Intelligent Reflecting Surface-Assisted Wireless Communications with Non-ideal CSI

Caijun Zhong

Professor, Zhejiang University

(Email: caijunzhong@zju.edu.cn)

浙江省信息通信技术前沿论坛

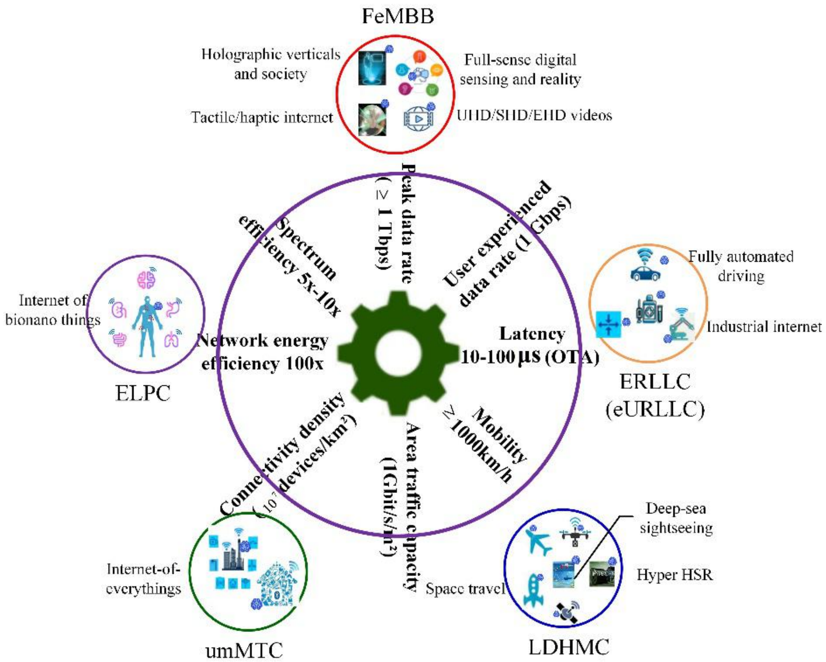
November 8, 2020

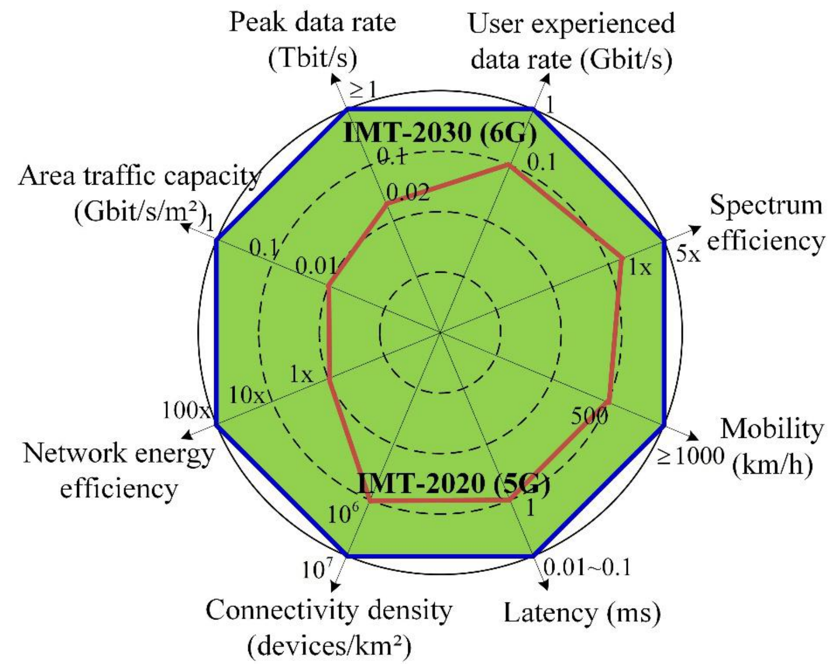
Outline

- Basics of intelligent reflecting surface (IRS)
- Channel estimation for IRS systems
- Active and passive beamforming design
- Conclusion

Motivation

- B5G/6G Scenario and key performance indicator

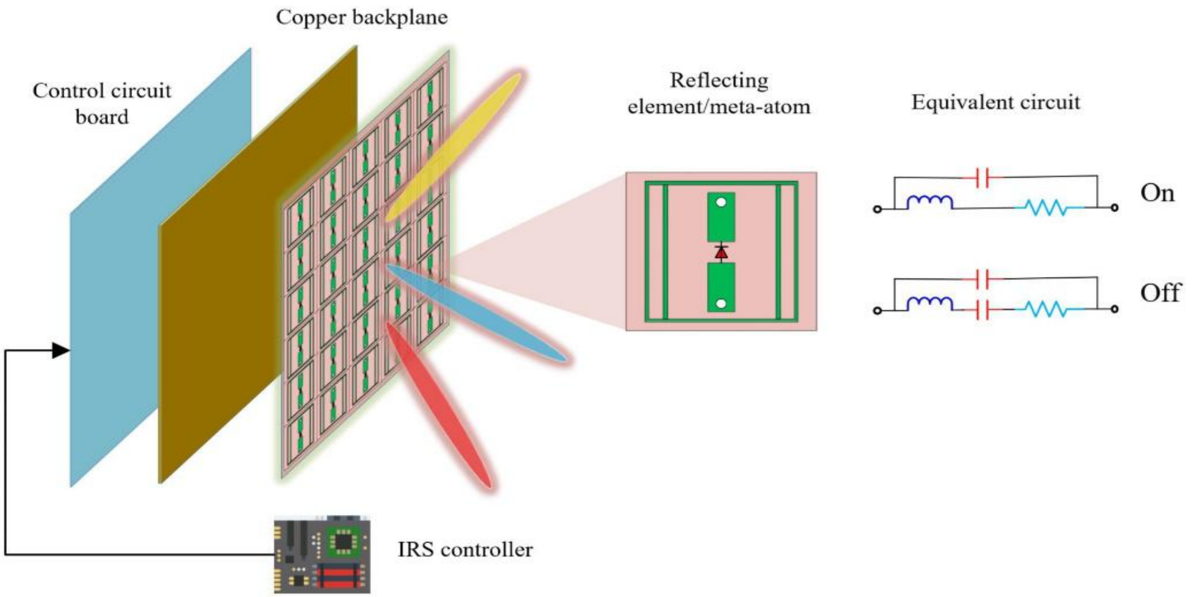




High spectral and resource efficiency, **low cost**

Why IRS?

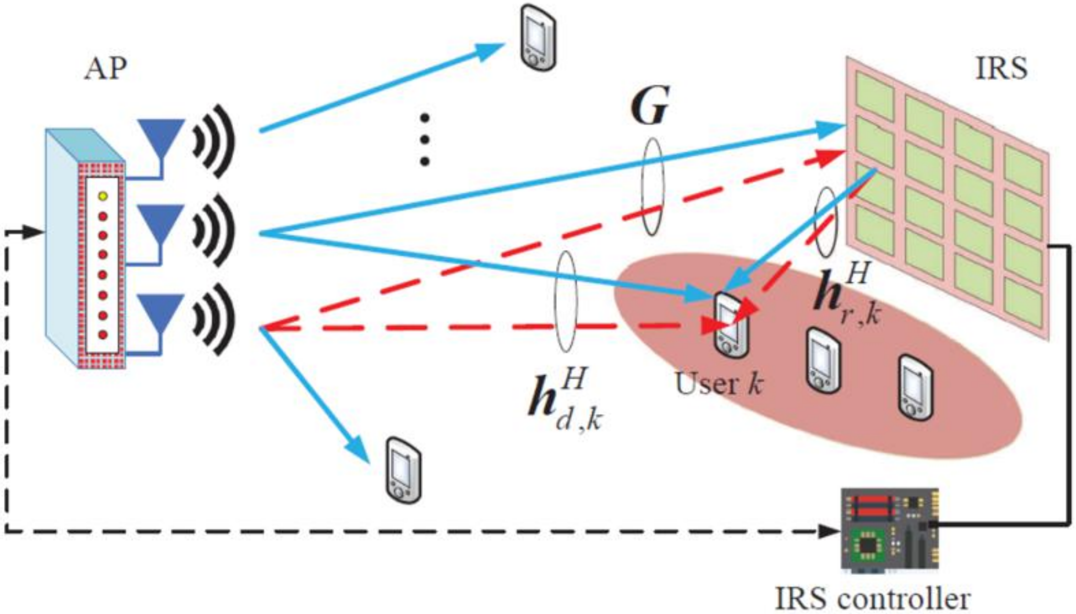
- Key features (Wu, Com Mag 2020)



a) Reconfigurable metamaterials with massive low- cost sub-wavelength reflecting meta-atoms
b) Passive device (low energy consumption, green communication)
c) Low cost (without mixer, ADC/DAC, PA)
d) High spectrum efficiency (full- duplex, noiseless reflection)
e) Full band response (sub-6G, mmWave, THz)
f) Flexible deployment

Why IRS?

How IRS works



a) Each element induces an amplitude and/or phase change to the incident signal independently
b) Beamforming: Signals are combined in phase at the receiver

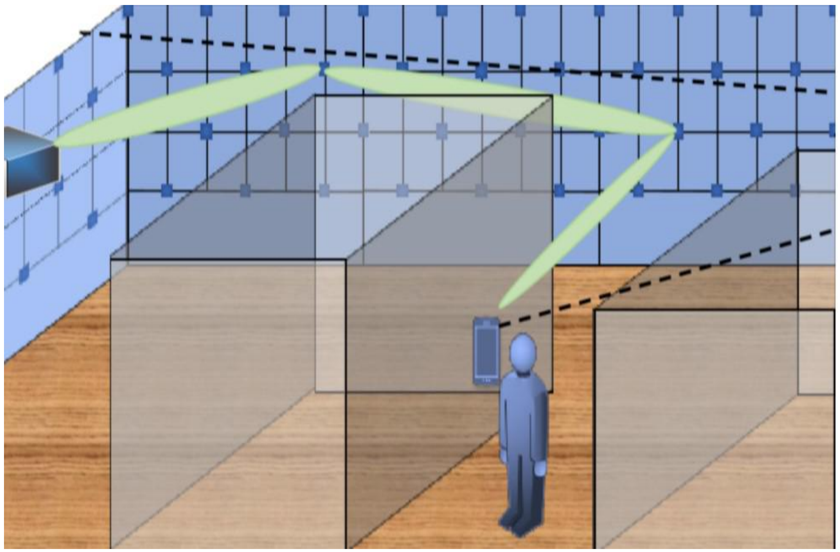
Why IRS?

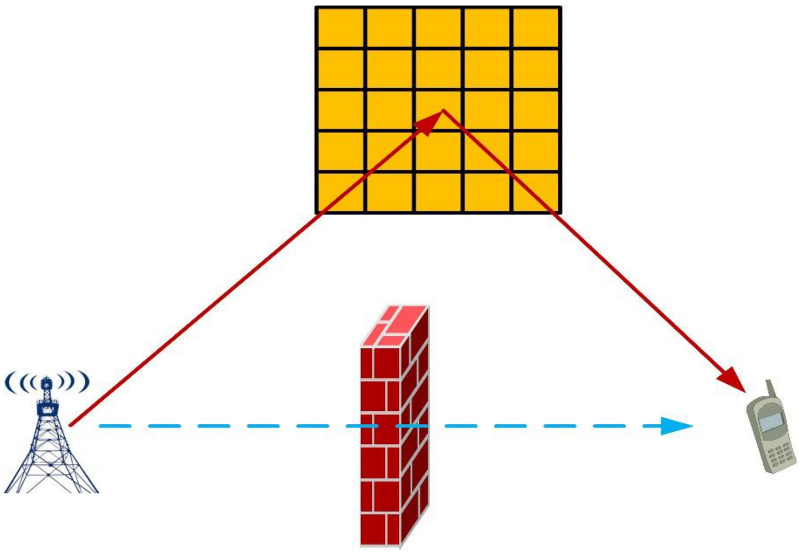
- Comparison with multi-antenna relay

	IRS	Relay
Mode	Passive	Active
Mechanism	Reflecting	Transmit and receive
Duplex	Full-duplex	High/full duplex
Deployment	Flexible	Inflexible
Scalability	Easy	Difficult
RF chain	No	Yes
Power consumption	Low	High
Hardware Cost	Low	High

IRS: Applications

- Coverage hole, Non-Line of Sight

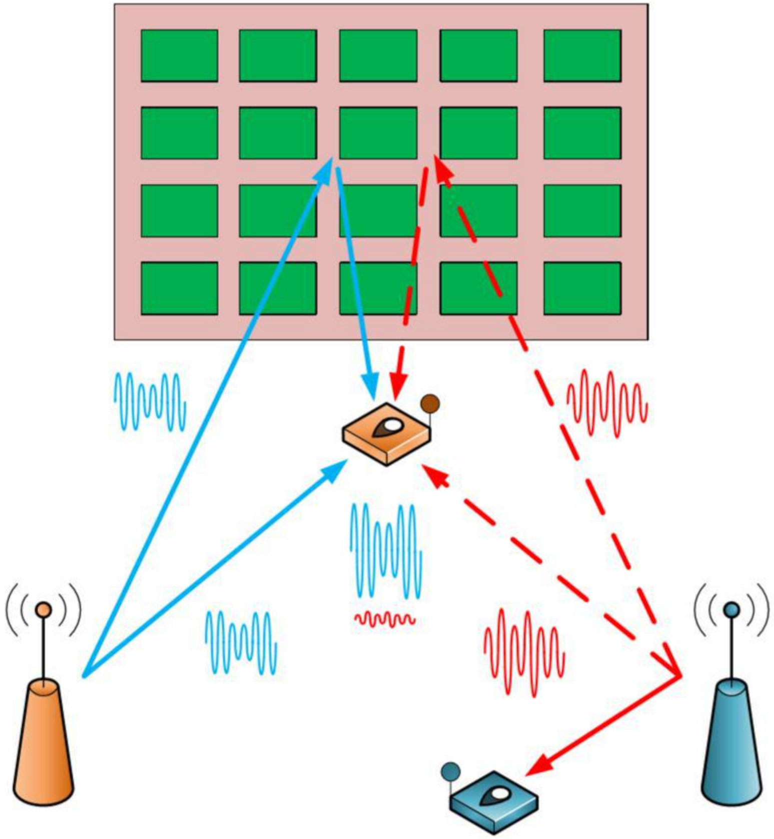




- ➢ Solve "dead zone" problem in mmWave/THz indoor coverage
- ➢ Create LoS link by smart reflection to bypass obstacle

IRS: Applications

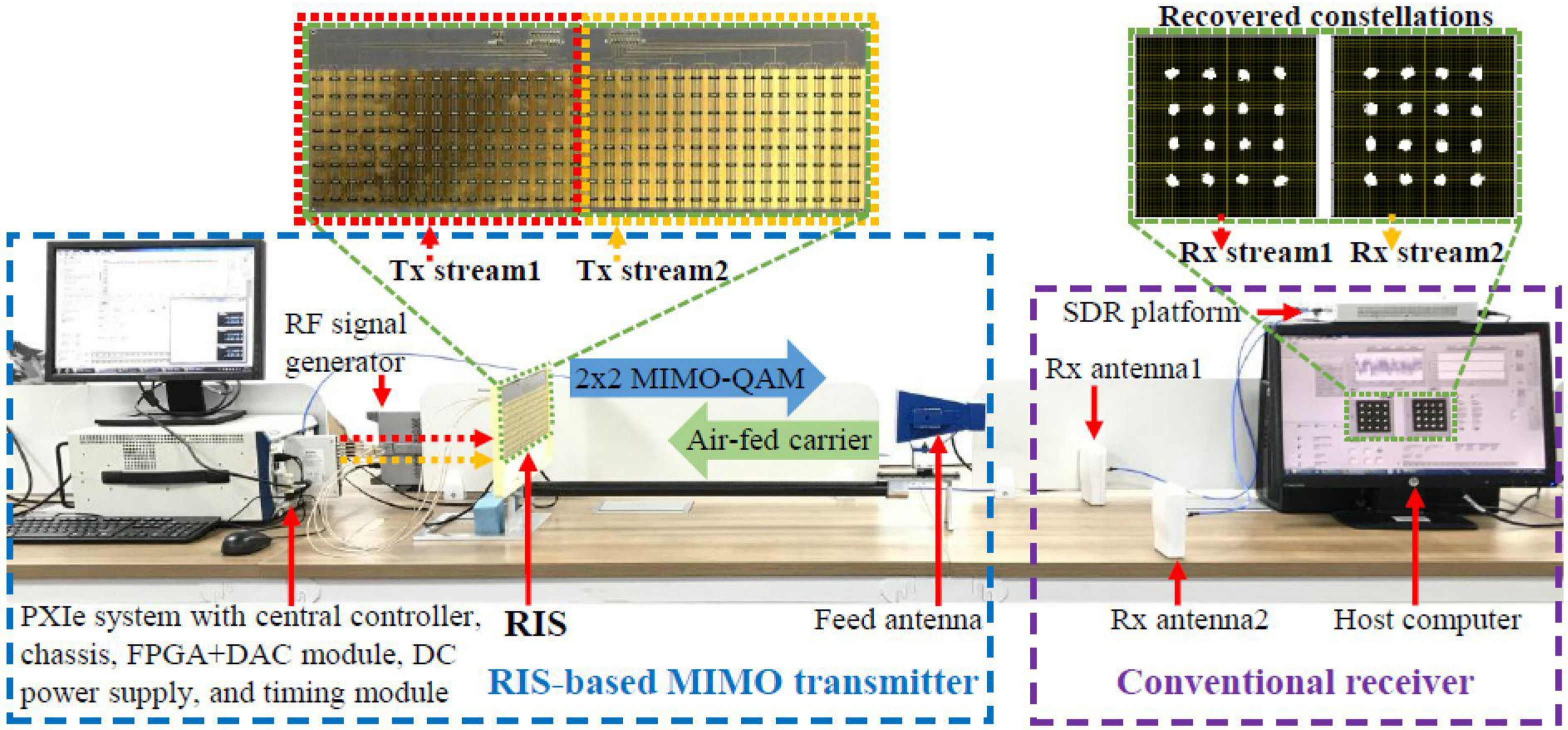
- Enhance cell edge performance



> ➢ Deploy the IRS at the cell edge to improve the signal power of edge users
>
> ➢ Suppress co-channel interference and create "signal hotspot"

Lab prototyping

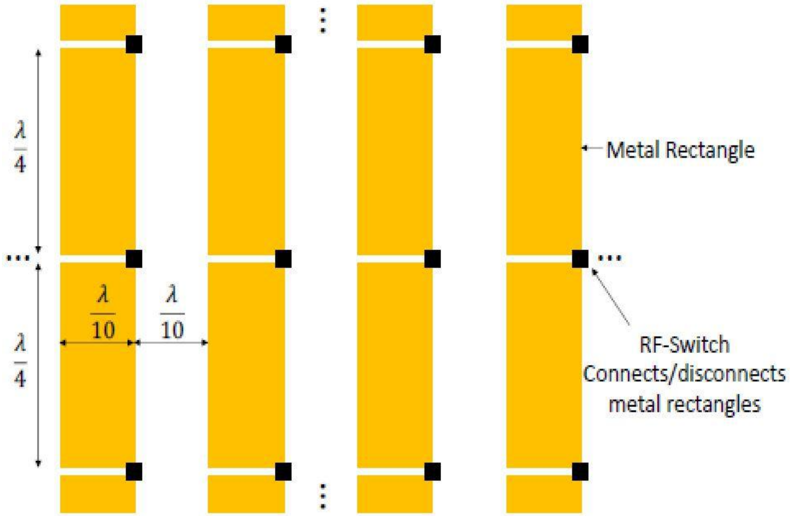
- Southeast University: 2 by 2 MIMO



W. Tang, et al, "Wireless communications with programmable metasurface: New paradigms, opportunities, and challenges on transceiver design," IEEE Wireless Commun., 2020.

Lab prototyping

- MIT: RFocus

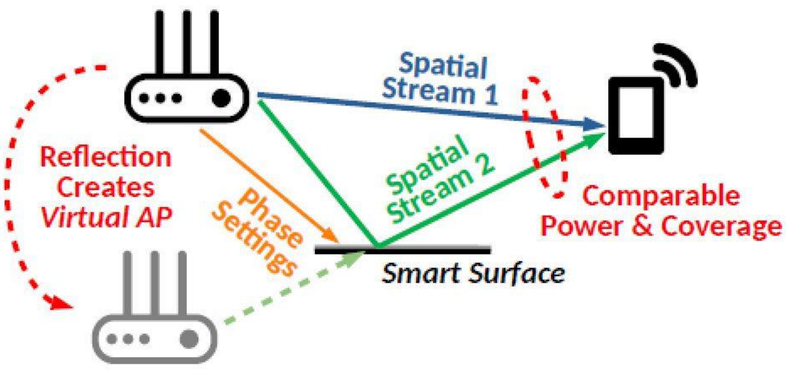


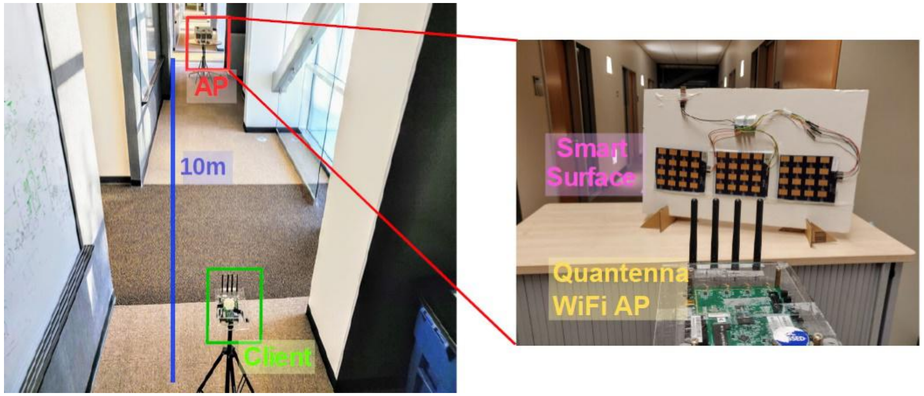
- Simple On-off protocol; 3200 elements, 2X capacity
- Desirable to place the surface close to the end points
- Robust to element failure. With 1/3 failed elements, the performance only drops by 50%
- No mobility support

V. Arun and H. Balakrishnan, "RFOCUS: Beamforming using thousands of passive antennas," Proceedings of the 17th USENIX symposium on Networked Systems Design and Implementation (NSDI' 20), Santa Clara, USA, 2020.

Lab prototyping

UCSD: Scatter MIMO



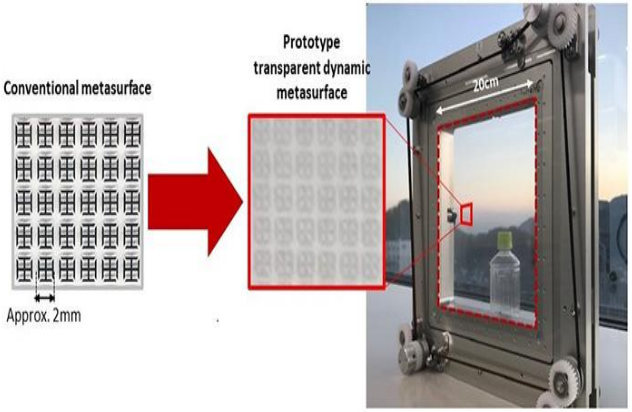


- Use smart reflector as a virtual AP, which has the same transmit power as traditional AP, therefore providing spatial multiplexing and SNR improvement
- 4 X 12 antenna surface; 2 X mean throughput gain, 50% increase in range

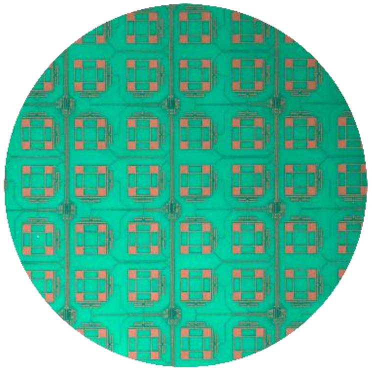
M. Dunna, C. Zhang, D. Sievenpiper, and D. Bharadia, "Scatter MIMO: Enabling virtual MIMO with smart surfaces," MobiCom' 20, London, UK, 2020.

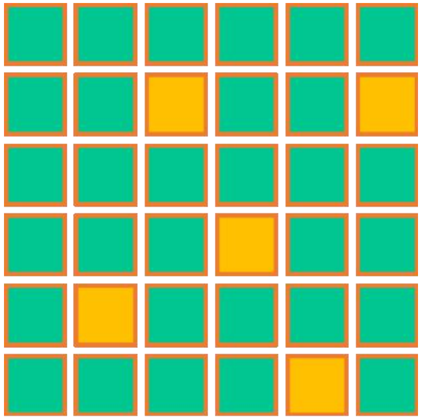
Industry initiatives

- DoCoMo with Metawave (Automotive Radar and 5G)



- Greenwave (4G imaging radar, Electronically steerable antennas)

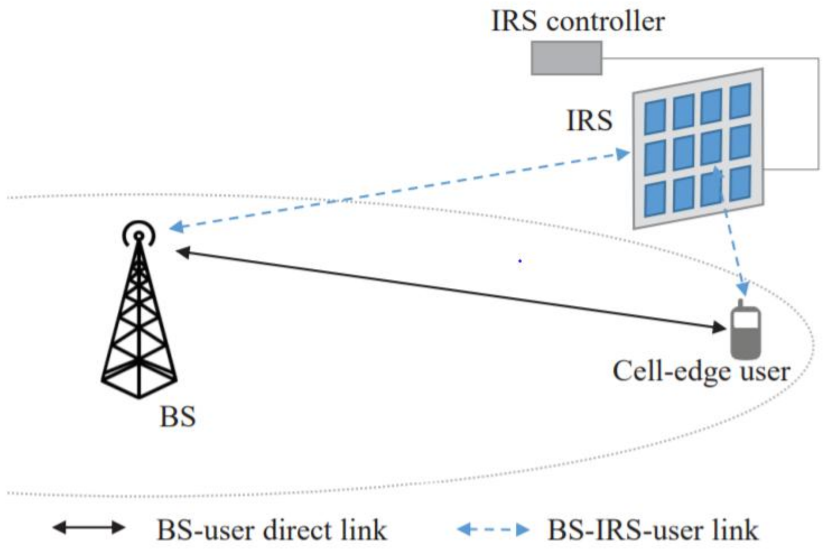




Channel estimation

- 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
- Key Challenges
  - Passive architecture: IRS is generally not equipped with any radio frequency (RF) chains and thus not capable of performing any baseband processing functionality.
  - Large overhead: the number of reflecting element is very large.

Estimate the cascaded channel



- Received signal:
$$y = \mathbf{h}_c^T diag(\boldsymbol{\theta})\mathbf{h}_r s + h_d s = \mathbf{g}^T \boldsymbol{\theta} s + h_d s$$

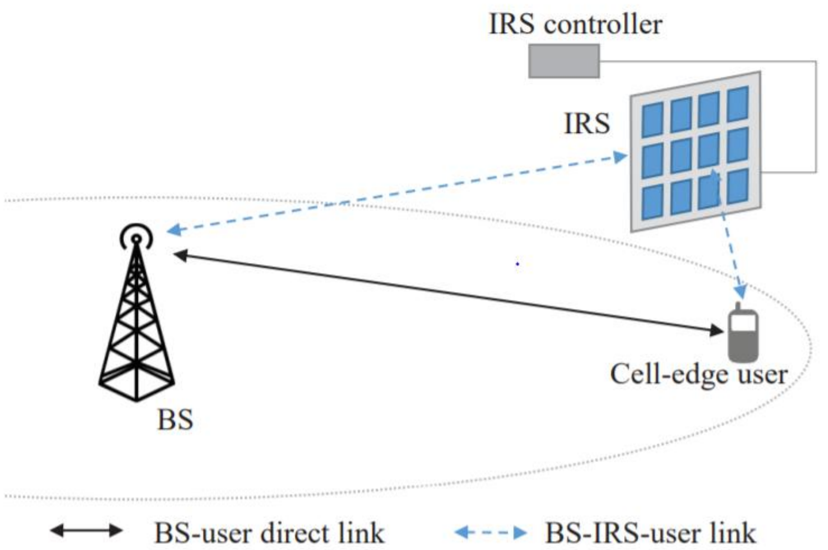
- Cascaded Channel:
$$\mathbf{g}^T = \mathbf{h}_c^T diag(\mathbf{h}_r)$$

- Estimate the direct channel: Turn off the IRS and estimate the direct channel by uplink training.
- Estimate the cascaded channel: The IRS are turned on and the user send pilots to the BS.

Two Steps:

1. Cancel the interference from the direct channel.
2. Estimate the cascaded user-IRS-AP channels at the BS, based on the user pilot signals and time-varying IRS reflection pattern.

Estimate the cascaded channel



- Received signal:

$$y = \mathbf{h}_c^T diag(\boldsymbol{\theta})\mathbf{h}_r s + h_d s = \mathbf{g}^T \boldsymbol{\theta} s + h_d s$$

- Cascaded Channel:

$$\mathbf{g}^T = \mathbf{h}_c^T diag(\mathbf{h}_r)$$

ON-OFF based strategy

- One active IRS element each time

DFT based strategy

- All the IRS elements are on
- Reflection coefficients determined by the DFT matrix.

Lagrange-based strategy

- A Lagrange-based strategy to minimize the MSE by optimizing the IRS pattern.

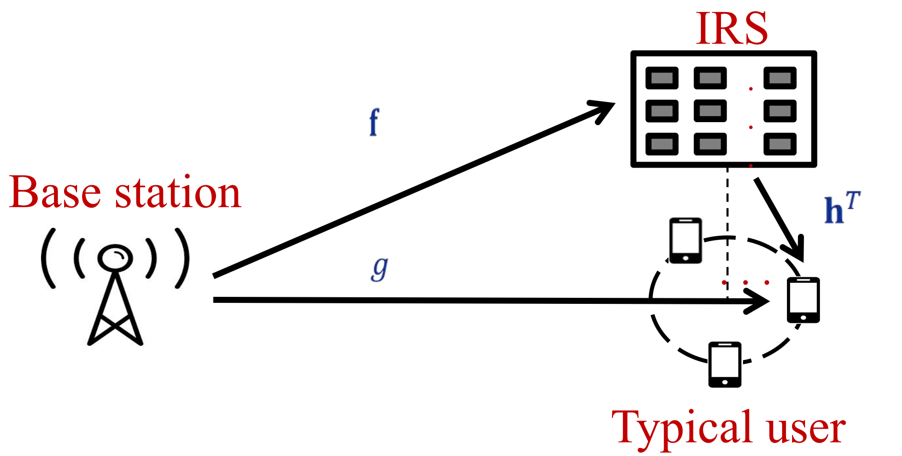
Compressed sensing based strategy

- Formulate the problem as a combined sparse matrix factorization and matrix completion problem.

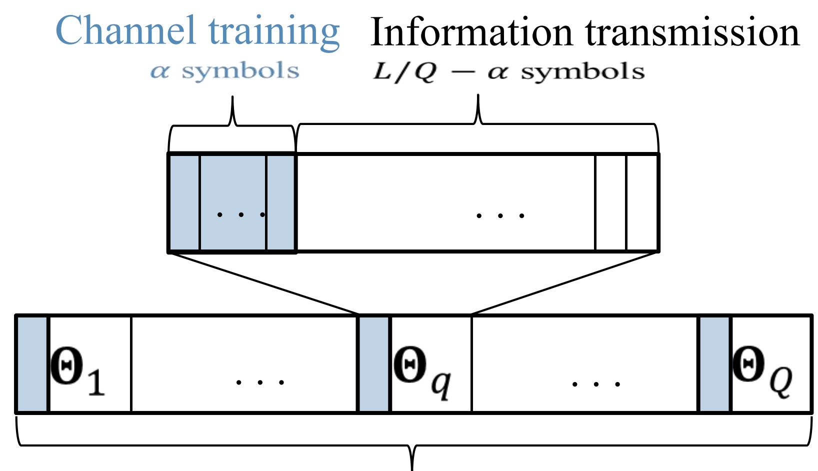
Active and passive beamforming design

- Random beamforming design
- Robust beamforming design
- Statistical CSI based beamforming design
- Angle-domain beamforming design

IRS-aided multicast systems with random reflecting



Single-antenna BS sends a common message to K>1 single-antenna users.



Q reflecting patterns in one channel coherence interval

➢ Transmission protocol:

- Each channel coherence interval is **equally** divided into Q ``reflecting slots", and the IRS reflects with a **random** set of coefficients over each time slot.
- BS sends α training symbols , all users estimate the effective channel, i.e., $g+\mathbf{h}^T\Theta_q\mathbf{f}$, at each reflecting slot, rather than each cascaded channels via IRS.
- BS starts to transmit information.

Qin Tao, Shuowen Zhang, Caijun. Zhong, and Rui Zhang "Intelligent Reflecting Surface Aided Multicasting with Random Passive Beamforming," IEEE Wireless Communications Letter.

IRS-aided multicast systems with random reflecting

➢ The outage probability for a given rate target τ (in bps/Hz) is defined as

$$P_{out} = \mathrm{P}\left\{ \left(\frac{1}{Q} - \frac{\alpha}{L}\right) \sum_{q=1}^{Q} \log_2 \left(1 + \gamma \,|\, g + \mathbf{h}^T \Theta_q \mathbf{f} \,|^2 \right) < \tau \right\}$$

- $\boldsymbol{\Theta}_q = \mathrm{diag}\{e^{j\theta_{1,q}}, e^{j\theta_{2,q}}, \ldots, e^{j\theta_{N,q}}\}$: phase shift matrix in slot q ;
- $\mathbf{f}$, g: Rayleigh fading channels; $\mathbf{h}$: LoS channels.
- $\gamma = P/N_0$;
- L: Total number of symbols in each coherence interval;
- Considering the high SNR regime, all users can perfectly estimate the equivalent CSI.

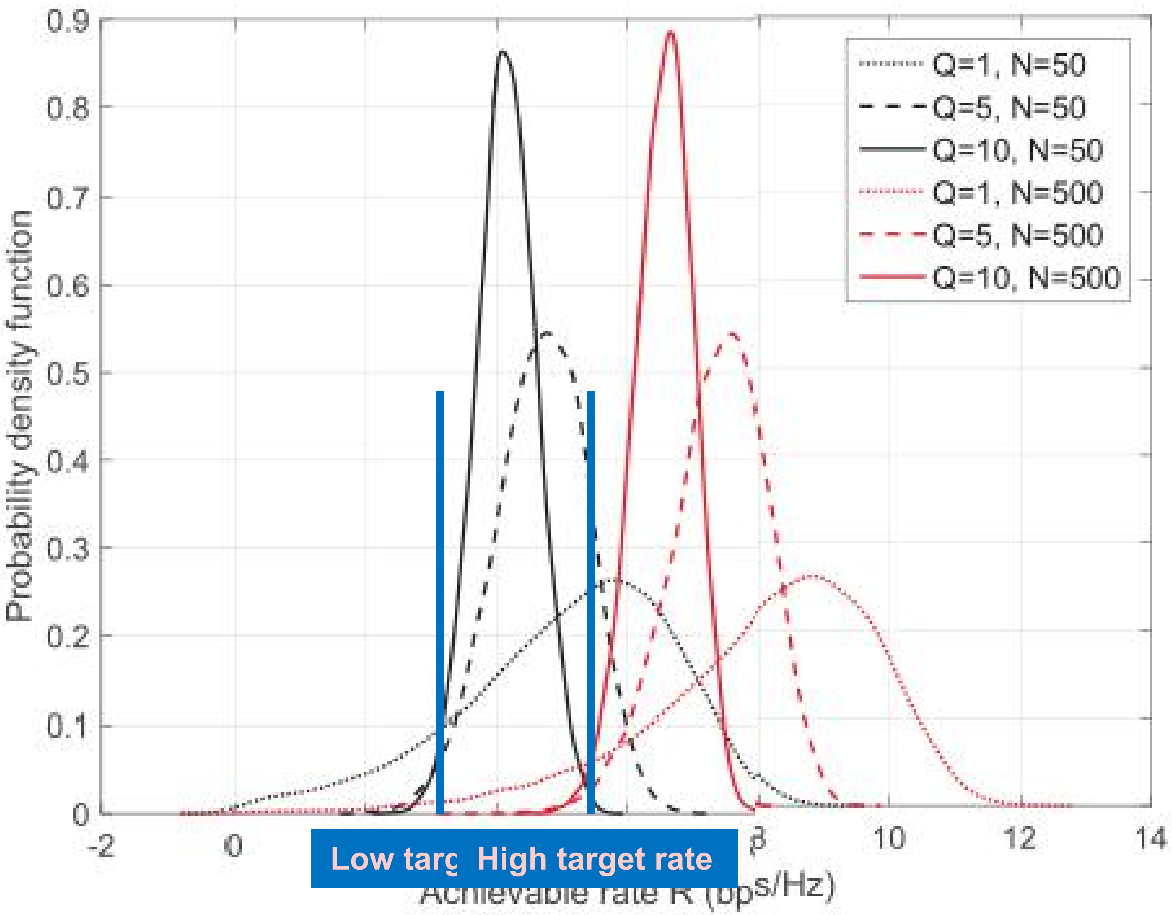
Optimal Q?

❑ **Tradeoff in P_{out}:**

◆ **Larger Q would provide more chance to avoid severe outage;**

◆ **On the other hand, more training time, i.e., αQ symbols, is needed.**

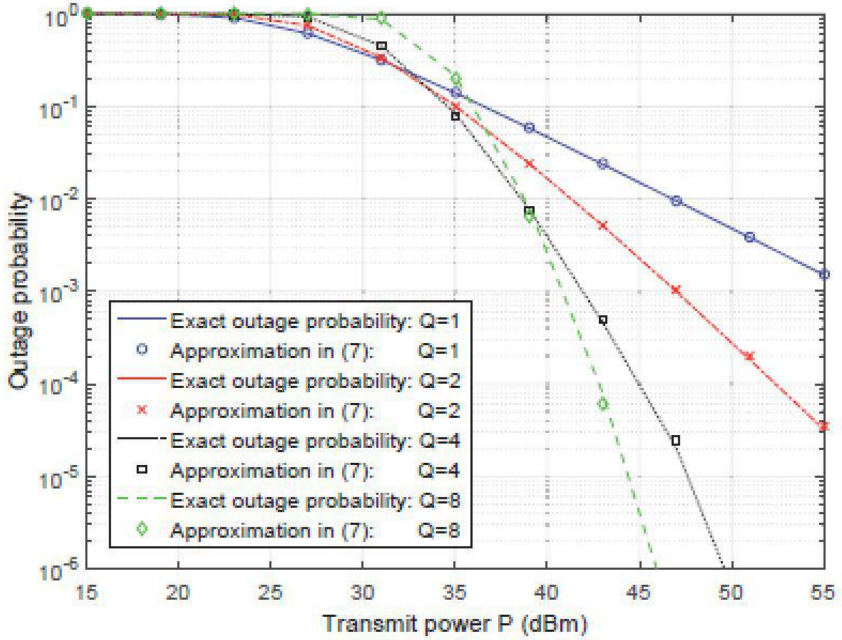
IRS-aided multicast systems with random reflecting

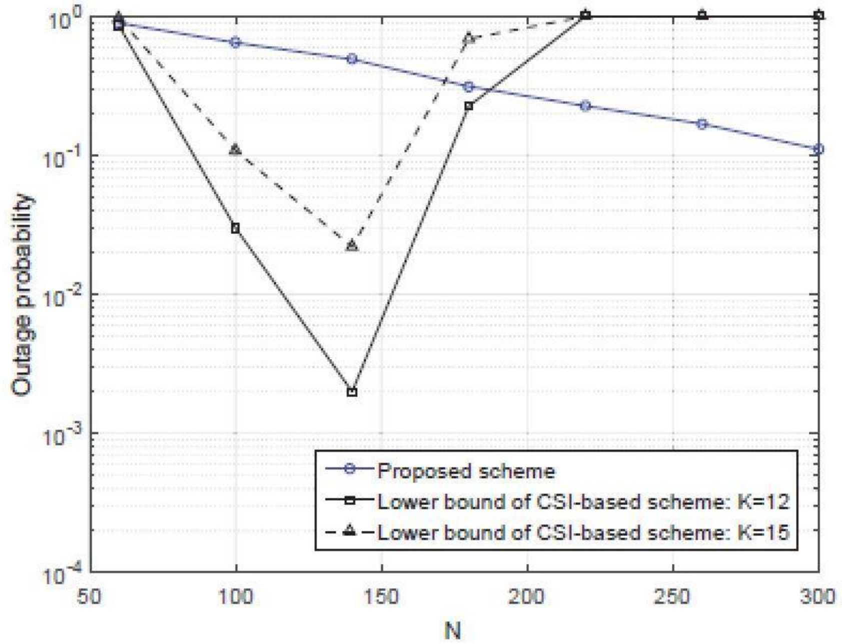


PDF for the achievable rate R.

- As Q increases, the PDF of achievable rate R becomes more centralized;
- As N increases, the PDF of R moves right.

IRS-aided multicast systems with random reflecting





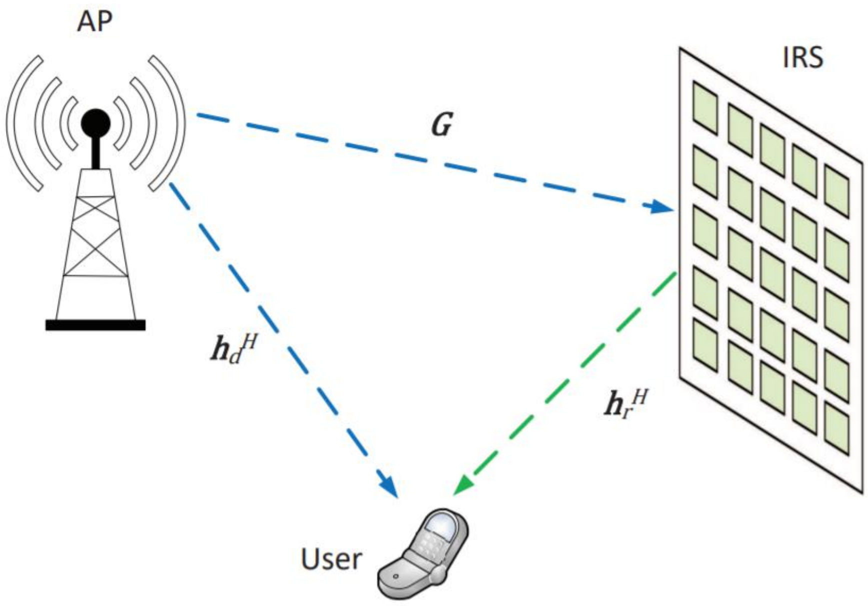
The achievable diversity order is Q

A large N is desirable;
The proposed scheme is insensitive to the change of K

Robust Beamforming

- True channel model
  - AP-IRS channel G
    - $G = \hat{G} + \Delta G$
  - AP-user direct link h_d
    - $h_d = \widehat{h_d} + \Delta h_d$
  - IRS-user channel h_r
    - $h_r = \widehat{h_r} + \Delta h_r$

$\hat{H}$: Estimated CSI
ΔH: CSI uncertainty



An IRS-assisted downlink MISO system

- CSI uncertainty model
  - ΔH is modeled as random process, e.g., complex Gaussian.

Jiezhi Zhang, Yu Zhang, Caijun Zhong, and Zhaoyang Zhang, "Robust Design for Intelligent Reflecting Surfaces Assisted MISO Systems," IEEE Communications Letters, 2020.

Robust Beamforming

- Problem formulation

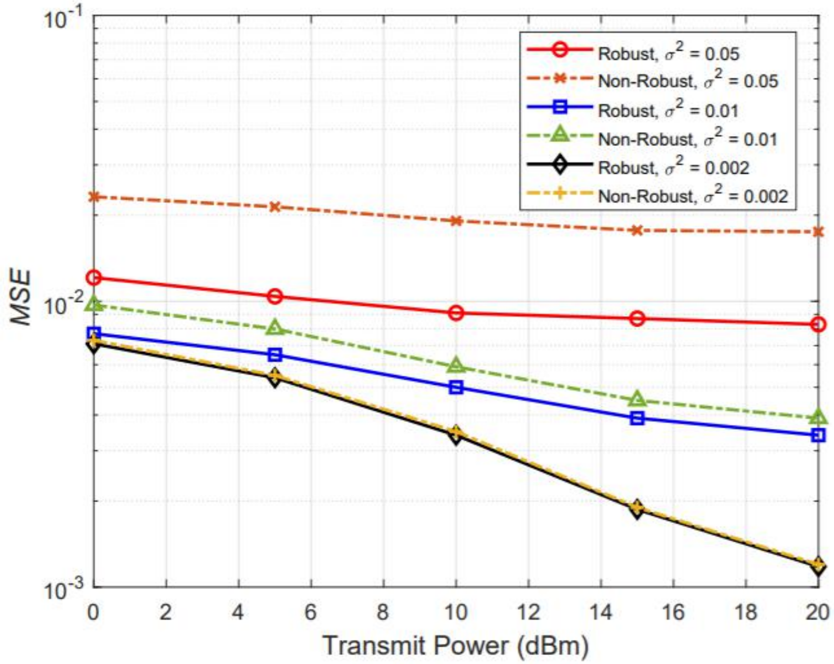
$$\min_{\mathbf{w},c,\mathbf{\Theta}} \quad \mathbb{E}\{|s - c((\mathbf{h}_r^H \mathbf{\Theta} \mathbf{G} + \mathbf{h}_d^H)\mathbf{w}s + n_0)|^2\}$$

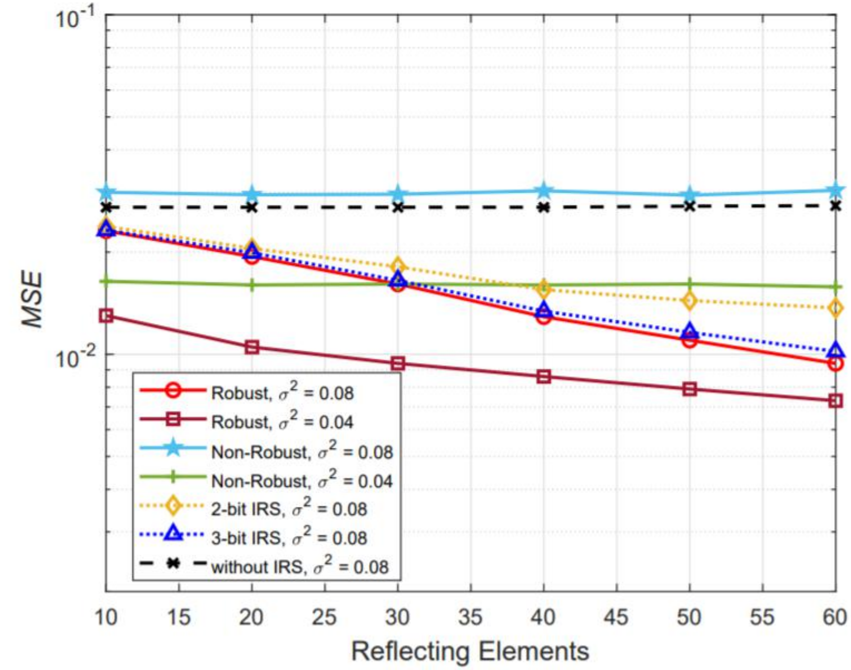
$$\text{s.t.} \quad \begin{cases} ||\boldsymbol{w}||^2 \le P_0, \\ 0 \le \theta_n < 2\pi, \quad \forall n = 1, \ldots, N. \end{cases}$$

  - Jointly optimize the transmit precoder $\boldsymbol{w}$, IRS phase shifts $\mathbf{\Theta}$, and the receive equalizer c.
  - Non-convex unimodular constraints at the IRS and coupled optimization variables in the objective.

- Solution
  - Alternating optimization and majorization-minimization
  - Closed-form solutions are obtained for the optimization variables during each iteration.

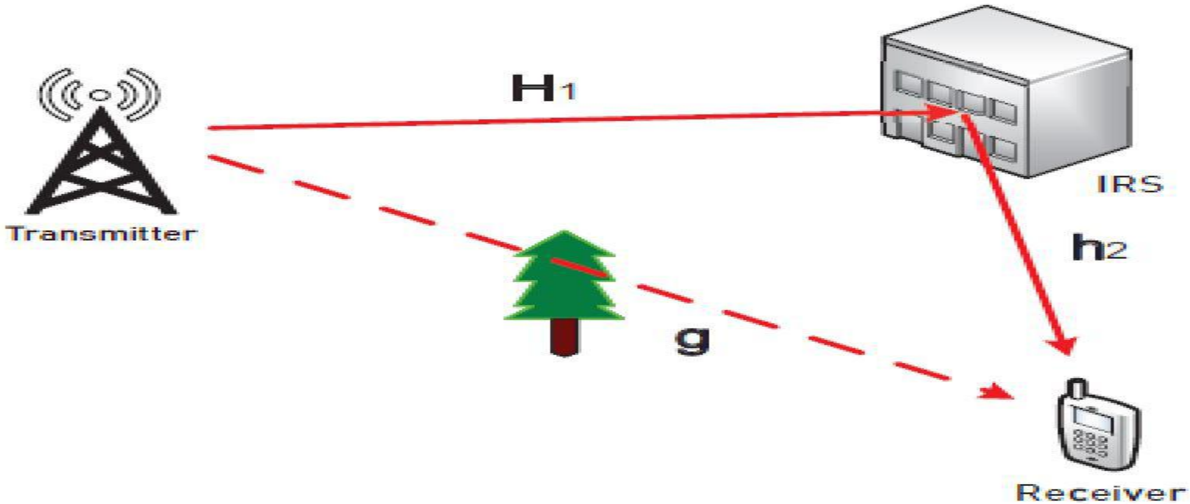
Robust Beamforming





1. The proposed robust design method (solid line) outperforms the conventional non-robust design scheme (Dotted line) in all CSI error configurations
2. The finite phase resolution scheme suffers performance loss compared to IRS with continuous phase shifts; 3-bit phase shifter (the dotted blue line) is sufficient

Statistical CSI: Single user case



- System model: BS with M antennas, IRS with N reflecting elements, a single antenna user
- Channel model: $\mathbf{H}_1$, $\mathbf{h}_2$, $\mathbf{g}$ follow Rician distribution
- CSI assumptions: Statistical CSI at the BS and IRS

Xiaoling Hu, Junwei Wang, and Caijun Zhong, "Statistical CSI based Design for Intelligent Reflecting Surface Assisted MISO Systems", Science China: Information Science, 2020.

Statistical CSI: Single user case

- System model:

$$y = \sqrt{P}\left(\frac{\mathbf{h}_2^T \mathbf{\Phi} \mathbf{H}_1}{\sqrt{d_1^{\alpha_1} d_2^{\alpha_2}}} + \frac{\mathbf{g}^T}{\sqrt{d_0^{\alpha_0}}}\right)\mathbf{f}x + n$$

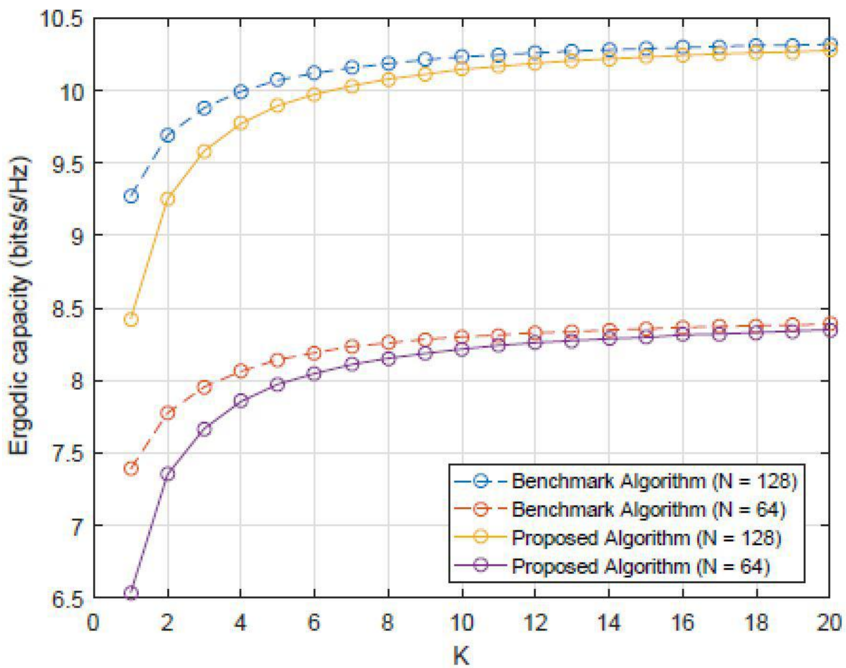
- Capacity upper bound:

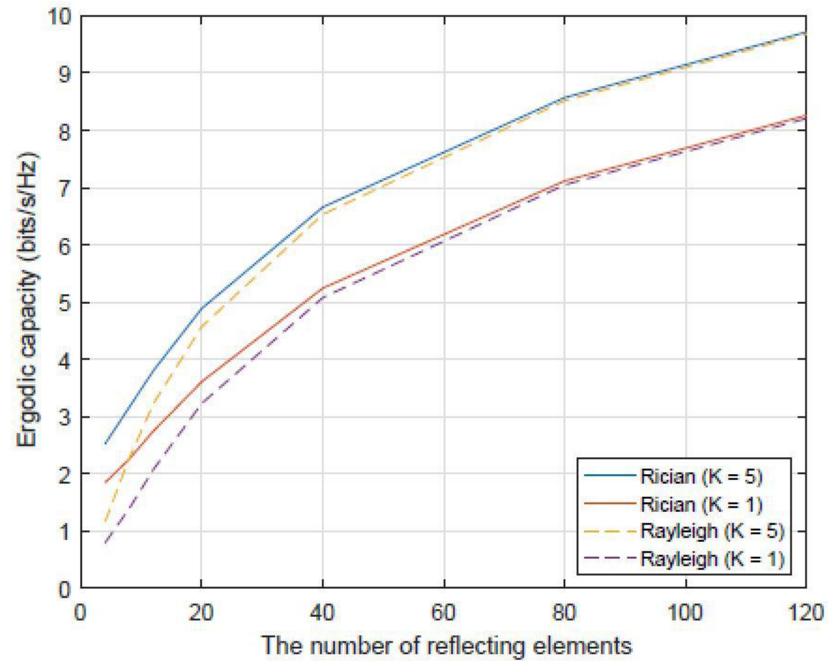
$$C_{\text{up}} = \log_2\left(1 + \gamma_0\left(\left|\left(a_2 a_1 \bar{\mathbf{h}}_2^T \mathbf{\Phi} \bar{\mathbf{H}}_1 + \lambda a_0 \bar{\mathbf{g}}^T\right)\mathbf{f}\right|^2 + b_2^2 a_1^2 \left\|\bar{\mathbf{H}}_1 \mathbf{f}\right\|^2 + \left(a_2^2 + b_2^2\right) b_1^2 N + \lambda^2 b_0^2\right)\right)$$

- Optimization Problem:

$$\begin{aligned} \max_{\mathbf{f},\phi} \quad & C_{\text{up}} \\ \text{s.t.} \quad & \|\mathbf{f}\|^2 = 1 \\ & |\phi_i| = 1, i = 1, \ldots, N. \end{aligned}$$

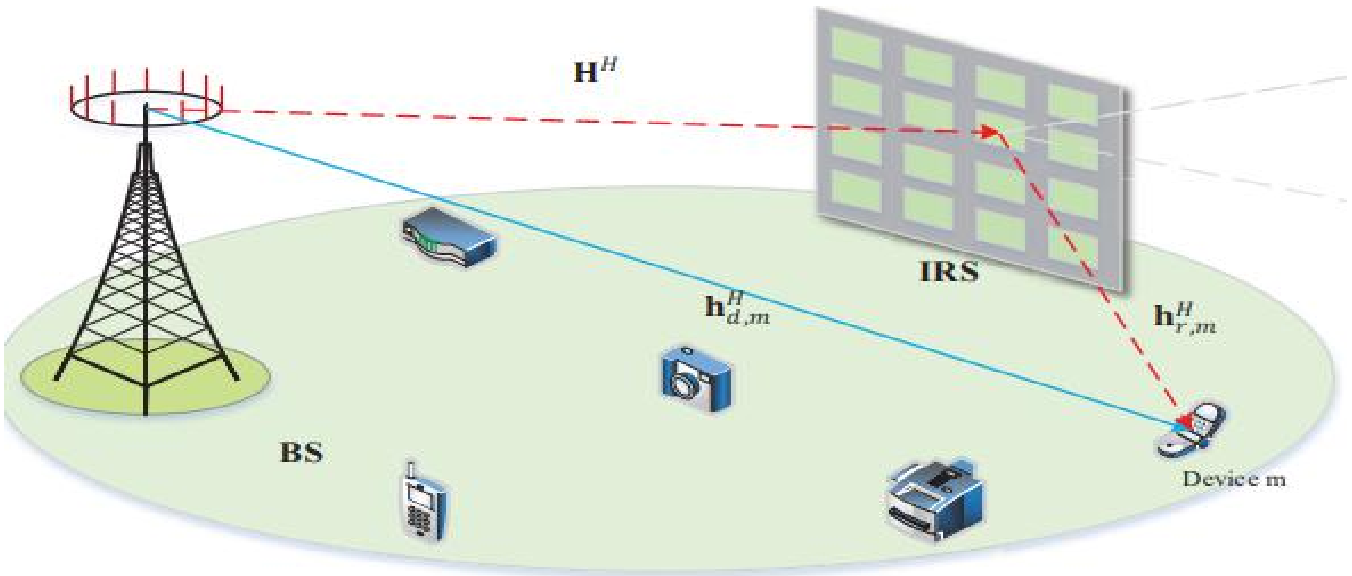
Statistical CSI: Single user case





Achieve similar performance as benchmark scheme with full CSI;
Rayleigh and Rician distributions have similar performance

Statistical CSI: Multi-user case



- System model: BS with M antennas, IRS with N reflecting elements, K single antenna user
- Effective Channel: $\mathbf{h}_m^H = (\mathbf{H}\Theta\mathbf{h}_{r,m} + \mathbf{h}_{d,m})^H$, $\mathbf{h}_{r,m}$: LoS channel; $\mathbf{h}_{d,m}$ and $\mathbf{H}$: Rician fading channel;
- CSI assumption: Two-time scale CSI at the BS

Statistical CSI: Multi-user case

- **Channel estimation:** Estimate the effective channel $\boldsymbol{h}_m$, the overhead is independent of N
- **DL precoding:** maximum ratio transmission (MRT)
- **Performance metric:** weighted sum rate (WSR)

$$\underline{R}(\boldsymbol{\theta}, \mathbf{p}) = \left(1 - \frac{\tau_p}{\tau_{\text{total}}}\right) \sum_{m=1}^{M} \omega_m \log_2 \left[1 + \underline{\gamma_m}(\boldsymbol{\theta}, \mathbf{p})\right]$$

$$\underline{\gamma_m}(\boldsymbol{\theta}, \mathbf{p}) = \frac{A_m}{B_m + C_m + D_m},$$

$$A_m = (\|\mathrm{H}_m \psi(\boldsymbol{\theta})\|_2^2 + K\sigma_1^2)^2 P_m,$$

$$B_m = \left[(\sigma_1^2 + \sigma^2)\|\mathrm{H}_m \psi(\boldsymbol{\theta})\|_2^2 + K\sigma_1^2\sigma^2\right] P_m,$$

$$C_m = \sum_{i=1, i\neq m}^{M} \left(\sigma^2\|\mathrm{H}_m \psi(\boldsymbol{\theta})\|_2^2 + \sigma_1^2\|\mathrm{H}_i \psi(\boldsymbol{\theta})\|_2^2 + |\psi^H(\boldsymbol{\theta})\mathrm{H}_i^H \mathrm{H}_m \psi(\boldsymbol{\theta})|^2 + K\sigma_1^2\sigma^2\right) P_i,$$

$$D_m = (\|\mathrm{H}_m \psi(\boldsymbol{\theta})\|_2^2 + K\sigma_1^2)\sigma_U^2.$$

1. $\underline{R}(\boldsymbol{\theta}, \mathbf{p})$ depends on statistic CSI;
2. $\underline{R}(\boldsymbol{\theta}, \mathbf{p})$ is a function of passive beamforming vector **θ** and power vector **p**.

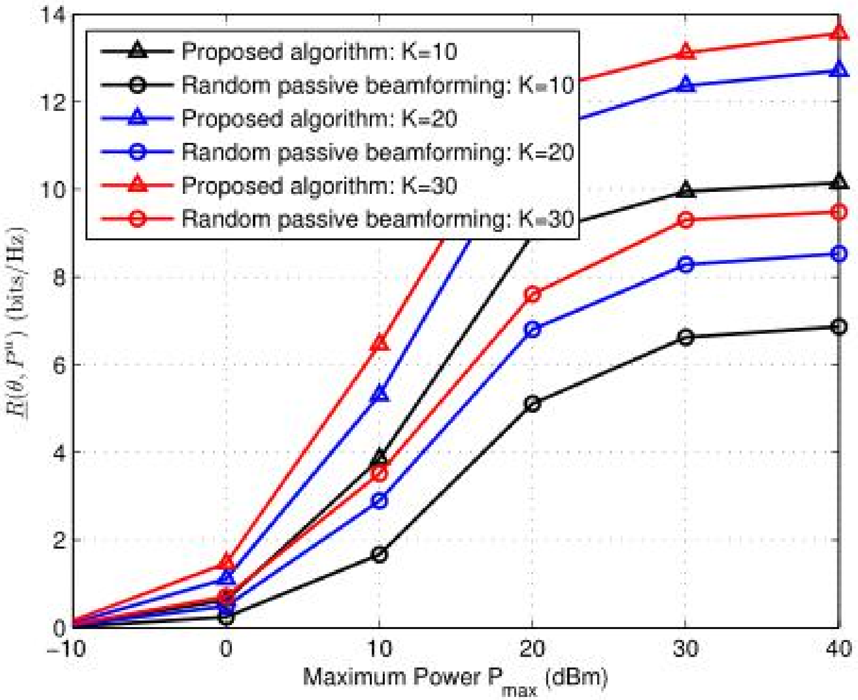
Statistical CSI: Multi-user case

Optimization problem:

$$
\begin{aligned}
(\mathrm{P}) \quad & \max_{\boldsymbol{\theta},\mathbf{p}} \underline{R}(\boldsymbol{\theta},\mathbf{p}), \\
\text{s.t.} \quad & |\theta_n| = 1, n = 1, \ldots, N, \\
& \sum_{m=1}^{M} P_m \le P_{\max}, \\
& P_m \ge 0, m = 1, \ldots, M,
\end{aligned}
$$

Solution:

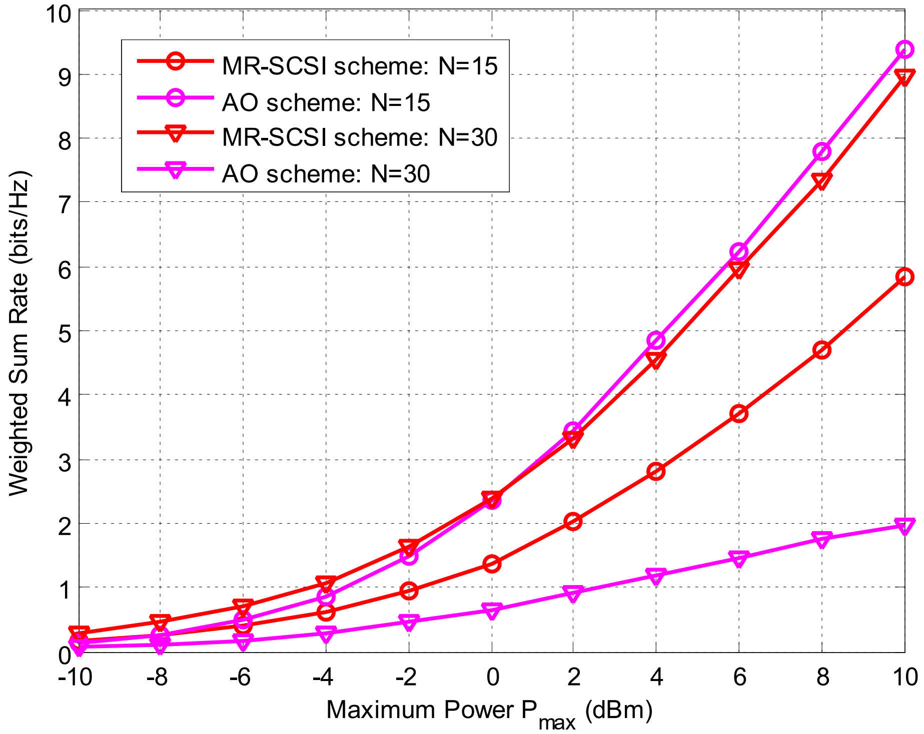
We handle the objective function via Lagrangian dual transform and quadratic transform to the fractional function, based on the more trackable objective function, we then optimize p and **θ** iteratively.



The proposed algorithm outperforms the random strategy with significant improvement.

Statistical CSI: Multi-user case

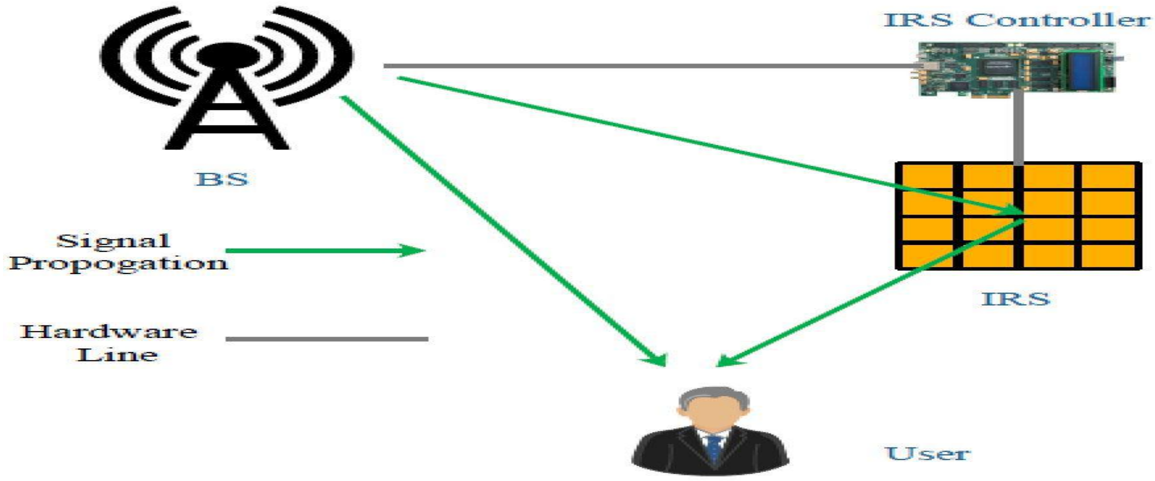
Comparing with the alternating optimization (AO) scheme proposed [HGuo], where the instantaneous CSI of each cascaded link is required, thus the channel estimation overhead scales with N.



The proposed MR-SCSI scheme outperforms the AO algorithm when N is large, indicating that we can achieve better capacity with less channel estimation overhead and computation complexity.

[HGuo] H. Guo, Y. Liang, J. Chen and E. G. Larsson, "Weighted sum-rate maximization for intelligent reflecting surface enhanced wireless networks," [Online]. Available: https://arxiv.org/abs/1905.07920.

Angle-domain beamforming



- System model: BS with M antennas, IRS with N reflecting elements, a single antenna user
- Both BS and IRS are equipped with uniform rectangular arrays
- Rician fading for all three channels

Xiaoling Hu, Caijun. Zhong, and Zhaoyang Zhang "Angle-Domain Intelligent Reflecting Surface Systems: Design and Analysis," submitted to IEEE Transactions on Communications, 2020.

Angle-domain beamforming

- System model:

$$y_{\mathrm{U}} = \left(\mathrm{h}_{\mathrm{B2U}}^{T} + \mathrm{h}_{\mathrm{I2U}}^{T}\Theta\mathrm{H}_{\mathrm{B2I}}\right)\mathbf{w}s + n_{\mathrm{U}}$$

$\boldsymbol{\Theta}$: phase shift matrix, $\mathbf{w}$: transmit beamforming vector

- Channel model:

$$\mathrm{H}_{\mathrm{B2I}} = \sqrt{\alpha_{\mathrm{B2I}}\frac{v_{\mathrm{B2I}}}{v_{\mathrm{B2I}}+1}}\mathrm{b}\left(\bar{\theta}_{\text{x-B2Ia}}, \bar{\theta}_{\text{y-B2Ia}}\right)\mathrm{a}^{T}\left(\bar{\theta}_{\text{x-B2I}}, \bar{\theta}_{\text{y-B2I}}\right) + \sqrt{\alpha_{\mathrm{B2I}}\frac{1}{v_{\mathrm{B2I}}+1}}\widetilde{\mathrm{H}}_{\mathrm{B2I}}$$

- Two Effective BS-IRS AODs:

$$\bar{\theta}_{\text{x-B2I}} = -\frac{2\pi d_{\mathrm{BS}}}{\lambda}\cos\theta_{\mathrm{B2I}}\cos\phi_{\mathrm{B2I}},$$

$$\bar{\theta}_{\text{y-B2I}} = -\frac{2\pi d_{\mathrm{BS}}}{\lambda}\cos\theta_{\mathrm{B2I}}\sin\phi_{\mathrm{B2I}},$$

- Two effective BS-IRS AOAs :

$$\bar{\theta}_{\text{x-B2Ia}} = \frac{2\pi d_{\mathrm{IRS}}}{\lambda}\cos\theta_{\mathrm{B2Ia}}\cos\phi_{\mathrm{B2Ia}},$$

$$\bar{\theta}_{\text{y-B2Ia}} = \frac{2\pi d_{\mathrm{IRS}}}{\lambda}\cos\theta_{\mathrm{B2Ia}}\sin\phi_{\mathrm{B2Ia}},$$

Angle-domain beamforming

- Estimation of the BS to User channel

$$\mathbf{r} = \mathbf{h}_{\mathrm{B2U}}^{*} q + \mathbf{n}_{\mathrm{BS}} = \sqrt{\frac{\alpha_{\mathrm{B2U}} v_{\mathrm{B2U}}}{v_{\mathrm{B2U}}+1}} \mathbf{a}\left(-\bar{\theta}_{\text{x-B2U}}, -\bar{\theta}_{\text{y-B2U}}\right) q + \sqrt{\frac{\alpha_{\mathrm{B2U}}}{v_{\mathrm{B2U}}+1}} \widetilde{\mathbf{h}}_{\mathrm{B2U}}^{*} q + \mathbf{n}_{\mathrm{BS}}$$

- Solution: Use the observed phase difference of signals received by different antennas to estimate BS-user effective AOAs ($\bar{\theta}_{x-B2U}$ and $\bar{\theta}_{y-B2U}$).

The ML estimators for $\bar{\theta}_{x-B2U}$ and $\bar{\theta}_{y-B2U}$ are given by

$$\hat{\bar{\theta}}_{\text{x-B2U}} = -\frac{6\sum_{n=1}^{N/2}\left(i_{N,n} - i_{N,m_n}\right)\Delta\bar{\theta}_{n,m_n}}{N\left(N-1\right)},$$

$$\hat{\bar{\theta}}_{\text{y-B2U}} = -\frac{6\sum_{n=1}^{N/2}\left(j_{N,n} - j_{N,m_n}\right)\Delta\bar{\theta}_{n,m_n}}{N\left(N-1\right)}.$$

$\bar{\theta}_{n,m_n}$: phase differences between antenna n and $m_n = N - n + 1$.

Angle-domain beamforming

- Optimization Problem

$$\max_{\{\boldsymbol{\Theta},\mathbf{w}\}} \quad P_r = \mathbf{w}^H \mathbf{T} \mathbf{w},$$

$$\text{s. t.} \qquad |\mathbf{w}|^2 \le P_{BS},$$

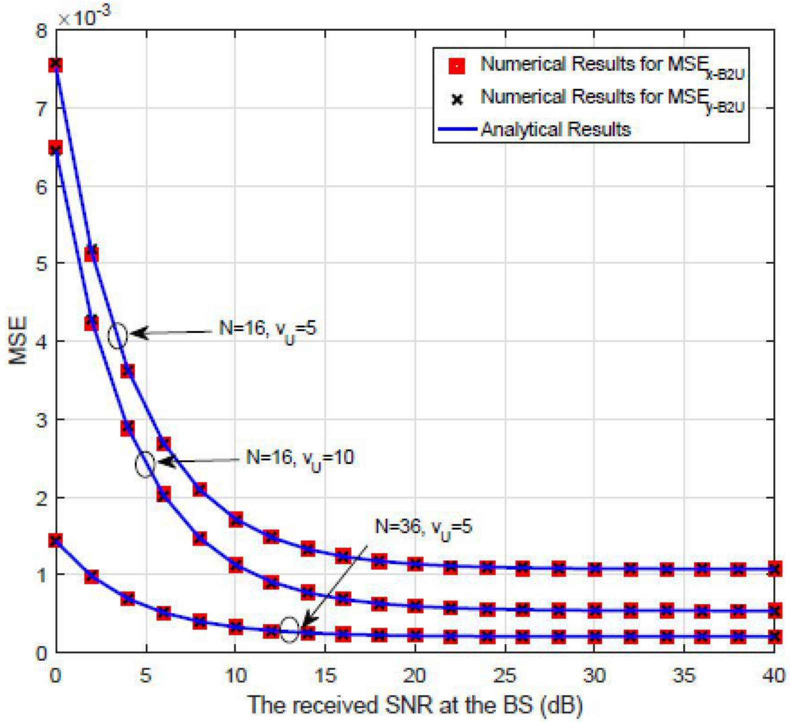
$$|[\boldsymbol{\Theta}]_{ii}| = 1, i = 1, \ldots, M,$$

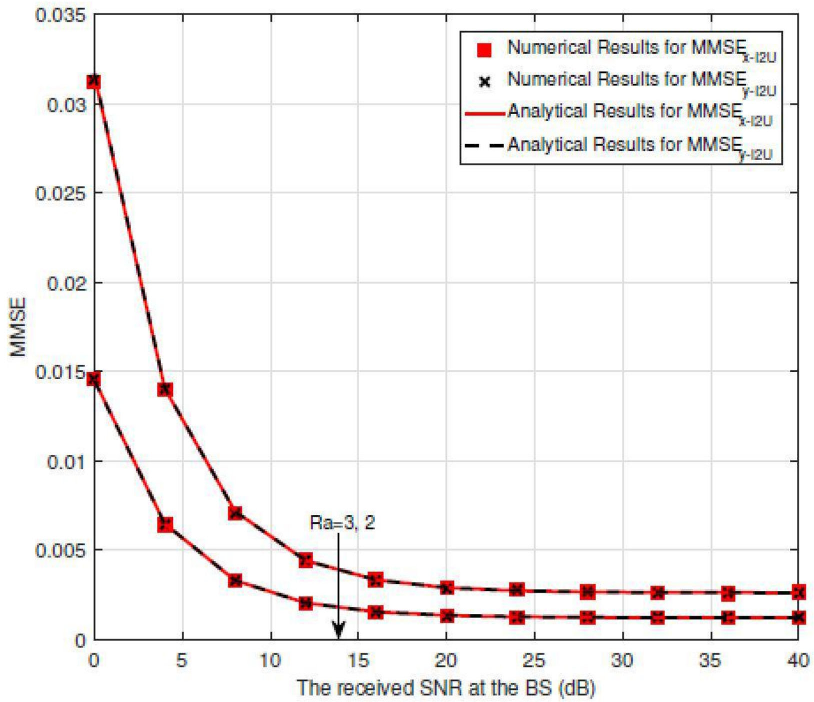
$$\mathbf{T} \triangleq \beta_{\text{B2I2U}} \left(\boldsymbol{\Theta}\bar{\mathbf{H}}_{\text{B2I}}\right)^H \mathbf{B}\boldsymbol{\Theta}\bar{\mathbf{H}}_{\text{B2I}} + \sqrt{\beta_{\text{B2I2U}}\beta_{\text{B2U}}} \left(\left(\boldsymbol{\Theta}\bar{\mathbf{H}}_{\text{B2I}}\right)^H \mathbf{C} + \mathbf{C}^H \boldsymbol{\Theta}\bar{\mathbf{H}}_{\text{B2I}}\right)$$

$$+ \beta_{\text{B2U}}\mathbf{A} + \sigma_{\text{NLOS}}^2 \mathbf{I}_N,$$

- Alternating Method:
  - Optimize transmit beamforming vector: convex problem
  - Optimize the phase shift vector: a gradient method.

Angle-domain beamforming

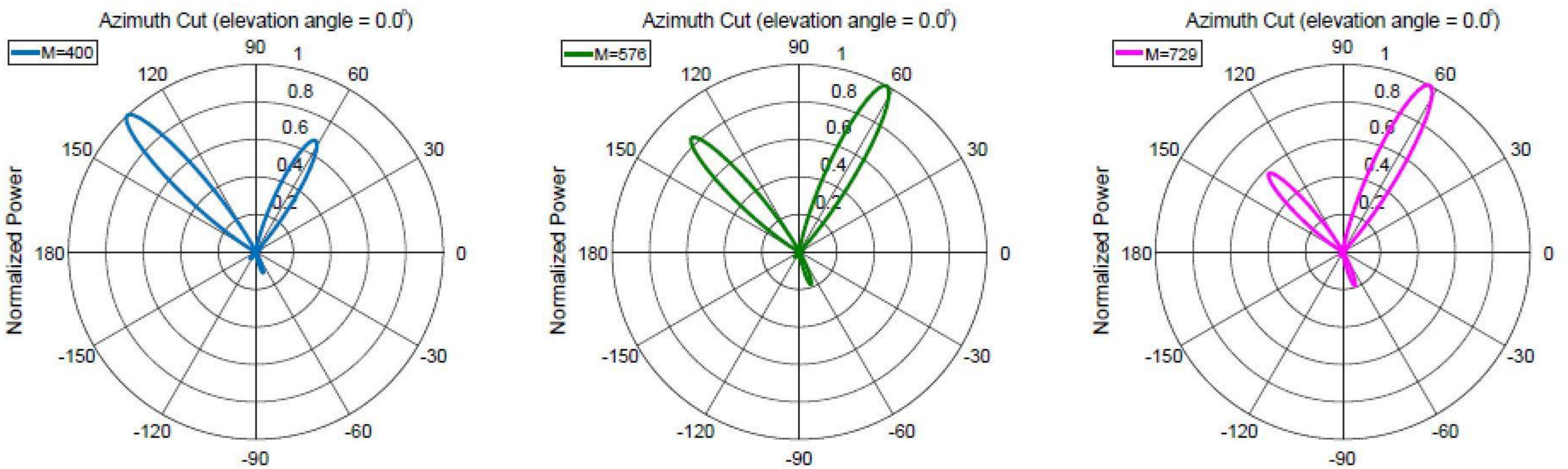




Large antenna number N; Strong LoS path; and High SNR Improve the angle estimation accuracy

The relative distance to the BS and IRS has a significant impact on the estimation accuracy

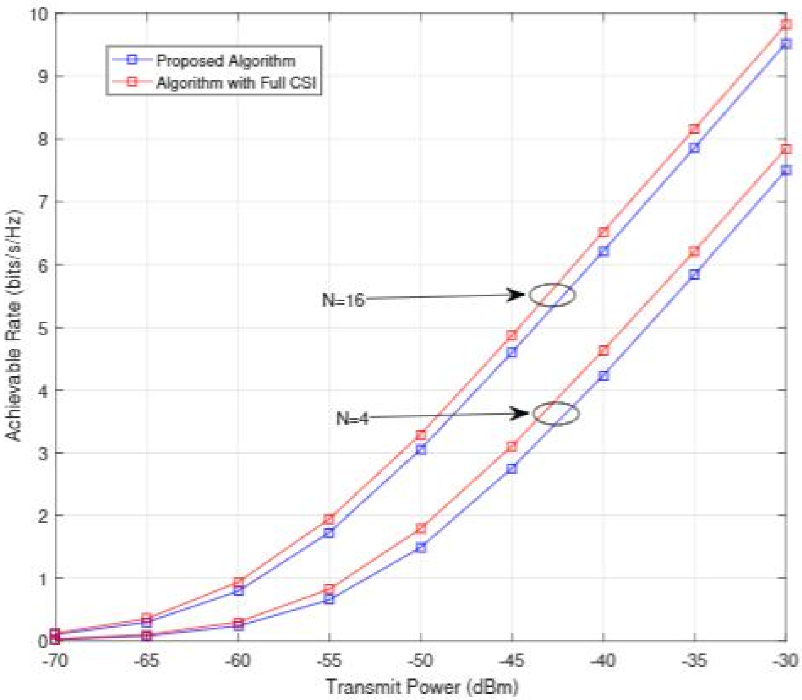
Angle-domain beamforming



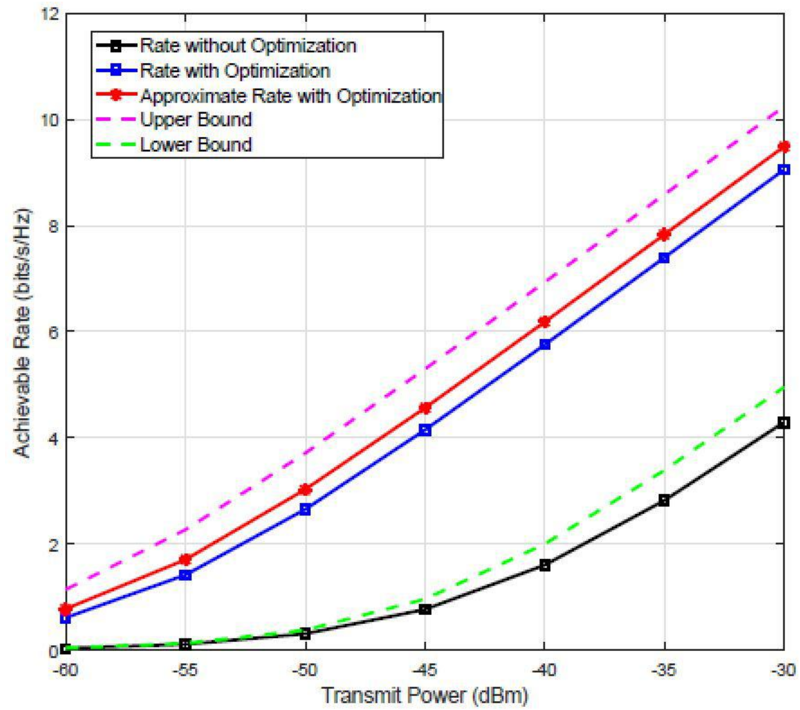
Setup： N=36； UE Location (41m, 133°, -16°), IRS Location (42m, 63°, -16°)

As the number of reflecting elements increases, the lobe in the user direction gradually becomes smaller and the main lobe appears in the IRS direction

Angle-domain beamforming



The proposed angle-based algorithm achieves nearly the same performance as the algorithm with full CSI



Lower bound: Without BS-UE Information; Optimization of the phase shift of IRS is essential

Conclusion

- Conclusions
  - IRS is a disruptive technology to realize **intelligent and reconfigurable** propagation environment for future wireless network
  - IRS can enhance the system performance by using **low-cost** passive reflecting elements
  - A paradigm shift of wireless communication from traditional "active component solely" to the new "active and passive" hybrid network
- Challenges from the communications perspective
  - IRS channel estimation
  - IRS reflection optimization

相关论文

1. Q. Tao, J. Wang, and C. Zhong, "Performance Analysis of Intelligent Reflecting Surface Aided Communication Systems," accepted to appear in **IEEE Communications Letter**, 2020.
2. X. Gan, C. Zhong, Y. Zhu, and Z. Zhang, "User Selection in Reconfigurable Intelligent Surface Assisted Communication Systems," submitted to **IEEE Communications Letter**, 2020.
3. J. Gao, C. Zhong, X. Chen, H. Lin and Z. Zhang, "Unsupervised Learning for Passive Beamforming," **IEEE Communications Letters**, vol. 24, no. 5, pp. 1052-1056, May 2020
4. Q. Tao, S. Zhang, C. Zhong, and R. Zhang, "Intelligent reflecting surface aided multicasting with random passive beamforming," accepted to appear in **IEEE Wireless Communications Letters**, 2020.
5. X. Hu, J. Wang, and C. Zhong, "Statistical CSI based design for intelligent reflecting surface assisted MISO systems," **Science China: Information Science**, vol. 63, no. 12, 222303, 2020..
6. G. Yu, X. Chen, C. Zhong, D. Ng, and Z. Zhang, "Analysis and Optimization of a Large Intelligent Reflecting Surface Aided B5G Cellular Internet of Things," **IEEE Internet of Things Journal**, vol. 7, no. 9, pp. 8902--8916, Sep. 2020.
7. X. Hu, C. Zhong, and Z. Zhang, "Angle-domain intelligent reflecting surface systems: Design and analysis," submitted to **IEEE Trans. Communications**, 2020.

相关论文

8. X. Hu, C. Zhong, Y. Zhang, X. Chen, and Z. Zhang, "Location information aided multiple intelligent reflecting surface systems," accepted to appear in **IEEE Tran. Communications**, 2020.
9. J. Zhang, Y. Zhang, C. Zhong, and Z. Zhang, "Robust design for intelligent reflecting surfaces assisted MISO systems," accepted to appear in **IEEE Communications Letters**, 2020.
10. X. Hu, C. Zhong, M. Alouini, and Z. Zhang, "Robust design for IRS-aided communication systems with user location uncertainty," accepted to appear in **IEEE Wireless Communications Letters**, 2020.
11. X. Hu, C. Zhong, Y. Zhu, X. Chen, and Z. Zhang, "Programmable metasurface based multicast systems: Design and analysis," **IEEE Journal on Selected Areas in Communications**, 2020.
12. Y. Zhang, C. Zhong, Z. Zhang, and W. Lu "Sum Rate Optimization for Two Way Communications With Intelligent Reflecting Surface", **IEEE Communications Letters**, vol. 24, no. 5, pp. 1090-1094, May 2020.

中国科学 信息科学
SCIENTIA SINICA Informationis

Science China Information Sciences: Call for Paper

Special Focus on Reconfigurable Intelligent Surfaces for Future Wireless Communications

Important Dates:
Manuscript submission deadline: **December 1, 2020**
Revision notification: March 1, 2021
Final manuscripts due: May 15, 2021
Publication: October 1, 2021

Guest Editors:
Ying-Chang Liang, University of Electronic Science and Technology of China, China,
Caijun Zhong, Zhejiang University, China
Liang Yang, Hunan University, China
Zhen-Qing He, University of Electronic Science and Technology of China, China,
Marco Di Renzo, CNRS & Paris-Saclay University, France