

Intelligent Massive NOMA towards 6G: what will be different?

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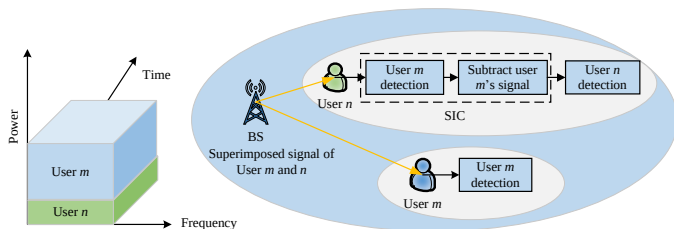
Outline

- 1 Power-Domain NOMA Basics
- 2 Signal Processing Advances for NOMA: A Machine Learning Approach
- 3 Semi-Grant-Free NOMA
- 4 Emerging Applications for NOMA: New Techniques to Investigate

From OMA to NOMA

- 1 **Question:** What is multiple access?
- 2 **Orthogonal multiple access (OMA):** e.g., FDMA, TDMA, CDMA, OFDMA.
- 3 New requirements in beyond 5G
 - Ultra-high spectrum efficiency.
 - Ultra-massive connectivity.
 - Heterogeneous QoS and mobility requirement.
- 4 **Non-orthogonal multiple access (NOMA):** to break orthogonality.
- 5 Standard and industry developments on NOMA
 - **Whitepapers:** DOCOMO, METIS, NGMN, ZTE, SK Telecom, etc.
 - **LTE Release 13:** a two-user downlink special case of NOMA.
 - **Next generation digital TV standard ATSC 3.0:** a variation of NOMA, termed Layer Division Multiplexing (LDM).

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](#)).

Power NOMA Basics

- 1 **Question:** Why NOMA is a popular proposition for beyond 5G?
- 2 Consider the following two scenarios.
 - If a user has poor channel conditions
 - The bandwidth allocated to this user via OMA cannot be used at a high rate.
 - NOMA - improves the bandwidth-efficiency.
 - If a user only needs a low data rate, e.g., IoT, sensor, etc.
 - The use of OMA gives rise to 2 nodes using separate bandwidth.
 - NOMA - improves the bandwidth-efficiency.

[1] 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](#)).

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 - If a user only needs a low data rate, e.g. IoT networks.
 - The use of OMA gives the IoT node more capacity than it needs.
 - NOMA - **heterogeneous QoS and massive connectivity.**

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Power NOMA Basics

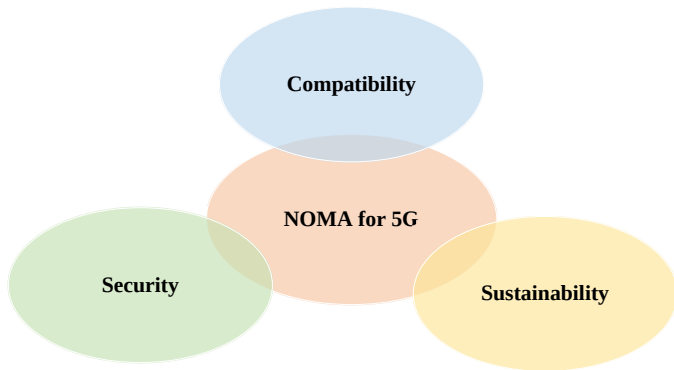
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What will NOMA for 6G be?

*Intelligent (AI) + Massive ((Semi-)Grant-Free) + Nonorthogonal
(Power/Code Domain)+ Compatibility (New techniques/scenarios)*

My Previous Research Contributions in NOMA



<http://www.eecs.qmul.ac.uk/~yuanwei/Publications.html>

Signal Processing Advances for NOMA: A Machine Learning Approach

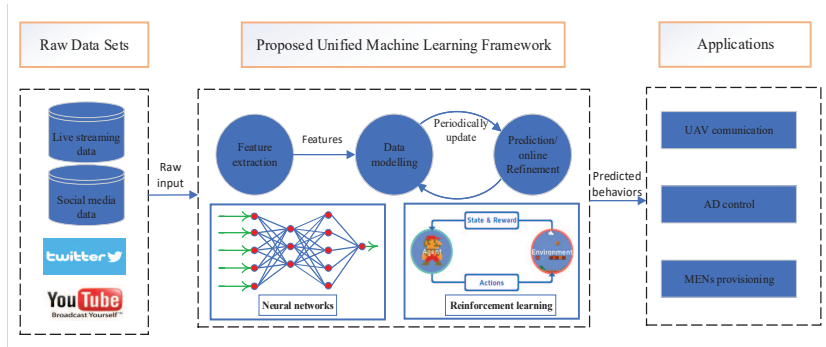


Fig.: Artificial intelligent algorithms for wireless communications.

[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?

Motivation and challenge of AI for NOMA networks

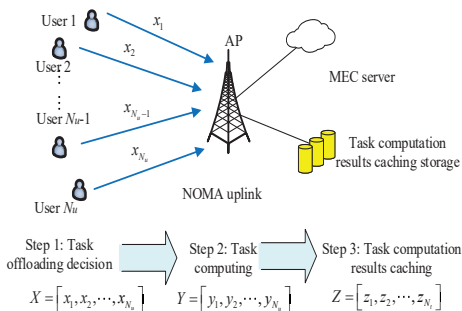
■ Motivation

- **User behavior/peculiarity** is considered
- Dynamic scenario with **heterogenous QoS requirements** and **heterogenous user mobility**
- **Long-term** benefits
- **Interactive** with environment
- Mixed-integer, and non-convex optimization problem

■ Challenges

- The hidden relationship between history and future information has no concrete **mathematical expressions**.
- Resource allocation for massive user and base station (BS) connection has high computational complexity.

Case Study: Cache-Aided NOMA MEC



- Multiple users are served by one MEC server.
- The computation tasks are capable of being computed locally at the mobile devices or in the MEC server.
- The computation results are selectively cached in the storage of the MEC server.

Fig.: An illustration of a multi-user cache-aided MEC.

[1] Z. Yang, **Y. Liu**, Y. Chen, N. Al-Dhahir, "Cache-Aided NOMA Mobile Edge Computing: A Reinforcement Learning Approach", *IEEE Transactions on Wireless Communications*, <https://arxiv.org/abs/1906.08812>.

System Model: Communication Model

The user with higher channel gain is decoded first, the signal-to-interference-plus-noise ratio (SINR) for user i at time t can be given by

$$\mathbf{R}_i(\mathbf{t}) = B \log_2 \left(1 + \frac{\rho_i(t) |h_i(t)|^2}{\sum_{l=i+1}^{N_{up}} \rho_l(t) |h_l(t)|^2 + \sigma^2} \right), \quad (1)$$

Accordingly, the offloading time for task j with input size π_j at time t is

$$\mathbf{T}_{i,j}^{\text{offload}}(\mathbf{t}) = \frac{\pi_j}{\mathbf{R}_i(\mathbf{t})}. \quad (2)$$

Meanwhile, the transmit energy consumption of offloading at time t is given by

$$\mathbf{E}_{i,j}^{\text{offload}}(\mathbf{t}) = \rho_i \frac{\pi_j}{\mathbf{R}_i(\mathbf{t})}. \quad (3)$$

System Model: Computation Model

- **Local Computing:** The computing time $T_{i,j}^{loc}$ and energy consumption $E_{i,j}^{loc}$ for task j with computational requirement ω_j are

$$T_{i,j}^{loc} = \frac{\omega_j}{\omega_i^{loc}}. \quad (4)$$

$$E_{i,j}^{loc} = P_i^{loc} \frac{\omega_j}{\omega_i^{loc}}. \quad (5)$$

- ω_i^{loc} : the local computing capability,
- P_i^{loc} : the energy consumption per second.

- **MEC Computing:** The computing time $T_{i,j}^{mec}(\mathbf{t})$ and energy consumption $E_{i,j}^{mec}(\mathbf{t})$ are

$$T_{i,j}^{mec}(\mathbf{t}) = \frac{\omega_j}{y_i(\mathbf{t}) C_{MEC}}. \quad (6)$$

$$E_{i,j}^{mec}(\mathbf{t}) = P^{mec} \frac{\omega_j}{y_i(\mathbf{t}) C_{MEC}}. \quad (7)$$

- y_i : the proportion of the computing resources allocated from the MEC server,
- P^{mec} : the energy consumption per second at MEC server.

Problem Formulation

The sum energy consumption is

$$\mathbf{E}(t, x_i(t), y_i(t), z_j(t)) = \left(\Pr_i^j (1 - z_j(t)) \left(x_i(t) \mathbf{E}_{i,j}^{\text{loc}} + (1 - x_i(t)) \mathbf{E}_{i,j}^{\text{offload}}(\mathbf{t}) + (1 - y_i(t)) \mathbf{E}_{i,j}^{\text{mec}}(\mathbf{t}) \right) \right). \quad (8)$$

The optimization problem is

$$(\mathbf{P1}) \min_{X,Y,Z} \sum_{t=1}^T \sum_{i=1}^{N_u} \mathbf{E}(t, x_i(t), y_i(t), z_j(t)), \quad (9a)$$

$$\text{s.t. } C_1 : x_i(t) \in \{0, 1\}, \forall i \in [1, N_u], t \in [1, T], \quad (9b)$$

$$C_2 : y_i(t) \in [0, 1], \forall i \in [1, N_u], t \in [1, T], \quad (9c)$$

$$C_3 : z_j(t) \in \{0, 1\}, \forall j \in [1, N_t], t \in [1, T], \quad (9d)$$

$$C_4 : \sum_{i=1}^{N_u} y_i(t) = 1, \forall t \in [1, T], \quad (9e)$$

$$C_5 : \sum_{j=1}^{N_t} z_j(t) \leq C_{\text{cache}}, \forall t \in [1, T], \quad (9f)$$

Resource allocation: From the Formulated Problem to Reinforcement Learning Model

A Markov decision process (MDP) model is a tuple $\langle \mathcal{S}, \mathcal{A}, \mathcal{R} \rangle$.

- 1 **Objective:** maximize the sum reward

$$V_{\pi}(s) = \mathbb{E}_{\pi} \left[\sum_{t=0}^{\infty} \gamma^t r_t \mid s_0 = s \right] \text{ of a trajectory}$$

$$s_0 \xrightarrow{a_1|r_1} s_1 \xrightarrow{a_2|r_2} s_2 \cdots \xrightarrow{a_n|r_n} s_n.$$

- 2 **State space ($\mathcal{S}$):**

$$s(t) = [x(t), y(t), z(t)] \in S = X \times Y \times Z.$$

- 3 **Action space ($\mathcal{A}$):** $a(t) = [\Delta x(t), \Delta y(t), \Delta z(t)] \in A.$

- 4 **Reward function (r):** the sum energy consumption of taking an action on a state

$$r_t = \sum_{i=1}^{N_u} \mathbf{E}_i(t-1, s_{t-1}) - \sum_{i=1}^{N_u} \mathbf{E}_i(t, s_t).$$

How to define State and Action Space? From Maze to the Proposed Framework

- **State Space:** High dimensional matrix related to the parameters in the objective function.
- **Action Space:** Moving granularity in each element of the state space.

	Maze game	UAV trajectory	Proposed Problem
State Space	$s(t) = [x(t), y(t)]$ $\in \mathcal{S} = \mathcal{X} \times \mathcal{Y}$	$s(t) = [x(t), y(t), z(t)]$ $\in \mathcal{S} = \mathcal{X} \times \mathcal{Y} \times \mathcal{Z}$	$s(t) = [x(t), y(t), z(t)]$ $\in \mathcal{S} = \mathcal{X} \times \mathcal{Y} \times \mathcal{Z}$
Action Space	$a(t) = [\Delta x(t), \Delta y(t)]$	$a(t) = [\Delta x(t), \Delta y(t), \Delta z(t)]$	$a(t) = [\Delta x(t), \Delta y(t), \Delta z(t)]$
	2 Dimensional	3 Dimensional	3 Dimensional

Fig.: Setting of state and action space.

Reinforcement Learning Model

The goal of reinforcement learning is to find an optimal policy that maximize the long-term sum rewards:

$$\pi^* = \arg \max_{\pi} \mathbb{E} \left[\sum_{t=0}^{\infty} \gamma^t r_t \mid \pi \right]. \quad (10)$$

- Policy π : a function from state to action that specifies what action to take in each state.

The Q-value function is adopted to measure the performance of the policy.

$$Q^*(s, a) = \max_{\pi} \mathbb{E} \left[\sum_{t=0}^{\infty} \gamma^t r_t \mid s = s_0, a = a_0, \pi \right]. \quad (11)$$

The optimal Q-value function satisfies the Bellman Equation

$$Q^*(s, a) = \mathbb{E}_{s' \sim \mathcal{E}} \left[r + \gamma \max_{a'} Q^*(s', a') \mid s, a \right]. \quad (12)$$

How does the Intelligent Agent Learn?

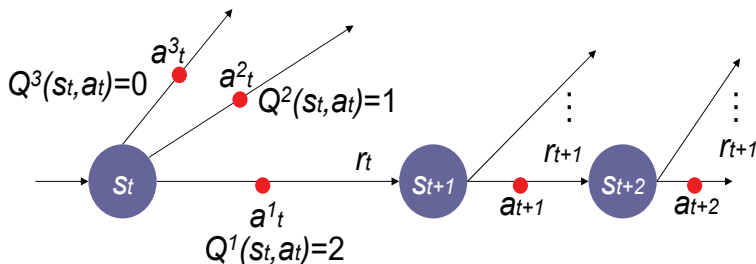
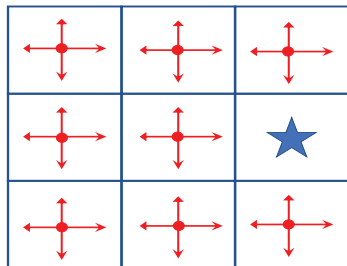


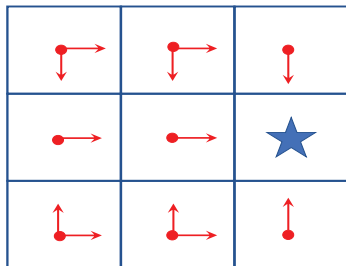
Fig.: Q-learning flow.

- The agent takes action a^1_t , because the corresponding Q value $Q^1(s_t, a_t)$ is max.

The Learning Results: A Maze Case Example



Random policy before learning



Optimal policy after training

Fig.: Q-learning expected result (star represents the treasure).

- After learning, we obtain the optimal action for each state.

Resource Allocation: The Proposed Reinforcement Learning for Cache-Aided NOMA MEC

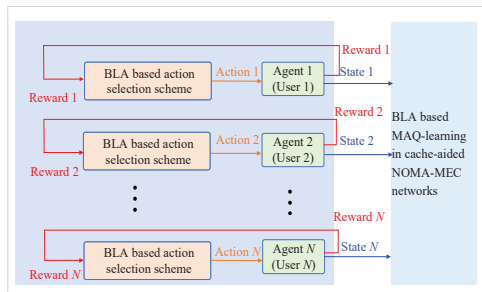


Fig.: Bayesian learning automata based multi-agent Q-learning for resource allocation.

- Each mobile user is set as a intelligent agent.
- Bayesian Learning automata (BLA) is capable of obtaining optimal action for two action case.
- The multiple intelligent agents operate in a selfish manner.

Numerical Results: Resource Allocation (the proposed Reinforcement Learning Algorithm)

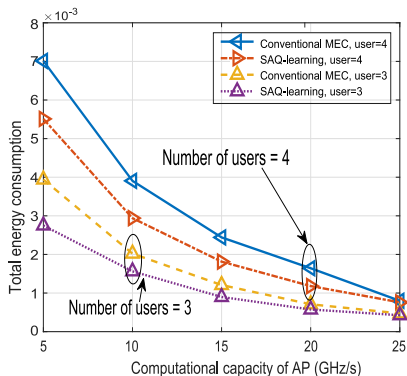


Fig.: Total energy consumption vs. the computation capacity of the AP.

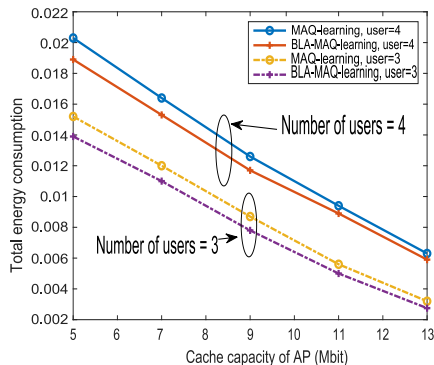


Fig.: Total transmit energy consumption vs. cache capacity of the AP.

Massive NOMA: Grant-Free NOMA

Grant-Free

- Low latency uplink transmission.
- Removing the uplink **scheduling requests** and **dynamic scheduling grants** compared to grant based transmission.

Grant-Free NOMA

- Frequent collision situation.
- NOMA for reducing the collisions of users with multi-user detection.
- Low-latency and high reliability.

Massive NOMA: from Grant-Free to Semi-Grant-Free Transmission (SGF)

What is SGF?

- Grant-free (GF) and grant-based (GB) users **share the resource blocks**. When a **GB user** has been **connected**, **part of GF users** can join into the same resource blocks via **SGF protocols**, i.e., open-loop protocol and dynamic protocol.

Motivation

- **Spectral efficiency** enhancement: The extra spectrum resources are utilized by newly connected GF users.
- **Few collision scenarios**: Exploiting **power-domain NOMA** to reduce the collisions of users.
- **Stability** enhancement: Employing **SGF protocol** to avoid too many GF users.

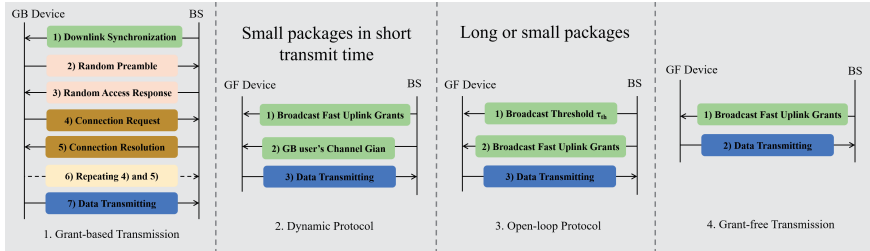
[1] C. Zhang, Y. Liu, Z. Qin and Z. Ding, "Semi-Grant-Free NOMA: A Stochastic Geometry Model," *IEEE Trans.*

Commun., <https://arxiv.org/abs/2006.13286>.

Dynamic protocol?

- Define a channel quality **threshold** $P_{GB}|h_{GB}|^2d_{GB}^{-\alpha}$, which is the **instantaneous channel gain** of the GB user.
 - P_{GB} : transmit power
 - $|h_{GB}|^2$: small scale fading
 - $d_{GB}^{-\alpha}$: large scale fading
- The GF users complicate a **comparison** between their channel gains and thresholds.
- The GF user with lower or higher channel gain will access into the NOMA pair.
 - **latency-sensitive GB user**: Choose GF users with **lower** channel gains - Avoid GB user with SIC process.
 - **latency-tolerant GB user**: Choose GF users with higher channel gains - Further reduce the latency of GF users.

Handshakes Comparison



- Handshakes Comparison among conventional GF, conventional GB and SGF transmission schemes.
- SGF have one more handshake than the conventional GF transmission but still handshake-reduced scheme compared to conventional GB transmission.

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**.

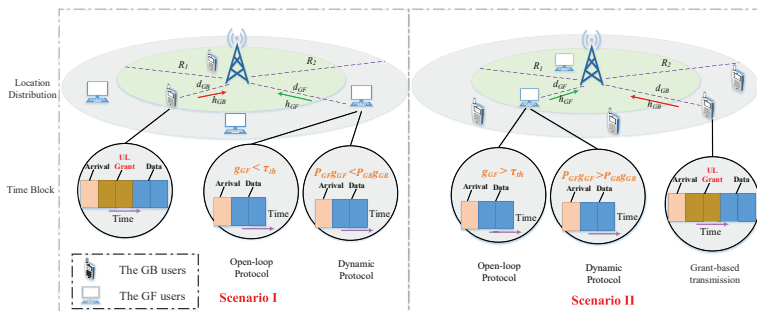
2 Advantages of Stochastic geometry

- 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.

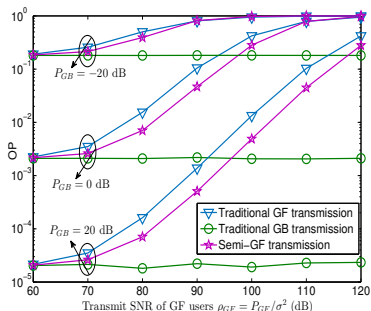
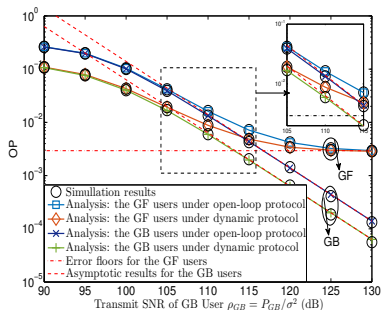
([Web of Science](#) [Hot paper](#))

System Model: Stochastic Geometry



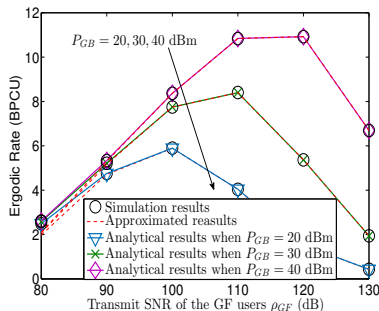
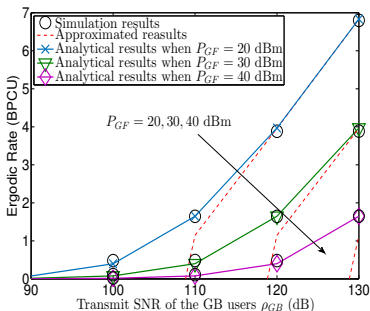
- Scenarios: 1) **Latency-sensitive GB user** as near user deployed in the **circle** as **Scenario I**; 2) **Latency-tolerant GB user** as far user deployed in the **ring** as **Scenario II**.
- Performance analysis: **Outage probability** and **ergodic rates** of two paired NOMA users in two scenarios.

Numerical Results on Outage Probability



- **Consistent** diversity gains: 1) one for near users (**linear relationship**) and 2) zero for far users (**error floors**).
- **Outage performance comparison**: the outage performance of SGF protocol is better than conventional GF transmission schemes but worse than conventional GB transmission schemes.

Numerical Results on Ergodic Rate



- The GB user: the ergodic rate of the GB user is **proportional** to the transmit power of the GB user P_{GB} but **inversely proportional** to the transmit power of GF users P_{GF} .
- The GF user: 1) the ergodic rate of the GF user is **inversely proportional** to P_{GB} ; 2) the ergodic rate has the **maximum value** when P_{GF} increases.

Interplay Between RIS/IRS and NOMA Networks

Motivations

- One the one hand, intelligent reflecting surface (**IRS**) 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 IRS**: 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 IRS-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*, <https://arxiv.org/abs/2003.02117>.

UAV Communications based on NOMA

Motivations

- One the one hand, **NOMA to UAV**: enhance the performance/efficiency/ and improve the connectivity of existing UAV networks.
- One the other hand, **UAV to NOMA**: The distinct channel conditions can be realized (e.g., to pair one static user with one moving UAV user) [1].

Challenges

- Heterogeneous mobility profiles and Heterogenous QoS requirements.
- New techniques like OTFS may require to exploit the heterogeneous mobility profiles.
- The new mobility models need to be exploited.

[1] Y. Liu et al., "UAV Communications Based on Non-Orthogonal Multiple Access", *IEEE Wireless Communications*, vol. 26, no. 1, pp. 52-57, Feb. 2019.

Why RIS and UAV Communications are good application scenarios for NOMA?

Common Parts

- Flexible decoding order: in conventional NOMA transmission, the SIC decoding orders among users are generally determined by the “**dumb**” channel conditions.
- UAVs and IRSs are both “**channel changing**” technologies: The channel conditions of users can be enhanced or degraded by exploiting UAVs’ mobility and/or adjusting IRS reflection coefficients, thus enabling a “**smart**” NOMA operation to be carried out.
- More distinct channel differences can be created

New Techniques to Investigate: NOMA-RIS/NOMA-UAV

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.
- Step 3: Good insights compared to existing benchmark schemes (power scaling law, diversity, etc.).
- Step 4: Exploit the possible timely interesting results.

Selected Research Contributions for NOMA-UAV

[1] Y. Liu et al., "UAV Communications Based on Non-Orthogonal Multiple Access", *IEEE Wireless Communications*, vol. 26, no. 1, pp. 52-57, Feb. 2019.

● Stochastic Geometry Based Analysis

- [2] T. Hou, Y. Liu, Z. Song, X. Sun, Y. Chen, "Multiple Antenna Aided NOMA in UAV Networks: A Stochastic Geometry Approach", *IEEE Transactions on Communications*, vol. 67, no. 2, pp. 1031-1044, Feb. 2019.
- [3] T. Hou, Y. Liu, Z. Song, X. Sun, Y. Chen, "Exploiting NOMA for Multi-UAV Communications in Large-Scale Networks", *IEEE Transactions on Communications*, vol. 67, no. 10, Oct. 2019.
- [4] T. Hou, Y. Liu, Z. Song, X. Sun, Y. Chen, "NOMA Enhanced Terrestrial and Aerial IoT Networks with Partial CSI", *IEEE Internet of Things*, vol. 7, no. 4, pp. 3254-3266, April 2020, <https://arxiv.org/abs/1907.05571>.
- [5] T. Hou, Y. Liu, Z. Song, X. Sun, Y. Chen, "UAV-to-Everything (U2X) Networks Relying on NOMA: A Stochastic Geometry Model", *IEEE Transactions on Vehicular Technology*, vol. 69, no. 7, pp. 7558-7568, July 2020, <https://arxiv.org/abs/1907.05571>.

● Convex Optimization/Machine Theory for Trajectory Design and Resource Allocation

- [6] X. Mu, Y. Liu, L. Guo, and J. Lin, "Non-Orthogonal Multiple Access for Air-to-Ground Communication", *IEEE Transactions on Communications*, vol. 68, no. 5, pp. 2934-2949, May 2020, <https://arxiv.org/abs/1906.06523>.
- [7] T. Zhang, Y. Wang, Y. Liu, W. Xu and A. Nallanathan, "Cache-enabling UAV Communications: Network Deployment and Resource Allocation", *IEEE Transactions on Wireless Communications*, <https://arxiv.org/abs/2007.11501>.
- [8] T. Zhang, Z. Wang, Y. Liu, W. Xu and A. Nallanathan, "Caching Placement and Resource Allocation for Cache Enabling UAV NOMA Networks", *IEEE Transactions on Vehicular Technology*, <https://arxiv.org/abs/2008.05168>.

● A Machine Learning Approach

- [9] J. Cui, Y. Liu, A. Nallanathan, "Multi-Agent Reinforcement Learning Based Resource Allocation for UAV Networks", *IEEE Transactions on Wireless Communications*; *accept to appear*.
- [10] X. Liu, Y. Liu, Y. Chen, and L. Hanzo, "Trajectory Design and Power Control for Multi-UAV Assisted Wireless Networks: A Machine Learning Approach", *IEEE Transactions on Vehicular Technology*, vol. 69, no. 7, pp. 7558-7568, July 2020, <https://arxiv.org/abs/1812.07665>.
- [11] X. Liu, Y. Liu, and Y. Chen, "Reinforcement Learning in Multiple-UAV Networks: Deployment and Movement Design", *IEEE Transactions on Vehicular Technology*; *accept to appear*, <https://arxiv.org/abs/1904.05242>.

Selected Research Contributions for NOMA-RIS (1/2)

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

● Conventional Performance Analysis and Stochastic Geometry Based Analysis

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[2] 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. <https://arxiv.org/abs/2005.00996>

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● Capacity Characterization, Beamforming and Resource Allocation

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● Deployment and Multiple Access

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● A Machine Learning Approach

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Research Opportunities and challenges for NOMA

- 1 Joint MIMO-NOMA-RIS design.
- 2 NOMA in Heterogenous Mobility Networks
- 3 Massive NOMA in IoT Networks
- 4 Grant/Semi-Grant Free NOMA
- 5 Error Propagation in SIC.
- 6 Imperfect SIC and limited channel feedback.
- 7 NOMA for UAV and areal-to-ground communications
- 8 Different variants of NOMA.
- 9 Novel coding and modulation for NOMA.
- 10 Hybrid multiple access
- 11 Security provisioning in NOMA

Thank you!

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