

AI Enabled UAV Communications Based Non-Orthogonal Multiple Access



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Outline

- ❑ Overview and Motivation
- ❑ Spatial Modelling and Performance Evaluation of NOMA-UAV networks
- ❑ Resource Allocation and Trajectory Design for NOMA-UAV networks
- ❑ Machine Learning for NOMA-UAV Networks
- ❑ Research Opportunities and Challenges for NOMA-UAV



Overview: Applications of UAV

Video streaming



Intelligent delivery



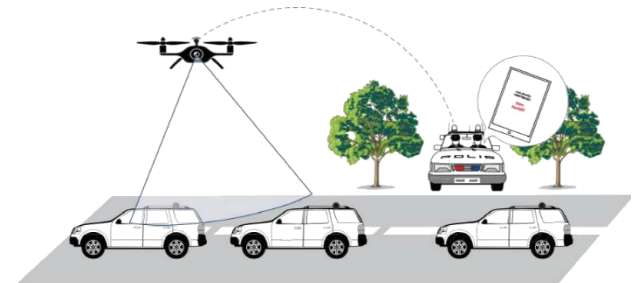
Aerial inspection



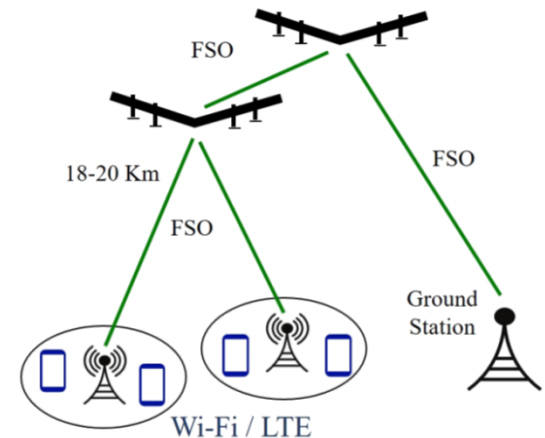
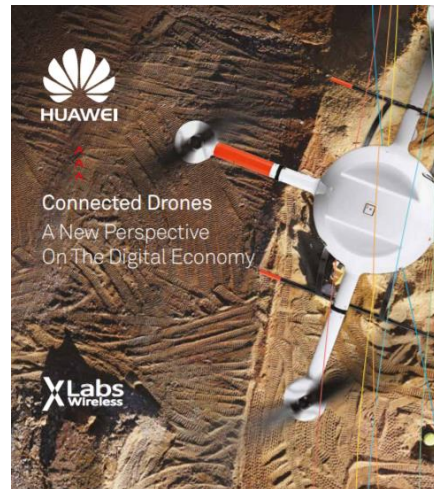
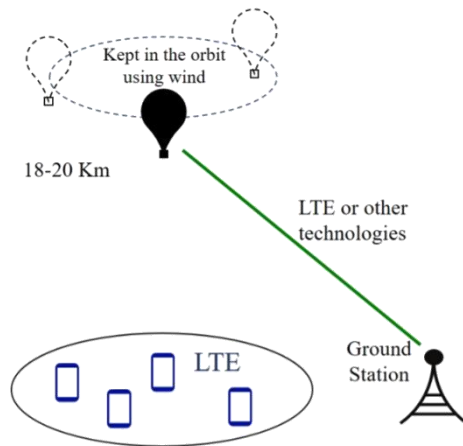
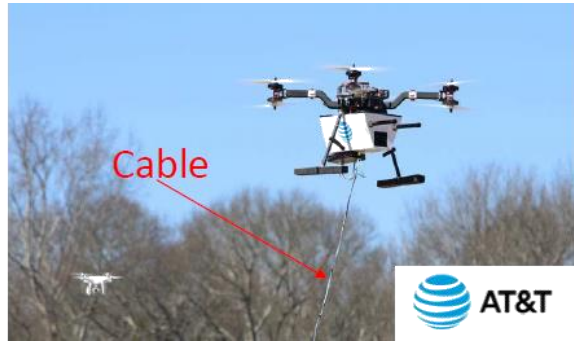
Precision agriculture



Traffic monitoring



Overview: Applications of UAV

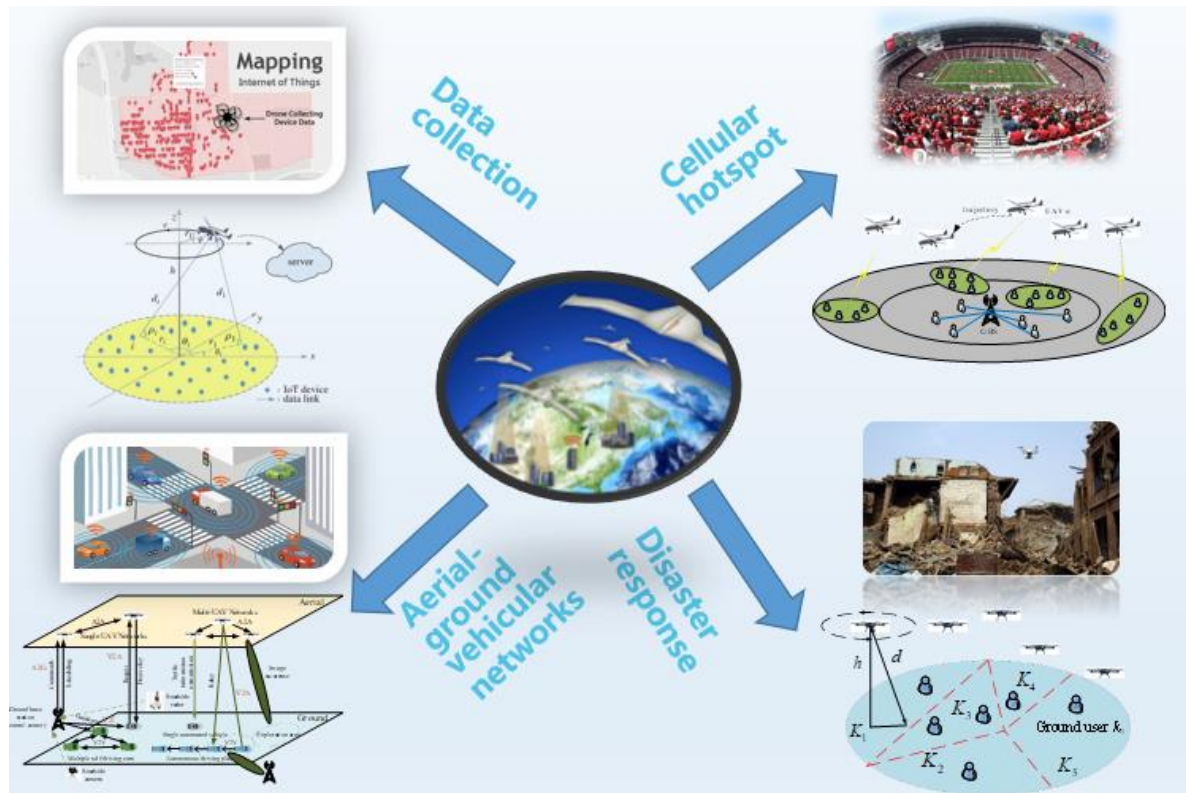


Overview: Different Type of UAV

	Fixed-wings	Rotary-wings
Speed	Up to 500 km/h	Typically $< 60\text{km/h}$
Altitude	Up to 20 Km	Typically $< 1\text{km}$
Flight time	Up to several hours	Typically $< 30\text{min}$
Applications	• airborne surveillance • carry cellular infrastructure	• recreation • sensing



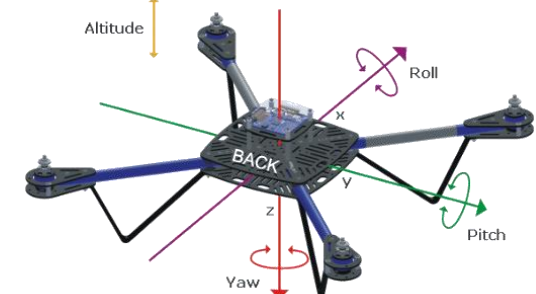
Overview and Motivation: UAV Communications



Which problems:

U2X: U2I, U2U, U2V

- ☐ UAV-enabled emergency communication after natural disaster
- ☐ UAV-Aided Offloading for Cellular Hotspot
- ☐ Aerial-ground vehicular networks for enhancing the driving safety of autonomous/connected vehicles



UAV Communications: What will be different?

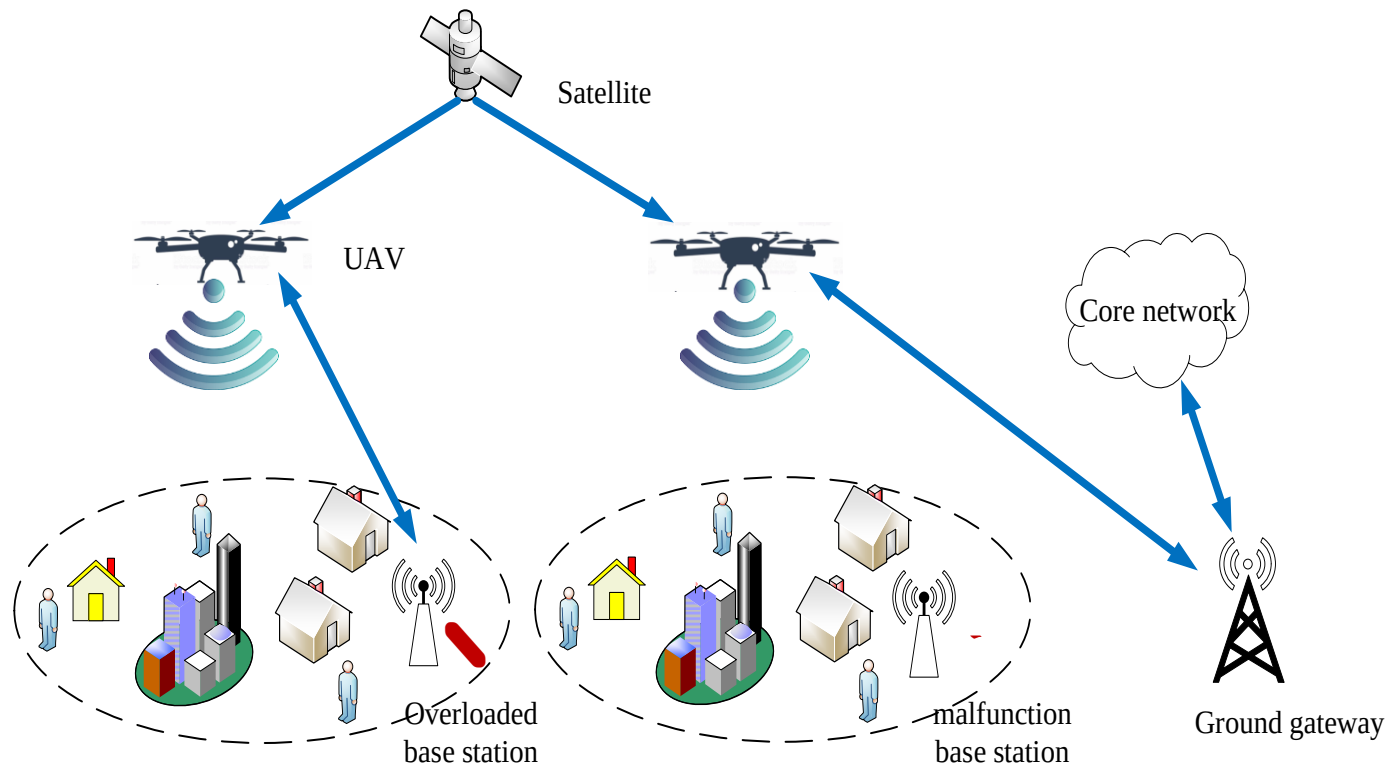
♦ **Characteristics of UAV Networks:** [1]

- ❑ **Path loss:** line-of-sight (LOS) and Non-LOS links.
- ❑ **Mobility:** the coverage areas becomes various.
- ❑ **Agility:** quickly deployed and positions can be adjusted within a 3D space flexibly.

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

Applications: UAV in Cellular Networks

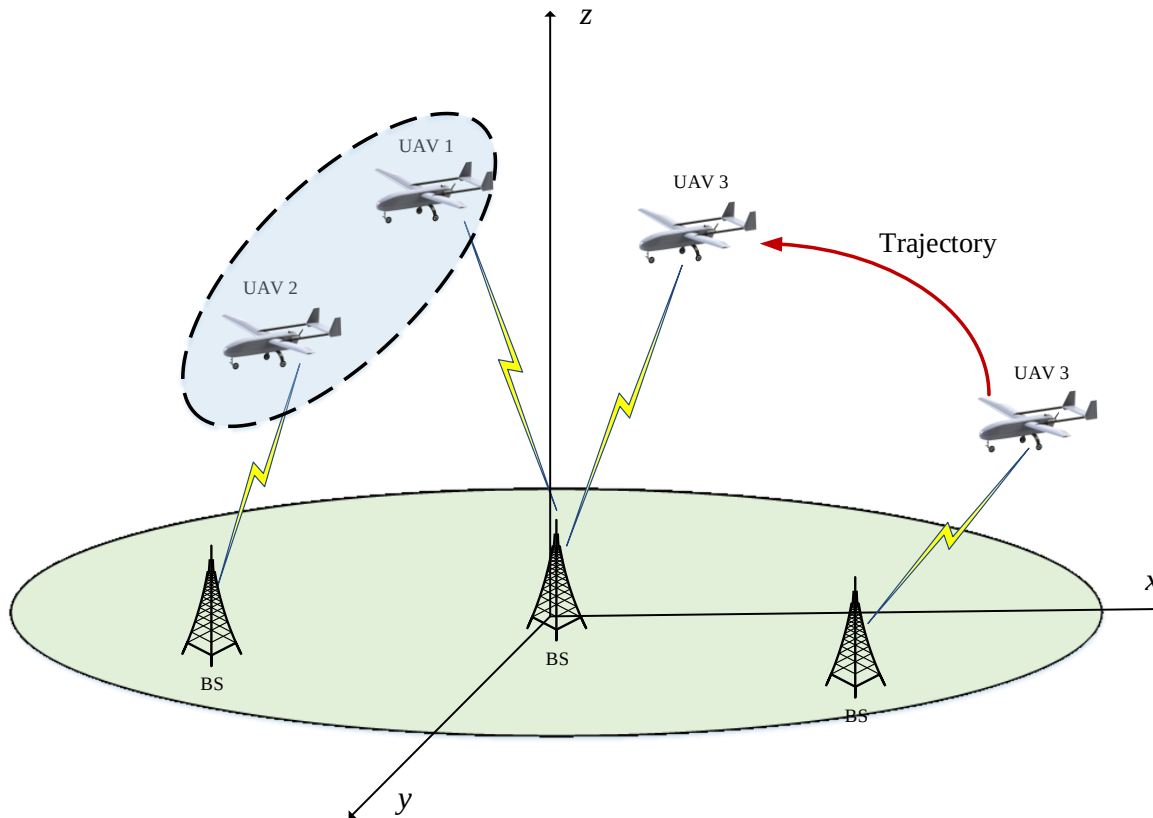
□ UAV-assisted cellular communication: UAVs serve as BSs



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

Applications: UAV in Cellular Networks

❑ Cellular-connected UAV communication: UAVs serve as users



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

Benefits VS Challenges

❑ UAV-Enabled Wireless Networks

❑ Benefits and Applications:

- Coverage and capacity enhancement
- LoS communications
- Internet of Things support
- On-demand communications
- Fast, flexible and efficient deployment
- Emergency situations and disaster relief
- No significant infrastructure: Low cost
- Information dissemination

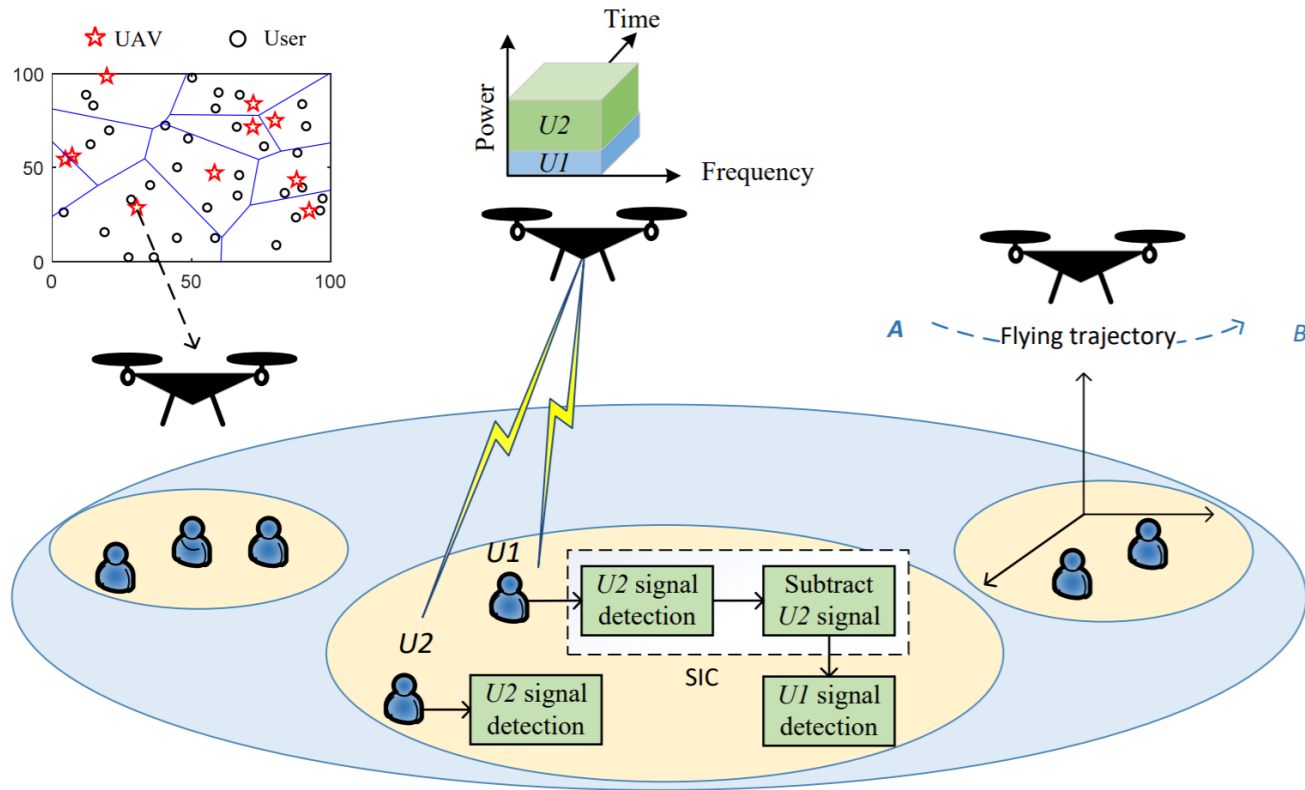
❑ Challenges:

- Optimal 3D placement
- Channel modeling
- Energy limitation
- Flight time constraints
- Performance analysis
- Trajectory/Path planning
- Interference management
- Security



UAV Communications Based on NOMA

□ Illustration of UAV-NOMA networks



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

UAV Communications Based on NOMA

◆ Motivations

- ❑ On the one hand, **NOMA to UAV**: enhance the performance/efficiency/ and improve the connectivity of existing UAV networks.
- ❑ On the other hand, **UAV to NOMA**: 1) The distinct channel conditions can be realized (e.g., to pair one static user with one moving UAV user) [1]. 2) UAV can provide flexible decoding order for NOMA as it is a “**channel changing**” technology.

◆ Challenges

- ❑ Heterogeneous mobility profiles and Heterogeneous 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 Non-Orthogonal Multiple Access”, *IEEE Wireless Communications*; vol. 26, no. 1, pp. 52-57, Feb. 2019.

New Techniques to Investigate: NOMA-UAV

◆ My Procedure

- ❑ **Step 1:** System Modelling, such as channel model (e.g., fading), signal model (e.g., SINR expressions), spatial model.
- ❑ **Step 2: Theoretical gains** over existing scheme (e.g., NOMA-UAV over OMA-UAV).
- ❑ **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).

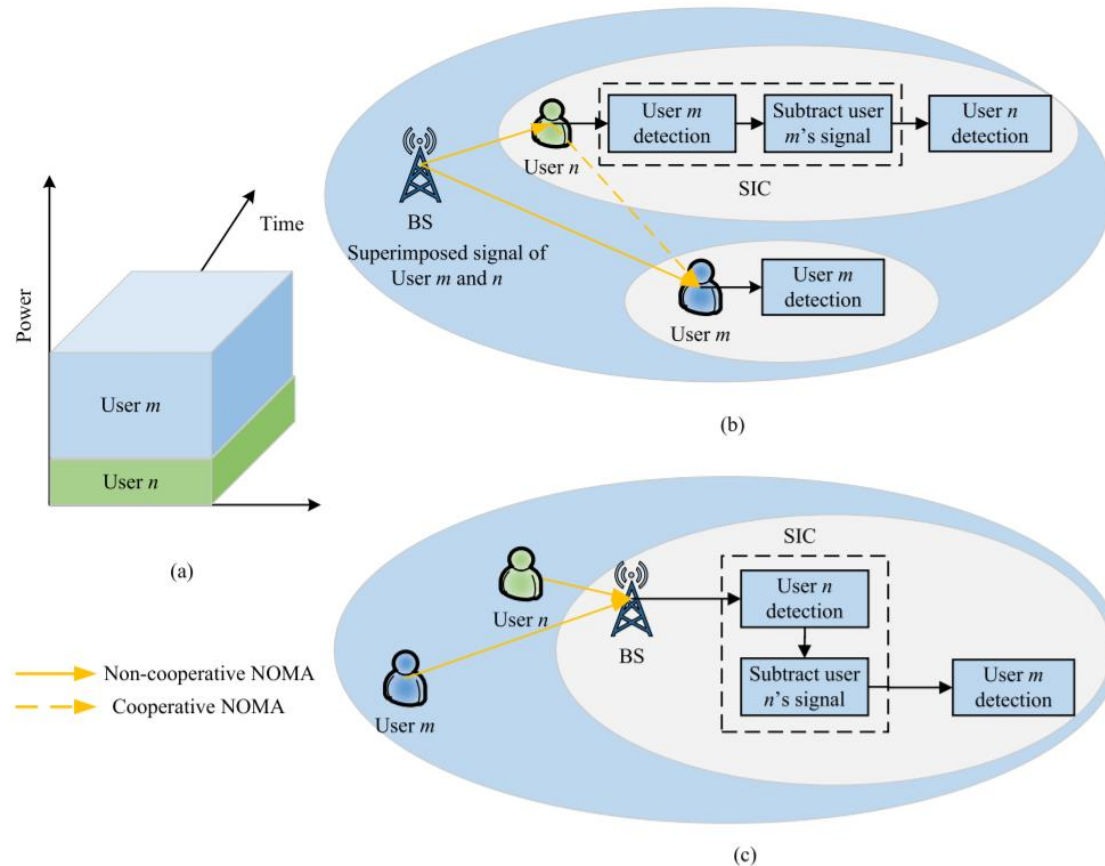
◆ Expected Outcomes

- ❑ **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.



NOMA Basics

□ Illustration of NOMA basics



Y. Liu, et al., “Non-Orthogonal Multiple Access for 5G and Beyond”, *Proceedings of the IEEE*; vol. 105, no. 12, pp. 2347-2381, Dec. 2017.

NOMA for UAV Communications

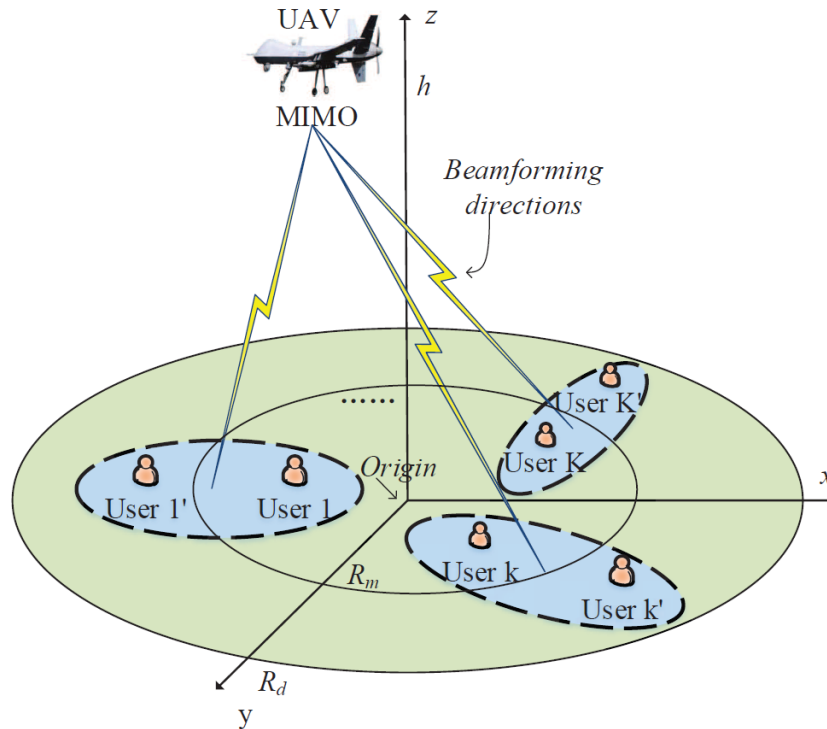
- ❑ **Stochastic Geometry:** Mathematical Modeling and Performance Evaluation
- ❑ **Convex Optimization:** Resource Allocation and Trajectory Design
- ❑ **Machine Learning:** Dynamic Deployment/Trajectory Design and Long Term Resource Allocation

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



Stochastic Geometry: Binomial Point Process (BPP)

◆ Single UAV: MIMO-NOMA UAV Networks



- ☐ There are probabilistic line-of-sight links.
- ☐ The small-scale fading follows Nakagami fading or Rice fading.
- ☐ The height of UAV can be a random variable or any arbitrary value.

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.

Stochastic Geometry: Poisson Point Process (PPP)

◆ NOMA for Multiple-UAV Networks

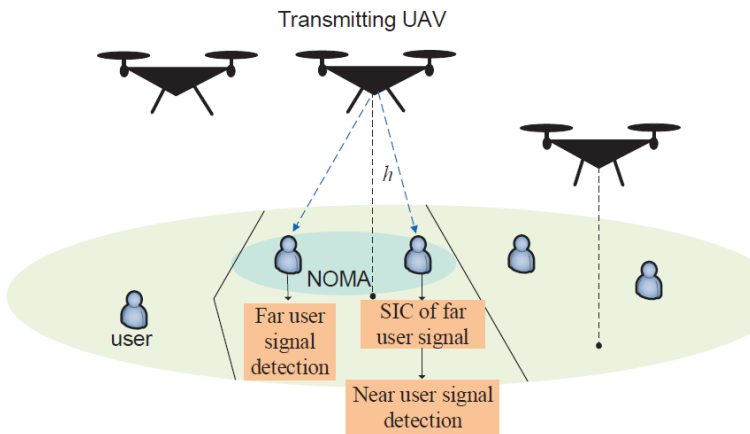
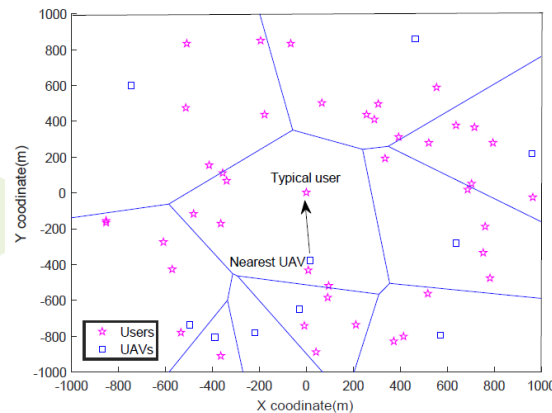


Fig.: An illustration of NOMA UAV in Cellular Networks.

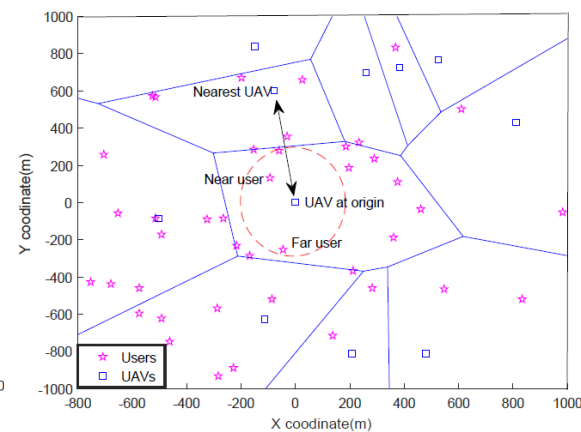
T. Hou, Y. Liu, Z. Song, X. Sun, Y. Chen, "Exploiting NOMA for Multi-UAV Communications in Large-Scale Networks", **IEEE Transactions on Communications**; vol. 67, no. 10, Oct. 2019.

Flexible user-association is required:
User-Centric Scenario VS UAV-Centric Scenario



● User-Centric Scenario

- All the ground users must be served.
- Association is decided by users according to distance.

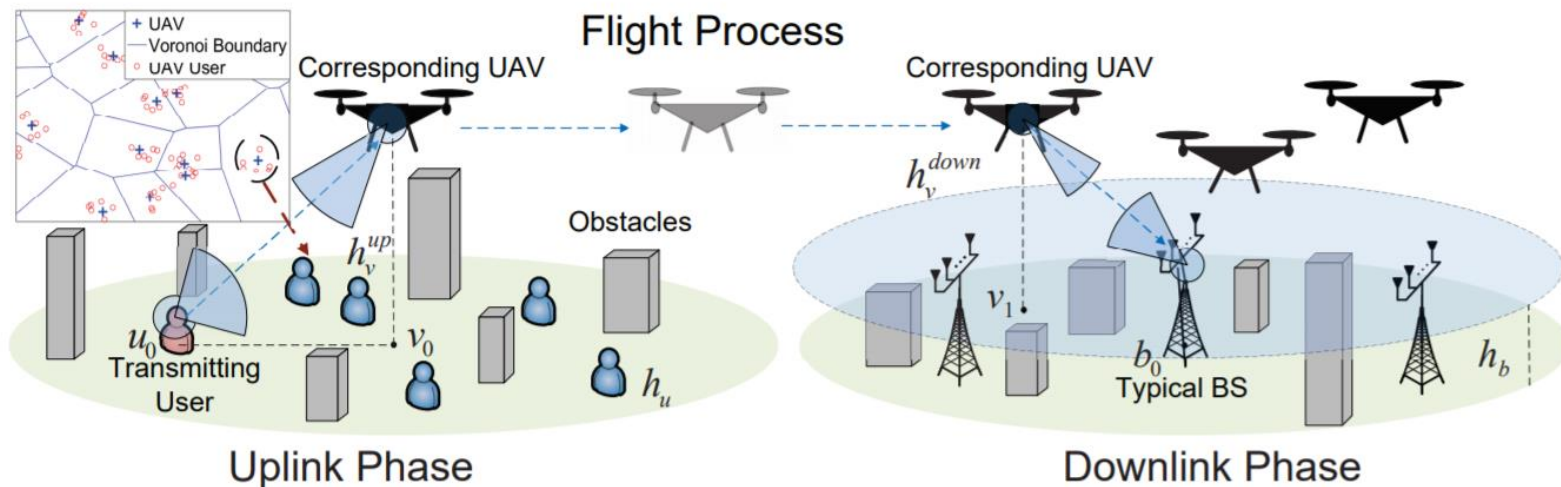


● UAV-Centric Scenario

- UAV only provides access services to users located in hot spot areas (e.g., offloading).

Stochastic Geometry: Poisson Point Process (PPP)

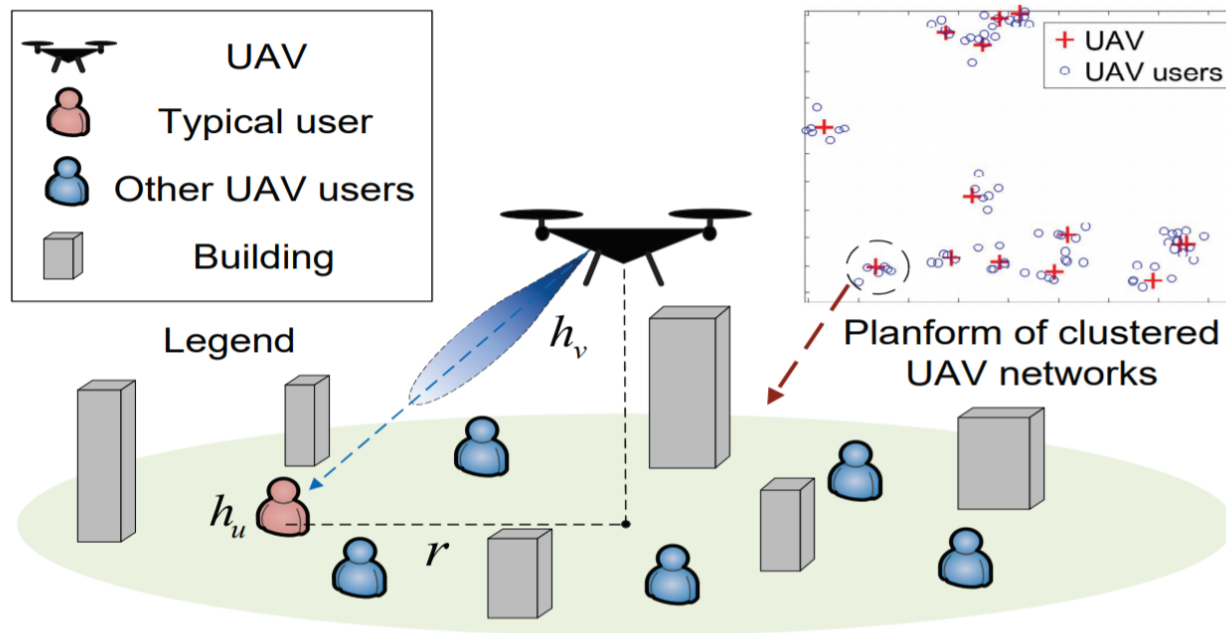
◆ UAV for Data collection



W. Yi, **Y. Liu**, E. Bodanese, A. Nallanathan, and G. K. Karagiannidis, "A Unified Spatial Framework for UAV-aided MmWave Networks", **IEEE Transactions on Communications**; vol. 67, no. 12, pp. 8801-8817, Dec. 2019.

Stochastic Geometry: Poisson Cluster Process (PCP)

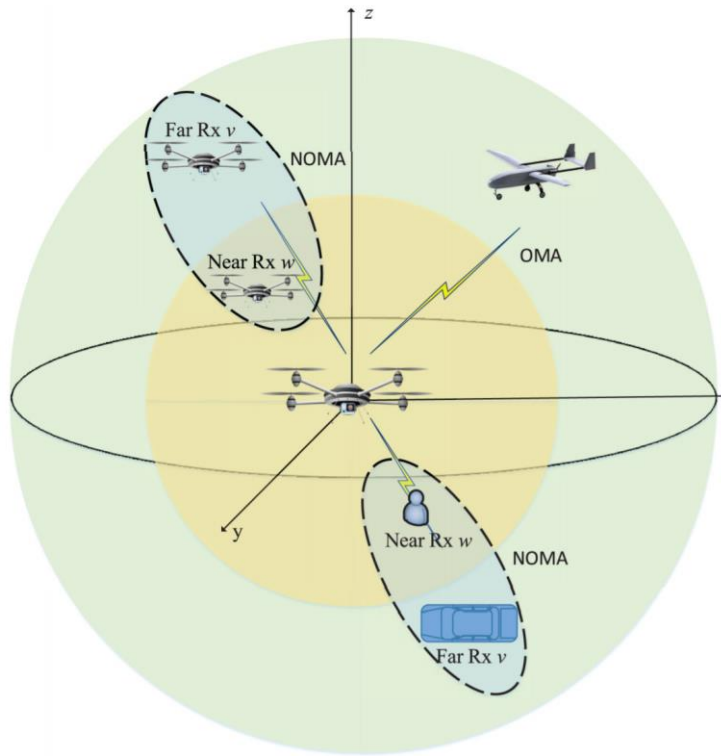
◆ MmWave Communications for UAV



W. Yi, **Y. Liu**, Y. Deng, A. Nallanathan, "Clustered UAV Networks with Millimeter Wave Communications: A Stochastic Geometry View", **IEEE Transactions on Communications**; vol. 68, no. 7, pp. 4342-4357, July 2020.

Stochastic Geometry: From 2D to 3D

◆ NOMA UAV-to-Everything (U2X) Networks



- ❑ Users or receivers are located on the ground or in the sky.
- ❑ The coverage space is a sphere.
- ❑ NOMA is deployed for providing enhanced connectivity.

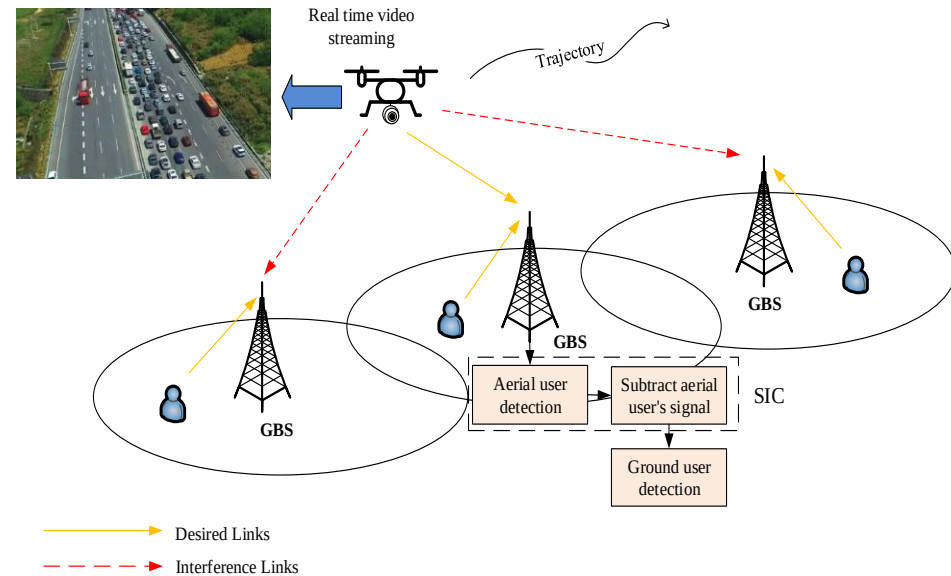
Access Mode	Rx	$\mathcal{D}$	$\mathcal{S}$
NOMA	Near	m	1
	Far	m	0
OMA	Near	m	0.5
	Far	m	0.5
	Only one	m	1

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.

Convex Optimization: Resource Allocation and Trajectory Design

◆ Ground-Aerial Uplink NOMA

- ❑ The associated BS first decodes the UAV's signal by treating its served ground user's signal as noise.
- ❑ After decoding the UAV's signal, the BS decodes the ground user's signal.



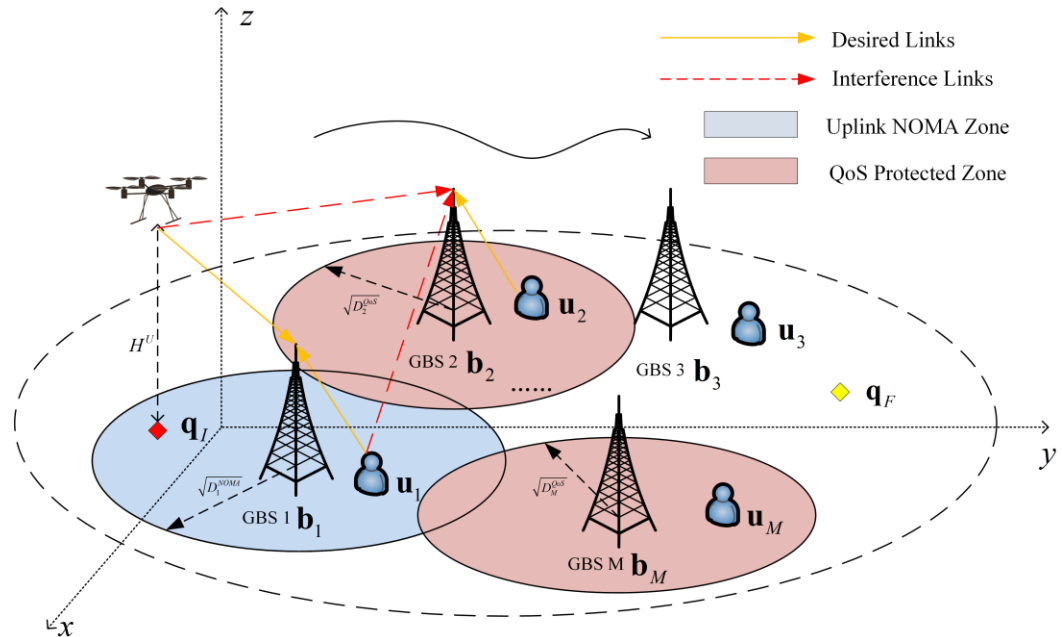
◆ Motivations

- ❑ **Asymmetric channel conditions** among ground and aerial users. (e.g., A2G channels are usually stronger than terrestrial channels)
- ❑ **Asymmetric communication requirements** in uplink transmission. (e.g., 4K/HD real-time aerial video transmission)
- ❑ **Limited** spectrum resources. (NOMA encourages to sharing spectrum)

X. Mu, Y. Liu, L. Guo and J. Lin, "Non-Orthogonal Multiple Access for Air-to-Ground Communication," *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 2934-2949, May 2020.

Ground-Aerial Uplink NOMA: System Model

- ❑ **UAV mission:** Fly from pre-determined initial location $\mathbf{q}_I$ to final location $\mathbf{q}_F$ to upload U_m bits data to each BS.
- ❑ **Channel Models:** Line-of-sight (LOS) channel for A2G links, and Rayleigh fading channel for terrestrial links



- ❑ **Uplink NOMA zone:** regions where the UAV and ground users can be served by the *associated* BS through uplink NOMA protocol.

$$0 \leq \|\mathbf{q}(t) - \mathbf{b}_m\|^2 \leq D_m^{NOMA}$$

- ❑ **QoS protected zone:** regions that the UAV cannot enter to guarantee the QoS of ground users served by *non-associated* BSs.

$$\|\mathbf{q}(t) - \mathbf{b}_n\|^2 \geq D_n^{QoS}$$

Problem Formulation

- Minimize mission completion time, subject to constraints on required uploading bits of the UAV and QoS demands of ground users.

$$(P1) : \min_{\mathbf{Q}, \mathbf{A}, T} T$$

$$\text{s.t. } \mathbf{q}(0) = \mathbf{q}_I,$$

$$\mathbf{q}(T) = \mathbf{q}_F,$$

$$\|\dot{\mathbf{q}}(t)\| \leq V_{\max}, 0 \leq t \leq T,$$

$$U_m > \tilde{U}_m, m \in \mathcal{M}_{BS},$$

$$a_m(t) \|\mathbf{q}(t) - \mathbf{b}_m\|^2 \leq D_m^{NOMA},$$

$$\forall m \in \mathcal{M}_{BS}, 0 \leq t \leq T,$$

$$\|\mathbf{q}(t) - \mathbf{b}_m\|^2 \geq (1 - a_m(t)) D_m^{QoS},$$

$$\forall i \in \mathcal{M}_{BS}, 0 \leq t \leq T,$$

$$\sum_{m=1}^M a_m(t) = 1, 0 \leq t \leq T,$$

$$a_m(t) \in \{0, 1\}, \forall m \in \mathcal{M}_{BS}.$$

UAV mobility constraints

UAV should delivery specific information bits to each BSs

Constraints on uplink NOMA and UAV-BS association orders

Proposed Solutions

■ Fly-Hover-Fly based Solution

- Step 1: Find the optimal hover location for each BS (user association).
- Step 2: Find BS-UAV association sequence with a modified **Travelling Salesman Problem** and **Floyd Algorithm**.
- Step 3: Determine the hovering time for given required uploading bits, and calculate the mission completion time.

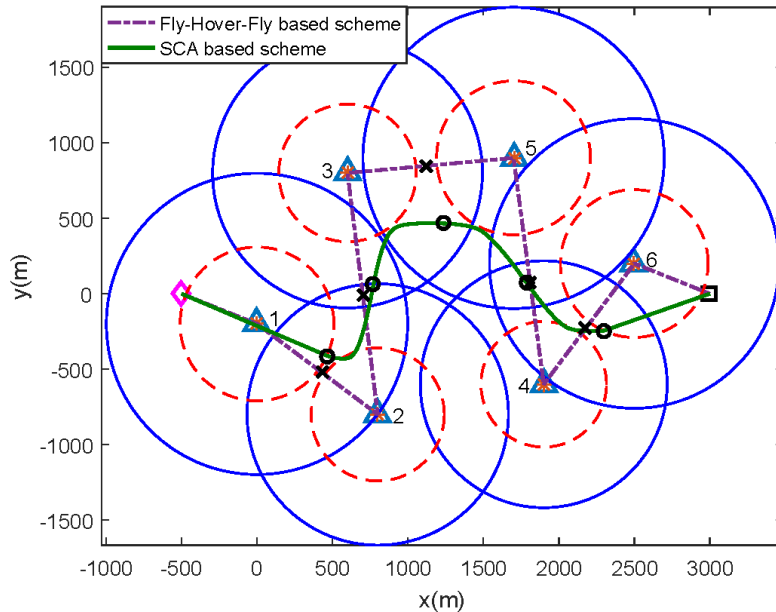
■ SCA based Solution

- Step 1: Discrete the continuous path into finite segments via path discretization method.
- Step 2: Optimize the mission minimization problem by employing **successive convex approximation (SCA)** technique.

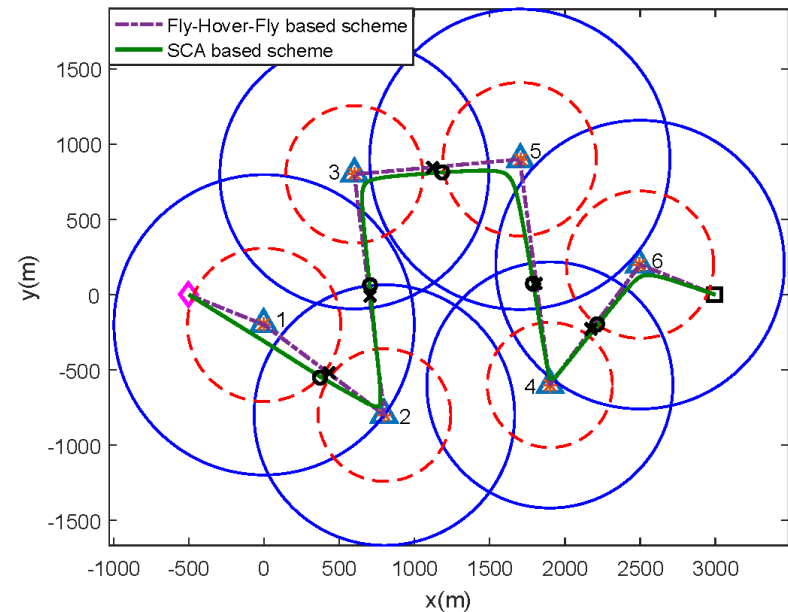
X. Mu, Y. Liu, L. Guo and J. Lin, "Non-Orthogonal Multiple Access for Air-to-Ground Communication," *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 2934-2949, May 2020.

Numerical Results

Illustration of Trajectory Designs with Different Required Uploading Bits



(a) $U=20$ Mbits

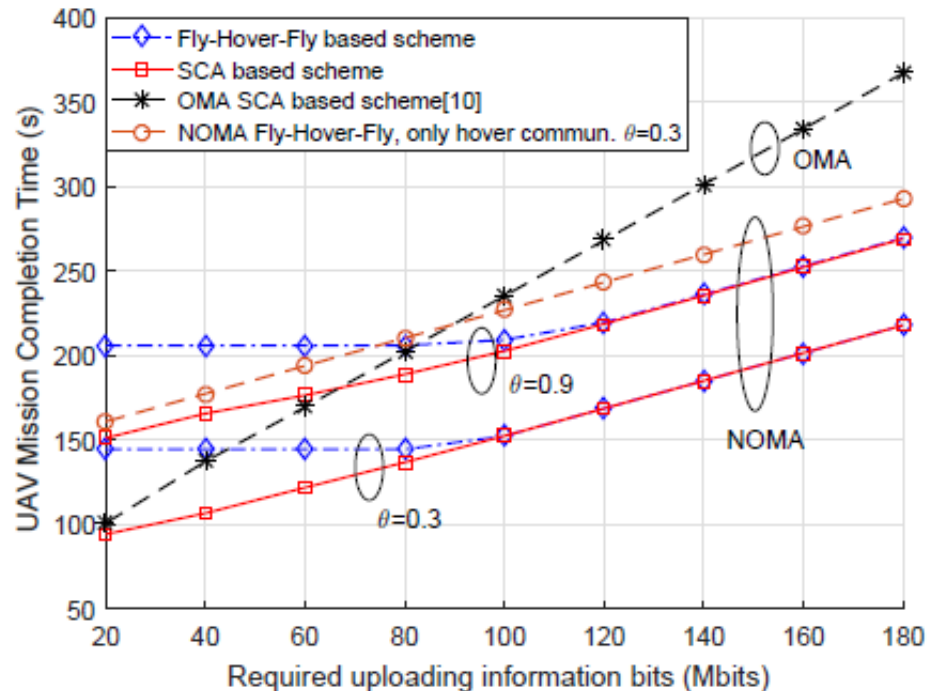


(b) $U=80$ Mbits

- ❑ The blue and red dash circles represent the uplink NOMA zones and the QoS protected zones, respectively. "o" and "x" represent the handover locations of each proposed scheme.
- ❑ The SCA scheme further refines the trajectory obtained by the fly-hover-fly scheme.
- ❑ When U is large, the trajectory of the two schemes are similar.

Numerical Results

Mission Completion Time versus Required Uploading Bits



- ❑ The proposed NOMA framework significantly outperform OMA, especially when the required uploading bits increases.
- ❑ The SCA based scheme always outperforms the fly-hover-fly based scheme.

Convex Optimization: Resource Allocation and Trajectory Design

◆ UAV-enabled IoT Systems

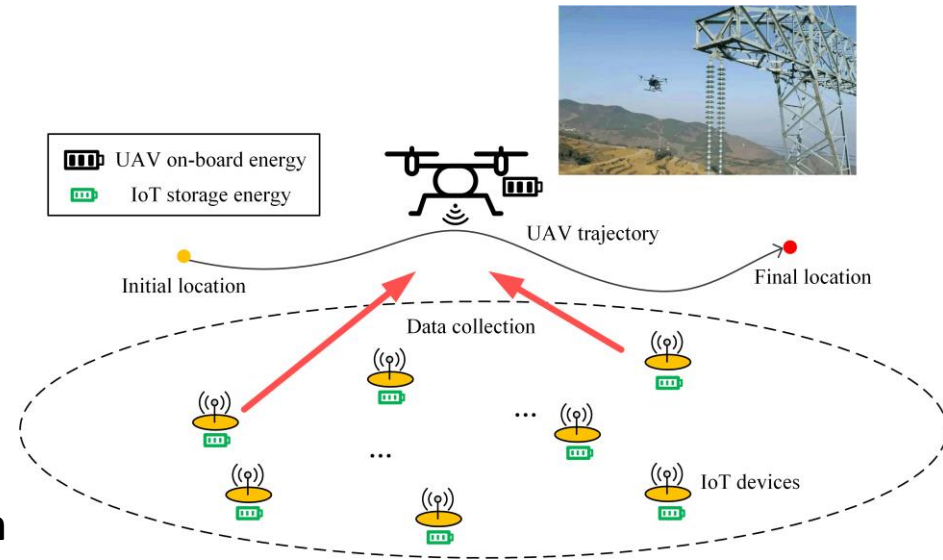
- ❑ Equipped with IoT sensing devices, UAVs are deployed to collect data from ground IoT devices.

◆ Advantages

- ❑ Low Cost
- ❑ Easy to be deployed
- ❑ LoS-dominated A2G channel condition

◆ Challenges

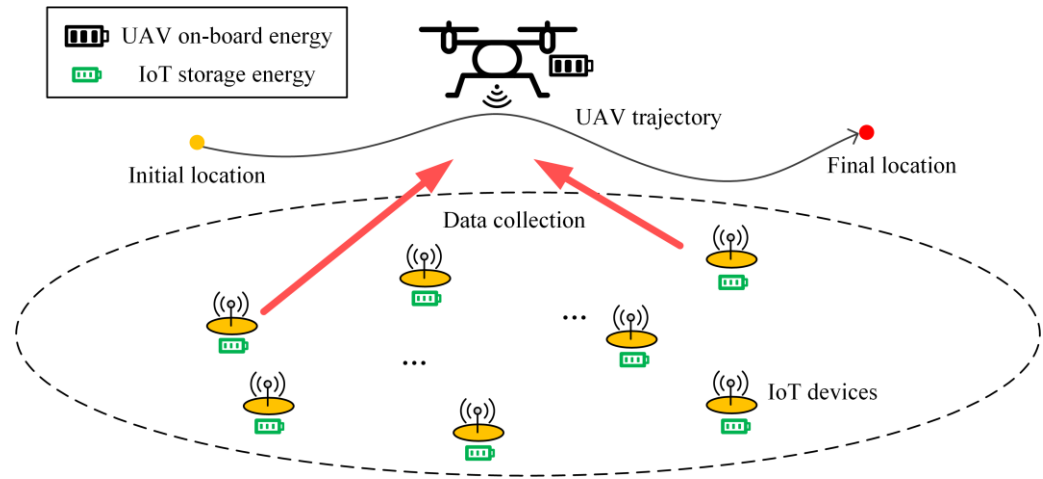
- ❑ **Double Energy Limitation:** Both the UAV and ground IoT devices are energy constrained.
- ❑ **Large number IoT devices:** Flexible and efficient resource allocation schemes are necessary.



X. Mu, Y. Liu, L. Guo and J. Lin, "Multiple Access Design for UAV-enabled IoT Systems," *IEEE IoT J.*, <https://arxiv.org/abs/1910.13630>

UAV-enabled IoT Systems: System Model

- ❑ **UAV mission:** Fly from an initial location to final location to collect data from each IoT device.
- ❑ **Channel Models:** Line-of-sight (LOS) channel for A2G links.
- ❑ **Multiple Access:** NOMA and OMA.



- ❑ **Communication Rate for NOMA:**

$$R_k^N[n] = \log_2 \left(1 + \frac{\gamma_0 p_k[n] |h_k[n]|^2}{\sum_{m \in \mathcal{K}, m \neq k} \alpha_{m,k}[n] \gamma_0 p_m[n] |h_m[n]|^2 + 1} \right)$$

- ❑ **Communication Rate for OMA:**

$$R_k^O[n] = \log_2 (1 + \gamma_0 h_k[n])$$

Problem Formulation

- Max-min collected throughput among IoT devices, subject to energy constraints at both the UAV and IoT devices.

□ NOMA

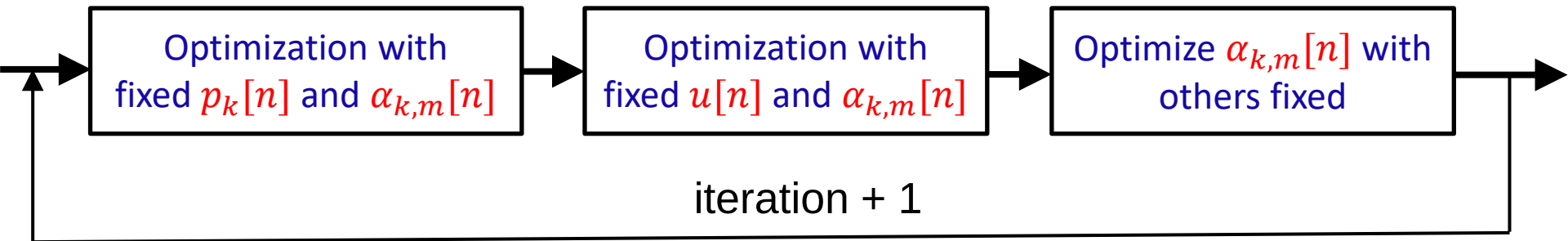
$$\begin{aligned}
 & \max_{\{\mathbf{u}[n], T[n], \tau[n], p_k[n], \alpha_{k,m}[n]\}} \min_{\forall k} Q_k^N \\
 \text{s.t. } & \mathbf{u}[1] = \mathbf{u}_I, \mathbf{u}[N] = \mathbf{u}_F, \\
 & \|\mathbf{u}[n+1] - \mathbf{u}[n]\| \leq \min(\delta, V_{\max} T[n]), \forall n, \\
 & \sum_{n=1}^N E[n] \leq E_U, \\
 & \sum_{n=1}^N \tau[n] p_k[n] \leq E_k, \forall k, \\
 & 0 \leq \tau[n] \leq T[n], \forall n, \\
 & 0 \leq p_k[n] \leq P_{\max}, \forall n, k, \\
 & \alpha_{k,m}[n] + \alpha_{m,k}[n] = 1, \forall k \neq m \in \mathcal{K}, \\
 & \alpha_{k,m}[n] \in \{0, 1\}, \forall k, m \in \mathcal{K},
 \end{aligned}$$

□ OMA

$$\begin{aligned}
 & \max_{\{\mathbf{u}[n], T[n], \tau_k[n], p_k[n]\}} \min_{\forall k} Q_k^O \\
 \text{s.t. } & \mathbf{u}[1] = \mathbf{u}_I, \mathbf{u}[N] = \mathbf{u}_F, \\
 & \|\mathbf{u}[n+1] - \mathbf{u}[n]\| \leq \min(\delta, V_{\max} T[n]), \forall n, \\
 & \sum_{n=1}^N E[n] \leq E_U, \\
 & \sum_{n=1}^N \tau_k[n] p_k[n] \leq E_k, \forall k, \\
 & \sum_{k=1}^K \tau_k[n] \leq T[n], \forall n, \\
 & \tau_k[n] \geq 0, \forall k, n, \\
 & 0 \leq p_k[n] \leq P_{\max}, \forall n, k,
 \end{aligned}$$

Proposed Solutions

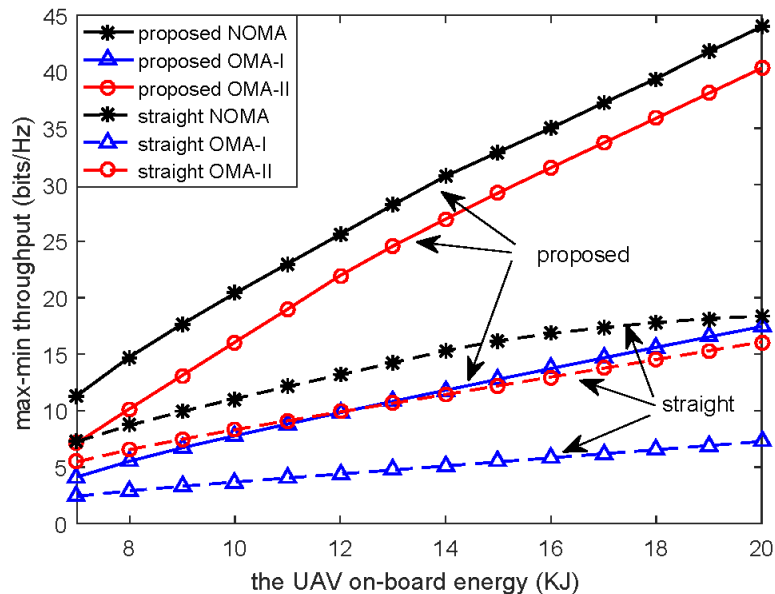
- ❑ The joint trajectory and resource optimization problems are usually difficult to be directly solved, due to the optimization variables are *high-coupled*.
- ❑ **Alternating Optimization:** alternately optimize some of variables (e.g., UAV trajectory) with the others (e.g., resource allocation) fixed. The AO-based iterative algorithm is capable of obtaining a locally optimal solution.
- ❑ For NOMA (similar for OMA)



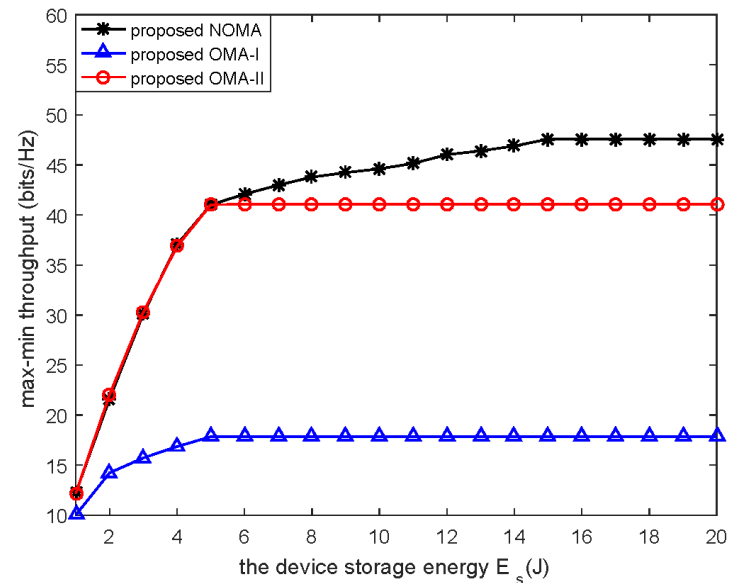
X. Mu, Y. Liu, L. Guo and J. Lin, "Multiple Access Design for UAV-enabled IoT Systems," *IEEE IoT J.*, <https://arxiv.org/abs/1910.13630>

Numerical Results

Max-min Collected Throughput versus Energy of the UAV and IoT Devices



(a) Versus UAV energy



(b) Versus IoT device energy

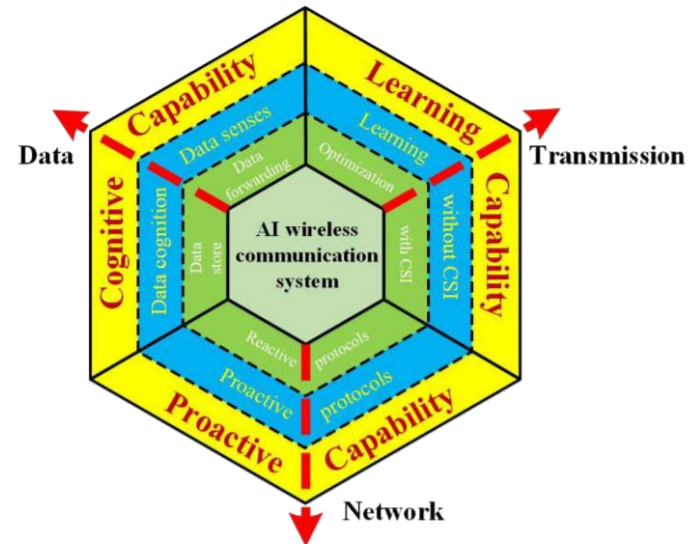
- ❑ The proposed AO-based algorithms significantly outperform those schemes with a straight line UAV trajectory.
- ❑ The proposed NOMA scheme can always achieve equal or higher max-min throughput than the OMA scheme with optimized resource allocation.

AI Enabled UAV Communications

- Cognitive Capability
- Learning Capability
- Proactive Capability



- Uncertain
- Dynamic
- Cooperative
- Interactive

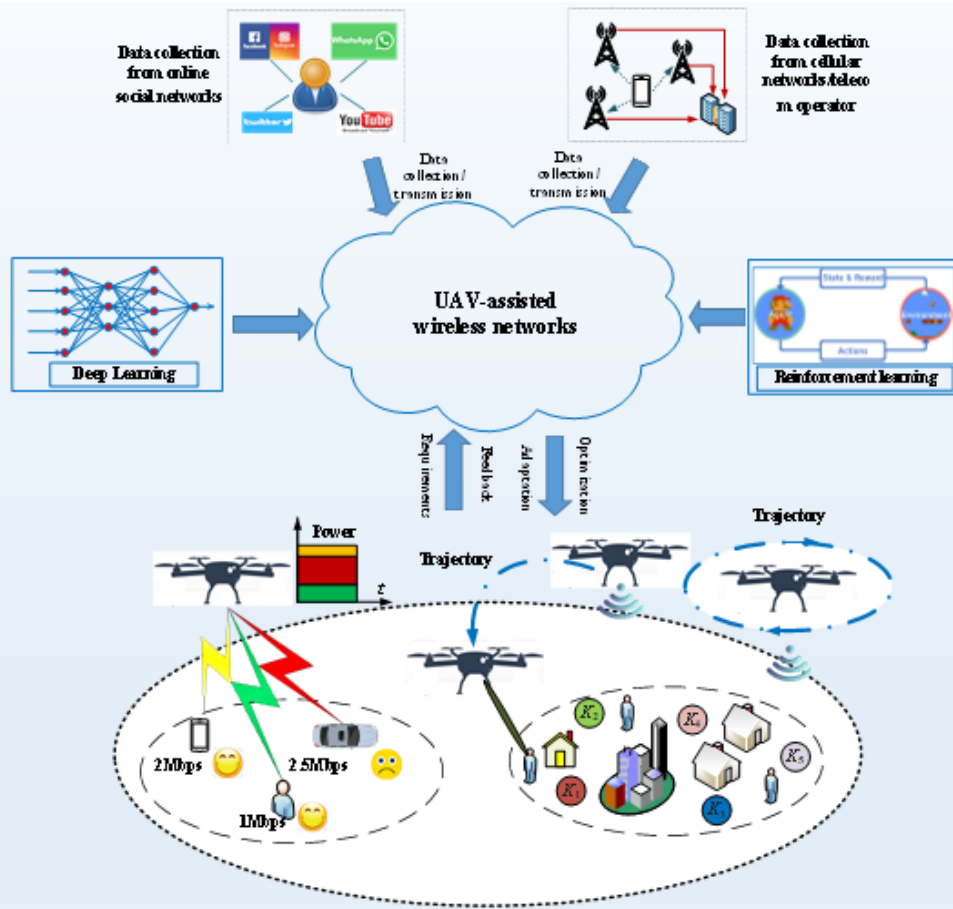


Motivations for invoking machine learning (ML) in UAV-aided networks

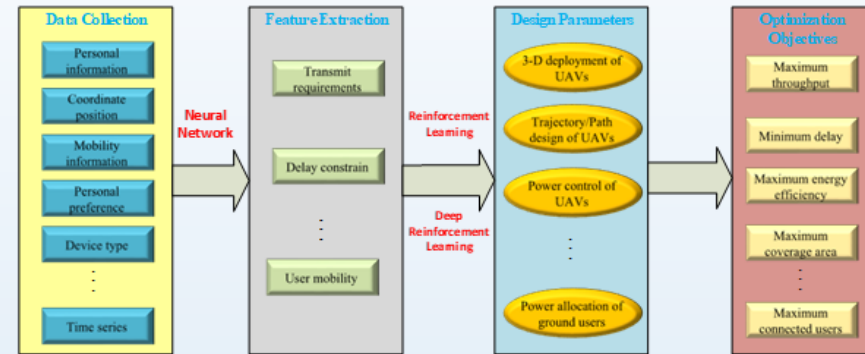
- ☐ Dynamic scenario with **heterogenous QoS requirements** and **user mobility**
- ☐ **Mixed-integer, non-linear** and **non-convex** optimization problem
- ☐ **Long-term** benefits
- ☐ **Interactive** with environment

Y. Liu, et al., “UAV Communications Based Non-Orthogonal Multiple Access”, **IEEE Wireless Communications**; vol. 26, no. 1, pp. 52-57, Feb. 2019.

AI Enabled UAV Communications



Research Framework



- ☐ 3D deployment of multi-UAV
- ☐ Dynamic trajectory design of multi-UAV
- ☐ Resource allocation from UAVs to users (power, bandwidth, cache, computing resource)
- ☐ Energy efficiency design of multi-UAV

X. Liu, M.Chen, **Y. Liu**, Y. Chen, S. Cui, and L. Hanzo, "Artificial Intelligence Aided Next-Generation Networks Relying on UAVs," **IEEE Wireless Communications**, accept to appear, <https://arxiv.org/abs/2001.11958>

AI Enabled UAV Communications

◆ Machine Learning Algorithms for UAV:

Challenges in the UAWN	Application scenarios			ML-based solutions					
	UAV-EC	UAV-CO	UAV-IoT	QL	DL	DQN	DDPG	EA	SARSA
3D deployment	✓	✓	✓	✓	✓	✓			✓
Trajectory/path planning	✓	✓	✓	✓	✓	✓	✓	✓	✓
Resource allocation	✓	✓	✓	✓	✓	✓		✓	
Interference management	✓	✓	✓	✓	✓				
3D channel model	✓	✓	✓		✓				
Energy management	✓	✓	✓	✓		✓			
Feature exaction	✓	✓			✓				
Security	✓	✓		✓	✓				

UAV-EC: UAV-aided emergency communications

UAV-CO: UAV-assisted cellular offloading

UAV-IoT: UAV-assisted Internet-of-Things systems

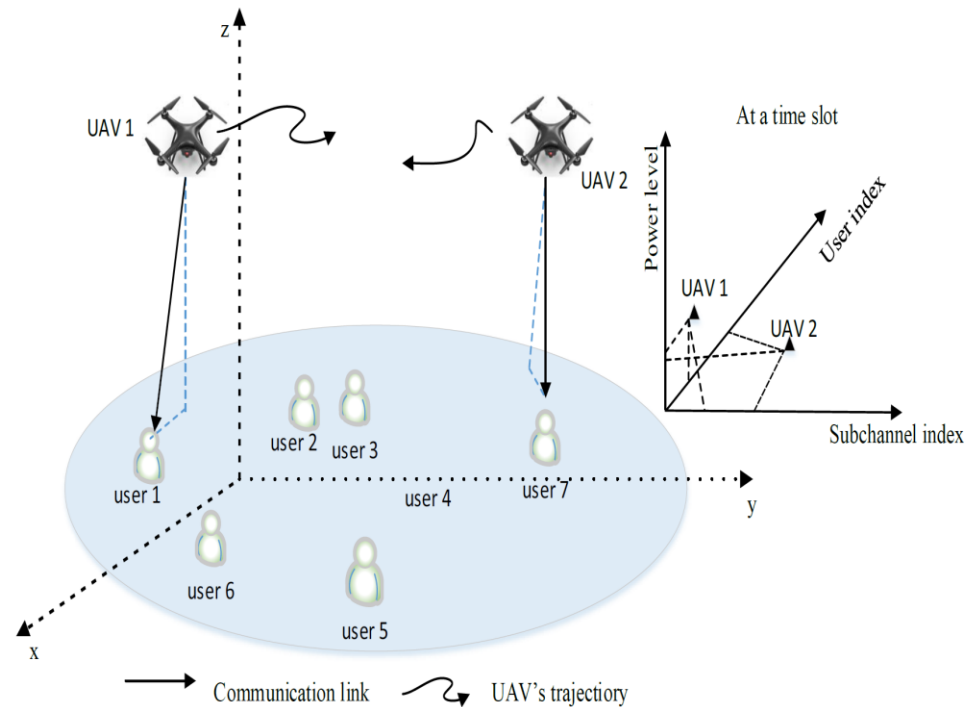
QL: Q-learning; DL: deep learning; DQN: deep Q-network;

DDPG: deep deterministic policy gradients; EA: evolutionary algorithm; SARSA: state–action–reward–state–action

X. Liu, M.Chen, **Y. Liu**, Y. Chen, S. Cui, and L. Hanzo, “Artificial Intelligence Aided Next-Generation Networks Relying on UAVs,” **IEEE Wireless Communications**, accept to appear, <https://arxiv.org/abs/2001.11958>

AI Enabled UAV Communications

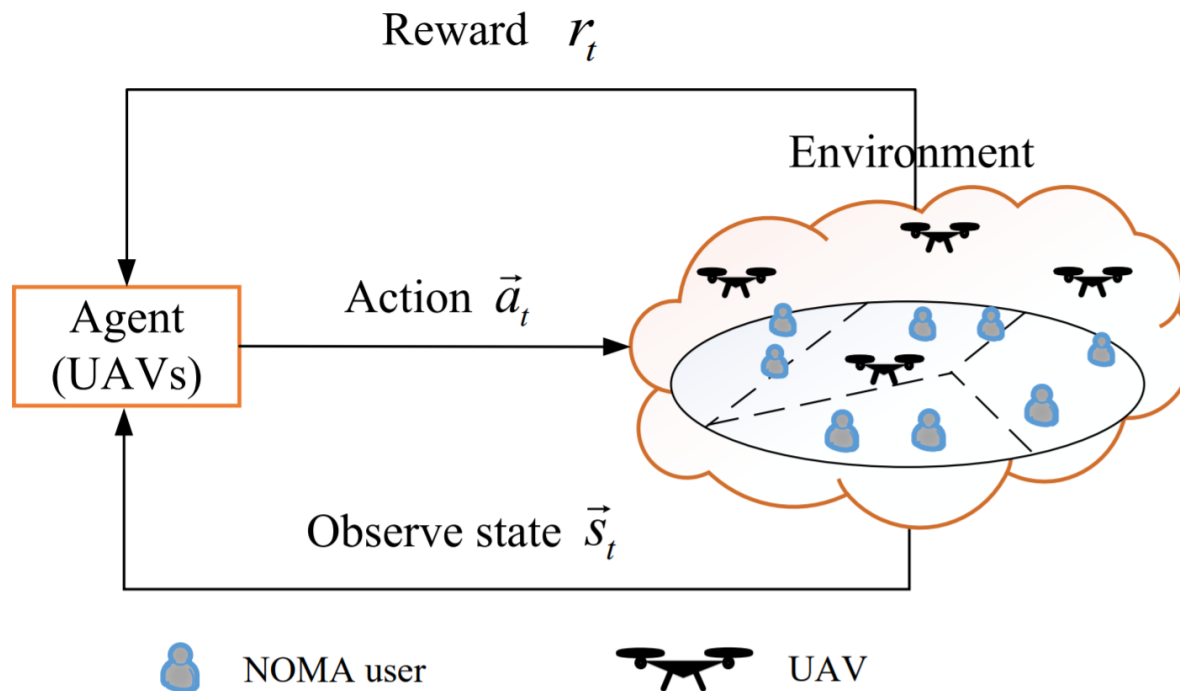
◆ Machine learning: Long Term Benefits (Static Users)



J. Cui, **Y. Liu**, A. Nallanathan "Resource Allocation for UAV Networks: A Multi-Agent Reinforcement Learning Approach", **IEEE Transactions on Wireless Communications**, vol. 19, no. 2, pp. 729-743, Feb. 2020
<https://arxiv.org/abs/1810.10408>

AI Enabled UAV Communications

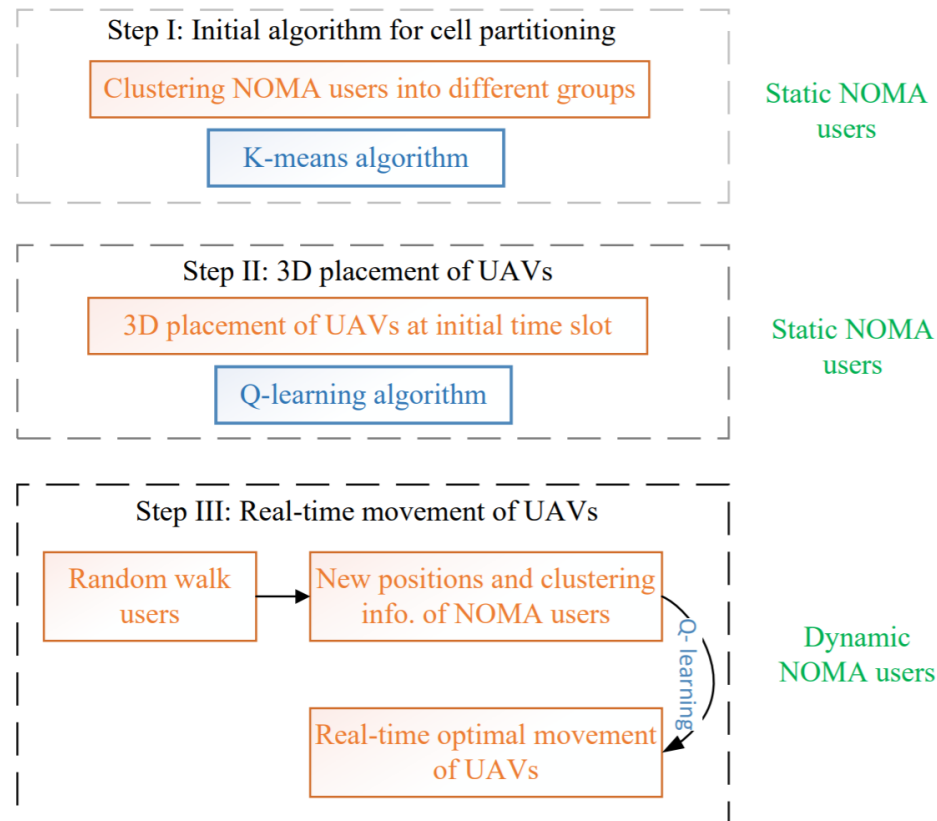
◆ Reinforcement Learning: Deployment and Movement Design (Dynamic Users)



X. Liu, **Y. Liu**, and Y. Chen, "Reinforcement Learning in Multiple -UAV Networks: Deployment and Movement Design", **IEEE Transactions on Communications**; vol. 68, no. 8, pp. 8036-8049, Aug. 2019. [Arxiv]

AI Enabled UAV Communications Based on NOMA

❑ Three-step machine-learning-based UAV placement and movement design.



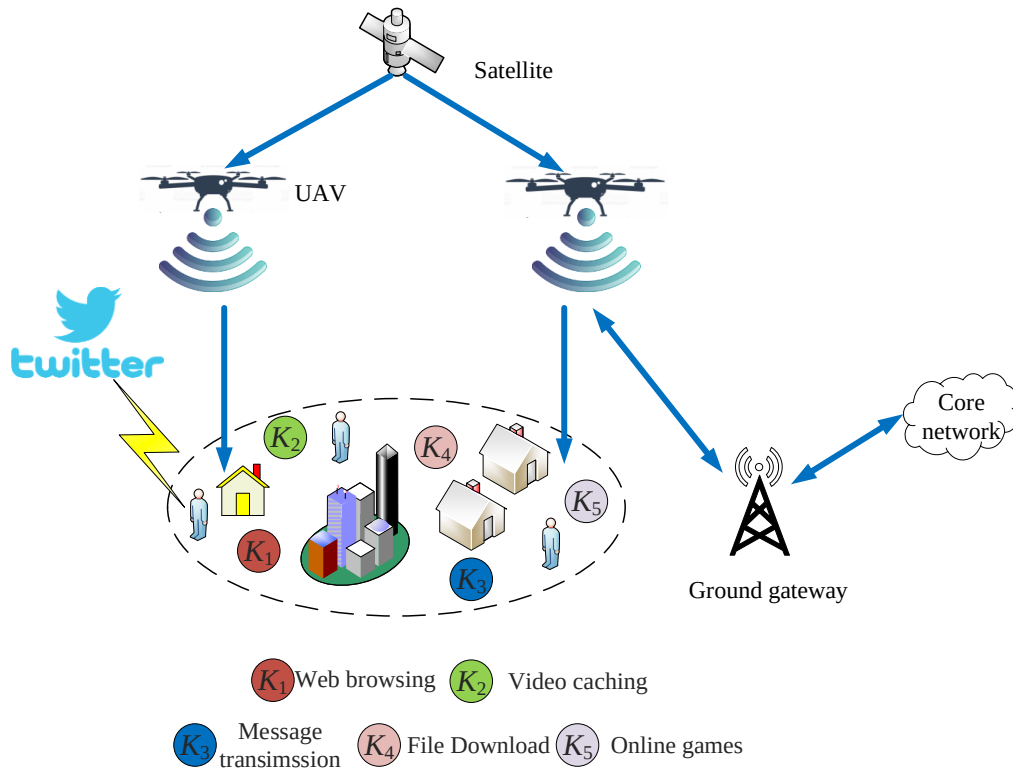
Y. Liu, et al., “UAV Communications Based Non-Orthogonal Multiple Access”, **IEEE Wireless Communications**; vol. 26, no. 1, pp. 52-57, Feb. 2019.

R. Zhong, X. liu, **Y. Liu**, and Y. Chen “Multi-Agent Reinforcement Learning in NOMA-aided UAV Networks for Cellular Offloading,” **IEEE Transactions on Wireless Communications**, under revision

<https://arxiv.org/abs/2010.09094>

AI Enabled UAV Communications

◆ Trajectory design and power control of multi-UAV



- ☐ Emergency communication scenario.
- ☐ Users are roaming
- ☐ UAV can be deployed in 3D environment
- ☐ Cooperative of multiple UAVs
- ☐ Design the trajectory and power level of multi-UAV

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 Trans. on Veh. Technol.**, vol. 68, no. 8, pp. 7957-7969, Aug. 2019.

Joint Trajectory Design and Power Control

□ The probability of LoS can be expressed as [R1]

$$P_{\text{LoS}}(\theta_{k_n}) = b_1 \left(\frac{180}{\pi} \theta_{k_n} - \zeta \right)^{b_2},$$

where $\theta_{k_n}(t) = \sin^{-1} \left(\frac{h_n(t)}{d_{k_n}(t)} \right)$ is the elevation angle between the UAV and ground user, $h_n(t)$ is the altitude of n -th UAV, $d_{k_n}(t)$ is the distance between of n -th UAV and ground user k_n , b_1 and b_2 are constant values reflecting the environment impact. ζ is also a constant value which is determined by antenna and environment.

□ Tradeoff in UAV trajectory design:

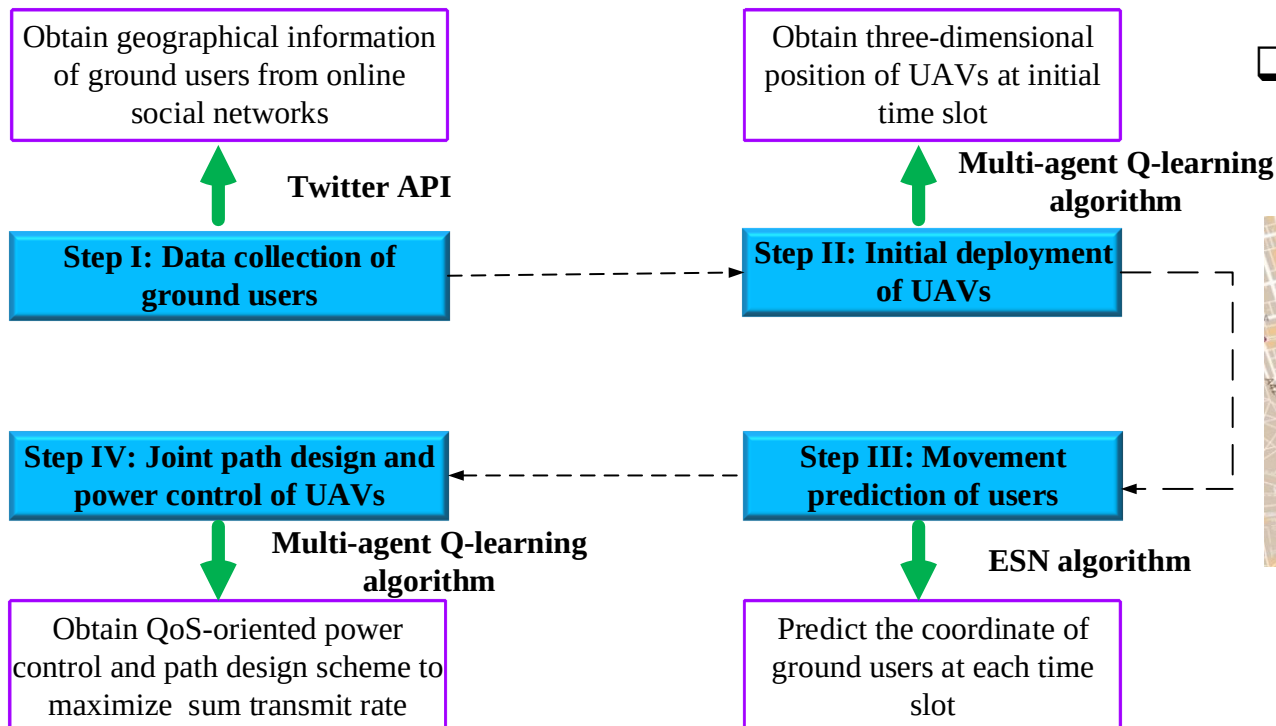
Increasing the UAVs altitude leads to a higher path loss but high LoS probability. The altitude of UAVs is supposed to be properly chosen in practice to balance between the probability of LoS channel and the path loss.

[R1] Mozaffari M, Saad W, Bennis M, et al. “Wireless communication using unmanned aerial vehicles (UAVs): Optimal transport theory for hover time optimization”. IEEE Transactions on Wireless Communications, 2017, 16(12): 8052-8066.

Trajectory design and power control of multi-UAV

♦ Algorithms structure:

- Twitter API: global position system (GPS) coordinates
- 14th, March 2018, in Oxford Street, London



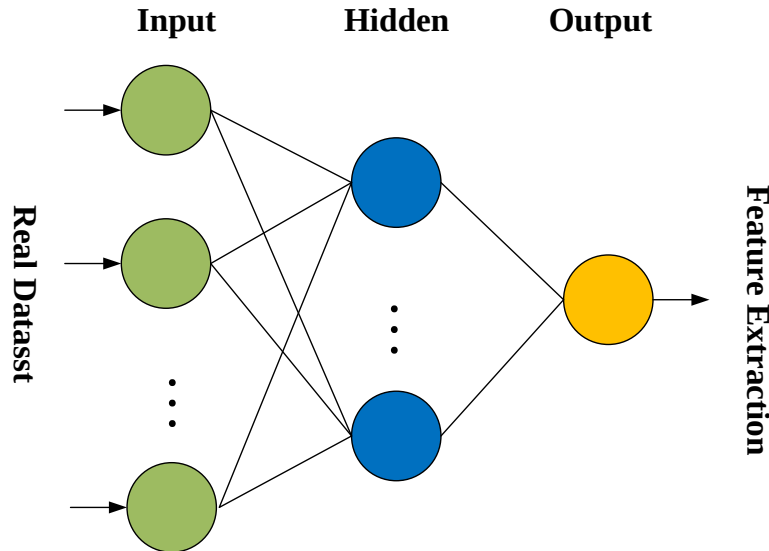
X. Liu, **Y. Liu**, Y. Chen, and Lajos Hanzo, "Trajectory Design and Power Control for Multi-UAV Assisted Wireless Networks: A Machine Learning Approach", **IEEE Trans. on Veh. Technol.**, vol. 68, no. 8, pp. 7957-7969, Aug. 2019..

Trajectory design and power control of multi-UAV

◆ User mobility/data demand prediction

Architecture:

- Input layer
(real dataset)
- Output layer
(feature extraction)
- Input weight matrix
(connections between the neurons in the input and hidden layers)
- Output weight matrix
(connections between the neurons in the output and hidden layers)
- Neuron weight matrix
(connections between the neurons in the hidden layers)



Trajectory design and power control of multi-UAV

◆ User mobility/data demand prediction

Real data collection

- User distribution/mobility information:
social networking applications like
Facebook, Twitter, Wechat, Weibo
- User data requirement information:
Dataset from Irish Central Statistics
Office
 - Census information
 - Cellular infrastructure deployment
 - Cellular data demand
- Real scenario and channel information:
3D building re-construction of QMUL

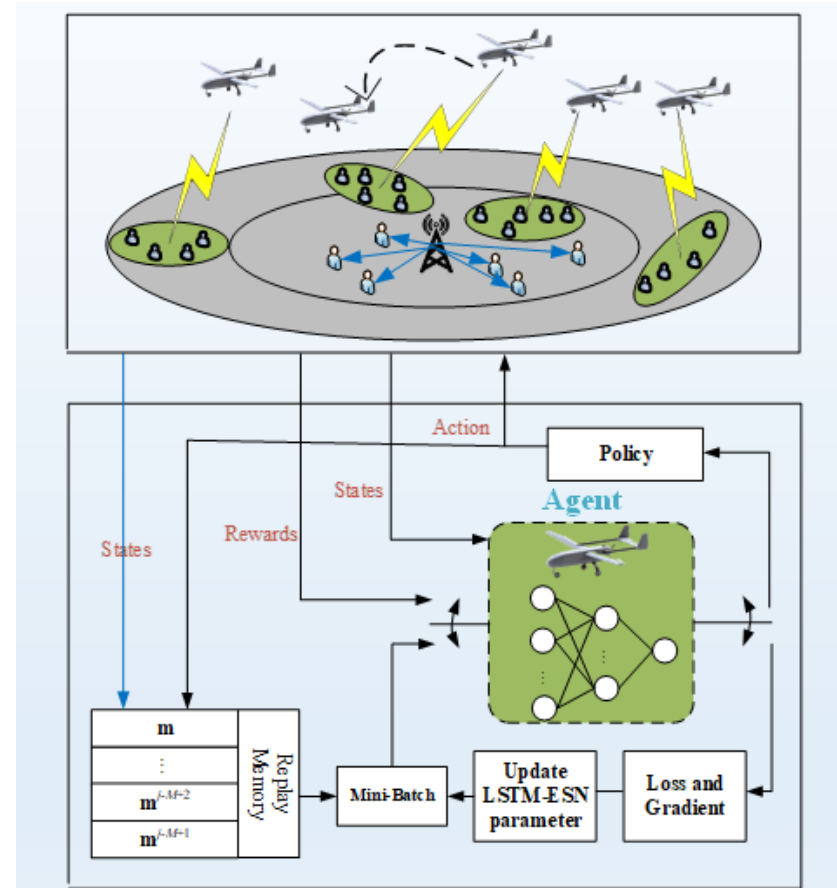


User mobility collection from Twitter

Trajectory design and power control of multi-UAV

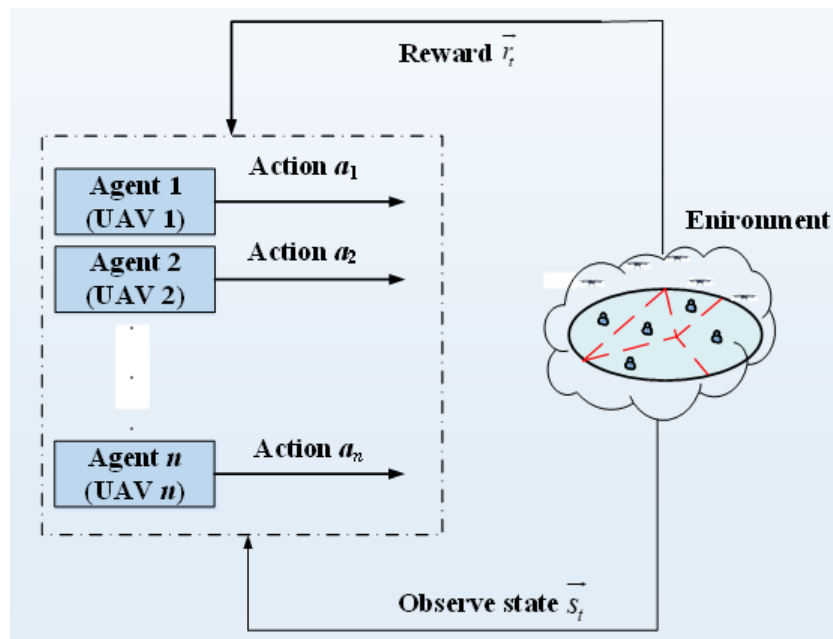
◆ The concept of deep Q-network (DQN) model

- RL can incorporate **farsighted system evolution** instead of myopically optimizing current benefits.
- RL can update decision policies through feedback based on the previous decisions.
 - learn from the environment
 - learn from the users
 - learn from the historical experience



Trajectory design and power control of multi-UAV

State-action space of DQN algorithm



Architecture:

- A set of agents N
(the UAVs)
- A set of state $S=\{s_1(t), \dots, s_k(t)\}$
(the coordinates of both the UAVs and the users; the power allocation coefficient)
- A set of actions $A=\{a_1(t), \dots, a_k(t)\}$
(the moving direction and distance of the UAVs; increment or decrement of the power allocation coefficient)
- A reward/penalty function $R=\{r_1(t), \dots, r_k(t)\}$
- A state transition function/policy $P: S \times A$

NOMA-RIS Enhanced UAV-Aided Wireless Networks

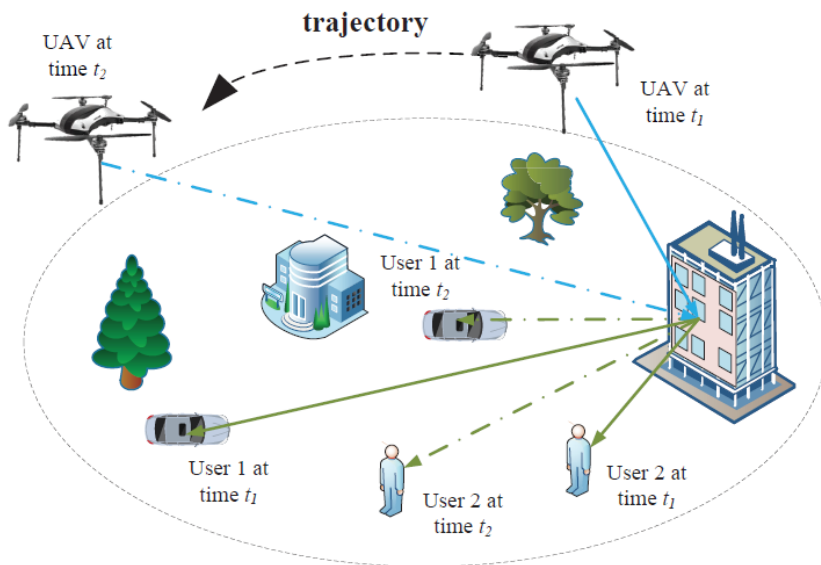
◆ Motivations

- RIS can be **directly invoked** in the UAV-enabled wireless networks
 - Does not need to change the standardization and hardware of the existing wireless networks
- RIS can be invoked for **improve the throughput performance**
 - Capability of proactively modifying the wireless communication environment
- RIS can be invoked for **reducing the energy consumption** of UAVs
 - With the aid of RIS, the movement of UAVs can be reduced
 - Propulsion energy consumption (hundreds times larger than communication-related energy) is considered



NOMA-RIS Enhanced UAV-Aided Wireless Networks

◆ System model



- A particular area (single cell)
- Both ground users and connected vehicles with variable data demand/mobility information
- Down-link communications
 - One UAV (M antenna)
 - K users (single antenna)
 - One RIS (equipped with N reflecting elements)

MISO downlink

X. Liu, **Y. Liu**, and Y. Chen, "Machine Learning Empowered Trajectory and Passive Beamforming Design in UAV-RIS Wireless Networks", **IEEE JSAC**

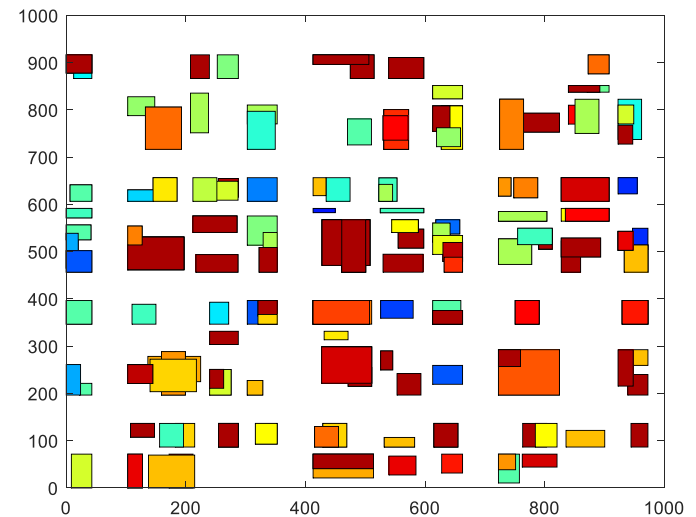
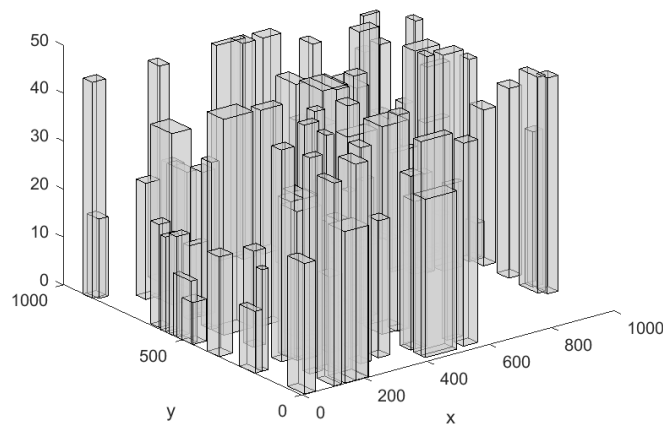
<https://arxiv.org/abs/2010.02749>

NOMA-RIS Enhanced UAV-Aided Wireless Networks

◆ System model

Channel model:

3D radio map reconstruction:



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

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NOMA-RIS Enhanced UAV-Aided Wireless Networks

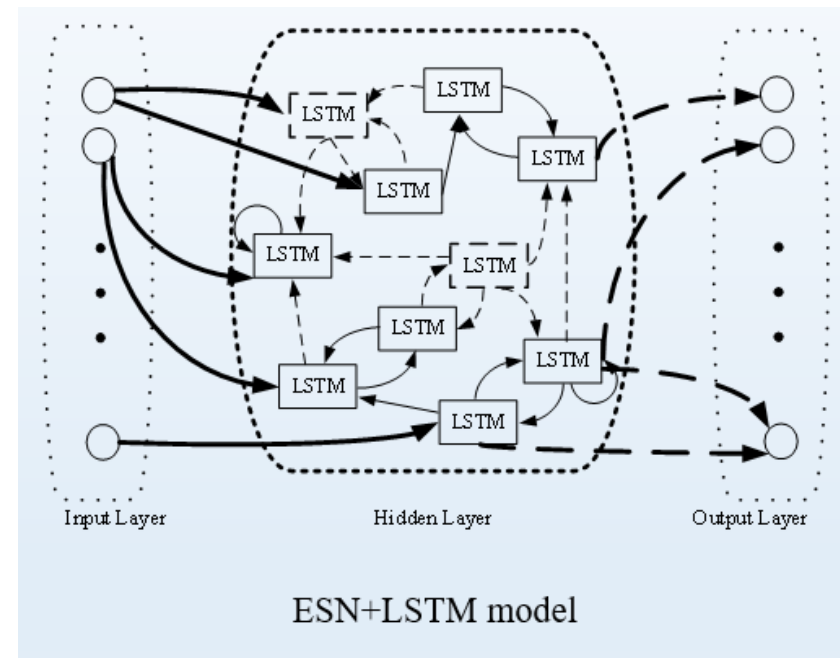
◆ Deep Learning (DL) user mobility/data demand prediction

Reasons for ESN+LSTM model

- Long-short-term-memory (LSTM): the computational training cost increases as the number of blocks increases.
- Echo state networks (ESN): it is possible to improve its performance by adjusting the hidden layer weights (sacrificing its simplicity).

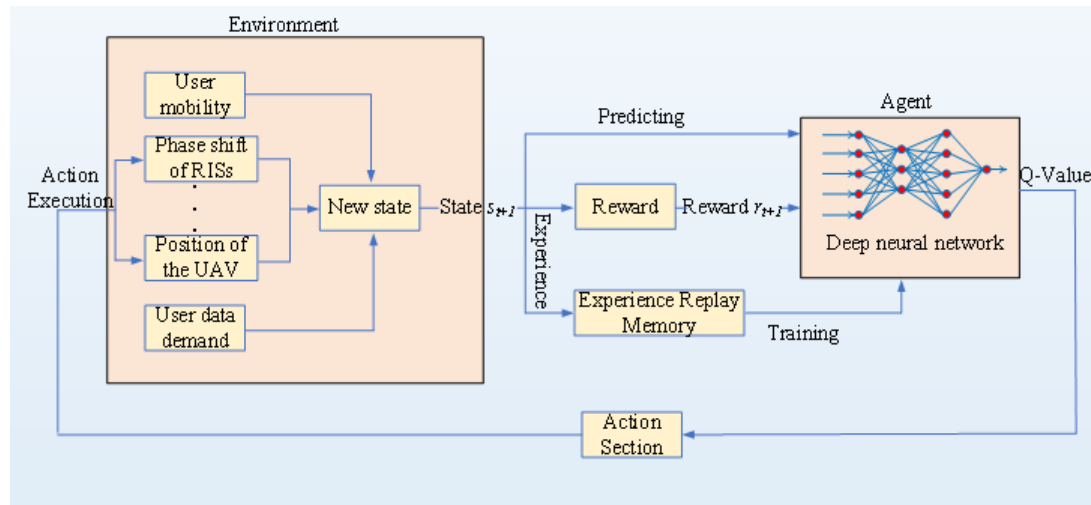
The concept of ESN+LSTM model

- A recurrent neural network model based on the architecture of an ESN model using hidden neurons LSTM units.



NOMA-RIS Enhanced UAV-Aided Wireless Networks

◆ Deep reinforcement learning (DRL) for decision making



- 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**.

Challenges in UAV-Aided Wireless Networks

Fatal **weakness** of the UAV-enabled wireless networks

► Limited energy

- Limited endurance of the UAV (less than 30 minutes)

► Limited size

- Energy harvesting is impossible for UAVs
- Free space optical (FSO) communications (UV band) is non-trivial for

UAVs

► Backhaul

- Cable counteract the agility of UAVs
- FSO is non-trivial
- Direct satellite-UAV link is not enough

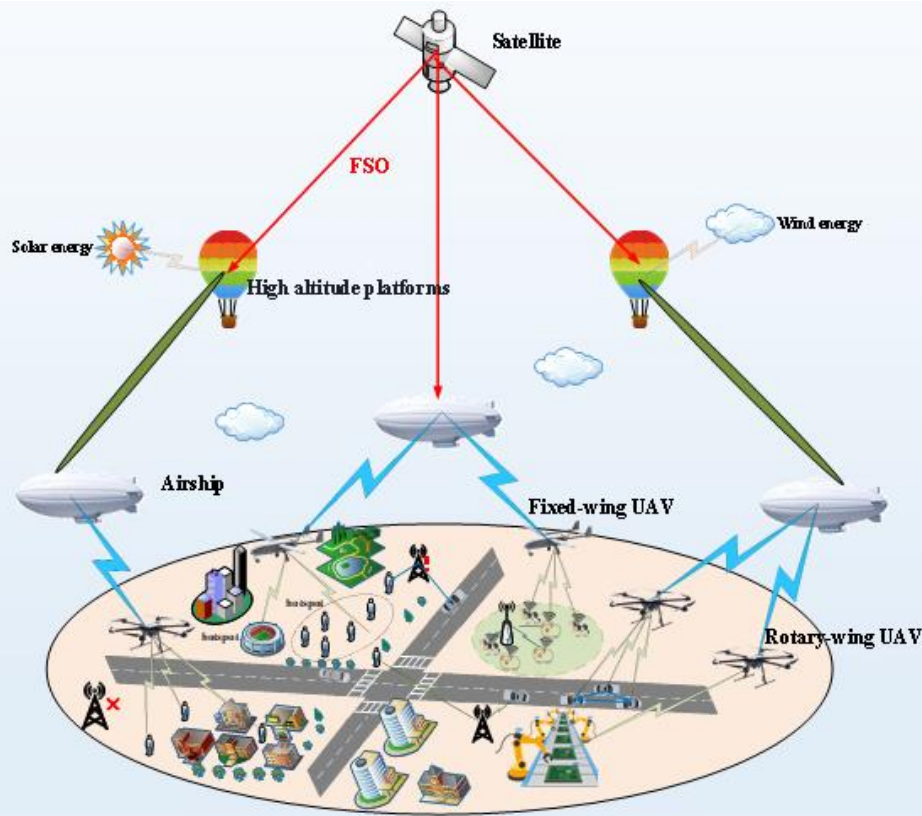


Research Opportunities and challenges for NOMA-UAV

1. Joint MIMO-NOMA-UAV design.
2. NOMA in Heterogenous Mobility UAV Networks
3. Massive NOMA in U2X Networks
4. NOMA for UAV and areal-to-ground communications
5. Security provisioning in NOMA-UAV Networks
6. Efficient machine learning algorithms for NOMA-UAV
7. NOMA enabled RIS-UAV networks
8. Spatial effect investigation for NOMA-UAV networks
9. Flexible user association for NOMA-UAV networks
10. Massive Non-Orthogonal Multiple Aerial Access (MNOMA²) for 5G and Beyond: From Satellite, HAP, to UAV Communication Networks



Massive Non-Orthogonal Multiple Aerial Access (MNOMA²) for 5G and Beyond: From Satellite, HAP, to UAV Communication Networks



Multi-tier

- Space: satellite
- Sky: high altitude platform, airship, UAV
- Terrestrial: cellular networks

Multi-function

- Satellite: backhaul (FSO: communication distance >10000km, 5.6Gbps)
- HAP: energy harvesting, backhaul (FSO to wireless radio)
- Airship: wireless charging for UAVs, backhaul (mmWave), aerial control/storage platform
- UAV: wireless service for ground users

Thanks for your attention



Queen Mary
University of London

