Reconfigurable Intelligent Surfaces (RIS) Aided Multi-user Systems: Interplay Between NOMA and RIS

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Outline

Ancestor Concepts Related to the RIS

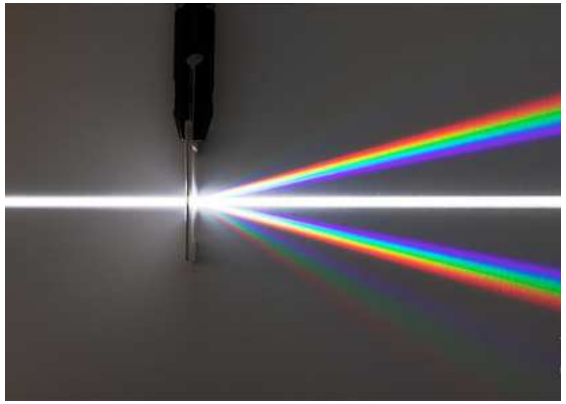


Fig.: Optical grating

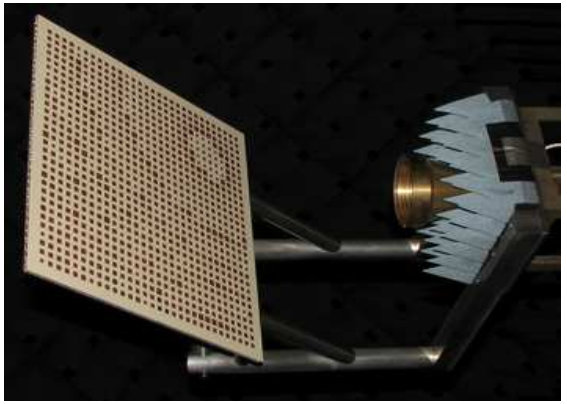


Fig.: Reflect-array antennas

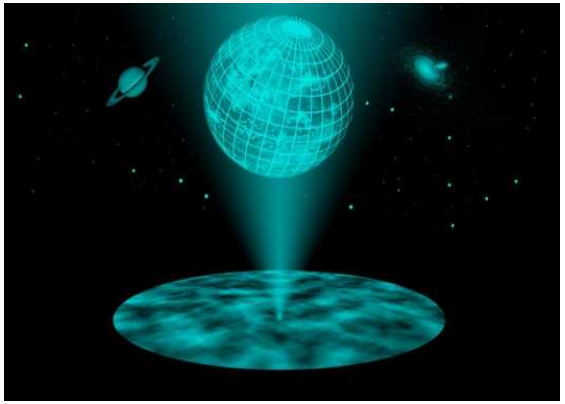


Fig.: Hologram

- A wireless signal is essentially an **EM wave** propagating in 3D space.
- According to the law of energy conservation, the RIS **redistributes the radiation power** into different directions, according to the information encrypted in the surface.

Achieving Reconfigurability of the RIS

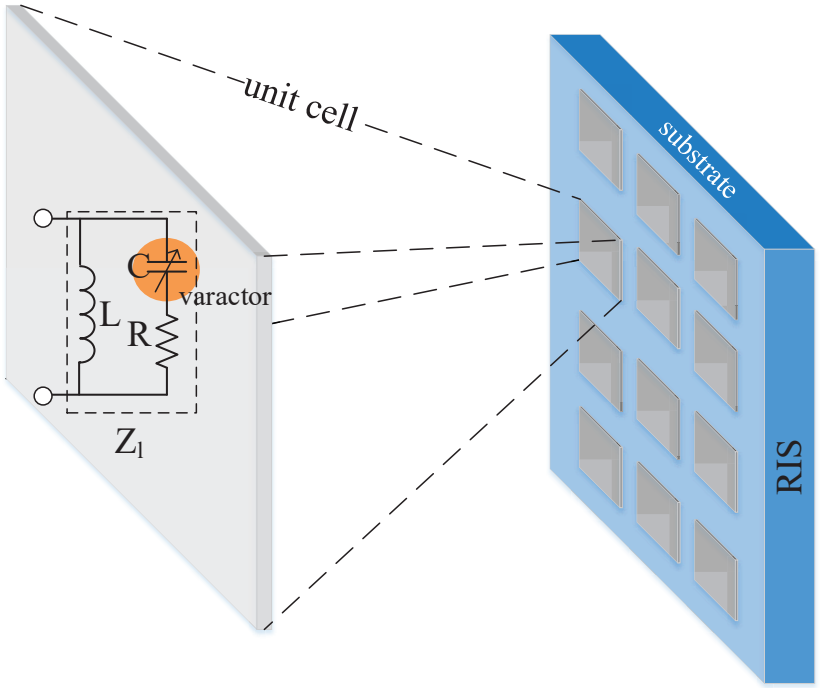


Fig.: Schemetic diagram of the varactor RIS

[1] **Y. Liu** *et.al.*, "Reconfigurable Intelligent Surfaces: Principles and Opportunities ", *https://arxiv.org/abs/2007.03435*

- The EM response of the RIS, such as phase discontinuity (**phase shift**), can be reconfigured. Various mechanisms support this tuning (**electrical voltage**, thermal excitation, optical pump, and physical stretching).
- The most important parameter of the RIS is the **reflection coefficient** $\tilde{r}$ at each element (cell), defined as: $\tilde{r} = \frac{E_r}{E_i} = \frac{Z_l - Z_0}{Z_l + Z_0}$

Reconfigurable Intelligent Surfaces (RISs) Aided Wireless Networks

- **Advantages of RIS [1]**
  - **Easy to deploy**: RISs can be deployed on several structures, including but not limited to building facades, indoor walls, aerial platforms, roadside billboards, highway polls.
  - **Spectrum efficiency enhancement**: Meet the diversified demands of services and applications of smart communications, e.g., receivers on the died-zones.
  - **Environment friendly**: More energy efficient compared to *relay*.
  - **Compatibility**: RIS can be compatible with the standards and hardware of existing wireless networks
  - This is **Next Generation Relay Networks or MIMO 2.0**.
  - Also namely as intelligent reflecting surface (IRS), large intelligent surface (LIS), metasurface, etc.
- **Challenges**
  - What **physical models** shall we use?

[1] **Y. Liu**, et. al. "Reconfigurable Intelligent Surfaces: Principles and Opportunities", ***IEEE Communications Survey and Tutorial***, *under revision, https://arxiv.org/abs/2007.03435*.

Possible Application Scenarios of RIS in the Wireless Networks [1]

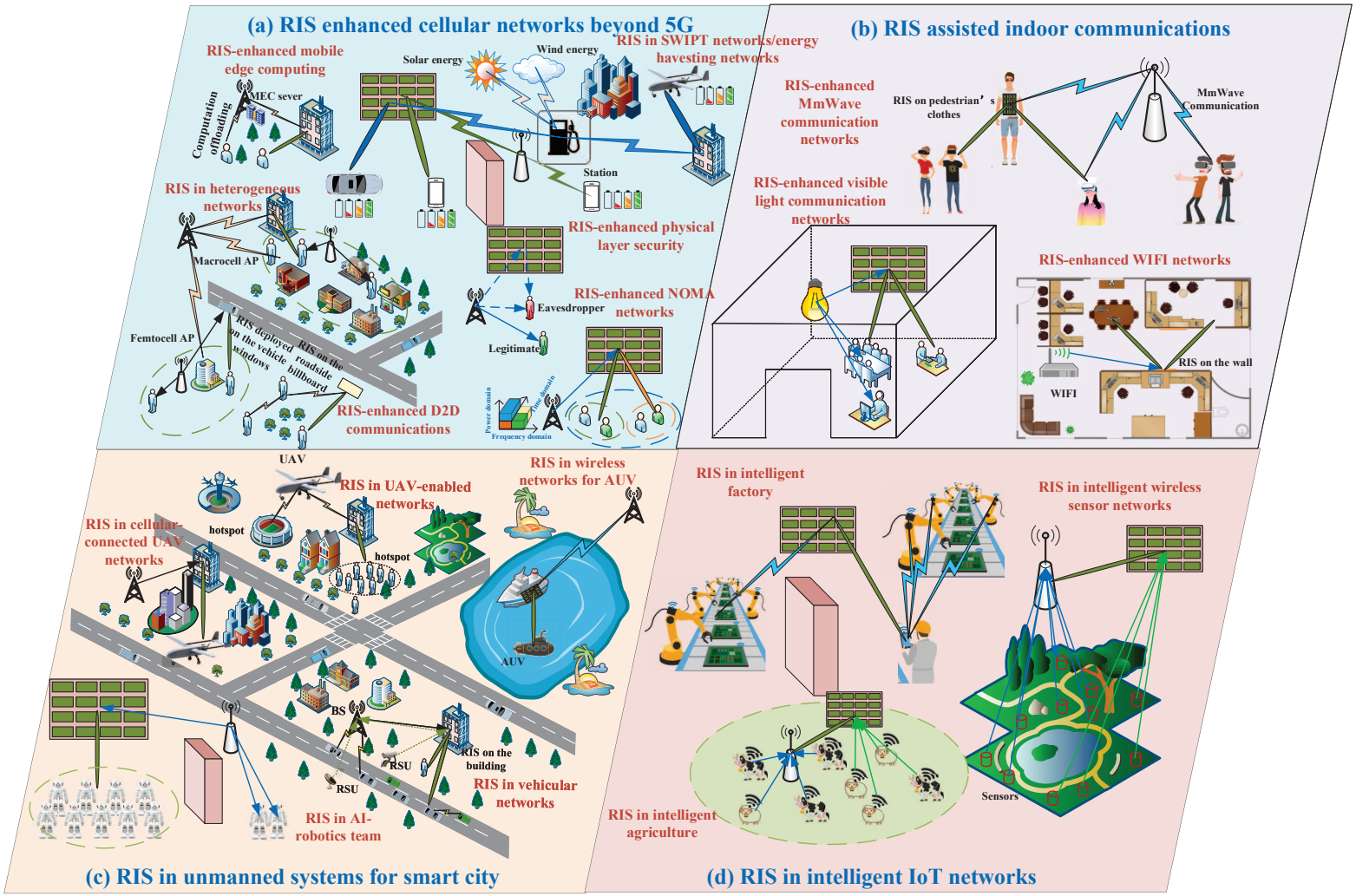
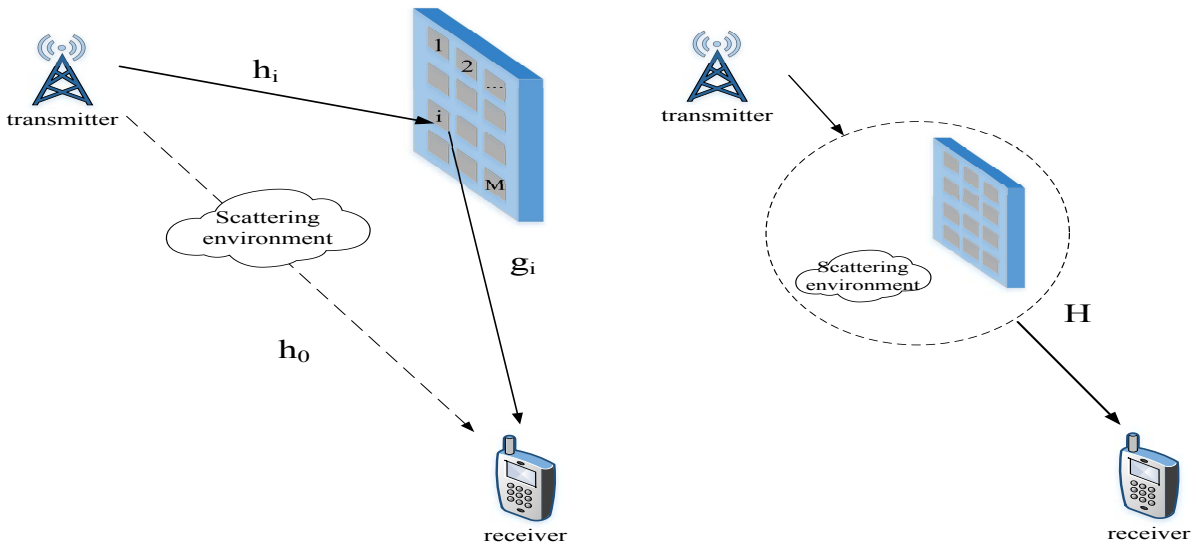


Fig.: RIS in the wireless communication networks.

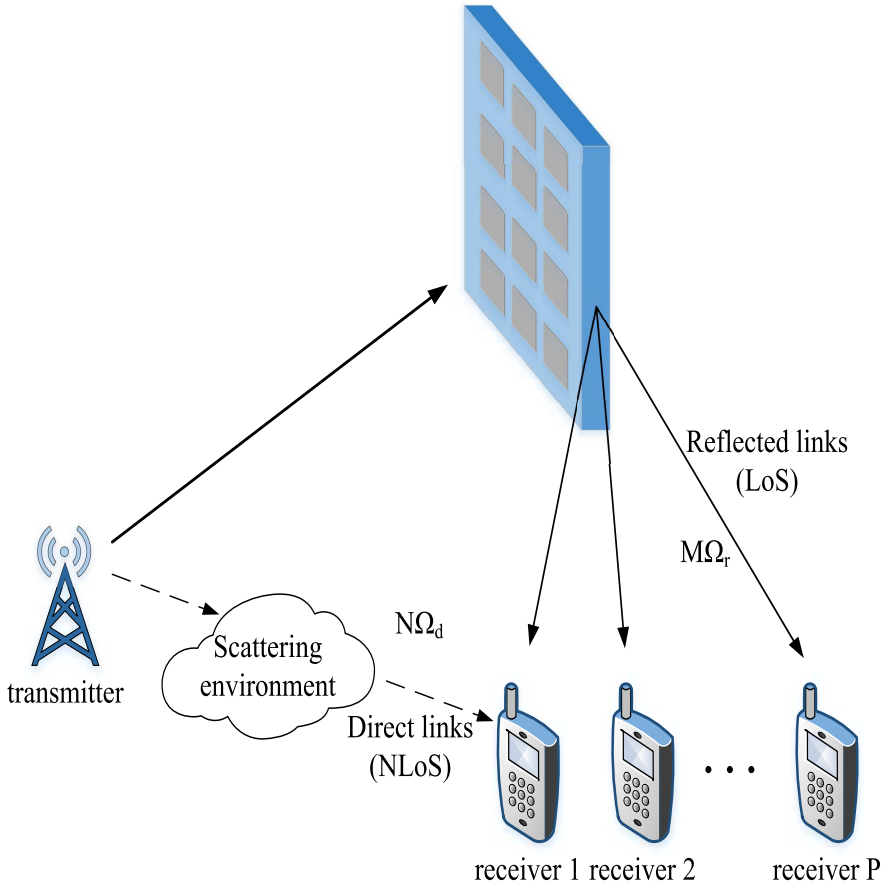
Modeling RIS-assisted Networks: Separate Model VS Joint Model



(a) Separate channel Model (b) Joint channel Model

- The separate model applies to more general scenarios, however, to obtain the overall channel for performance analysis is complex: $H = \sum h_i e^{j\theta_i} g_i + h_0$.
- The joint model is tidier. However, it applies to the scenario where T-RIS and RIS-R links are LoS-dominate.

Joint Model for RIS



- An RIS is deployed in the neighborhood to assist the downlink transmission from one single-antenna transmitter to P single-antenna users.
- A novel physics-based RIS channel model was proposed. We consider the RIS and the scattering environment **as a whole** by studying the signal's multipath propagation.

[1] J, Xu and **Y. Liu**, "A Novel Physics-based Channel Model for Reconfigurable Intelligent Surface-assisted Multi-user Communication Systems ", ***IEEE Transactions on Wireless Communications***, under review. *https://arxiv.org/abs/2008.00619*

Benefits of the Joint Channel Model

1. We can describe the magnitude of the overall channel using **well-known distributions** under joint channel model. For separate channel model, closed-form expressions for channel distribution are usually hard to obtain.
2. It is easier to obtain insights about how **physical parameters** of the system affect the overall channels.
3. The **power scaling law** and channel condition for **special cases of interest** can be derived in close-form.

[1] J, Xu and **Y. Liu**, "A Novel Physics-based Channel Model for Reconfigurable Intelligent Surface-assisted Multi-user Communication Systems ", ***IEEE Transactions on Wireless Communications***, under review. *https://arxiv.org/abs/2008.00619*

Channel Distribution for Discrete Phase Shift RIS

At the target direction, the overall received envelope has a **Rician distribution**: $H(t) \sim \mathcal{R}(K^{Eff}, \Omega_p)$, with shape factor and scale factor shown as follows:

$$K^{Eff} = \frac{Msinc^2(\Delta/2)}{1 - sinc^2(\Delta/2) + K_0^{-1}}, \tag{1}$$

$$\Omega_p = \Omega_r[M + (M^2 - M)sinc^2(\Delta/2)] + N\Omega_d, \tag{2}$$

where

- M: the number of elements of the RIS.
- Δ: the phase quantization error of the RIS (Discrete Phase Shift).
- K_0: the power ratio $K_0 = M\Omega_r/(N\Omega_d)$.

Insights

- Power scaling law:

$$P_r \sim P_t \cdot [sinc^2 \frac{\Delta}{2} M^2 + (1 - sinc^2 \frac{\Delta}{2}) M] \cdot, \tag{3}$$

- Some special cases:

Limits	P_r	Description
$\Delta = 0$	$\propto M^2 \cdot P_t$	Continuous phase shift
$\Delta = 2\pi$	$\propto M \cdot P_t$	Random phase shift

Limits	K^{Eff}	Description
$K_0 \to 0$	0	Pure Direct Link
$\Delta = 0$	MK_0	Continuous phase shift
$K_0 \to \infty$	Ms/(1-s)	Pure RIS

Limits of the Joint Channel Model

1. The joint model applies the best to scenarios where the T-RIS and RIS-R links are LoS dominated.
2. The separate channel model has the ability to show and analyse the diversity gain in general scenarios.

As a result, we present another performance analysis work base on the separate channel model [1]. In the separate channel model, the overall channel is **a summation** of M sub-channels, each associated with an element on the RIS.

[1] J, Xu and **Y. Liu**, " Reconfigurable Intelligent Surface-assisted Multi-user Systems: Phase Alignment Categories and Pattern Synthesis Schemes", ***IEEE ICC2021***, submitted.

Separate Model: A Categorizing Approach

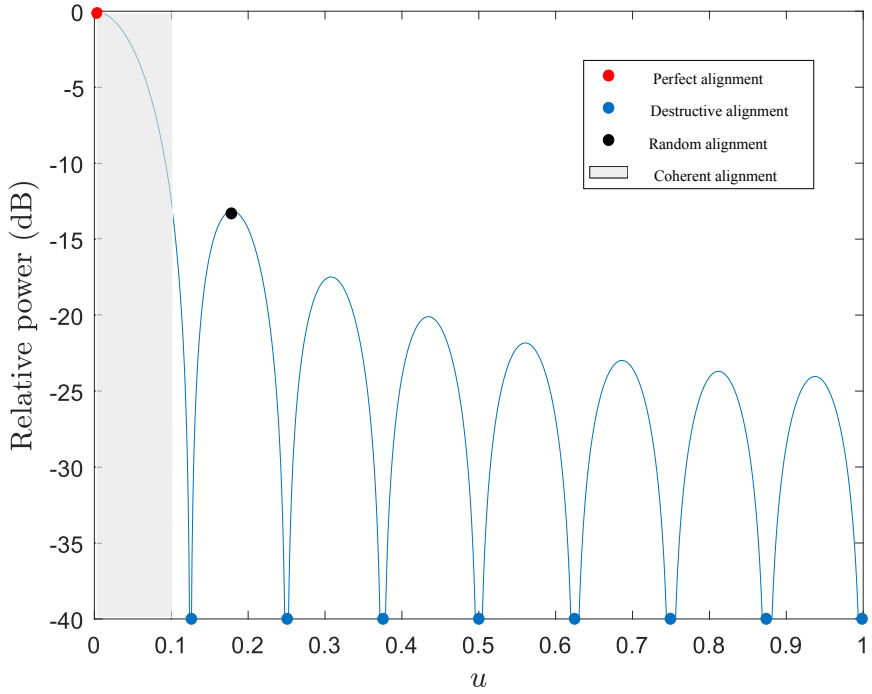
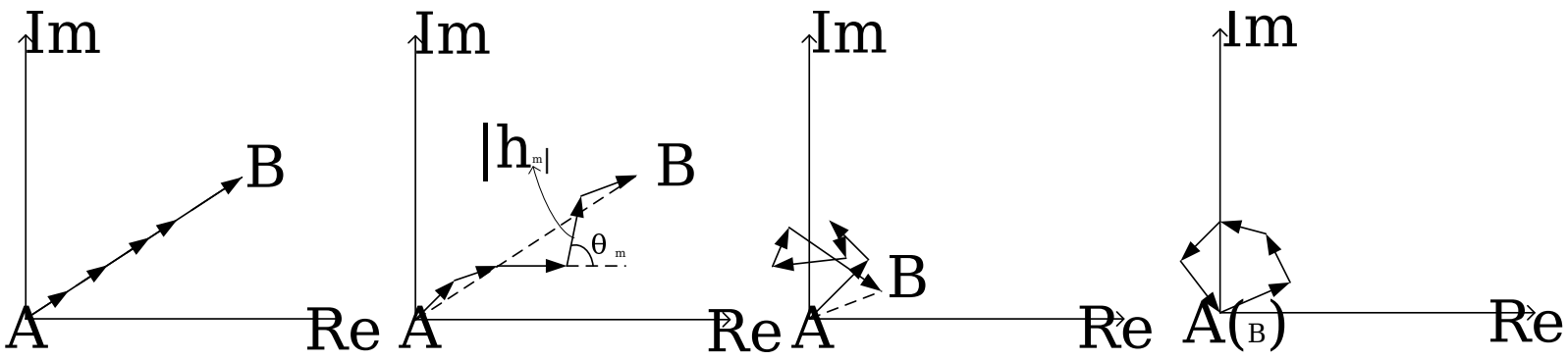


Fig.: Radiation pattern for a 16-element 1-D phase scanning RIS with phase alignment categories indicated at different angles.

- Even for a fixed RIS configuration, users experience different signal superposition conditions while being at different directions w.r.t the RIS.
- By proposing phase alignment categories, the overall channel, (which is **a summation**) can be categorized into different categories with different performance qualities.

Phase Alignment Categories of the Separate Model



a) Perfect phase alignment

b) Coherent phase alignment

c) Random phase alignment

d) Destructive phase alignment

Working conditions	Enhancing		Broadcasting	Cancelling
Phase alignment	(a) Perfect	(b) Coherent	(c) Random	(d) Destructive
$\mathbb{E}[\|H\|]$	$M\bar{h}$	$\sqrt{\pi/2\beta}L_{1/2}(-\alpha^2/(2\beta^2))$	$\sqrt{M\pi\bar{h^2}/2}$	0
$Var[\|H\|]$	$M(\bar{h^2}-(\bar{h})^2)$	$\alpha^2+2\beta^2-(\mathbb{E}[H])^2$	$M\bar{h^2}(4-\pi)/4$	$M(\bar{h^2}-(\bar{h})^2)$
Diversity order	M	less or close to M	1	0

Table: Channel statistics different phase alignment categories (The expectation value of random phase alignment category ($\mathbb{E}[|H|] \sim \sqrt{M}$) is analogy to "2-D random walk problem")

where $\bar{h} = \mathbb{E}[h_m]$, $\bar{h^2} = \mathbb{E}[h_m^2]$, all h_m are independent and identically distributed, $\alpha = M\bar{h}sinc(\pi/(2L))$, $\beta^2 = M\bar{h^2}[1 - sinc(\pi/L)]/2$, and $L_{1/2}(x)$ denoting the Laguerre polynomial.

Single User Case

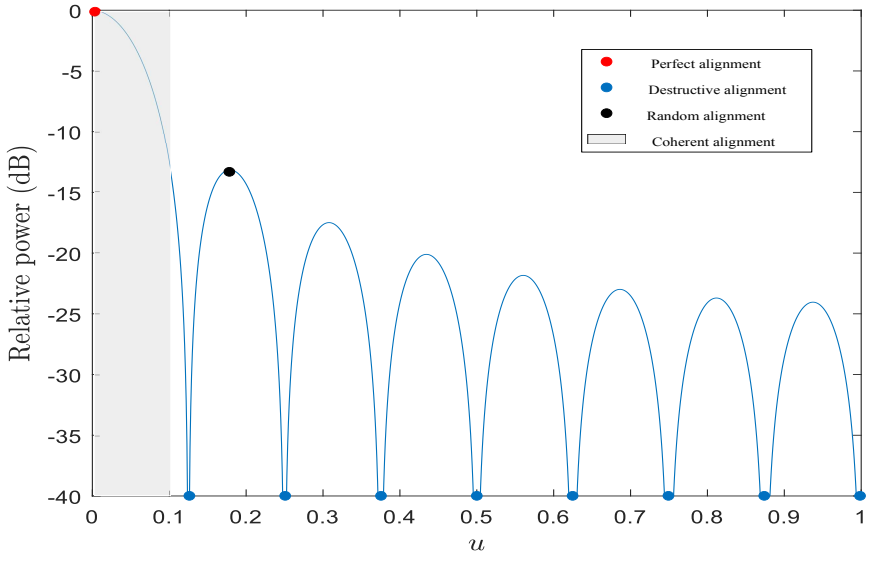


Fig.: Radiation pattern for a 16-element 1-D phase scanning RIS with phase alignment categories indicated at different angles.

RIS phase shift	CSI	Phase alignment at target direction
Continuous	Perfect	Perfect alignment
Continuous	Partial	Coherent alignment
Continuous	None	Random alignment
Discrete	Perfect	Coherent alignment
Discrete	Partial	Coherent alignment
Discrete	None	Random alignment

- Perfect alignment:

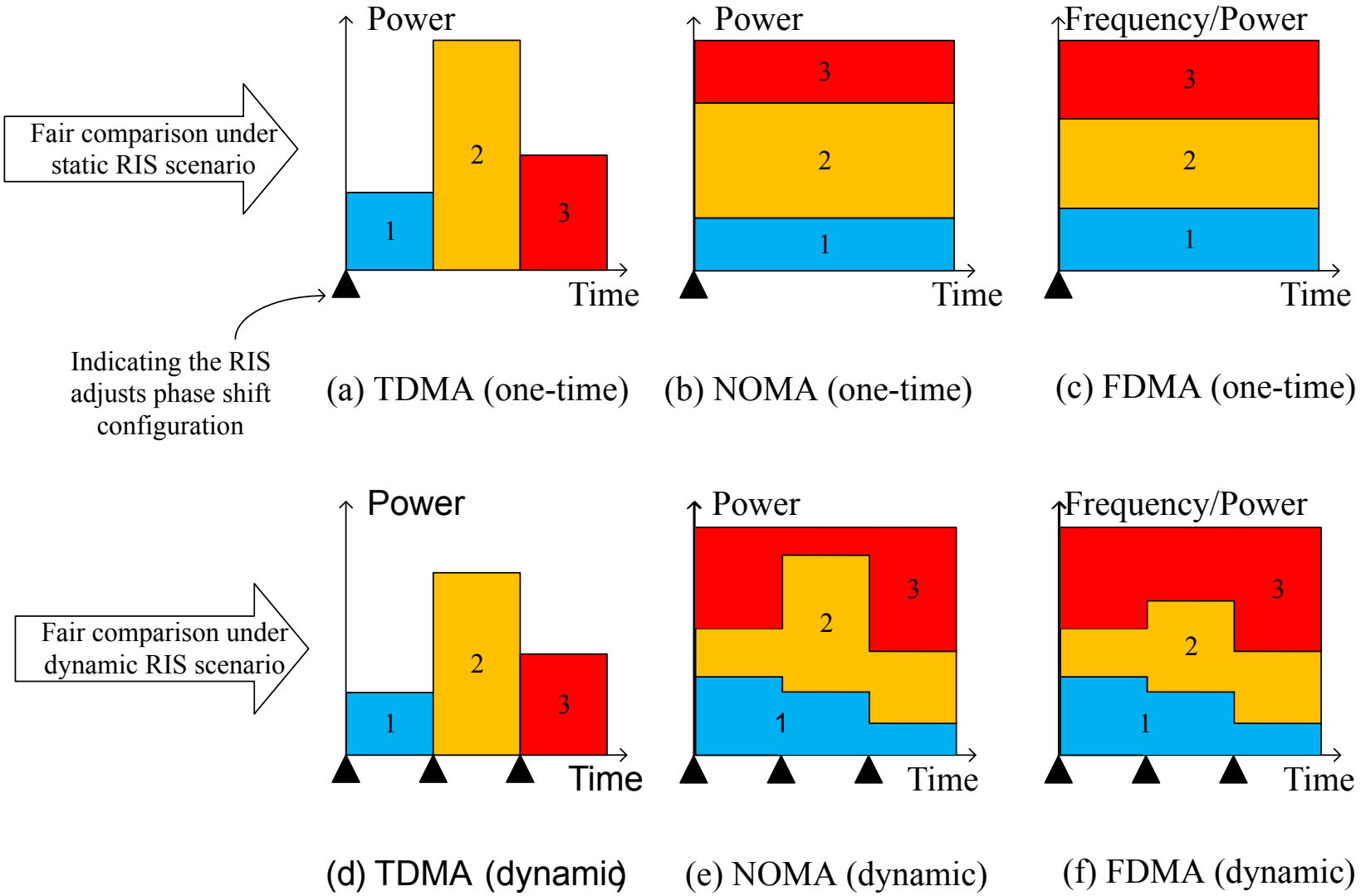
$$P_{out}(\gamma_0) \approx \frac{b^{-M}\gamma_0^M}{(2M)!}\gamma_t^{-M}. \quad (4)$$

- Random alignment:

$$P_{out}(\gamma_0) \approx 1 - e^{-\frac{\gamma_0}{M\gamma_t}}. \quad (5)$$

- Coherent alignment: Various scenarios fall into the category as coherent phase alignment.

Multi-User Case: fair comparison for RIS + Multiple Access



(a) TDMA (one-time) (b) NOMA (one-time) (c) FDMA (one-time)

(d) TDMA (dynamic) (e) NOMA (dynamic) (f) FDMA (dynamic)

It can be proved that the one-time NOMA and dynamic NOMA have **superior performance** than TDMA and FDMA in both *static RIS scenario* and *dynamic RIS scenario*, respectively.

Single User Case: users located at different angular directions

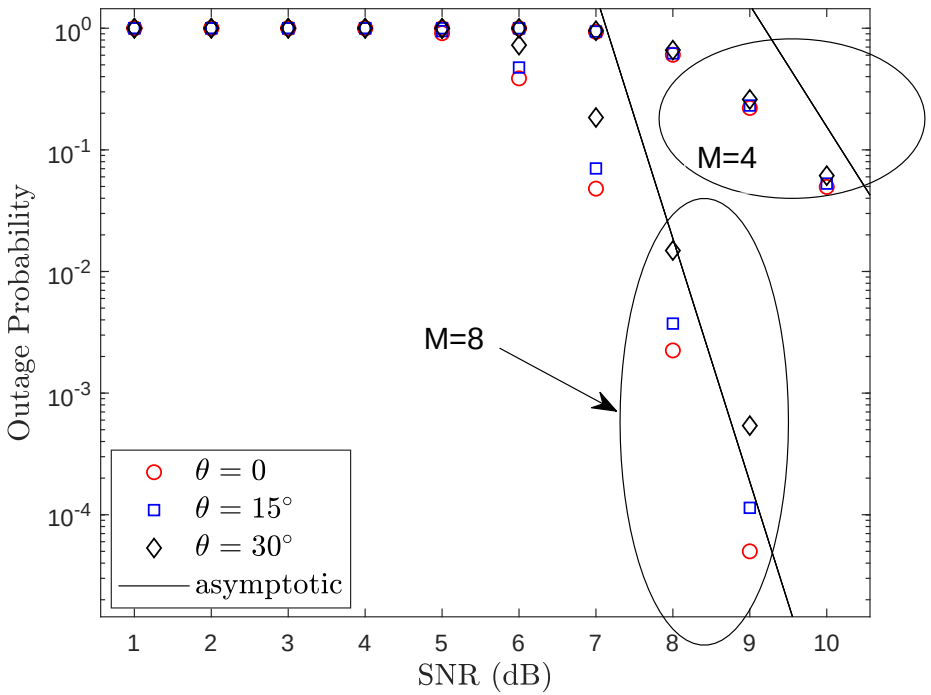


Fig.: Outage probability for a single user assisted by 4-element and 8-element continuous phase shift RIS.

- As the direction of the user moves away from the target direction, the outage probability increases.
- This increment is more observable for RIS with large number of elements (M). (Reason: the full-diversity order enabling beamwidth decrease with the number of elements.)

Multi-User Case (NOMA/OMA): One-Time and Dynamic

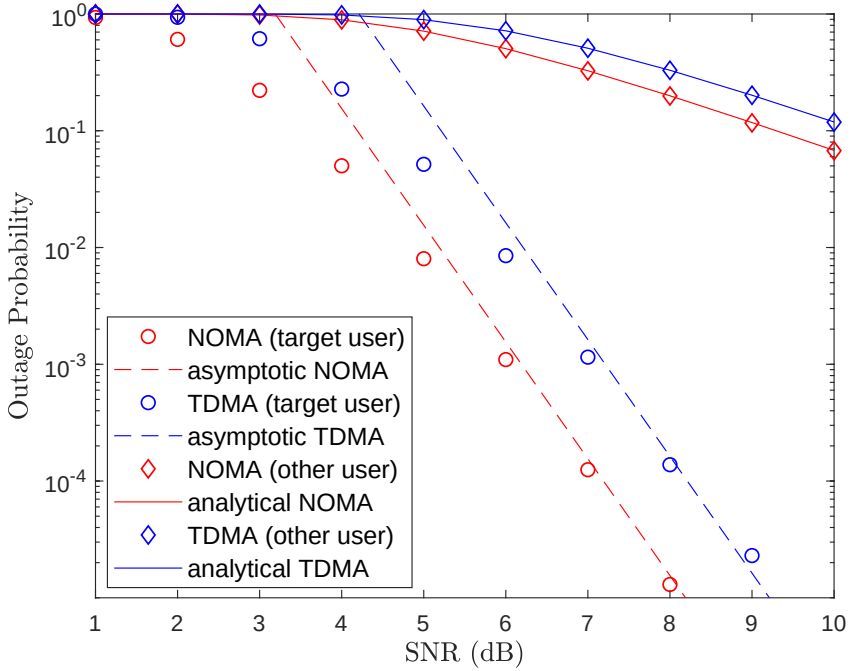


Fig.: Outage probability for 4-element continuous phase shift static RIS scenario under NOMA (**one-time**) and TDMA schemes.

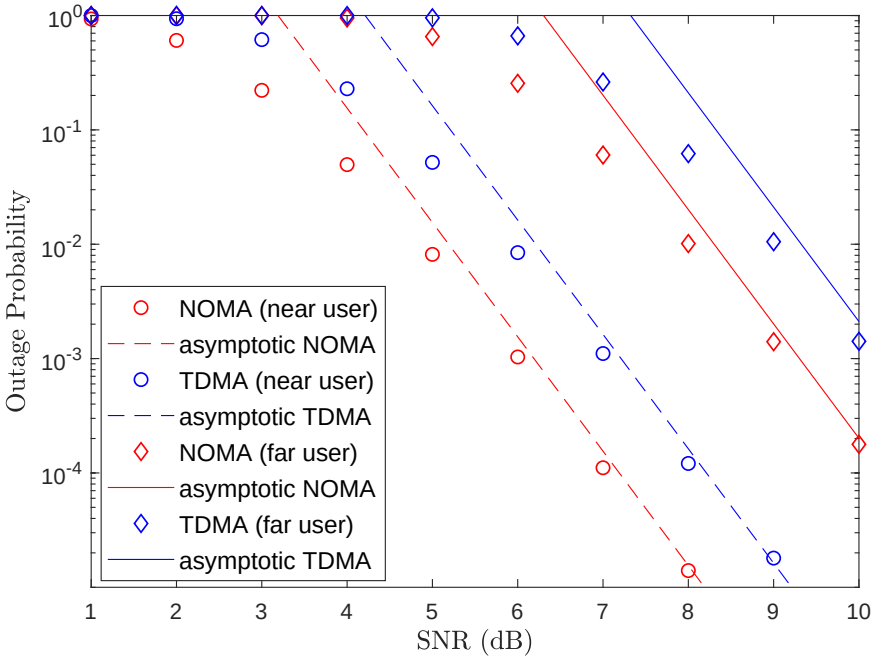


Fig.: Outage probability for 4-element continuous phase shift dynamic RIS scenario under NOMA (**dynamic**) and TDMA schemes.

Interplay Between RIS/IRS and NOMA Networks

Motivations

- One the one hand, RIS to NOMA: 1) enhance the performance of existing NOMA networks; 2) Provide **high flexibility** for NOMA networks, from channel quality based NOMA to QoS based NOMA; 3) **reduce the constraints** for MIMO-NOMA design as IRS provides additional signal processing ability [1].
- One the other hand, **NOMA to RIS**: NOMA can provide more efficient multiple access scheme for multi-user IRS aided networks.

Challenges

- For multi-antenna NOMA transmission, additional decoding rate conditions need to be satisfied to guarantee successful SIC.
- Both the active and passive beamforming in RIS-NOMA affect the decoding order among users.

[1] T, Hou, **Y. Liu**, Z. Song, X. Sun, and Y. Chen "MIMO-NOMA Networks Relying on Reconfigurable Intelligent Surface: A Signal Cancellation Based Design", ***IEEE Transactions on Communications***, *vol. 68, no. 11, pp. 6932-6944, Nov. 2020, https://arxiv.org/abs/2003.02117*.

RIS/IRS-Aided NOMA Neworks: Uplink and Downlink with Continues Phase Shift

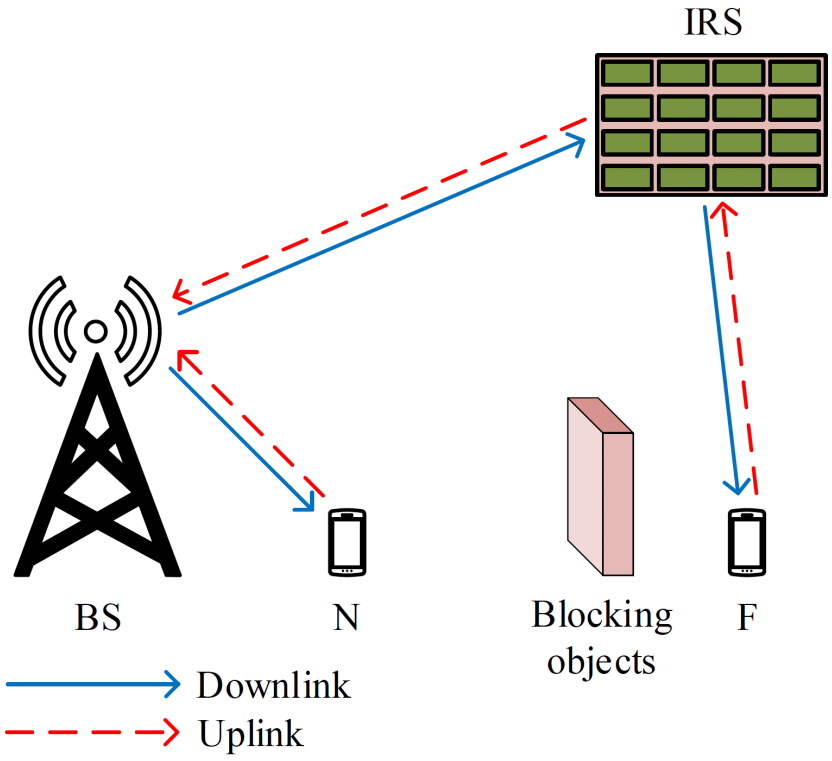


Fig. IRS-aided NOMA system model.

- An IRS assists a far user.
- Continuous phase shifts.

Motivation

- Exact channel statistics of the BS-IRS-user link.
- The performance of IRS-aided systems.

Contributions

- Downlink and uplink IRS-adied NOMA and OMA systems.
- Outage probability and ergodic rate.
- The diversity order and the high-SNR slope are obtained.
- The IRS outperforms the full-duplex relay in the high-SNR regime.

Y. Cheng, K. H. Li, **Y. Liu**, K. C. Teh, and H. V. Poor, "Downlink and uplink intelligent reflecting surface aided networks: NOMA and OMA," ***IEEE Transactions on Wireless Communications***, major revision. [Online]. Available: https://arxiv.org/abs/2005.00996

Insights Summary I

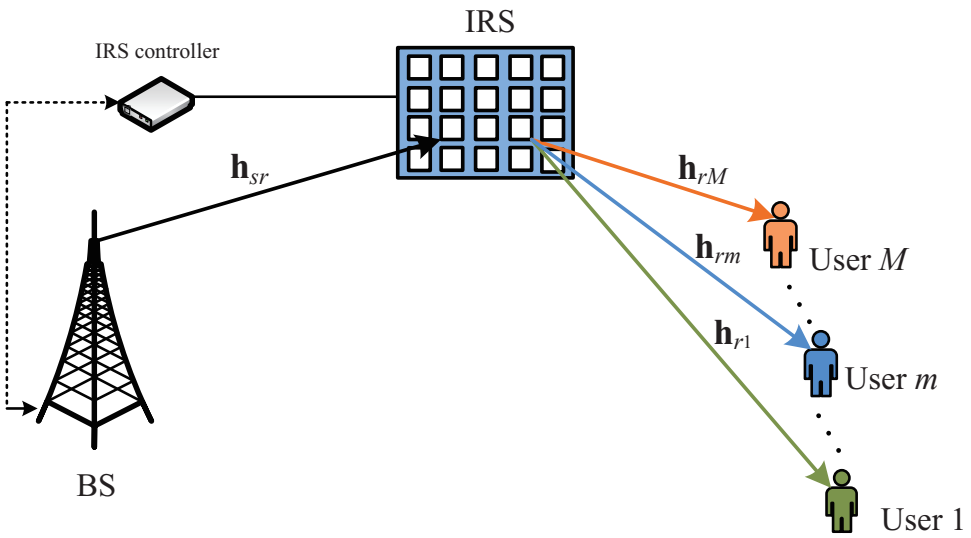
Table: Diversity order and high-SNR slope for each scenario

Multiple-access scheme	User	Downlink		Uplink	
		d	S	d	S
NOMA	N	1	1	0	0
	F	$m_s K$	0	0	1
OMA	N	1	0.5	1	0.5
	F	$m_s K$	0.5	$m_s K$	0.5

$m_s = \min\{m_G, m_g\}$, where m_G and m_g are the Nakagami fading parameters of BS-IRS and IRS-user links, respectively.

K is the number of reflecting elements in the IRS.

RIS/IRS-NOMA: Discrete Phase shift and Imperfect SIC



1. Considering an IRS-assisted NOMA communication scenario, where BS sends the superposed signals to M terminal users **with the assistance of an IRS** [1].
2. Both **imperfect and perfect SIC** are taken into account for IRS-assisted NOMA networks.
3. **1-bit coding scheme** is proposed to achieve the discrete phase shift levels.

[1] X. Yue and **Y. Liu**, "Performance Analysis of Intelligent Reflecting Surface Assisted NOMA Networks", ***IEEE Transactions on Wireless Communications***, under revision [Online]. Available: https://arxiv.org/abs/2002.09907v2.

SINRs for RIS-NOMA users with imperfect SIC

On the basis of NOMA principle, the SINR at the m-th user to detect the q-th user's information ($m \geq q$) is given by

$$\gamma_{m \to q} = \frac{\rho \left| \mathbf{h}_{sr}^{H} \mathbf{\Theta} \mathbf{h}_{rm} \right|^{2} a_q}{\rho \left| \mathbf{h}_{sr}^{H} \mathbf{\Theta} \mathbf{h}_{rm} \right|^{2} \sum_{i=q+1}^{M} a_i + \varpi \rho \left| \mathbf{h}_{\mathbf{I}} \right|^{\mathbf{2}} + 1}, \tag{6}$$

where $\varpi = 0$ and $\varpi = 1$ denote the pSIC and ipSIC operations. After striking out the previous $M-1$ users' signals with SIC, the received SINR at the M-th user to detect its own information can be given by

$$\gamma_{M} = \frac{\rho \left| \mathbf{h}_{sr}^{H} \mathbf{\Theta} \mathbf{h}_{rM} \right|^{2} a_M}{\varpi \rho \left| \mathbf{h}_{\mathbf{I}} \right|^{\mathbf{2}} + \mathbf{1}}. \tag{7}$$

RIS-aided NOMA Networks: with Direct Link and Continues Phase Shift

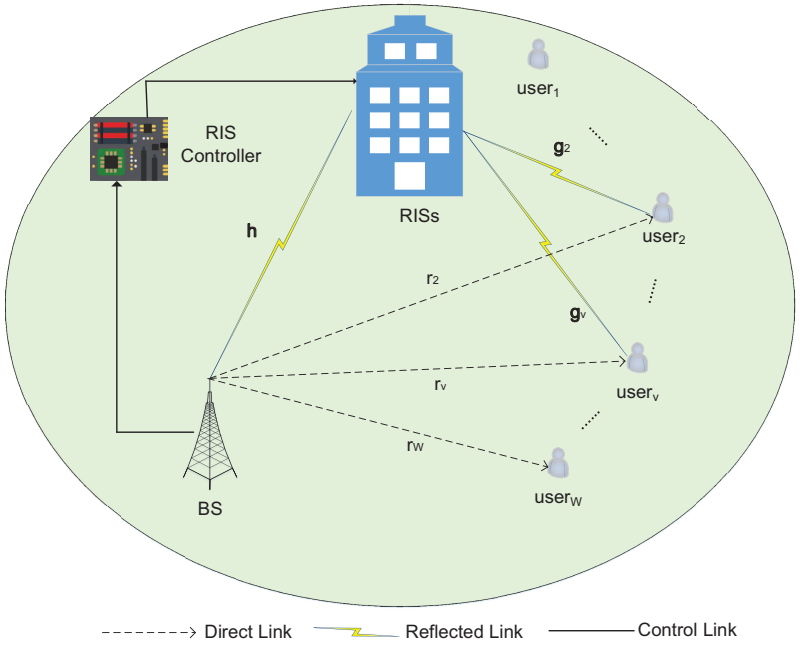
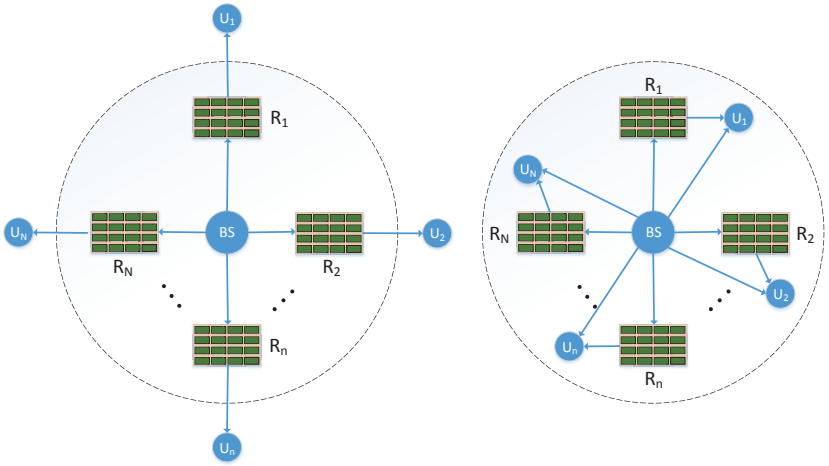


Fig.: RIS-aided NOMA Networks.

- W single antenna users.
- N RISs.
- Both direct and reflection links are considered
- Improve the prioritized user with the best channel gain.

[1] T, Hou, **Y. Liu**, Z. Song, X. Sun, Y. Chen and L. Hanzo, "Reconfigurable Intelligent Surface Aided NOMA Networks", ***IEEE Journal on Selected Areas (JSAC) in Communications***, *vol. 38, no. 11, pp. 2575-2588, Nov. 2020*.

NOMA Assisted by Multiple IRSs with Discrete Phase Shifts



(a) The scenario where UDs cannot communicate with the BS directly.

(b) The scenario where UDs can communicate with the BS directly.

Fig. IRS-aided NOMA system model.

- A BS, and N IRSs, N users in a NOMA group.
- Two scenarios.
- Discrete phase shifts.

Motivation

- More practical to use discrete phase shifts.
- The performance difference between continuous phase shifts and discrete phase shifts.

Contributions

- IRS-aided NOMA systems with discrete phase shifts are studied.
- The BS-IRS-user link can be either LoS and NLoS.
- The high-SNR approximation of the outage probability is derived.
- The diversity order is obtained.

Y. Cheng, K. H. Li, **Y. Liu**, K. C. Teh, and G. K. Karagiannidis, "Non-orthogonal multiple access (NOMA) with multiple intelligent reflecting surfaces," ***IEEE TWC***, under review, https://arxiv.org/abs/2011.00211.

Theoretical Results I

Table: Diversity order of U_n (the nth user) for each scenario

Multiple access scheme	NOMA		OMA	
Phase shifts	Discrete	Continuous	Discrete	Continuous
Scenario I (Without direct links)	nm_sK	nm_sK	m_sK	m_sK
Scenario II (With direct links)	$n(m_h + m_sK)$	$n(m_h + m_sK)$	$m_h + m_sK$	$m_h + m_sK$

n is the order of user.
$m_s = \min\{m_G, m_g\}$, where m_G and m_g are the Nakagami fading parameters of BS-IRS and IRS-user links, respectively.
m_h is the Nakagami fading parameter of the BS-user link.
K is the number of reflecting elements in the IRS.

Signal Cancellation Design: RIS-aided MIMO-NOMA Networks

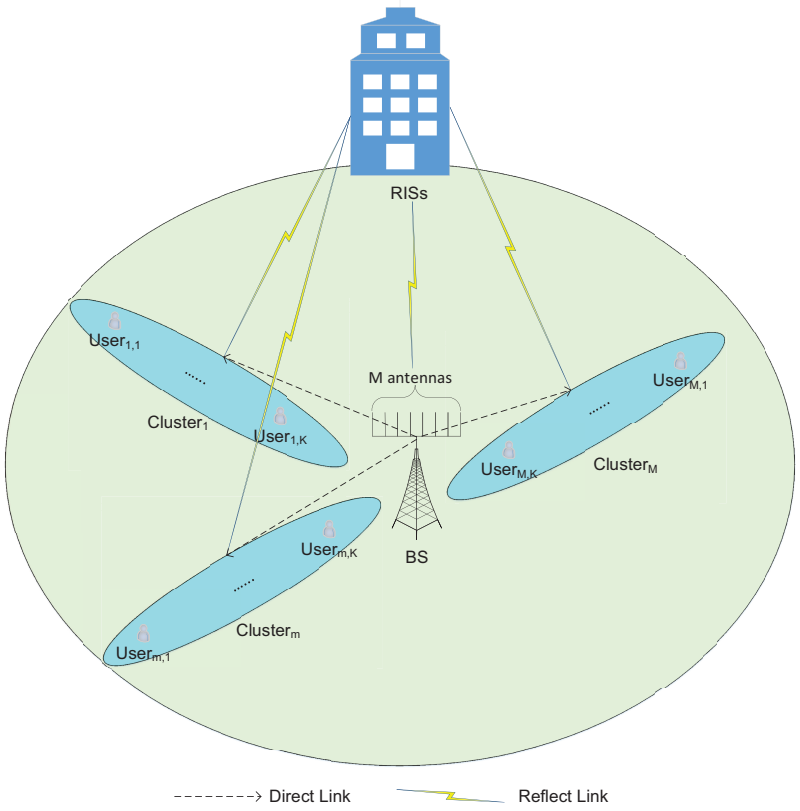


Fig.: RIS-aided MIMO-NOMA networks.

- RISs are also capable of mitigating signals, i.e., interference cancellation.
- M transmitting antennas, M clusters, K users in each cluster, L receiving antenna at each users.
- Relax the constraints for conventional MIMO-NOMA.

[1] T, Hou, **Y. Liu**, Z. Song, X. Sun, and Y. Chen "MIMO-NOMA Networks Relying on Reconfigurable Intelligent Surface: A Signal Cancellation Based Design", ***IEEE Transactions on Communications***, *vol. 68, no. 11, pp. 6932-6944, Nov. 2020, https://arxiv.org/abs/2003.02117*.

Stochastic Geometry Based Analysis: Why do we need Stochastic Geometry?

1. **Limitations of Conventional Analysis [1]**
   - Ignore the **density and mobility of nodes**.
   - Mathematical modelling and optimization for large-scale networks are **intractable**.
2. **Advantages of Stochastic geometry**
   - Capture the **spatial randomness** of the networks.
   - Provide tractable analytical results for the average network behaviors according to some distributions.

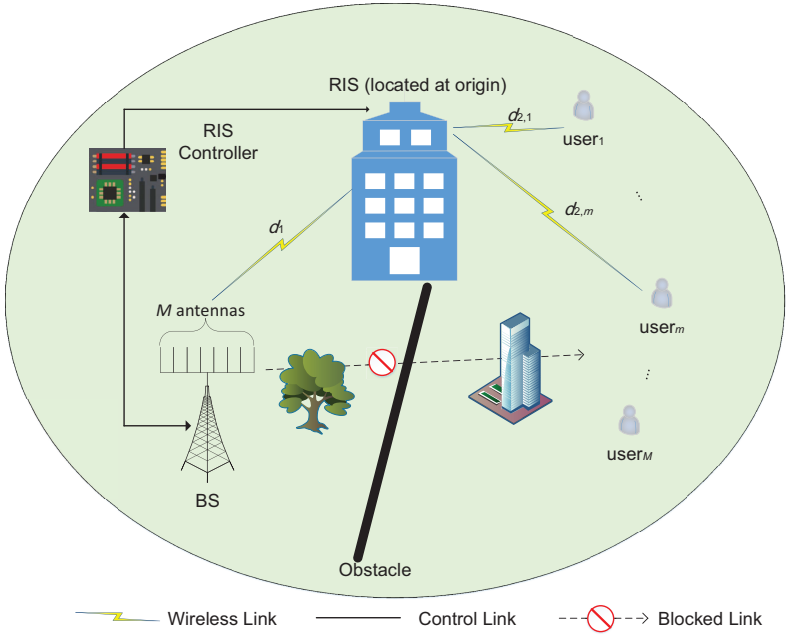
[1] **Y. Liu** *et al.*, "Non-Orthogonal Multiple Access for 5G and Beyond", ***Proceedings of the IEEE***; Dec 2017.

Stochastic Geometry Based Analysis for RIS-NOMA

1. **Motivations of RIS-aided NOMA**
   - Investigate the spatial effect of RIS-NOMA in large-scale networks for **practical deployment guideline**.
   - Channel quality enhancement: We motivate to exploit RISs to enhance the channel quality of **blocked users**.
   - High flexibility on SIC: Achieve **flexible decoding orders** according to the quality of service (QoS) conditions.
2. **Challenges of RIS-aided NOMA**
   - Feasible analysis for single/Multi-Cell stochastic geometry model.
   - How do the RISs reflect received signals in **multi-cell scenarios**?
   - The correct and efficient physical model of RISs as **linear material** [1].

[1] C. Zhang, W. Yi and **Y. Liu**, "Reconfigurable Intelligent Surfaces Aided Multi-Cell NOMA Networks: A Stochastic Geometry Model," ***IEEE Trans. Wireless Commun.***, https://arxiv.org/abs/2008.08457.

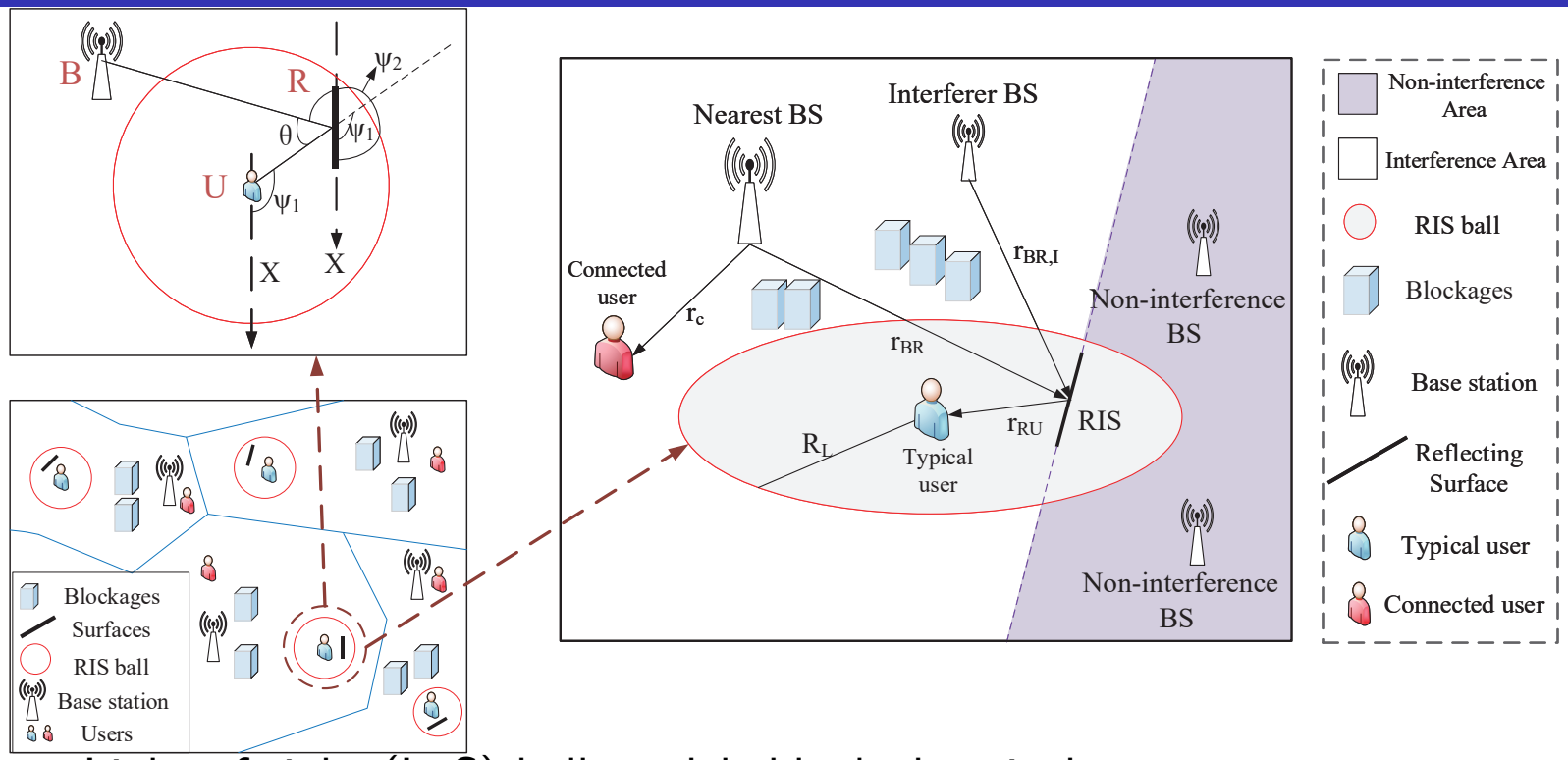
Stochastic Geometry Based Analysis: MIMO-RIS Single Cell



- M transmit antennas is communicating with M users, each equipped with K receive antennas, where the MN surfaces serve M users [1].
- Homogeneous Poisson point processes (HPPPs) is used to model the locations of users.

[1] T, Hou, **Y. Liu**, Z. Song, X. Sun, and Y. Chen "MIMO Assisted Networks Relying on Large Intelligent Surfaces: A Stochastic Geometry Model", ***IEEE Transactions on Vehicular Technology***, *under revision, https://arxiv.org/abs/1910.00959*.

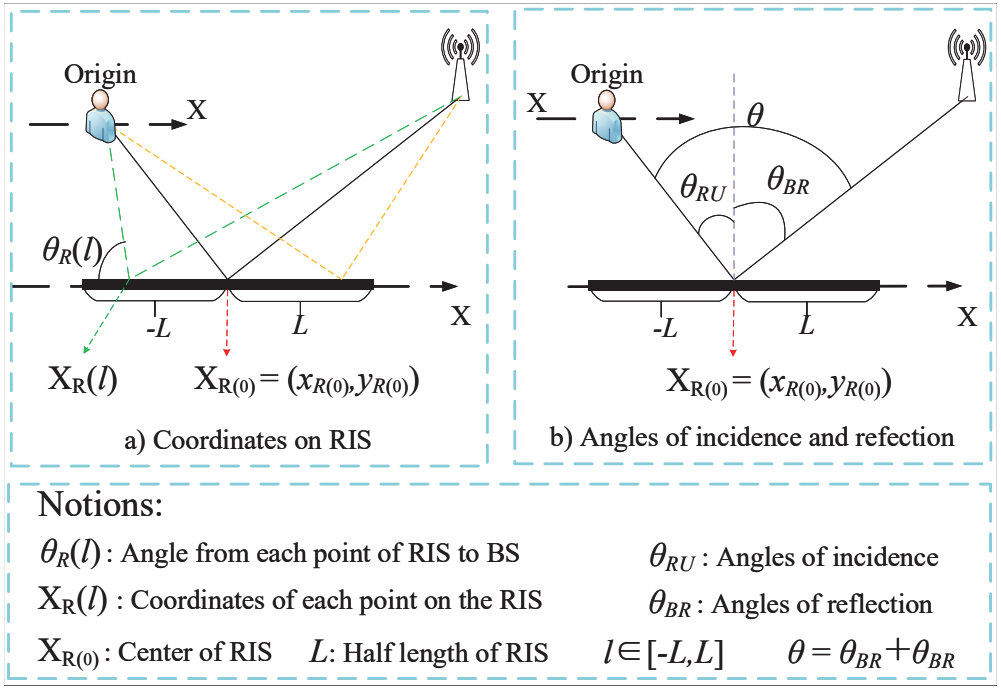
Stochastic Geometry Based Analysis: Multi-Cell RIS



- Light-of-sight (LoS) ball model: blocked typical user.
- Matern cluster process (MCP) pattern of **Poisson Cluster Process (PCP)**: 1) BSs (parent point process) and users are modeled according to two independent homogeneous Poisson point processes (HPPPs); 2) A RIS (daughter point process) is uniformly deployed in the LOS ball.

[1] C. Zhang, W. Yi and **Y. Liu**, "Reconfigurable Intelligent Surfaces Aided Multi-Cell NOMA Networks: A Stochastic Geometry Model," ***IEEE Trans. Wireless Commun.***, https://arxiv.org/abs/2008.08457..

Efficient physical model of RISs as linear material



- The BS-RIS-User angle (θ) is **uniformly** distributed in $[0, \pi]$, for **each three (BS-RIS-User) HPPP points**.
- Path loss Model: $P_t(\mathbf{x}_b, \mathbf{x}_R) = \left| \int_{-L}^{+L} \Psi(l) \exp(-jk\Omega(l))\, dl \right|^2$.
  - Amplitude function: $\Psi(x) = \frac{\cos(\theta_{\mathrm{BR}}(l)) + \cos(\theta_{\mathrm{RU}}(l))}{8\pi\sqrt{r_{\mathrm{BR}}(l) r_{\mathrm{RU}}(l)}}$.
  - Phase-shift function: $\Omega(x) = r_{\mathrm{BR}}(l) + r_{\mathrm{RU}}(l) - \Theta(l)$.

Numerical Results

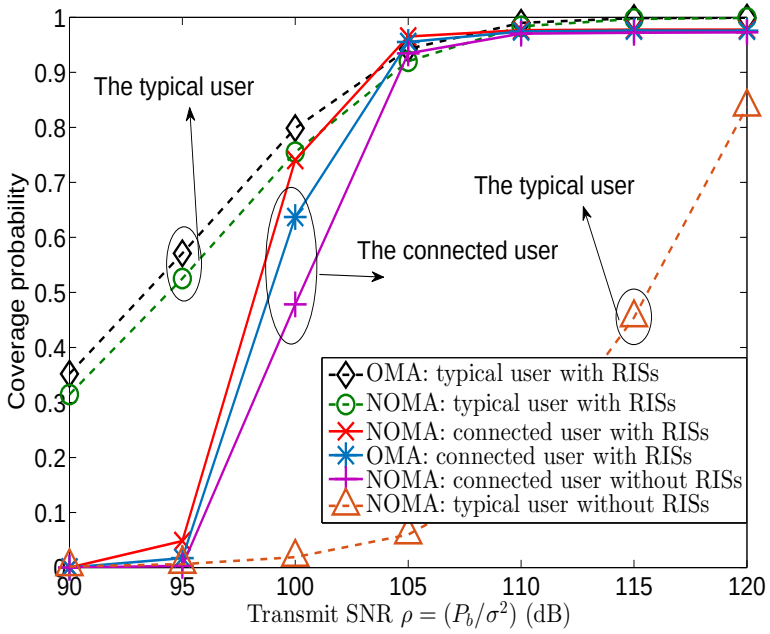


Fig.: A comparison: conventional NOMA, RIS-OMA and RIS-NOMA..

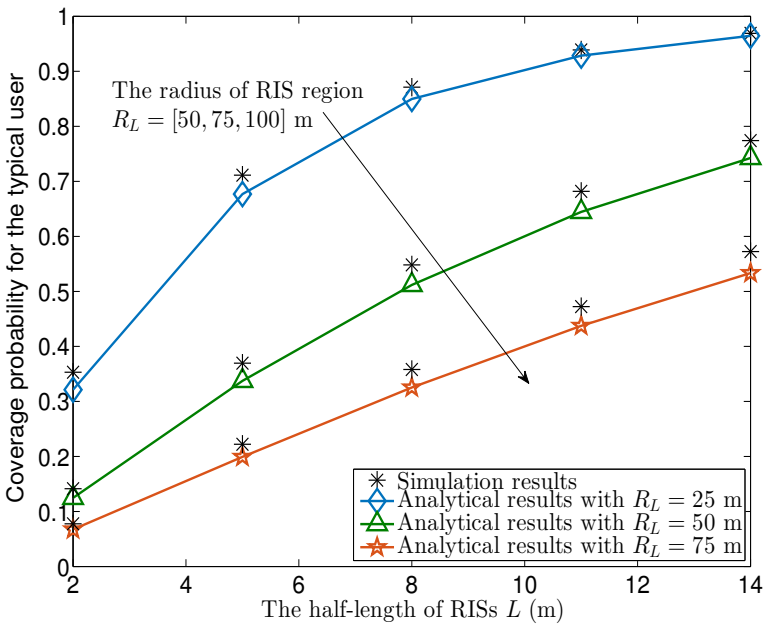


Fig.: Performance versus the half-length of RISs L.

- The achievable rates reach an **upper limit** when the length of RISs increases.
- The condition $L \to \infty$ holds: $S = \lim_{L\to\infty} \frac{\mathrm{E}\left[R_t^{RIS}\right]|_{L\to\infty}}{\log(L)} = 0.$

Summary and Discussions for Performance Analysis of RISs

1. **Discussions for Conventional Analysis**
   - The accurate closed-form results are non-trivial to obtain. [1]
     - Central-limittheorem-based (**CLT-based**) distribution (good for low-medium SNR regime).
     - Approximated distribution or large-scale antenna analysis (e.g. **large-number approximation**).
2. **Discussions for Stochastic Geometry Analysis**
   - The **angle information** assumption brings new challenges for stochastic geometry analysis.
   - The **flexible decoding orders** enabled by RIS brings new variants for **user association**.

[1] **Y. Liu**, et. al. "Reconfigurable Intelligent Surfaces: Principles and Opportunities", ***IEEE Communications Survey and Tutorial***, *under revision, https://arxiv.org/abs/2007.03435*.

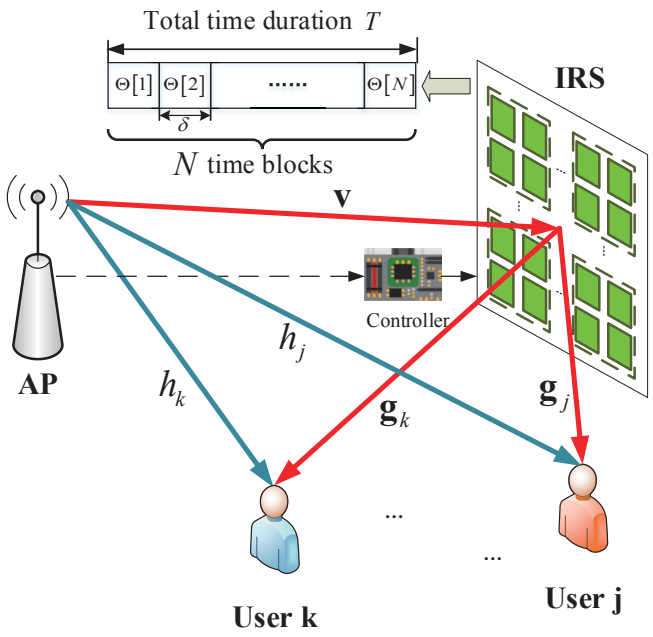
Capacity Characterization for IRS-aided Multi-user System: An Information Theoretic Perspective

Motivation

- What is the optimal transmission (**capacity-achieving**) strategy of IRS-aided multi-user communication?

System Model

- Let T denote the duration of one channel coherence block, which is divided into N time slots with duration of δ, i.e., $T = N\delta$. Let δ the time consumption for reconfiguring the IRS.
- ***Dynamic IRS Configuration***: The IRS reflection matrix can be reconfigured at the beginning of each time block $n \in \mathcal{N}$ and remains fixed within each time block, i.e. $\Theta[n], n \in \mathcal{N}$.



[1] X. Mu, **Y. Liu**, L. Guo, J. Lin, N. Al-Dhahir "Capacity and Optimal Resource Allocation for IRS-assisted Multi-user Communication Systems", ***IEEE Transactions on Communications, major revision***, *https://arxiv.org/abs/2001.03913*.

Different Setups: Static Scenario versus High-Speed Mobile Scenario

Static Channel Model[1] **($T \gg \delta$)**

- Focus on one channel coherence block, where the channels remain approximately constant, $\left\{h_k, \mathbf{g}_k^H, \mathbf{v}, n \in \mathcal{N}\right\}$. (e.g., users are static or moving slowly).
- An *artificial varying channel* can be created by dynamically reconfiguring the IRS, i.e., $h_k + \mathbf{g}_k^H \mathbf{\Theta}[n] \mathbf{v}, n \in \mathcal{N}$.
- When $\mathcal{N} = 1$, the IRS reflection matrix is fixed through the whole transmission, which has been adopted in most existing research contributions.

Fading Channel Model[2]

- High-speed mobile scenario and T is short. Focus on total $\mathcal{I}$ channel coherence blocks, i.e., $\left\{h_k[i], \mathbf{g}_k^H[i], \mathbf{v}[i], i \in \mathcal{I}\right\}$.
- *Dynamic IRS Configuration* ($T \approx \delta$): The IRS can be reconfigured for each fading state i, the effective channel is $h_k[i] + \mathbf{g}_k^H[i] \mathbf{\Theta}[i] \mathbf{v}[i], i \in \mathcal{I}$.
- *One-time IRS Configuration* ($T \ll \delta$): All fading states share the same IRS reflection matrix, the effective channel is $h_k[i] + \mathbf{g}_k^H[i] \mathbf{\Theta} \mathbf{v}[i], i \in \mathcal{I}$.

[2] Y. Guo, Z. Qin, **Y. Liu**, N. Al-Dhahir "Intelligent Reflecting Surface Aided Multiple Access Over Fading Channels",***IEEE Transactions on Communications, major revision***, https://arxiv.org/abs/2006.07090.

Capacity Region Characterization: An Information Theoretic Perspective

- If NOMA is employed, the achievable rate of user k at the nth time block is given by

$$R_k^N[n] = \log_2\left(1 + \frac{\left|h_k + \mathbf{g}_k^H \mathbf{\Theta}[n]\mathbf{v}\right|^2 p_k[n]}{\sum_{\mu_i[n]>\mu_k[n]}\left|h_k + \mathbf{g}_k^H \mathbf{\Theta}[n]\mathbf{v}\right|^2 p_i[n] + \sigma^2}\right). \quad (8)$$

  The average achievable rate of user k over the entire period T is $\overline{R}_k^N = \frac{1}{N}\sum_{n=1}^{N} R_k^N[n]$.

- The capacity region achieved by NOMA is defined as

$$\mathcal{C}(b, N) \triangleq \bigcup_{\{\mathbf{\Theta}[n], p_k[n]\}\in\mathcal{X}^N} \left\{\bar{\mathbf{r}} : 0 \le \bar{r}_k \le \overline{R}_k^N, \forall k\right\}, \quad (9)$$

  which consists of the set of average rate-tuples for all users that can be simultaneously achieved over the period T. b denotes the finite phase resolution bits of the IRS.

Ideal Case versus General Case

Ideal case, $N \to \infty$:

- (P1) satisfies the time-sharing condition, and the strong duality holds.
- The *optimal solution* to (P1) can be obtained via its dual problem using the Lagrange duality method.
- By deciding time-sharing ratio among the optimal solutions obtained from the dual problem, the capacity region is derived.

General case, finite N:

- Construct the IRS reflection matrix at each time slot $\mathbf{\Theta}[n]$ based on the obtained solutions in ideal case.
- Under given $\mathbf{\Theta}[n]$, solve the resulting power allocation problem (P1) employing SCA.
- A high-quality suboptimal solution to (P1) can be derived, namely *capacity region inner bound*.

Numerical Results for Ideal Case

Capacity/rate region in the ideal case, $N \to \infty$

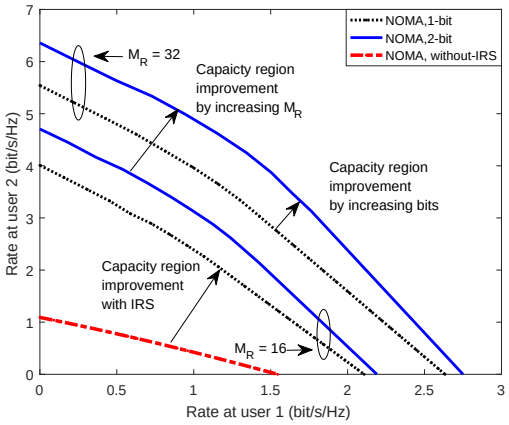


Fig.: Capacity region using NOMA.

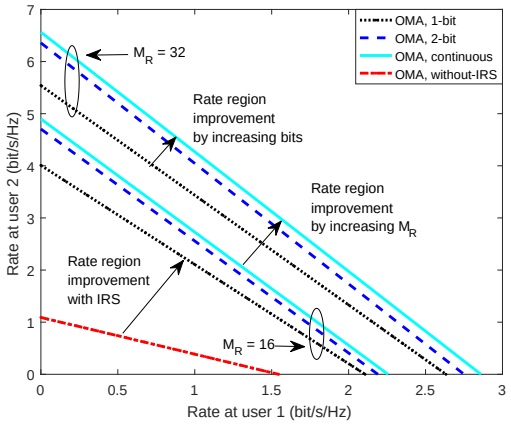


Fig.: Rate region using OMA.

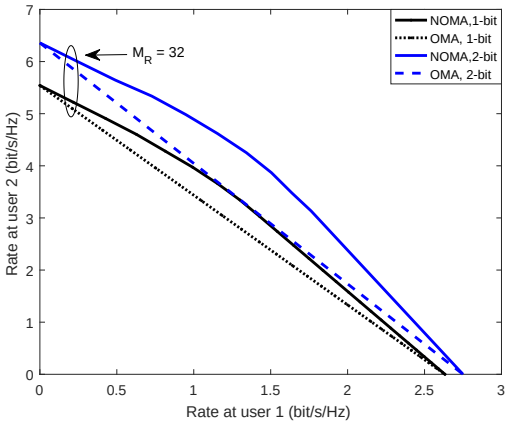


Fig.: Comparison between NOMA and OMA.

- Considerable capacity/rate region improvement can be achieved by deploying the IRS.
- More number of reflecting elements and higher phase resolution bits lead to higher capacity gain.
- **NOMA is over OMA** for ideal case (dynamic).

Numerical Results for General Case

Capacity/rate region in the general case, finite N

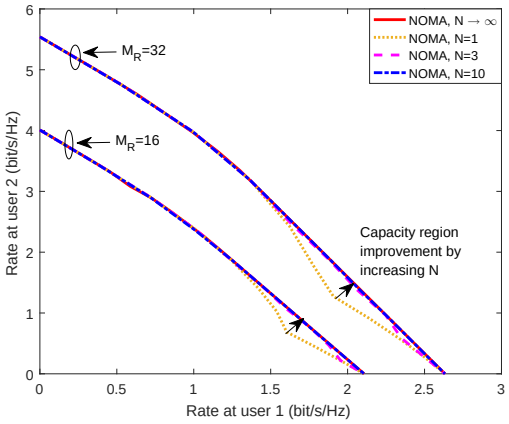


Fig.: Capacity region (inner bound) using NOMA.

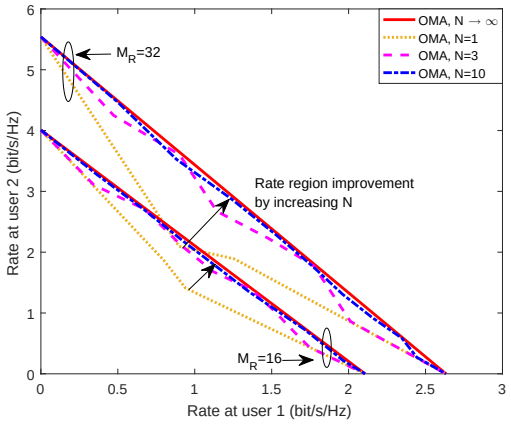


Fig.: Rate region (inner bound) using OMA.

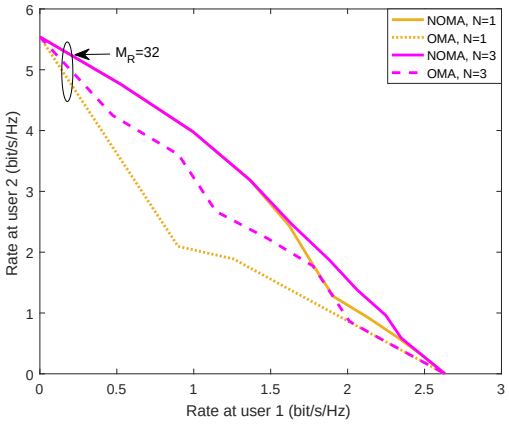
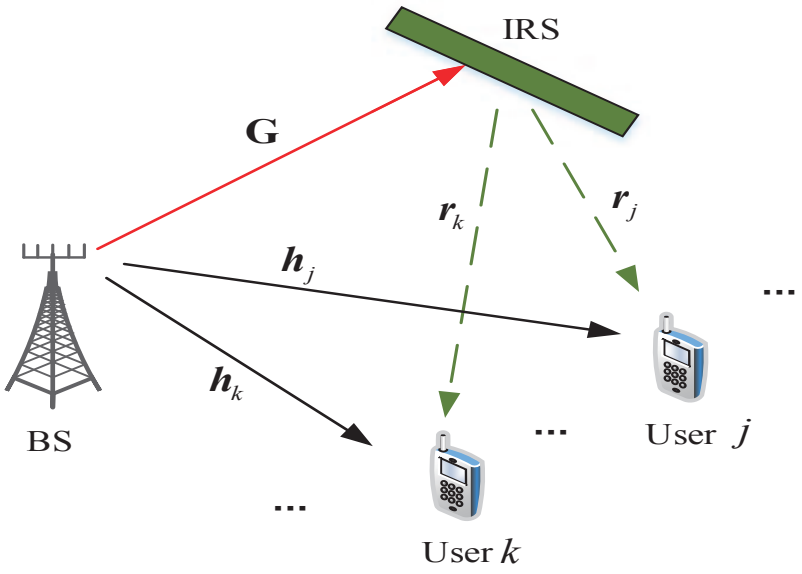


Fig.: Comparison between NOMA and OMA.

- Dynamically reconfiguring the IRS reflection matrix can increase the capacity/rate gain, especially for OMA;
- NOMA not only achieves a higher capacity but also requires **less hardware complexity** for real-time IRS control.
- **NOMA is over OMA** for general case (one-time/dynamic).

Joint Beamforming Design in NOMA-RIS Systems (Beamformer-Based design [2])

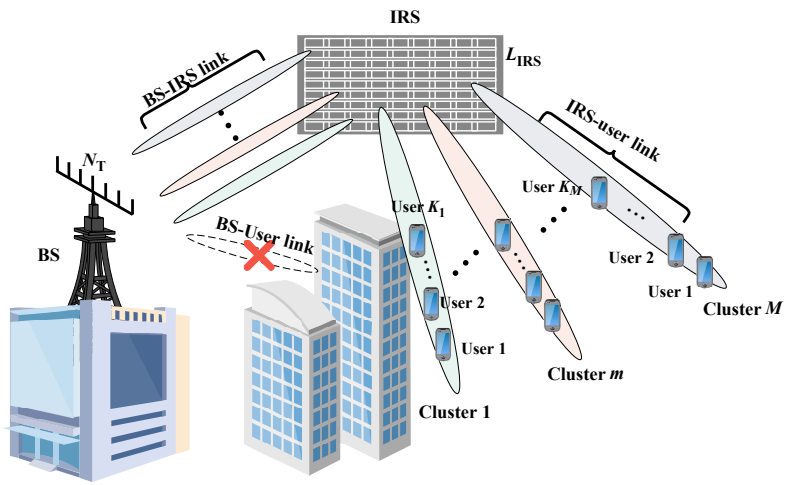


- An N-antenna base station serves K single-antenna users through the NOMA protocol with the aid of an IRS with M passive reflecting elements
- $\Theta = \mathrm{diag}\,(\mathbf{u}) \in \mathbb{C}^{M\times M}$ denotes the diagonal reflection coefficients matrix of the IRS with $\mathbf{u} = [u_1, u_2, \cdots, u_M]$ and $u_m = \beta_m e^{j\theta_m}$.

[1] X. Mu, **Y. Liu**, L. Guo, J. Lin, N. Al-Dhahir "Exploiting Intelligent Reflecting Surfaces in NOMA Networks: Joint Beamforming Optimization", ***IEEE TWC***, *vol. 19, no. 10, pp. 6884-6898, Oct. 2020, https://arxiv.org/abs/1910.13636*.

[2] **Y. Liu**, *et. al.*, "Multiple Antenna Assisted Non-Orthogonal Multiple Access", ***IEEE Wireless Communications; vol. 25, no. 2, pp. 17-23, April 2018***.

Intelligent Reflecting Surface Enhanced Millimeter-Wave NOMA Systems (Cluster Based Design [2])



- An N_{T}-antenna base station communicates with K single-antenna users through the NOMA protocol with the aid of an IRS.
- The set of **discrete phase shift** values is given by:

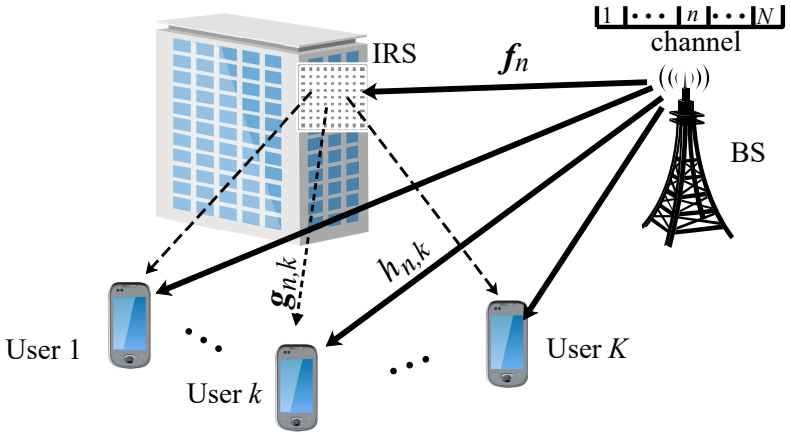
$$\theta_l \in \Omega \triangleq \left\{0, \frac{2\pi}{2^B}, \cdots, \frac{2\pi\left(2^B-1\right)}{2^B}\right\}.$$

- The K users are grouped into M clusters, K_m denotes the number of users in cluster m.

[1] J. Zuo, **Y. Liu**, E. Basar and O. A. Dobre, "Intelligent Reflecting Surface Enhanced Millimeter-Wave NOMA Systems", ***IEEE Communications Letters***, vol. 24, no. 11, pp. 2632-2636, Nov. 2020.

[2] **Y. Liu**, *et. al.*, "Multiple Antenna Assisted Non-Orthogonal Multiple Access", ***IEEE Wireless Communications;*** vol. 25, no. 2, pp. 17-23, April 2018.

Resource Allocation: Single-Cell RIS-NOMA



- A single-antenna base station serves K single-antennas users through the NOMA protocol with the aid of an IRS.
- **Subchannel Assignment**: there are N subchannels, where each subchannel can be assigned to K_n users at most and each user is assigned only one subchannel.
- $\mathbf{\Theta} = \mathrm{diag}\left\{\lambda_1 e^{j\theta_1}, \lambda_2 e^{j\theta_2}, \cdots, \lambda_M e^{j\theta_M}\right\}$ denote the reflection coefficients matrix, with $\theta_m \in [0, 2\pi]$ and $\lambda_m \in [0, 1]$.

[1] J. Zuo, **Y. Liu**, Z. Qin and N. Al-Dhahir, "Resource Allocation in Intelligent Reflecting Surface Assisted NOMA Systems", ***IEEE Transactions on Communications***, vol. 68, no. 11, pp. 7170-7183, Nov. 2020.

Optimization Problem Formulation

The optimized problem is given as

$$\max_{\boldsymbol{\delta},\boldsymbol{\pi},\mathbf{p},\boldsymbol{\Theta}} \sum_{n=1}^{N} \sum_{k=1}^{K} R_{n,k}, \tag{10a}$$

$$\text{s.t. } R_{n,\bar{k}\to k} \geq R_{n,k\to k}, \text{ if } \pi_n(k) \leq \pi_n\left(\bar{k}\right), \tag{10b}$$

$$R_{n,k\to k} \geq R_{\min}, \; n \in \mathcal{N}, \tag{10c}$$

$$\sum_{n=1}^{N} \sum_{k=1}^{K} \delta_{n,k} p_{n,k} \leq P_{\max}, \tag{10d}$$

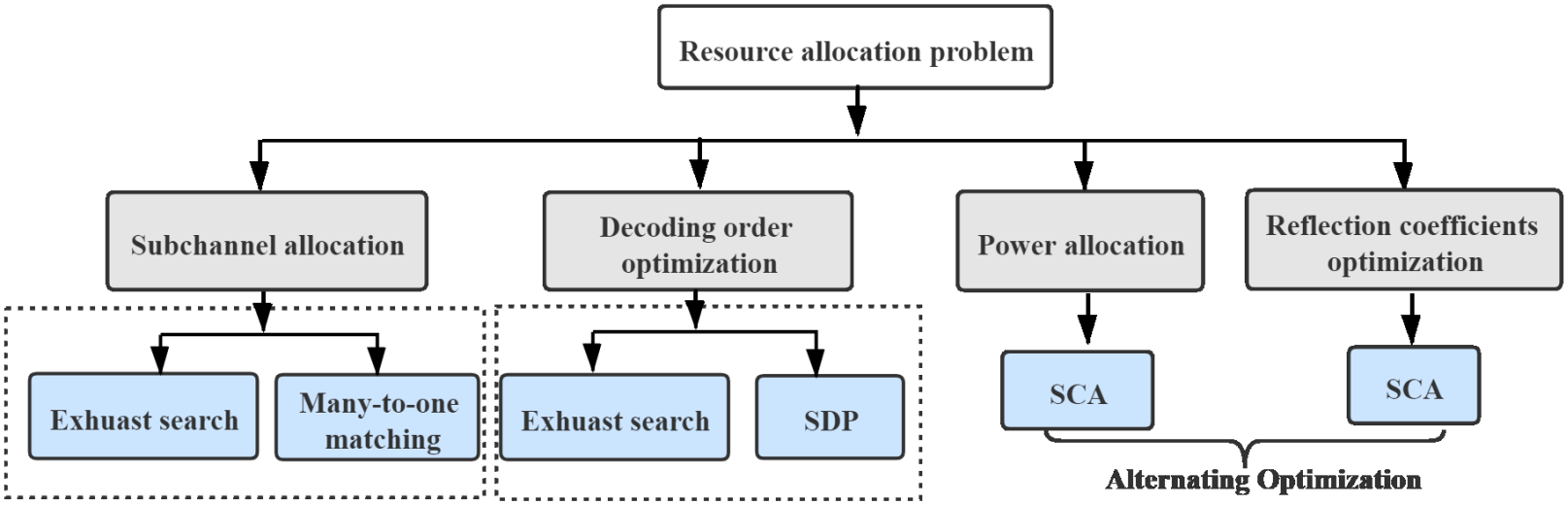
$$|\boldsymbol{\Theta}_{m,m}| \leq 1, \tag{10e}$$

$$\sum_{k=1}^{K} \delta_{n,k} = K_n, \tag{10f}$$

$$\sum_{n=1}^{N} \delta_{n,k} = 1, \tag{10g}$$

$$\pi_n \in \Omega. \tag{10h}$$

Proposed Algorithms



The main challenges to solve resource allocation problem

- Due to the binary constraint, it is a **NP-hard problem**.
- The decoding order can be controlled by the IRS reflection coefficients, it is difficult to obtain the **optimal decoding order**.
- The transmit power and reflection coefficients are highly coupled.

Numerical Results

System throughput for Single Cell IRS

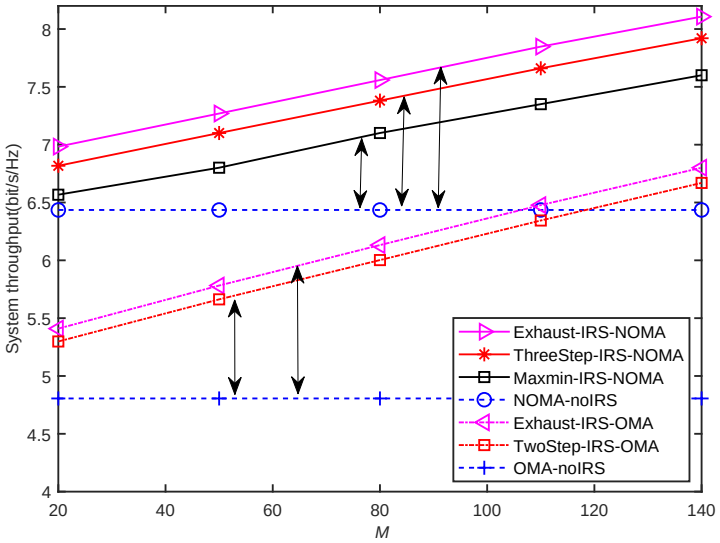


Fig.: System throughput versus the number of reflecting elements.

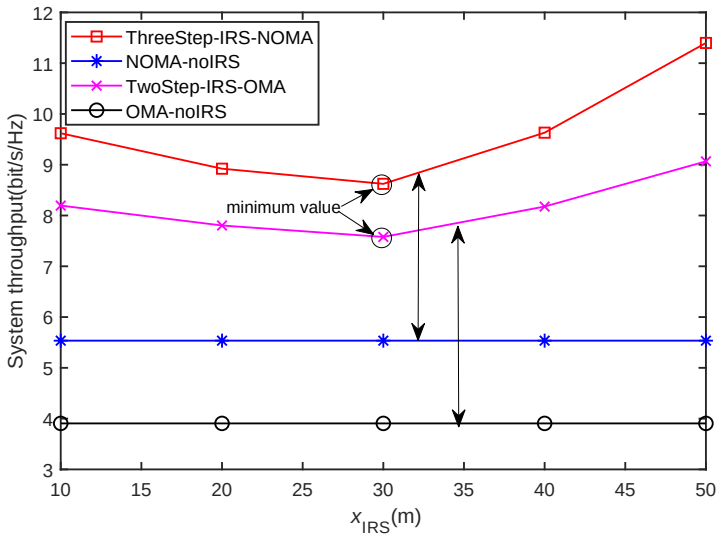


Fig.: System throughput versus the location of IRS coordinate.

- There is an **optimal deployment point** for IRS, which motivates us to investigate the deployment of IRS [1].

[1] X. Mu, **Y. Liu**, L. Guo, J. Lin, R. Schober "Joint Deployment and Multiple Access Design for Intelligent Reflecting Surface Assisted Networks", ***IEEE TWC, major revision***, *https://arxiv.org/abs/2005.11544*.

From Single Cell to Multi-Cell RIS/IRS-NOMA Networks

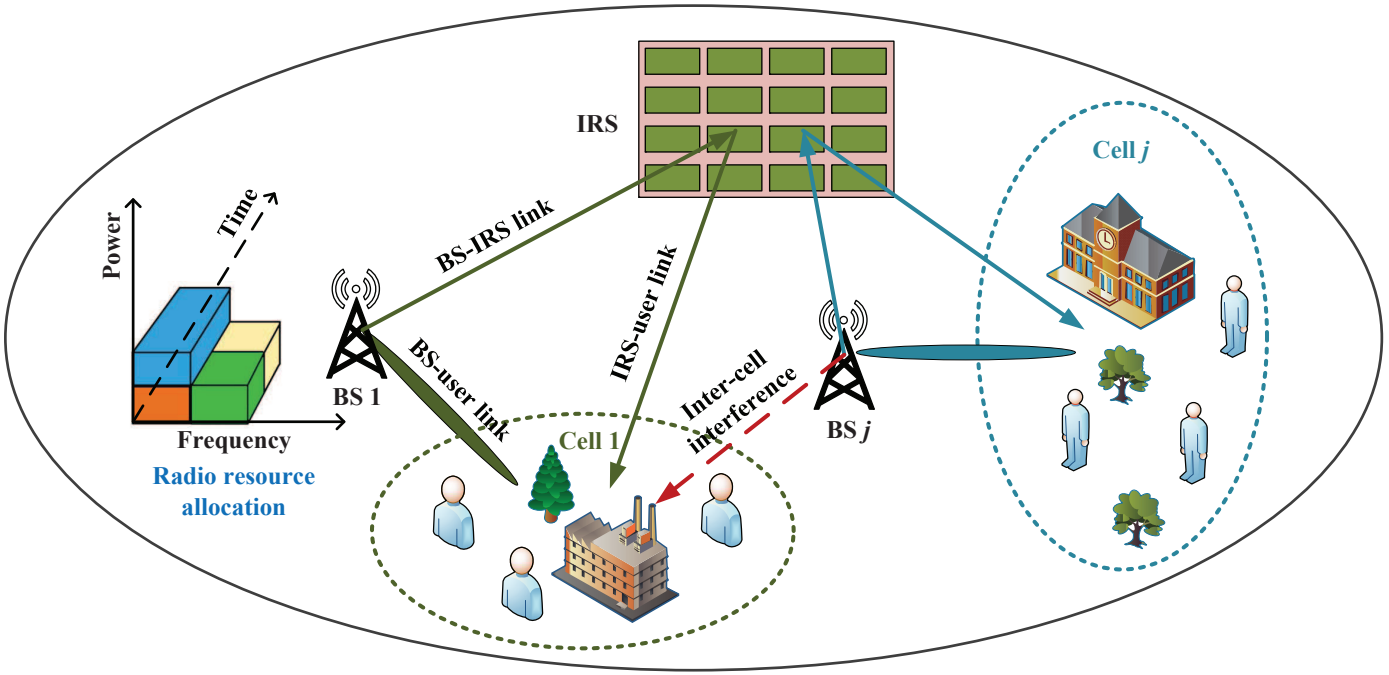


Fig.: An illustration of the system model for the IRS-aided multi-cell NOMA network, where an IRS with M reflecting elements is deployed to assist the wireless communication from J single-antenna BSs to I single-antenna users.

[1] W. Ni, X. Liu, Y. Liu, H. Tian, and Y. Chen, "Resource allocation for multi-cell IRS-aided NOMA networks," ***IEEE Trans. Wireless Commun.***, ***major revision***, https://arxiv.org/abs/2006.11811

[2] W. Ni, X. Liu, Y. Liu, H. Tian, and Y. Chen, "Intelligent reflecting surface aided multi-cell NOMA networks," in ***Proc. IEEE GLOBECOM Workshops***, ***accepted to appear***.

IRS-Aided Multi-Cell NOMA Networks: Joint User Association and Subchannel Assignment

- Let $\alpha_{ij} \in \{0,1\}$ and $\beta_{jk} \in \{0,1\}$ denote the **user association** indicator and **subchannel assignment** factor, respectively. Then, the superimposed signal, x_{jk}, broadcasted by the j-th BS on the k-th subchannel can be given by

$$x_{jk} = \underbrace{\alpha_{ij}\beta_{jk}\sqrt{p_{ijk}}x_{ijk}}_{\textbf{signal for user i}} + \underbrace{\sum\nolimits_{t=1,t\neq i}^{I} \alpha_{tj}\beta_{jk}\sqrt{p_{tjk}}x_{tjk}}_{\textbf{signal for other paired users}}, \tag{11}$$

where x_{ijk} and p_{ijk} denote the signal and power transmitted by BS j on subchannel k for user i, respectively.

[1] W. Ni, X. Liu, **Y. Liu**, H. Tian, and Y. Chen, "Resource allocation for multi-cell IRS-aided NOMA networks," ***IEEE Trans. Wireless Commun.***, ***major revision***, https://arxiv.org/abs/2006.11811

IRS-Aided Multi-Cell NOMA Networks: Solution Design

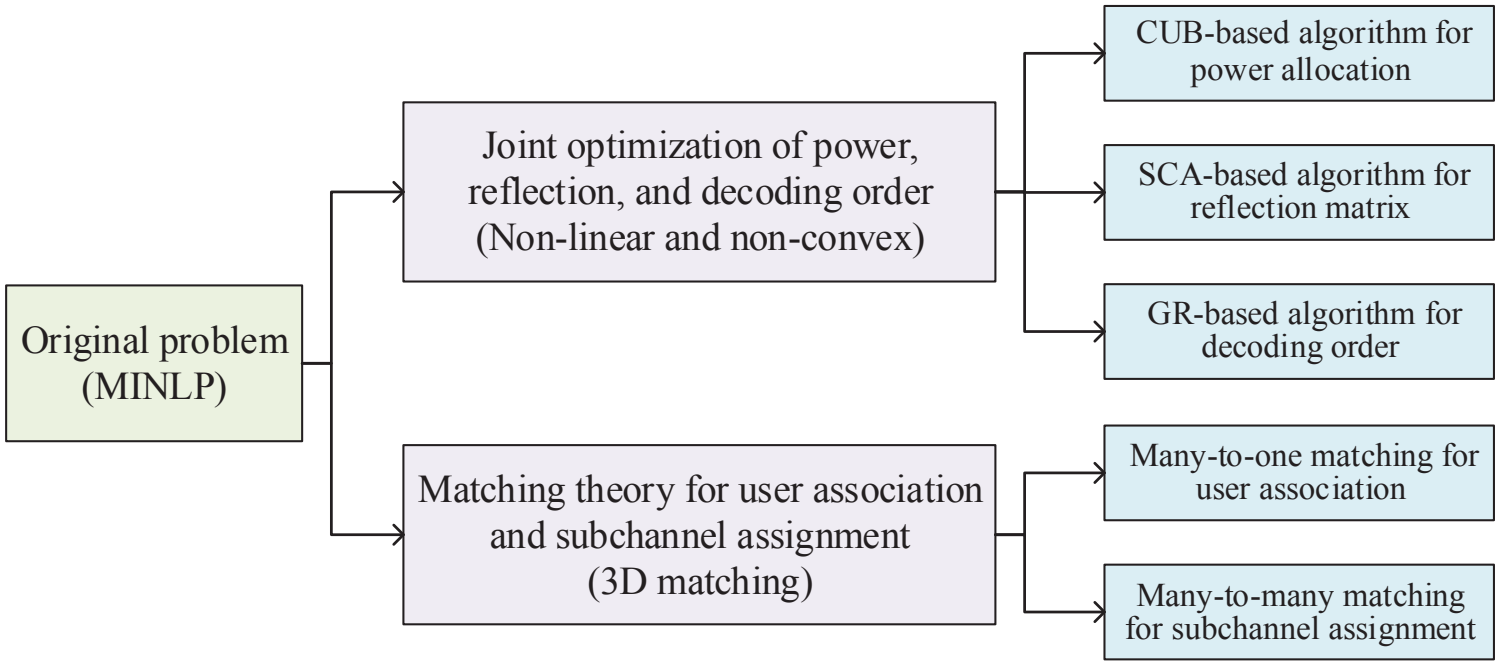
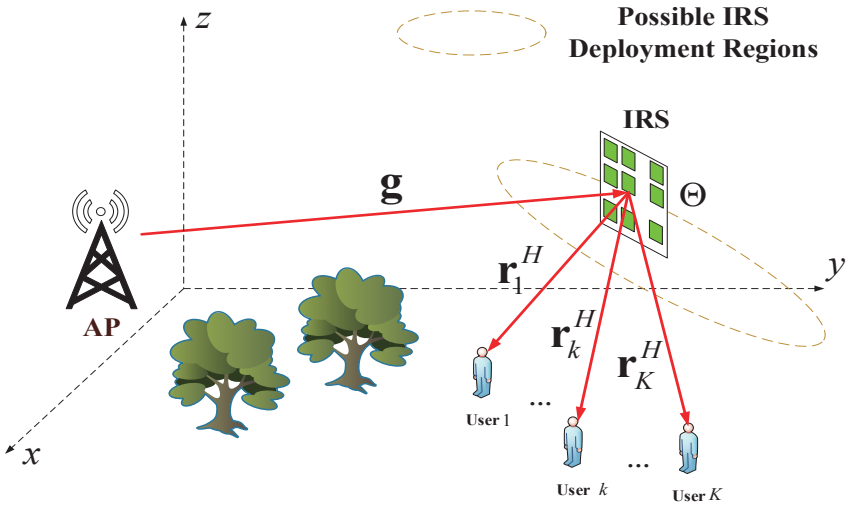


Fig.: A roadmap for problem decomposition and proposed algorithms.

[1] W. Ni, X. Liu, **Y. Liu**, H. Tian, and Y. Chen, "Resource allocation for multi-cell IRS-aided NOMA networks," ***IEEE Trans. Wireless Commun.***, ***major revision***, https://arxiv.org/abs/2006.11811

IRS Deployment and Multiple Access



- An IRS is deployed in a predefined region to assist the downlink transmission from one single-antenna AP to K single-antenna users.
- The locations of the AP, the IRS, and the kth user are denoted by $\mathbf{b} = (x_b, y_b, H_b)^T$, $\mathbf{s} = (x_s, y_s, H_s)^T$, and $\mathbf{u}_k = (x_k, y_k, H_k)^T$, respectively.

[1] X. Mu, **Y. Liu**, L. Guo, J. Lin, R. Schober "Joint Deployment and Multiple Access Design for Intelligent Reflecting Surface Assisted Networks", ***IEEE Transactions on Wireless Communications, major revision***, *https://arxiv.org/abs/2005.11544*.

Multiple Access Schemes

- **NOMA (one-time)**: Let $\mu(k)$ denote the decoding order of user k. The achievable rate of user k in NOMA can be expressed as

$$R_k^N = \log_2\left(1 + \frac{|\mathbf{q}_k\mathbf{v}|^2 p_k}{|\mathbf{q}_k\mathbf{v}|^2 \sum_{\mu(i)>\mu(k)} p_i + \sigma^2}\right), \tag{12}$$

- **FDMA (one-time)**: AP serves the users in orthogonal frequency bands of equal size.

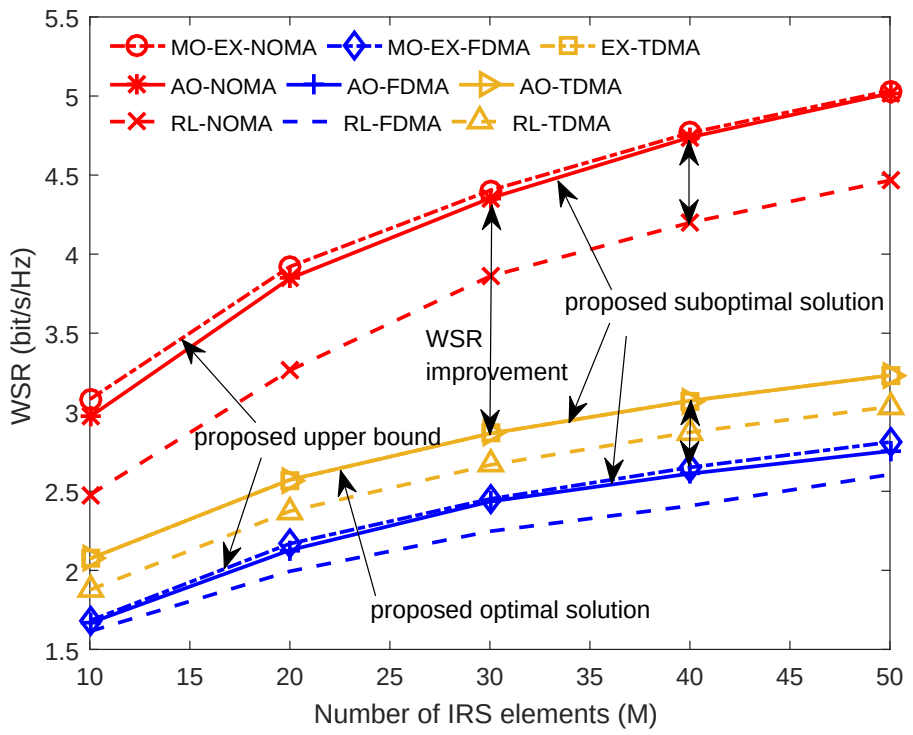
$$R_k^F = \frac{1}{K}\log_2\left(1 + \frac{|\mathbf{q}_k\mathbf{v}|^2 p_k}{\frac{1}{K}\sigma^2}\right). \tag{13}$$

- **TDMA (Dynamic)**: AP serves the users in orthogonal time slots of equal size. The IRS reflection coefficients can assume different values in each time slot, namely, **time-selectivity**.

$$R_k^T = \frac{1}{K}\log_2\left(1 + \frac{|\mathbf{q}_k\mathbf{v}_k|^2 P_{\max}}{\sigma^2}\right), \tag{14}$$

Numerical Results: Performance for NOMA, TDMA and FDMA

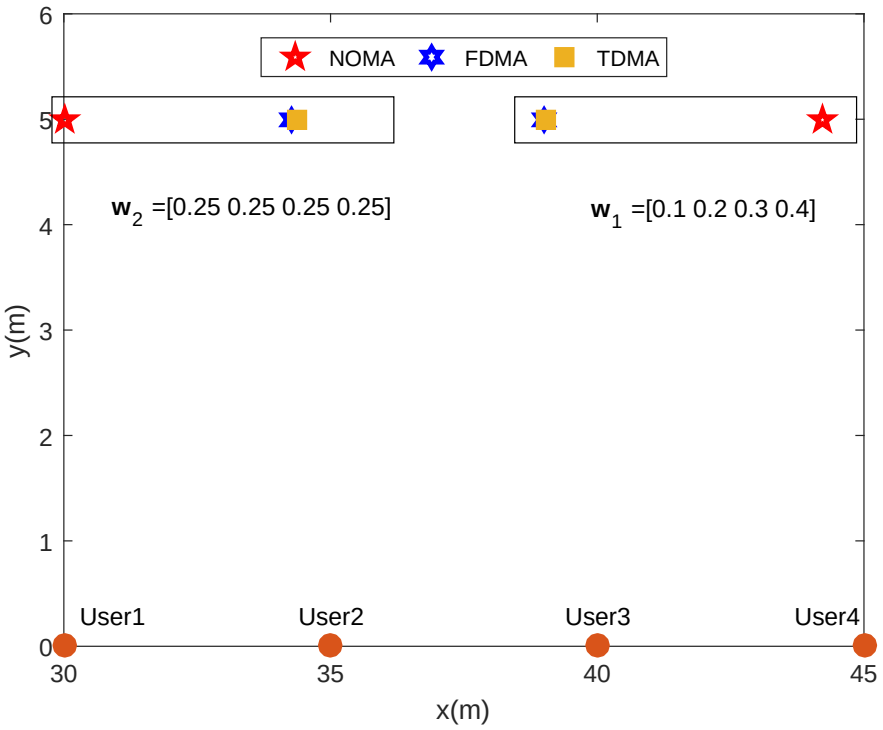
WSR versus the number of IRS elements



- The proposed suboptimal AO algorithms achieve **near-optimal** performance, closely approaching the proposed upper bound.
- Significant performance gain can be achieved by optimizing the IRS deployment location.
- NOMA (one-time) has the best performance, TDMA (Dynamic) is in the middle, and FDMA (one-time) achieves the worst performance.

Numerical Results: Priority Deployment Strategy

Optimal IRS Deployment Locations of Different Transmission Schemes



- For NOMA, it is preferable to deploy the IRS in an ***asymmetric*** manner to achieve distinct channel conditions for different users.
- The IRS deployment strategy for OMA is more ***symmetric*** across all users than that for NOMA.

Signal Processing Advances for RIS-NOMA Networks: A Machine Learning Approach

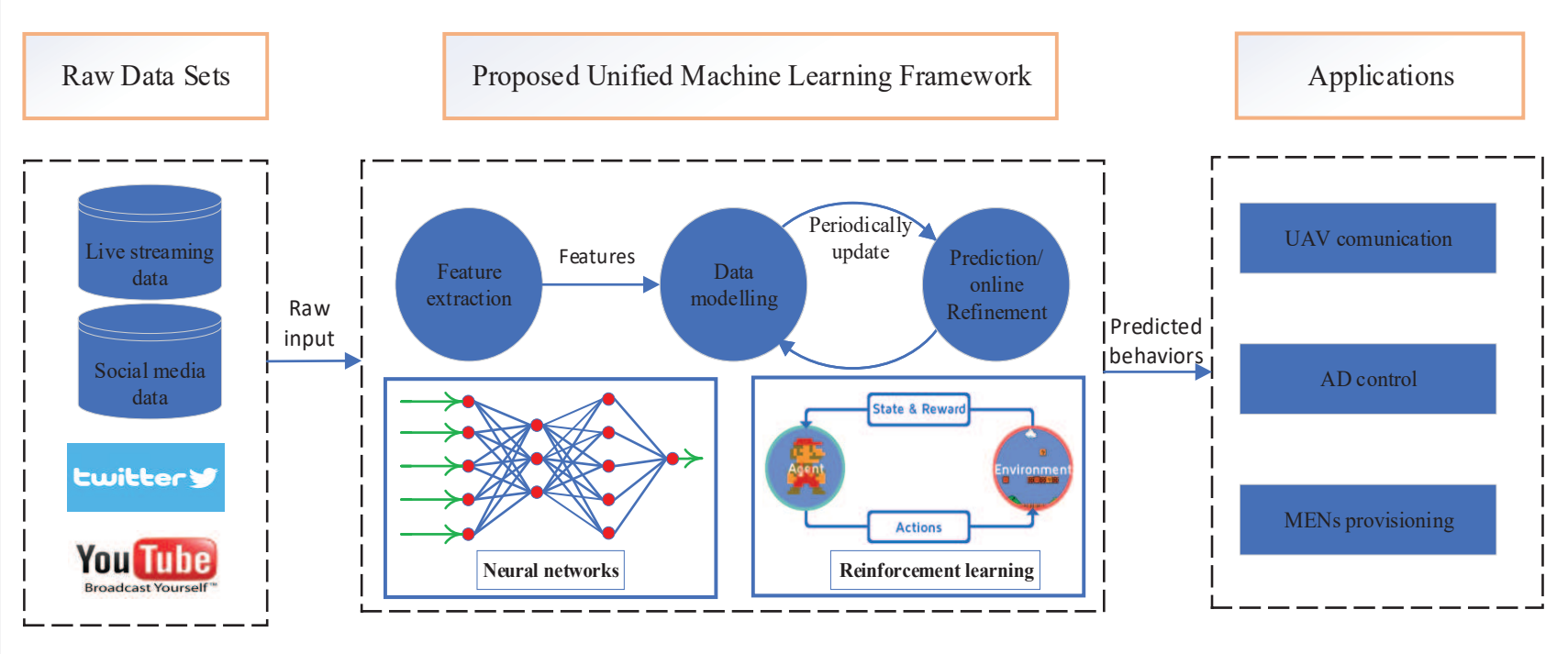


Fig.: Artificial intelligent algorithms for wireless communications.

[1] **Y. Liu**, S. Bi, Z. Shi, and L. Hanzo, "When Machine Learning Meets Big Data: A Wireless Communication Perspective", ***IEEE Vehicular Communication Magazine, vol. 15, no. 1, pp. 63-72, March 2020***, *https://arxiv.org/abs/1901.08329*.

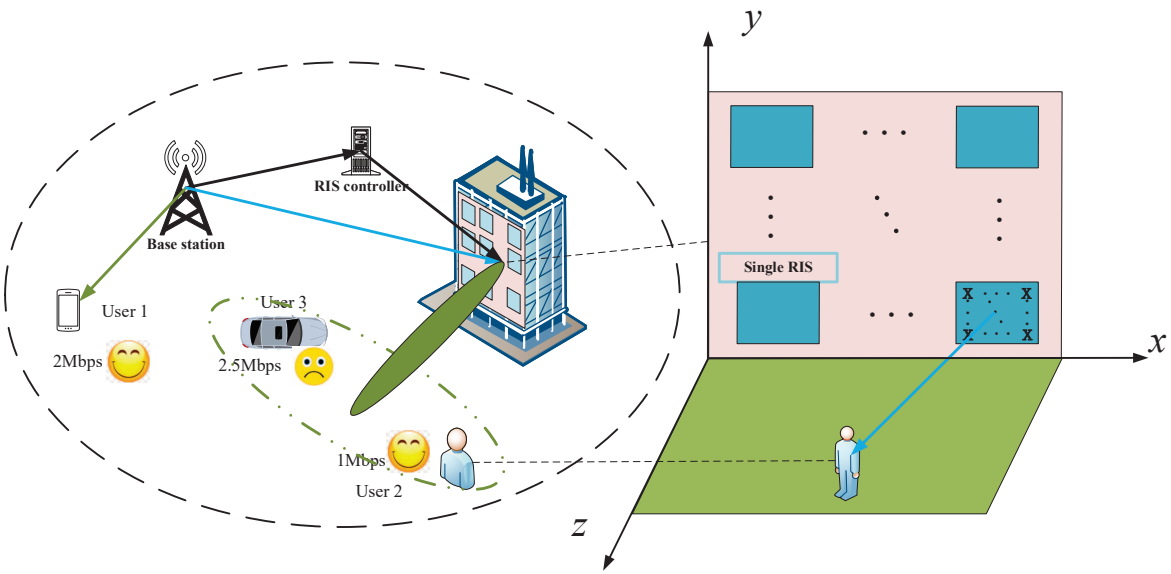
Discussions for Applying Machine Learning in Wireless Communications

- **Two most successful applications for ML**
  - Computer Vision and Natural Language Processing
- **Why and what are the key differences?**
  - Dataset: CV and NLP are data oriented/driven and exist rich dataset
  - Well established mathematical models in wireless communications
- **Before Problem formulation**
  - Can this problem be solved by conventional optimization approach?
  - If yes, what is the key advantages of using machine learning?

Machine Learning for Deployment and Beamforming of IRS Networks

- Motivations for deployment design of the IRS
  - **User behavior/peculiarity** is considered: the IRS have to be periodically **repositioned** accordingly.
- Motivations for invoking machine learning (ML) in NOMA-IRS enhanced networks
  - Dynamic scenario with **heterogenous QoS requirements** and **heterogenous user mobility**
  - Mixed-integer, and non-convex optimization problem
  - **Long-term** benefits
  - **Interactive** with environment: Dynamic Configuration

ML Enabled IRS Deployment with Heterogenous QoS Requirements



- **MISO-NOMA** downlink transmission, **dynamic configuration** for RIS.
- **Heterogenous QoS requirements**: dynamically changing during different time period.

[1] X. Liu, **Y. Liu**, Y. Chen, and V. Poor "RIS Enhanced Massive Non-orthogonal Multiple Access Networks: Deployment and Passive Beamforming Design", ***IEEE Journal of Selected Areas in Communications (JSAC), accept to appear***, *https://arxiv.org/abs/2001.10363*.

Optimization Problem

The energy efficiency maximization problem is formulated as follows

$$\max_{\boldsymbol{\theta},\boldsymbol{P},\boldsymbol{\pi},\boldsymbol{C}} \ \overline{\eta}_{EE} \tag{15a}$$

$$\text{s.t.} \quad R_{l,i}(t) \geq R_{\min}^{l,i}(t), \forall k, \forall l, \forall i \in \{a, b\}, \tag{15b}$$

$$|\phi_n(t)| = 1, \forall n, \tag{15c}$$

$$c_l^I \in c_m^O, \forall l, \forall m, \tag{15d}$$

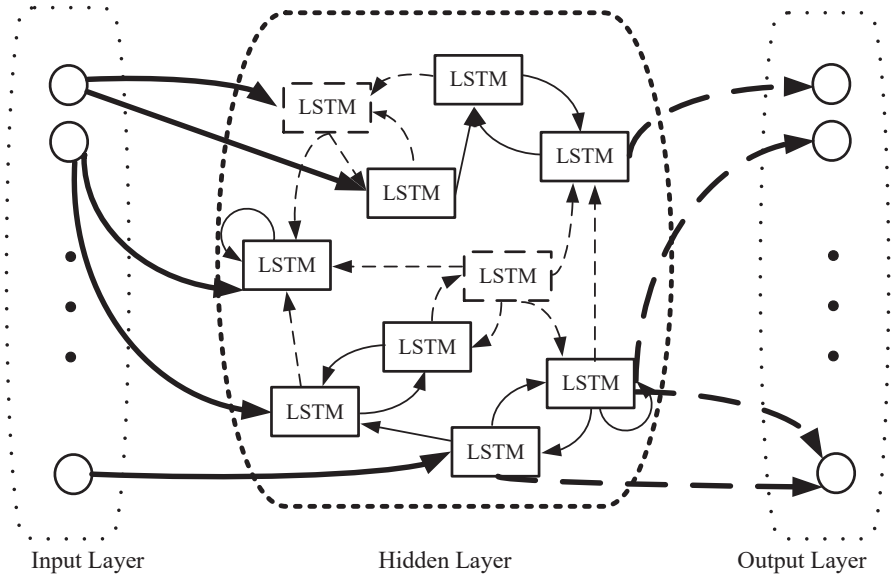
$$R_{l,b\to l,a}(t) \geq R_{l,b\to l,b}(t), \pi_l(a) \geq \pi_l(b), \forall l, \tag{15e}$$

$$\sum_{l=1}^{L} \left(\|\boldsymbol{w}_{l,a}\|^2 + \|\boldsymbol{w}_{l,b}\|^2 \right) \leq P_{\max}, \forall k, \tag{15f}$$

- $R_{\min}^{l,i}(t)$ denotes the **time-variant heterogenous QoS requirements**.
- (15e) represents the **dynamic decoding order** constraint.

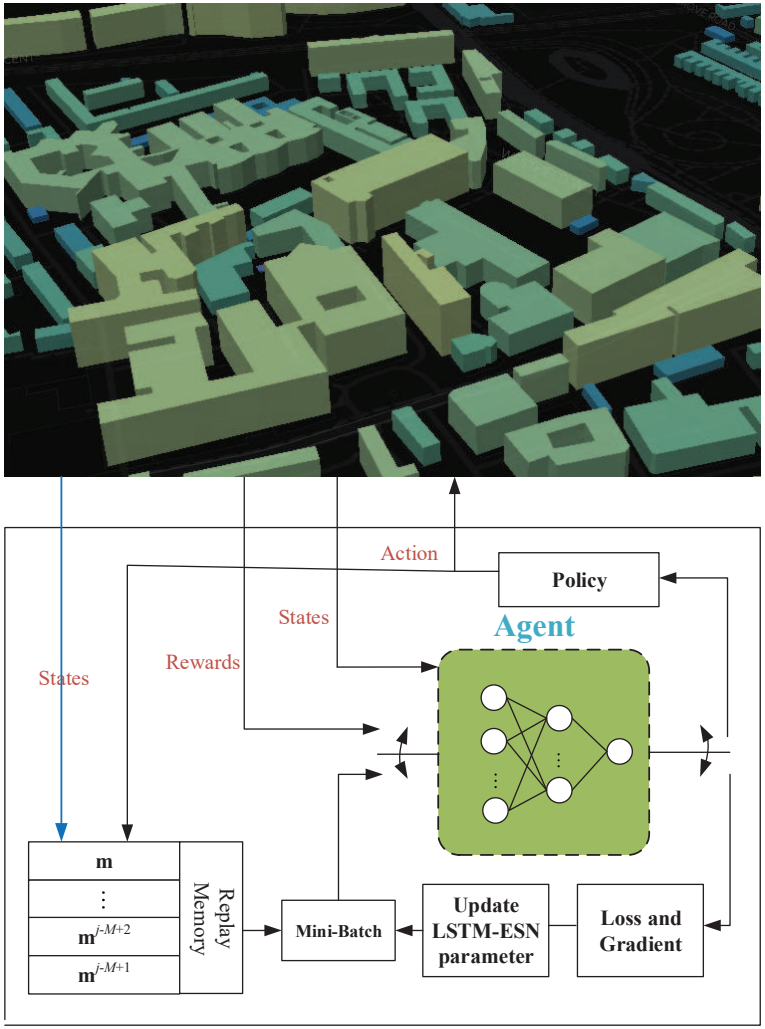
LSTM-based ESN Algorithm for Predicting the Data Traffic Density

Heterogenous QoS requirements prediction with the aid of **neural network**



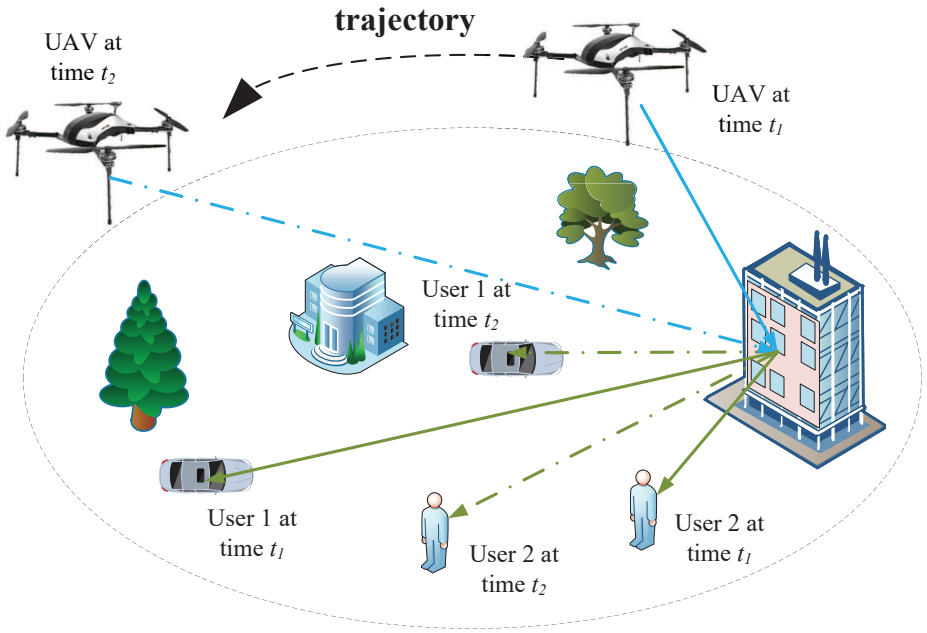
A recurrent neural network model based on the architecture of an echo state networks (ESN) model using hidden neurons long-short-term-memory (LSTM) units.

Decaying Double Deep Q-network (D^3QN) Based Algorithm for Jointly Deploying and Designing the IRS



- D^3QN model **incorporate farsighted system evolution** instead of just optimizing current benefits.
- D^3QN model can update decision policies timely
  - learn from the **environment**
  - learn from the **users**
  - learn from the **historical experience**

ML Enabled UAV-RIS-NOMA Network with Heterogenous User Mobility



- **Obstacle avoidance** for UAVs in dense urban area based on 3D radio map
- **Heterogenous user mobility**: UAVs are moving according to NOMA Users' mobility, high-mobility user is paring with low-mobility users for achieving **district channel differences**.
- Tackle **energy limitation** of UAVs via virtual LoS links generated by RIS

[1] X. Liu, **Y. Liu**, and Y. Chen, "Machine Learning Empowered Trajectory and Passive Beamforming Design in UAV-RIS Wireless Networks", ***IEEE JSAC, accept to appear*** ,https://arxiv.org/pdf/2010.02749.pdf.

Problem Formulation

$$\min_{\boldsymbol{\theta},\boldsymbol{P},\boldsymbol{Q}} \; E_{\text{UAV}} = \sum_{t=0}^{T} \bar{E}(t) \tag{16a}$$

$$\text{s.t.} \quad R_k(t) \geq R_k^{\min}, \forall k, \forall t, \tag{16b}$$

$$|\phi_n(t)| = 1, \forall n, \forall t, \tag{16c}$$

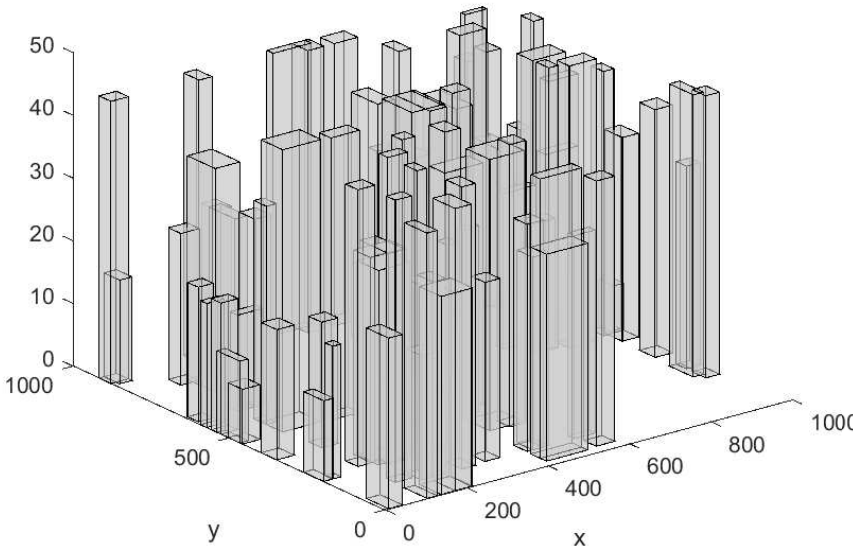
$$x_{\min} \leq x_{\text{UAV}}(t) \leq x_{\max}, y_{\min} \leq y_{\text{UAV}}(t) \leq y_{\max}, \forall t, \tag{16d}$$

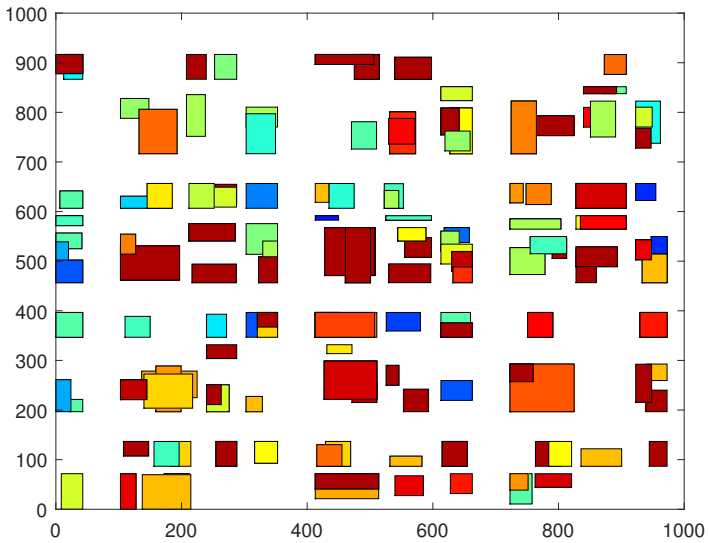
$$R_{l,b\to l,a}(t) \geq R_{l,b\to l,b}(t), \pi_l(a) \geq \pi_l(b), \forall l, \tag{16e}$$

$$\text{tr}\left(\boldsymbol{P}\left(\boldsymbol{H}^H\boldsymbol{H}\right)^{-1}\right) \leq P_{\max}, \forall k, \forall t, \tag{16f}$$

- (16b) denotes that the data demand of all mobile users has to be satisfied at each timeslot.
- (16b) formulates the altitude bound of UAVs, which indicates that the UAV can only move in this particular area.
- (16e) represents the **dynamic decoding order** constraint.

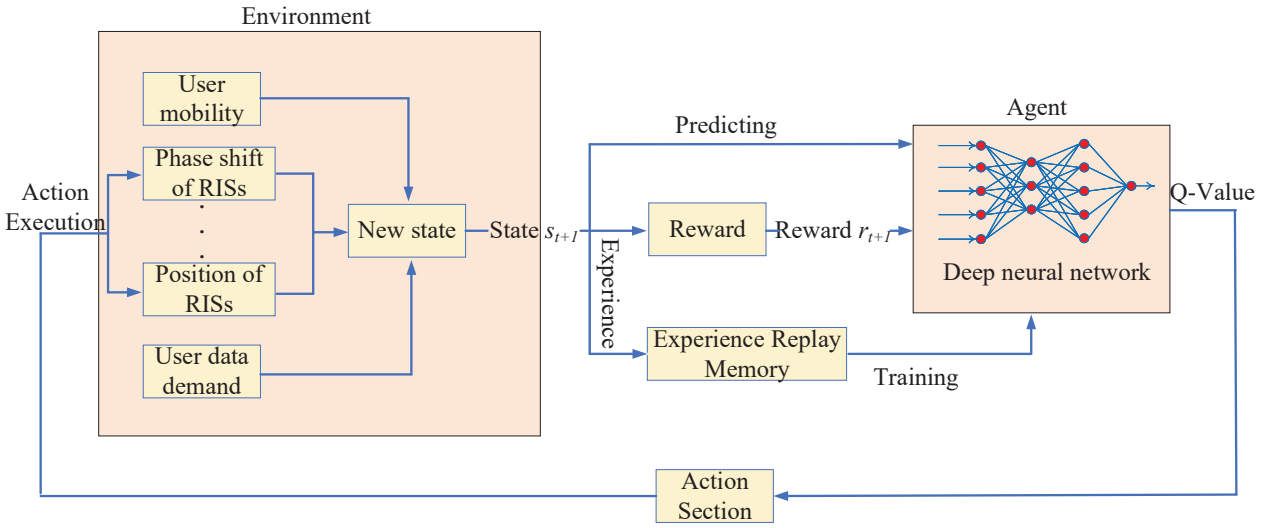
3D Radio Map of a dense urban area for UAVs





We model the urban city environment as a set of **buildings**, where each building is modeled as a set of **cubes**.

Decaying Deep Q-network (D-DQN) Based Algorithm for Trajectory and Passive Beamforming Design



- Maximizing the **long-term discounted rewards**.
- Learning the optimal policy via Q-learning by **updating Q-values** at each timeslot.
- Combining conventional Q-learning with **neural network** for approximating Q-table.
- Striking a balance between the exploration and exploitation by ϵ-**greedy exploration**.

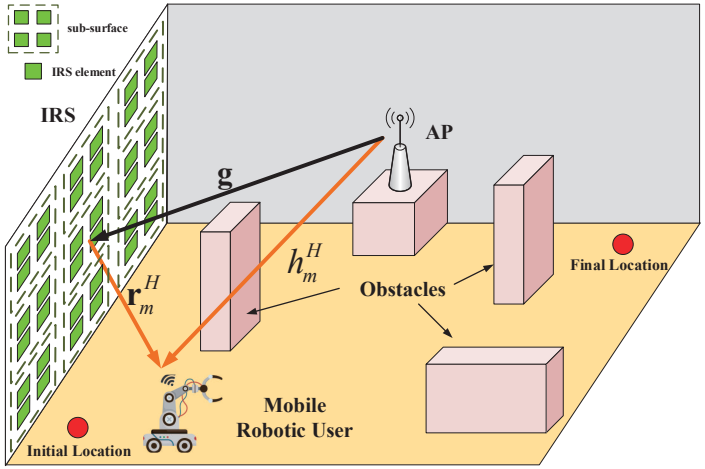
Other Recent Work for RIS

1. IRS-enhanced Indoor Robot Path Planning: A Radio Map Approach
2. Federated learning in multi-RIS aided systems
3. Deep Reinforcement learning for user grouping/clustering of RIS-NOMA
4. Machine learning for mobility prediction and joint beaforming of RIS-MIMO-NOMA networks
5. RIS aided multiple access over fading channel
6. PLS for RIS-NOMA
7. RIS for Cooperative NOMA: Cooperative or NOT?

Move to Indoor: IRS-enhanced Indoor Robot Path Planning

Connected Robot

- Integrate robots into cellular networks as robotic users to be served by BSs or APs.
- More cost-efficient and less computation-constrained than automated robots.
- **Signal blockage** is the major bottleneck for the application of connected robots.



IRS-enhanced robot systems

- Deploying an IRS to assist the communication between APs and connected robots.

[1] X. Mu, **Y. Liu**, L. Guo, J. Lin, R. Schober "Intelligent Reflecting Surface Enhanced Indoor Robot Path Planning: A Radio Map based Approach", ***IEEE Transactions on Wireless Communications, under review,***, *https://arxiv.org/abs/2009.12804*.

IRS Enhanced Federated Learning

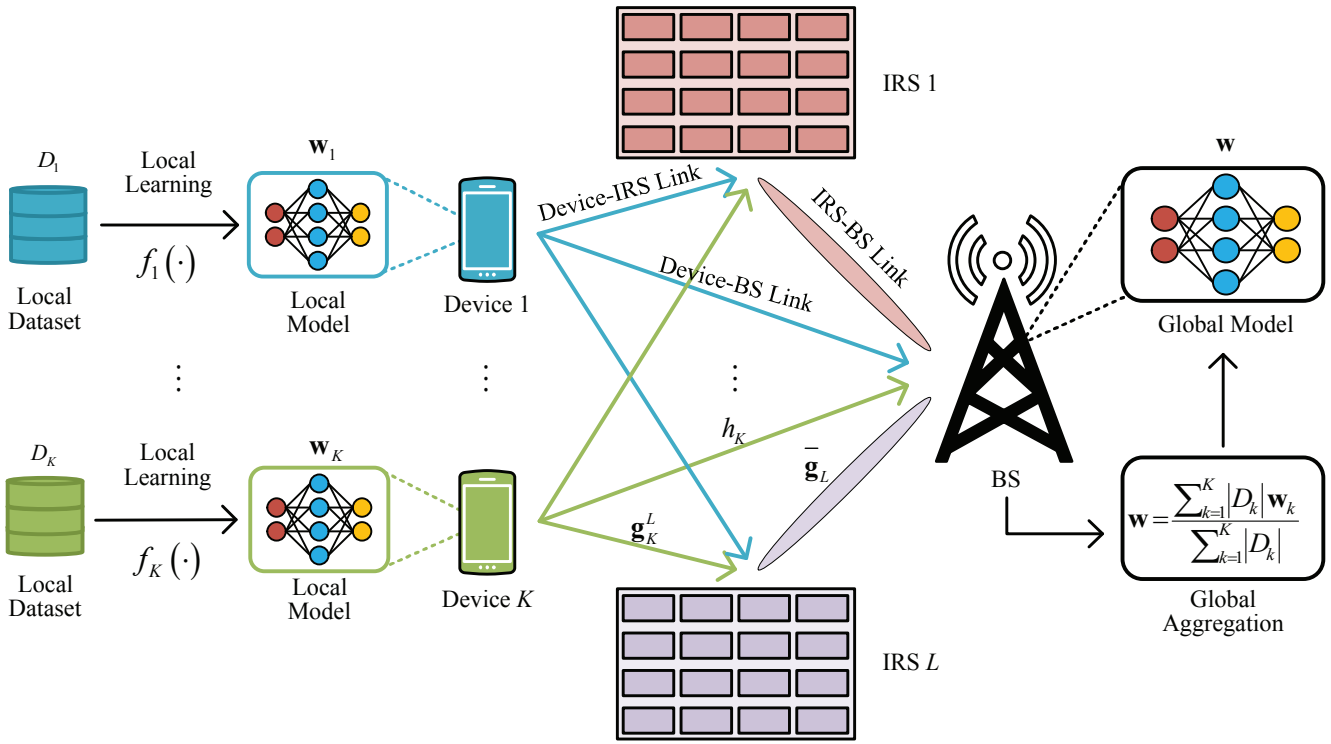


Fig.: An illustration of federated learning in multi-IRS aided system. The objective of FL is to collaboratively train a global machine learning model at the BS while keeping the training dataset processed in a distributed manner to **preserve user privacy**.

[1] W. Ni, **Y. Liu**, Z. Yang, H. Tian, and X. Shen, "Federated learning in multi-RIS aided systems," ***IEEE Trans. Wireless Commun.***, https://arxiv.org/abs/2010.13333.

Research Opportunities and challenges for RIS

1. Performance Analysis for joint RIS model
2. Performance evaluation for different angular direction
3. Accurate Closed-Form analytical results for RIS OMA/NOMA systems
4. Stochastic geometry analysis for RIS networks
5. Interference mitigation for multi-cell RIS-NOMA networks.
6. Effective joint beamforming design for MIMO-NOMA-RIS networks.
7. Security provisioning in NOMA-RIS networks
8. RIS and NOMA enabled application scenarios
9. Machine learning for RIS/IRS
10. Channel estimation for RIS/IRS
11. Grant/Semi-Grant Free NOMA for RIS networks

Thank you!

Thank you!