

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

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Outline

- 1 RIS Basics and Modelling: Joint Modelling versus Separated Modelling
- 2 Performance Evaluation for RIS: NOMA and OMA
 - Conventional Analysis for RIS-NOMA Networks
 - Stochastic Geometry Based Analysis
- 3 Capacity Characterization, Beamforming and Resource Allocation for RIS-aided Multi-user System
 - Capacity Characterization for RIS-aided Multi-user System: An Information Theoretic Perspective
 - Beamforming Design in NOMA RIS Systems
 - Resource Allocation NOMA-RIS Systems
- 4 Deployment and Multiple Access in Multi-user RIS Networks
- 5 Machine Learning for RIS-NOMA Networks
- 6 Recent Results and Research Opportunities for RIS

Ancestor Concepts Related to the RIS

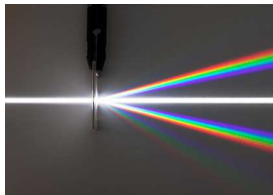


Fig.: Optical grating

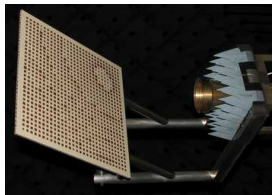


Fig.: Reflect-array antennas

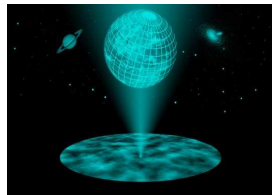


Fig.: Hologram

- 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

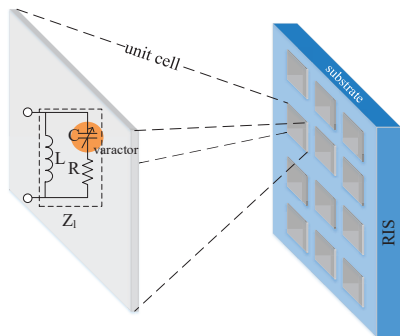


Fig.: Schematic diagram of the varactor RIS

[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: $\tilde{r} = \frac{E_r}{E_i} = \frac{Z_i - Z_0}{Z_i + Z_0}$

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*

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

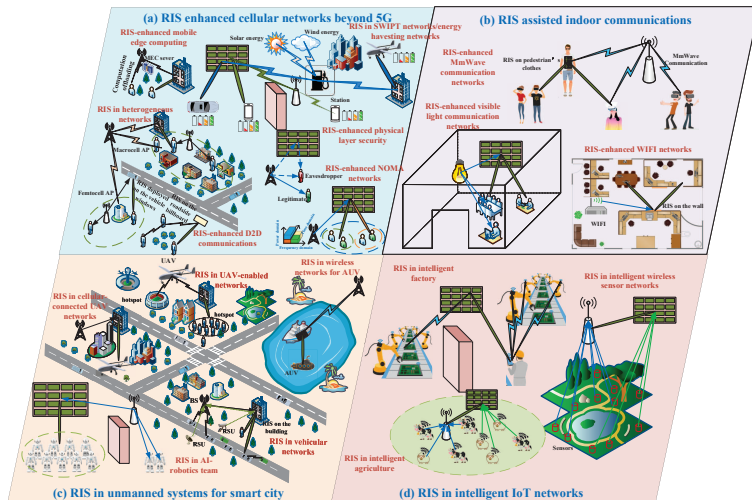
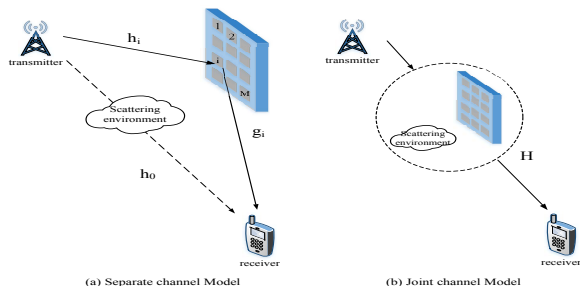


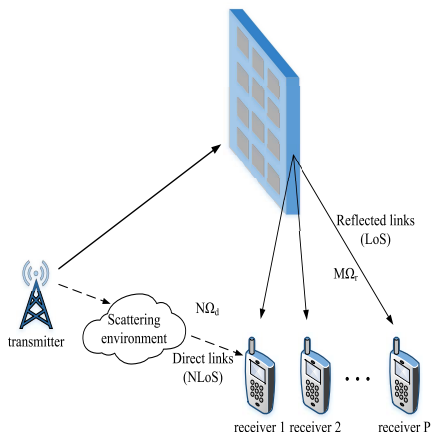
Fig.: RIS in the wireless communication networks.

Modeling RIS-assisted Networks: Separate Model VS Joint Model



- 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-dominant.

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:

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

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

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 $K_0 = M \Omega_r / (N \Omega_d)$.

- Power scaling law:

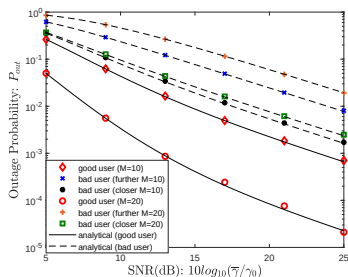
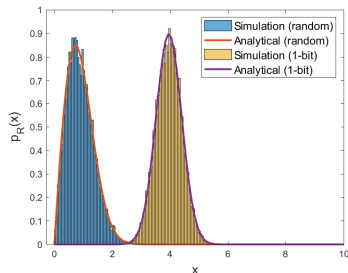
$$P_r \sim P_t \cdot \left[\text{sinc}^2 \frac{\Delta}{2} M^2 + (1 - \text{sinc}^2 \frac{\Delta}{2}) M \right], \quad (3)$$

- 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
$K_0 \rightarrow 0$	0	Pure Direct Link
$\Delta = 0$	MK_0	Continuous phase shift
$K_0 \rightarrow \infty$	Ms/(1-s)	Pure RIS

Numerical Results



- Outage probability of the good user (red) decreases as M increases.
- For the bad user, outage probability does not decrease monotonously with the increase of M . (So what are the other factors?)

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 Transactions on Wireless Communications*, to be submitted.

Separate Model: A Categorizing Approach

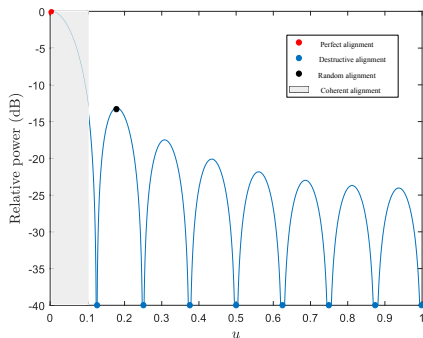
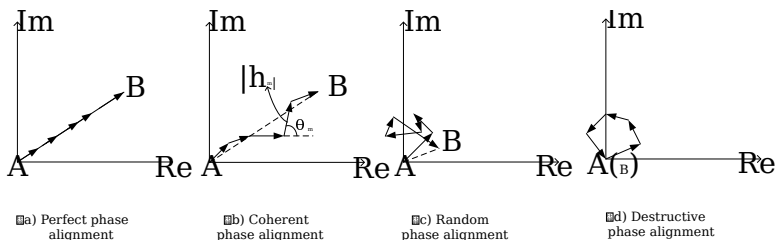


Fig.: Radiation pattern for a 16-element 1-D phase scanning RIS with phase alignment categories indicated at different angles.

- 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



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
$\text{Var}[H]$	$M(\bar{h}^2 - (\bar{h})^2)$	$\alpha^2 + 2\beta^2 - (\mathbb{E}[H])^2$	$M\bar{h}^2(4 - \pi)/4$	$M(\bar{h}^2 - (\bar{h})^2)$
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, $\alpha = M\bar{h}\text{sinc}(\pi/(2L))$, $\beta^2 = M\bar{h}^2[1 - \text{sinc}(\pi/L)]/2$, and $L_{1/2}(x)$ denoting the Laguerre polynomial.

Single User Case

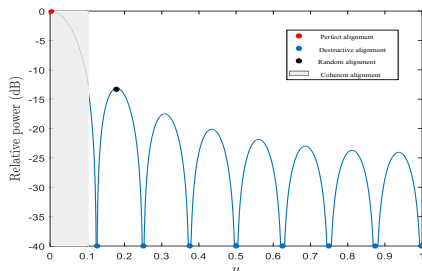


Fig.: Radiation pattern for a 16-element 1-D phase scanning RIS with phase alignment categories indicated at different angles.

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:

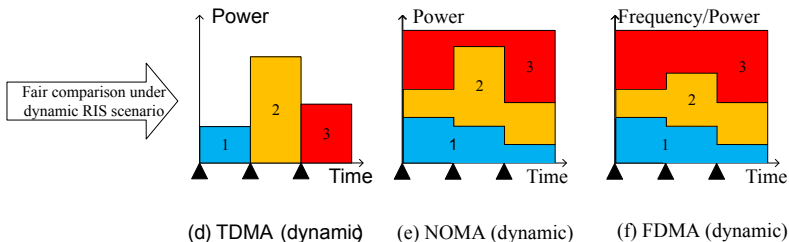
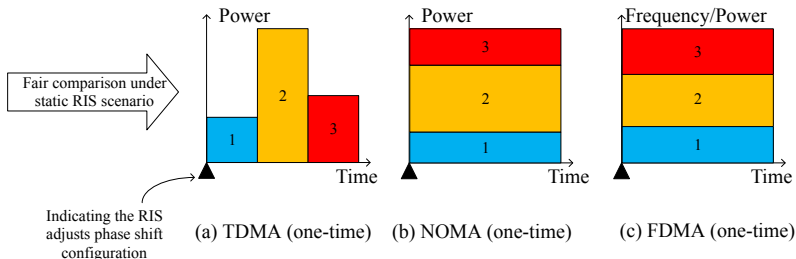
$$P_{out}(\gamma_0) \approx \frac{b^{-M} \gamma_0^M}{(2M)!} \gamma_t^{-M}. \quad (4)$$

- 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



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

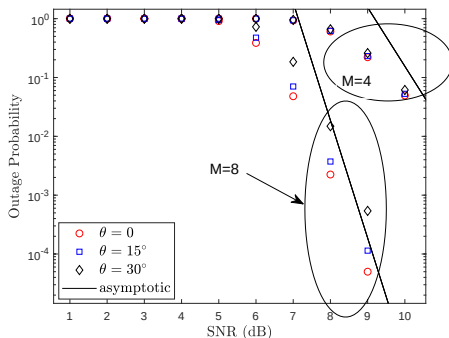


Fig.: Outage probability for a single user assisted by 4-element and 8-element continuous phase shift RIS.

- 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

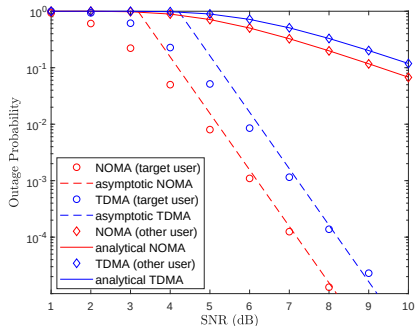


Fig.: Outage probability for 4-element continuous phase shift static RIS scenario under NOMA (**one-time**) and TDMA schemes.

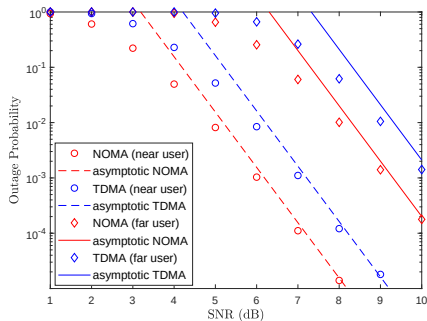
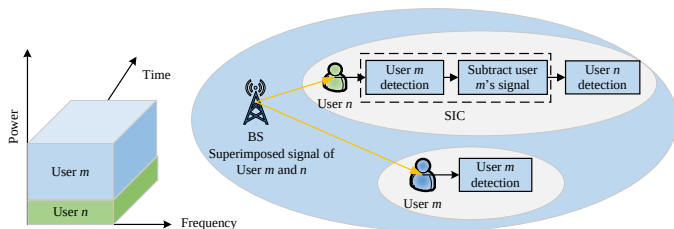


Fig.: Outage probability for 4-element continuous phase shift dynamic RIS scenario under NOMA (**dynamic**) and TDMA schemes.

Power-Domain NOMA Basics



- 1 Supports multiple access within a given resource block (time/frequency/code), using **different power levels** for distinguishing/separating them [1].
- 2 Apply successive interference cancellation (SIC) at the receiver for separating the NOMA users [2].
- 3 If their power is similar, PIC is a better alternative.

[1] Y. Liu et al., "Non-Orthogonal Multiple Access for 5G", *Proceedings of the IEEE*; Dec 2017. ([Web of Science Hot paper](#))

[2] Z. Ding, Y. Liu, et al. (2017), "Application of Non-orthogonal Multiple Access in LTE and 5G Networks", *IEEE Communication Magazine*;([Web of Science Hot paper](#)).

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*, accept to appear

<https://arxiv.org/abs/2003.02117>.

New Techniques to Investigate: RIS-NOMA

My procedure

- Step 1: System Modeling, such as channel model (e.g., fading), signal model (e.g., SINR expressions), spatial model.
- Step 2: **Theoretical gains** over existing scheme (e.g., capacity gain from information theoretical perspective).
- Step 3: Find interesting '**spark point**' to study: from simple/ideal case to complex/practical case with existing mature mathematical tools (e.g., convex optimization, stochastic geometry, matching theory, etc).
- Step 4: Ways to more '**practical**' and '**interesting**' scenarios with advanced mathematical tool (e.g., machine learning).

Expected Outcomes

- Step 1: A clean and tidy model to work on with balancing the analysis-complexity tradeoff.
- Step 2: Good capacity gain over existing scheme, such as RIS-NOMA over RIS-OMA, conventional NOMA, etc.
- Step 3: Good insights compared to existing benchmark schemes (power scaling law, diversity, etc.).
- Step 4: Exploit the possible timely interesting results.

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

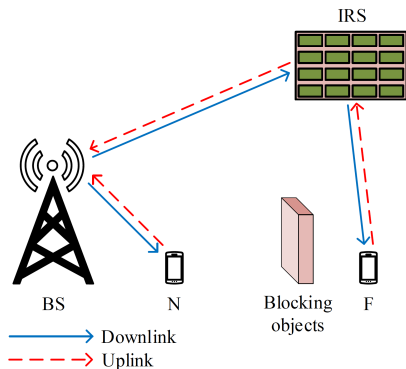


Fig. IRS-aided NOMA system model.

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

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>

Motivation

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

Contributions

- Downlink and uplink IRS-aided 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.

Insights Summary I

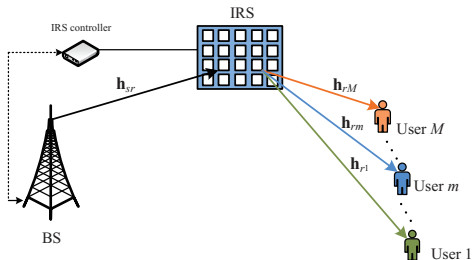
Table: Diversity order and high-SNR slope for each scenario

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", 2020. [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

$$\gamma_{m \rightarrow q} = \frac{\rho |\mathbf{h}_{sr}^H \mathbf{\Theta} \mathbf{h}_{rm}|^2 a_q}{\rho |\mathbf{h}_{sr}^H \mathbf{\Theta} \mathbf{h}_{rm}|^2 \sum_{i=q+1}^M a_i + \varpi \rho |\mathbf{h}_l|^2 + 1}, \quad (6)$$

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

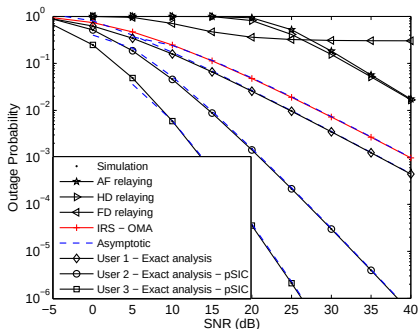
$$\gamma_M = \frac{\rho |\mathbf{h}_{sr}^H \mathbf{\Theta} \mathbf{h}_{rM}|^2 a_M}{\varpi \rho |\mathbf{h}_l|^2 + 1}. \quad (7)$$

Obtained Remarks Based Outage Probability

- The diversity order of the m -th user with ipSIC for IRS-NOMA is equal to **zero**.
- The diversity orders of the m -th user with pSIC for cases $Q = 1$ and $Q \geq 2$ are **mK** and **mP** , respectively.
- The diversity order of the m -th user are in connection with **the number of reflecting elements of IRS and channel ordering**.

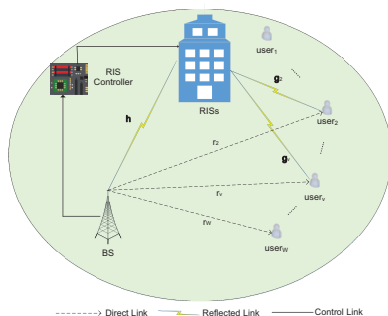
Numerical Results

Outage probability versus the transmit SNR



- The nearest user (User 3) attains the higher diversity order than that of the distant users (User 1)
- IRS-NOMA with pSIC are superior than that of IRS-OMA, variable gain AF relaying, FD relaying and HD relaying.

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



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

Fig.: RIS-aided NOMA Networks.

[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*, accept to appear.

RIS-aided NOMA Networks: Prioritized User

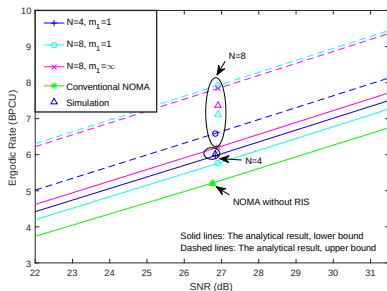


Fig.: Ergodic rate of the prioritized user.

- Passive beamforming design focus on maximizing the prioritized user's received power.

•

$$\begin{aligned}
 & \text{Max}(\mathbf{g}_W \Phi \mathbf{h} + r_W) \\
 & \text{subject to } \beta_1 \cdots \beta_N = 1 \\
 & \theta_1 \cdots \theta_N \in [0, 2\pi).
 \end{aligned} \tag{8}$$

RIS-aided NOMA Networks: Non-prioritized User

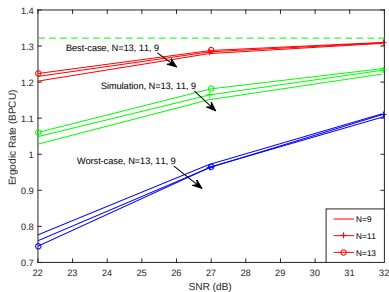


Fig.: Ergodic rate of the non-prioritized user.

- Non-prioritized users share the leaked signals.
- The ergodic rate ceiling exists in the high-SNR regime.
- Passive beamforming has nearly no negative impacts on the non-prioritized user.

NOMA Assisted by Multiple IRSs with Discrete Phase Shifts

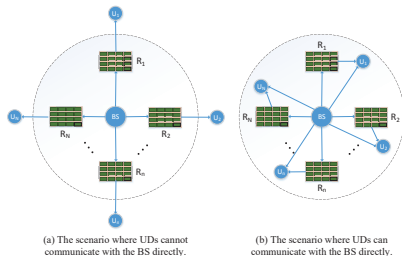


Fig. IRS-aided NOMA system model.

- 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 Transactions on Wireless Communications*, under review.

Theoretical Results I

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

Multiple access scheme	NOMA		OMA	
	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

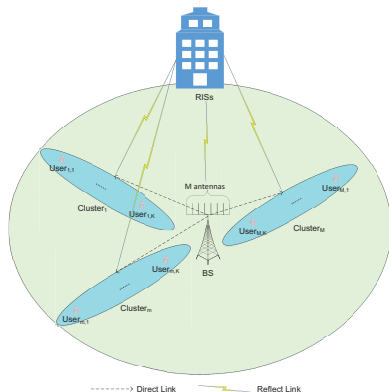


Fig.: RIS-aided MIMO-NOMA networks.

- 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*, accept to appear

<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.

([Web of Science](#) [Hot paper](#))

Stochastic Geometry Based Analysis for RIS-NOMA

1 Motivations of RIS-aided NOMA

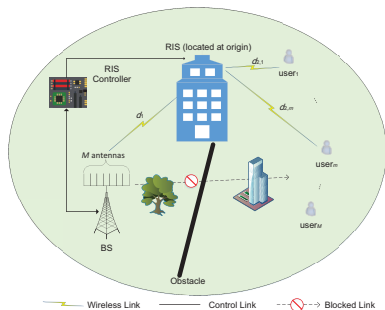
- Investigate the spatial effect of RIS-NOMA in large-scale networks for **practical deployment guideline**.
- Channel quality enhancement: We motivate to exploit RISs to enhance the channel quality of **blocked users**.
- High flexibility on SIC: Achieve **flexible decoding orders** according to the 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>.

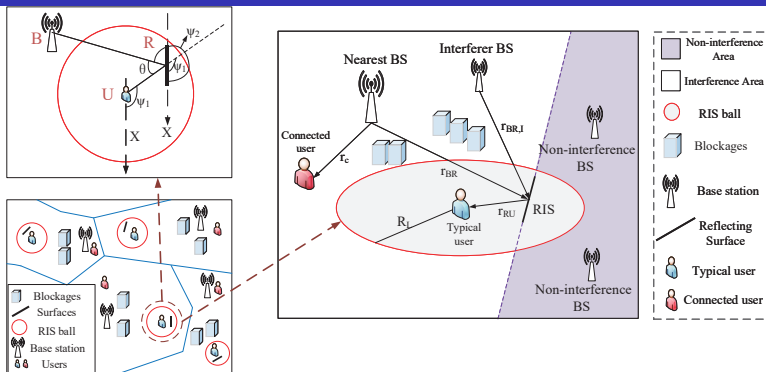
Stochastic Geometry Based Analysis: MIMO-RIS Single Cell



- 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

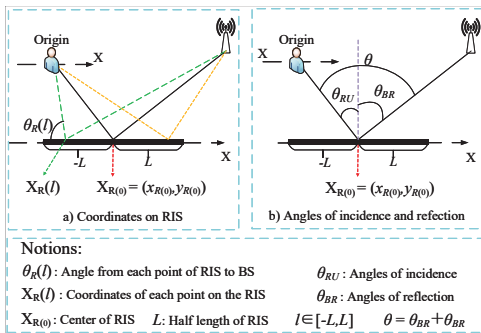


- Light-of-sight (LoS) ball model: blocked typical user.
- Matern cluster process (MCP) pattern of **Poisson Cluster Process (PCP)**: 1) BSs (parent point process) and users are modeled according to two independent homogeneous Poisson point processes (HPPPs); 2) A RIS (daughter point process) is uniformly 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: $\Psi(x) = \frac{\cos(\theta_{BR}(l)) + \cos(\theta_{RU}(l))}{8\pi\sqrt{r_{BR}(l)r_{RU}(l)}}$.
 - Phase-shift function: $\Omega(x) = r_{BR}(l) + r_{RU}(l) - \Theta(l)$.

Numerical Results

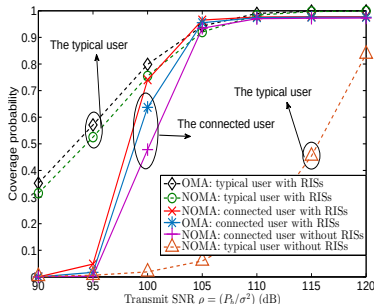


Fig.: A comparison: conventional NOMA, RIS-OMA and RIS-NOMA..

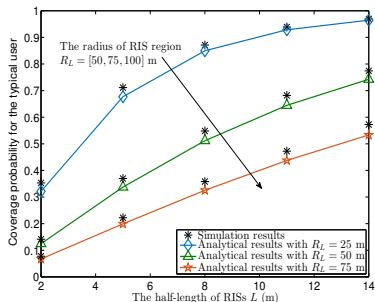


Fig.: Performance versus the half-length of RISs L .

- The achievable rates reach an **upper limit** when the length of RISs increases.

- The condition $L \rightarrow \infty$ holds: $S = \lim_{L \rightarrow \infty} \frac{E[R_t^{RIS}]|_{L \rightarrow \infty}}{\log(L)} = 0$.

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>.

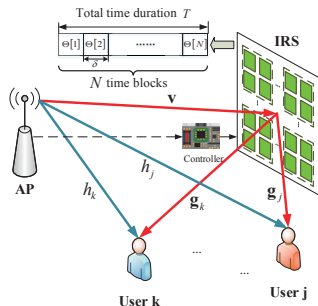
Capacity Characterization for IRS-aided Multi-user System: An Information Theoretic Perspective

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, $\{h_k, \mathbf{g}_k^H, \mathbf{v}, n \in \mathcal{N}\}$. (e.g., users are static or moving slowly).
- An *artificial varying channel* can be created by dynamically reconfiguring the IRS, i.e., $h_k + \mathbf{g}_k^H \Theta[n] \mathbf{v}, n \in \mathcal{N}$.
- 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., $\{h_k[i], \mathbf{g}_k^H[i], \mathbf{v}[i], i \in \mathcal{I}\}$.
- *Dynamic IRS Configuration* ($T \approx \delta$): The IRS can be reconfigured for each fading state i , the effective channel is $h_k[i] + \mathbf{g}_k^H[i] \Theta[i] \mathbf{v}[i], i \in \mathcal{I}$.
- *One-time IRS Configuration* ($T \ll \delta$): All fading states share the same IRS reflection matrix, the effective channel is $h_k[i] + \mathbf{g}_k^H[i] \Theta \mathbf{v}[i], i \in \mathcal{I}$.

[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 n th time block is given by

$$R_k^N[n] = \log_2 \left(1 + \frac{|h_k + \mathbf{g}_k^H \mathbf{\Theta}[n] \mathbf{v}|^2 p_k[n]}{\sum_{\mu_i[n] > \mu_k[n]} |h_k + \mathbf{g}_k^H \mathbf{\Theta}[n] \mathbf{v}|^2 p_i[n] + \sigma^2} \right). \quad (9)$$

The average achievable rate of user k over the entire period T is

$$\bar{R}_k^N = \frac{1}{N} \sum_{n=1}^N R_k^N[n].$$

- The capacity region achieved by NOMA is defined as

$$\mathcal{C}(b, N) \triangleq \bigcup_{\{\mathbf{\Theta}[n], p_k[n]\} \in \mathcal{X}^N} \left\{ \bar{\mathbf{r}} : 0 \leq \bar{r}_k \leq \bar{R}_k^N, \forall k \right\}, \quad (10)$$

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.

Capacity Region Characterization: Optimal Resource Allocation

The *Pareto boundary* of the capacity region can be characterized by solving a series of sum rate maximization problems as follows:

$$(P1) : \max_{R^N, \bar{r}, \{\Theta[n], p_k[n]\}} R^N \quad (11a)$$

$$\text{s.t. } \bar{r}_k \geq \alpha_k R^N, \forall k, \quad (11b)$$

$$\Theta[n] \in \mathcal{S}, \forall n, \quad (11c)$$

$$\sum_{k=1}^K p_k[n] \leq P_{\max}, \forall n, \quad (11d)$$

$$p_k[n] \geq 0, \forall k, n, \quad (11e)$$

$$\left| h_k + \mathbf{g}_k^H \Theta[n] \mathbf{v} \right|^2 \geq \left| h_j + \mathbf{g}_j^H \Theta[n] \mathbf{v} \right|^2, \text{ if } \mu_j[n] < \mu_k[n] \forall k, j, n, \quad (11f)$$

where $\alpha = [\alpha_1, \alpha_2, \dots, \alpha_K]$ denote a rate-profile vector, α_k represents the rate allocation among the K users, $\sum_{k=1}^K \alpha_k = 1$ and $\alpha_k \geq 0, \forall k$.

Ideal Case versus General Case

Ideal case, $N \rightarrow \infty$:

- (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 $\Theta[n]$ based on the obtained solutions in ideal case.
- Under given $\Theta[n]$, 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, $N \rightarrow \infty$

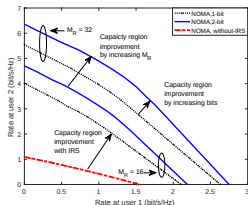


Fig.: Capacity region using NOMA.

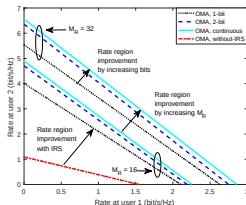


Fig.: Rate region using OMA.

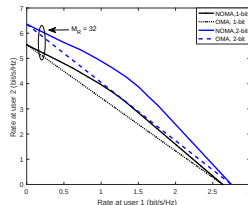


Fig.: Comparison between NOMA and OMA.

- 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

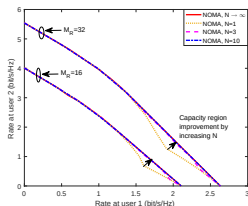


Fig.: Capacity region (inner bound) using NOMA.

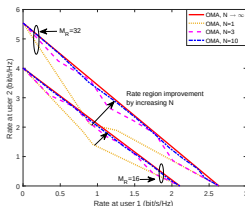


Fig.: Rate region (inner bound) using OMA.

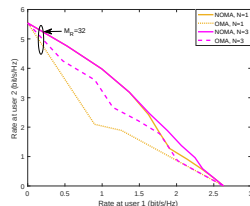
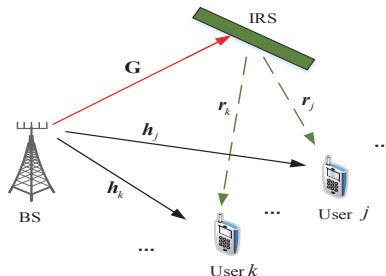


Fig.: Comparison between NOMA and OMA.

- 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
- $\Theta = \text{diag}(\mathbf{u}) \in \mathbb{C}^{M \times M}$ denotes the diagonal reflection coefficients matrix of the IRS with $\mathbf{u} = [u_1, u_2, \dots, u_M]$ 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*, accept <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.

IRS elements assumptions

- **Ideal IRS:** Both the reflection amplitudes and phase shifts can be optimized.

$$\Phi_1 = \{u_m || u_m|^2 \in [0, 1]\} . \quad (12)$$

- **Non-ideal IRS:**

- Continuous phase shifters with the unit modulus constraint.

$$\Phi_2 = \{u_m || u_m|^2 = 1, \theta_m \in [0, 2\pi)\} . \quad (13)$$

- Discrete phase shifters with B resolution bits:

$$\Phi_3 = \{u_m || u_m|^2 = 1, \theta_m \in \mathcal{D}\} , \quad (14)$$

where $\mathcal{D} = \{\frac{n2\pi}{2^B}, n = 0, 1, 2, \dots, 2^B - 1\}$.

Received Signal Model

- The received signal at user k can be expressed as

$$y_k = (\mathbf{h}_k^H + \mathbf{r}_k^H \Theta \mathbf{G}) \sum_{k=1}^K \mathbf{w}_k s_k + n_k, \quad (15)$$

- Based on the NOMA principle, the received **SINR** of user j to decode user k is given by

$$\text{SINR}_{k \rightarrow j} = \frac{|\left(\mathbf{h}_j^H + \mathbf{r}_j^H \Theta \mathbf{G}\right) \mathbf{w}_k|^2}{\sum_{\Omega(i) > \Omega(k)} \left|\left(\mathbf{h}_j^H + \mathbf{r}_j^H \Theta \mathbf{G}\right) \mathbf{w}_i\right|^2 + \sigma^2}. \quad (16)$$

- The corresponding decoding rate is $R_{k \rightarrow j} = \log_2 (1 + \text{SINR}_{k \rightarrow j})$.
- Conditions of successful SIC:** $R_{k \rightarrow j} \geq R_{k \rightarrow k}$ for $\Omega(j) > \Omega(k)$.

Optimization Problem

The considered sum rate maximization problem:

$$(P1) : \max_{\Omega, \Theta, \{\mathbf{w}_k\}} \sum_{k=1}^K R_{k \rightarrow k} \quad (17a)$$

$$\text{s.t. } R_{k \rightarrow j} \geq R_{k \rightarrow k}, \Omega(j) > \Omega(k), \quad (17b)$$

$$\left| (\mathbf{h}_k^H + \mathbf{r}_k^H \Theta \mathbf{G}) \mathbf{w}_{\Omega(i)} \right|^2 \leq \left| (\mathbf{h}_k^H + \mathbf{r}_k^H \Theta \mathbf{G}) \mathbf{w}_{\Omega(j)} \right|^2, \forall k, i, j, \Omega(i) > \Omega(j), \quad (17c)$$

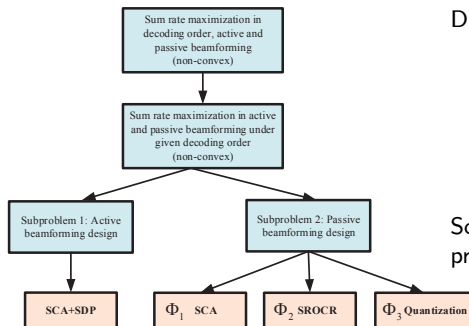
$$\sum_{k=1}^K \|\mathbf{w}_k\|^2 \leq P_T \quad (17d)$$

$$u_m \in \Phi, \quad (17e)$$

$$\Omega \in \Pi. \quad (17f)$$

- Φ denotes different IRS assumptions.
- Π denotes the set of all possible SIC decoding orders.

Proposed Solutions



Difficulties:

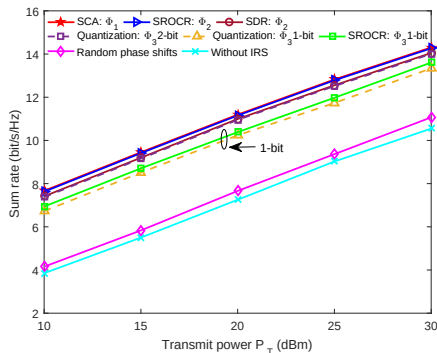
- Decoding order and beamforming vectors are **highly coupled**.
- Active and passive beamforming vectors both affect the conditions of success SIC.

Solutions: Divide the complicated problem into some ease of subproblems.

[1] X. Mu, Y. Liu, L. Guo, J. Lin, N. Al-Dhahir "Exploiting Intelligent Reflecting Surfaces in NOMA Networks: Joint Beamforming Optimization", *IEEE Transactions on Wireless Communications*, <https://arxiv.org/abs/1910.13636>.

Numerical Results

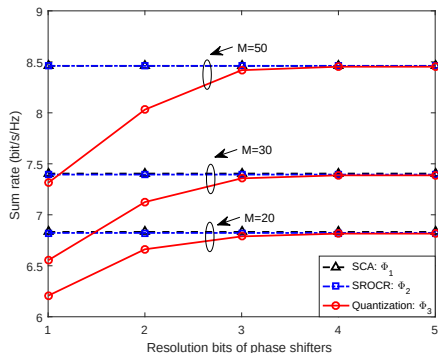
Sum Rate versus Transmit Power



- Significant sum rate gains can be achieved by deploying IRSs with the proposed algorithms.
- The performance gaps between the case of ideal IRS and continuous phase shifters can be ignored.
- The performance degradation caused by finite resolution phase shifters decreases as the bit resolution increases.

Numerical Results

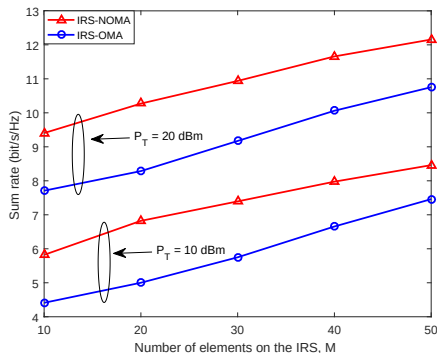
Sum Rate versus the Resolution Bits



- The ideal IRS case achieves the best performance, while the discrete phase shifters case achieves the worst performance.
- “1-bit” and “2-bit” schemes can achieve 80% and 90% performance of the ideal IRS case, respectively.
- The performance loss between the “3-bit” scheme and the ideal IRS is negligible.

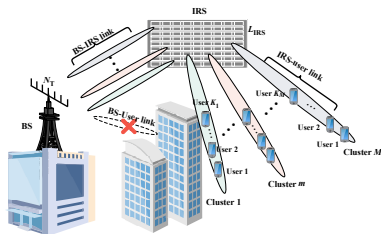
Numerical Results

Performance Comparison with OMA



- The IRS-NOMA scheme significantly outperforms the IRS-OMA scheme since all users can be served simultaneously through the NOMA protocol compared with the OMA scheme.

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:

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

- 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*, **Accepted**.

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

Received Signal Model for Cluster Based Design

- The signal received at user k in cluster m is

$$\begin{aligned}
 y_{m,k} = & \underbrace{\mathbf{h}_{m,k} \mathbf{w}_m \sqrt{p_{m,k}} x_{m,k}}_{\text{desired signal}} + \underbrace{\mathbf{h}_{m,k} \mathbf{w}_m \sum_{i \in \{\mathcal{K}_m/k\}} \sqrt{p_{m,i}} x_{m,i}}_{\text{intra-cluster interference}} \\
 & + \underbrace{\mathbf{h}_{m,k} \sum_{n \in \{\mathcal{M} \setminus m\}} \mathbf{w}_n \sum_{j \in \mathcal{K}_n} \sqrt{p_{n,j}} x_{n,j}}_{\text{inter-cluster interference}} + \underbrace{n_{m,k}}_{\text{noise}},
 \end{aligned} \tag{18}$$

- For any two users with the decoding order $\mathfrak{D}_m(j) > \mathfrak{D}_m(k)$, the SINR of user j to decode user k is defined as

$$\gamma_{j \rightarrow k}^m = \frac{|\mathbf{h}_{m,j} \mathbf{w}_m|^2 p_{m,k}}{|\mathbf{h}_{m,j} \mathbf{w}_m|^2 P_{m,k} + \sum_{n \in \{\mathcal{M} \setminus m\}} |\mathbf{h}_{m,j} \mathbf{w}_n|^2 + \sigma^2}, \tag{19}$$

Optimization Problem Formulation

The joint active beamforming, passive beamforming and power allocation optimization problem is formulated as

$$\max_{\theta_l, \mathbf{w}_m, p_{m,k}} \sum_{m \in \mathcal{M}} R_{m,K_m}, \quad (20a)$$

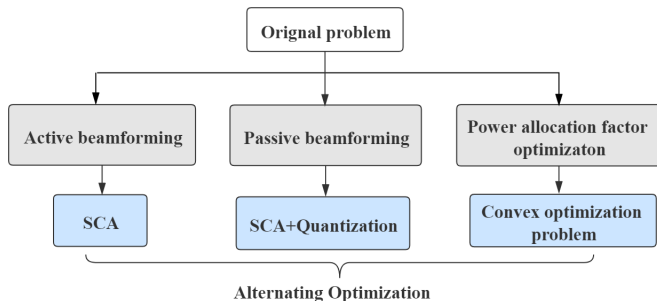
$$s.t. \sum_{m \in \mathcal{M}} \|\mathbf{w}_m\|_2^2 \leq P_{\max}, \quad (20b)$$

$$\sum_{k \in \mathcal{K}_m} p_{m,k} = 1, m \in \mathcal{M}, \quad (20c)$$

$$\theta_l \in \left\{ 0, \frac{2\pi}{2^B}, \dots, \frac{2\pi(2^B - 1)}{2^B} \right\}, \quad (20d)$$

$$\min_{j \in \{k, \dots, K_m\}} \log_2(1 + \gamma_{j \rightarrow k}^m) \geq R_{m,k}^{\min}, \quad (20e)$$

Proposed Algorithms



The main challenges to solve the optimization problem

- It is a mixed integer non-linear (MINL) optimization problem.
- The decoding order can be affected by the inter-cluster interference and be controlled by the IRS.
- The optimization variables are **highly coupled**.

Numerical Results

Sum rate for IRS-mmWave-NOMA networks

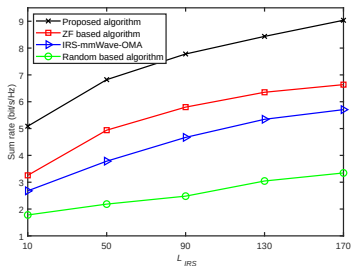


Fig.: Sum rate versus the number of reflecting elements

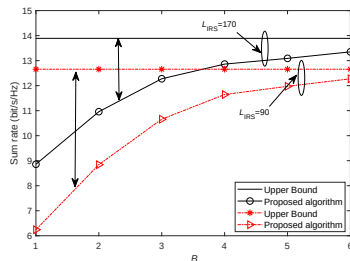
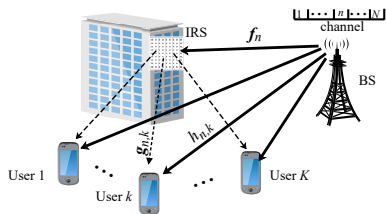


Fig.: Sum rate versus the resolution bits.

- The proposed IRS-mmWave-NOMA outperforms the IRS-mmWave-OMA design.
- The system sum rate gap between the continuous and discrete phase shifts gradually decreases as the resolution bits increases.

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.

- $\Theta = \text{diag} \{ \lambda_1 e^{j\theta_1}, \lambda_2 e^{j\theta_2}, \dots, \lambda_M e^{j\theta_M} \}$
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, Accepted*.

Optimization Problem Formulation

The optimized problem is given as

$$\max_{\delta, \pi, \mathbf{p}, \Theta} \sum_{n=1}^N \sum_{k=1}^K R_{n,k}, \quad (21a)$$

$$\text{s.t. } R_{n, \bar{k} \rightarrow k} \geq R_{n, k \rightarrow k}, \text{ if } \pi_n(k) \leq \pi_n(\bar{k}), \quad (21b)$$

$$R_{n, k \rightarrow k} \geq R_{\min}, \quad n \in \mathcal{N}, \quad (21c)$$

$$\sum_{n=1}^N \sum_{k=1}^K \delta_{n,k} p_{n,k} \leq P_{\max}, \quad (21d)$$

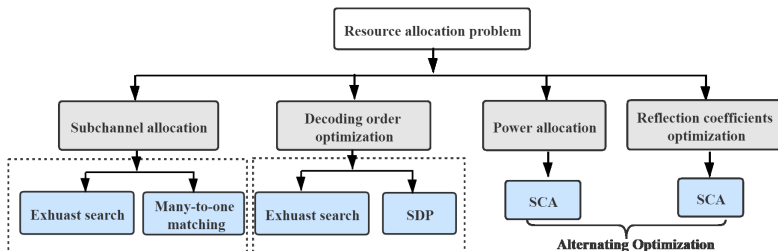
$$|\Theta_{m,m}| \leq 1, \quad (21e)$$

$$\sum_{k=1}^K \delta_{n,k} = K_n, \quad (21f)$$

$$\sum_{n=1}^N \delta_{n,k} = 1, \quad (21g)$$

$$\pi_n \in \Omega. \quad (21h)$$

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

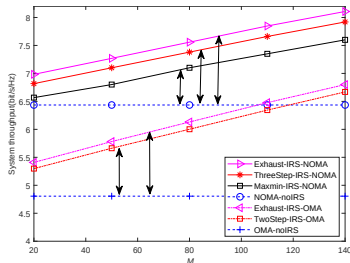


Fig.: System throughput versus the number of reflecting elements.

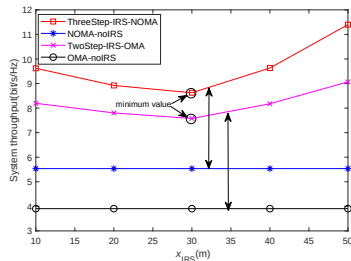


Fig.: System throughput versus the location of IRS coordinate.

- In comparison with OMA based algorithms, the NOMA based algorithms yield a significant performance gain and **near-optimal** performance.
- There is an **optimal deployment point** for IRS, which motivates us to investigate the deployment of IRS [1].

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

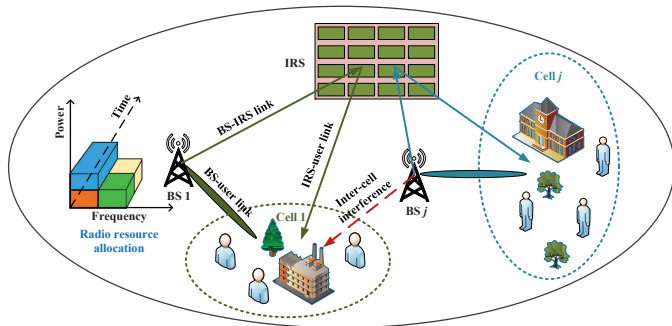


Fig.: An illustration of the system model for the IRS-aided multi-cell NOMA network, where an IRS with M reflecting elements is deployed to assist the wireless communication from J single-antenna BSs to I single-antenna users.

[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

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

$$x_{jk} = \underbrace{\alpha_{ij}\beta_{jk}\sqrt{p_{ijk}}x_{ijk}}_{\text{signal for user } i} + \underbrace{\sum_{t=1, t \neq i}^I \alpha_{tj}\beta_{jk}\sqrt{p_{tjk}}x_{tjk}}_{\text{signal for other paired users}}, \quad (22)$$

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: Problem Formulation

- The **sum-rate maximization** problem can be formulated as

$$\text{var} \quad \{\alpha_{ij}, \beta_{jk}, \Theta, p_{ijk}, \pi_{jk}(i) \mid \forall i, j, k\}, \quad (23a)$$

$$\max \quad \sum_{i=1}^I \sum_{j=1}^J \sum_{k=1}^K R_{ijk}, \quad (23b)$$

$$\text{s.t.} \quad \Delta_{jk}(i, \tilde{i}) \geq 0, \text{ if } \pi_{jk}(i) \leq \pi_{jk}(\tilde{i}), \quad (23c)$$

$$\sum_{j=1}^J \sum_{k=1}^K R_{ijk} \geq R_{\min}, \quad \forall i, \quad (23d)$$

$$\sum_{i=1}^I \sum_{k=1}^K P_{ijk} \leq P_{\max}, \quad \forall j, \quad (23e)$$

$$\sum_{j=1}^J \alpha_{ij} = 1, \quad \forall i, \quad 2 \leq \sum_{i=1}^I \alpha_{ij} \leq A_{\max}, \quad \forall j, \quad (23f)$$

$$\sum_{k=1}^K \beta_{jk} \geq 1, \quad \forall j, \quad \sum_{j=1}^J \beta_{jk} \geq 1, \quad \forall k, \quad (23g)$$

$$\alpha_{ij}, \beta_{jk} \in \{0, 1\}, \quad \forall i, j, k, \quad \theta_m \in [0, 2\pi], \quad \forall m, \quad (23h)$$

$$p_{ijk} \geq 0, \quad \forall i, j, k, \quad \pi_{jk} \in \Omega, \quad \forall j, k. \quad (23i)$$

IRS-Aided Multi-Cell NOMA Networks: Solution Design

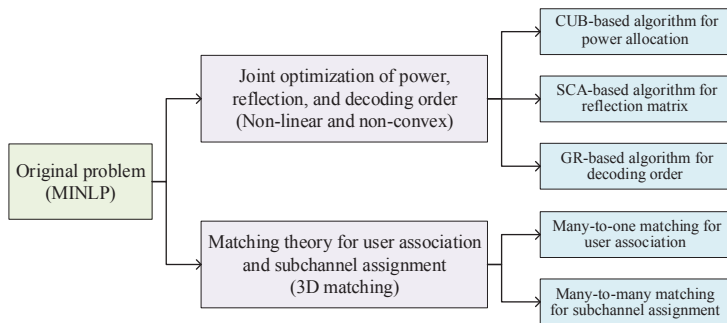


Fig.: A roadmap for problem decomposition and proposed algorithms.

[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-Aided Multi-Cell NOMA Networks: Numerical Results

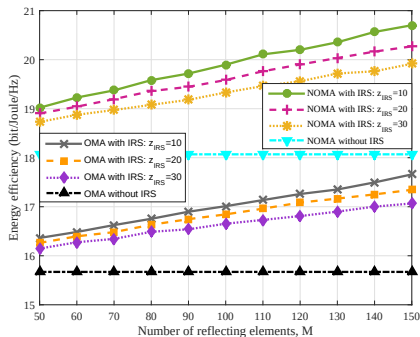
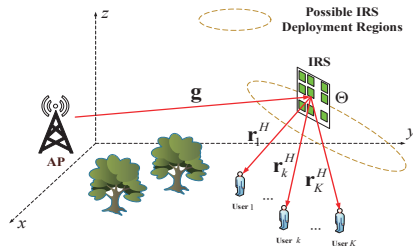


Fig.: Energy efficiency vs. M .

- NOMA-IRS outperforms OMA-IRS (one-time configuration).
- The IRS-aided NOMA and OMA networks are capable of enjoying higher energy efficiency than the conventional NOMA and OMA schemes, respectively.

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 k th 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*, under review, <https://arxiv.org/abs/2005.11544>.

System Model for Deployment

- For small scale fading, the AP-IRS link and the IRS-user links are modeled as Rician fading channels.
- For large scale fading, the path loss $L_{IRS,k}$ between the AP and user k via the IRS is given by

$$L_{IRS,k} = \frac{\rho_0}{d_{AI}^{\alpha_{AI}}} \frac{\rho_0}{d_{IU,k}^{\alpha_{IU}}}, \quad (24)$$

which follows the **product-distance path loss model**.

- The combined channel power gain of user k can be expressed as

$$c_k = L_{IRS,k} |\mathbf{r}_k^H \Theta \mathbf{g}|^2 = |\mathbf{q}_k \mathbf{v}|^2, \quad (25)$$

which is determined by **the IRS reflection coefficient** and **deployment location**.

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

$$R_k^N = \log_2 \left(1 + \frac{|\mathbf{q}_k \mathbf{v}|^2 p_k}{|\mathbf{q}_k \mathbf{v}|^2 \sum_{\mu(i) > \mu(k)} p_i + \sigma^2} \right), \quad (26)$$

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

$$R_k^F = \frac{1}{K} \log_2 \left(1 + \frac{|\mathbf{q}_k \mathbf{v}|^2 p_k}{\frac{1}{K} \sigma^2} \right). \quad (27)$$

- **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**.

$$R_k^T = \frac{1}{K} \log_2 \left(1 + \frac{|\mathbf{q}_k \mathbf{v}_k|^2 P_{\max}}{\sigma^2} \right), \quad (28)$$

Optimization Problem

If NOMA is employed, the weighted sum rate (WSR) maximization problem is formulated as follows

$$\text{(NOMA)} : \max_{\{p_k\}, \mathbf{v}, \mathbf{s}} \sum_{k=1}^K w_k R_k^N \quad (29a)$$

$$\text{s.t. } \mathbf{s} \in \Omega, \quad (29b)$$

$$|\mathbf{v}_m| = 1, \forall m \in \mathcal{M}, \quad (29c)$$

$$\mu(k) \in \mathcal{D}, \forall k \in \mathcal{K}, \quad (29d)$$

$$|\mathbf{q}_k \mathbf{v}|^2 \geq |\mathbf{q}_j \mathbf{v}|^2, \text{ if } \mu(k) > \mu(j), \quad (29e)$$

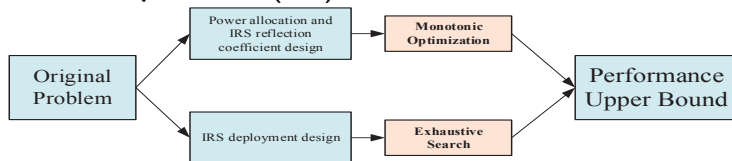
$$0 \leq p_k \leq p_j \text{ if } \mu(k) > \mu(j), \quad (29f)$$

$$\sum_{k=1}^K p_k \leq P_{\max}, \quad (29g)$$

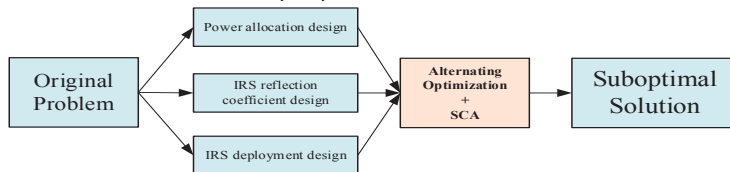
- w_k is the non-negative rate weight for user k .
- Ω denotes possible IRS deployment regions.
- $\mathcal{D}$ denotes all possible decoding order combinations.

Proposed Solutions

- **Monotonic Optimization (MO)-based solution:**



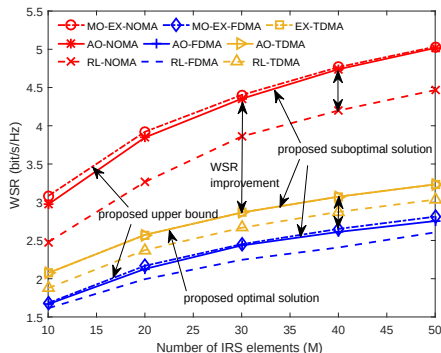
- **Alternating Optimization (AO)-based solution:**



[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*, under review, <https://arxiv.org/abs/2005.11544>.

Numerical Results: Performance for NOMA, TDMA and FDMA

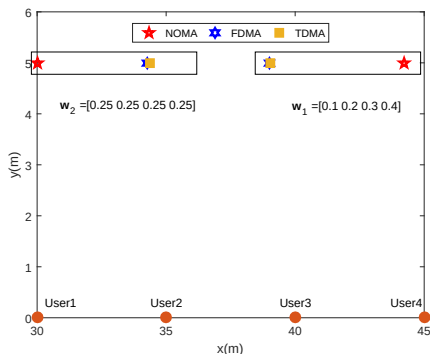
WSR versus the number of IRS elements



- 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

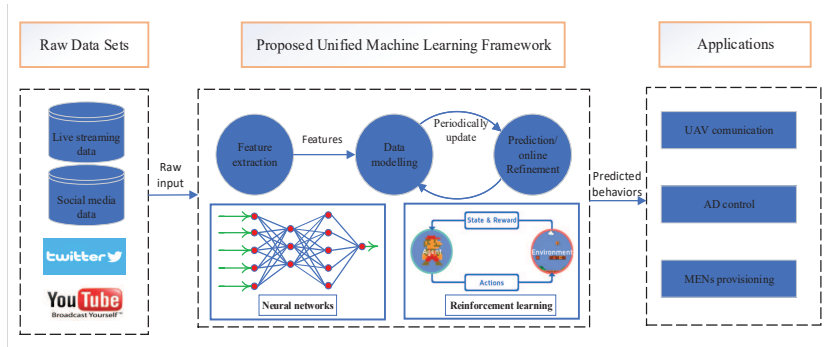


Fig.: Artificial intelligent algorithms for wireless communications.

[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

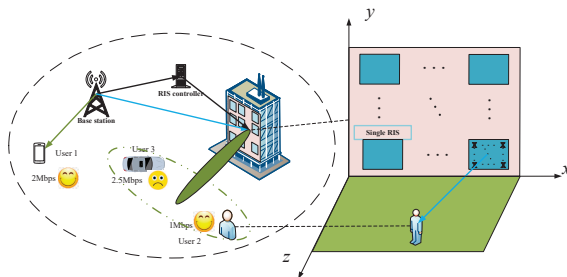
■ Before Problem formulation

- 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>.

ML Enabled IRS Deployment with Heterogenous QoS Requirements

Long-term energy efficiency is defined as the ratio between the system achievable **sum mean-of-sight (MOS)** and the sum energy dissipation in Joule,

$$\bar{\eta}_{EE} = \frac{1}{T} \sum_{t=0}^T \left\{ \frac{\sum_{l=1}^L [Q_{l,a}(t) + Q_{l,b}(t)]}{P} \right\}. \quad (30)$$

The total amount of **power consumption** is given by

$$P = \sum_{l=1}^L \left(\|\mathbf{w}_{l,a}\|^2 + \|\mathbf{w}_{l,b}\|^2 \right) + KP_{\text{MU}} + P_{\text{BS}} + NP_n, \quad (31)$$

where P_{MU} denotes the hardware energy dissipated in the k -th MU device, while P_{BS} and P_{IRS} represent the total hardware energy dissipated at the BS and the power dissipation at the IRS, respectively.

Optimization Problem

The energy efficiency maximization problem is formulated as follows

$$\max_{\theta, P, \pi, C} \bar{\eta}_{EE} \quad (32a)$$

$$\text{s.t.} \quad R_{l,i}(t) \geq R_{\min}^{l,i}(t), \forall k, \forall l, \forall i \in \{a, b\}, \quad (32b)$$

$$|\phi_n(t)| = 1, \forall n, \quad (32c)$$

$$c_l^I \in c_m^O, \forall l, \forall m, \quad (32d)$$

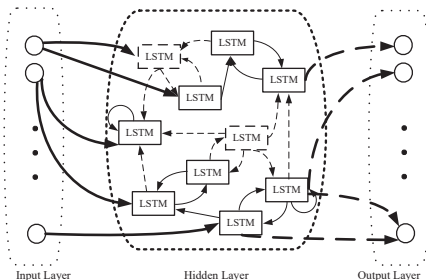
$$R_{l,b \rightarrow l,a}(t) \geq R_{l,b \rightarrow l,b}(t), \pi_l(a) \geq \pi_l(b), \forall l, \quad (32e)$$

$$\sum_{l=1}^L (\|\mathbf{w}_{l,a}\|^2 + \|\mathbf{w}_{l,b}\|^2) \leq P_{\max}, \forall k, \quad (32f)$$

- $R_{\min}^{l,i}(t)$ denotes the **time-variant heterogenous QoS requirements**.
- (32e) represents the **dynamic decoding order** constraint.

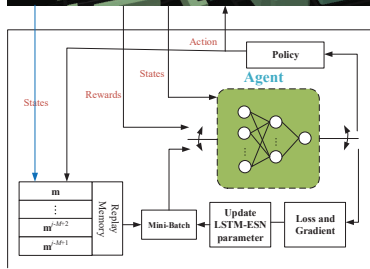
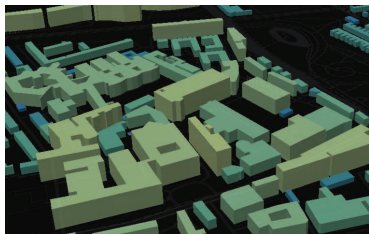
LSTM-based ESN Algorithm for Predicting the Data Traffic Density

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



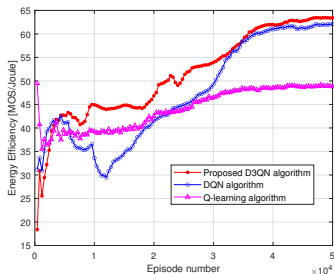
A recurrent neural network model based on the architecture of an echo state networks (ESN) model using hidden neurons long-short-term-memory (LSTM) units.

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

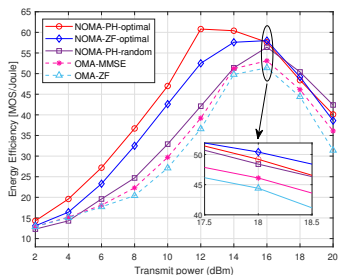


- D^3QN model **incorporate farsighted system evolution** instead of just optimizing current benefits.
- D^3QN model can update decision policies timely
 - learn from the **environment**
 - learn from the **users**
 - learn from the **historical experience**

Numerical Results

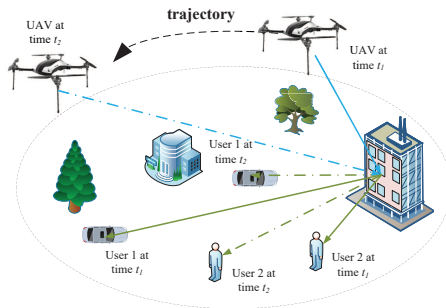


- The proposed D³QN algorithm outperforms the DQN algorithm and Q-learning algorithm due to the advantage of invoking the **double Q-learning** concept and **decaying ϵ -greedy policy**.



- The NOMA-assisted IRS system is capable of obtaining **better performance** in terms of energy efficiency compared to the OMA-assisted IRS system.

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*, **major revision**, <https://arxiv.org/pdf/2010.02749.pdf>.

Problem Formulation

$$\min_{\theta, P, Q} E_{\text{UAV}} = \sum_{t=0}^T \bar{E}(t) \quad (33a)$$

$$\text{s.t.} \quad R_k(t) \geq R_k^{\min}, \forall k, \forall t, \quad (33b)$$

$$|\phi_n(t)| = 1, \forall n, \forall t, \quad (33c)$$

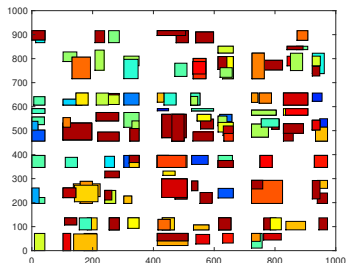
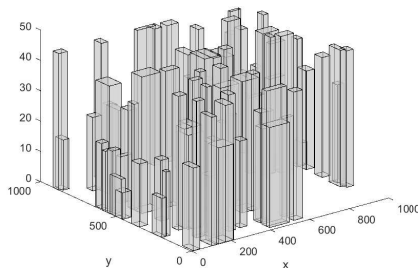
$$x_{\min} \leq x_{\text{UAV}}(t) \leq x_{\max}, y_{\min} \leq y_{\text{UAV}}(t) \leq y_{\max}, \forall t, \quad (33d)$$

$$R_{l,b \rightarrow l,a}(t) \geq R_{l,b \rightarrow l,b}(t), \pi_l(a) \geq \pi_l(b), \forall l, \quad (33e)$$

$$\text{tr} \left(\mathbf{P} \left(\mathbf{H}^H \mathbf{H} \right)^{-1} \right) \leq P_{\max}, \forall k, \forall t, \quad (33f)$$

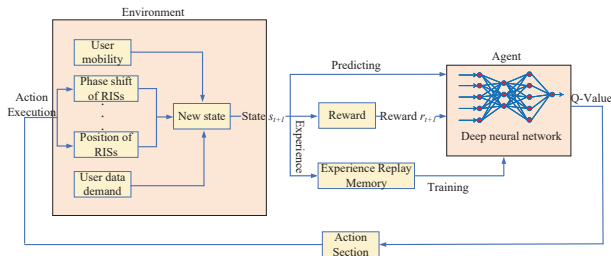
- (33b) denotes that the data demand of all mobile users has to be satisfied at each timeslot.
- (33b) formulates the altitude bound of UAVs, which indicates that the UAV can only move in this particular area.
- (33e) represents the **dynamic decoding order** constraint.

3D Radio Map of a dense urban area for UAVs



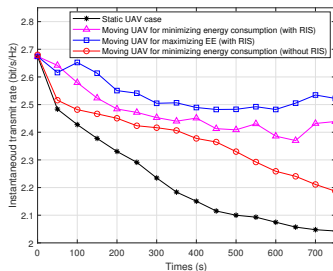
We model the urban city environment as a set of **buildings**, where each building is modeled as a set of **cubes**.

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

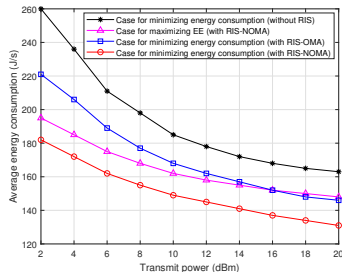


- Maximizing the **long-term discounted rewards**.
- Learning the optimal policy via Q-learning by **updating Q-values** at each timeslot.
- Combining conventional Q-learning with **neural network** for approximating Q-table.
- Striking a balance between the exploration and exploitation by **ϵ -greedy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

Numerical Results



- With the aid of the IRS, a **higher transmit rate** can be achieved at each timeslot than the case of without IRS.



- With the aid of the IRS, the energy consumption of the UAV is **reduced**. The IRS-NOMA case outperforms the IRS-OMA case in terms of energy consumption.

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 beamforming 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?

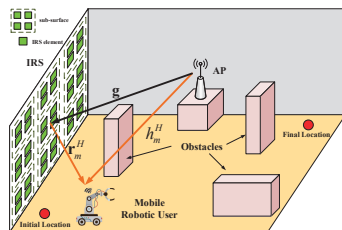
Move to Indoor: IRS-enhanced Indoor Robot Path Planning

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.

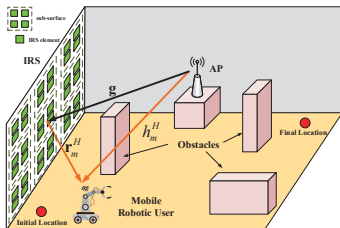


[1] X. Mu, Y. Liu, L. Guo, J. Lin, R. Schober "Intelligent Reflecting Surface Enhanced Indoor Robot Path Planning: A Radio Map based Approach", *IEEE Transactions on Wireless Communications, under review*, <https://arxiv.org/abs/2009.12804>.

System Model

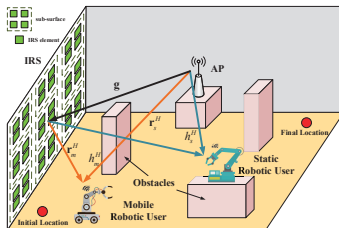
Single-user scenario

- One mobile robotic user communicates with the AP using a dedicated resource block.



Multiple-user scenario

- One *mobile* and one *static* robotic user simultaneously communicates with the AP employing either NOMA or OMA.



Objective: Minimize the time/distance of the mobile robotic user from an initial to a final location, subject to constraints on the communication quality.

Numerical Examples (multiple-user)

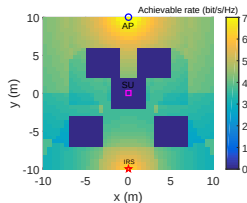


Fig.: Rate map of OMA with IRS.

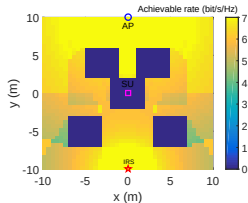


Fig.: Rate map of NOMA with IRS.

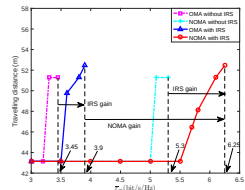


Fig.: Travelling distance versus the required rate target $\bar{r}_m$.

- Significant rate improvement can be achieved by NOMA over OMA.
- The robot travelling distance can be reduced and the maximum rate target can be significantly improved by deploying the IRS and employing NOMA.

IRS Enhanced Federated Learning

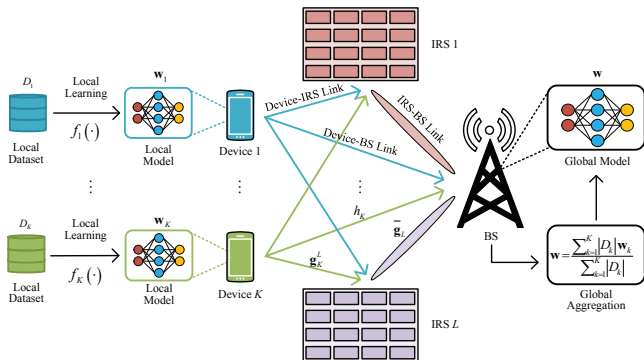
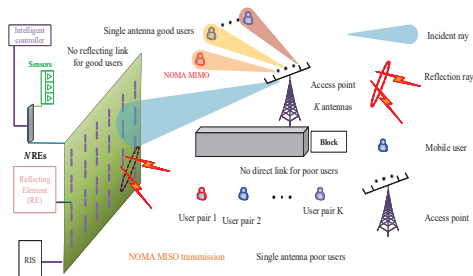


Fig.: An illustration of federated learning in multi-IRS aided system. The objective of FL is to collaboratively train a global machine learning model at the BS while keeping the training dataset processed in a distributed manner to **preserve user privacy**.

RIS-aided NOMA: User Clustering and Long-term Resource Allocation



- A RIS-aided NOMA downlink network.
- $\Theta = \text{diag}(\mathbf{q}) \in \mathbb{C}^{N \times M}$ represents the diagonal reflection coefficients matrix of the RIS with $\mathbf{q} = [q_1, \dots, q_N]$ and $q_n = \beta_n e^{j\theta_n}$.

[1] Z. Yang, Y. Liu, Y. Chen, J. T. Zhou "Deep Reinforcement learning for RIS-Aided Non-Orthogonal Multiple Access Downlink Networks", in Proc. IEEE Global Commun. Conf. (GLOBECOM), 2020

Machine learning for RIS-MIMO-NOMA Networks

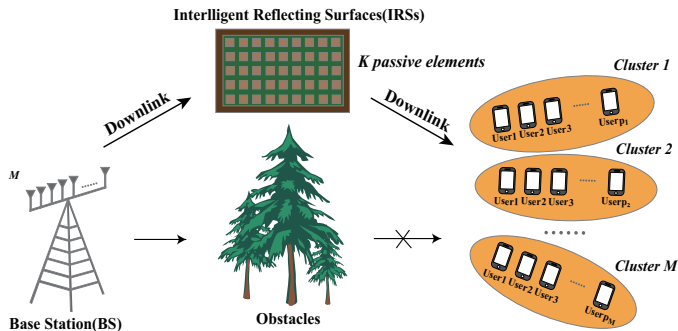


Fig.: Illustration of the IRS-aided MISO-NOMA network.

[1] X. Gao, **Y. Liu**, X. Liu, and Z. Qin, "Resource allocation in IRSs aided MISO-NOMA networks: A Machine Learning Approach," in *Proc. IEEE GLOBECOM*, accepted to appear.

IRS-Aided MISO-NOMA Networks: A Machine learning Approach

- Since the **positions of all users are not determined**, which needs to be predicted at each timeslot. Thus, the conventional non-convex optimization method cannot be applied to handle this difficulty. We consider employing a machine learning method to solve this problem. The main flowchart is shown as follows.

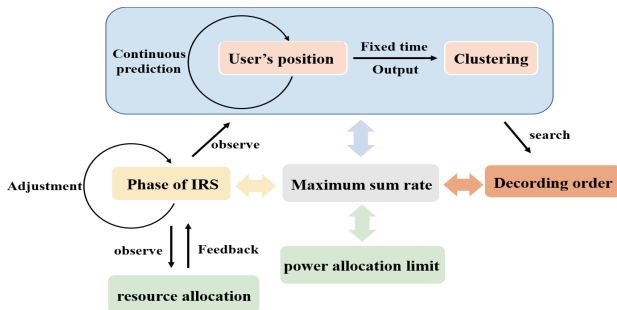


Fig.: Illustration of the IRS-aided MISO-NOMA network.

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!