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Accessing From Sky: UAV/Drone Communications for 5G and Beyond

Rui Zhang

The Chinese University of Hong Kong, Shenzhen and National University of Singapore
Fellow of IEEE, Fellow of Academy of Engineering Singapore
Clarivate Analytics Highly Cited Researcher
e-mail: rzhang@cuhk.edu.cn, elezhang@nus.edu.sg

IEEE VTS Webinar Series on Advanced Air Mobility
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Outline

- ❑ Integrating UAVs/Drones into Future Wireless Networks
  - ➢ Motivations and benefits
  - ➢ What’s new over terrestrial communications?
- ❑ Two Main Challenges
  - ➢ Trajectory optimization for UAV-assisted communication
  - ➢ Aerial-ground interference mitigation in cellular-connected UAV
- ❑ Conclusion and Future Work

UAV/Drone Applications

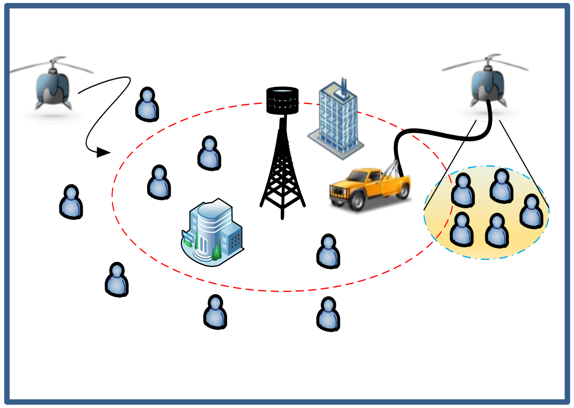
Aerial photography

Inspection

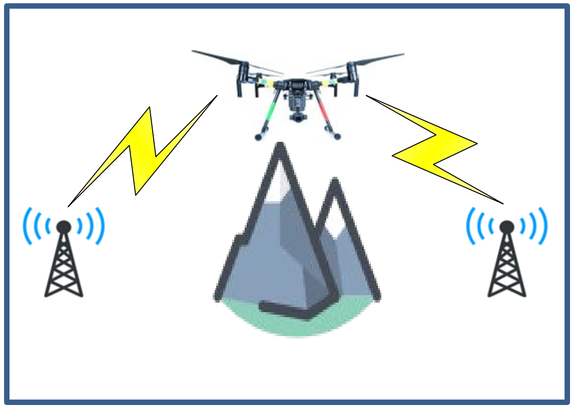
Drone Delivery

Precision Agriculture

Traffic offloading



Mobile relay



IoT Data Harvesting

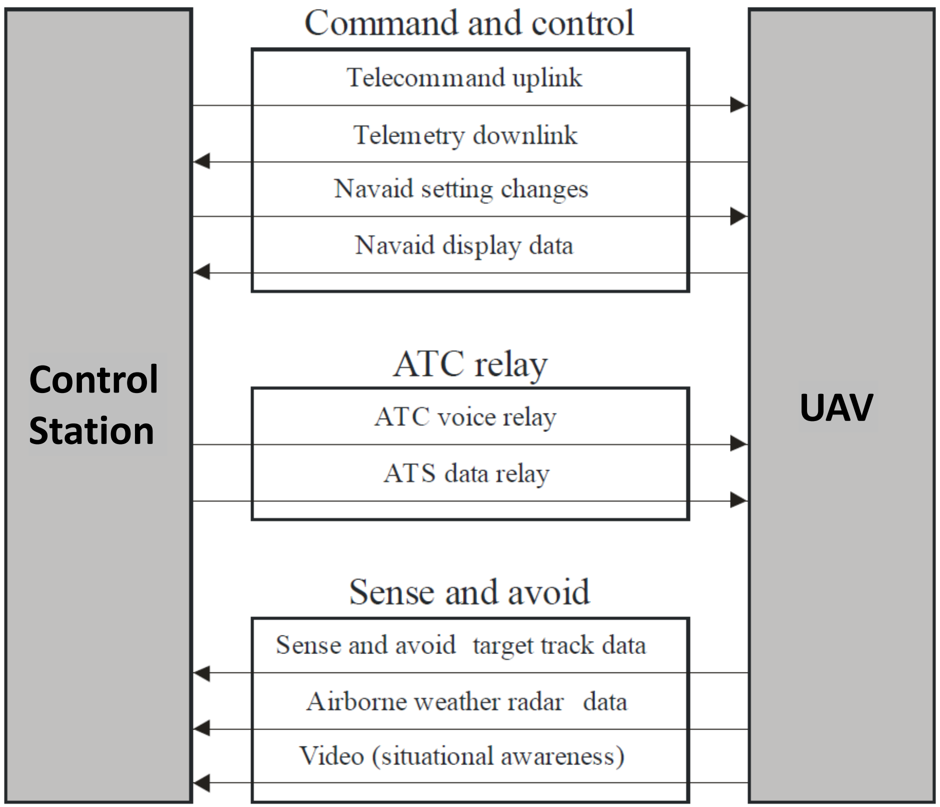
Wireless Communications for UAVs: Basic Requirement

❑ Control and Non-Payload Communications (CNPC)

- ➢ Ensure safe, reliable, and effective flight operation
- ➢ Low data rate, high reliability, high security, low latency

❑ Payload Communications

- ➢ Application specific data (e.g., HD/4K video, internet data)
- ➢ Much higher rate than CNPC, less stringent on reliability/latency



CNPC information flows [ITUReportM.2171]

ITU, "Characteristics of unmanned aircraft systems and spectrum requirements to support their safe operation in non-segregated airspace," Tech. Rep. M.2171, Dec. 2009.

3GPP UAV Communication Requirement

	Data Type	Data Rate	Reliability	Latency
Downlink **(DL: BS to UAV)**	Command and control	60-100 Kbps	10^{-3} packet error rate	50 ms
Uplink **(UL: UAV to BS)**	Command and control	60-100 Kbps	10^{-3} packet error rate	--
	Application data	Up to 50 Mbps	--	Similar to terrestrial user

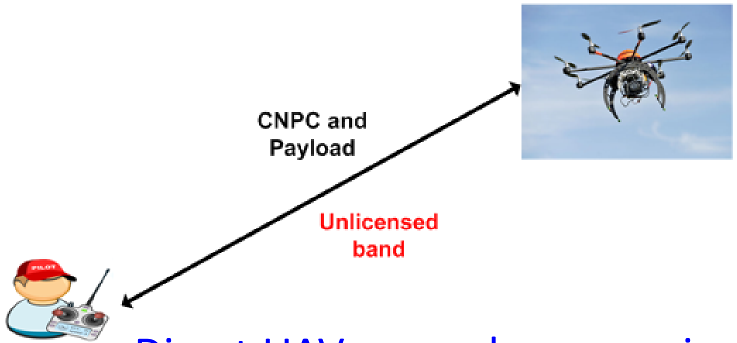
3GPP TR 36.777: "Technical specification group radio access network: study on enhanced LTE support for aerial vehicles", Dec. 2017.

China Mobile Requirement for Typical Payload

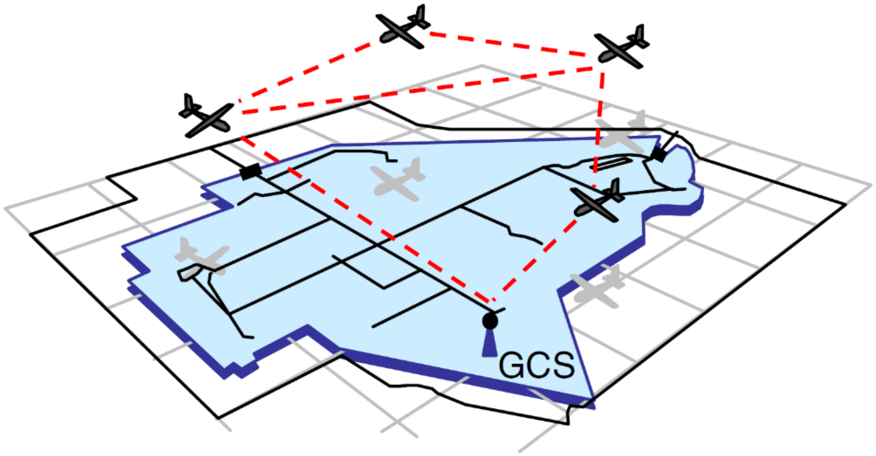
UAV Application	Height coverage	Payload traffic latency	Payload data rate (DL/UL)
Drone delivery	100 m	500 ms	300 Kbps/200 Kbps
Drone filming	100 m	500 ms	300 Kbps/30 Mbps
Access point	500 m	500 ms	50 Mbps/50 Mbps
Infrastructure inspection	100 m	3000 ms	300 Kbps/10 Mbps
Drone fleet show	200 m	100 ms	200 Kbps/200 Kbps
Precision agriculture	300 m	500 ms	300 Kbps/200 Kbps

“China mobile technical report: Internet of drones (in Chinese),”
http://www.jintiankansha.me/t/AE9FsWW9tc

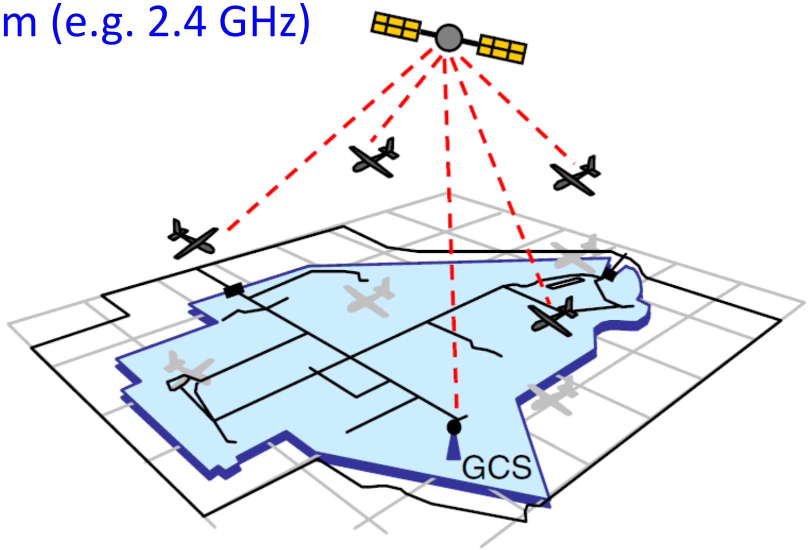
Existing Wireless Technologies for UAV Communications



Direct UAV-ground communication
in unlicensed spectrum (e.g. 2.4 GHz)

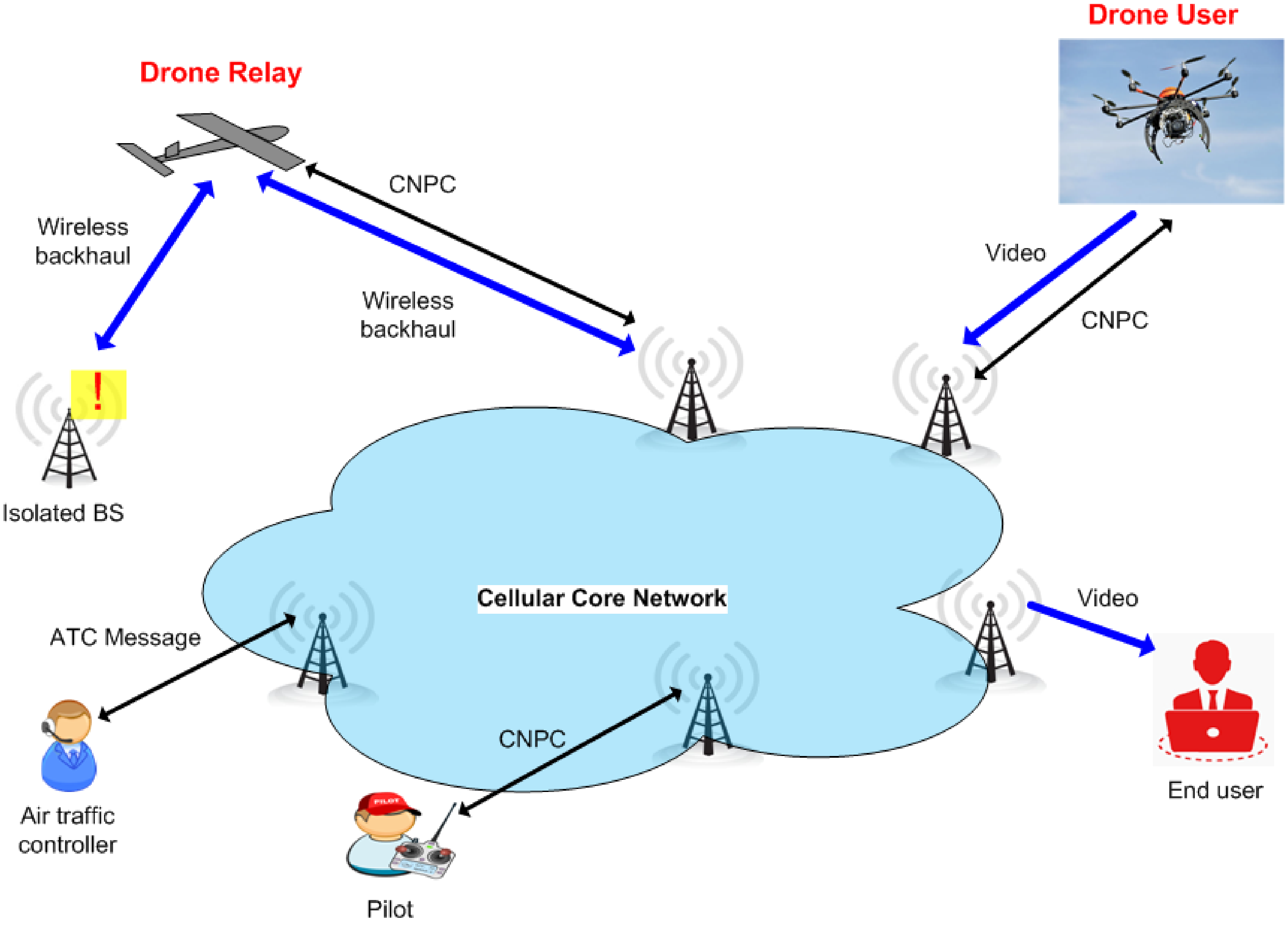


Flying ad-hoc network of UAVs



Satellite-UAV communication

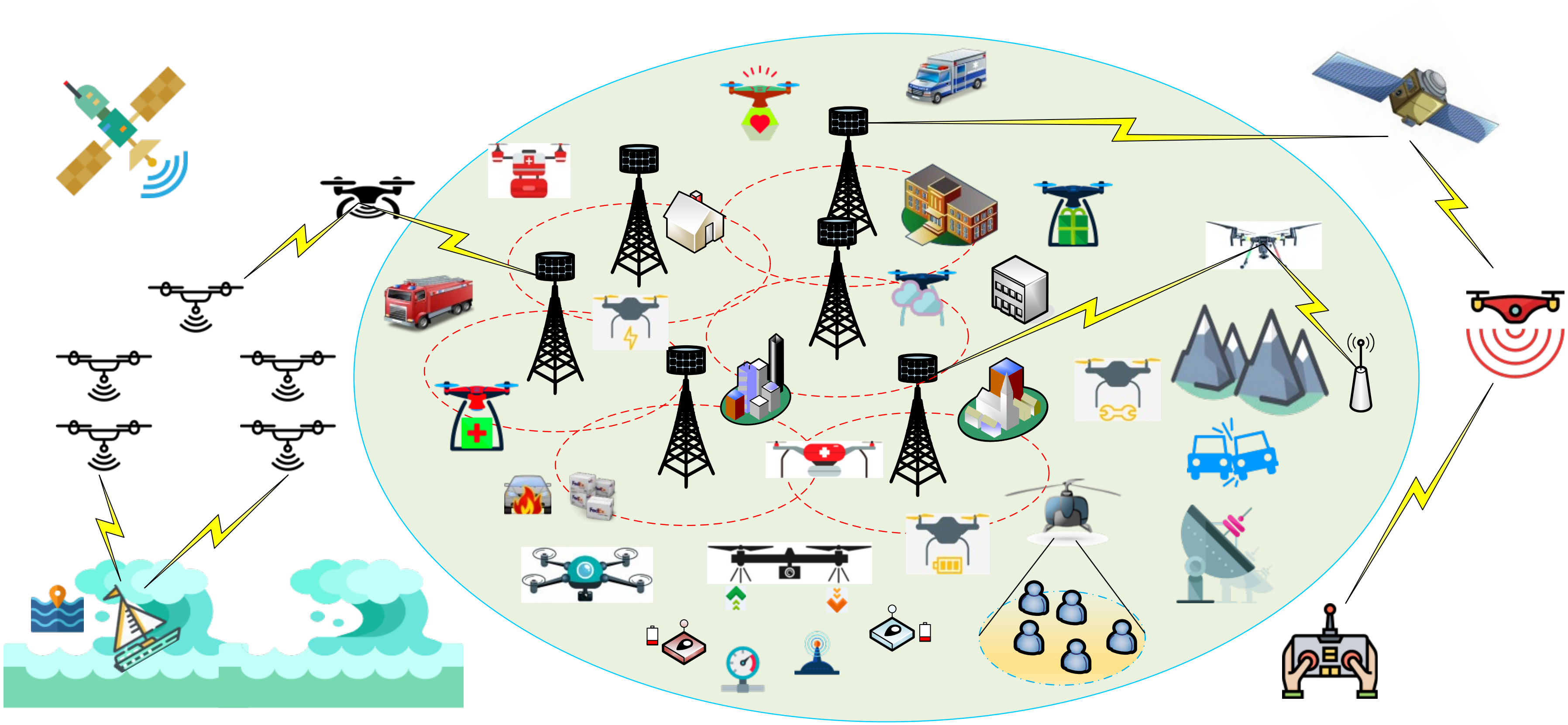
New Approach: Cellular-Connected UAV



Comparison of Wireless Technologies for UAV

Technology	Advantages	Disadvantages
Direct WiFi	• Simple • Low cost	• Limited range/data rate • Vulnerable to interference • Non-scalable for massive deployment
Satellite	• Global coverage	• Costly • Heavy/bulky/energy consuming equipment • High latency
Ad-hoc network	• Robust and adaptable • Support for high mobility	• Low spectrum efficiency • Intermittent connectivity • Complex routing protocol
Cellular network	• Almost ubiquitous accessibility • Cost-effective • Superior performance and scalability	• Unavailable in remote areas • Potential interference with terrestrial communications

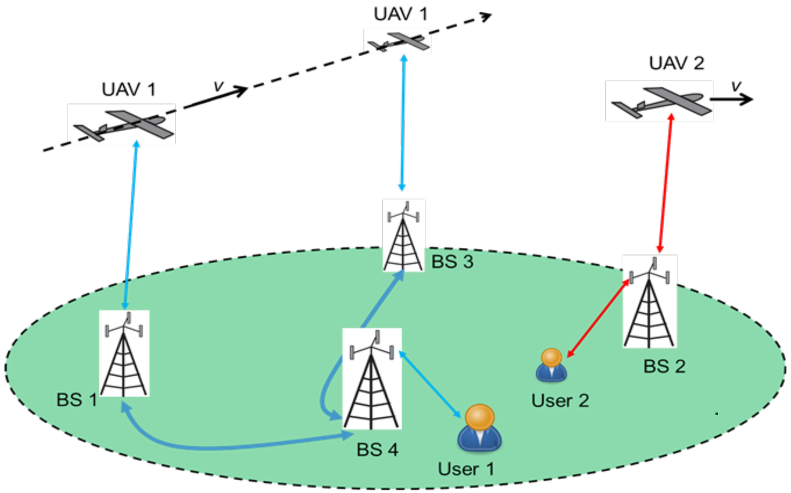
Future UAV Networks: An Air-Ground Integrated Architecture



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)

Focus of This Talk: Integrating UAVs into Cellular

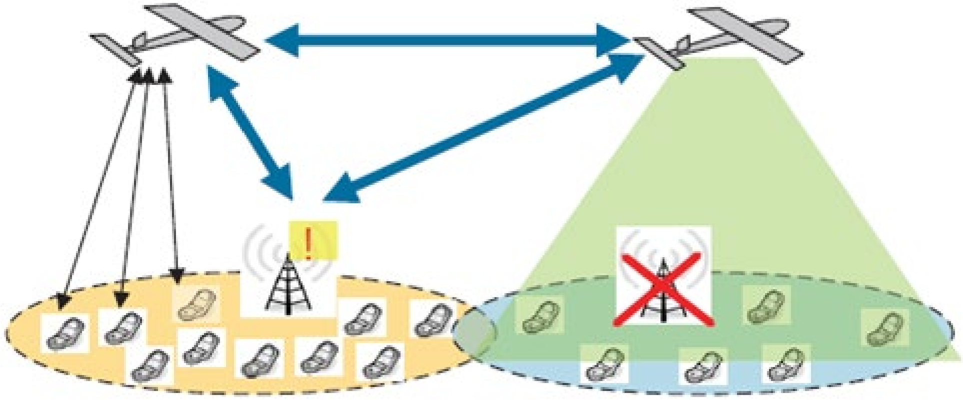
- ☐ Cellular-Connected UAV: UAV as new aerial user/terminal in cellular network



Typical applications:

- ✓ 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/6G 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
- Cellular positioning (with cm accuracy): UAV localization/detection
- Massive MIMO: 3D coverage, aerial-terrestrial interference mitigation
- Edge-computing: UAV computing offloading, autonomous flight/navigation

❑ UAVs for 5G/6G:

- 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)

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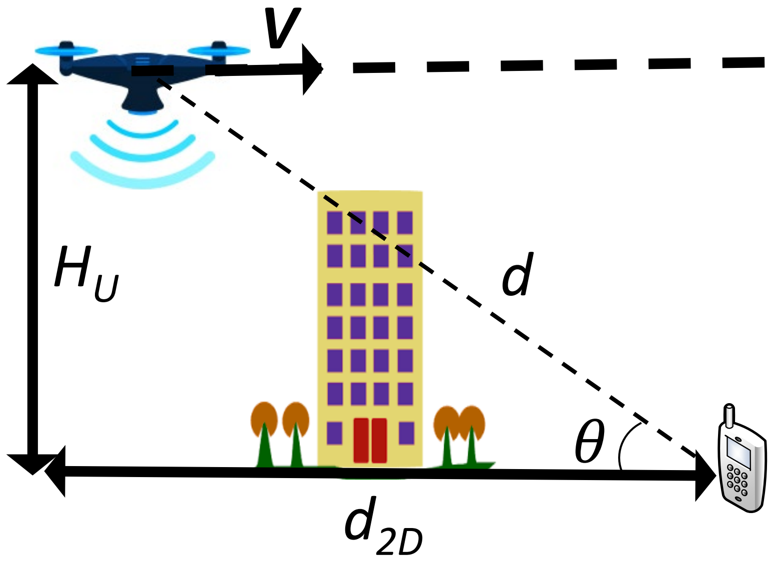
- ❑ Conclusion and Future Work

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

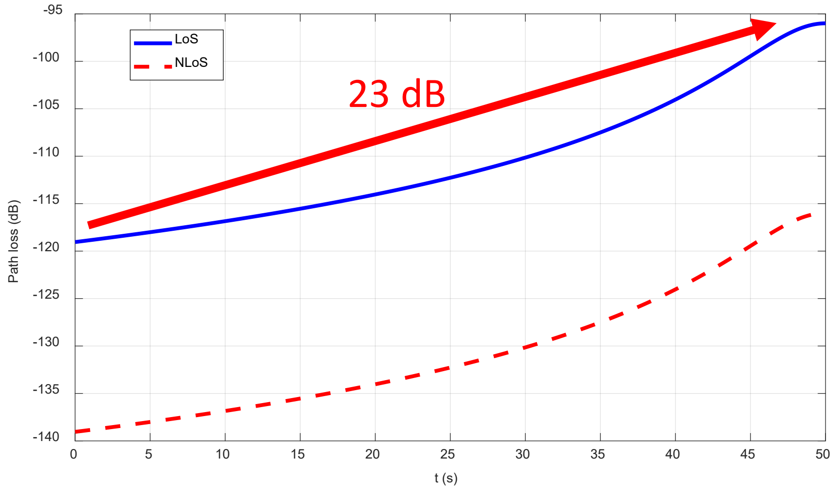
- ☐ Assume the probabilistic LoS Channel model
- ☐ Large-scale channel power model for LoS and NLoS conditions

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

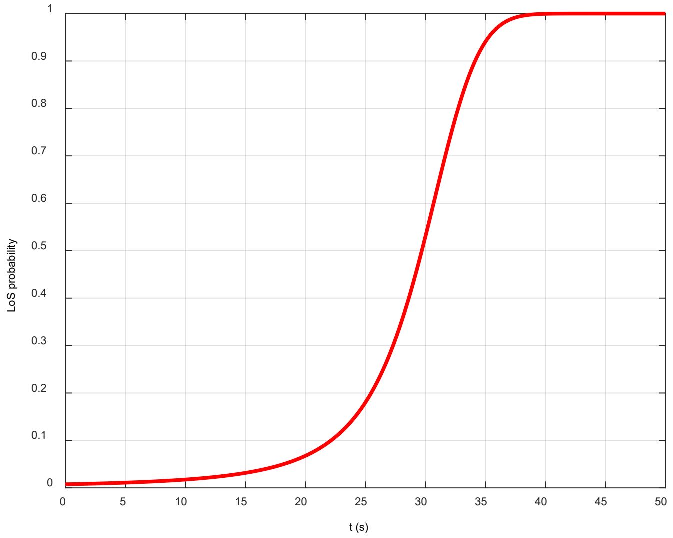
$\kappa < 1$: additional attenuation for NLoS

- ☐ LoS probability: $P_{LoS}(\theta)=\dfrac{1}{1+a\exp\left(-b(\theta-a)\right)}$
- ☐ Expected channel gain: $E\left[\beta(d)\right]=P_{LoS}(\theta)\beta_0 d^{-\alpha}+\left(1-P_{LoS}(\theta)\right)\kappa\beta_0 d^{-\alpha}$

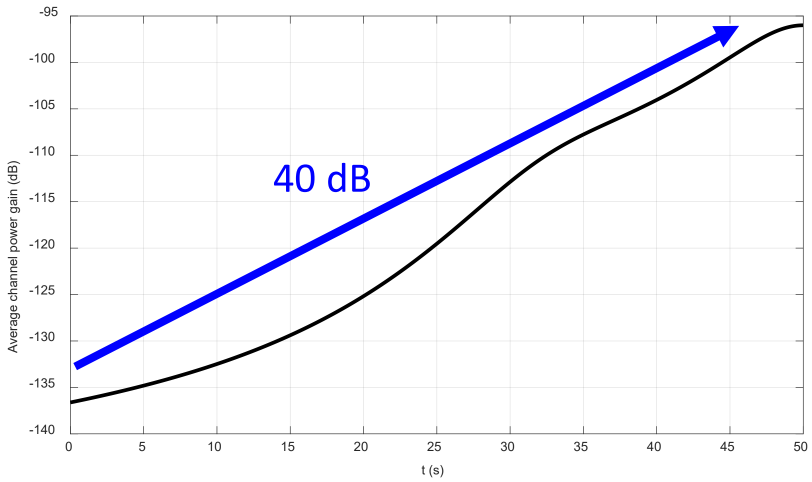
Exploiting UAV Mobility: How Much Can We Gain?



Channel gain for LoS and NLoS



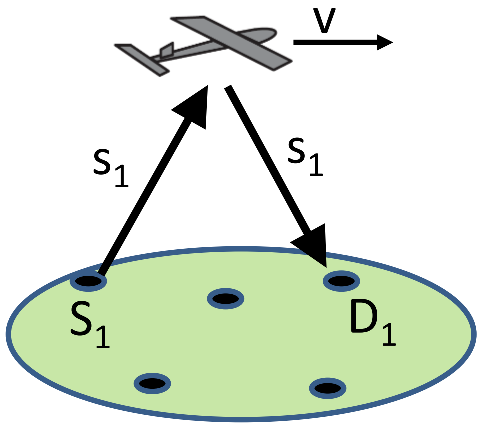
LoS probability



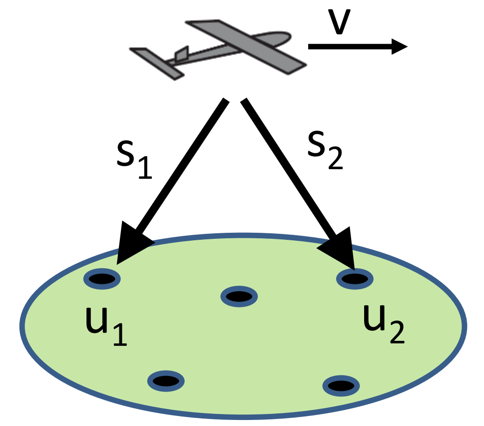
Expected channel gain

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	$a = 10, b = 0.6, \kappa = 0.01$

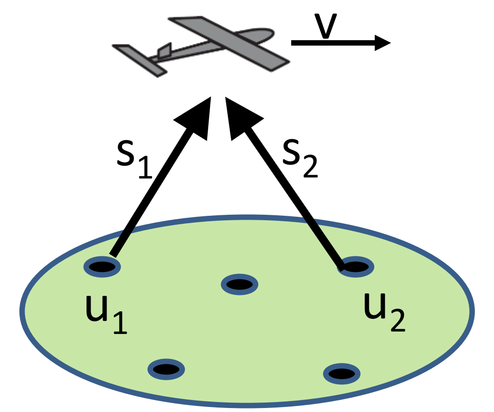
UAV-Assisted Communication: Fundamental Models



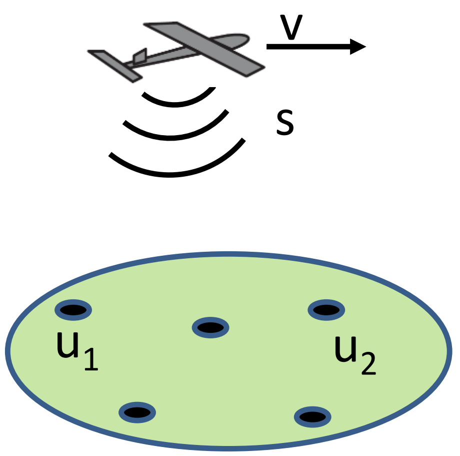
Relaying



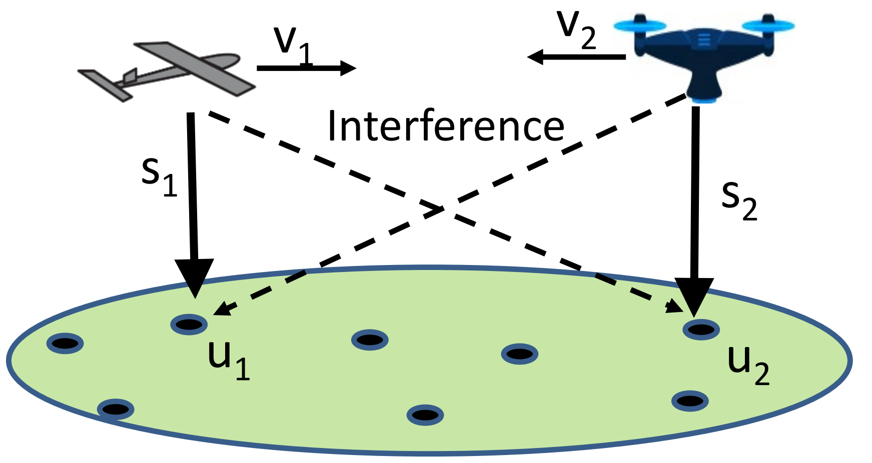
Downlink



Uplink



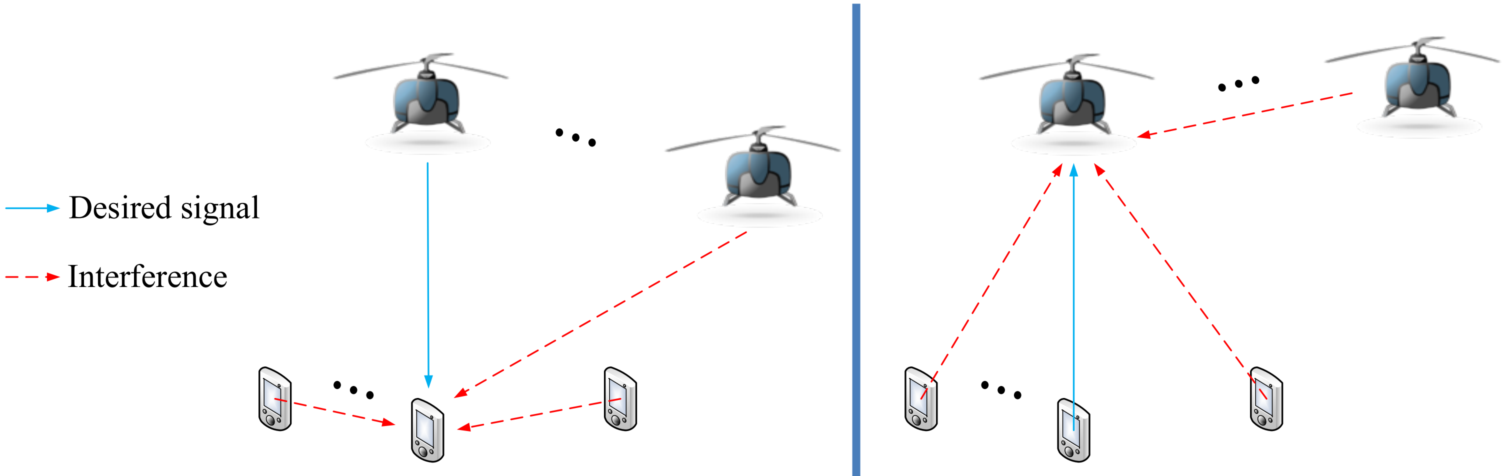
Multicasting



Multi-UAV Interference Channel

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

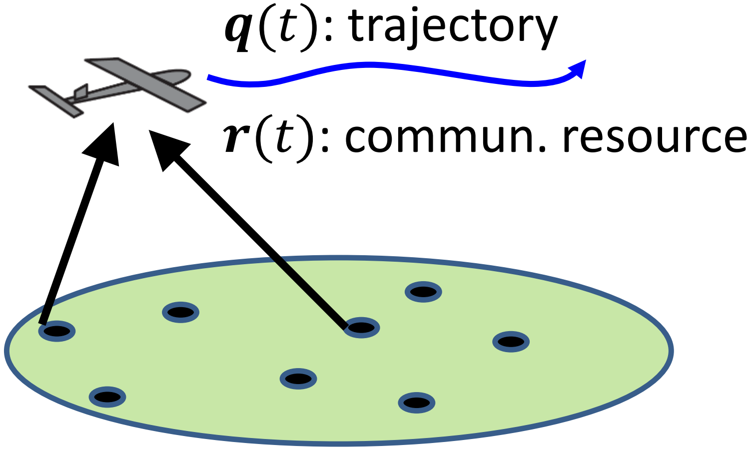
(b) UAV as a receiver

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

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

Joint Trajectory-Communication Optimization: Continuous Time Formulation

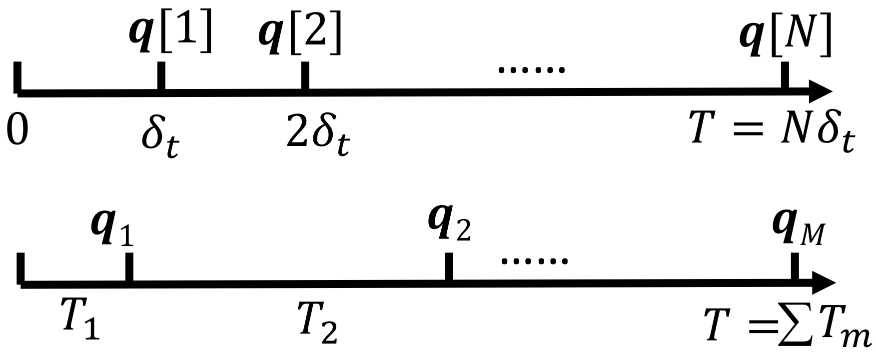
$$
\begin{aligned}
\max_{\{\mathbf{q}(t)\},\{\mathbf{r}(t)\}} \quad & U\left(\{\mathbf{q}(t)\},\{\mathbf{r}(t)\}\right) \\
\text{s.t.} \quad & f_i\left(\{\mathbf{q}(t)\}\right) \geq 0, \; i = 1, \cdots, I_1, \\
& g_i\left(\{\mathbf{r}(t)\}\right) \geq 0, \; i = 1, \cdots, I_2, \\
& h_i\left(\{\mathbf{q}(t)\},\{\mathbf{r}(t)\}\right)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



- 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

Time vs. Path Discretization

- ☐ Path discretization: generalized time discretization with variable slot length



Time discretization: T must known

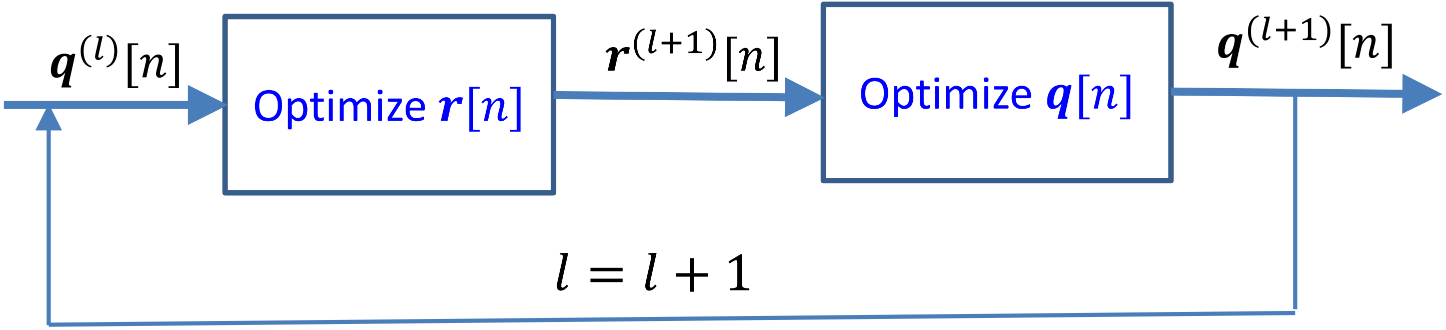
Path discretization: T can be unknown

	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

Discrete Time Formulation and Block Coordinate Descent

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

- 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



$\boldsymbol{q}^{(l)}[n]$

Optimize $\boldsymbol{r}[n]$

$\boldsymbol{r}^{(l+1)}[n]$

Optimize $\boldsymbol{q}[n]$

$\boldsymbol{q}^{(l+1)}[n]$

$l = l + 1$

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

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

Non-convex optimization problem

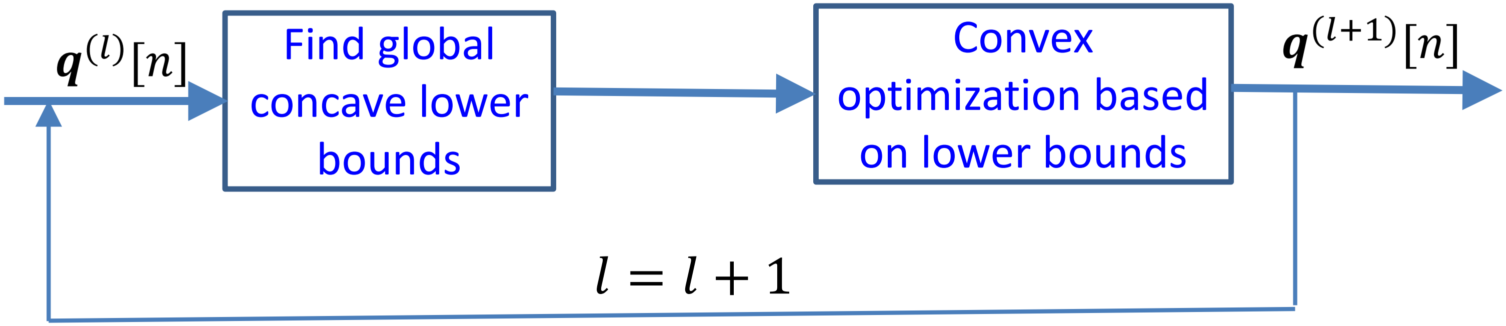
Global concave lower bound

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

$$\begin{aligned} \max_{\{\mathbf{q}[n]\}} \quad & f_{0,\mathrm{lb}}^{(l)}\left(\{\mathbf{q}[n]\}\right) \\ \text{s.t.} \quad & f_{i,\mathrm{lb}}^{(l)}\left(\{\mathbf{q}[n]\}\right) \ge 0,\ i = 1, \cdots, I. \end{aligned}$$

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

Successive Convex Approximation



- Communication rate maximization:

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

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

- Minimum speed constraint:

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

$$\Uparrow$$

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

Case Studies

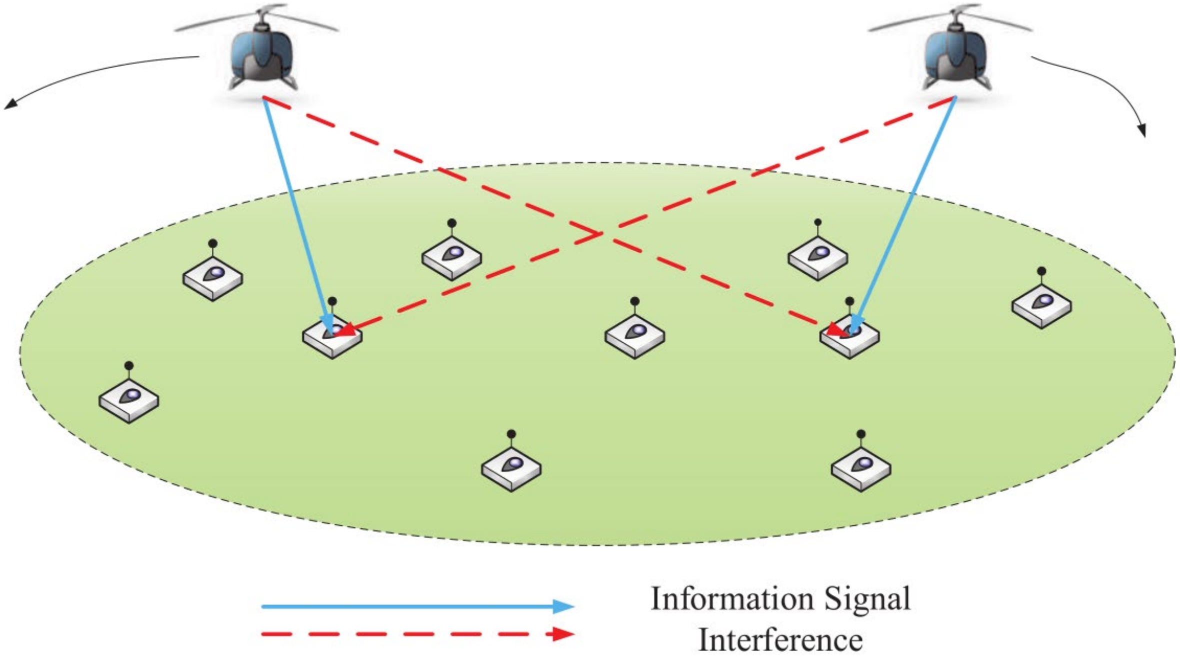
- ☐ Multi-UAV enabled wireless network

Q. Wu, Y. Zeng, and R. Zhang, "Joint trajectory and communication design for multi-UAV enabled wireless networks," *IEEE Trans. Wireless Commun.,* Mar. 2018. . **(IEEE Communications Society Young Author Best Paper Award , 2021)**

- ☐ 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

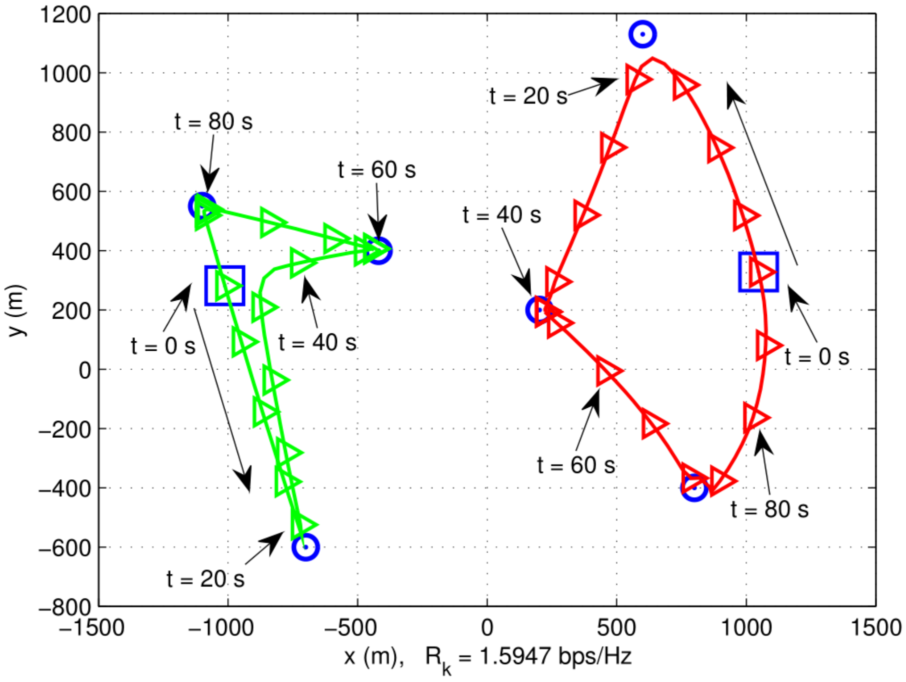
Problem Formulation

$$
\begin{aligned}
\max_{\eta,\mathbf{A},\mathbf{Q},\mathbf{P}} \quad & \eta \\
\text{s.t.} \quad & \frac{1}{N}\sum_{n=1}^{N}\sum_{m=1}^{M}\alpha_{k,m}[n]\log_2\left(1+\gamma_{k,m}[n]\right) \geq \eta, \forall\, k, && \leftarrow \boxed{\text{Minimum rate requirement}} \\
& \sum_{k=1}^{K}\alpha_{k,m}[n] \leq 1, \forall\, m,n, && \leftarrow \boxed{\text{TDMA constraints}} \\
& \sum_{m=1}^{M}\alpha_{k,m}[n] \leq 1, \forall\, k,n, && \leftarrow \boxed{\text{TDMA constraints}} \\
& \alpha_{k,m}[n] \in \{0,1\}, \forall\, k,m,n, && \leftarrow \boxed{\text{TDMA constraints}} \\
& ||\mathbf{q}_m[n+1]-\mathbf{q}_m[n]||^2 \leq S_{\max}^2, n=1,\ldots,N-1, && \leftarrow \boxed{\text{UAV mobility constraint}} \\
& \mathbf{q}_m[1]=\mathbf{q}_m[N], \forall\, m, && \leftarrow \boxed{\text{Initial/final location constraint}} \\
& ||\mathbf{q}_m[n]-\mathbf{q}_j[n]||^2 \geq d_{\min}^2, \forall\, n,m,j\neq m, && \leftarrow \boxed{\text{collision avoidance constraint}} \\
& 0 \leq p_m[n] \leq P_{\max}, \forall\, m,n. && \leftarrow \boxed{\text{power constraint}}
\end{aligned}
$$

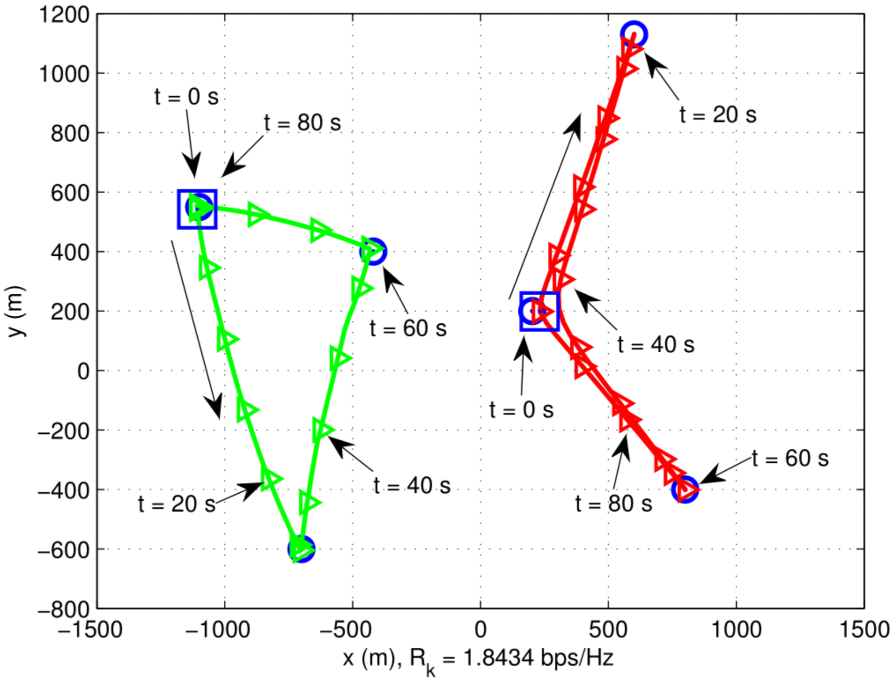
- ☐ Nonconvex, solved by time-discretization and block coordinate descent

Simulation Results

- ❑ New interference-mitigation approach: coordinated multi-UAV trajectory design

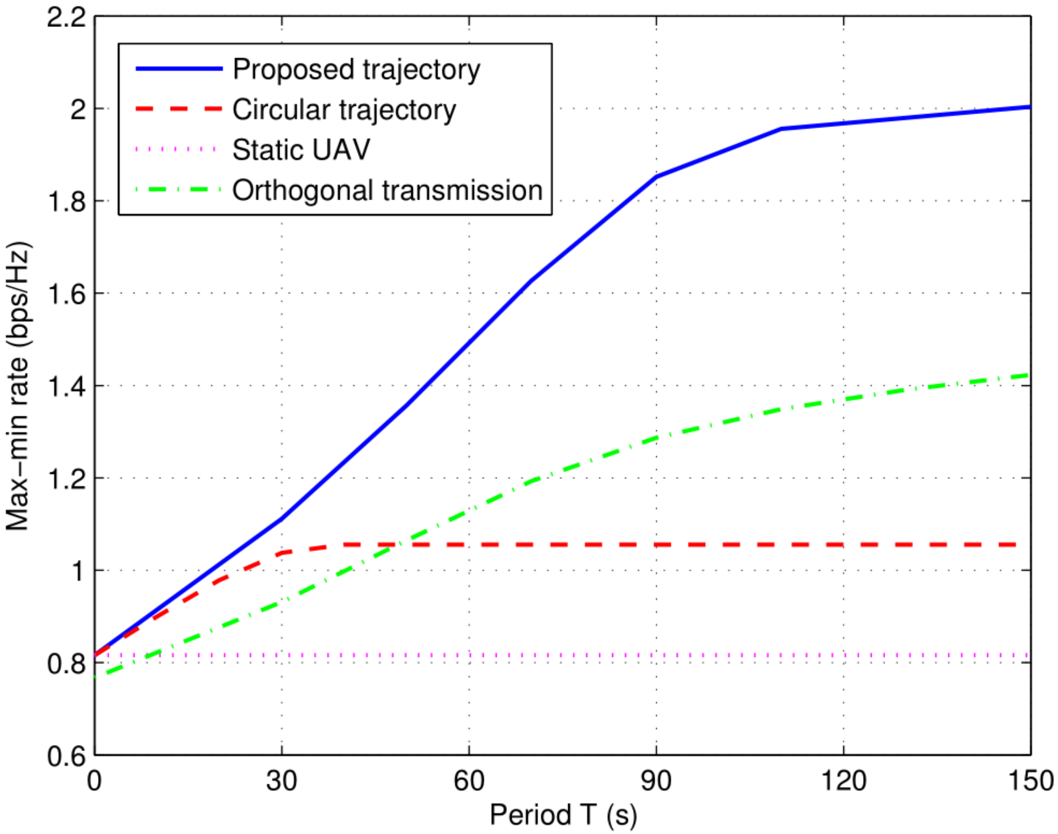


(a) Optimized UAV trajectories without power control.



(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: a fundamental Throughput-Delay Tradeoff

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

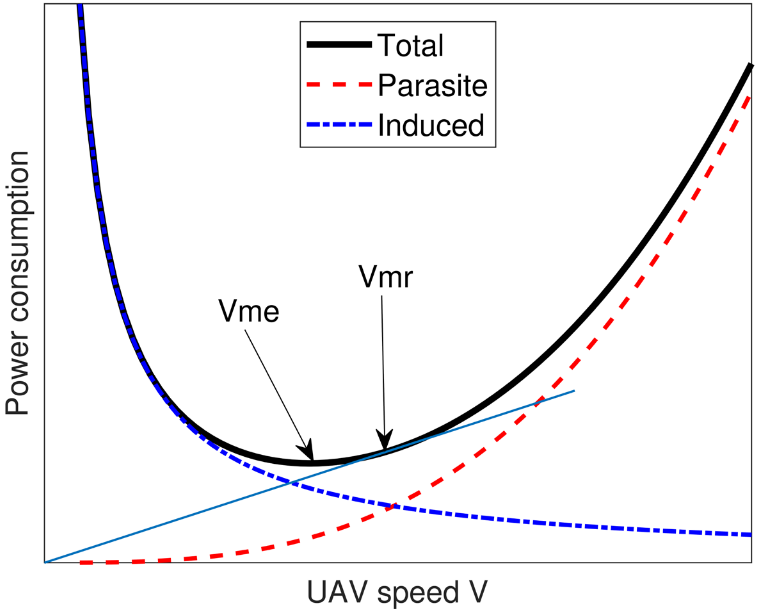
Y. Zeng and R. Zhang, "Energy-Efficient UAV Communication with Trajectory Optimization," *IEEE Trans. Wireless Commun.*, June 2017. **(IEEE Marconi Prize Paper Award in Wireless Communications, 2020)**

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

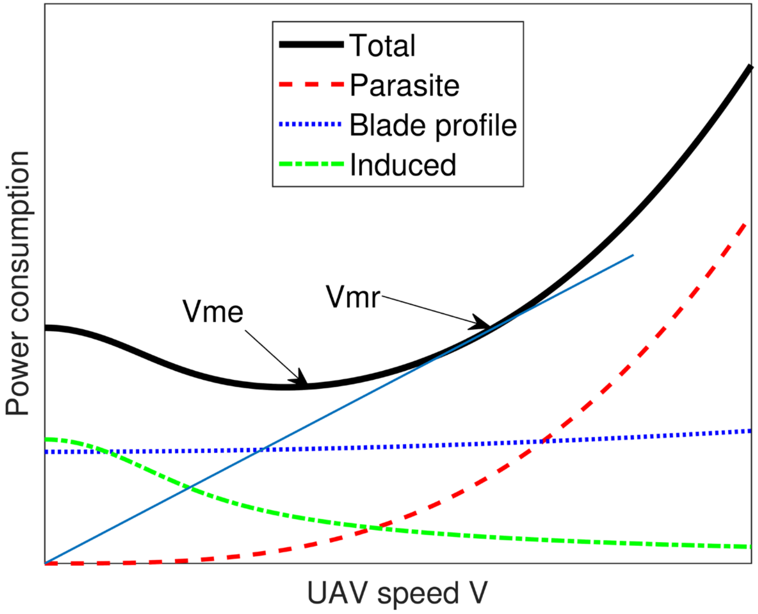
Energy Model Comparison: Straight and level flight

	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



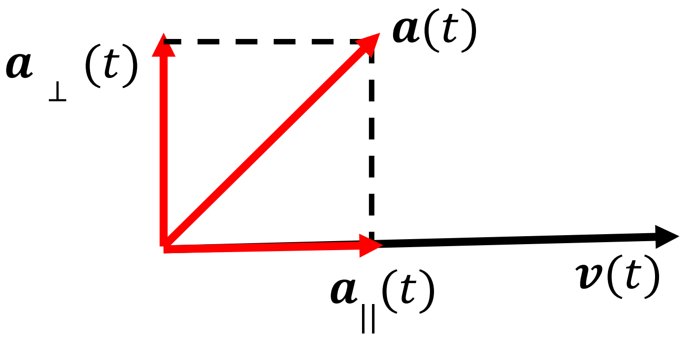
Rotary-Wing



Energy Model with General Level Flight (Fixed-Wing)

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

- ❑ 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):

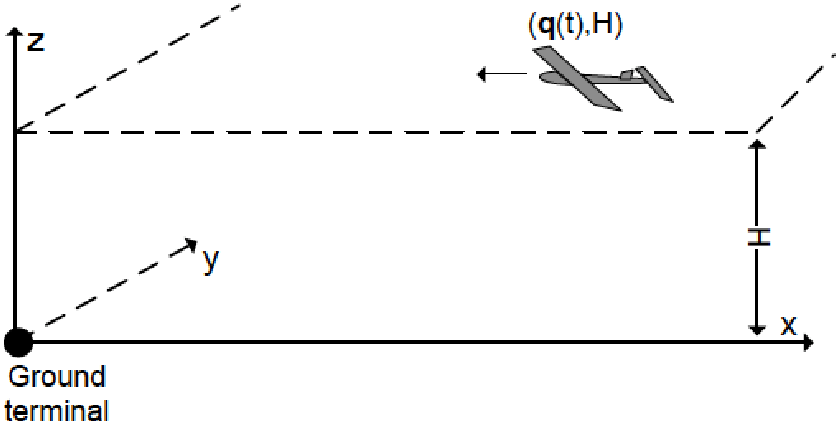
$$\bar{E}(\mathbf{q}(t)) = \int_0^T \left[c_1\|\mathbf{v}(t)\|^3 + \frac{c_2}{\|\mathbf{v}(t)\|}\left(1 + \frac{\|\mathbf{a}(t)\|^2 - \frac{(\mathbf{a}^T(t)\mathbf{v}(t))^2}{\|\mathbf{v}(t)\|^2}}{g^2}\right)\right] dt + \frac{1}{2}m\left(\|\mathbf{v}(T)\|^2 - \|\mathbf{v}(0)\|^2\right)$$

- ☐ 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

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

$$C_1: \ \mathbf{q}(0) = \mathbf{q}_0$$

$$C_2: \ \mathbf{q}(T) = \mathbf{q}_F$$

$$C_3: \ V_{\min} \leq \|\mathbf{v}(t)\| \leq V_{\max}, \forall t$$

$$C_4: \ \mathbf{v}(0) = \mathbf{v}_0$$

$$C_5: \ \mathbf{v}(T) = \mathbf{v}_F$$

$$C_6: \ \|\mathbf{a}(t)\| \leq a_{\max}, \forall t,$$

Initial/final location constraint

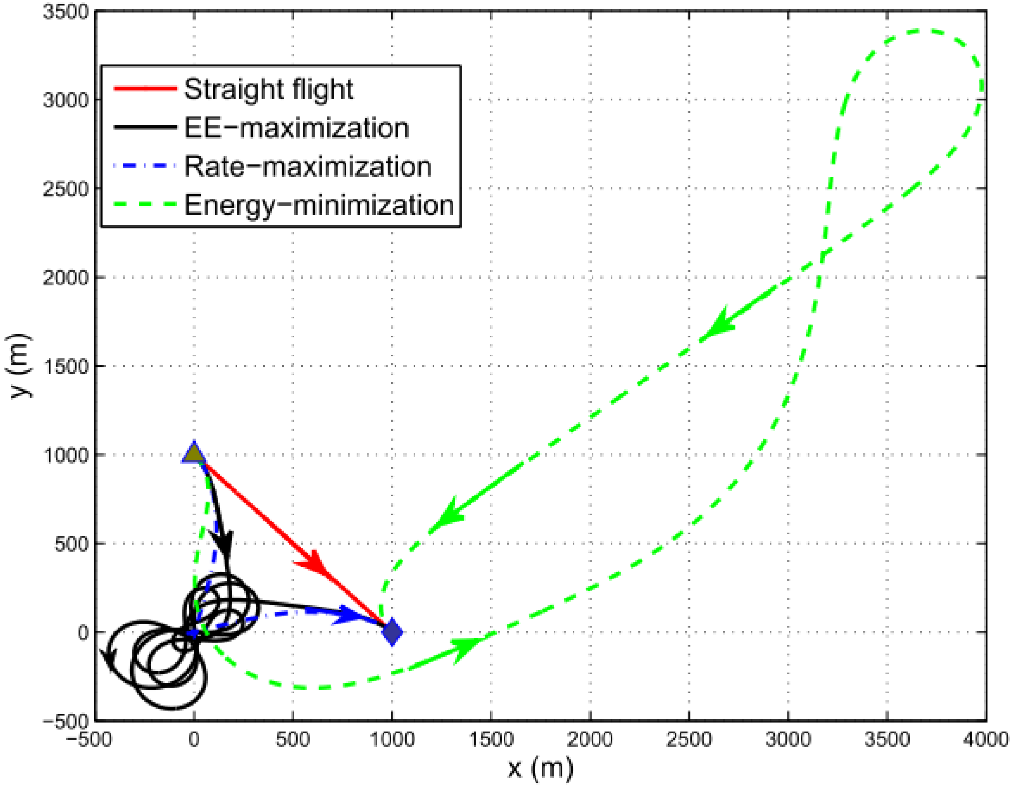
Min./Max. speed constraint

Initial/final velocity constraint

Max. acceleration constraint

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

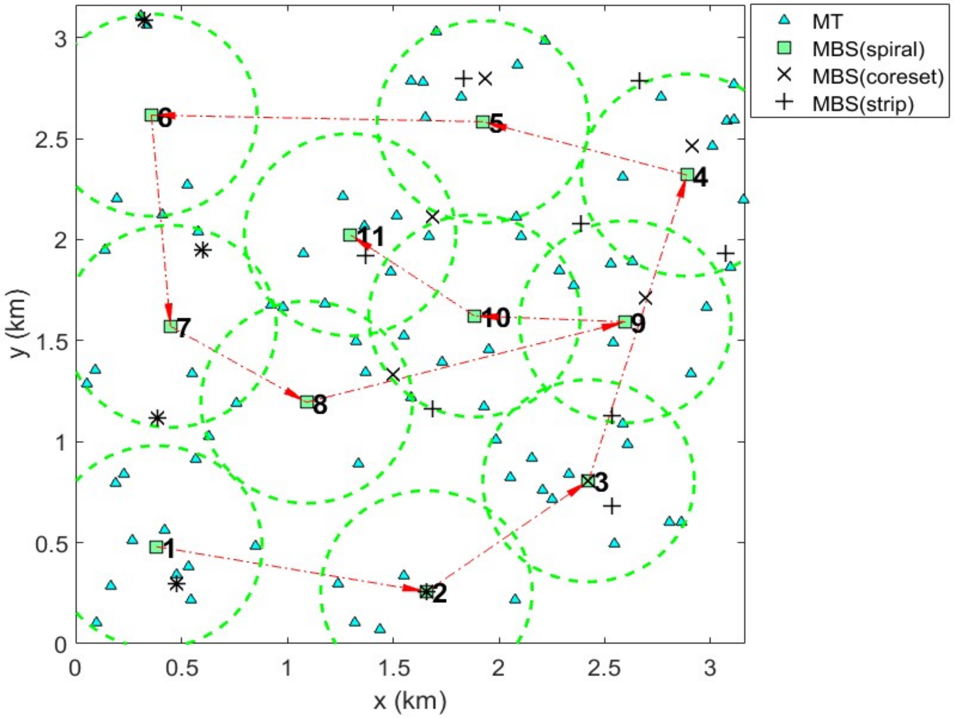
Simulation Results: Throughput-Energy Tradeoff



- ☐ 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
- ☐ A fundamental Throughput-Energy Tradeoff

UAV BS Placement: A Special Case of Trajectory Optimization

- Minimize required number of UAV BSs to ensure all ground terminals are covered
- Core-sets based algorithm, optimal, but with exponential complexity
- New spiral-based BS placement algorithm, linear complexity
- Example with 80 terminals: Proposed spiral: 11 BSs
    - Optimal core-sets: 11 BSs
    - Benchmark strip-based: 13 BSs



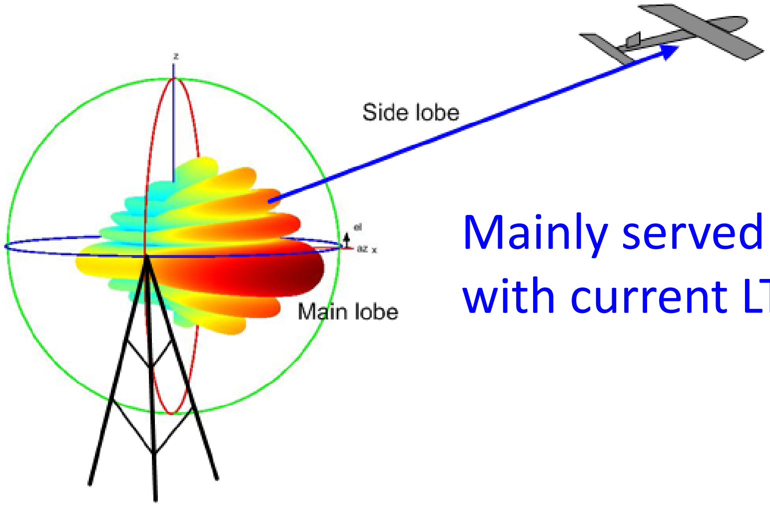
J. Lyu, Y. Zeng, R. Zhang, and T. J. Lim, "Placement Optimization of UAV-Mounted Mobile Base Stations", *IEEE Commun. Letters,* Mar. 2017. (IEEE Communications Society Heinrich Hertz Award, 2020)

Outline

- ❑ Integrating UAVs/Drones into Future Wireless Networks
  - ➢ Motivations and benefits
  - ➢ What's new over terrestrial communications?
- ❑ Two Main Challenges
  - ➢ Trajectory optimization for UAV-assisted communication
  - ➢ **Aerial-ground interference mitigation in cellular-connected UAV**
- ❑ Conclusion and Future Work

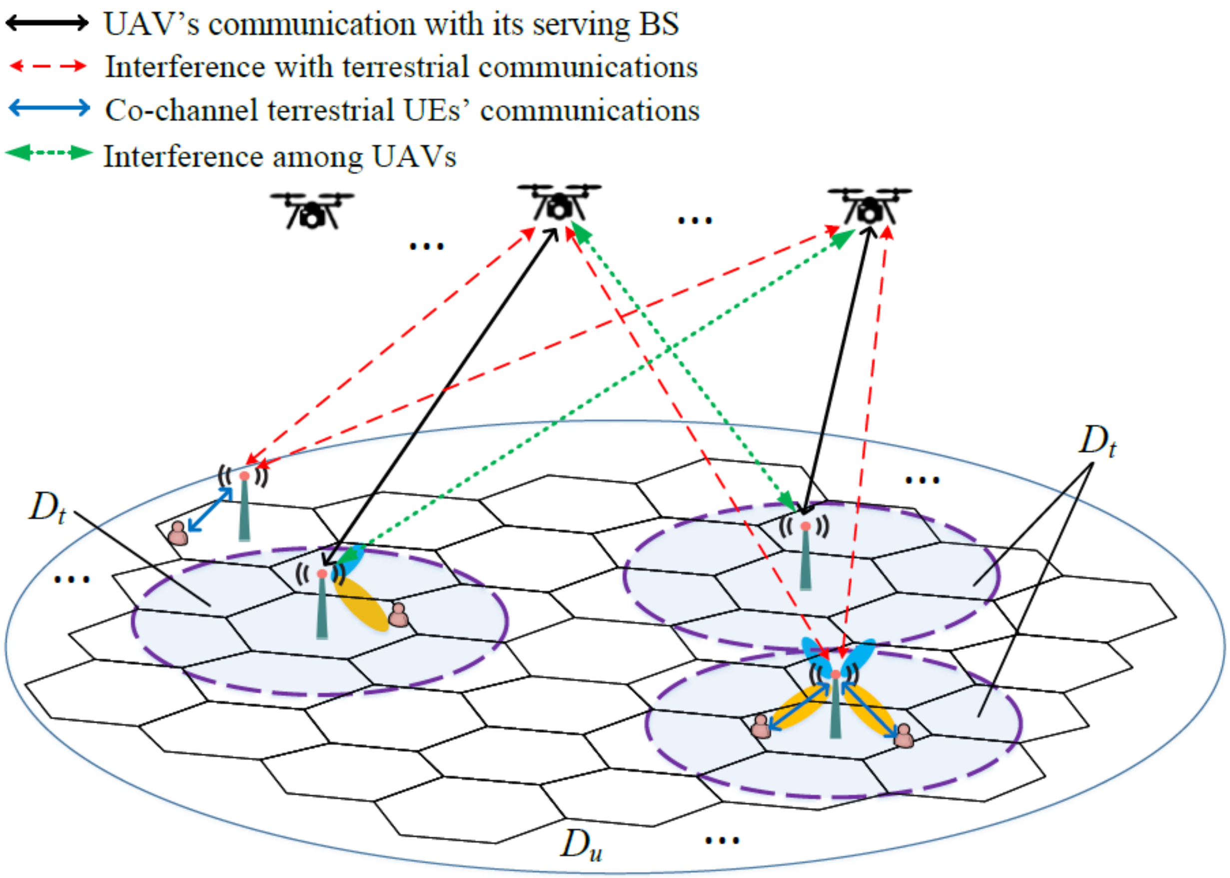
Cellular-Connected UAV: Main Challenges

- 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 (vs. terrestrial NLoS channels)**
  - Pro: High macro-diversity gain: a UAV can connect with more ground BSs
  - Con: Severe aerial-ground interference: a UAV can cause/receive interference to/from more ground users/BSs



Mainly served by antenna side-lobe with current LTE BS

Aerial-Ground Interference



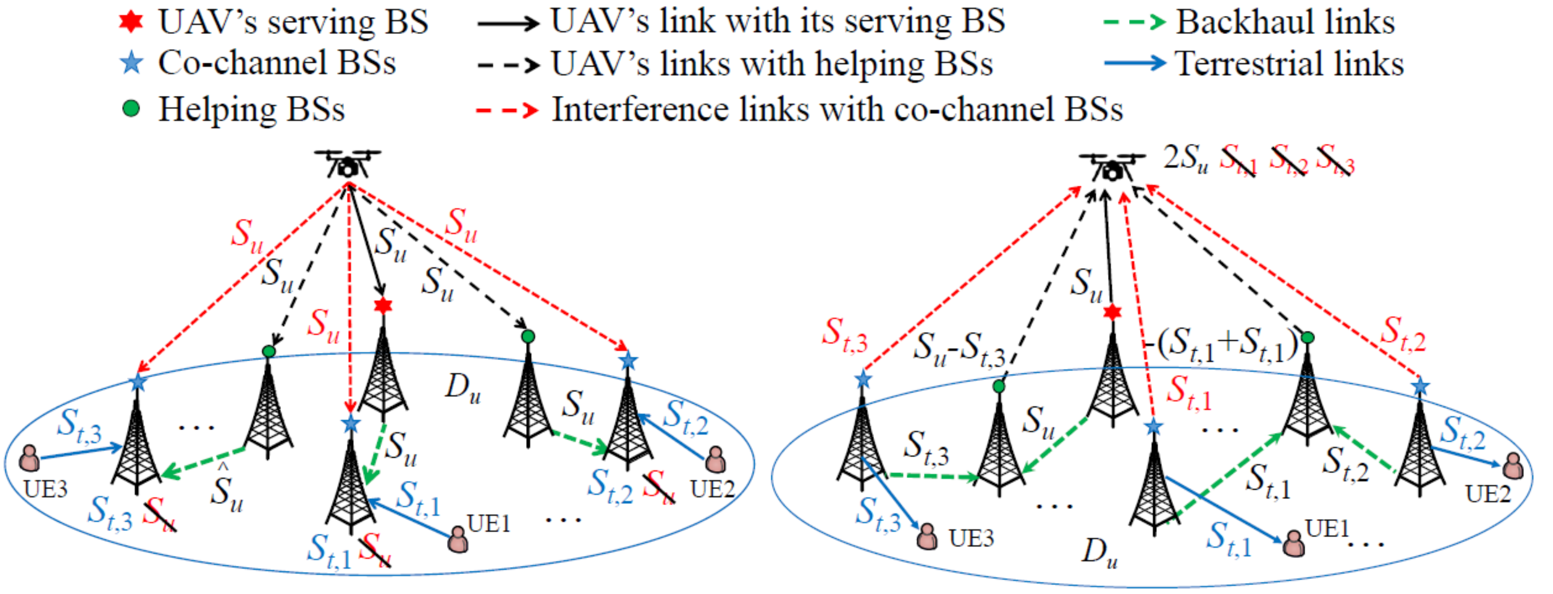
- ☐ Aerial-ground interference is more severe than terrestrial interference
- ☐ Conventional terrestrial interference mitigation techniques may be ineffective to deal with the stronger UAV-ground interference

Aerial-Ground Interference Mitigation

- New aerial-ground interference mitigation techniques:
  - 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

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

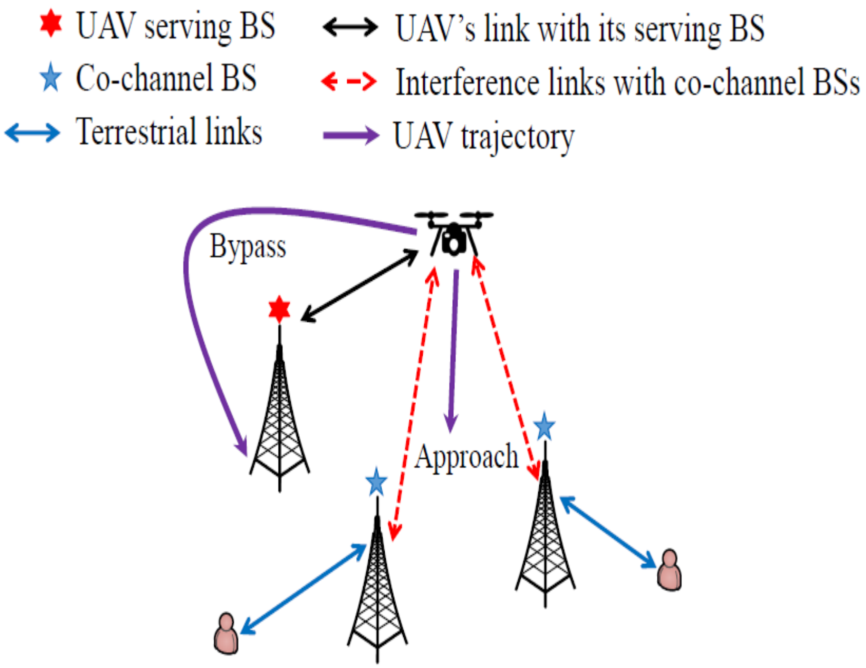


(a) Uplink CIC (b) Downlink CIC

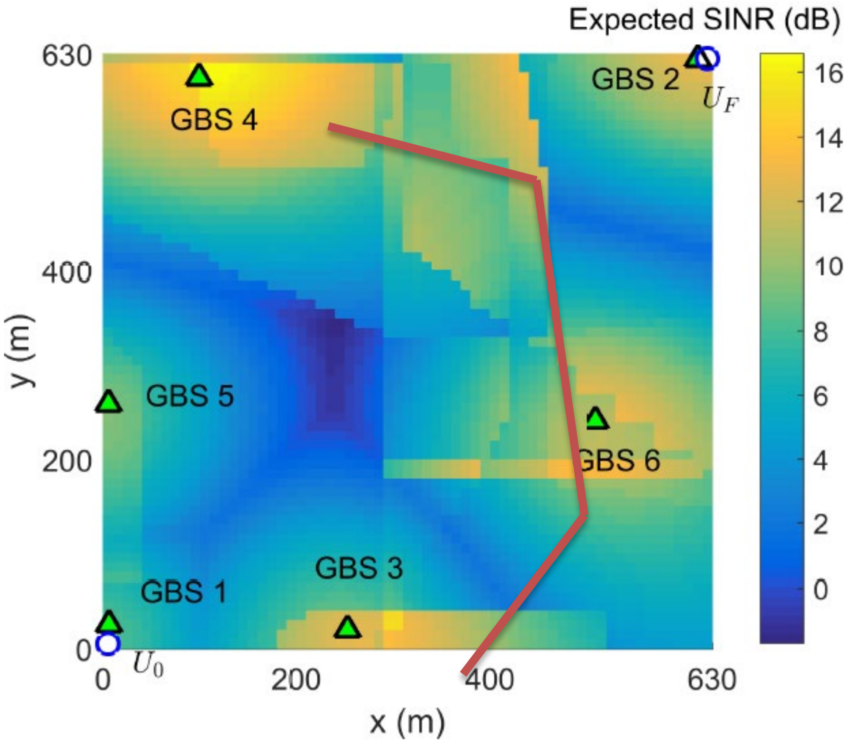
L. Liu, S. Zhang, and R. Zhang, "Multi-beam UAV communication in cellular uplink: cooperative interference cancellation and sum-rate maximization," *IEEE Transactions on Wireless Communications*, October 2019.

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

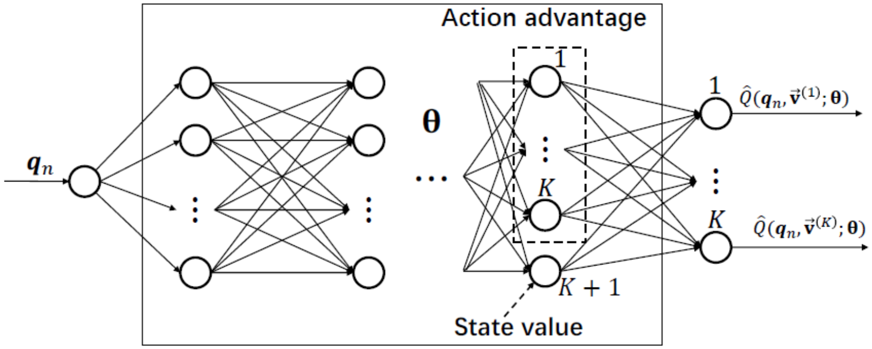


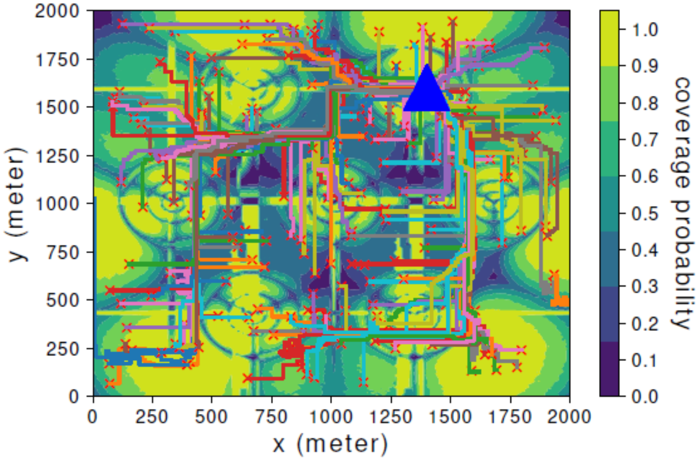
Radio-map/SINR-map based trajectory design

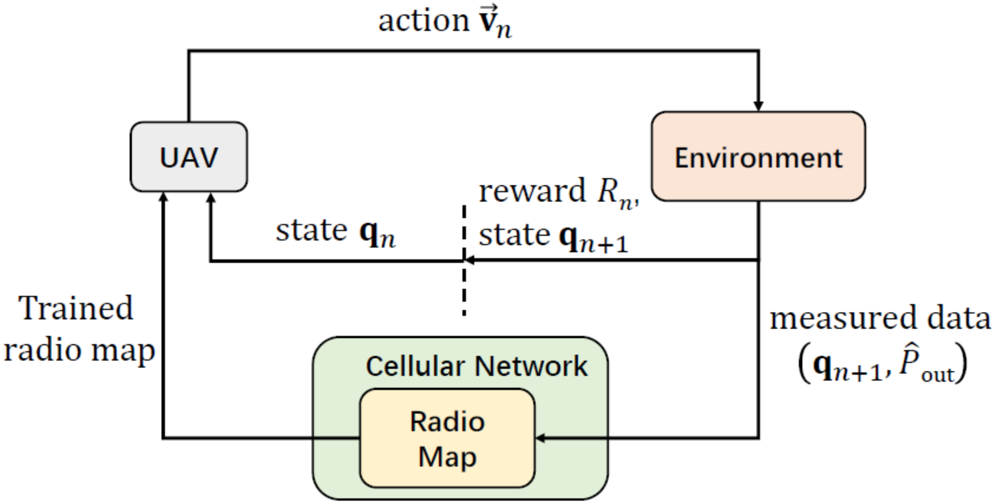
S. Zhang, Y. Zeng, and R. Zhang, "Cellular-enabled UAV communication: a connectivity-constrained trajectory optimization perspective," *IEEE Transactions on Communications*, March 2019. (IEEE Communications Society Young Author Best Paper Award, 2022)

S. Zhang and R. Zhang, "Radio map based 3D path planning for cellular-connected UAV," *IEEE Transactions on Wireless Communications*, March 2021.

Simultaneous Navigation and Radio Mapping via Deep Reinforcement Learning






action $\vec{\mathbf{v}}_n$

UAV

Environment

reward R_n,

state $\mathbf{q}_{n+1}$

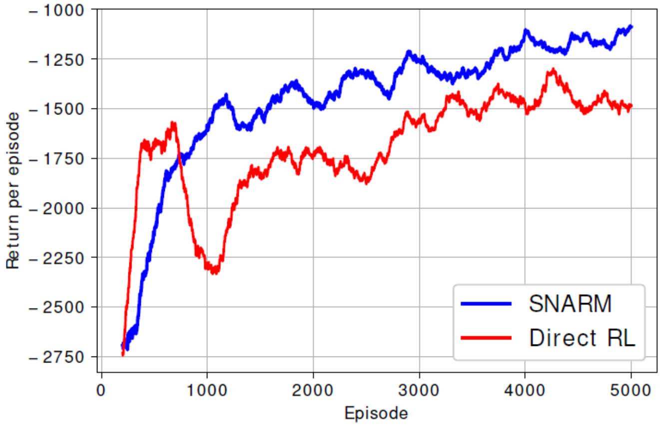
state $\mathbf{q}_n$

Trained radio map

measured data $(\mathbf{q}_{n+1}, \hat{P}_{\text{out}})$

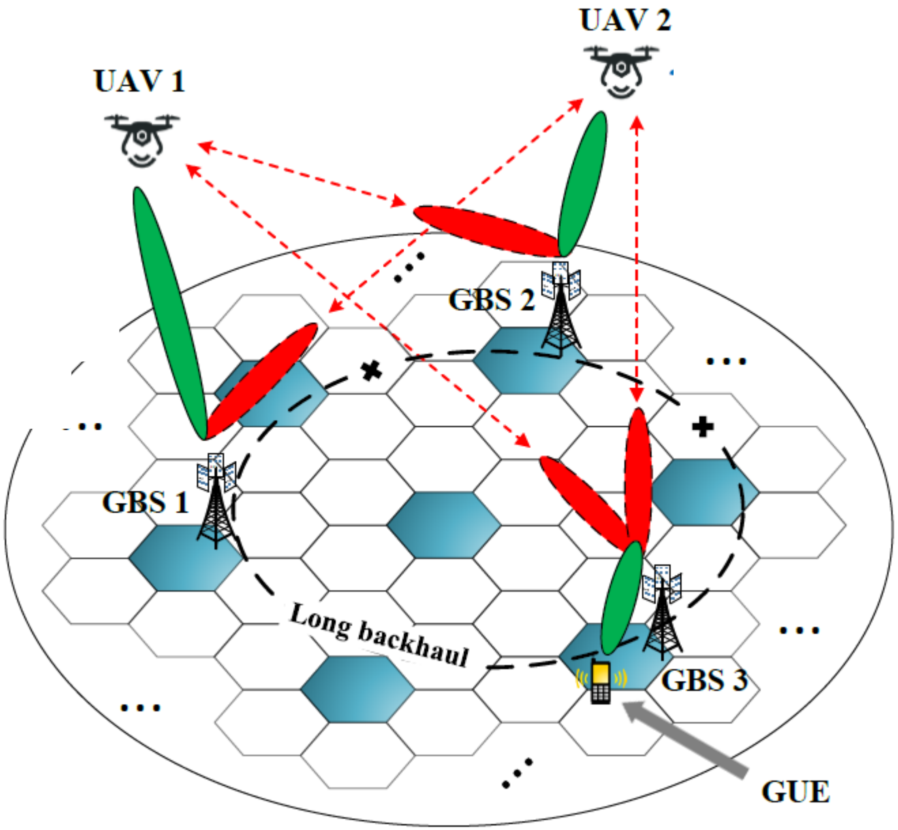
Cellular Network

Radio Map

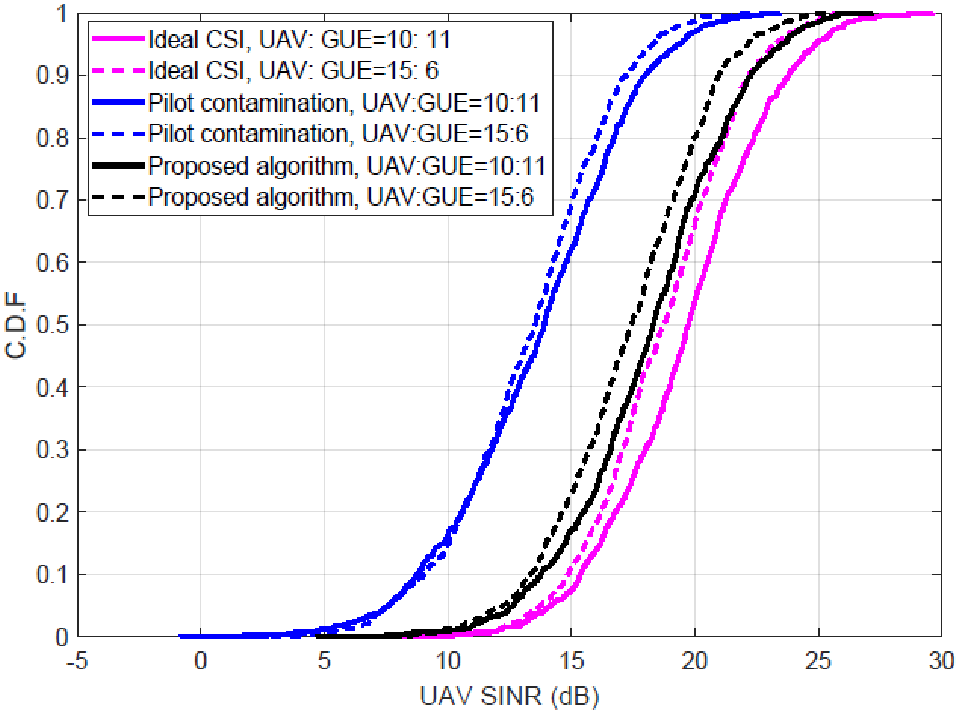


Y. Zeng, X. Xu, S. Jin, and R. Zhang, "Simultaneous navigation and radio mapping for cellular-connected UAV with deep reinforcement learning," *IEEE Transactions on Wireless Communications*, July 2021.

Massive MIMO with Pilot Decontamination



UAV-induced pilot contamination in massive MIMO



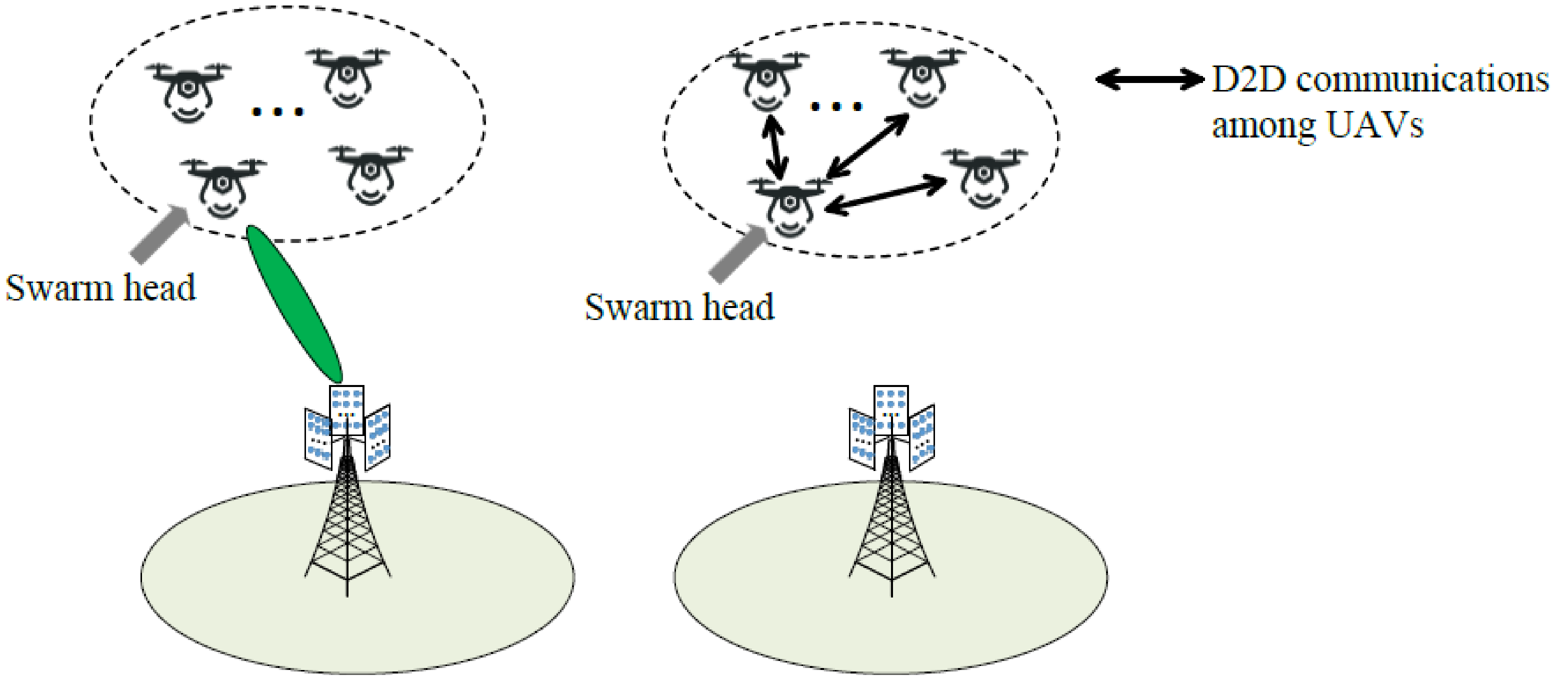
Average UAV SINR distribution in the downlink before vs. after pilot decontamination

R. Lu, Q. Wu, and R. Zhang, "Pilot decontamination for massive MIMO network with UAVs," *IEEE Wireless Communications Letters,* November 2020.

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



Phase I: GBS transmits (common) message to swarm head

Phase II: Swarm head broadcasts the message to the other UAVs

Y. Han, L. Liu, L. Duan, and R. Zhang, "Towards reliable UAV swarm communication in D2D-enhanced cellular network," *IEEE Transactions on Wireless Communications,* March 2021.

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/relay/data collector
- ☐ Many challenges, among them two crucial ones are
  - ➢ Joint trajectory/placement and communication design
  - ➢ Aerial-ground interference mitigation
- ☐ Much more to be investigated
  - ➢ safety/security issues, integration with satellite, energy replenishment, integrated communication and sensing, etc.

Directions for Future Work

- 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 reflecting surface (IRS), etc.
- UAV/LEO/Satellite integrated communication systems
- UAV sensing and communication integrated design
- AI for UAV communications and networking
- UAV-5G/6G integration, standardization

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