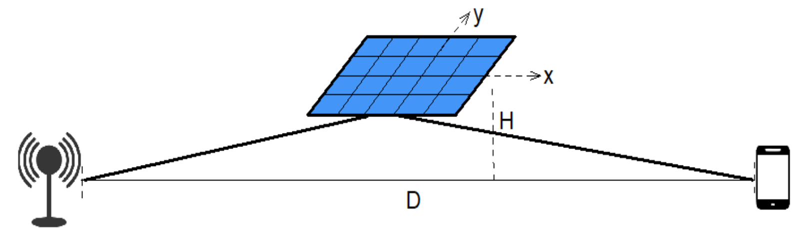
$$\text{s.t.}\quad |[\boldsymbol{\Theta}]_n|=1,\quad \forall n\in\mathcal{N},$$

$$x_{\mathrm{AI}}+x_{\mathrm{IU}}=D,$$

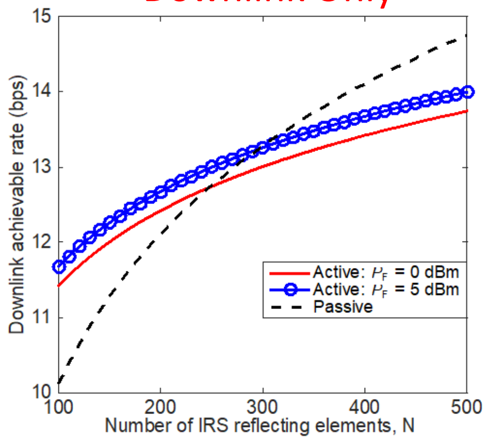
$$x_{\mathrm{AI}}\geq 0, x_{\mathrm{IU}}\geq 0,$$

$$\eta\geq 1,$$

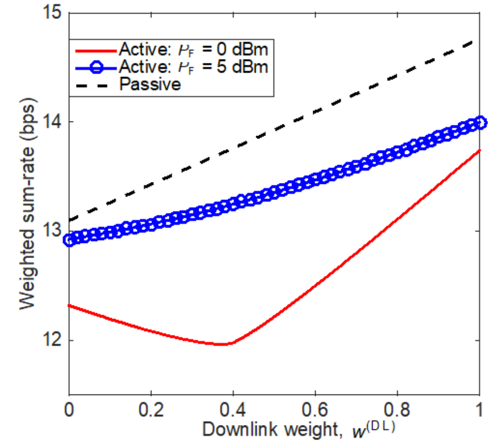
$$\eta^2(P_{\mathrm{A}}\|\boldsymbol{\Theta}\boldsymbol{h}_{\mathrm{AI}}\|^2+\sigma_{\mathrm{F}}^2\|\boldsymbol{\Theta}\mathbf{I}_N\|^2)\leq P_{\mathrm{F}}$$



Downlink Only



Downlink and Uplink

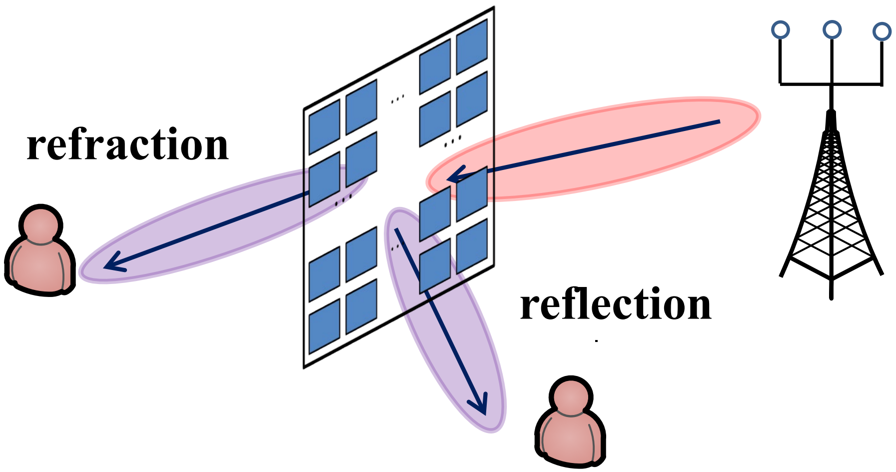


- Optimal Deployment
  - ✓ **Active IRS: closer to receiver with decreasing IRS reflection power, thus needs to balance uplink and downlink transmissions for practical deployment**
  - ✓ Passive IRS: close to transmitter or receiver, no much difference for uplink and downlink
- Power Scaling Order
  - ✓ Active IRS: O(N) -> due to IRS amplification noise
  - ✓ Passive IRS: $O(N^2)$

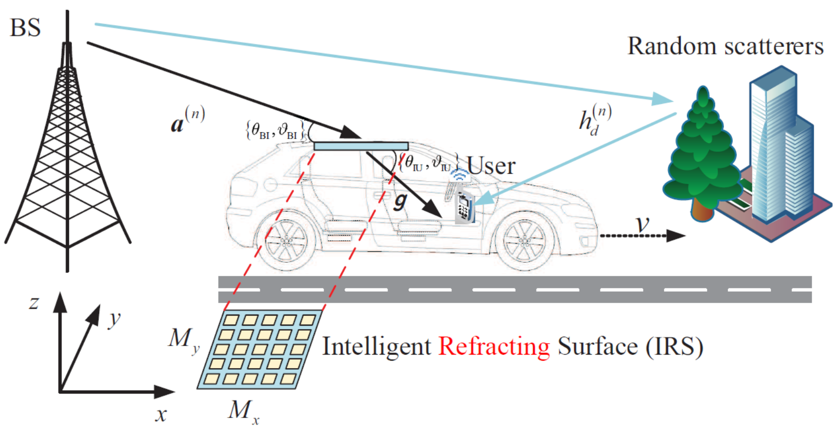
Refraction-based IRS: Intelligent Refracting Surface

- Z. Huang, B. Zheng, and R. Zhang, "Transforming fading channel from fast to slow: intelligent refracting surface aided high-mobility communication," to appear in IEEE Transactions on Wireless Communications.

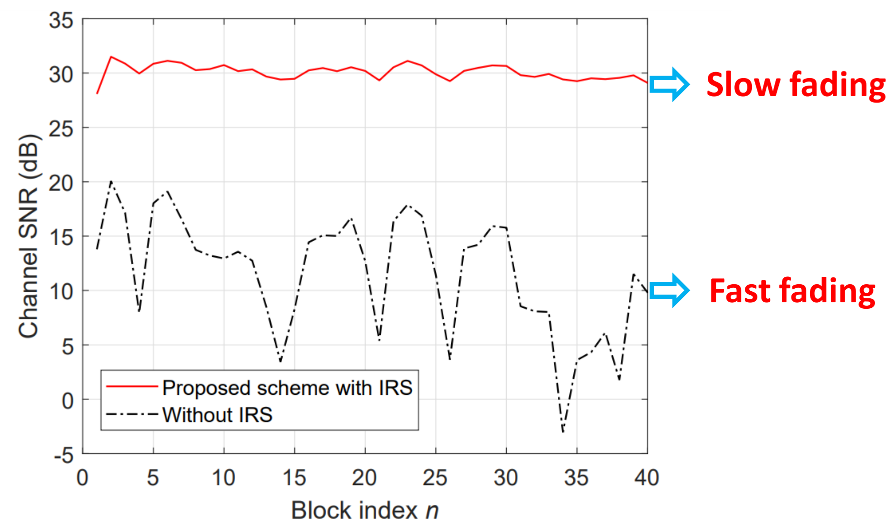
Refraction-based IRS: Intelligent Refracting Surface



- **Objectives:** (convert the effective channel from fast to slow fading by designing IRS refraction vector)
  - Mitigate the Doppler effect
  - Achieve the IRS passive beamforming gain
  - Reduce the training overhead



Proposed on/in-vehicle IRS-aided communication system for high-mobility user



A realization of the end-to-end channel SNRs in one transmission frame.

Relaying IRS

- B. Zheng and R. Zhang, "IRS meets relaying: joint resource allocation and passive beamforming optimization," IEEE Wireless Communications Letters, vol. 10, no. 9, pp. 2080-2084, September 2021.

Relaying IRS: Active Relay Meets Passive IRS

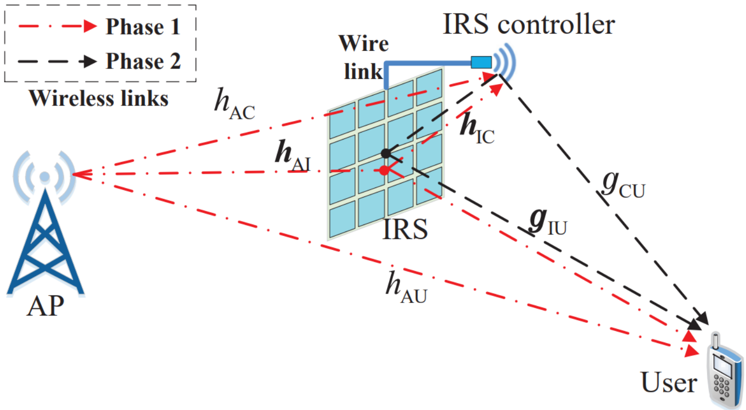


Fig. 1. A relaying IRS-assisted communication system.

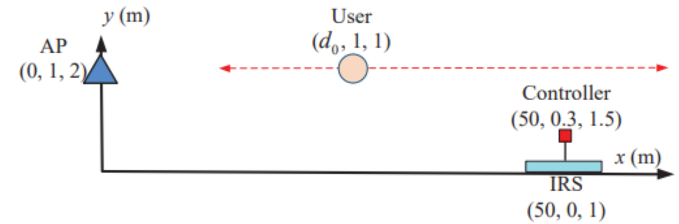


Fig. 2. Simulation setup (top view).

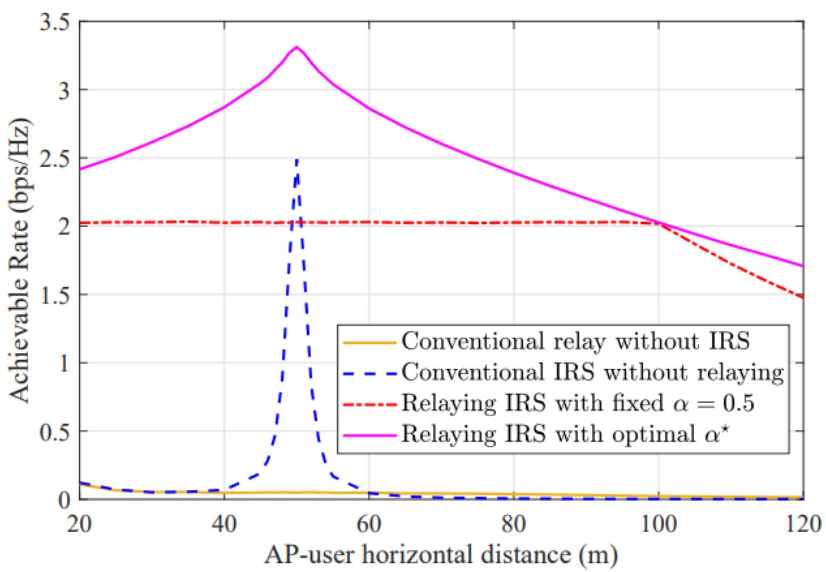


Fig. 3. Achievable rate versus AP-user horizontal distance d_0.

❑ Relaying IRS-assisted communication

- Exploiting **IRS controller** for active relaying
- IRS helps for both passive relaying and active relaying
- Optimal mode switching between passive (full duplex) and active relaying (half duplex, DF)
- Enlarge IRS coverage without increasing deployment/hardware cost
- **Optimal IRS deployment: in the middle of AP and user (similar to active relay)**

Aerial IRS

- C. You, Z. Kang, Y. Zeng, and R. Zhang, "Enabling smart reflection in integrated air-ground wireless network: IRS meets UAV," IEEE Wireless Communications, Dec. 2021.

- H. Lu, Y. Zeng, S. Jin, and R. Zhang, "Aerial intelligent reflecting surface: joint placement and passive beamforming design with 3D beam flattening," IEEE Transactions on Wireless Communications, vol. 20, no. 7, pp. 4128-4143, July 2021.

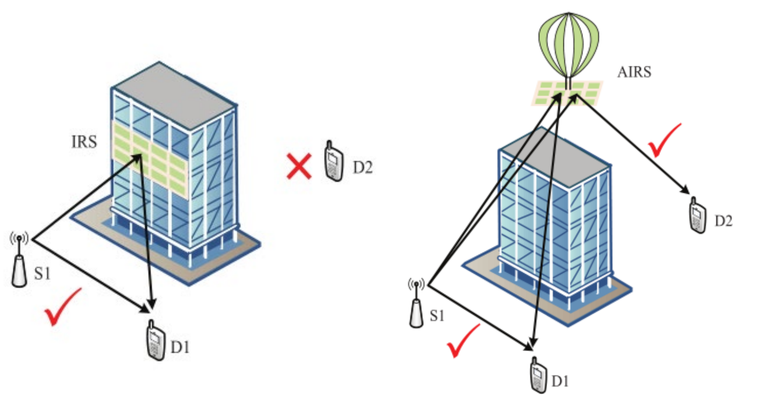
Aerial IRS vs Terrestrial IRS

❑ Terrestrial IRS

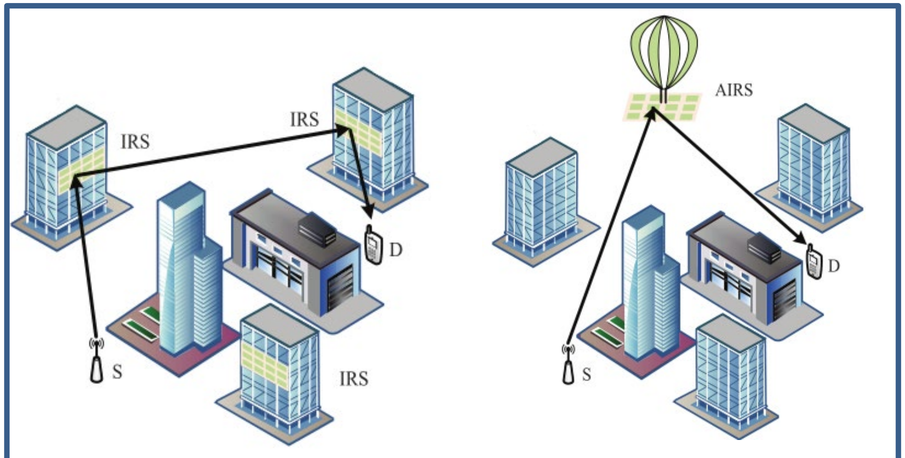
- 180 half-space reflection only
- Multiple reflections required due to NLoS
- Constrained deployment

❑ Aerial IRS

- 360° panoramic full-angle reflection
- One reflection suffices due to LoS
- Flexible deployment

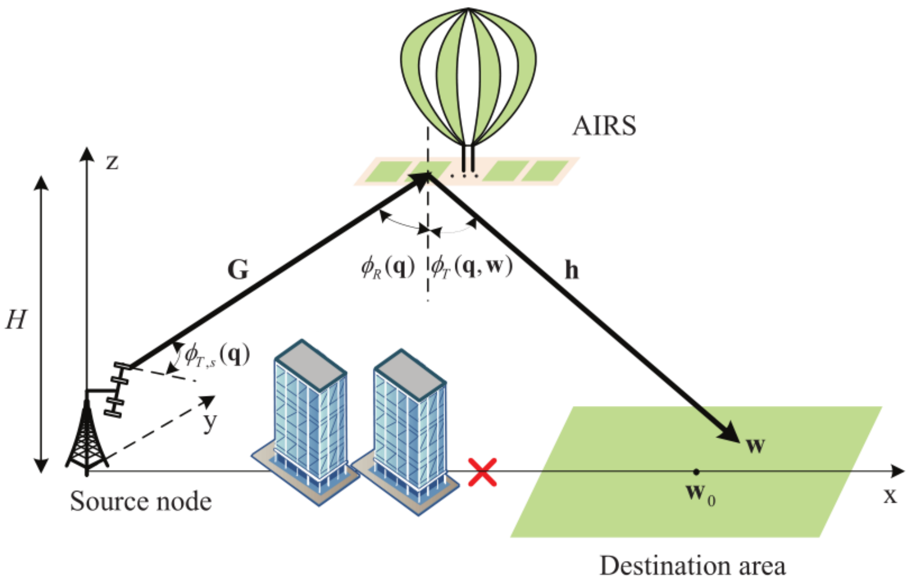


360° panoramic full-angle reflection by AIRS



Reduced number of reflections by AIRS

Optimal Aerial IRS Placement



- ❑ AIRS-assisted communication system: enabling intelligent reflection from the sky
- ❑ Enhance signal coverage over a given target area
- ❑ Exploit LoS air-ground channel for beam flattening

- ❑ The placement of AIRS can be flexibly optimized to further improve the communication performance
- ❑ Objective: maximize the minimum SNR within the rectangular area by jointly optimizing the transmit beamforming of the source node, the placement and phase shifts of the AIRS
  - ➢ The objective function is the minimum SNR over a 2D area (i.e., "beam flattening"), which is difficult to be expressed in terms of the optimization variables
  - ➢ The optimization problem is highly non-convex and the optimization variables are intricately coupled with each other in the objective function

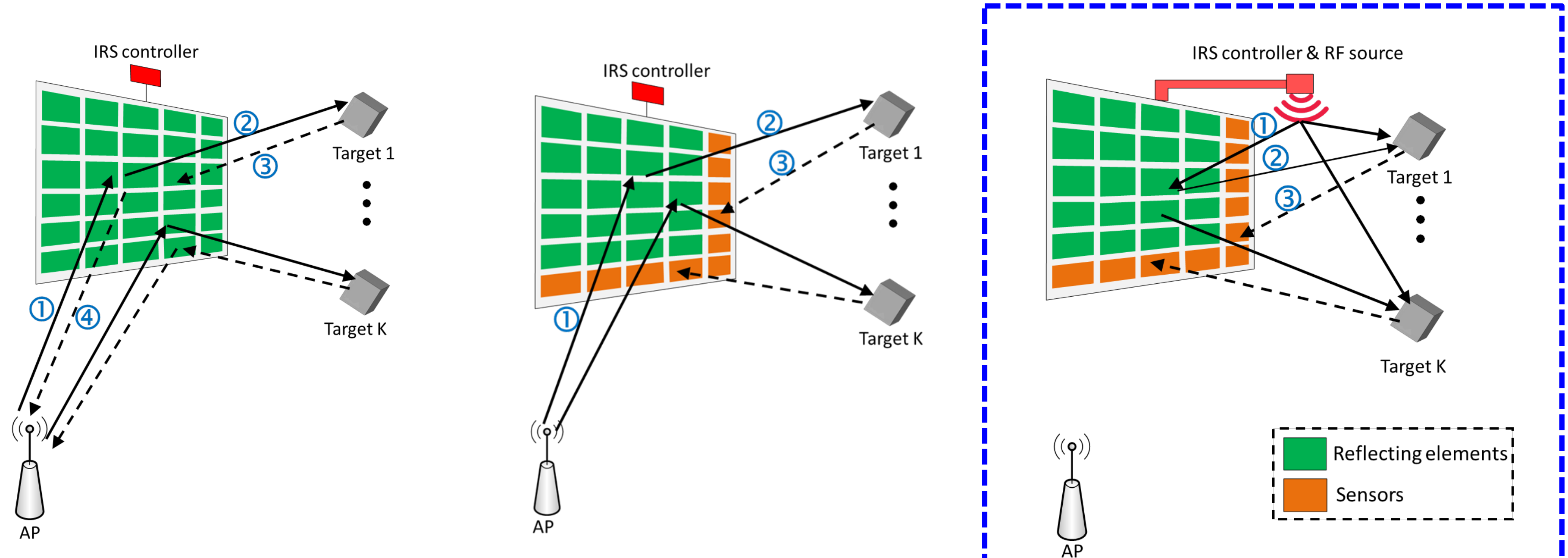
Outline

- ❑ Intelligent Reflecting Surfaces (IRS): Motivation and Applications
- ❑ IRS-aided Wireless Communications
- ❑ **IRS-aided Sensing**
  - ➢ IRS-aided sensing architectures: pons and cons
  - ➢ Algorithms
  - ➢ Performance comparison
- ❑ Conclusions

IRS-aided Sensing

- X. Shao, C. You, W. Ma, X. Chen, and R. Zhang, “Target sensing with intelligent reflecting surface: architecture and performance,” IEEE Journal on Selected Areas in Communications, special issue on Integrated Sensing and Communication, accepted.

IRS-aided (Radar) Sensing: System Architectures



(a) IRS passive sensing (b) IRS semi-passive sensing (c) IRS active sensing (proposed)

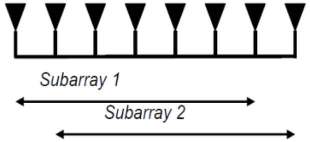
- IRS passive sensing
  - 3-hop reflections, severe path-loss
- IRS semi-passive sensing
  - 2-hop reflections
  - Long distance from TX/AP to IRS
- IRS active sensing
  - **IRS controller** transmits probing signals
  - Sensing with dedicated sensors on IRS
  - **2-hop reflection** (controller → IRS elements → target →sensor)
  - **Much shorter distance from Tx to IRS than semi-passive sensing**

IRS-aided Sensing Architectures: Pros and Cons

Architectures	Range	Hardware cost	Sensing accuracy	Need a BS?	Path-loss	Required prior knowledge
IRS active sensing	Long	Medium	High	No	Low (two-hop)	Location of IRS
IRS semi-passive sensing	Short	Low	Medium	Yes	High (two-hop)	Location of IRS
IRS passive sensing	Very short	Very low	Low	Yes	Very high (three-hop)	Locations of BS and IRS

IRS-aided Sensing Algorithms

- **Background interference cancelation**
  - Offline training phase: estimate channels from IRS controller and fixed clutters (with IRS reflection patterns)
  - Online estimation phase: cancel background interference
- **DOA estimation: MUSIC algorithm**
  - Principle: sensors array steering vector $\mathbf{b}(\theta)$ is orthogonal to noise subspace $\mathbf{U}_z$
  - Find noise subspace from signal covariant matrix
  - Peak search and determine DOA $P_{\text{MUSIC}}(\theta) = \dfrac{1}{\mathbf{b}(\theta)^H \mathbf{U}_z \mathbf{U}_z^H \mathbf{b}(\theta)}$.
  - Pros: Higher accuracy and resolution
  - Cons: Higher computational complexity and storage (extensive searching)
- **DOA estimation: ESPRIT algorithm**
  - Principle: rotational invariance of both sensor array manifolds and signal subspaces $\mathbf{b}_2(\theta) = \mathbf{b}_1(\theta)\underbrace{e^{-j\pi\frac{d_s}{\lambda}\sin(\theta)}}_{\omega}$ $\mathbf{U}_{s2} = \mathbf{U}_{s1}\boldsymbol{\Psi}$
  - The eigenvalue of $\boldsymbol{\Psi}$, i.e., η is equal to ω
  - DOA estimates $\hat{\theta} = \arcsin(\dfrac{j\ln(\hat{\eta})\lambda}{\pi d_s})$



  - Pros: Lower ccomputational complexity and storage (closed-form solution)
  - Cons: Lower accuracy and resolution
- **IRS reflect beamforming**
  - Assume no prior knowledge
  - Maximize average received signal power at the sensors in the worst-case scenario w.r.t. IRS steering matrix
  - Optimal strategy: **omnidirectional IRS beampattern**

IRS-aided Sensing: Performance Comparison

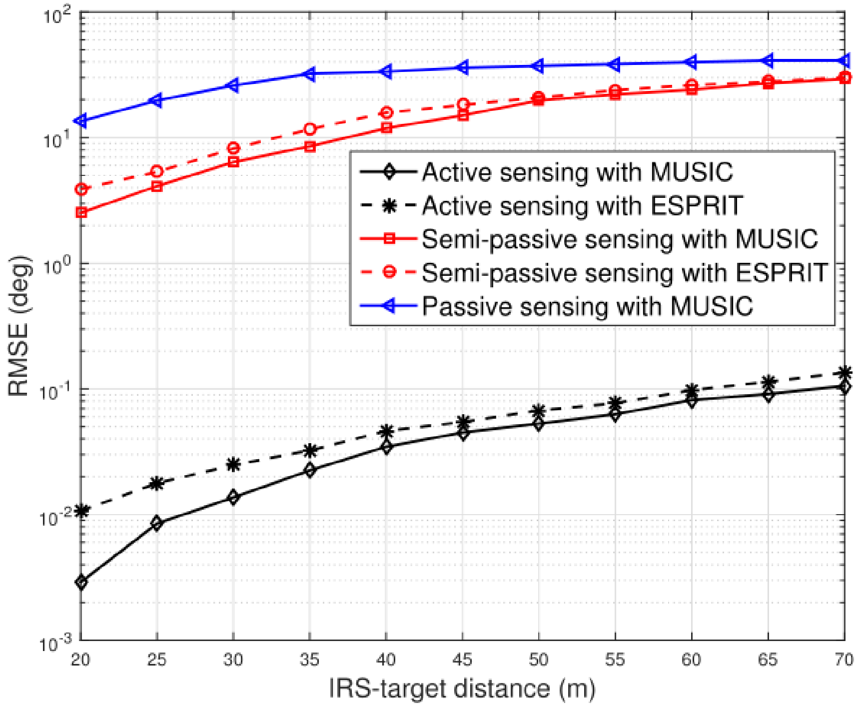


Fig. 1. **Single target**: RMSE versus distance between IRS/sensors and target.

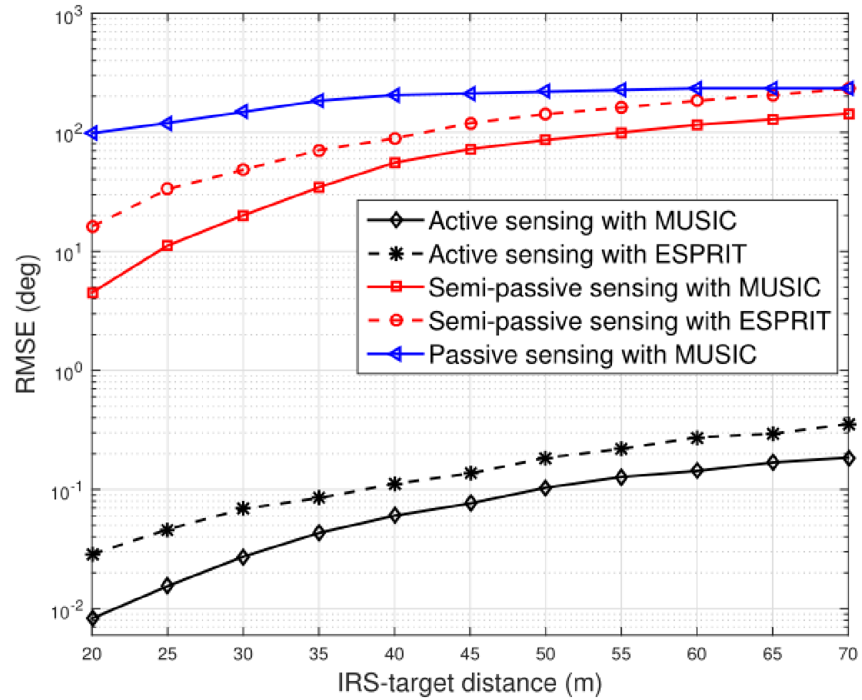


Fig. 2. **Multiple targets**: RMSE versus distance between IRS/sensors and target.

- ❑ Active sensing achieves higher sensing accuracy/longer sensing range than passive/semi-passive sensing
- ❑ MUSIC performs better than ESPRIT, and the performance gap increases with the number of targets

Outline

- ❑ Intelligent Reflecting Surfaces (IRS): Motivation and Applications
- ❑ IRS-aided Wireless Communications
- ❑ IRS-aided Sensing
- ❑ **Conclusions**

Conclusions

- IRS achieves high spectral/energy efficiency and high sensing accuracy with low-cost passive reflecting elements
- IRS makes a paradigm shift of wireless networks from traditional "active component solely" to a new "active and passive" hybrid
- IRS self-sensing greatly facilitates system implementation for achieving dual functions of communication and sensing
- Main challenges (from communication/sensing design perspectives):
  - IRS reflection optimization
  - IRS channel acquisition
  - IRS deployment
  - Sensing architectures/algorithms customized for IRS
  - Integrated communication/sensing
  - ....