Capacity Enhancement for Irregular Reconfigurable Intelligent Surface-Aided Wireless Communications

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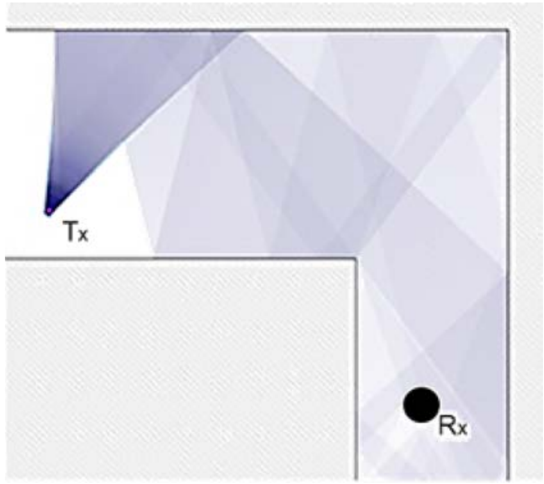
4 **Summary**

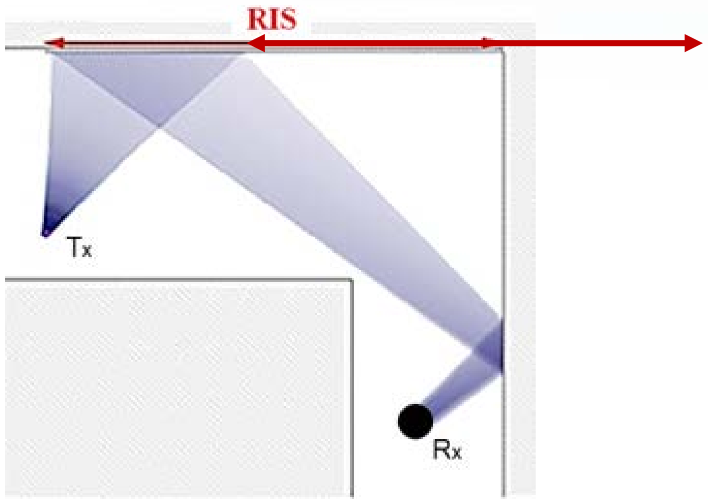
Background

- **Reconfigurable intelligent surface (RIS)**
  - **A two-dimensional electromagnetic metasurface**
  - **Control the propagation of electromagnetic waves**
  - **Manipulate the wireless environment to improve the quality of the signal**



Traditional wireless communications:
Heavily rely on the environment

RIS

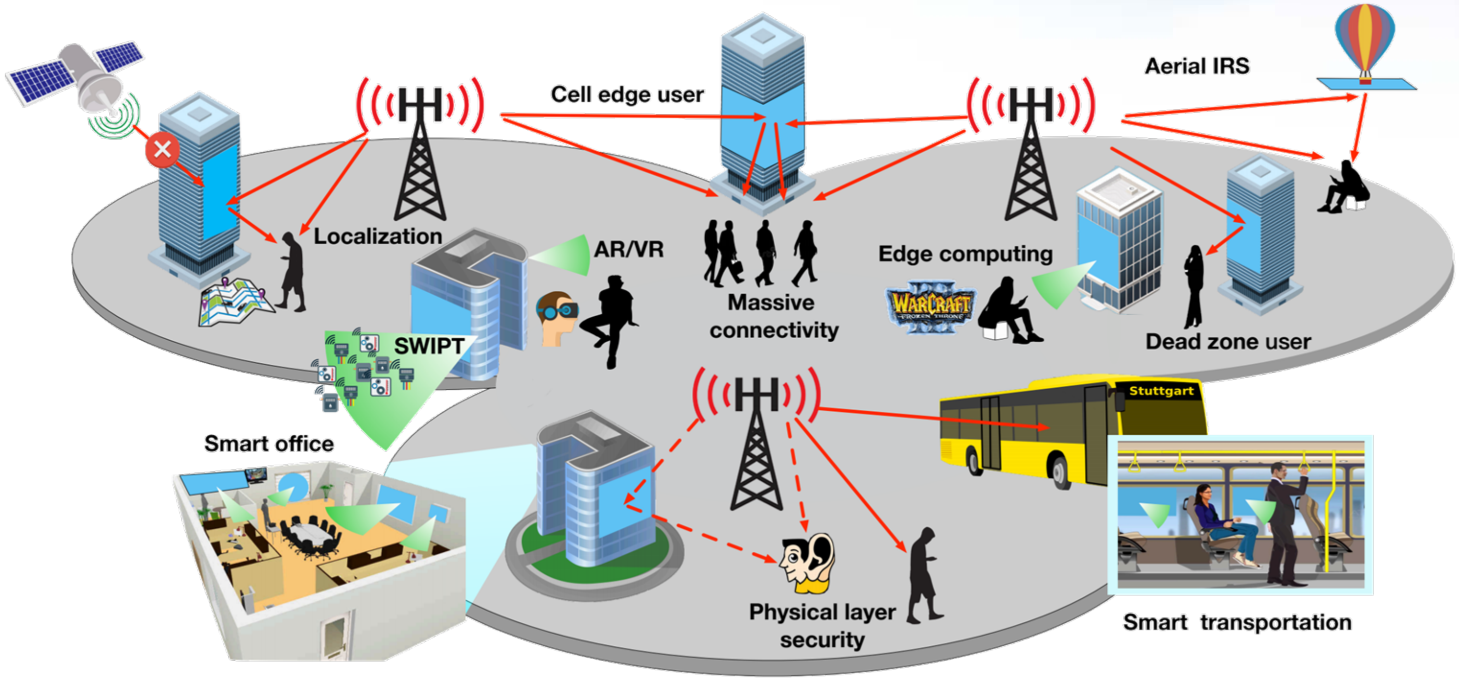


RIS-aided wireless communications:
Intelligently control the environment

E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116753-116773, Jul. 2019.

Background

- **RIS-aided wireless communications**
  - Overcome the blockage
  - Enhance the signal quality
  - Save the power consumption

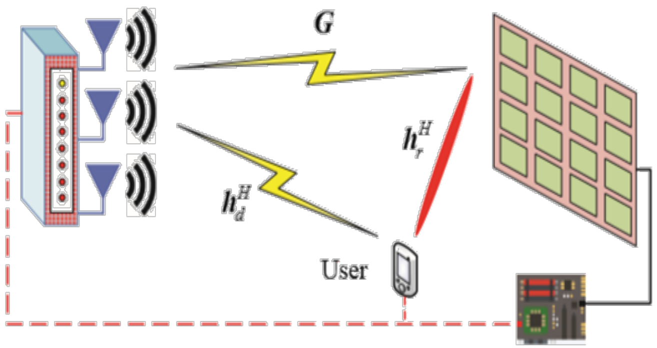


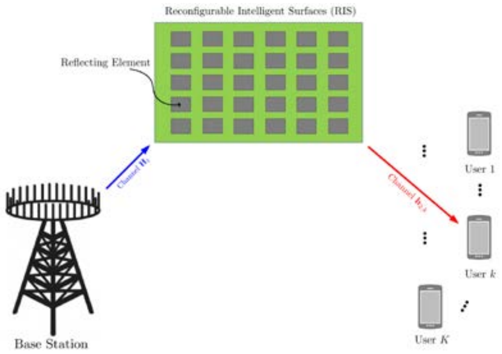
Q. Wu, S. Zhang, B. Zheng, C. You, R. Zhang, "Intelligent reflecting surface aided wireless communications: A tutorial," *arXiv preprintarXiv:2007.02759*, Jul. 2020.

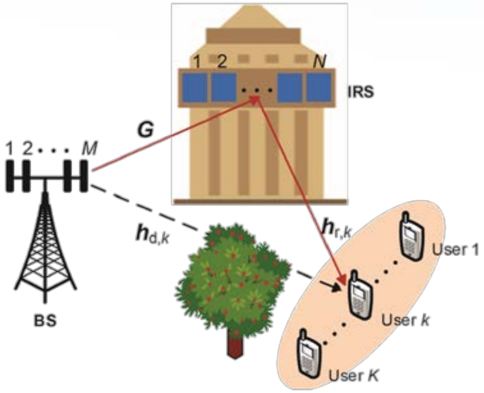
Background

- **Beamforming design**
  - **Base station (BS) + RIS + user ends (UE)**
  - **Line-of-sight path (BS-UE) + reflection path (BS-RIS-UE)**
  - **Precoding (BS) + reflection coefficients (RIS)**

- **Optimization objective**
  - **Sum-rate**
  - **Energy efficiency**
  - **Transmit power**





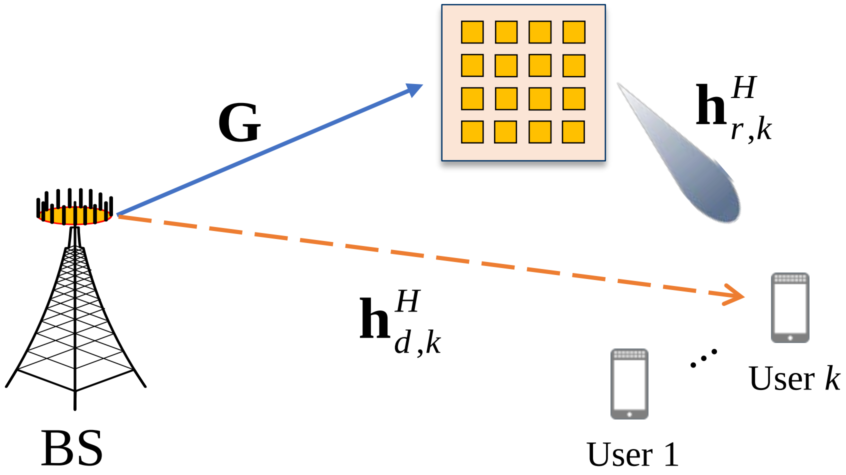


[1] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen, "Reconfigurable intelligent surfaces for energy efficiency in wireless communication," *IEEE Trans. Wireless Commun.*, vol. 18, no. 8, pp. 4157–4170, Aug. 2019.
[2] H. Guo, Y.-C. Liang, J. Chen, and E. G. Larsson, "Weighted sumrate optimization for intelligent reflecting surface enhanced wireless networks," *arXiv preprint arXiv:1905.07920v2*, May 2019.
[3] 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.

Background

- **Challenge**
  - **Prior works have only considered the regular RIS structure**
  - **Regular RIS: High capacity requires a large number of RIS elements**
  - **Unbearable system complexity and signal processing overhead**

Regular RIS



How to improve the capacity with a limited number of RIS elements?

[1] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116753-116773, Jul. 2019.

[2] C. Hu and L. Dai, "Two-timescale channel estimation for reconfigurable intelligent surface aided wireless communications," *arXiv preprint arXiv:1912.07990*, Dec. 2019.

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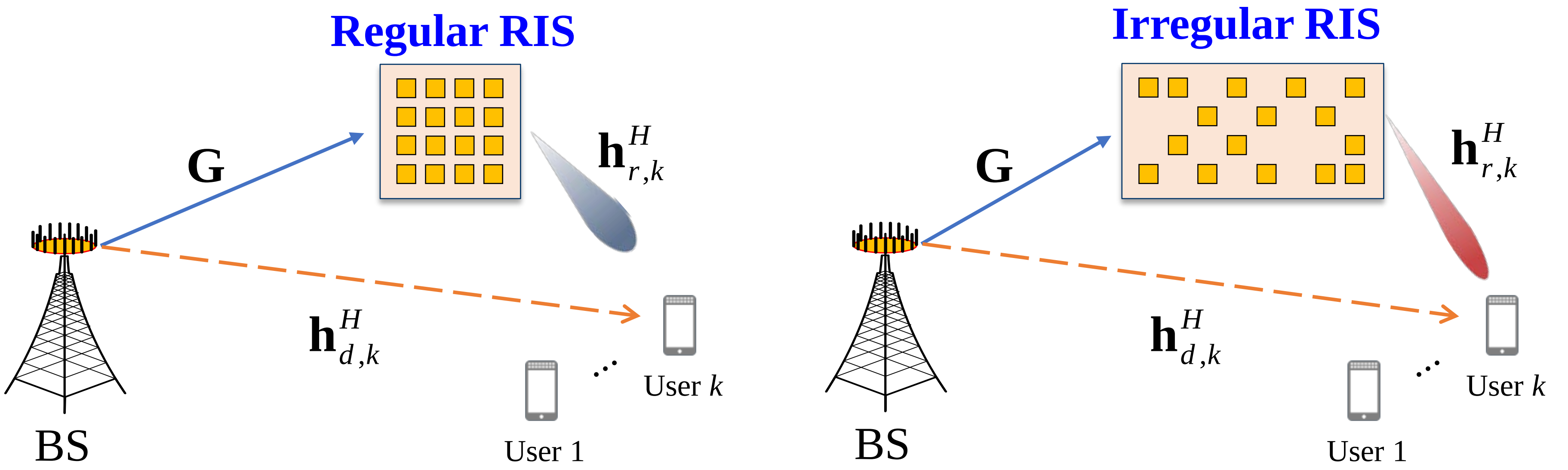
Capacity Enhancement by Irregular RIS

- **Challenge**
  - **Regular array**: Elements are **regularly arranged** with constant interelement spacing
  - High capacity requires a **large** number of RIS elements
- **Proposal**
  - **Irregular array**: Elements are **irregularly arranged** on an enlarged surface
  - Additional **degrees of freedom and spatial diversity** for more capacity



More space leads to more system capacity

System Model

- **Irregular RIS-aided communications**
  - ➢ ***K*** **single-antenna users, BS with** ***M*** **antennas**
  - ➢ **Irregular RIS comprising** ***N*** **elements distributed over** N_s **grid points**

$$\mathbf{y} = \left(\mathbf{H}_r^H \mathbf{Z}\boldsymbol{\Theta}\mathbf{G} + \mathbf{H}_d^H\right)\mathbf{x} + \mathbf{n}, \quad \mathbf{x} = \sum_{k=1}^{K} \mathbf{w}_k s_k$$

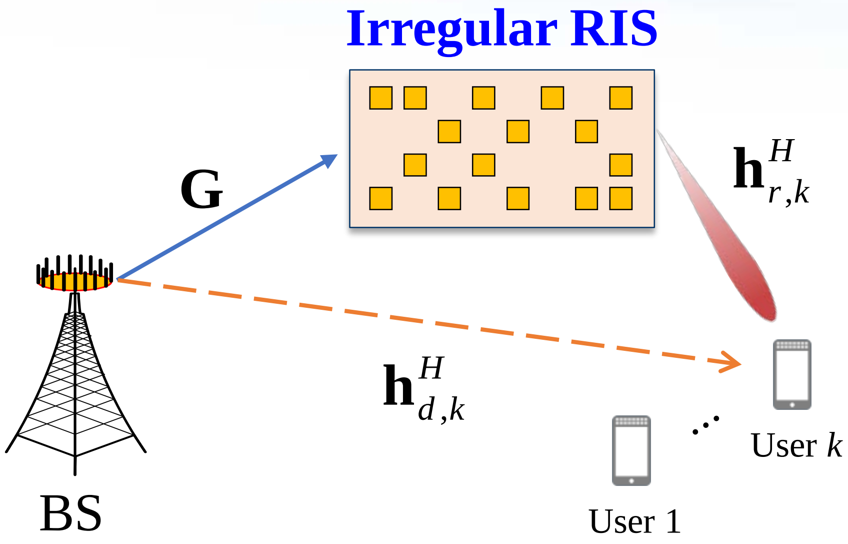
RIS topology

$$\mathbf{Z} = \mathrm{diag}(\mathbf{z}), \quad \mathbf{z} = [z_1, z_2, \cdots, z_{N_s}]^T, \quad z_i \in \{1, 0\}$$

$$\boldsymbol{\Theta} = \mathrm{diag}([\beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, \cdots, \beta_{N_s} e^{j\theta_{N_s}}]), \quad \beta_n = 1, \quad \theta_n \in F = \{0, \pi\}$$

- ➢ **The signal-to-interference-plus-noise ratio (SINR) of user** ***k***

$$\gamma_k = \frac{\left|\left(\mathbf{h}_{r,k}^H \mathbf{Z}\boldsymbol{\Theta}\mathbf{G} + \mathbf{h}_{d,k}^H\right)\mathbf{w}_k\right|^2}{\sum_{i \neq k}^{K} \left|\left(\mathbf{h}_{r,k}^H \mathbf{Z}\boldsymbol{\Theta}\mathbf{G} + \mathbf{h}_{d,k}^H\right)\mathbf{w}_i\right|^2 + \sigma^2}$$



System Model

- **Channel model**

$$\mathbf{y}=\left(\mathbf{H}_r^H\mathbf{Z}\boldsymbol{\Theta}\mathbf{G}+\mathbf{H}_d^H\right)\mathbf{x}+\mathbf{n},\quad \mathbf{H}_d^H=\left[\mathbf{h}_{d,1},\mathbf{h}_{d,2},\cdots,\mathbf{h}_{d,K}\right]^H\in\mathbb{C}^{K\times M},\quad \mathbf{H}_r^H=\left[\mathbf{h}_{r,1},\mathbf{h}_{r,2},\cdots,\mathbf{h}_{r,K}\right]^H\in\mathbb{C}^{K\times N_s}$$

  - **The small-scale fading: uncorrelated Rayleigh fading channel model**
  - **The large-scale fading: distance-dependent path loss**
  - **Path loss: BS-RIS-UE channel**

$$f_r(d_{\mathrm{BR}},d_{\mathrm{RU}})=C_{\mathrm{r}}d_{\mathrm{BR}}^{-\alpha_{\mathrm{BR}}}d_{\mathrm{RU}}^{-\alpha_{\mathrm{RU}}},$$

Distance

Channel fading

  - **Path loss: BS-UE channel**

$$f_d(d_{\mathrm{BU}})=C_{\mathrm{d}}d_{\mathrm{BU}}^{-\alpha_{\mathrm{BU}}}$$

Path loss exponent

[1] O.Ozdogan, E. Björnson, and E. G. Larsson, "Intelligent reflecting surfaces: Physics, propagation, and pathloss modeling," *IEEE Wireless Commun. Lett.*, vol. 9, no. 5, pp. 581–585, May 2020.

[2] Z. Zhang and L. Dai, "A joint precoding framework for wideband reconfigurable intelligent surface-aided cell-free network," *arXiv preprint arXiv:2002.03744v2*, Feb. 2020.

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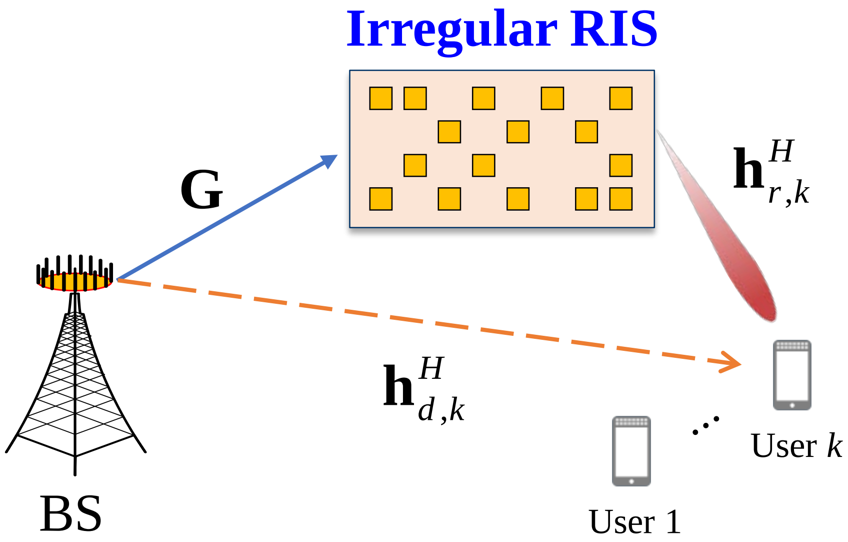
Problem Formulation

- **Weighted sum-rate (WSR) maximization**
  - ➢ **Joint optimization: RIS topology and beamforming design**
  - ➢ **The topology design lacks methodological guidance**



$$
\begin{aligned}
\mathcal{P}_1: \quad & \max_{\mathbf{Z},\mathbf{W},\boldsymbol{\Theta}} \quad R = \sum_{k=1}^{K} \omega_k \log_2(1+\gamma_k) \\
\text{s.t.} \quad & C_1: \sum_{k=1}^{K} \|\mathbf{w}_k\|_2^2 \le P_{\mathrm{T}}, \\
& C_2: \theta_n \in \mathcal{F}, \forall n = 1, 2, \cdots, N_{\mathrm{s}}, \\
& C_3: z_i(z_i - 1) = 0, \forall i = 1, 2, \cdots, N_{\mathrm{s}}, \\
& C_4: \mathbf{1}^T \mathbf{z} = N.
\end{aligned}
$$

Transmit power constraint

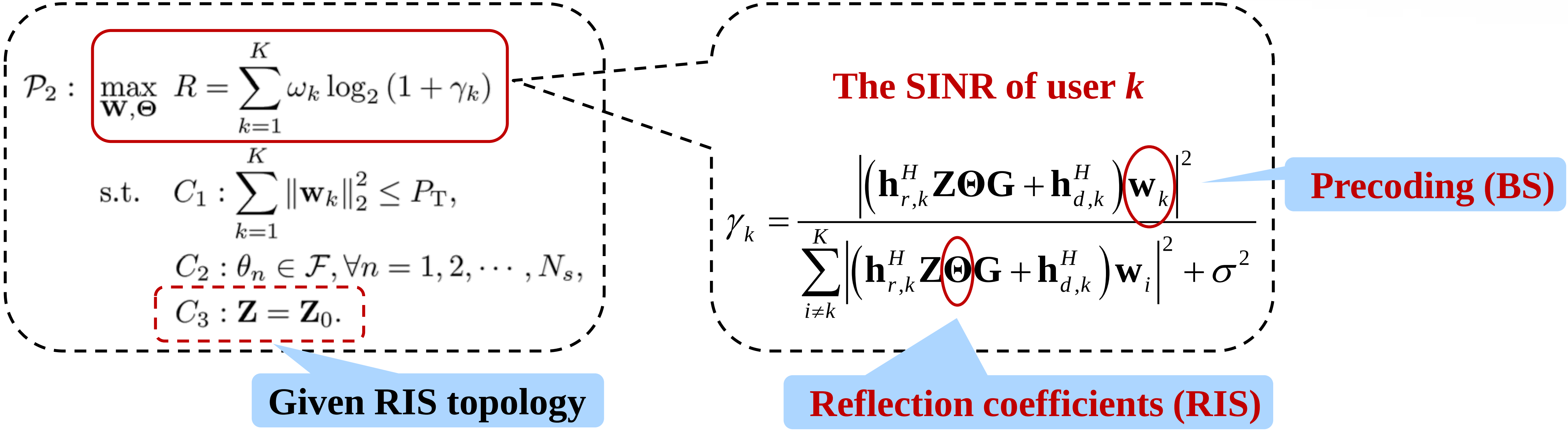
Discrete phase shifts constraint

Sparsity constraints

Non-convex: hard to solve

Problem Formulation

- **Solution**
  - **Decouple the RIS topology design and the beamforming optimization**
  - **For a given topology: Convert the original problem to P_2**
  - **Let $\mathbf{Z}_0 = \mathbf{I}_N$: Equivalent to regular RIS-aided wireless communications**



$$\mathcal{P}_2: \boxed{\max_{\mathbf{W},\boldsymbol{\Theta}} \; R = \sum_{k=1}^{K} \omega_k \log_2(1+\gamma_k)}$$

$$\text{s.t.} \quad C_1: \sum_{k=1}^{K} \|\mathbf{w}_k\|_2^2 \le P_{\mathrm{T}},$$

$$C_2: \theta_n \in \mathcal{F}, \forall n = 1, 2, \cdots, N_s,$$

$$C_3: \mathbf{Z} = \mathbf{Z}_0.$$

Given RIS topology

The SINR of user *k*

$$\gamma_k = \frac{\left|\left(\mathbf{h}_{r,k}^H \mathbf{Z}\boldsymbol{\Theta}\mathbf{G} + \mathbf{h}_{d,k}^H\right)\mathbf{w}_k\right|^2}{\sum_{i\neq k}^{K}\left|\left(\mathbf{h}_{r,k}^H \mathbf{Z}\boldsymbol{\Theta}\mathbf{G} + \mathbf{h}_{d,k}^H\right)\mathbf{w}_i\right|^2 + \sigma^2}$$

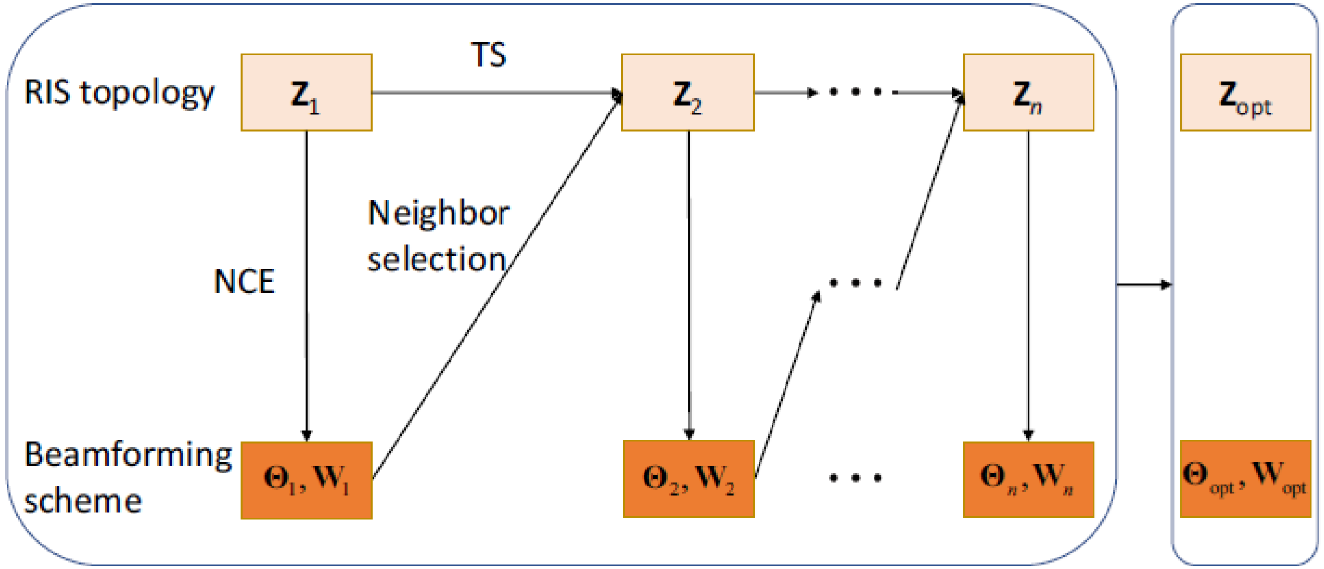
Precoding (BS)

Reflection coefficients (RIS)

Contents

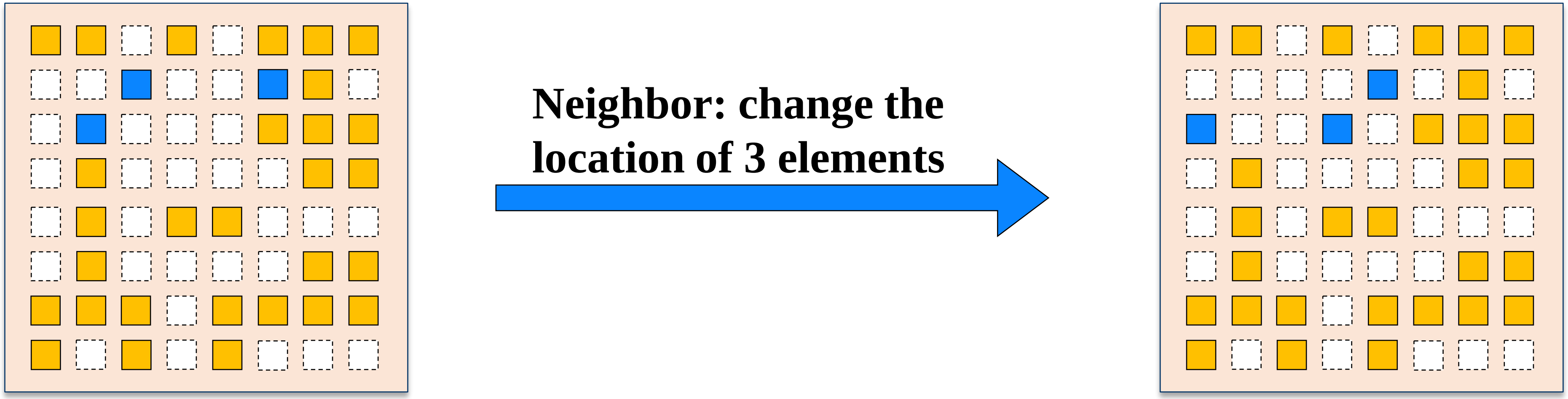
Joint Optimization Framework

- **Overview**
  - **Alternating optimization: Decouple the decision variables in P_1**
  - **RIS topology: Tabu search (TS) method**
  - **Beamforming: Neighbor extraction-based cross-entropy (NCE) method**
  - **General solution to the classical sum-rate optimization problem**



Joint Optimization Framework: RIS Topology

- **TS-based sparse deployment of RIS**
  - **Input: Tabu list, storage size, neighbor distance, neighborhood size, iterations**
  - **Output: Optimal RIS topology Z**
  - **Generate alternative neighbors**
  - **Select the candidate with the maximum WSR in each iteration**



Neighbor: change the location of 3 elements

X. Gao, L. Dai, C. Yuen, and Z. Wang, "Turbo-like beamforming based on tabu search algorithm for millimeter-wave massive MIMO systems," *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, pp. 5731–5737, Jul. 2016.

Joint Optimization Framework: Beamforming Scheme

- **NCE-based beamforming optimization**
  - **Input: RIS topology, iterations, number of candidates/elites, quantized phase shifts set**
  - **Output: Phase shifts matrix $\boldsymbol{\Theta}$, precoding matrix W**
  - **Generate candidates based on the probability distribution function**

$$\Xi(\boldsymbol{\Theta};\mathbf{P}^{(i)}) = \prod_{n=1}^{N_s}\left(\prod_{k=1}^{2^b}(p_{n,k}^{(i)})^{\delta(\theta_n - F(k))}\right)$$

  - **Neighbor extraction: Change each effective element of the current optimal $\boldsymbol{\Theta}$ in each iteration**
  - **Weighted probability transfer criterion**

$$\mathbf{P}^{(i+1)} = \arg\max_{\mathbf{P}^{(i)}} \frac{1}{C_{\text{elite}}}\sum_{c=1}^{C_{\text{elite}}}\eta_c \ln \Xi\left(\boldsymbol{\Theta}^{(c)};\mathbf{P}^{(i)}\right), \quad \eta_c = \frac{R(\boldsymbol{\Theta}^{(c)})C_{\text{elite}}}{\sum_{c=1}^{C_{\text{elite}}} R(\Theta^{(c)})}$$

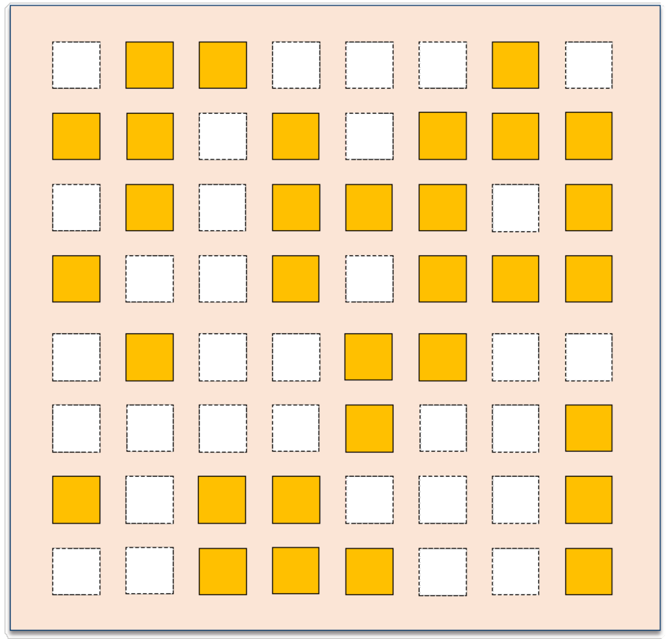
- **BS: Zero forcing precoding**

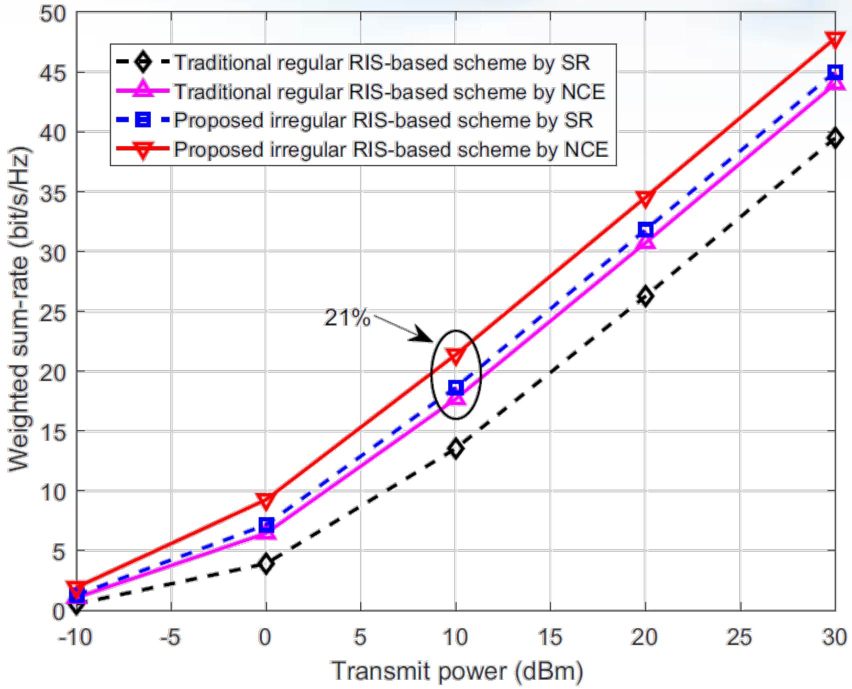
$$\mathbf{W} = \mathbf{H}_{\text{eq}}^{H}(\mathbf{H}_{\text{eq}}\mathbf{H}_{\text{eq}}^{H})^{-1}\mathbf{P}_{\text{B}}^{\frac{1}{2}}$$

R. Y. Rubinstein and D. P. Kroese, *The cross-entropy method: A unified approach to combinatorial optimization, Monte-Carlo simulation and machine learning*, Springer Science and Business Media, 2013.

Simulations

- **WSR versus the transmit power**
    - **Antennas of BS: M=4，users: K=4**
    - **RIS elements: N=32，grid points: N_s=64**

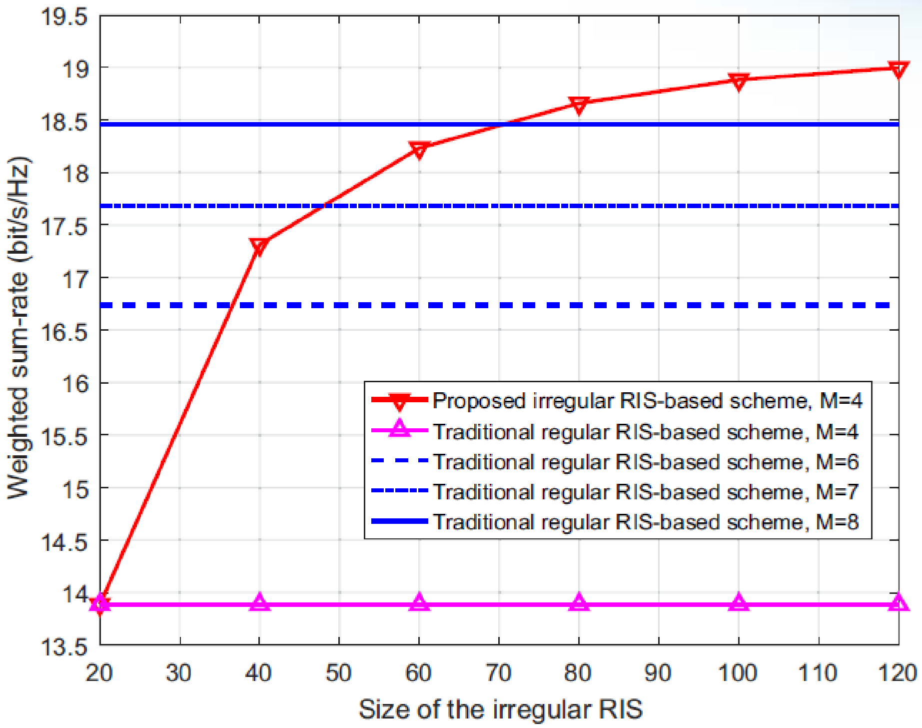




The irregular RIS outperforms the regular RIS

Simulations

- **WSR versus the size of the irregular RIS**
  - **Antennas of BS: *M*=4， users: *K*=4**
  - **RIS elements: *N*=32**



The sparse ratio of RIS: tradeoff between the cost and the performance

Contents

Summary

- **Challenge**
  - **Regular RIS: High capacity requires a large number of RIS elements**
  - **Unbearable system complexity and signal processing overhead**

- **Solution**
  - **Irregular RIS: Additional degrees of freedom in space for more capacity**
  - **Propose a joint optimization framework**

- **Conclusion**
  - **The proposed irregular RIS can significantly improve the system capacity compared to the traditional regular RIS**

- **Further works**
  - **The influence of mutual coupling effect at the RIS**
  - **Channel estimation for irregular RIS-aided communications**

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Thank you

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