Signal Processing and Optimization in UAV Communication and Trajectory Design

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One World Signal Processing Seminar Series

Joint Seminar with IEEE SPS Distinguished Lectures

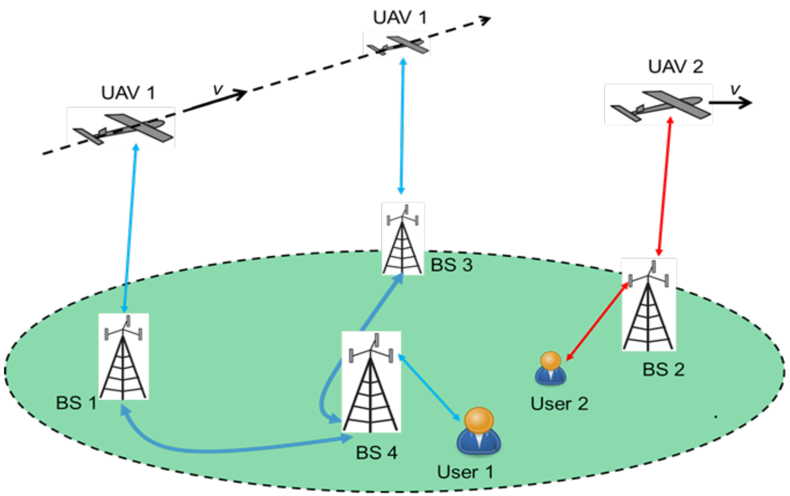
July 3, 2020

Outline

- Integrating UAVs into Cellular
  - Motivations and benefits
  - What’s new over terrestrial communications?
- Two Main (Signal Processing) Challenges
  - **UAV trajectory and communication joint design**
  - **UAV-terrestrial interference mitigation**
- Conclusion and Future Work

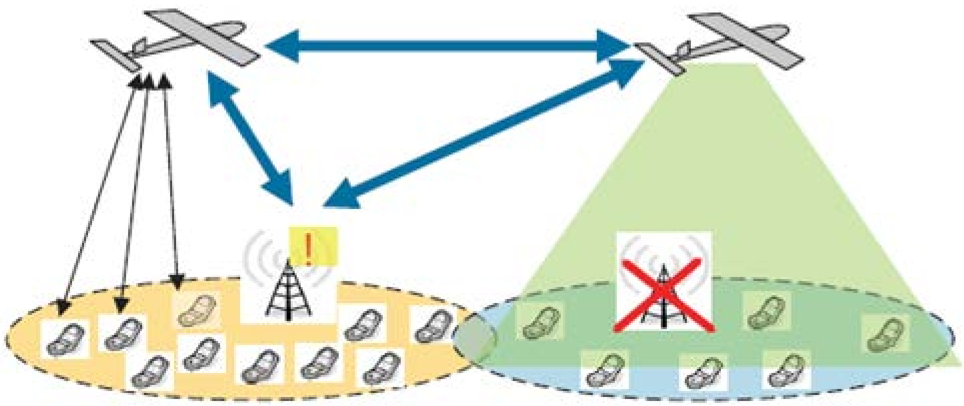
Integrating UAVs into Cellular: Two Main Paradigms

- Cellular-Connected UAV: UAV as new aerial user/terminal in cellular network



Typical applications:
- ✓ Control and Non-Payload Communications (CNPC)
- ✓ Video/photo upload
- ✓ Edge computing
- ✓ Localization (for UAV)

- UAV-Assisted Communication: UAV as new aerial communication platform



Typical applications:
- ✓ Aerial BS/AP/relay
- ✓ IoT data harvesting
- ✓ Wireless power transfer
- ✓ Localization (for ground terminal)

Integrating UAVs into 5G/6G: A Win-Win Technology

❑ 5G for UAVs:

- URLLC (with <20ms latency, >99.99% reliability): more secure CNPC
- eMBB (with 20 Gbps peak rate): real-time UHD video payload for VR/AR
- mMTC/D2D: UAV swarm communications and networking
- Massive MIMO: 3D coverage, aerial-terrestrial interference mitigation
- Cellular positioning (with cm accuracy): UAV localization/detection
- Edge-computing: UAV computing offloading, autonomous flight/navigation

❑ UAVs for 5G:

- New business opportunities by incorporating UAVs as new aerial users
- More robust and cost-effective cellular network with new aerial communication platforms

UAV Communications: What's New over Terrestrial?

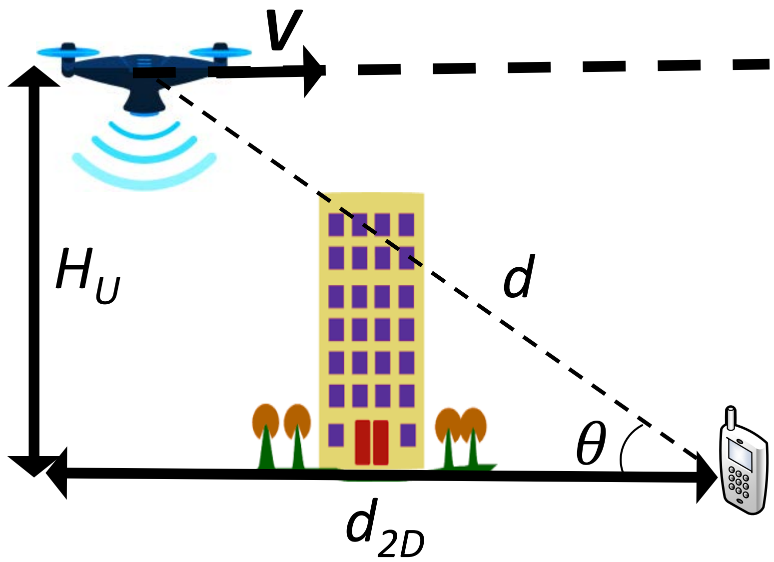
Characteristic	Opportunities	Challenges
High altitude	• Wide ground coverage as aerial BS/relay	• Require 3D cellular coverage for aerial user
High LoS probability	• Strong and reliable communication link • High macro-diversity • Slow communication scheduling and resource allocation	• Severe aerial-terrestrial interference • Susceptible to terrestrial jamming/eavesdropping
High 3D mobility	• Traffic-adaptive deployment • QoS-aware trajectory design	• Frequent handover • Time-varying wireless backhaul
Size, weight, and power (SWAP) constraint	—	• Limited payload and endurance • Energy-efficient design • Compact and lightweight antenna/RF design

Y. Zeng, Q. Wu, and R. Zhang, "Access from the Sky: a tutorial on UAV communications for 5G and beyond," *Proceedings of the IEEE*, Dec. 2019 (Invited Paper)

Outline

- ❑ Integrating UAVs into Cellular
  - ➢ Motivations and benefits
  - ➢ What's new over terrestrial communications?
- ❑ Two Main (Signal Processing) Challenges
  - ➢ **Trajectory optimization for UAV-assisted communication**
  - ➢ Aerial-ground interference mitigation for cellular-connected UAV
- ❑ Conclusion and Future Work

Exploiting UAV Mobility: How Much Can We Gain?



- UAV flies towards a ground terminal
- Double gains to improve the channel quality:
  - Shorter link distance
  - Less signal obstruction

- Assume the probabilistic LoS Channel model
- Large-scale channel power model for LoS and NLoS conditions

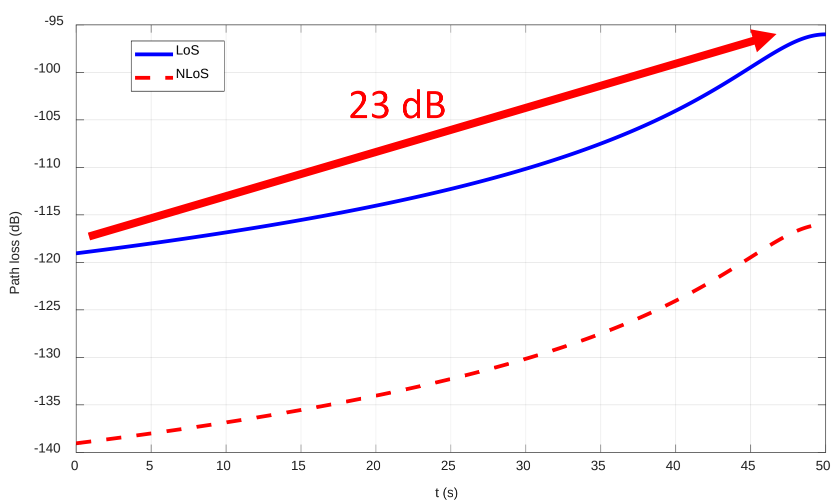
$$\beta(d) = \begin{cases} \beta_0 d^{-\alpha}, & \text{LoS Link} \\ \kappa \beta_0 d^{-\alpha}, & \text{NLoS Link} \end{cases}$$

$\kappa < 1$: additional attenuation for NLoS

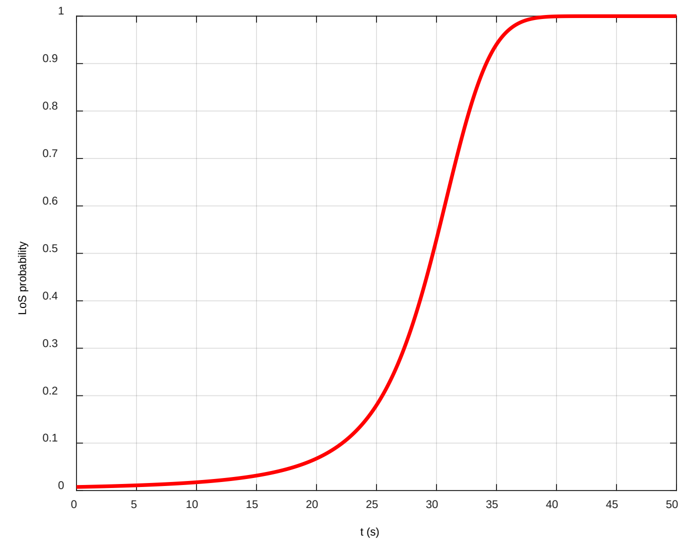
- LoS probability: $P_{LoS}(\theta) = \dfrac{1}{1 + a\exp(-b(\theta - a))}$

- Expected channel gain: $E[\beta(d)] = P_{LoS}(\theta)\beta_0 d^{-\alpha} + (1 - P_{LoS}(\theta))\kappa\beta_0 d^{-\alpha}$

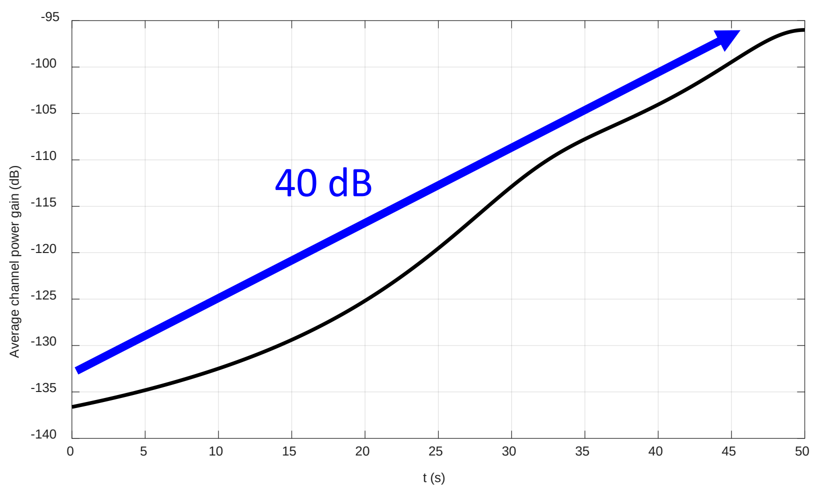
Exploiting UAV Mobility: How Much Can We Gain?



Channel gain for LoS and NLoS



LoS probability



Expected channel gain

Initial distance d_{2D}	1000 m
UAV altitude H_u	100 m
Flying speed v	20 m/s
Path loss exponent α	2.3
Reference channel gain β_0	-50 dB
Probabilistic LoS model parameters	$a = 10, b = 0.6,$ $\kappa = 0.01$

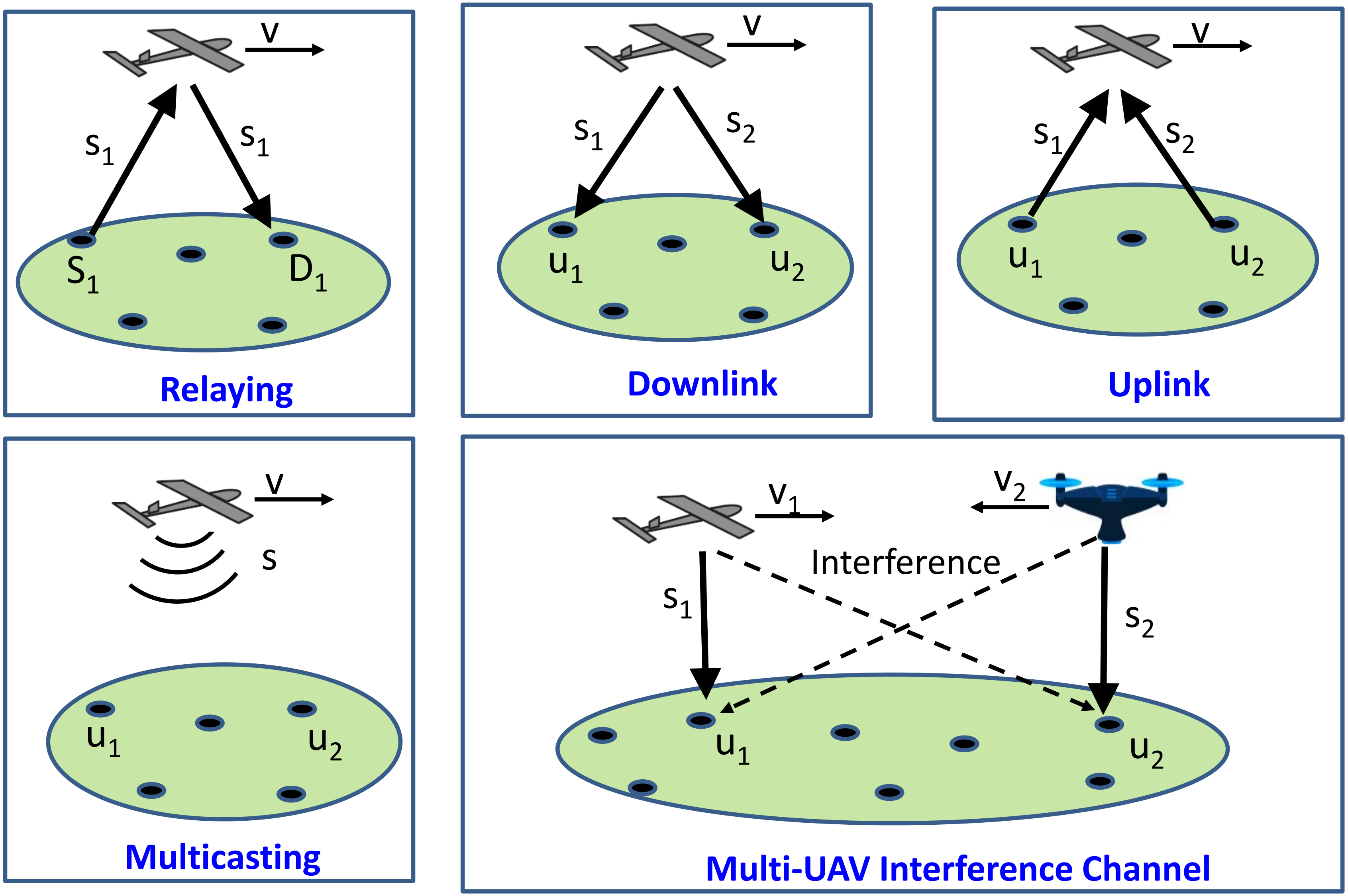
Exploiting UAV Mobility for Communication: Key Points

- Moving UAV closer to ground terminals brings significant performance gain, beyond the conventional communication design

- Main considerations for UAV trajectory design:
  - 3D channel model (path loss, LoS probability)
  - Interference (air-to-air, air-to-ground)
  - Wireless backhaul (location dependent, time varying)
  - Limited on-board battery/endurance

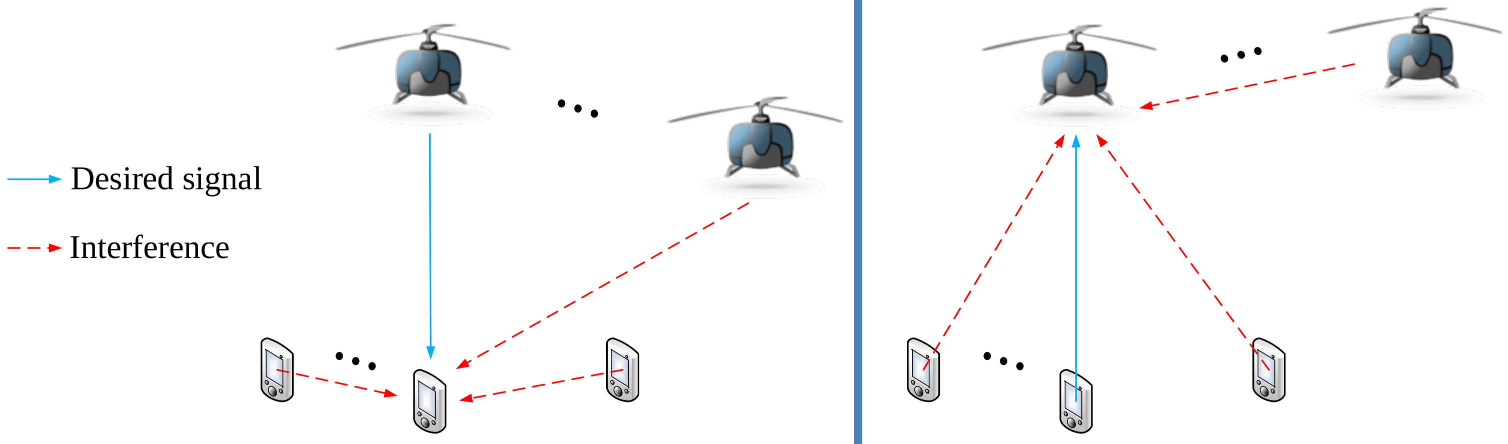
- Useful techniques for trajectory and communication co-design
  - Graph theory (e.g., travelling salesman problem, shortest-path problem)
  - Quantization techniques (trajectory time/path discretization)
  - Optimization techniques (block-coordinate descent, successive convex approximation, etc.)

UAV-Assisted Communication: Fundamental Models



UAV Communication: Performance Metric

- Signal to interference-plus-noise ratio (SINR)
- Outage/coverage probability
- Communication throughput/delay
- Spectral/energy efficiency
- All dependent on UAV location/trajectory



(a) UAV as a transmitter

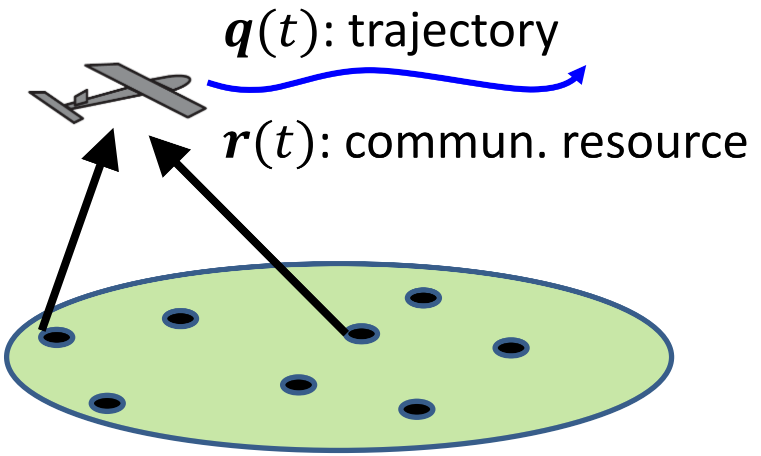
(b) UAV as a receiver

$$\gamma_k(\mathrm{Q}) = \frac{S(\mathbf{q}_k)}{I_{\text{ter}} + I_{\text{aer}}(\mathrm{Q}_k^-) + \sigma^2}$$

$$\gamma_k(\mathrm{Q}) = \frac{S(\mathbf{q}_k)}{I_{\text{ter}}(\mathbf{q}_k) + I_{\text{aer}}(\mathrm{Q}) + \sigma^2}$$

Joint Trajectory-Communication Optimization: Generic Formulation

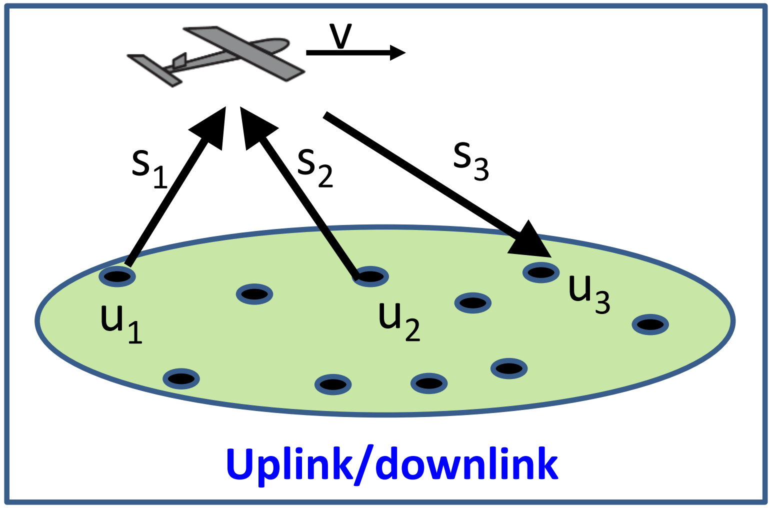
$$
\begin{aligned}
\max_{\{\mathbf{q}(t)\},\{\mathbf{r}(t)\}} \quad & U\left(\{\mathbf{q}(t)\},\{\mathbf{r}(t)\}\right) \\
\text{s.t.} \quad & f_i\left(\{\mathbf{q}(t)\}\right) \geq 0,\ \ i=1,\cdots,I_1, \\
& g_i\left(\{\mathbf{r}(t)\}\right) \geq 0,\ \ i=1,\cdots,I_2, \\
& h_i\left(\{\mathbf{q}(t)\},\{\mathbf{r}(t)\}\right) \geq 0,\ \ i=1,\cdots,I_3.
\end{aligned}
$$



- U: utility functions, e.g., communication rate, SINR, coverage probability, spectrum/energy efficiency
- f_i: trajectory constraints, e.g., speed constraint, obstacle/collision avoidance
- g_i: communication resource constraints, e.g., power, bandwidth
- h_i: coupled constraints, e.g., maximum tolerable interference power, minimum SINR requirement
- Include 3D UAV placement as a special case (not discussed today)

Path Planning: Travelling Salesman Problem

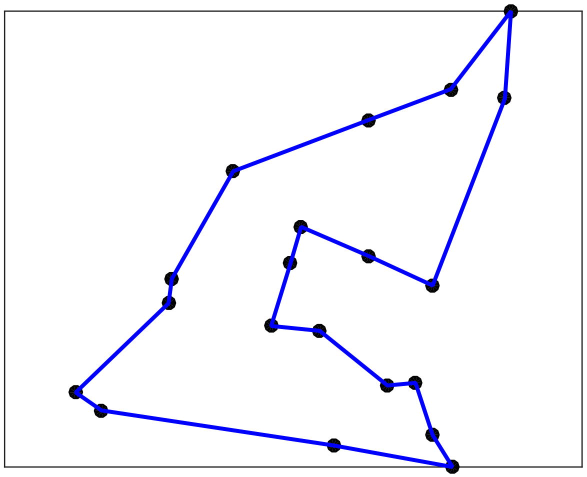
- UAV path planning: For UAV-enabled communications with ground users, determine the optimal flying path to serve them sequentially
- Intuition: fly to each ground user as close as possible



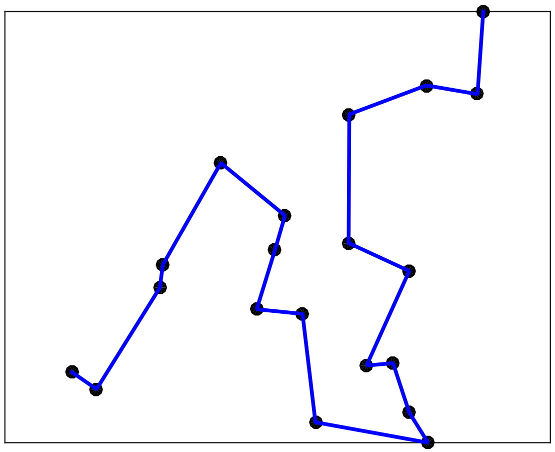
- Travelling salesman problem (TSP): Given K cities and the distances between each pair of cities, find the shortest route that visits each city and returns to the origin city
  - Complexity by exhaustive search: $K!$ (NP hard)
  - Many heuristic and optimal algorithms (up to tens of thousands of cities) have been proposed

Variations of Travelling Salesman Problem (TSP)

- The standard TSP requires the traveler return to the origin city
- For UAV communications, the UAV may not necessarily return to the original location, and the initial and/or final locations may be pre-specified
  - TSP Variation 1: No return
  - TSP Variation 2: No return, specified initial and final locations $\boldsymbol{q}_0$ and $\boldsymbol{q}_F$
  - TSP Variation 3: No return, specified initial location $\boldsymbol{q}_0$, any final location



Standard TSP

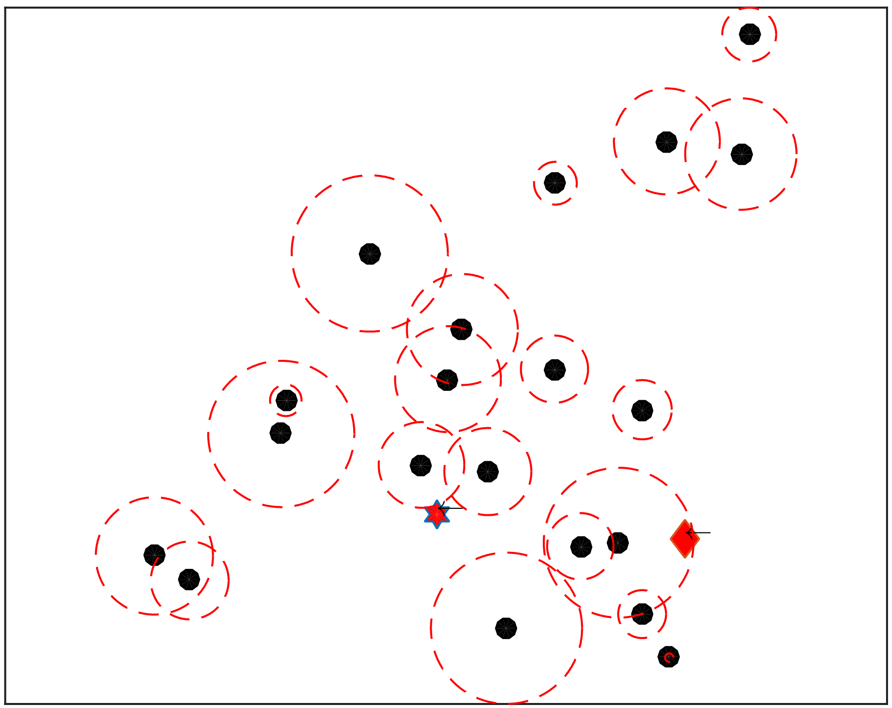


No Return

Y. Zeng, X. Xu, and R. Zhang, "Trajectory design for completion time minimization in UAV-enabled multicasting", *IEEE Trans. Wireless Commun.*, April 2018.

Travelling Salesman Problem with Neighborhood

- When the total operation time T is small, the UAV may not be able to visit all users
- TSP with neighborhood (TSPN): Given K cities and the neighborhoods of each city, find the shortest route that visits each neighborhood once
- A generalization of TSP, also NP-hard



$$\min_{\{\mathbf{q}_k\},\{\pi(k)\}} \sum_k \left\| \mathbf{q}_{\pi(k+1)} - \mathbf{q}_{\pi(k)} \right\|$$

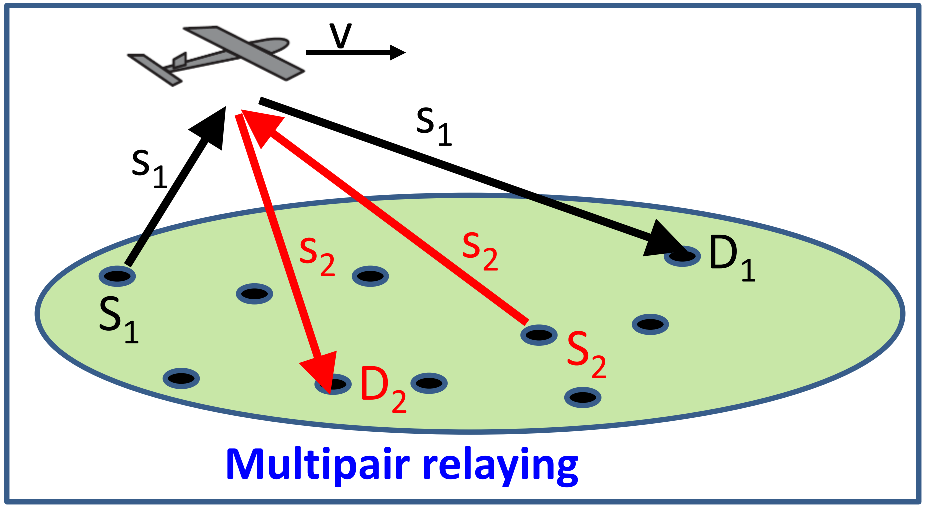
$$\text{s.t.} \quad \left[\pi(1),\ldots,\pi(k)\right] \in \mathrm{P}$$

$$\left\| \mathbf{q}_k - \mathbf{w}_k \right\| \le r_k, \forall k$$

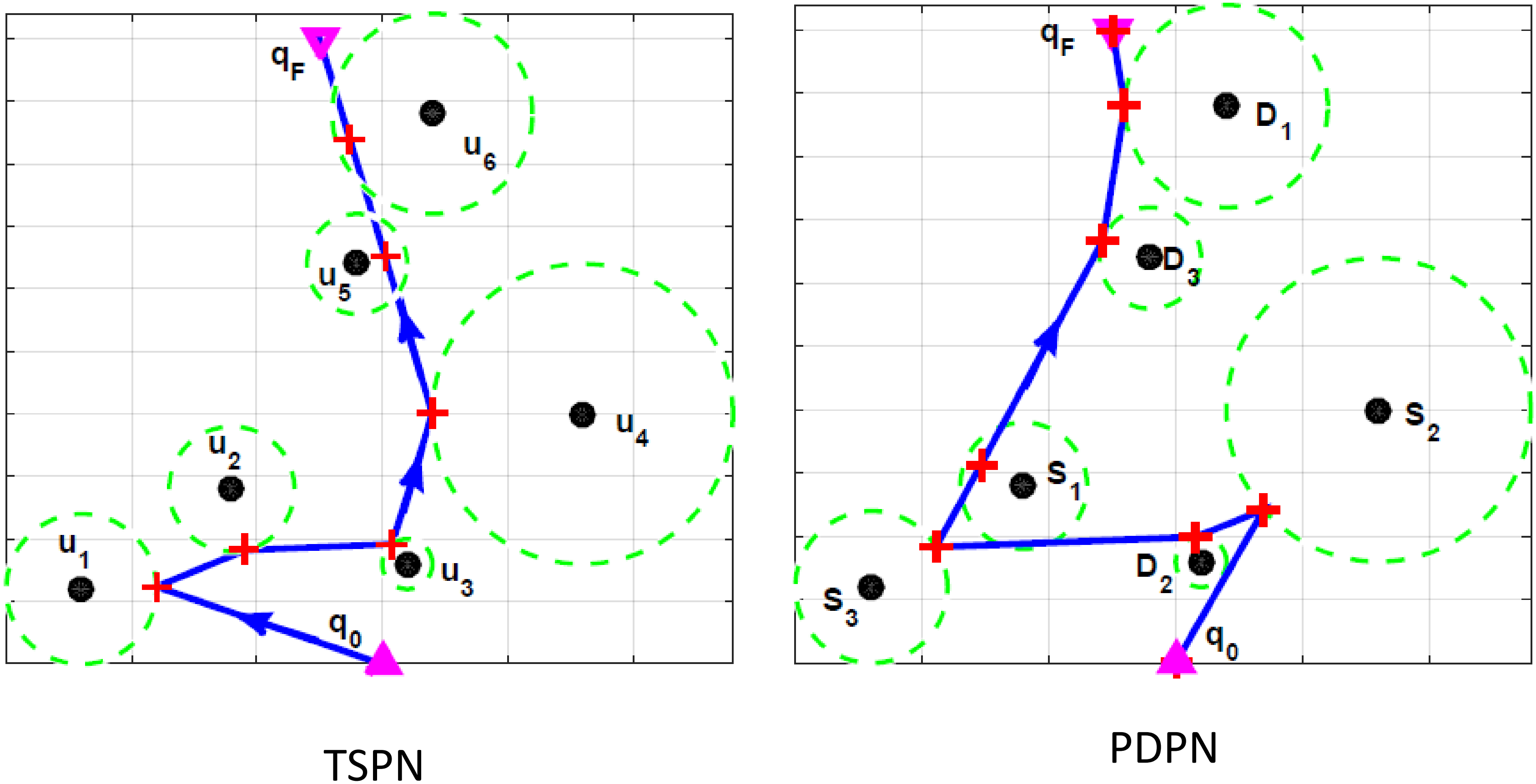
$\mathcal{P}$: set of all $K!$ possible permutations

Pickup-and-Delivery Problem (PDP)

- For UAV-enabled multi-pair relaying, determine the UAV flying path subject to
  - Information-causality constraint: UAV needs to first receive data from a source before forwarding to its destination
- Pickup-and-Delivery Problem (PDP): A generalization of TSP with precedence constraints: for each source-destination pair, visit source before destination
- NP-hard, while algorithms for high-quality solutions exist
- PDP with neighborhood (PDPN)



UAV Path Planning with TSPN and PDPN



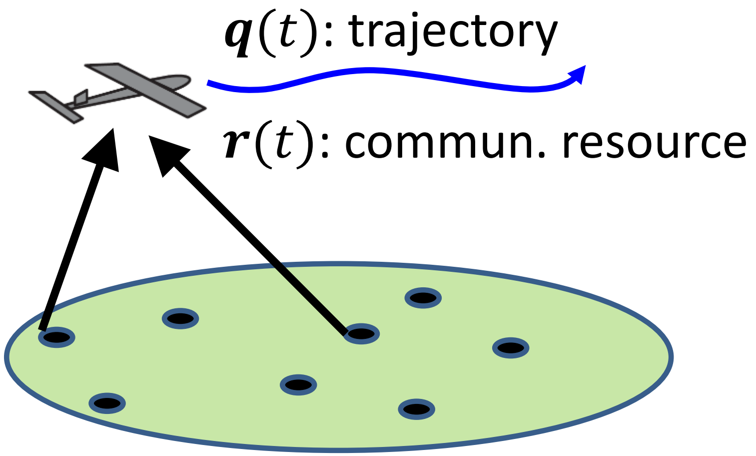
J. Zhang, Y. Zeng, and R. Zhang, "UAV-enabled radio access network: multi-mode communication and trajectory design," *IEEE Trans. Signal Process.*, Oct. 2018.

Limitations of TSP/PDP For Trajectory Optimization

- Suboptimal trajectory in general:
  - Straight flight between waypoints only (i.e., piecewise linear), while optimal trajectory for communication are curved in general
- Ignores various communication/trajectory constraints:
  - Rate requirement, interference, obstacle avoidance, maximum/minimum speed, no-fly zone….
- Only gives UAV flying path, but trajectory optimization includes both path planning and speed optimization
- A general framework: joint UAV trajectory and communication resource allocation optimization, by employing
  - TSP/PDP-based path for initial trajectory
  - Time/path discretization
  - Optimization (block coordinate descent, successive convex approximation, etc.)

Joint Trajectory-Communication Optimization: Continuous-Time Formulation

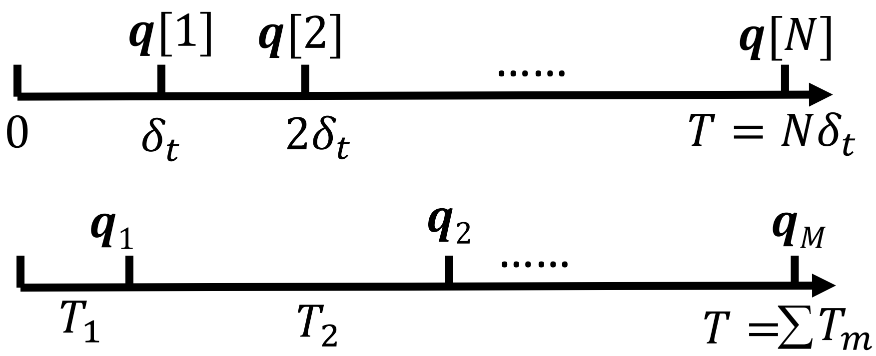
$$\begin{aligned} \max_{\{\mathbf{q}(t)\},\{\mathbf{r}(t)\}} \quad & U\left(\{\mathbf{q}(t)\},\{\mathbf{r}(t)\}\right) \\ \text{s.t.} \quad & f_i\left(\{\mathbf{q}(t)\}\right) \geq 0,\ i = 1,\cdots,I_1, \\ & g_i\left(\{\mathbf{r}(t)\}\right) \geq 0,\ i = 1,\cdots,I_2, \\ & h_i\left(\{\mathbf{q}(t)\},\{\mathbf{r}(t)\}\right) \geq 0,\ i = 1,\cdots,I_3. \end{aligned}$$



- The continuous-time representation of trajectory involves infinite number of variables
- Discretization is necessary for optimization and computation purposes
- Two discretization methods: time discretization and path discretization

Time vs. Path Discretization

- Path discretization: generalized time discretization with variable slot length



Time discretization: T must known

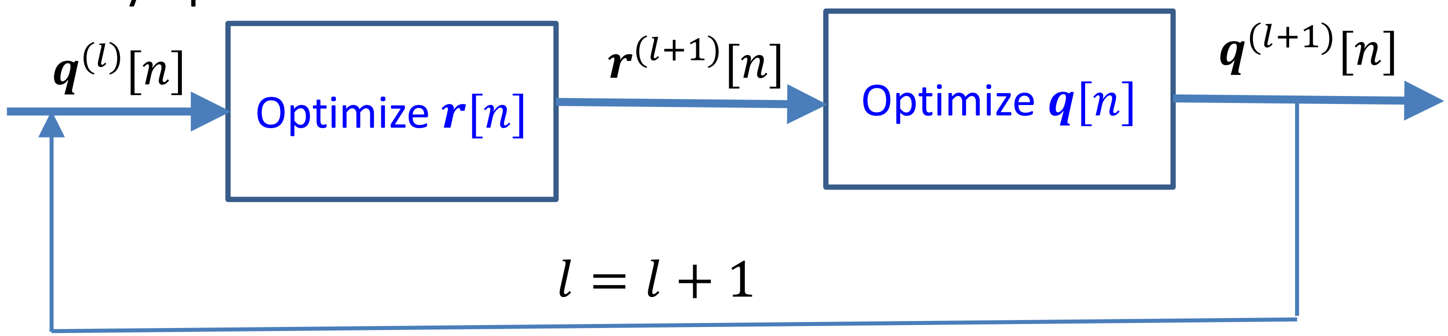
Path discretization: T can be unknown

	Time Discretization	Path Discretization
Pros	• Equal time slot length • Linear state-space representation • Incorporate maximum acceleration constraint easily	• Fewer variables if UAV hovers or flies slowly • No need to know *T a priori*
Cons	• Excessively large number of time slots when UAV moves slowly • Needs to know *T a priori*	• More variables if UAV flies with high/maximum speed most of the time

Block Coordinate Descent

$$\max_{\{\mathbf{q}[n]\},\{\mathbf{r}[n]\}} \quad U\left(\{\mathbf{q}[n]\},\{\mathbf{r}[n]\}\right)$$
$$\text{s.t.} \quad f_i\left(\{\mathbf{q}[n]\}\right) \geq 0, \ i = 1,\cdots,I_1,$$
$$g_i\left(\{\mathbf{r}[n]\}\right) \geq 0, \ i = 1,\cdots,I_2,$$
$$h_i\left(\{\mathbf{q}[n]\},\{\mathbf{r}[n]\}\right) \geq 0, \ i = 1,\cdots,I_3.$$

- Time or path discretization converts the problem into a discrete form
- The (discrete) joint trajectory and resource optimization problems are generally non-convex and difficult to solve
- Block coordinate descent: alternately update one block of variables (say, trajectory) with the other (resource allocation) fixed. Monotonically converge to a locally optimal solution



Successive Convex Approximation

- Even with given resource allocation, UAV trajectory optimization is usually non-convex, and thus difficult to solve
  - Non-concave objective functions: e.g., rate maximization
  - Non-convex constraints: e.g., obstacle/collision avoidance, minimum speed
- Successive convex approximation (SCA):
  - local optimization via solving a sequence of convex problems
  - converges to a KKT solution if appropriate local bounds are found

$$\max_{\{\mathbf{q}[n]\}} \; f_0\left(\{\mathbf{q}[n]\}\right) \quad \text{s.t.} \; f_i\left(\{\mathbf{q}[n]\}\right) \geq 0, \; i = 1, \cdots, I.$$

Non-convex optimization problem

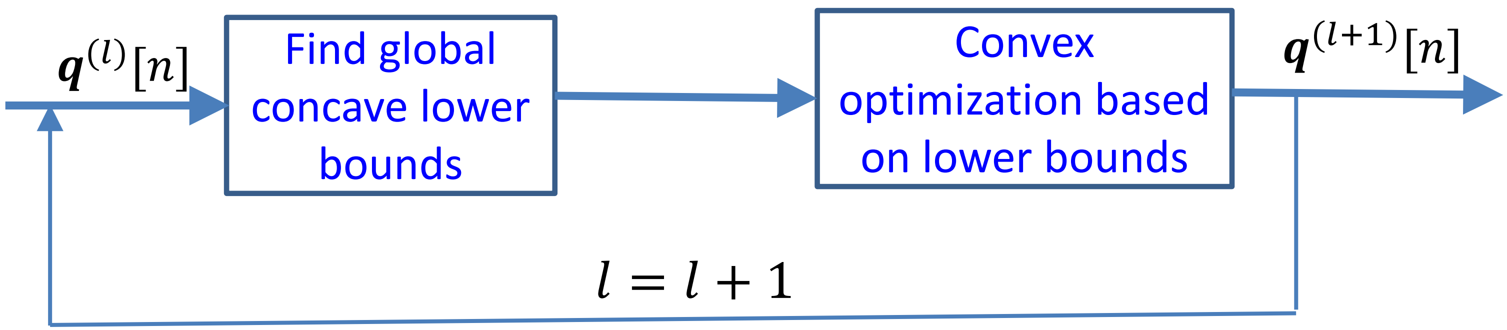
Global concave lower bound

$$f_i\left(\{\mathbf{q}[n]\}\right) \geq f_{i,\text{lb}}^{(l)}\left(\{\mathbf{q}[n]\}\right), \forall \mathbf{q}[n], \; i = 0, \cdots, I$$

$$\max_{\{\mathbf{q}[n]\}} \; f_{0,\text{lb}}^{(l)}\left(\{\mathbf{q}[n]\}\right) \quad \text{s.t.} \; f_{i,\text{lb}}^{(l)}\left(\{\mathbf{q}[n]\}\right) \geq 0, \; i = 1, \cdots, I.$$

- Convex optimization problem
- Solution is feasible to the original non-convex problem

Successive Convex Approximation



- Communication rate maximization:

$$\log_2\left(1+\frac{\gamma_0}{\|\mathbf{q}[n]-\mathbf{w}_k\|^{\alpha}}\right) \geq A_k - B_k\left(\|\mathbf{q}[n]-\mathbf{w}_k\| - \|\mathbf{q}^{(l)}[n]-\mathbf{w}_k\|\right)$$

A_k, B_k: poisitive coefficients depending on $\boldsymbol{q}^{(l)}[n]$

- Minimum speed constraint:

$$\|\mathbf{v}[n]\| \geq V_{\min}$$

$$\|\mathbf{v}[n]\|^2 \geq \|\mathbf{v}^{(l)}[n]\|^2 + 2\mathbf{v}^{(l)T}[n]\left(\mathbf{v}[n]-\mathbf{v}^{(l)}[n]\right) \geq V_{\min}^2$$

Complexity Reduction

- BSUMM (Block Successive Upper bound minimization Method of Multipliers) based optimization
  - Generalization of ADMM (Alternating Direction Method of Multipliers)
  - Jointly optimize commun. scheduling and UAV trajectory (instead of using BCD)
  - Enable parallel optimization over multiple UAVs, thus more efficient if implemented with a multi-core processor
- Receding horizon (sliding window) based optimization
  - Block-by-block trajectory optimization with a moving window of finite duration
  - Unequal time/path discretization in each window to trade-off between performance and complexity

C. Shen, T.-H. Chang, J. Gong, Y. Zeng, and R. Zhang, "Multi-UAV interference coordination via joint trajectory and power control," *IEEE Transactions on Signal Processing*, January 2020.

J. Zhang, Y. Zeng, and R. Zhang, "Receding horizon optimization for energy-efficient UAV communication," *IEEE Wireless Communications Letters*, April 2020.

Case Studies

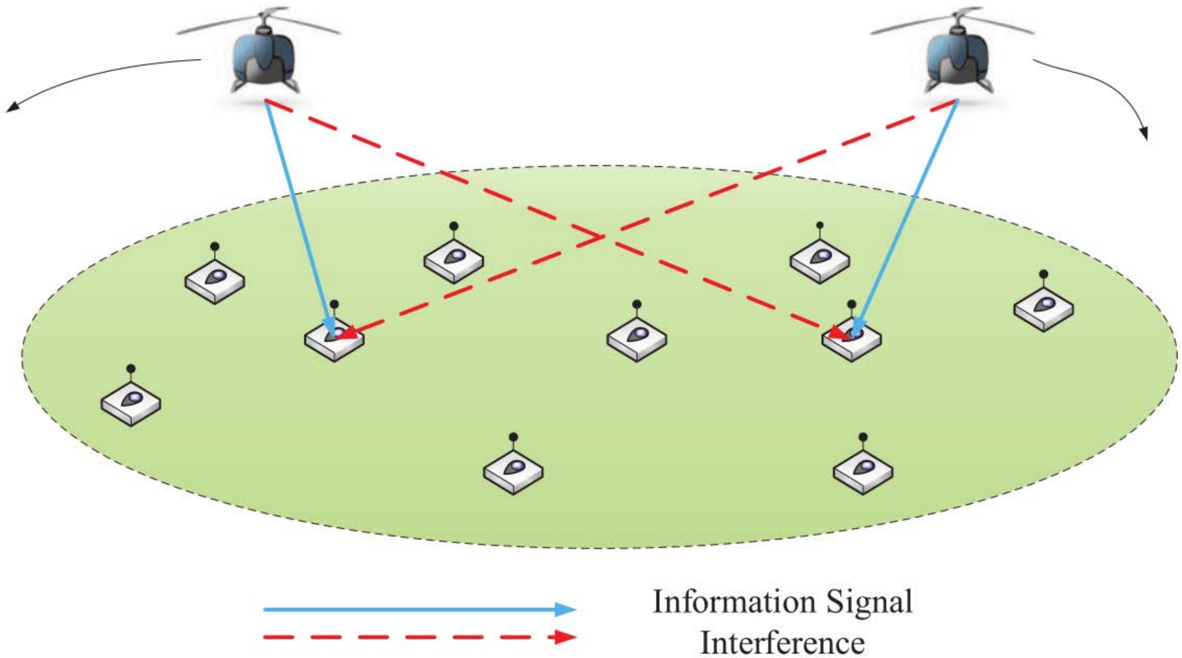
- Multi-UAV enabled wireless network

Q. Wu, Y. Zeng, and R. Zhang, "Joint trajectory and communication design for multi-UAV enabled wireless networks," *IEEE Trans. Wireless Commun.,* Mar. 2018.

- Energy-efficient UAV communication

Y. Zeng and R. Zhang, "Energy-Efficient UAV Communication with Trajectory Optimization," *IEEE Trans. Wireless Commun.*, June 2017. **(IEEE Marconi Prize Paper Award in Wireless Communications, 2020)**

Multi-UAV Enabled Wireless Network



- Multi-UAV downlink communications with ground users
- TDMA for user communication scheduling
- Problem: maximize the minimum average rate of all users via joint communication (scheduling, power control) and UAV trajectories optimization

Problem Formulation

$$\max_{\eta, \mathbf{A}, \mathbf{Q}, \mathbf{P}} \quad \eta$$

$$\text{s.t.} \quad \frac{1}{N}\sum_{n=1}^{N}\sum_{m=1}^{M} \alpha_{k,m}[n]\log_2\left(1+\gamma_{k,m}[n]\right) \geq \eta, \forall k,$$ ← Minimum rate requirement

$$\sum_{k=1}^{K} \alpha_{k,m}[n] \leq 1, \forall m, n,$$

$$\sum_{m=1}^{M} \alpha_{k,m}[n] \leq 1, \forall k, n,$$

$$\alpha_{k,m}[n] \in \{0,1\}, \forall k, m, n,$$

← TDMA constraints (the three constraints above)

$$||\mathbf{q}_m[n+1] - \mathbf{q}_m[n]||^2 \leq S_{\max}^2, n = 1, ..., N-1,$$ ← UAV mobility constraint

$$\mathbf{q}_m[1] = \mathbf{q}_m[N], \forall m,$$ ← Initial/final location constraint

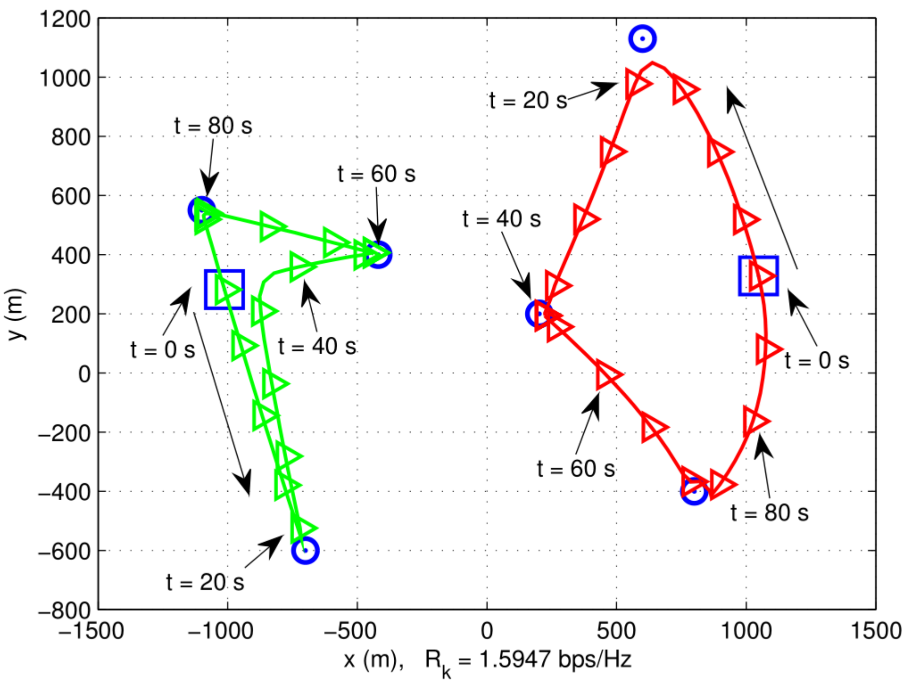
$$||\mathbf{q}_m[n] - \mathbf{q}_j[n]||^2 \geq d_{\min}^2, \forall n, m, j \neq m,$$ ← collision avoidance constraint

$$0 \leq p_m[n] \leq P_{\max}, \forall m, n.$$ ← power constraint

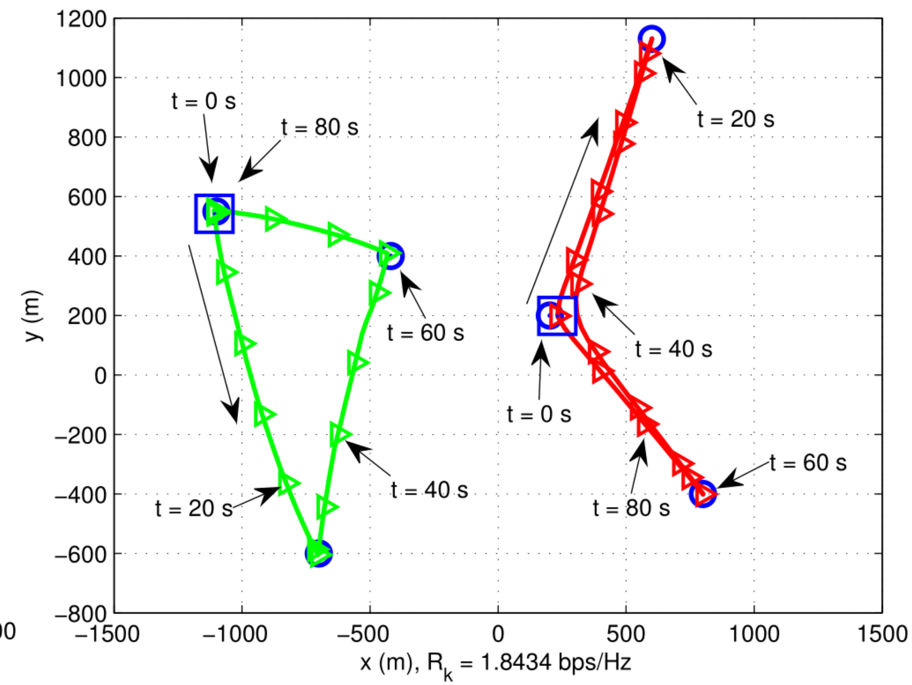
- Nonconvex, solved by time-discretization and block coordinate descent

Simulation Results

- New Interference-mitigation approach: coordinated multi-UAV trajectory design

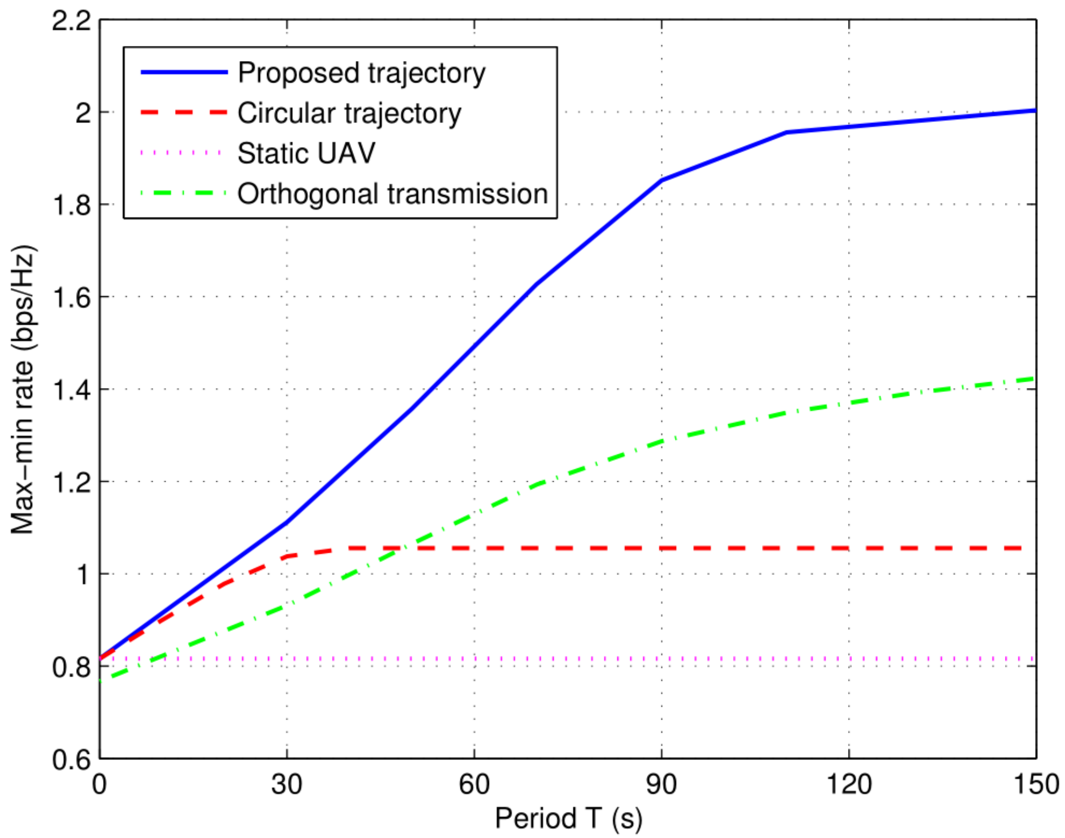


(a) Optimized UAV trajectories without power control.



(b) Optimized UAV trajectories with power control.

Simulation Results: Throughput-Delay Tradeoff



- ❑ Longer flight period achieves higher throughput than static UAV, but incurs larger user delay on average

UAV Energy Consumption Model

- **Limited on-board energy**: critical issue in UAV communication, for both UAV as user or BS/relay
- UAV energy consumption: Propulsion energy >> Communication energy
- Empirical and Heuristic Models:
  - Empirical model based on measurement results, e.g.,
    - ✓ Fuel cost modelled by L1 norm of control force
    - ✓ Fuel cost proportional to the square of speed
- Analytical Model
  - Closed-form model based on well-established results in aircraft literature
  - Propulsion power as a function of speed and acceleration

Y. Zeng and R. Zhang, "Energy-Efficient UAV Communication with Trajectory Optimization," *IEEE Trans. Wireless Commun.*, June 2017. **(IEEE Marconi Prize Paper Award in Wireless Communications, 2020)**

Y. Zeng, J. Xu, and R. Zhang, "Energy minimization for wireless communication with rotary-wing UAV," *IEEE Trans. Wireless Commun.,* Apr. 2019.

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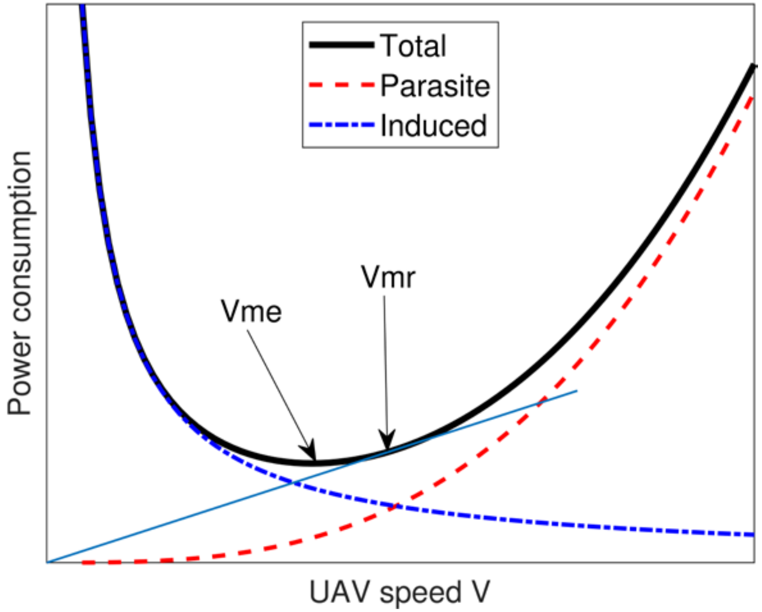
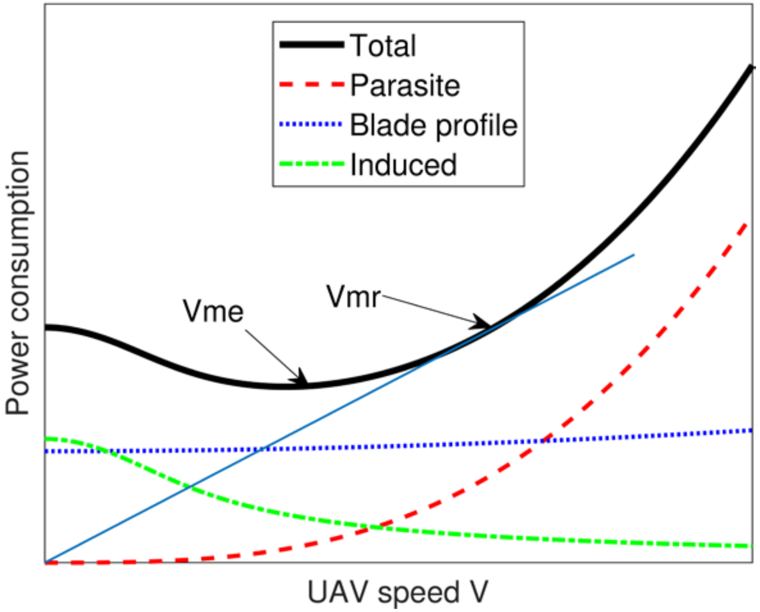
Energy Model Comparison: Straight and level flight

	Fixed-Wing	Rotary-Wing
Convexity with respect to V	Convex	Non-convex
Components	Induced and parasite	Induced, parasite, and blade profile
$V = 0$	Infinity	Finite

Fixed-Wing



Rotary-Wing



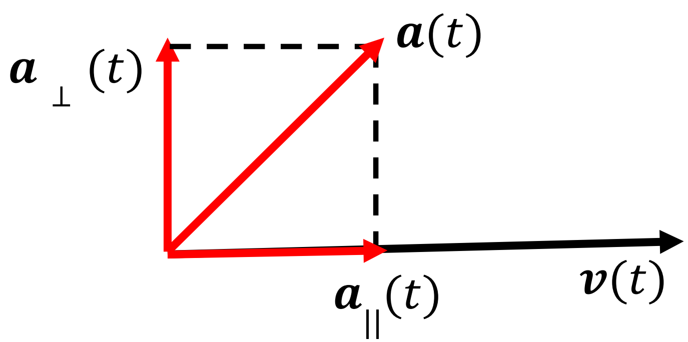
Energy Model with General Level Flight (Fixed-Wing)

$$\bar{E}(\mathbf{q}(t)) = \underbrace{\int_0^T \left[c_1 \|\mathbf{v}(t)\|^3 + \frac{c_2}{\|\mathbf{v}(t)\|} \left(1 + \frac{\overbrace{\|\mathbf{a}(t)\|^2 - \frac{(\mathbf{a}^T(t)\mathbf{v}(t))^2}{\|\mathbf{v}(t)\|^2}}^{\boldsymbol{a}_\perp^2(t)}}{g^2} \right) \right] dt}_{\text{Work required to overcome air resistance}} + \underbrace{\frac{1}{2} m \left(\|\mathbf{v}(T)\|^2 - \|\mathbf{v}(0)\|^2 \right)}_{\text{Change in kinetic energy}}$$

Work required to overcome air resistance

Change in kinetic energy

- Only depends on speed and centrifugal acceleration (causing heading change)
- Independent of actual location or tangential acceleration (causing speed change)
- Work-energy principle interpretation



Energy-Efficient UAV Communication

- UAV energy consumption (fixed-wing):

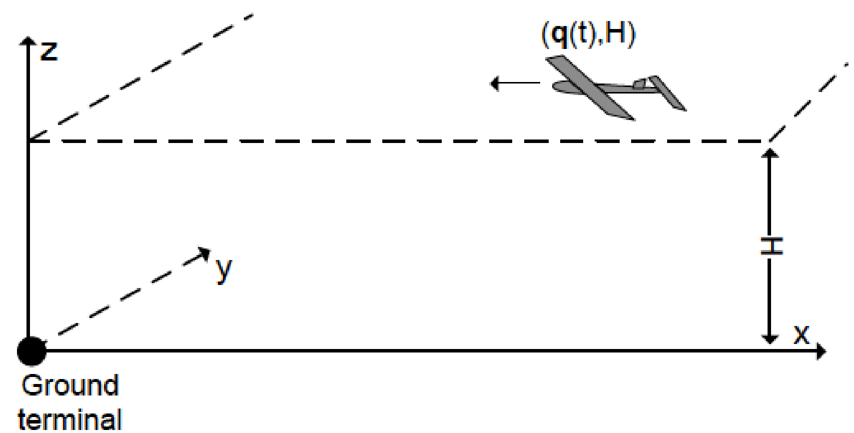
$$\bar{E}(\mathbf{q}(t)) = \int_0^T \left[c_1 \|\mathbf{v}(t)\|^3 + \frac{c_2}{\|\mathbf{v}(t)\|} \left(1 + \frac{\|\mathbf{a}(t)\|^2 - \frac{(\mathbf{a}^T(t)\mathbf{v}(t))^2}{\|\mathbf{v}(t)\|^2}}{g^2} \right) \right] dt + \frac{1}{2} m \left(\|\mathbf{v}(T)\|^2 - \|\mathbf{v}(0)\|^2 \right)$$

- Aggregate throughput as a function of UAV trajectory

$$\bar{R}(\mathbf{q}(t)) = \int_0^T B \log_2 \left(1 + \frac{\gamma_0}{H^2 + \|\mathbf{q}(t)\|^2} \right) dt$$

- Energy efficiency in bits/Joule:

$$\mathrm{EE}(\mathbf{q}(t)) = \frac{\bar{R}(\mathbf{q}(t))}{\bar{E}(\mathbf{q}(t))}$$



Energy Efficiency Maximization

- Maximize energy efficiency in bits/Joule via trajectory optimization

$$\max_{\mathbf{q}(t)} \ \mathrm{EE}(\mathbf{q}(t))$$

$$C_1: \ \mathbf{q}(0) = \mathbf{q}_0$$
$$C_2: \ \mathbf{q}(T) = \mathbf{q}_F$$
$$C_3: \ V_{\min} \le \|\mathbf{v}(t)\| \le V_{\max}, \forall t$$
$$C_4: \ \mathbf{v}(0) = \mathbf{v}_0$$
$$C_5: \ \mathbf{v}(T) = \mathbf{v}_F$$
$$C_6: \ \|\mathbf{a}(t)\| \le a_{\max}, \forall t,$$

Initial/final location constraint (C_1, C_2)

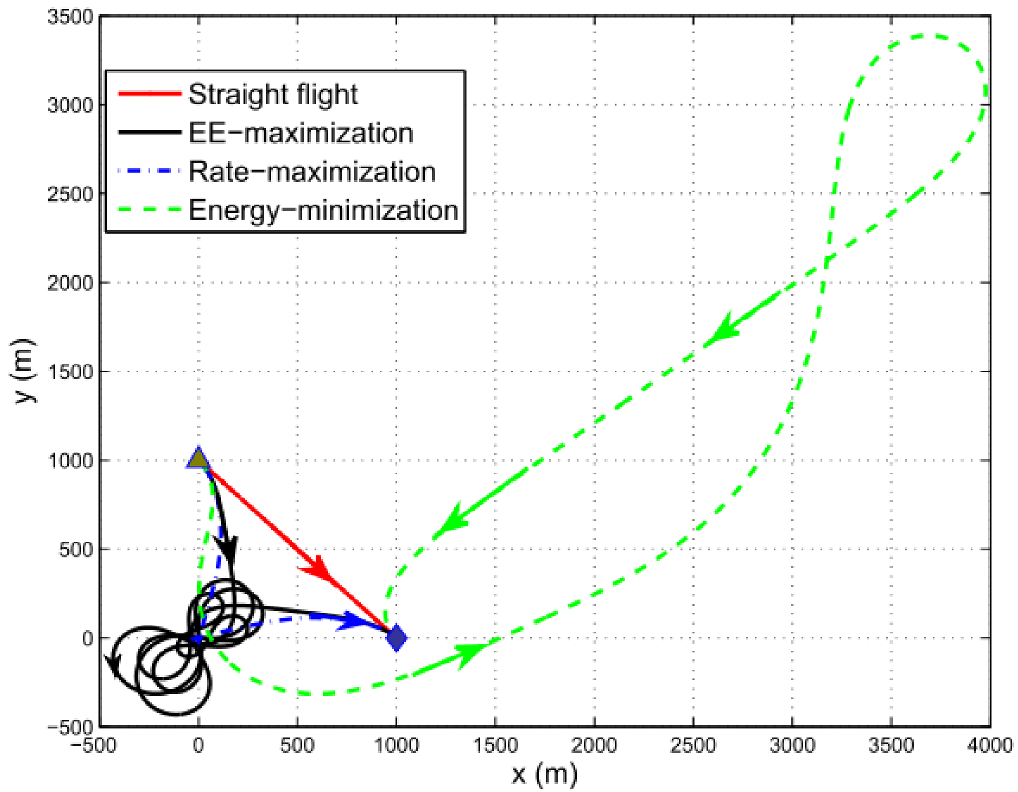
Min./Max. speed constraint (C_3)

Initial/final velocity constraint (C_4, C_5)

Max. acceleration constraint (C_6)

- Non-convex, solved by time discretization and successive convex approximation (SCA)

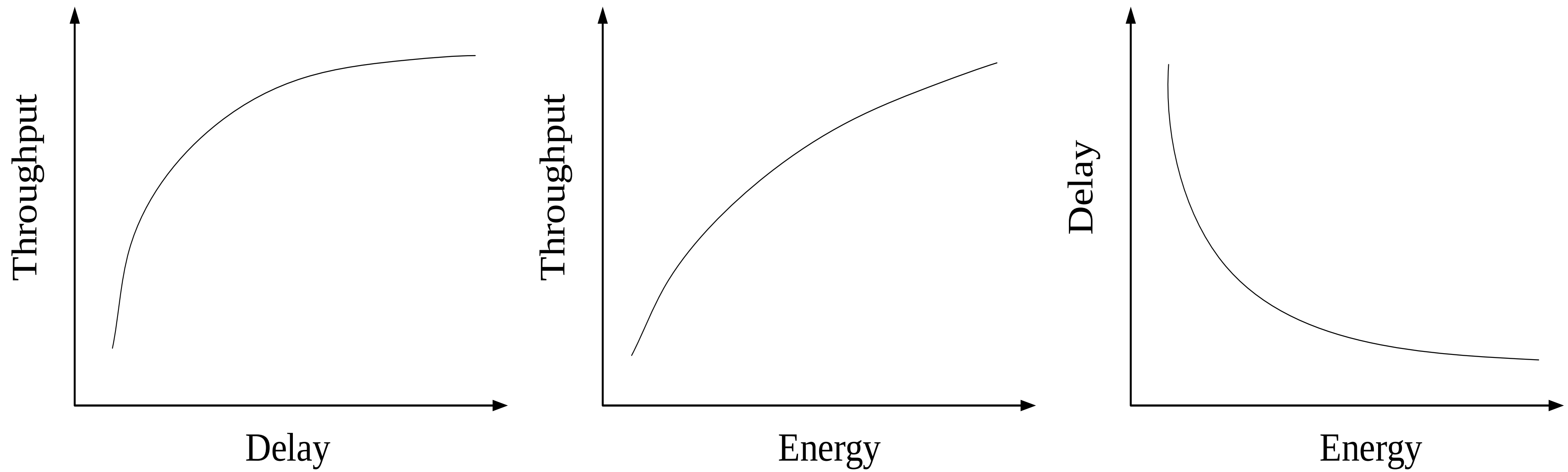
Simulation Results: Throughput-Energy Tradeoff



- Rate-max trajectory: stay as close as possible with the ground terminal
- Energy-min trajectory: less acute turning
- EE-max trajectory: balance the two, “8” shape trajectory

Fundamental Tradeoffs in UAV Trajectory and Communication Design

- Throughput-Delay Tradeoff
- Throughput-Energy Tradeoff
- Delay-Energy Tradeoff



Q. Wu, L. Liu, and R. Zhang, "Fundamental tradeoffs in communication and trajectory design for UAV-enabled wireless network," *IEEE Wireless Communications*, Feb. 2019.

Trajectory Optimization: Recent Results

- 3D trajectory optimization in Rician fading channel

C. You and R. Zhang, "3D trajectory optimization in Rician fading for UAV-enabled data harvesting," *IEEE Transactions on Wireless Communications*, June 2019.

- Hybrid offline-online trajectory design in probabilistic LoS channel

C. You and R. Zhang, "Hybrid offline-online design for UAV-enabled data harvesting in probabilistic LoS channel," *IEEE Transactions on Wireless Communications,* June 2020.

Elevation-angle Dependent Rician Fading Channel

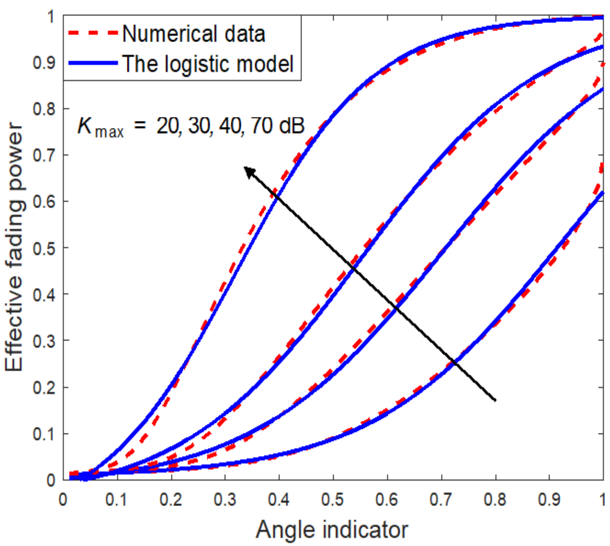
- Urban areas with high UAV altitude: Non-negligible small-scale fading
- Elevation-angle dependent Rician factor: $K = A_1 \exp(A_2\theta)$
- Outage-aware achievable rate:

$$R = \log_2\left(1 + \frac{\varphi\gamma}{||\mathbf{q}-\mathbf{w}||^2 + z^2}\right)$$

φ : effective fading power (regulation term w.r.t LoS model)

$$F(\varphi) = 1 - Q_1\left(\sqrt{2K}, \sqrt{2(K+1)\varphi}\right) = \epsilon$$

- Data regression and model fitting



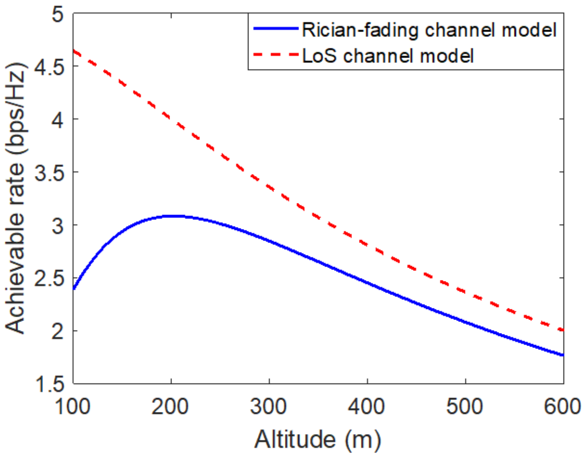
$$\varphi \approx \tilde{\varphi} = f(\mathbf{q}, z)$$

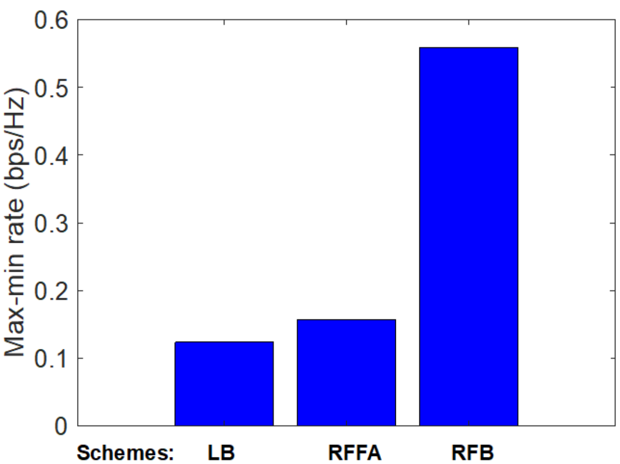
$$= C_1 + \frac{C_2}{1 + \exp\left(-\left(B_1 + B_2\frac{z}{\sqrt{||\mathbf{q}-\mathbf{w}||^2 + z^2}}\right)\right)}$$

- Depends on 3D UAV trajectory
- If $K_{\max} \to \infty$, then Rician fading $\to$ LoS channel
- If $K_{\max} \to 0$, then Rician fading $\to$ Rayleigh fading

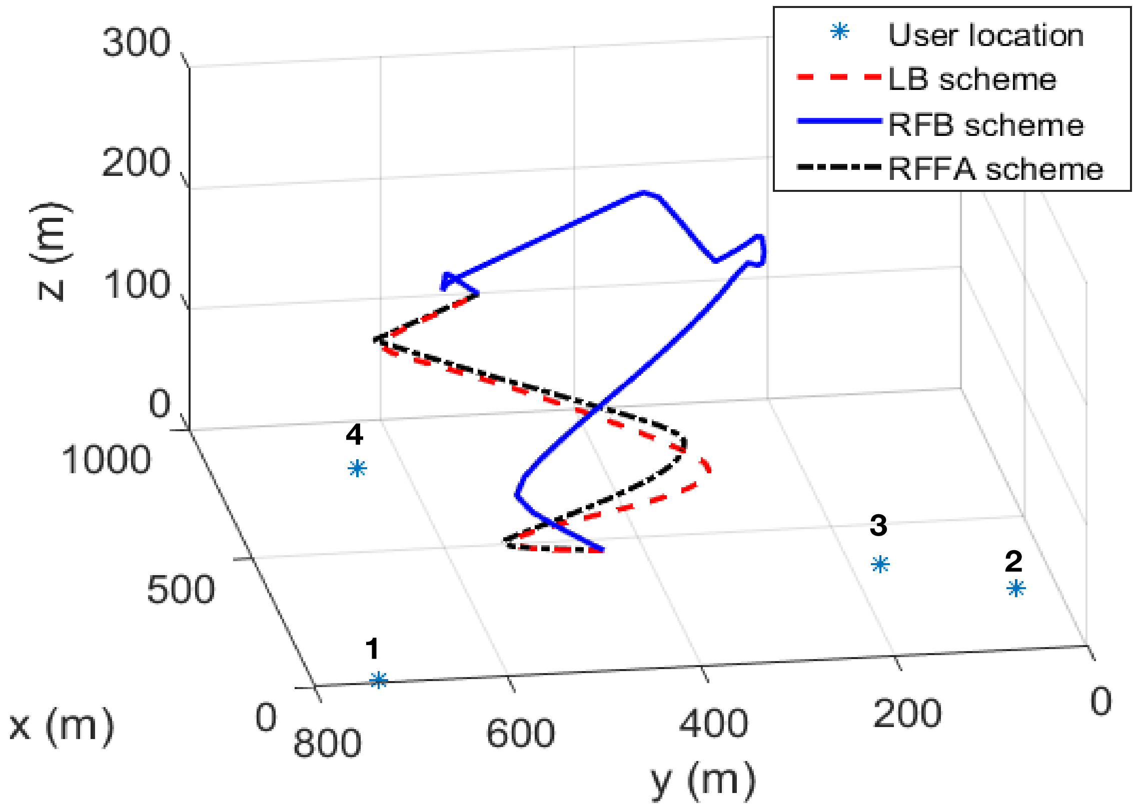
3D Trajectory Optimization for UAV Data Harvesting

- Distance-angle tradeoff





- 3D UAV trajectory



LB: LoS based (2D)
RFFA: Rician-fading with fixed altitude (2D)
RFB: Rician-fading based (proposed, 3D)

Hybrid Offline-Online 3D Trajectory Design for UAV Data Harvesting

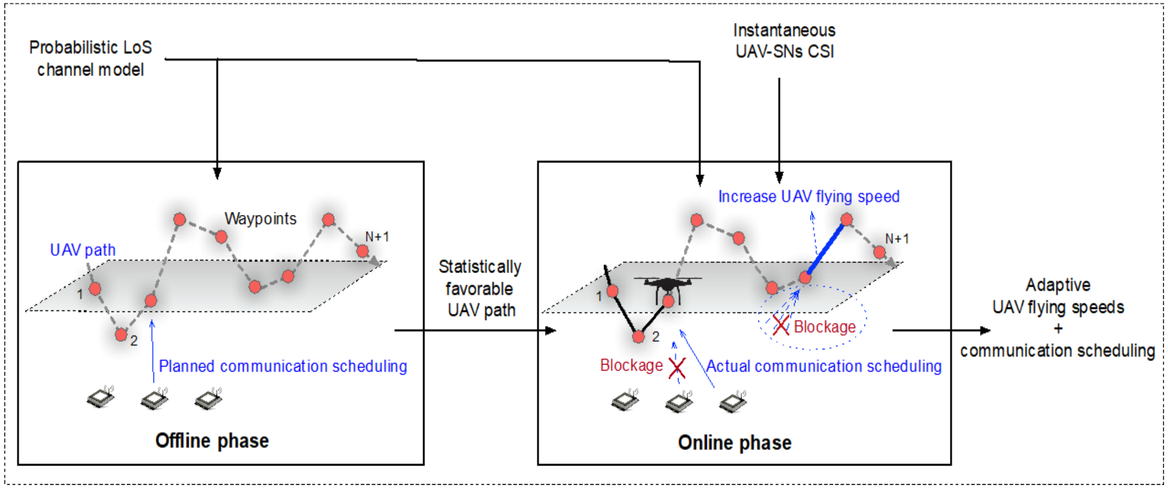
- Urban areas with low UAV altitude: Non-negligible shadowing
- LoS probability: generalized logistic function (data-regression and model fitting)

$$P_{\mathrm{L}}(\theta) = B_3 + \frac{B_4}{1 + e^{-(B_1 + B_2\theta)}}$$

- Significant disparity between channel gains under LoS and NLoS states

$$h_{\mathrm{L}} = \beta_0 d^{-\alpha_{\mathrm{L}}}, \quad h_{\mathrm{N}} = \mu\beta_0 d^{-\alpha_{\mathrm{N}}}$$

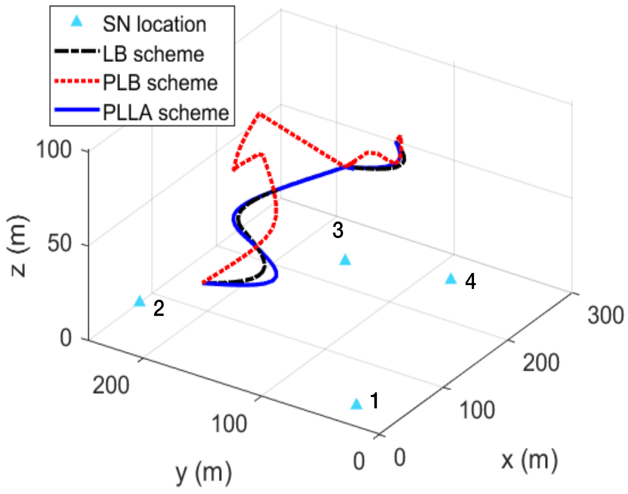
- Conventional offline design: no adaptation to real-time channels
- New hybrid offline-online trajectory design

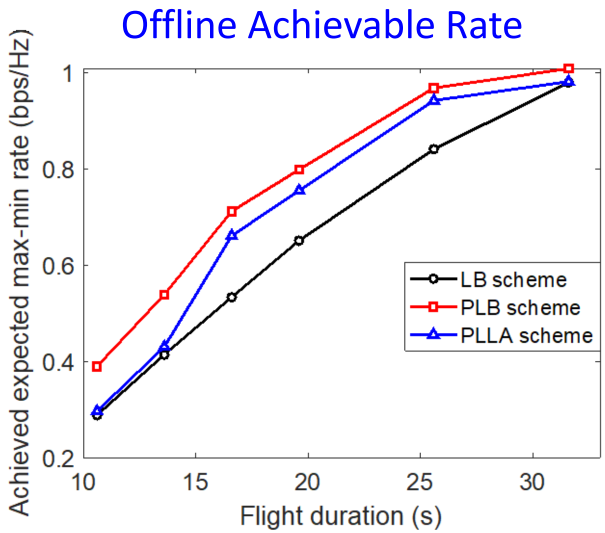


- Offline: statistically high-quality UAV path
- Online: adaptive UAV flying speed and commu. scheduling with fixed UAV path
- Low complexity
- Real-time adaptation

Simulation Results

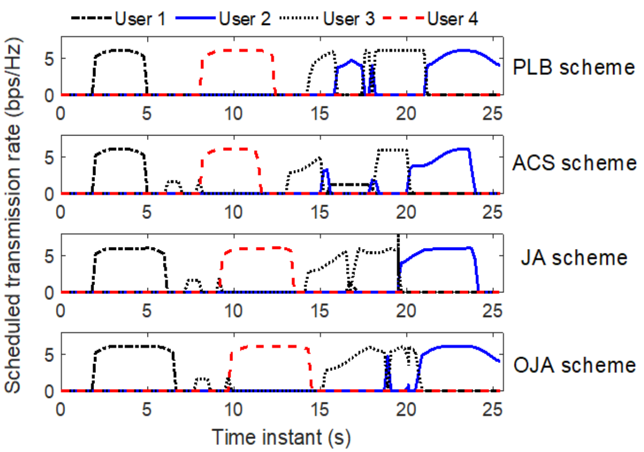
- Offline 3D UAV path

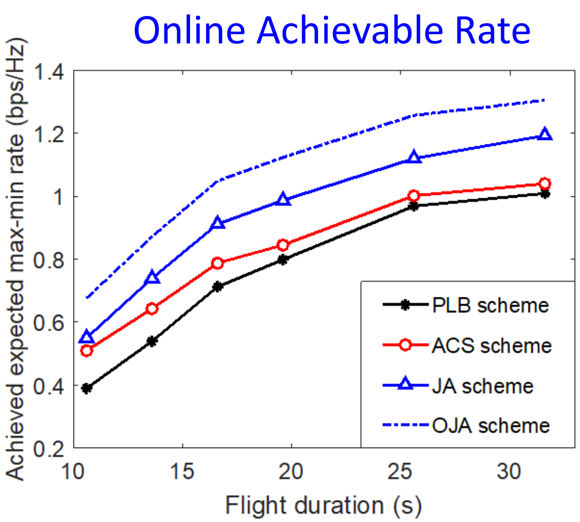




- LB: LoS based (2D)
- PLLA: probabilistic-LoS with lowest altitude (2D)
- PLB: probabilistic-LoS based (proposed, 3D)

- Online adaptation





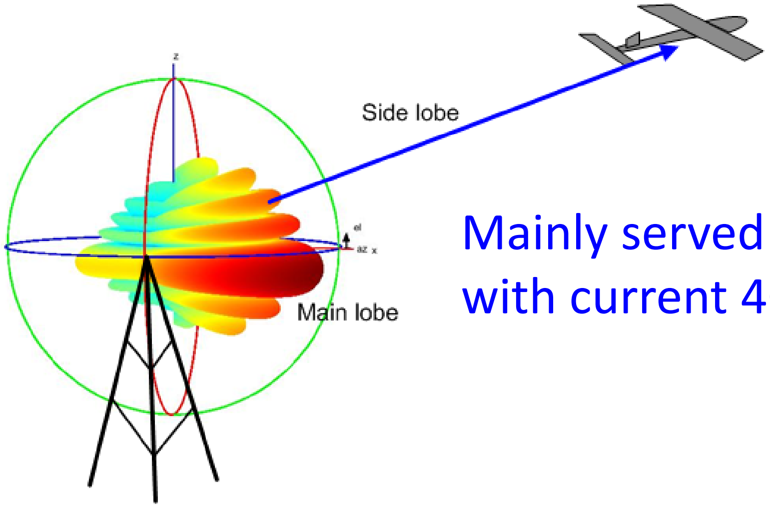
- PLB: probabilistic-LoS based trajectory w/o adaptation
- ACS: with adaptive commun. scheduling only
- JA: joint UAV speed and commun. scheduling adaptation (proposed)
- OJA: optimal joint adaptation with perfect CSI

Outline

- Integrating UAVs into Cellular
  - Motivations and benefits
  - What's new over terrestrial communications?
- Two Main (Signal Processing) Challenges
  - Trajectory optimization for UAV-assisted communication
  - **Aerial-ground interference mitigation for cellular-connected UAV**
- Conclusion and Future Work

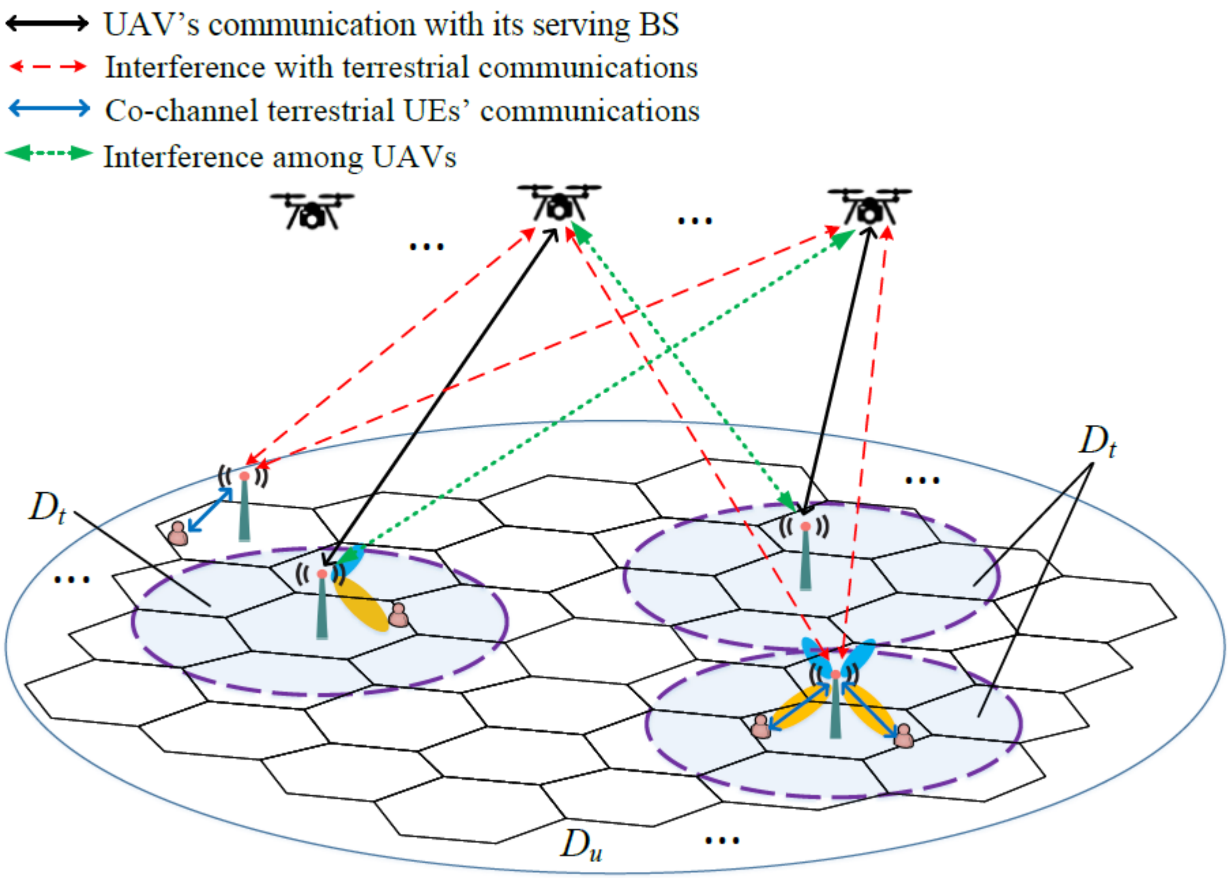
Cellular-Connected UAV: Main Challenges

- High altitude
  - 3D coverage is challenging: existing BS antennas tilted downwards
- High 3D mobility
  - Frequent handovers, cell selection
- Asymmetric downlink/uplink: ultra-reliable CNPC versus high-rate payload data
- **Strong air-ground LoS dominant channel**
  - Pro: High macro-diversity
  - Con: Severe aerial-ground interference



Mainly served by antenna side-lobe with current 4G/LTE BS

Aerial-Ground/UAV-Terrestrial Interference



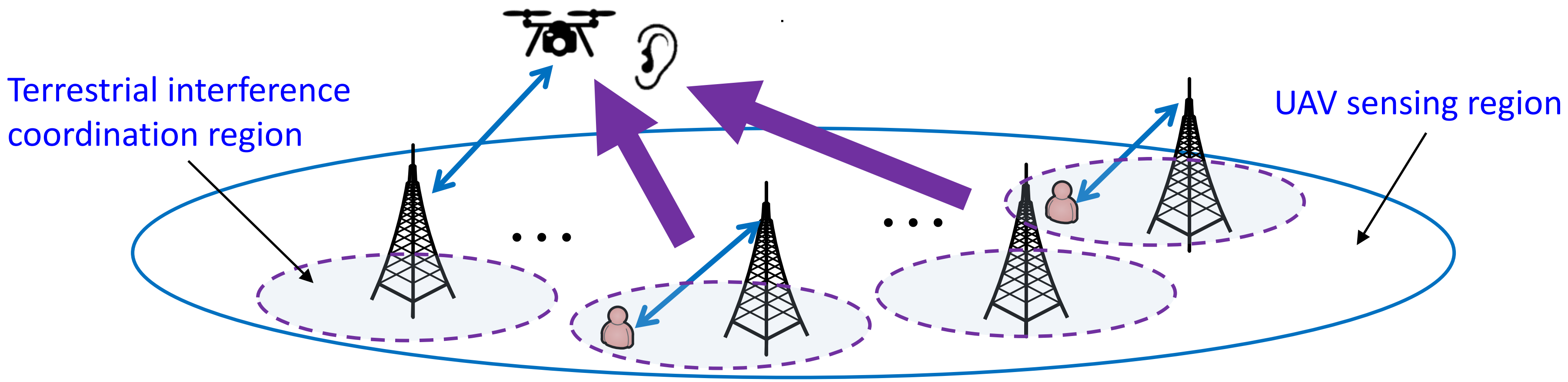
- Aerial-ground interference is more severe than terrestrial interference
- Conventional terrestrial interference mitigation techniques may be ineffective to deal with the stronger UAV-ground interference

Aerial-Ground Interference Mitigation

- New aerial-ground interference mitigation techniques:
  - UAV sensing aided interference coordination
  - Cooperate interference cancelation
  - Interference-aware trajectory design
  - Simultaneous navigation and radio mapping via deep reinforcement learning
  - Massive MIMO with pilot decontamination
  - D2D-assisted UAV swarm communications

UAV Sensing Aided Interference Coordination

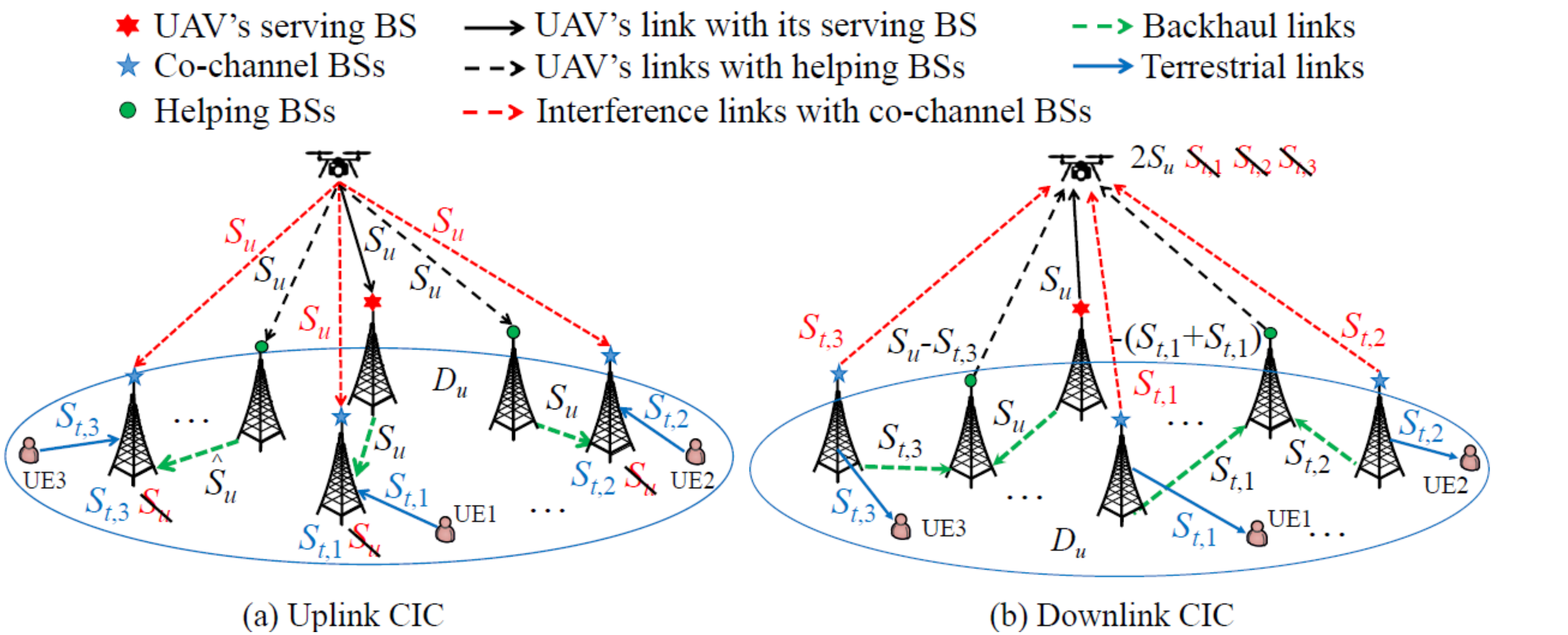
- Exploiting UAV-ground LoS channel for UAV spectrum sensing
  - Downlink: UAV measures interference power over frequency and helps its serving BS select RBs with low interference power (to avoid interference from terrestrial UEs)
  - Uplink: UAV senses uplink transmissions from terrestrial UEs and helps its serving BSs select RBs with low sensed powers (to avoid interference to terrestrial UEs)
  - Enlarge the effective interference coordination region in a distributed and low-complexity manner



W. Mei and R. Zhang, "UAV-sensing-assisted cellular interference coordination: a cognitive radio approach," *IEEE Wireless Communications Letters*, June 2020.

Cooperate Interference Cancelation

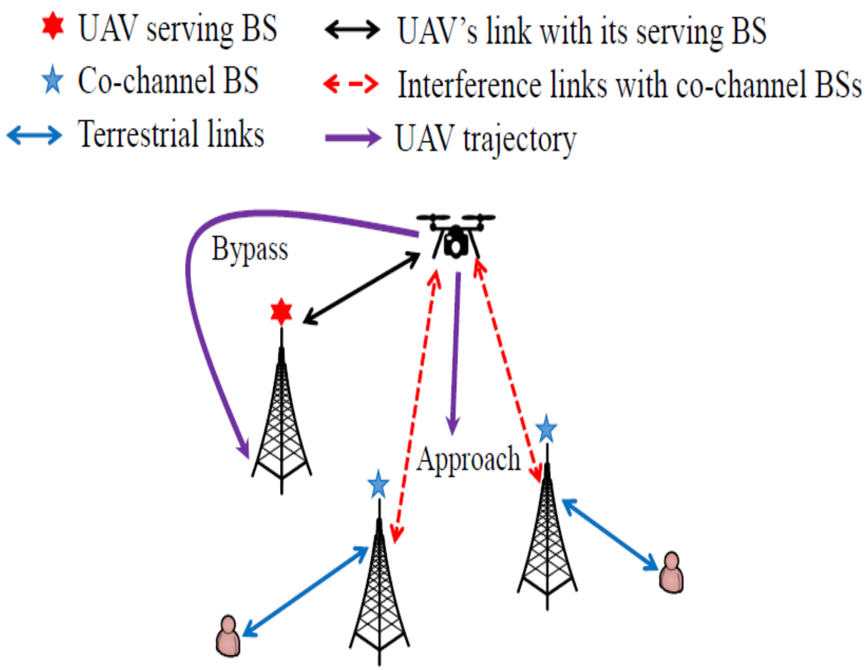
- Cooperate interference cancelation (CIC)
  - Idle helping BSs decode/transmit interference in the UL/DL to facilitate interference cancelation at the co-channel BS/UAV
  - Different from conventional CoMP and NOMA



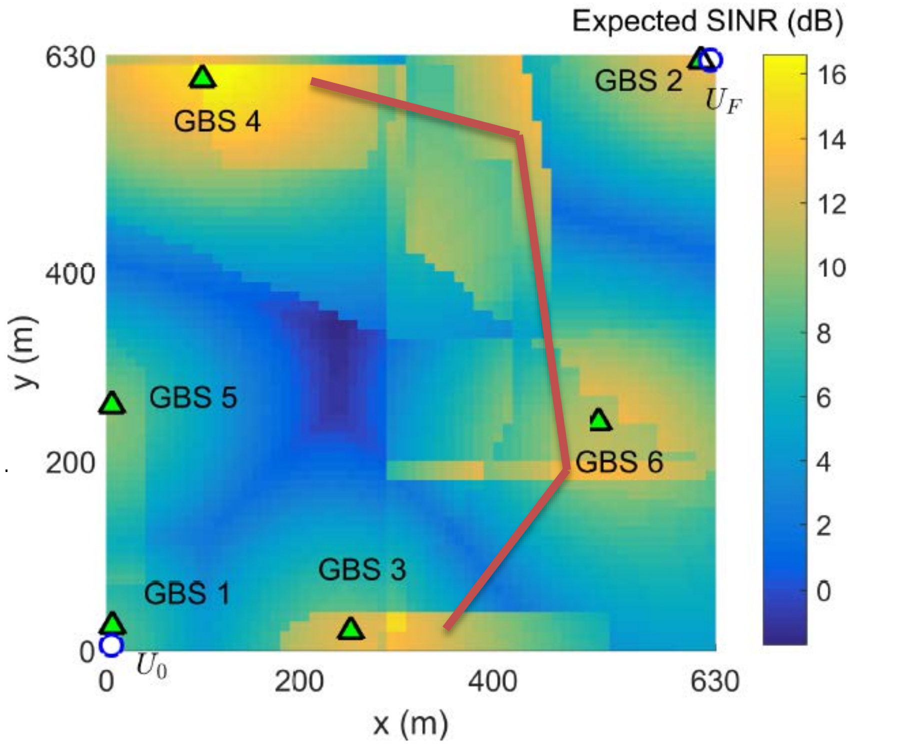
L. Liu, S. Zhang, and R. Zhang, "Multi-beam UAV communication in cellular uplink: cooperative interference cancellation and sum-rate maximization," *IEEE Transactions on Wireless Communications*, October 2019.

W. Mei and R. Zhang, "Cooperative downlink interference transmission and cancellation for cellular-connected UAV: A divide-and-conquer approach," *IEEE Transactions on Communications*, February 2020.

Interference-Aware Trajectory Design



Trajectory adaptation to avoid strong interference with ground BS

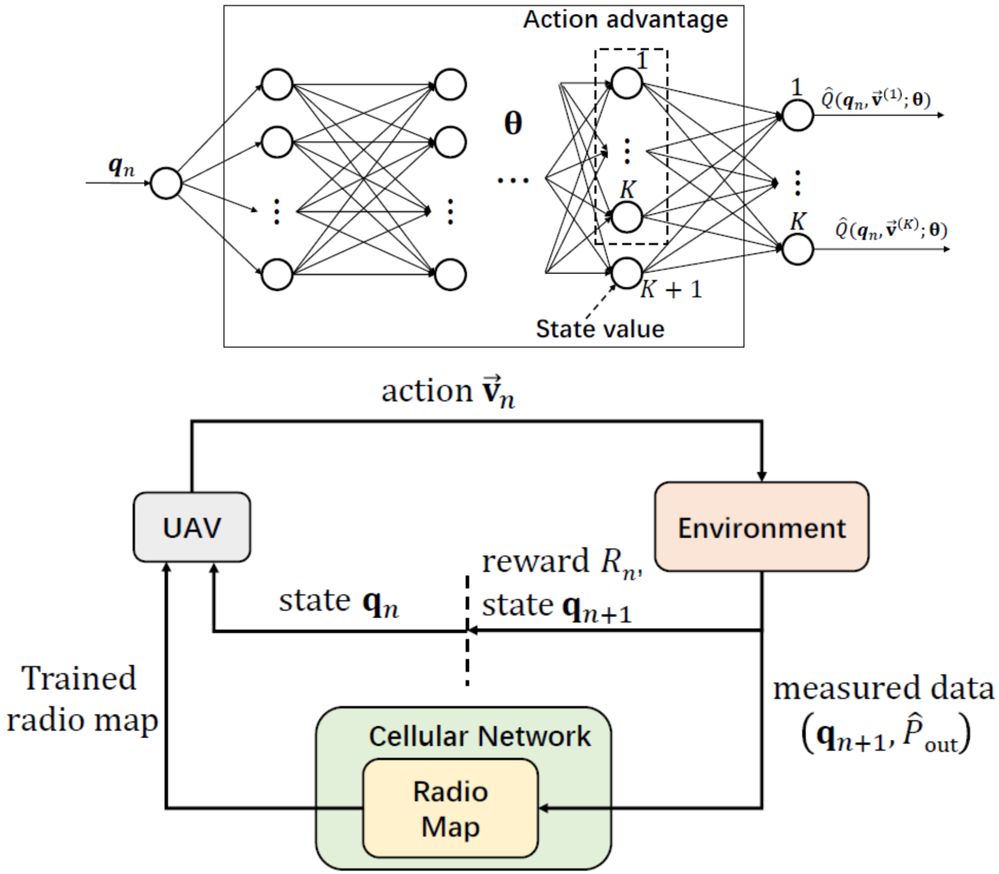


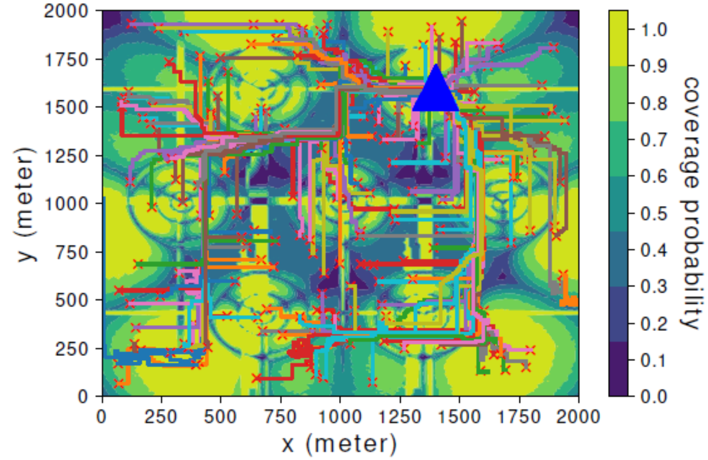
Radio-map/SINR-map based trajectory design

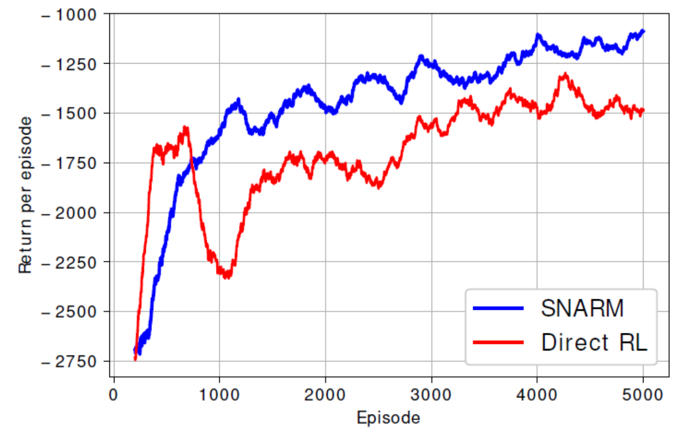
Y. Huang, W. Mei, J. Xu, L. Qiu, and R. Zhang, "Cognitive UAV communication via joint maneuver and power control," *IEEE Transactions on Communications*, November 2019.

S. Zhang and R. Zhang, "Radio map based 3D path planning for cellular-connected UAV," submitted to *IEEE Transactions on Wireless Communications.*

Simultaneous Navigation and Radio Mapping via Deep Reinforcement Learning

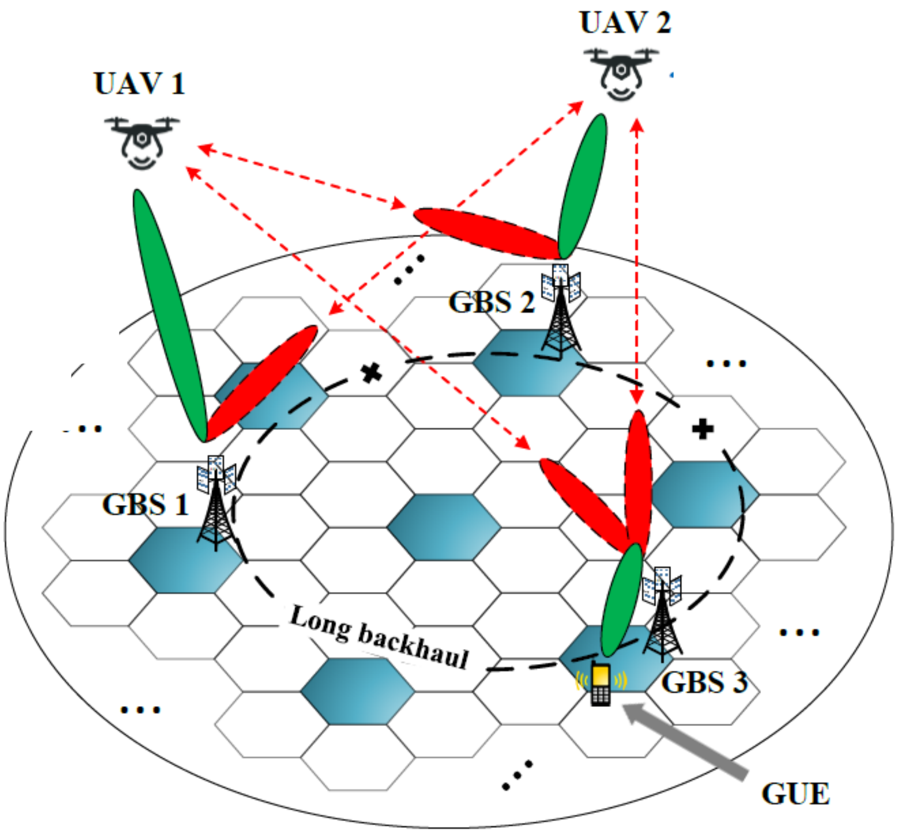




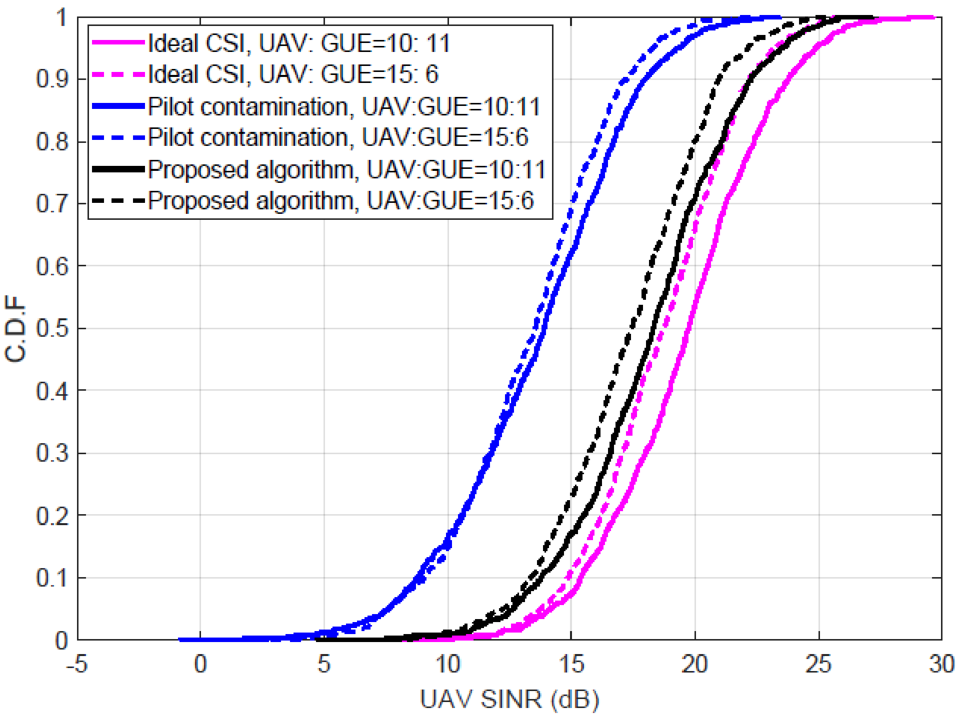


Y. Zeng, X. Xu, S. Jin, and R. Zhang, "Simultaneous navigation and radio mapping for cellular-connected UAV with deep reinforcement learning," submitted to *IEEE Transactions on Wireless Communications*.

5G Massive MIMO with Pilot Decontamination



UAV-induced pilot contamination in massive MIMO

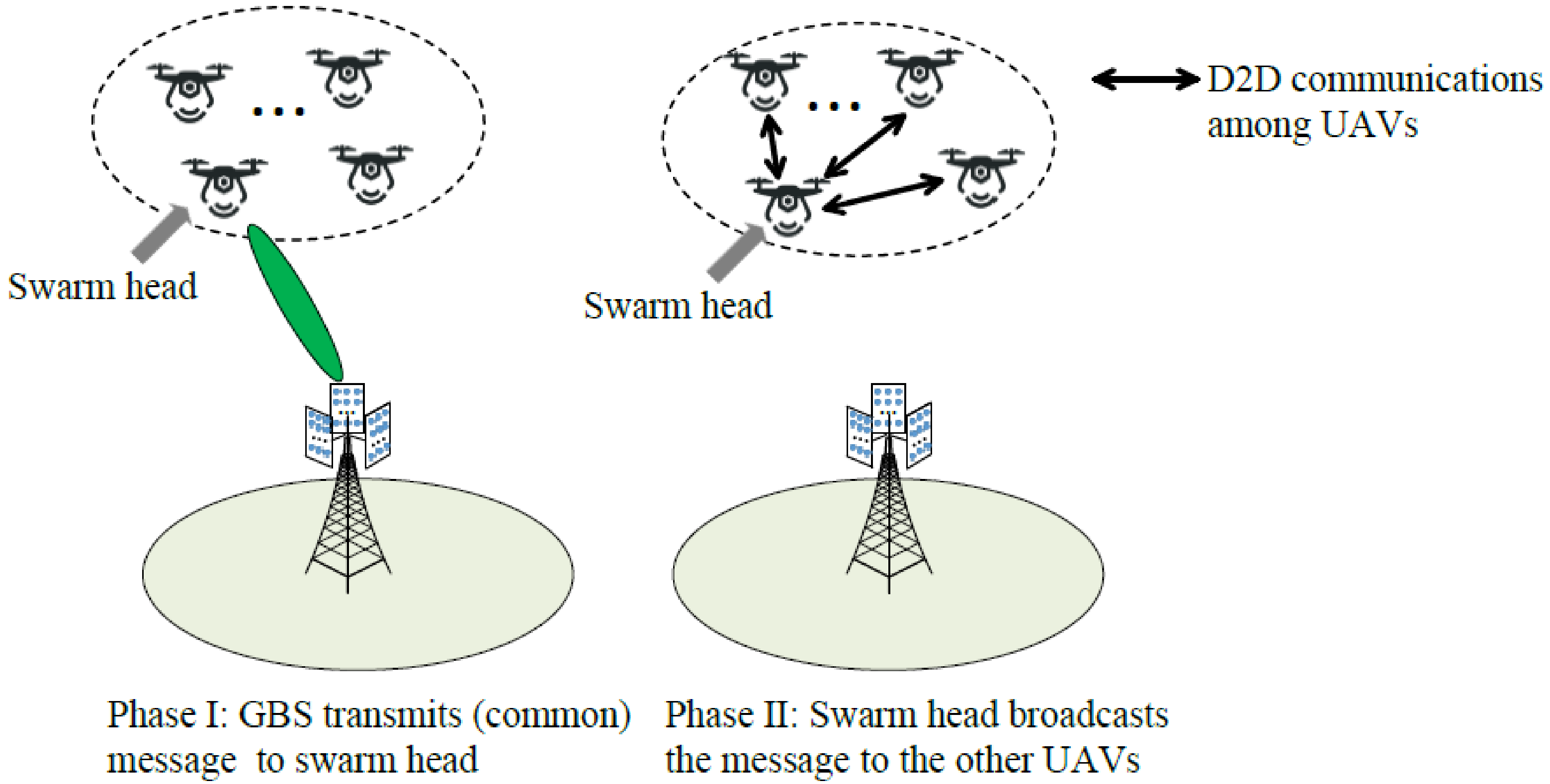


Average UAV SINR distribution in the downlink before vs. after pilot decontamination

R. Lu, Q. Wu, and R. Zhang, "Pilot decontamination for massive MIMO network with UAVs," to appear in *IEEE Wireless Communications Letters.*

D2D-assisted UAV Swarm Communications

- Challenges for Massive MIMO to support UAV swarm communications
  - More severe pilot contamination than single UAV
  - Insufficient spatial resolution due to small inter-UAV distance in swarm



Y. Han, L. Liu, L. Duan, and R. Zhang, "Towards reliable UAV swarm communication in D2D-enhanced cellular network," submitted to *IEEE Transactions on Wireless Communications.*

Conclusion

- Integrating UAVs into 5G and beyond: a promising paradigm to embrace the new era of Internet-of-drones (IoD)
- Cellular-Connected UAV: UAV as new aerial user/terminal
- UAV-Assisted Communication: UAV as mobile BS/AP/relay
- Two Main Challenges (from signal processing/commun. perspective):
  - UAV trajectory and communication co-design
  - UAV-terrestrial interference mitigation
- Much more to be done…

Extensions/Future Work Directions

- UAV-BS/UE channel modelling and experimental verification
- 3D network modelling and performance analysis
- General UAV energy model and energy-efficient design
- Security issues in UAV communications
- Massive MIMO/mmWave for UAV swarm communications
- Low-complexity UAV trajectory/placement design
- UAV communications with limited wireless backhaul
- UAV meets wireless power/energy harvesting/caching/edge computing/intelligent surface, etc.
- UAV-cellular-satellite integrated network
- Machine learning/AI for UAV communications and networking
- ……

IEEE JSAC Special Issue

"UAV Communications in 5G and Beyond Networks"

This special issue will focus on key theoretical and practical design issues for both paradigms of cellular-connected UAVs and UAV-assisted wireless communications. Topics of interest in this special issue include but not limited to the following:

- Channel modeling for UAV-ground and UAV-UAV communications
- New architectures and communication protocols for cellular-connected UAVs
- Spectrum management and multiple access schemes for cellular-connected UAVs
- Interference mitigation for cellular-connected UAVs
- Cellular systems with coexisting aerial and ground users
- 3D beamforming for cellular-connected UAVs
- Massive MIMO/Millimeter wave communications for cellular-connected UAVs
- 3D aerial base station placement
- UAV-aided eMBB, MMTC, URLLC
- Online/offline and machine learning based UAV trajectory optimization
- Joint trajectory design and resource allocation for UAV-assisted wireless communication
- Spectrum sharing and coordination between aerial and ground BSs
- Fundamental tradeoffs in UAV wireless networks
- Energy-efficient UAV communications
- UAV swarm in 5G and beyond
- UAV channel estimation and pilot decontamination
- UAV meets wireless power transfer, caching, edge computing, etc.
- Physical layer security and techniques in wireless networks with UAVs

Submission deadline:
1 October 2020

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