UAV Meets Wireless Communication in 5G and Beyond: Main Research Challenges and Key Enabling Techniques

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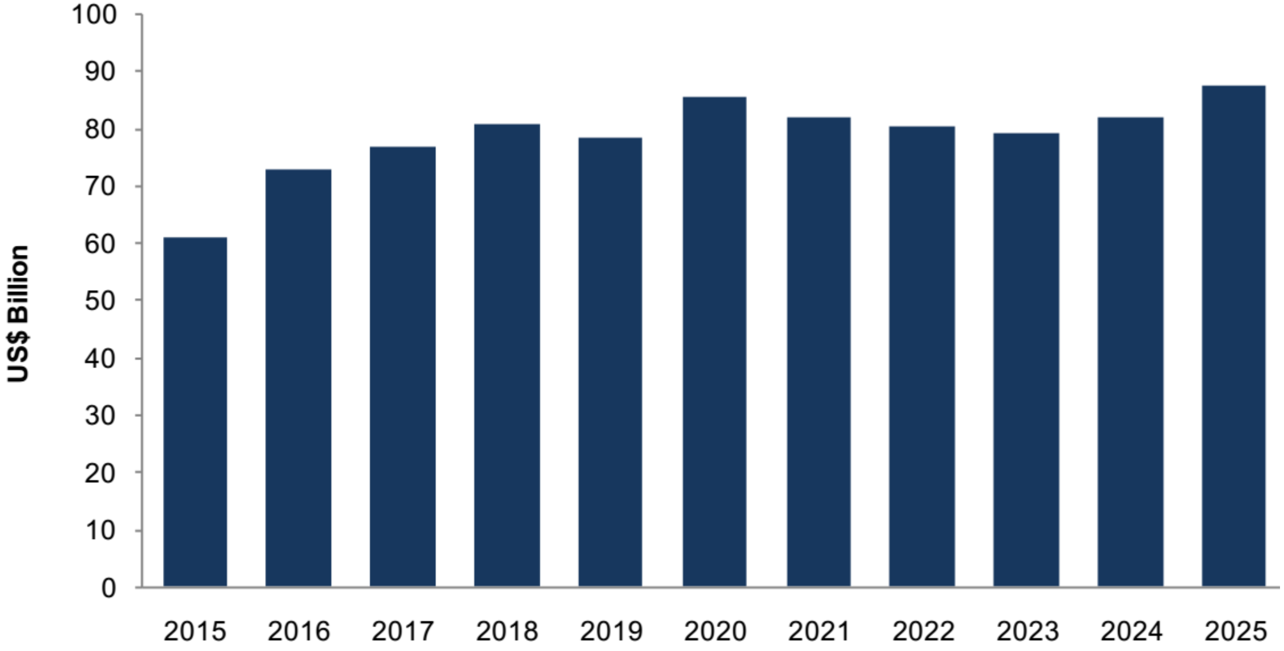
Outline

- ☐ Part 1: Overview
  - ➢ Introduction
  - ➢ Integrating UAVs into 5G and Beyond: Two Paradigms
    - ☐ Cellular-Connected UAVs
    - ☐ UAV-Assisted Terrestrial Communications

- ☐ Part 2: Case Study
  - ➢ UAV-enabled mobile relaying
  - ➢ Multi-UAV enabled wireless network
  - ➢ Energy-efficient UAV communication
  - ➢ Cellular-connected UAV: QoS-aware trajectory design

UAV: Whose Time is Coming

Figure 1: Global UAV Market (US$ Billion), 2015–2025



Source: SDI analysis. https://www.marketresearch.com/product/sample-8691316.pdf

- Create more than **100,000 new jobs** in US over the next 10 years
- **Numerous applications**: military, traffic control, cargo delivery, precision agriculture, video streaming, aerial inspection, rescue and search, ……

FAA Rules for Small UAS

- ☐ June 2016: US Federal Aviation Administration (FAA) released new rules for commercial use of small unmanned aircraft systems (UAS) (Part 107)
  - Small UAS: 55 pounds (25 kg)
  - Visual line-of-sight (VLOS) only
  - Daylight-only operation
  - Maximum ground speed: 100mph (161km/h)
  - Maximum altitude: 400 feet (122 m)
  - Operations are allowed in uncontrolled airspace (Class G) without air traffic control (ATC) permission
- ☐ The road ahead:
  - Beyond LoS operation?
  - Completely autonomous flying?

Source: FAA, “Operation and Certification of Small Unmanned Aircraft Systems”, https://www.faa.gov/uas/media/RIN_2120-AJ60_Clean_Signed.pdf

Aerial photography

Source: https://www.multirotor.net/en/

Drone Delivery

Source: Google Image

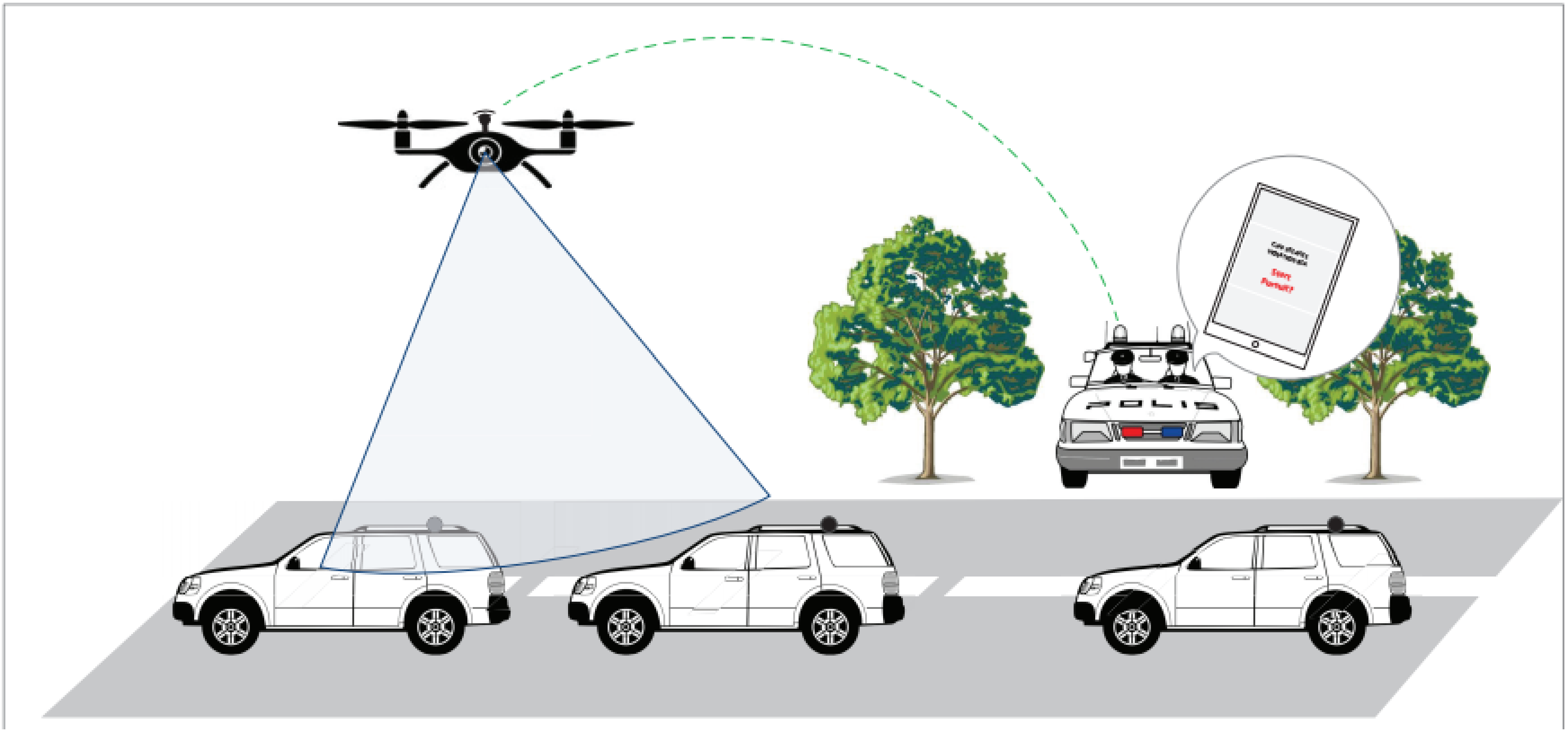
Aerial Inspection

Source: https://www.multirotor.net/en/

Precision Agriculture

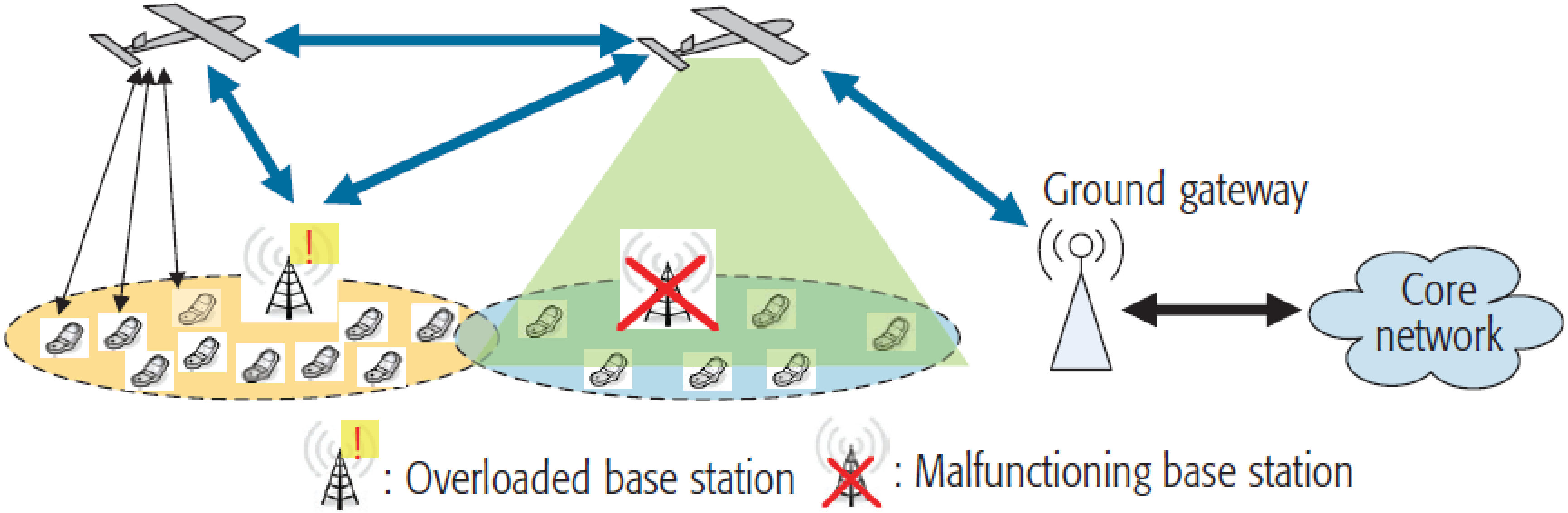
Source: Google image

Traffic Monitoring



H. Menouar, et. al, “UAV-Enabled Intelligent Transportation Systems for the Smart City: Applications and Challenges”, *IEEE Commun. Mag.*, Mar. 2017

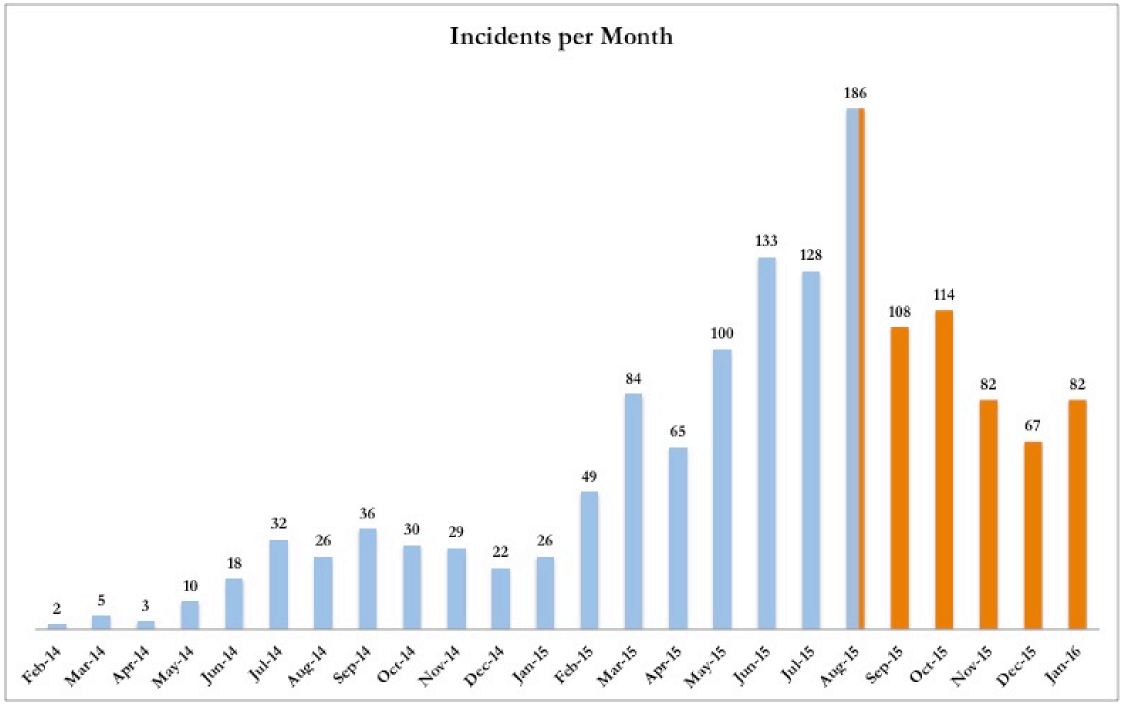
Airborne Communication Platform

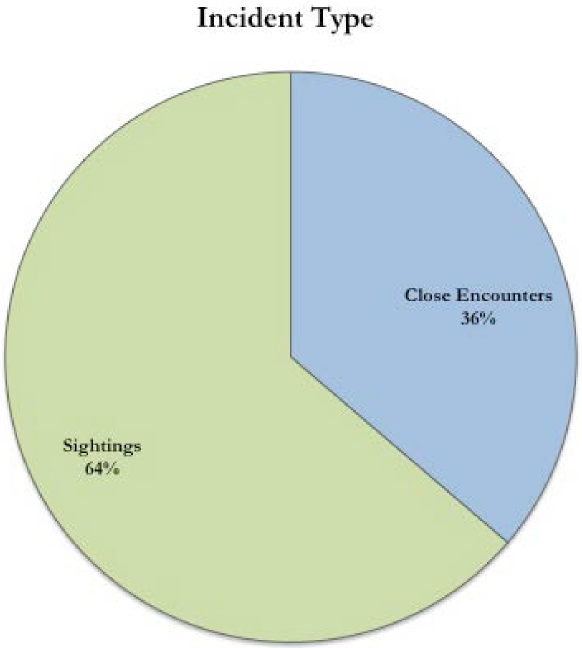


Y. Zeng, R. Zhang, and T. J. Lim, “Wireless communications with unmanned aerial vehicles: opportunities and challenges,” *IEEE Commun. Mag.*, May 2016

Are We Ready for the Drone Era?

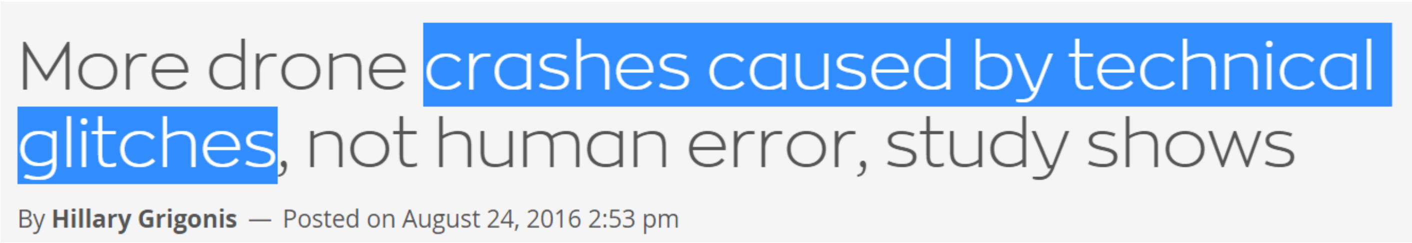
- **582 new incidents** in U.S. within 6 months (Aug. 2015 to Jan. 2016)
  - **Close Encounters** (Near MidAir Collision): drone within 500 feet of a manned aircraft
  - **Sightings**: drone within aircraft flight paths but no immediate potential threat.





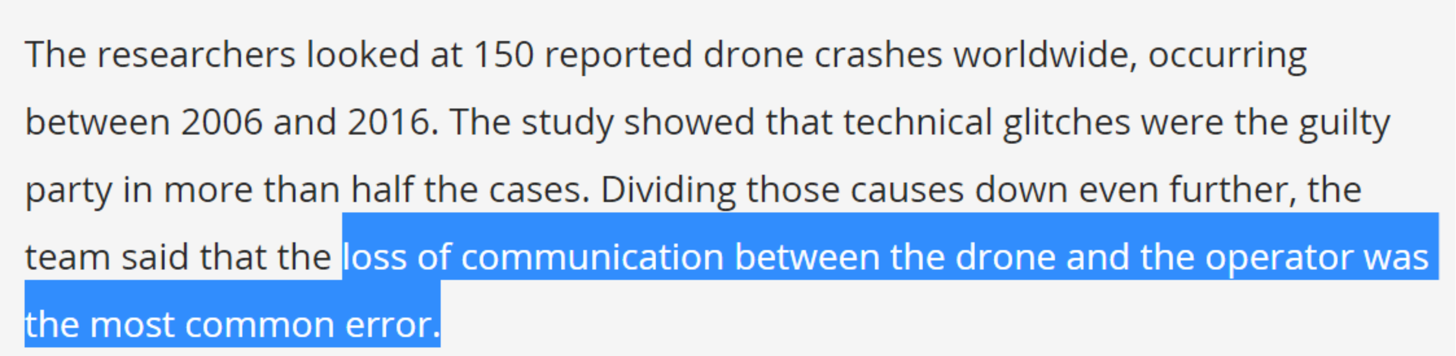
Source: http://dronecenter.bard.edu/analysis-3-25-faa-incidents/

Are We Ready for the Drone Era?



More drone crashes caused by technical glitches, not human error, study shows

By **Hillary Grigonis** — Posted on August 24, 2016 2:53 pm



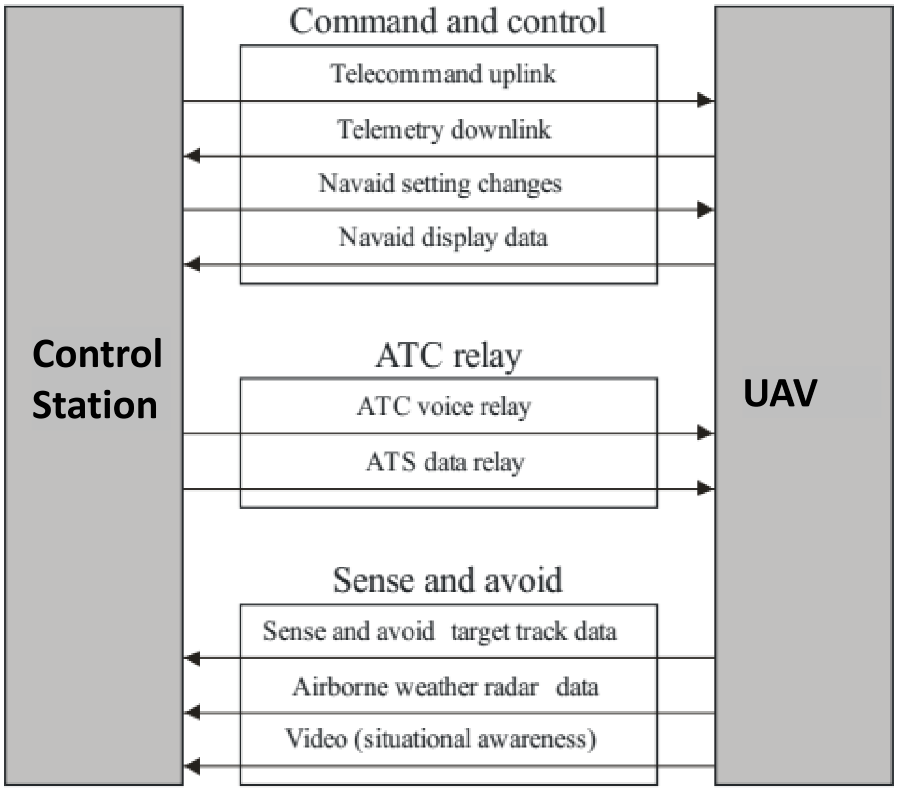
The researchers looked at 150 reported drone crashes worldwide, occurring between 2006 and 2016. The study showed that technical glitches were the guilty party in more than half the cases. Dividing those causes down even further, the team said that the loss of communication between the drone and the operator was the most common error.

Source: https://www.digitaltrends.com/cool-tech/drone-crashes-caused-by-technical-glitches/?utm_source=feedly&utm_medium=webfeeds

- **150 reported drone crashes** in the past 10 years
- Loss of communication was the most common error
- **Wireless Communication: the CORE technology for securing drones**

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
  - Telemetry (UAV status reporting)
  - Command and control
  - Navigation aids
  - Sense and avoid (S&A)
  - Air traffic control (ATC) relay,……
- **Payload Communications**
  - Application specific information
  - Typically higher rate than CNPC



Control Station

Command and control
- Telecommand uplink
- Telemetry downlink
- Navaid setting changes
- Navaid display data

ATC relay
- ATC voice relay
- ATS data relay

Sense and avoid
- Sense and avoid target track data
- Airborne weather radar data
- Video (situational awareness)

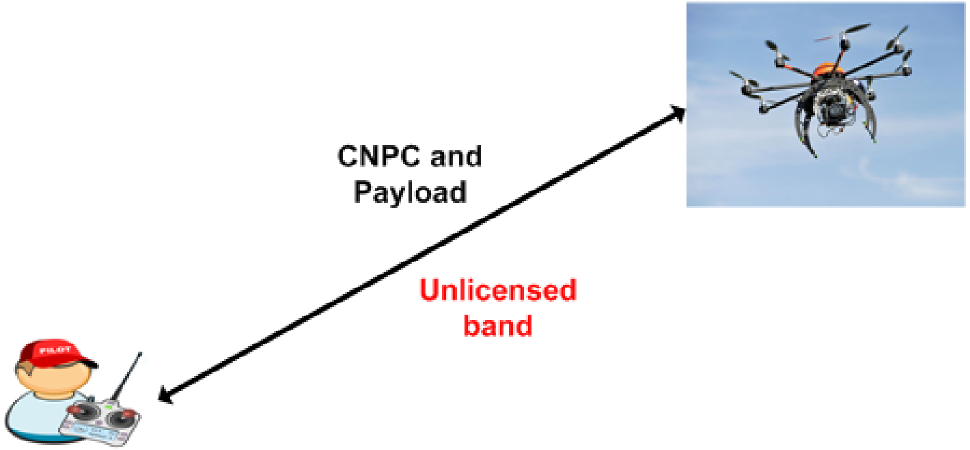
UAV

CNPC information flows [ITUReportM.2171]

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

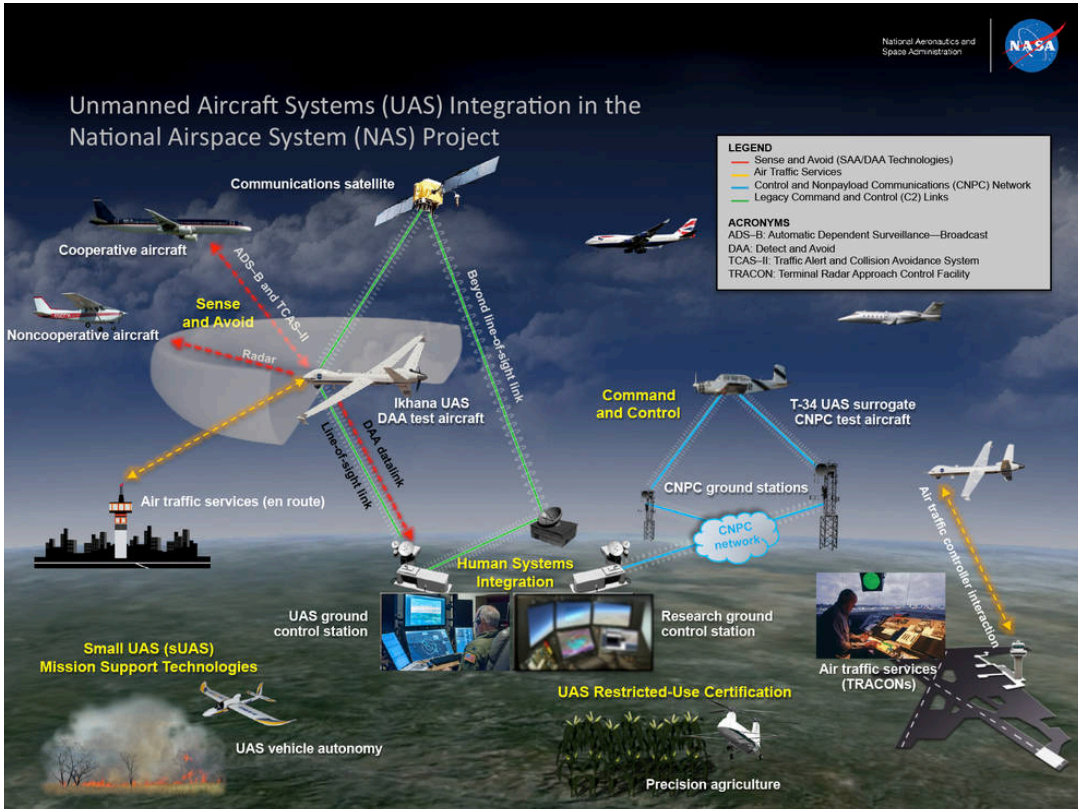
Wireless Communications for UAVs: Existing Technologies

- ☐ Direct ground-to-UAV communications
- ☐ Unlicensed spectrum (2.4 GHz)
- ☐ Main limitations:
  - Unreliable
  - Insecure
  - Vulnerable to interference
  - Limited data rate
  - Visual line of sight (LoS) operation
  - Difficult to legitimately monitor and manage



Integration of UAS into National Airspace (NAS)

- ❑ Routine access to the global airspace for all classes of UAS (Unmanned Aircraft Systems)
- ❑ NASA's UAS Integration in the NAS Project



- ➢ New infrastructure (e.g., control station) dedicated for UAV?
- ➢ Cost?
- ➢ Business model?
- ➢ Spectrum?

Source: https://www.nasa.gov/aeroresearch/programs/iasp/uas/about-us

Spectrum Requirement

- ☐ The maximum amount of spectrum required for CNPC [ITUReportM.2171] :
  - ➢ **34 MHz** for terrestrial systems
  - ➢ **56 MHz** for satellite systems (for beyond LoS CNPC)
- ☐ International Civil Aviation Organization (ICAO) requires that CNPC link must operate over protected aviation spectrum
- ☐ WRC-12: allocated the band 5030-5091 MHz for CNPC
- ☐ WRC-15: “Assignments to stations of geostationary Fixed Satellite Service (FSS) networks may be used for CNPC links of UAS” [WRC-15Outcomes]

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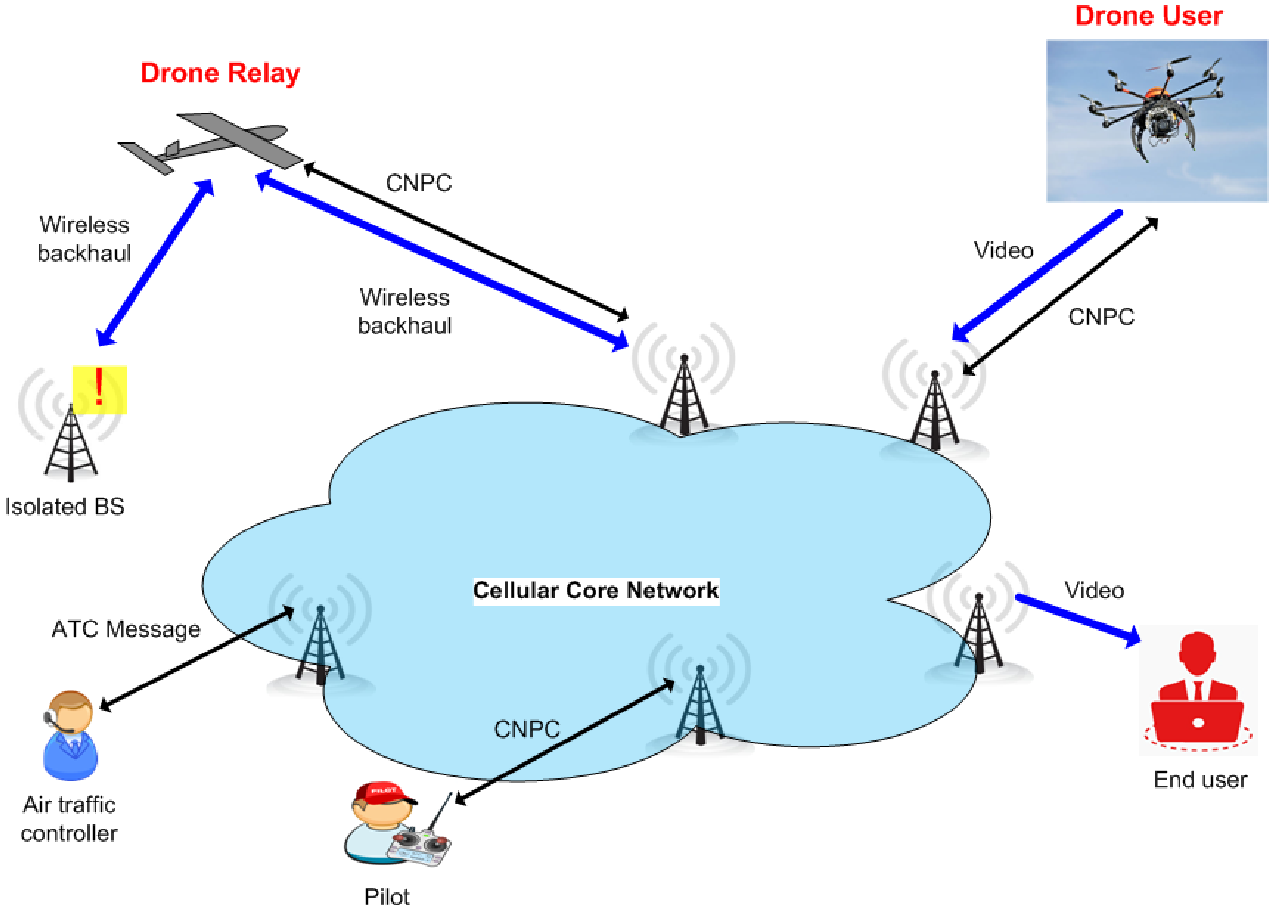
Integrating UAVs into Cellular



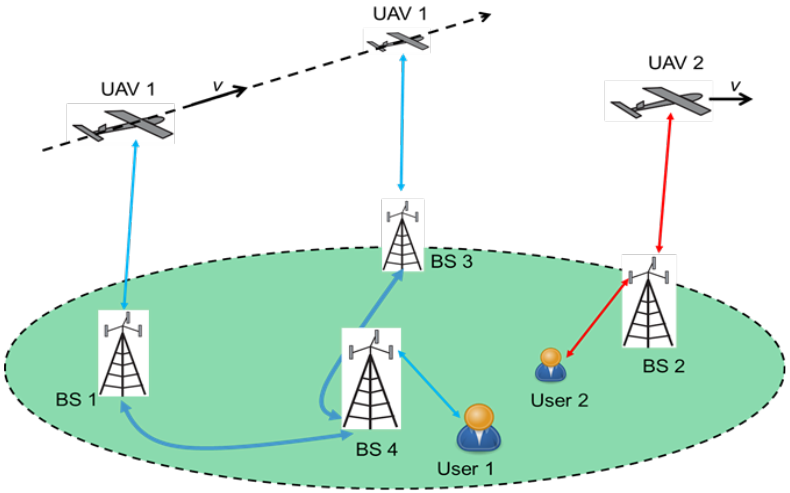
Y. Zeng, J. Lyu, and R. Zhang, “Cellular-connected UAV: potentials, challenges and promising technologies,” submitted to *IEEE Wireless Communications.*

Integrating UAVs into Cellular: A Win-Win Technology

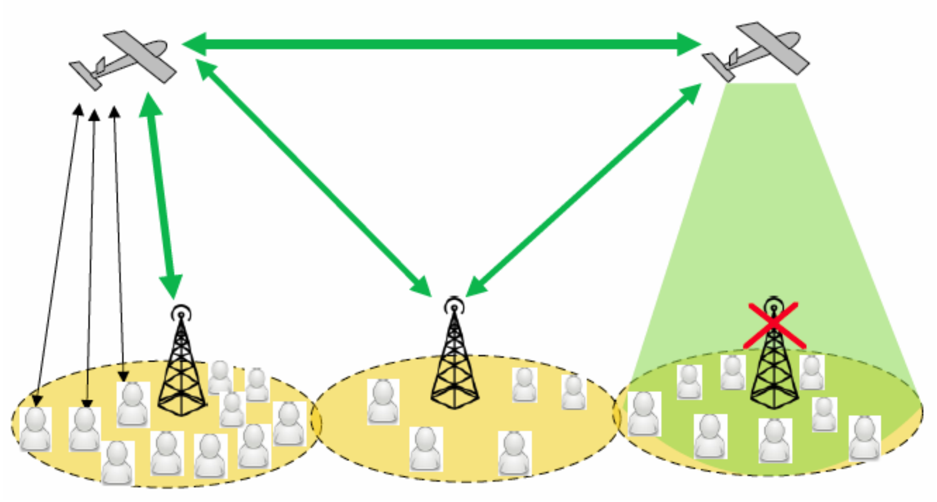
- ☐ Integrating UAVs into cellular networks (LTE, 5G, B5G…)
- ☐ For UAV industry:
  - More reliable and secure CNPC
  - Unlimited operation range without relying on satellite
  - High capacity enabled by advanced cellular techniques
  - Cost effective: avoid building new infrastructure for UAV communication
  - Enhanced air traffic management: legitimate control takeover when needed
- ☐ For cellular industry:
  - New business opportunities by incorporating aerial users
  - More robust and cost-effective cellular network with aerial communication platform

Integrating UAVs into Cellular: Two Paradigms

- Cellular-Connected UAVs: UAVs as aerial users with their own missions
- UAV-Assisted Terrestrial Communications: UAVs as aerial communication platforms (e.g. BS, relay, access point)



Cellular-Connected UAV



UAV-Assisted Terrestrial Communications

Integrating UAVs into Cellular: What's New?

- ☐ High altitude: 3D aerial coverage, LoS channels
- ☐ High 3D mobility: 3D MIMO channel, Doppler effect
- ☐ Unique channel characteristics:
  - UAV-terminal channel
  - UAV-BS channel
  - UAV-UAV channel
- ☐ Aerial-ground interference
- ☐ Size, weight, and power (SWAP) constraints of UAV
- ☐ Additional design degrees of freedom:
  - 3D placement
  - Controllable UAV trajectory

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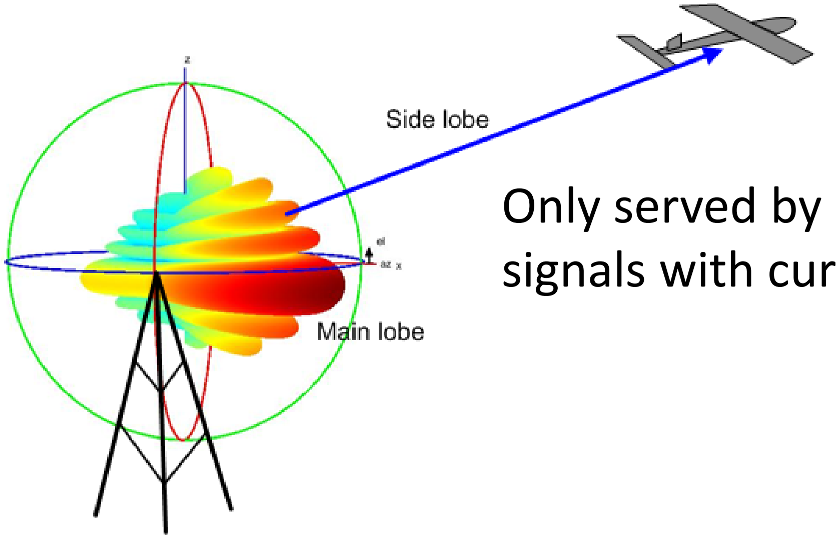
Cellular-Connected UAVs: Industry Efforts

February 2016	Intel and AT&T	demonstrated the world’s first LTE-connected drone at the 2016 Mobile World Congress
August 2016	Ericsson and China Mobile	so-called world’s first 5G-enabled drone prototype field trial in WuXi of China
September 2016	Qualcomm	Feasibility proof of drone operation over commercial LTE networks up to 400 feet
March 2017	3GPP	approved the work item “study on enhanced support for aerial vehicles using LTE”
November 2017	Huawei Wireless X Labs	announced the "Digital Sky Initiative“ to “spur development of drone applications and enable the low airspace digitized economy via enhanced low airspace network coverage”

Cellular-Connected UAVs: New Challenges

- High altitude
  - 3D coverage requirement: existing BS antenna tilted downwards
  - unique channel characteristics: strong LoS link
- High 3D mobility
- Both CNPC and payload communications
- Severe aerial interference: uplink and downlink
- Additional design degree of freedom with UAV mobility control

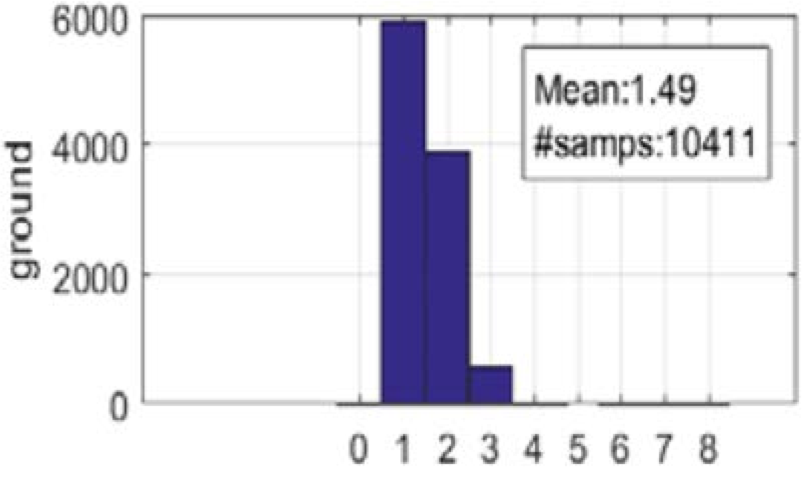


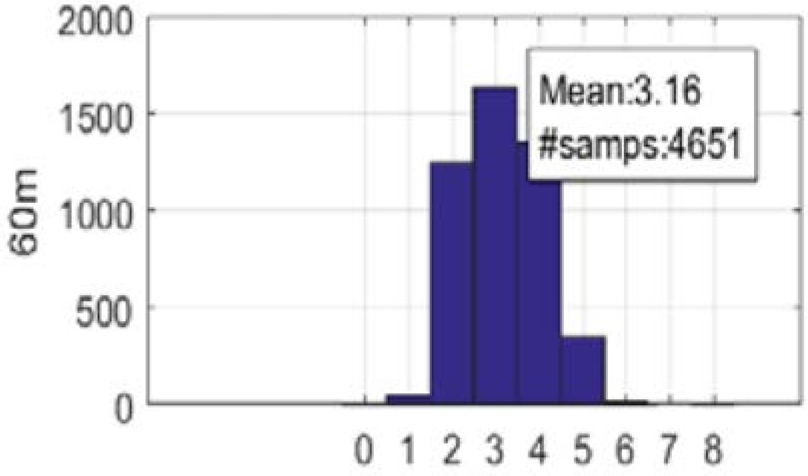
Only served by side-lobe or reflected signals with current LTE BS

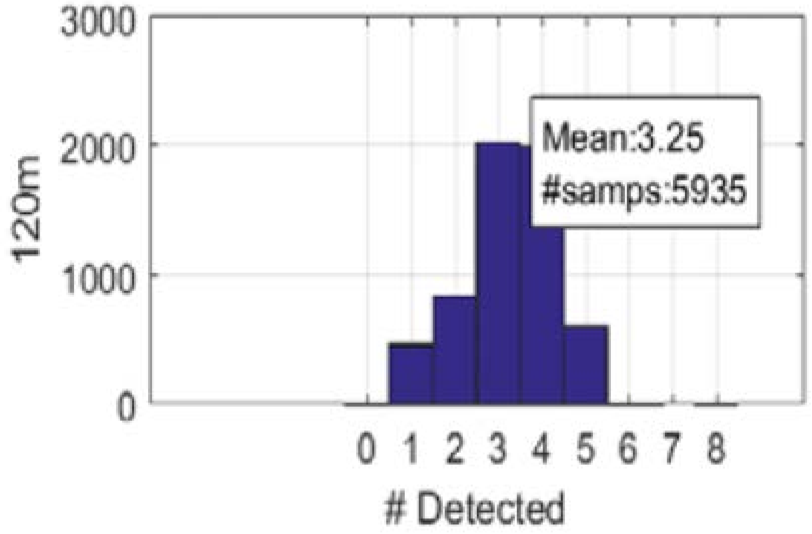
Cellular-Connected UAVs: Recent Results

- Field measurement over LTE network: Qualcom, Huawei, …
- Overview
  - B. V. D. Bergh, A. Chiumento, and S. Pollin, “LTE in the sky: trading off propagation benefits with interference costs for aerial nodes,” *IEEE Commun. Mag.*, May 2016.
  - X. Lin, et al., “The sky is not the limit: LTE for unmanned aerial vehicles,” *IEEE Commun. Mag.*, 2018.
  - **Y. Zeng, J. Lyu, and R. Zhang, "Cellular-connected UAV: potentials, challenges and promising technologies," submitted to *IEEE Wireless Commun.***
- UAV-BS Channel measurement and modeling
  - Rafhael Amorim, et al., “Radio channel modeling for UAV communication over cellular networks”, *IEEE Wireless Commun. Lett.*, Aug., 2017.
  - A. Al-Hourani and K. Gomez, "Modeling cellular-to-UAV path-loss for suburban environments," *IEEE Wireless Commun. Lett.*, Feb. 2018.
- Performance analysis and simulation
  - M. M. Azari, Y. Murillo, O. Amin, F. Rosas, M. S. Alouini, and S. Pọllin, “Coexistence of Terrestrial and Aerial Users in Cellular Networks,” IEEE Globecom 2017 Workshop
  - M. M. Azari, F. Rosas, and S. Pollin, “Reshaping Cellular Networks for the Sky: The Major Factors and Feasibility,” arXiv
  - H. C. Nguyen, R. Amorim, J. Wigard, I. Z. Kovcs, T. B. Srensen, and P. Mogensen, “How to ensure reliable connectivity for aerial vehicles over cellular networks,” IEEE Access, Feb. 2018.
- Massive MIMO for drones
  - P. Chandhar, D. Danev, and E. G. Larsson, “Massive MIMO for communications with drone swarms,” *IEEE Trans. Wireless Commun.,* Mar. 2018.
- Millimeter wave UAV
  - Z. Xiao, P. Xia, and X.-G. Xia, “Enabling UAV Cellular with Millimeter-Wave Communication: Potentials and Approaches, IEEE Commun. Mag., May 2016.
- Trajectory design with connectivity constraint
  - **S. Zhang, Y. Zeng, and R. Zhang, “Cellular-enabled UAV communication: Trajectory optimization under connectivity constraint ,” ICC 2018, accepted**
  - E. Bulut and I. Guvenc, “Trajectory Optimization for Cellular-Connected UAVs with Disconnectivity Constraint,” ICC 2018 Workshop

Cellular-Connected UAVs: Number of Detected Cells





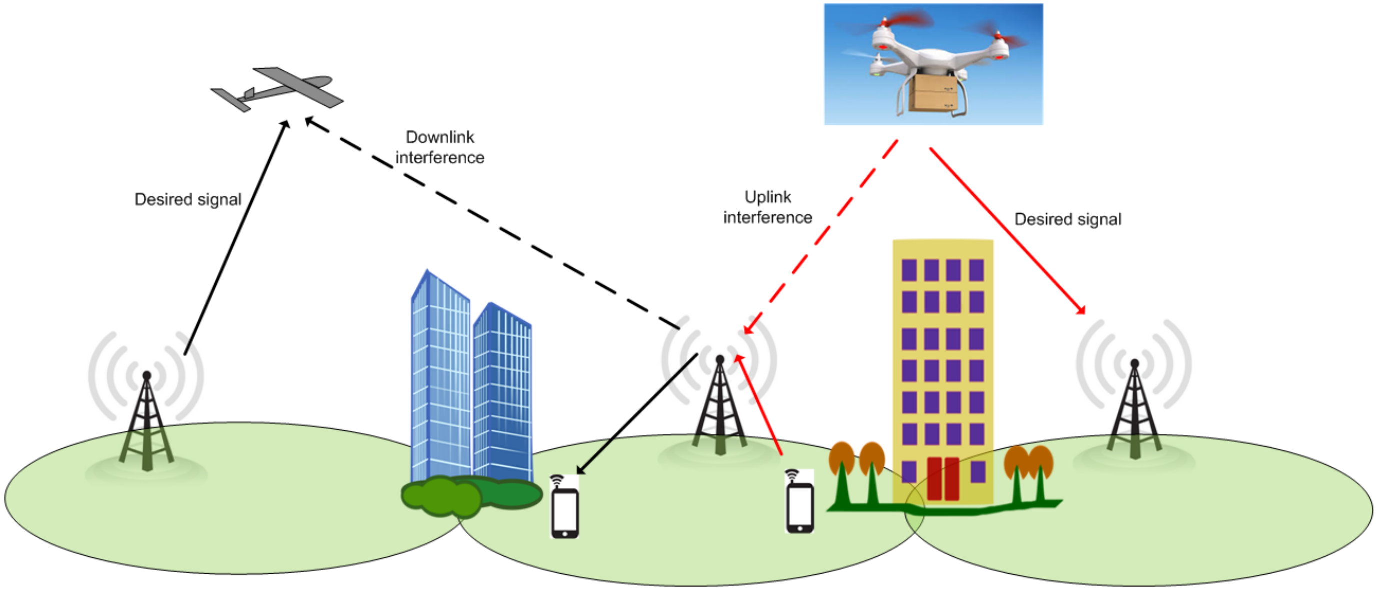


- Field measurements by Qualcom
- Strong signal strength for drone UES, despite down-tilted BS antennas
- Number of detected cells generally increases with altitude
- Expected due to free space propagation at higher altitude

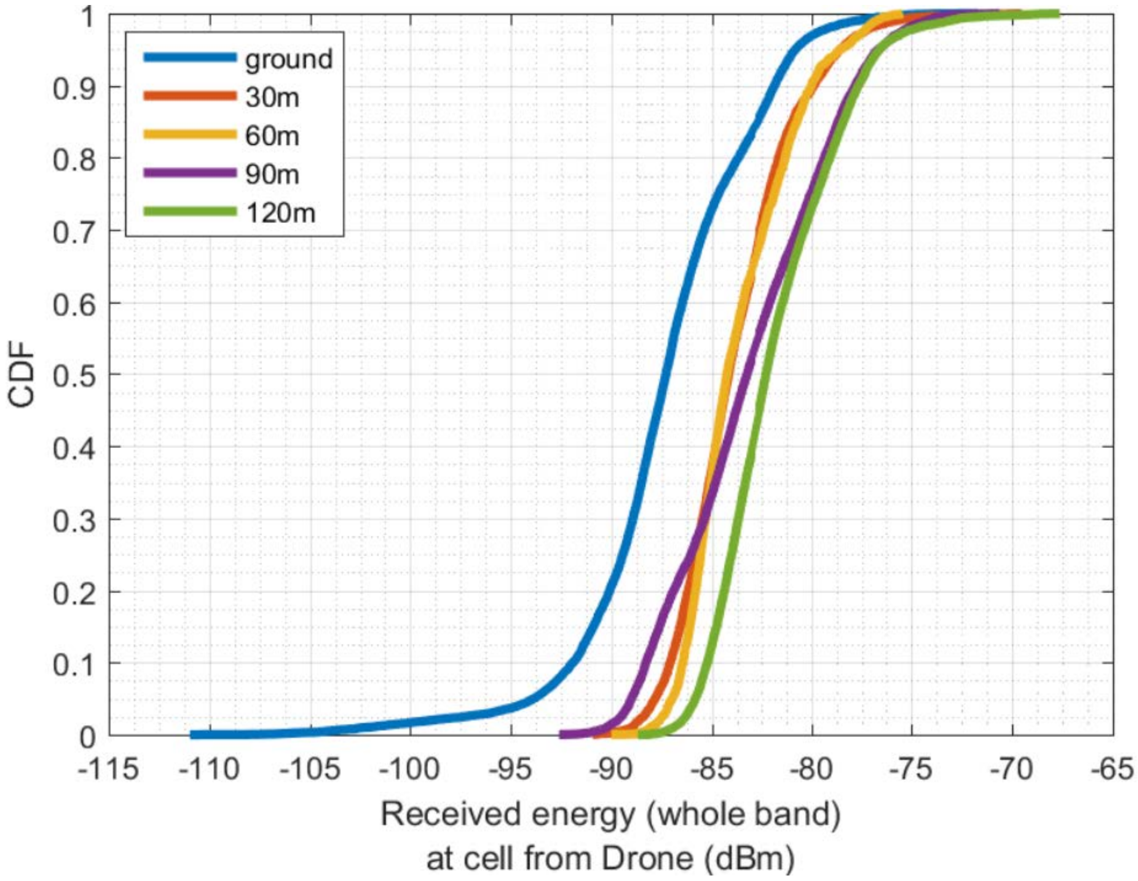
Qualcom, “LTE Unmanned Aircraft Systems”, Trial Report, v1.0.1, May 2017

Severe Aerial-Ground Interferences

- ❑ More severe interference due to strong LoS link for BS-UAV channels
- ❑ Interference between UAV and terrestrial users
- ❑ Uplink: more interference imposed to neighbouring BSs
- ❑ Downlink: more interference received from neighbouring BSs



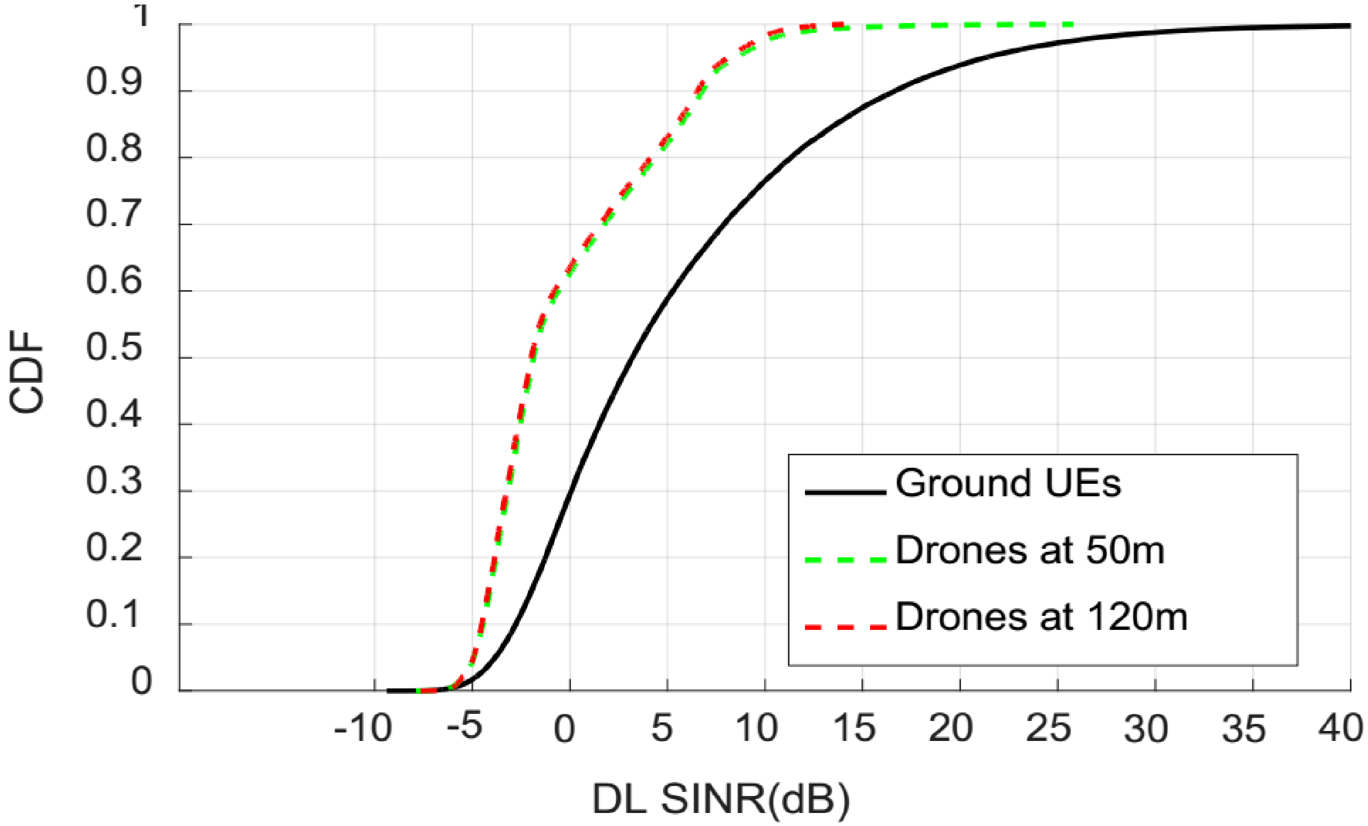
Uplink Interference due to Drone Transmissions



- ☐ More interference caused by drone users than ground users

Qualcom, “LTE Unmanned Aircraft Systems”, Trial Report, v1.0.1, May 2017

Downlink SINR of Drone Users



- ☐ Lower SINR for drone users than ground users, due to higher interference from neighbor cells via free space propagation

Qualcom, “LTE Unmanned Aircraft Systems”, Trial Report, v1.0.1, May 2017

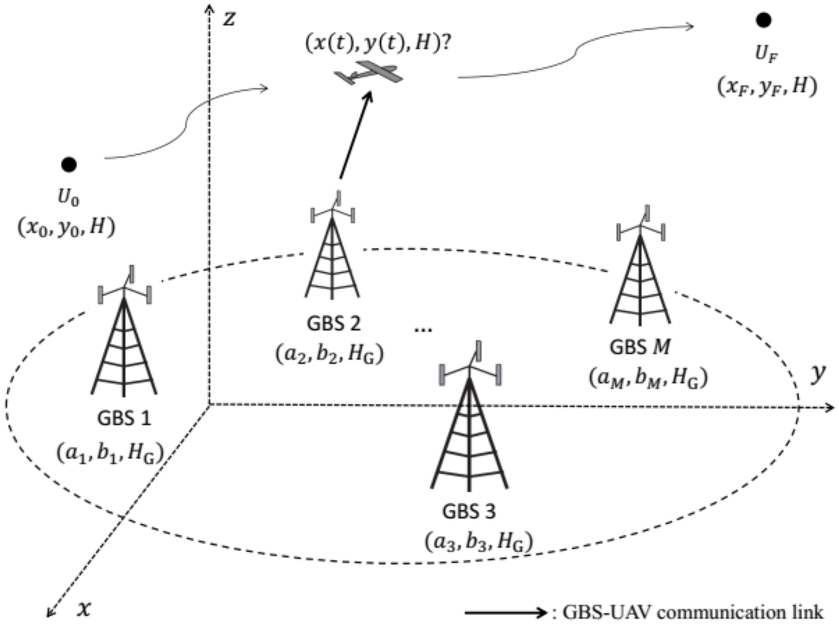
Reshaping Cellular Networks to the Sky

- ❑ New techniques needed to enable highly heterogonous network with both terrestrial and aerial users
- ❑ Possible spectrum allocation:
  - ➢ Protected aviation spectrum licensed to cellular operators for UAV CNPC
  - ➢ Cellular spectrum shared by aerial and terrestrial users with interference mitigation
- ❑ Interference management techniques:
  - ➢ Sub-sector in elevation domain
  - ➢ **3D beamforming**
  - ➢ Multi-cell cooperation
  - ➢ Terrestrial-aerial NOMA
  - ➢ **Joint resource allocation and trajectory design**

Y. Zeng, J. Lyu, and R. Zhang, “Cellular-connected UAV: potentials, challenges and promising technologies,” submitted to *IEEE Wireless Communications.*

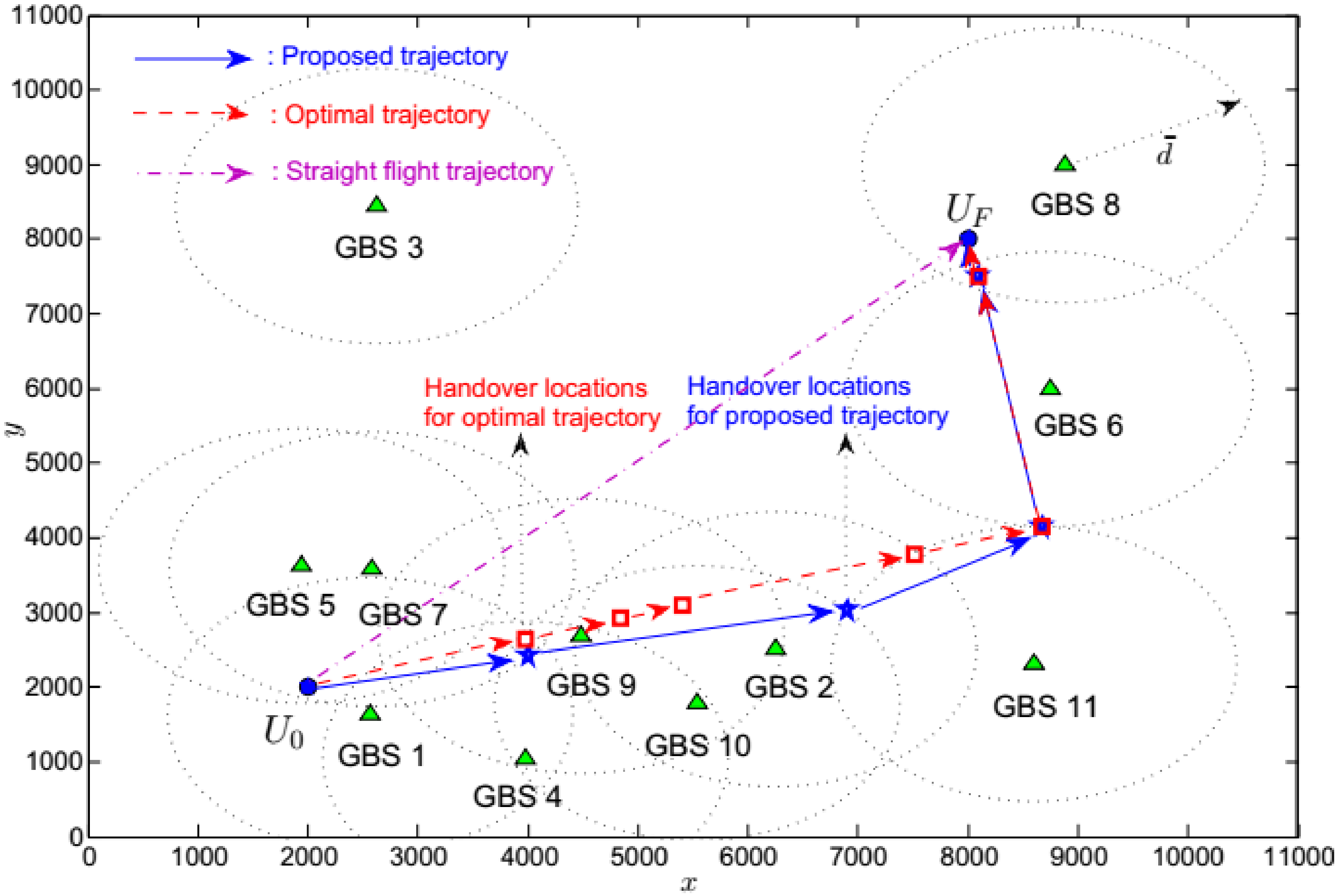
QoS-Aware Trajectory Optimization

- Each BS has certain coverage region for aerial users
- Optimize the UAV trajectory to
  - Minimize travelling time from initial to final locations
  - Ensure connectivity constraint at all time
- Near-optimal solution with graph theory and convex optimization



S. Zhang, Y. Zeng, R. Zhang, “Cellular-Enabled UAV Communication: Trajectory Optimization Under Connectivity Constraint “, to appear in IEEE ICC, May 2018.

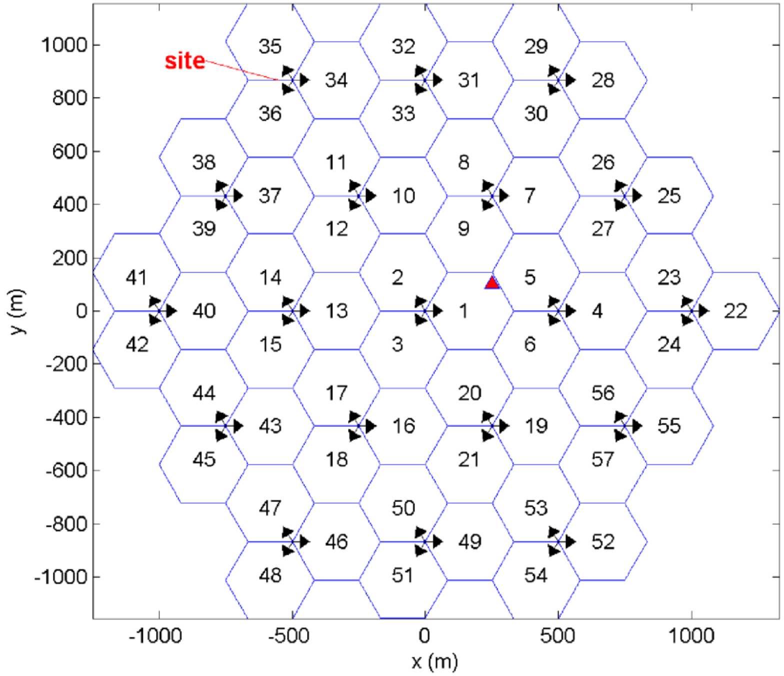
QoS-Aware Trajectory Optimization



- ❑ More details to be given in Part 2

Cellular-Connected UAV: Simulation Results (1/6)

- ☐ Cellular-connected UAV in 3GPP urban macro (UMa) scenario
- ☐ 19 sites, each constituting 3 sectors (57 cells)
- ☐ Inter-site distance (ISD) 500 m, cell radius 166.7 m
- ☐ Two different array configurations: fixed pattern versus 3D beamforming



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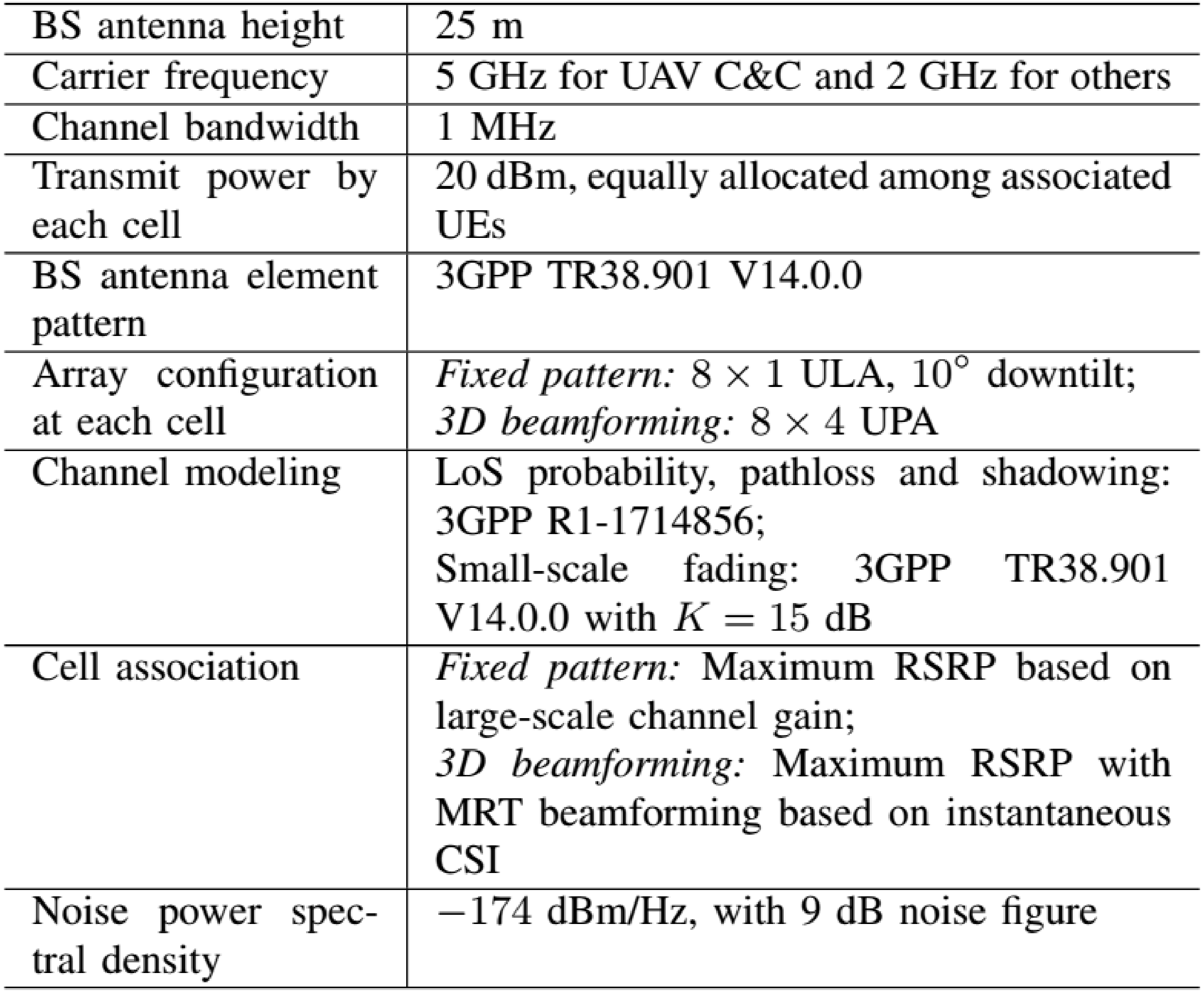
Cellular-Connected UAV: Simulation Results (2/6)

- Cellular-connected UAV simulation setup:

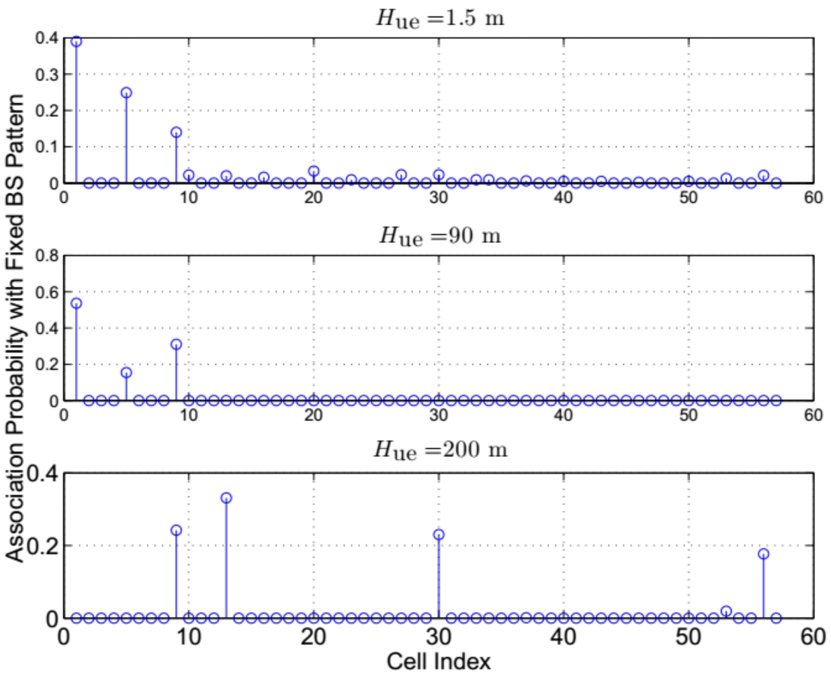


BS antenna height	25 m
Carrier frequency	5 GHz for UAV C&C and 2 GHz for others
Channel bandwidth	1 MHz
Transmit power by each cell	20 dBm, equally allocated among associated UEs
BS antenna element pattern	3GPP TR38.901 V14.0.0
Array configuration at each cell	*Fixed pattern:* 8×1 ULA, 10° downtilt; *3D beamforming:* 8×4 UPA
Channel modeling	LoS probability, pathloss and shadowing: 3GPP R1-1714856; Small-scale fading: 3GPP TR38.901 V14.0.0 with $K = 15$ dB
Cell association	*Fixed pattern:* Maximum RSRP based on large-scale channel gain; *3D beamforming:* Maximum RSRP with MRT beamforming based on instantaneous CSI
Noise power spectral density	-174 dBm/Hz, with 9 dB noise figure

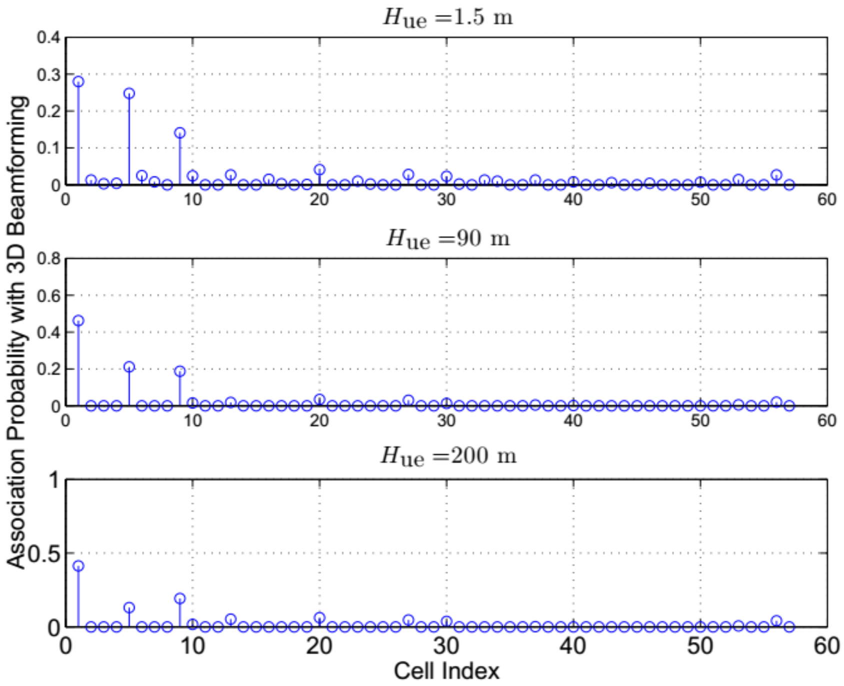
Cellular-Connected UAV: Simulation Results (3/6)

- Scenario 1: UAV communication in dedicated channel
  - Focus on one particular UAV with horizontal coordinate (250 m, 100 m)
  - One channel is allocated exclusively (interference-free)
  - Three UAV altitudes: 1.5 m, 90 m, and 200 m
- Scenario 2: Shared channel by UAV and ground user
  - Multi-user downlink communication with both UAV and ground users
  - All users share the same channel
  - Total users is 20, but with varying number of aerial users (UAVs)
  - Horizontal locations uniformly distributed
  - Ground users: height fixed to 1.5 m
  - Aerial users: altitude uniform between 1.5 m and 300 m

Cellular-Connected UAV: Simulation Results (4/6)



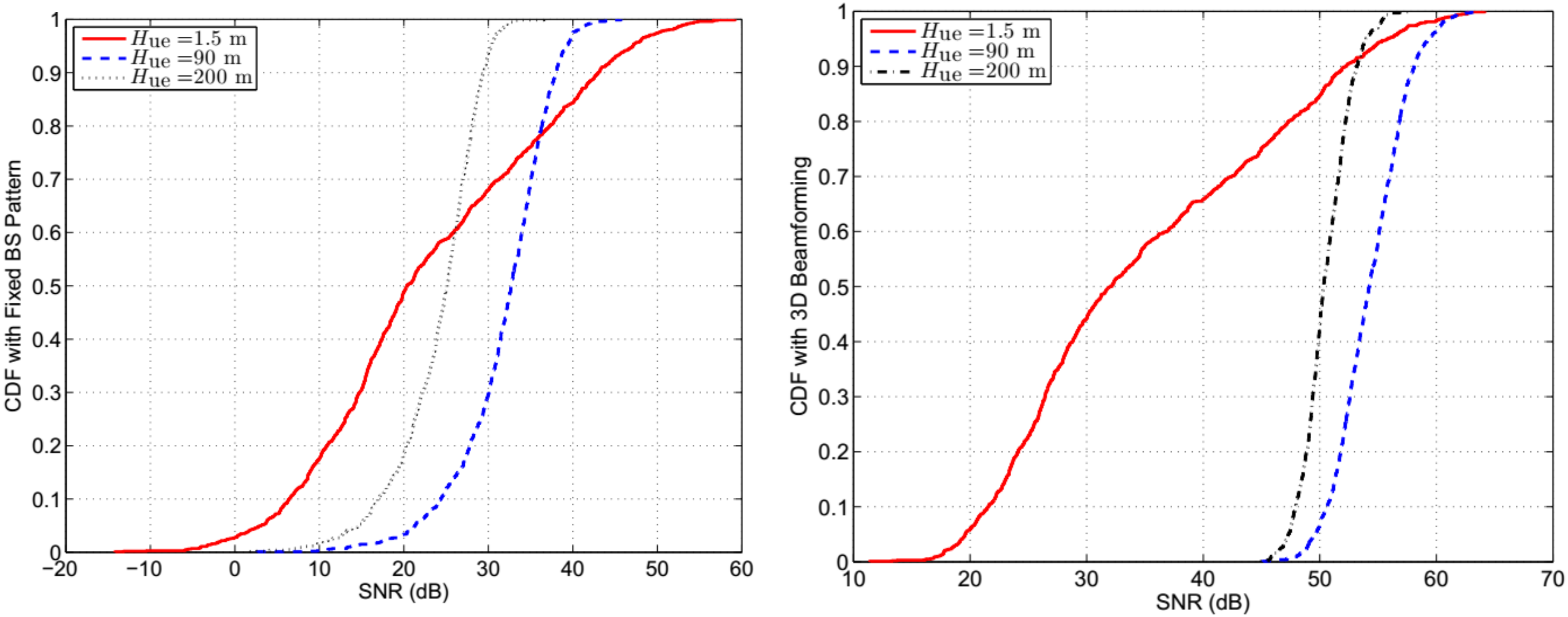
(a) Fixed BS pattern



(b) 3D Beamforming

- ❑ **Fixed BS pattern:**
  - ➢ Low altitude: UAV likely to be associated with nearby cells (cells 1, 5, 9)
  - ➢ High altitude: UAV likely to be associated with distant cells (via antenna side lobe)
- ❑ **3D beamforming:** likely associated with nearby cells for all altitudes

Cellular-Connected UAV: Simulation Results (5/6)

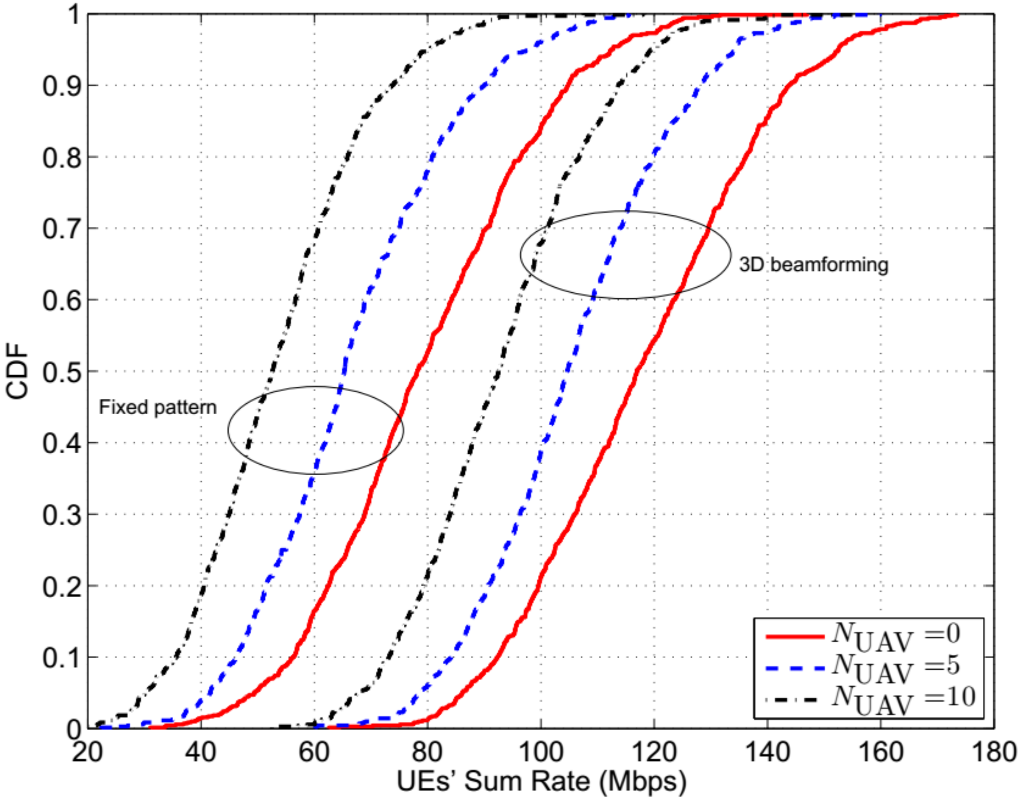


(a) Fixed BS pattern

(b) 3D beamforming

- High altitude: less SNR variation (due to reduced scattering)
- 3D beamforming significantly improves the SNR performance

Cellular-Connected UAV: Simulation Results (6/6)



- ❑ Sum rate for different number of UAVs with shared channel
- ❑ Overall spectrum efficiency degrades as number of UAVs increases
- ❑ Expected since aerial users suffer from more severe interference due to LoS-dominating channel

Promising Research Directions

- New architectures/protocols for cellular-connected UAVs
- Field measurement and prototype for LTE-connected UAVs
- Channel measurement and modelling for UAV-BS communications
- Performance analysis for aerial coverage
- Security and safety issues of UAV systems
- Spectrum management and multiple access schemes
- Interference mitigation for cellular-connected UAVs
- Cellular systems with coexisting aerial and terrestrial users
- 3D beamforming
- MIMO/massive MIMO/mmWave technologies for cellular UAV systems
- Offline/online UAV trajectory design with QoS constraints
- Cellular-enabled UAV swarm
- ……

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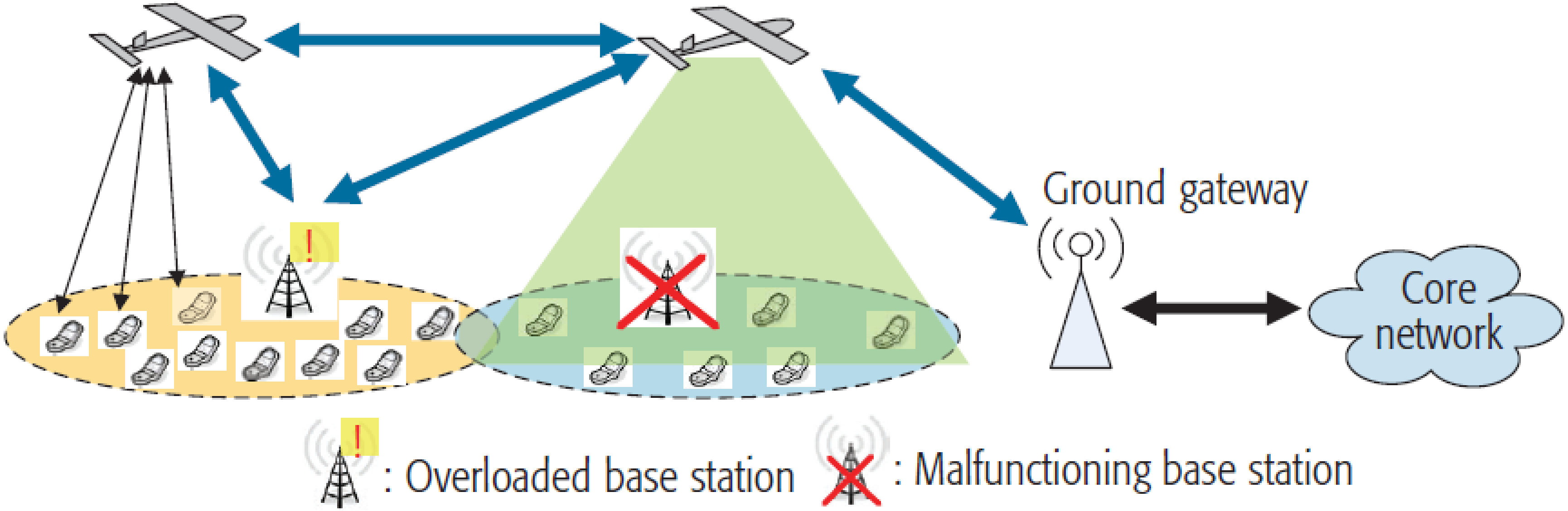
Wireless Connection from the Sky: Candidate Solutions

- ☐ Satellite: very high altitude
- ☐ High-altitude platform (HAP) ~20km
  - ➢ Google loon project
- ☐ Low-altitude platform (LAP): a few km
  - ➢ By helikite (EU ABSOLUTE project)
  - ➢ By UAV
- ☐ Advantages of UAV-assisted communications
  - ➢ On demand deployment, fast response
  - ➢ Cost effective
  - ➢ Controllable mobility in 3D
  - ➢ Short-distance LoS link
- ➢ Three typical use cases
  - ➢ UAV-aided ubiquitous coverage
  - ➢ UAV-aided mobile relaying
  - ➢ UAV-aided information dissemination/data collection

UAV-Aided Ubiquitous Coverage

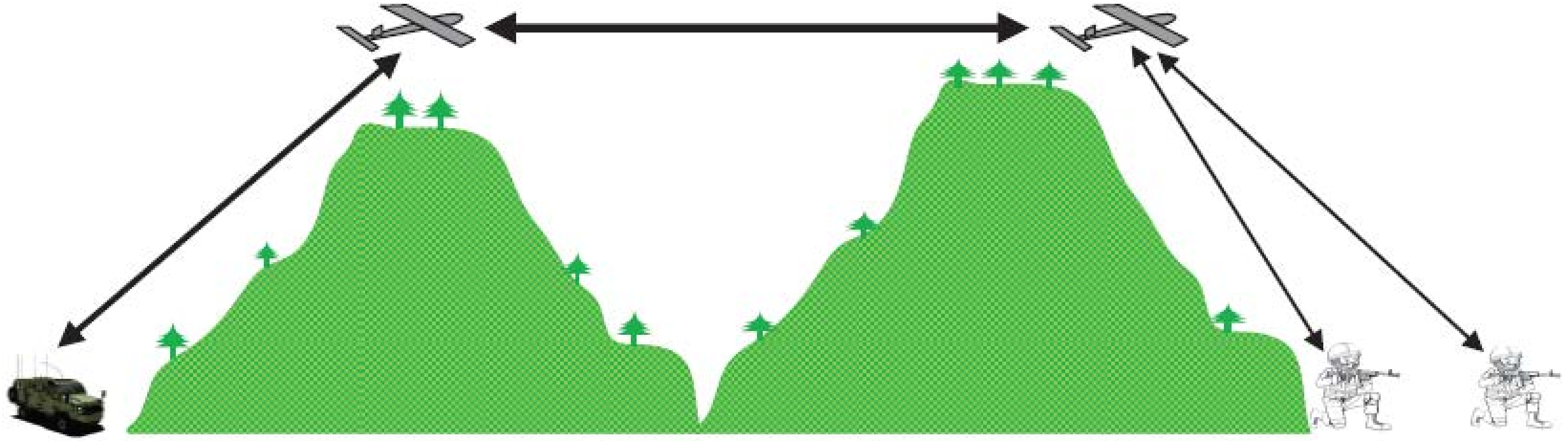
- ☐ Provide seamless coverage within the serving area
- ☐ Application scenarios:
  - ➢ fast service recovery after natural disaster
  - ➢ BS offloading at hotspot



Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: opportunities and challenges," *IEEE Commun. Mag.*, May 2016

UAV-Aided Mobile Relaying

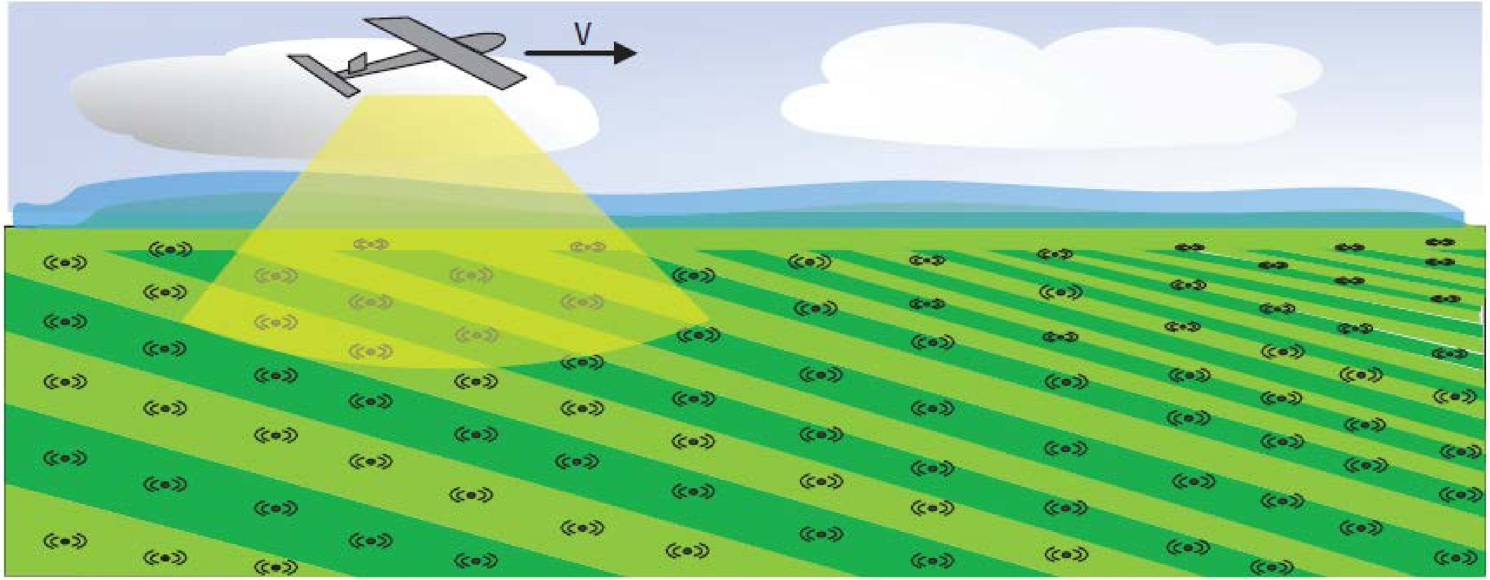
- ☐ Connecting two or more distant users or user groups
- ☐ Application scenarios:
  - ➢ Emergency response, e.g., between frontline and headquarter
  - ➢ Military network



Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: opportunities and challenges," *IEEE Commun. Mag.*, May 2016

UAV-Aided Information Dissemination/Data Collection

- ☐ Application scenarios:
  - ➢ Periodic sensing
  - ➢ IoT communications
  - ➢ Multicasting



Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: opportunities and challenges," *IEEE Commun. Mag.*, May 2016

UAV-Assisted Communications: New Design Considerations

- Unique channel characteristics: LoS dominant
- Fully controllable UAV mobility: joint trajectory and resource optimization
- Sparse and intermittent network/backhaul connectivity
- Size, weight and power (SWAP) constraint: limited endurance
- Integration with terrestrial networks: spectrum sharing, interference management
- MIMO communication for high-mobility UAVs
- UAV swarm operation: inter-UAV coordination, interference mitigation

UAV-Assisted Communications: Recent Results (1/5)

❑ Overview

- **Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: opportunities and challenges," *IEEE Commun. Mag.*, May 2016**
- I. B. Yaliniz and H. Yanikomeroglu, "The new frontier in RAN heterogeneity: multi-tier drone-cells," *IEEE Commun. Mag.*, Nov. 2016

❑ UAV-ground channel measurement and modeling

- A. A. Hourani, S. Kandeepan, and A. Jamalipour, "Modeling air-to-ground path loss for low altitude platforms in urban environments," in Proc. IEEE Global Commun. Conf. (Globecom), 2014.
- D. W. Matolak and R. Sun, "Unmanned aircraft systems: air-ground channel characterization for future applications," *IEEE Veh. Technol. Mag.*, Jun. 2015.
- W. Khawaja, I. Guvenc, D. W. Matolaky, U. C. Fiebigz, and N. Schneckenberger, "A survey of air-to-ground propagation channel modelling for unmanned aerial vehicles," arXiv

❑ UAV as quasi-stationary BS/relay

➢ 2D/3D BS placement

- A. Al-Hourani, S. Kandeepan, and S. Lardner, "Optimal LAP Altitude for Maximum Coverage," *IEEE Wireless Commun. Lett.*, vol. 3, no. 6, Dec. 2014, pp. 569–72.
- R. Yaliniz, A. El-Keyi, and H. Yanikomeroglu, "Efficient 3-D placement of an aerial base station in next generation cellular networks," in ICC, Kuala Lumpur, Malaysia, May 2016
- Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Efficient deployment of multiple unmanned aerial vehicles for optimal wireless coverage," *IEEE Commun. Letters*, Aug. 2016.
- E. Kalantari, H. Yanikomeroglu, and A. Yongacoglu, "On the number and 3D placement of drone base stations in wireless cellular networks," in *VTC-Fall*, Sep. 18-21, 2016.
- M. Alzenad, A. El-keyi, F. Lagum, and H. Yanikomeroglu, "3D placement of an unmanned aerial vehicle base station (UAV-BS) for energy-efficient maximal coverage," *IEEE Wireless Commun. Lett.*, Aug. 2017.
- **J. Lyu, Y. Zeng, R. Zhang, and T. J. Lim, "Placement optimization of UAV-mounted mobile base stations," *IEEE Commun. Letters*, vol. 21, no. 3, pp. 604–607, Mar. 2017.**

UAV-Assisted Communications: Recent Results (2/5)

☐ UAV as quasi-stationary BS/relay/AP

➢ Optimal altitude with adjustable beamwidth

- **H. He, S. Zhang, Y. Zeng, and R. Zhang, "Joint altitude and beamwidth optimization for UAV-enabled multiuser communications," *IEEE Commun. Lett.,* Feb., 2018**

➢ Performance analysis

- M. Mozaffari *et al.*, "Drone Small Cells in the Clouds: Design, Deployment and Performance Analysis," *Proc. IEEE GLOBECOM*, San Diego, CA, Dec. 2015
- M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Unmanned aerial vehicle with underlaid device-to-device communications: Performance and tradeoffs," IEEE Trans. Wireless Commun., Jun. 2016.
- C. Zhang and W. Zhang, "Spectrum Sharing for Drone Networks," *IEEE JSAC*, 2016
- A. Al-Hourani, S. Chandrasekharan, G. Kaandorp, W. Glenn, A. Jamalipour, and S. Kandeepan, "Coverage and rate analysis of aerial base stations," *IEEE Trans. Aerospace and Elect. Sys.*, Dec. 2016.
- V. V. Chetlur and H. S. Dhillon, "Downlink coverage analysis for a finite 3-D wireless network of unmanned aerial vehicles," *IEEE Trans. Commun.*, Oct. 2017
- M. M. Azari, F. Rosas, K.-C. Chen, and S. Pollin, "Ultra reliable UAV communication using altitude and cooperation diversity," *IEEE Trans. Commun.*, Jan. 2018

➢ Radio map application

- J. Chen and D. Gesbert, "Optimal positioning of flying relays for wireless networks: A LOS map approach," in Proc. IEEE Int. Conf. Commun., Paris, France, May 2017.
- J. Chen, U. Yatnalli, and D. Gesbert, "Learning radio maps for UAV aided wireless networks: A segmented regression approach," in Proc. IEEE Int. Conf. Commun., Paris, France, May 2017.
- **S. Bi, J. Lyu, Z. Ding, and R. Zhang, "Engineering radio map for wireless resource management," submitted to *IEEE Wireless Communications***

UAV-Assisted Communications: Recent Results (3/5)

☐ UAV as mobile BS/relay/AP

➢ Trajectory optimization

- Z. Han, A. L. Swindlehurst, and K. J. R. Liu, "Optimization of MANET connectivity via smart deployment/movement of unmanned air vehicles," IEEE Trans. Veh. Technol., Sep. 2009
- F. Jiang and A. L. Swindlehurst, "Optimization of UAV heading for the ground-to-air uplink," IEEE J. Sel. Areas Commun., Jun. 2012.
- **Y. Zeng, R. Zhang, and T. J. Lim, "Throughput maximization for UAV-enabled mobile relaying systems," *IEEE Trans. Commun.*, Dec., 2016**
- **Y. Zeng, X. Xu, and R. Zhang, "Trajectory optimization for completion time minimization in UAV-enabled multicasting," *IEEE Trans. Wireless Commun.*, April 2018**
- **C. Zhan, Y. Zeng, and R. Zhang, "Trajectory design for distributed estimation in UAV enabled wireless sensor network," IEEE Transactions on Vehicular Technology, submitted.**

➢ Joint resource allocation and trajectory optimization

- **Q. Wu, Y. Zeng, and R. Zhang, "Joint trajectory and communication design for multi-UAV enabled wireless networks," *IEEE Trans. Wireless Commun.*, March 2018**
- **Q. Wu, J. Xu, and R. Zhang, "Capacity characterization of UAV-enabled two-user broadcast channel," IEEE Journal on Selected Areas in Communications, submitted**

➢ Throughput-delay trade-off

- **J. Lyu, Y. Zeng, and R. Zhang, "Cyclical multiple access in UAV-aided communications: a throughput-delay tradeoff", *IEEE Wireless Commun. Lett.*, Dec., 2016**
- **Q. Wu and R. Zhang, "Common throughput maximization in UAV-enabled OFDMA system with delay consideration," *IEEE Trans. Commun.*, submitted**

➢ Hybrid UAV and ground BSs

- **J. Lyu, Y. Zeng, and R. Zhang, "UAV-aided offloading for cellular hotspot," *IEEE Trans. Wireless Commun,* accepted.**

UAV-Assisted Communications: Recent Results (4/5)

☐ UAV as mobile BS/relay/AP

➢ UAV meets caching

- M. Chen, M. Mozaffari, W. Saad, C. Yin, M. Debbah, and C. S. Hong, “Caching in the sky: proactive deployment of cache-enabled unmanned aerial vehicles for optimized quality-of-experience,” *IEEE J. Sel. Areas Commun.,* May 2017.
- **X. Xu, Y. Zeng, Y. L. Guan, and R. Zhang, “Overcoming endurance issue: UAV-enabled communications with proactive caching,” *IEEE J. Sel. Areas Commun.,* accepted**

➢ UAV Enabled Wireless Power Transfer/WPCN

- **J. Xu, Y. Zeng, and R. Zhang, “UAV-enabled wireless power transfer: trajectory design and energy optimization,” *IEEE Trans. Wireless. Commun.,* submitted**
- **L. Xie, J. Xu, and R. Zhang “Throughput maximization for UAV-enabled wireless powered communication networks,” *IEEE VTC* 2018**

➢ Secure UAV Communication

- **A. Li, Q. Wu, and R. Zhang, “UAV-enabled cooperative jamming for improving secrecy of ground wiretap channel,” *IEEE Wireless Commun. Lett.,* submitted**
- **G. Zhang, Q. Wu, M. Cui, and R. Zhang, “Securing UAV communications via joint trajectory and power control,” *IEEE Trans. Wireless Commun.,* submitted**
- **G. Zhang, Q. Wu, M. Cui, and R. Zhang, “Securing UAV communications via trajectory optimization,” IEEE Globecom 2017**

➢ UAV-based CoMP

- **L. Liu, S. Zhang, and R. Zhang, “CoMP in the sky: UAV placement and movement optimization for multi-user communications,” *IEEE Trans. Wireless Commun.,* submitted**

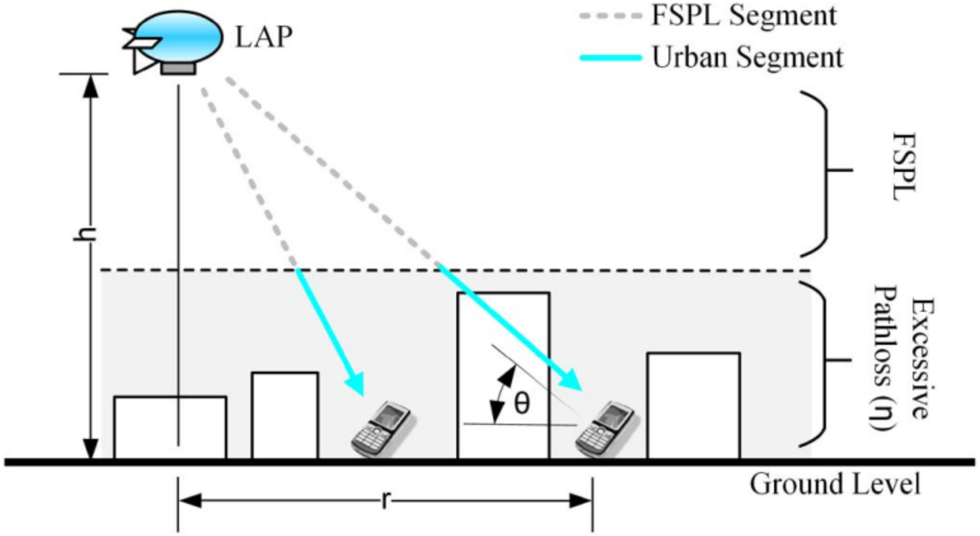
UAV-Assisted Communications: Recent Results (5/5)

❑ Energy-efficient UAV communications

- ➢ UAV propulsion energy
  - **Y. Zeng and R. Zhang, "Energy-Efficient UAV Communication with Trajectory Optimization," *IEEE Trans. Wireless Commun.,* Jun., 2017.**
  - **Y. Zeng, J. Xu, and R. Zhang, "Energy minimization for wireless communication with rotary-wing UAV," *IEEE Trans. Wireless Commun.,* submitted**
  - J. Zhang, Y. Zeng, and R. Zhang, "Spectrum and energy efficiency maximization in UAV-enabled mobile relaying," *IEEE International Conference on Communications (ICC)*, 2017.
- ➢ UAV transmission energy
  - M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Mobile internet of things: Can UAVs provide an energy-efficient mobile architecture," in *Proc. IEEE Global Commun. Conf. (GLOBECOM),* Dec. 2016
- ➢ Energy minimization of ground nodes
  - **C. Zhan, Y. Zeng, and R. Zhang, "Energy-efficient data collection in UAV enabled wireless sensor network," IEEE Wireless Commun. Lett., accepted.**
- ➢ Energy trade-off between UAV and ground nodes
  - **D. Yang, Q, Wu, Y. Zeng, and R. Zhang, "Energy trade-off in ground-to-UAV communication via trajectory design," *IEEE Trans. Veh. Technol.,* accepted.**
- ➢ Energy-efficient UAV edge computing
  - S. Jeong, O. Simeone, and J. Kang, "Mobile edge computing via a UAV- mounted cloudlet: Optimization of bit allocation and path planning," *IEEE Trans. Veh. Technol.,* 2017.

UAV-Ground Channel Models

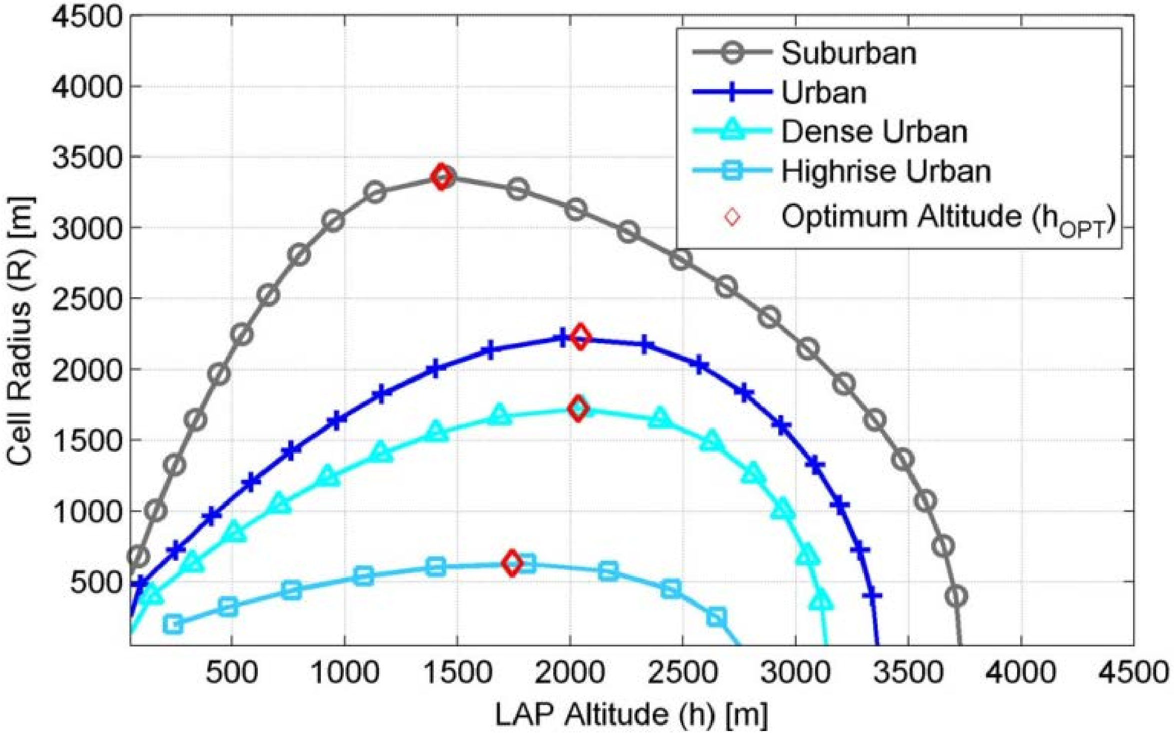
- Free space line-of-sight (LoS) model: rural or suburban environment, or UAV altitude sufficiently high
- Rician fading model [MatolakVTM15]: LoS component plus scattered fading component. Rician factor 15 dB for L-band and 28 dB for C-band in hilly terrain
- Probabilistic LoS model [HouraniWCL14]: LoS probability increases with elevation angle θ (Urban environment)



$$P(\mathrm{LOS}) = \frac{1}{1 + \alpha \exp\left(-\beta\left[\frac{180}{\pi}\theta - \alpha\right]\right)}$$

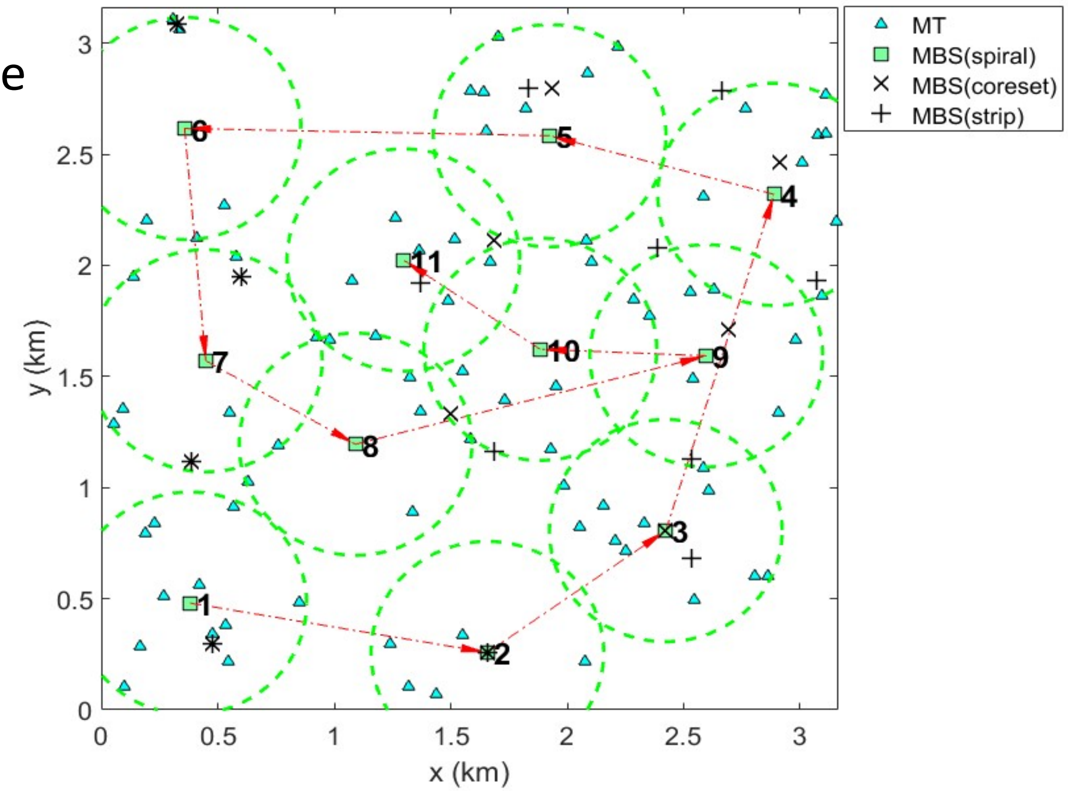
Aerial BS Placement: Optimal Altitude

- Free-space LoS channel model: altitude as low as possible
- Probabilistic LoS model:
  - Tradeoff: the higher altitude, the longer the link distance, but also higher LoS probability
  - Exists an optimal UAV altitude for maximum cell coverage [HouraniWCL14]



Spiral-Based Aerial BS Placement: Fixed Altitude

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



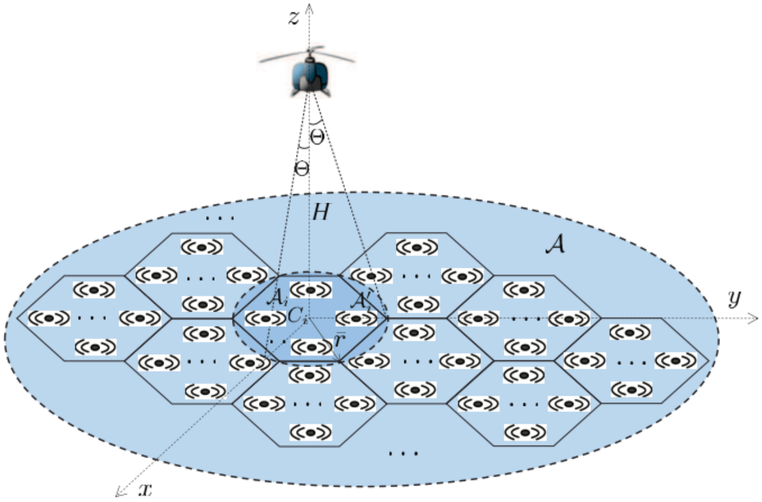
J. Lyu, Y. Zeng, R. Zhang, and T. J. Lim, "Placement Optimization of UAV-Mounted Mobile Base Stations", *IEEE Commun. Letters,* vol. 21, no. 3, pp. 604-607, Mar. 2017.

Optimal UAV Altitude with Adjustable Beamwidth

- UAV antenna with adjustable beamwidth

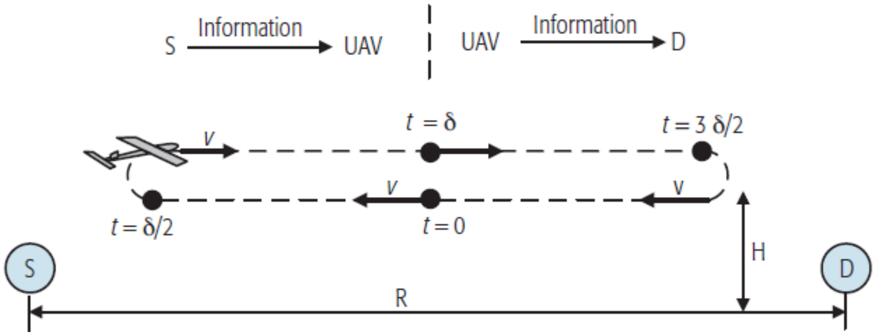
$$G = \begin{cases} \frac{G_0}{\Theta^2}, & -\Theta \le \theta \le \Theta, -\Theta \le \psi \le \Theta \\ g \approx 0, & \text{otherwise,} \end{cases}$$

- Fly-hover-communicate protocol
- Downlink multicasting: altitude as high as possible, optimal beamwidth decreases with altitude
- Downlink broadcasting: altitude as low as possible, beamwidth as small as possible
- Uplink multiple access: altitude/beamwidth doesn't matter

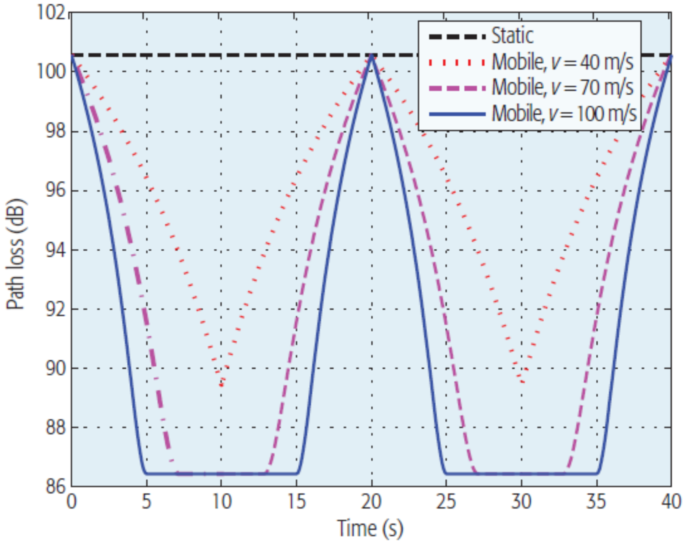


H. He, S. Zhang, Y. Zeng, and R. Zhang, "Joint altitude and beamwidth optimization for UAV-enabled multiuser communications," *IEEE Commun. Lett.,* Feb. 2018.

Exploit UAV Mobility: Toy Example (1/2)



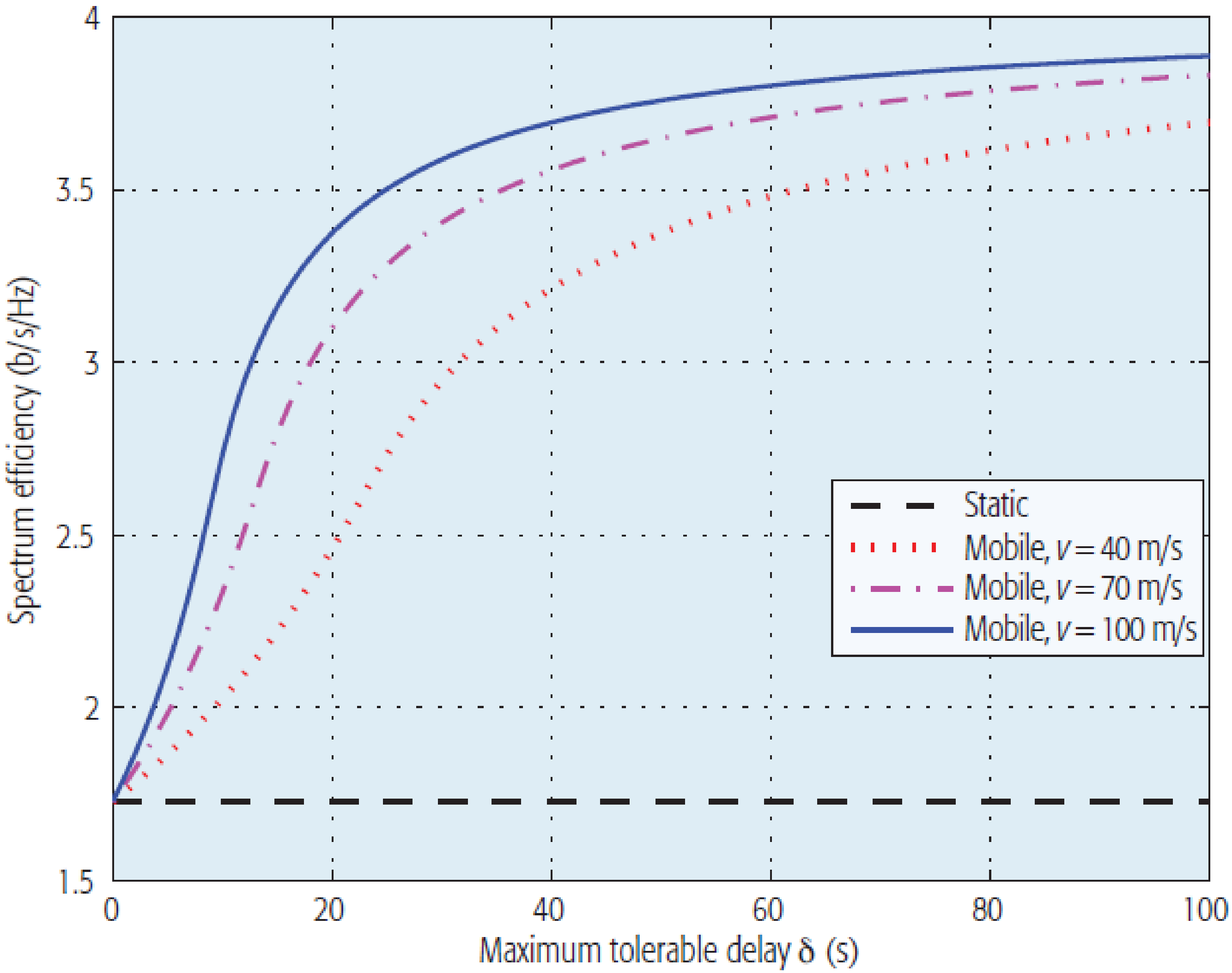
- ☐ UAV-enabled mobile relaying
- ☐ UAV closer to source: receiving
- ☐ UAV closer to destination: relaying



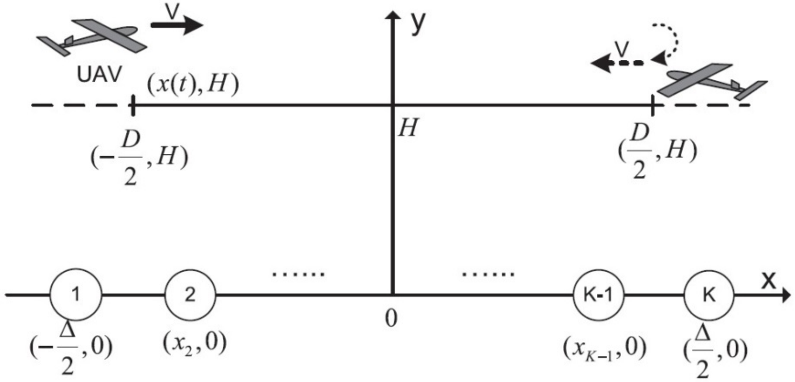
- ☐ Always enjoy smaller path loss than static relaying
- ☐ Better channel in average for higher UAV maximum speed
- ☐ Advanced trajectory design with mathematical optimization (Part 2)

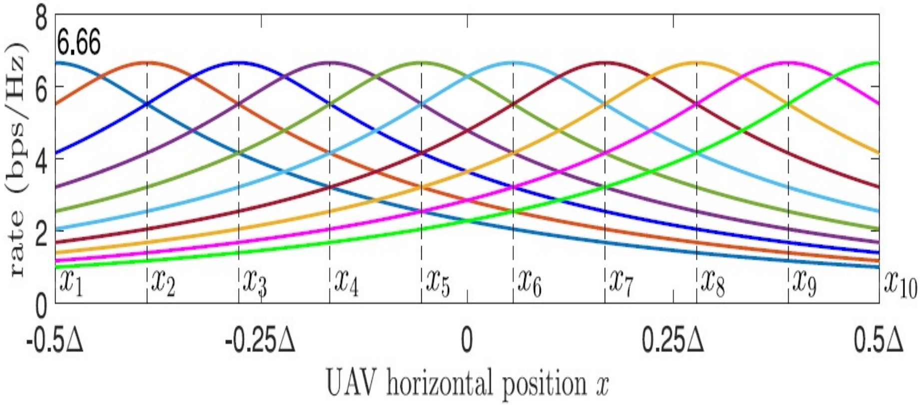
Y. Zeng, R. Zhang, and T. J. Lim, “Wireless communications with unmanned aerial vehicles: opportunities and challenges,” *IEEE Commun. Mag.*, May 2016

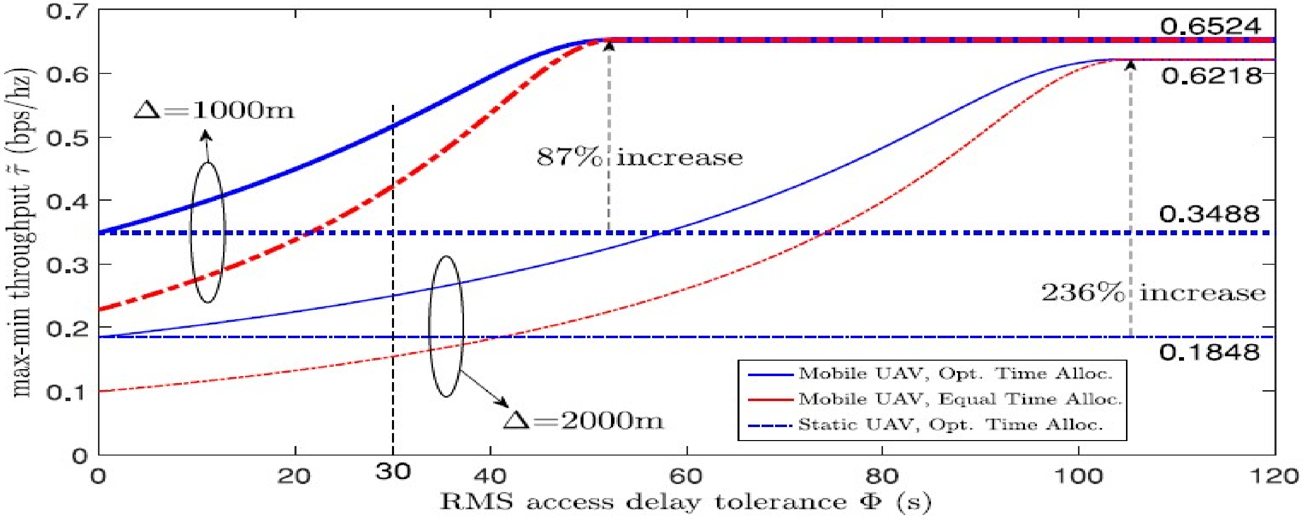
Exploit UAV Mobility: Toy Example (2/2)



Cyclical Multiple Access and Throughput-Delay Trade-off





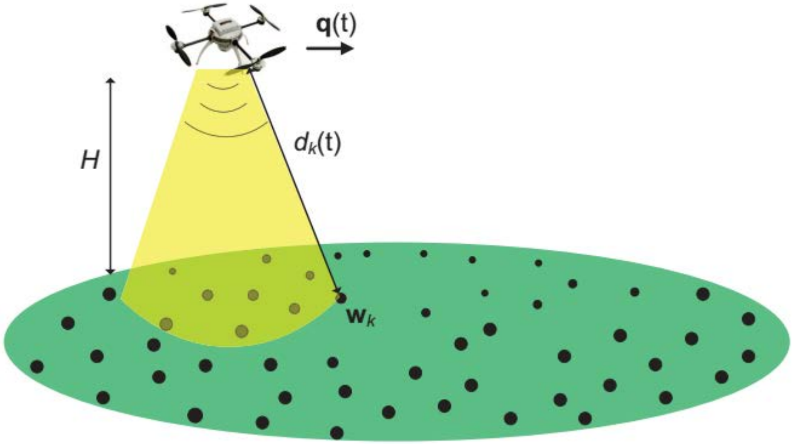


- More delay tolerance leads to larger throughput gain over static BS

J. Lyu, Y. Zeng, R. Zhang, "Cyclical Multiple Access in UAV-Aided Communications: A Throughput-Delay Tradeoff," *IEEE Wireless Commun. Lett.*, Dec. 2016.

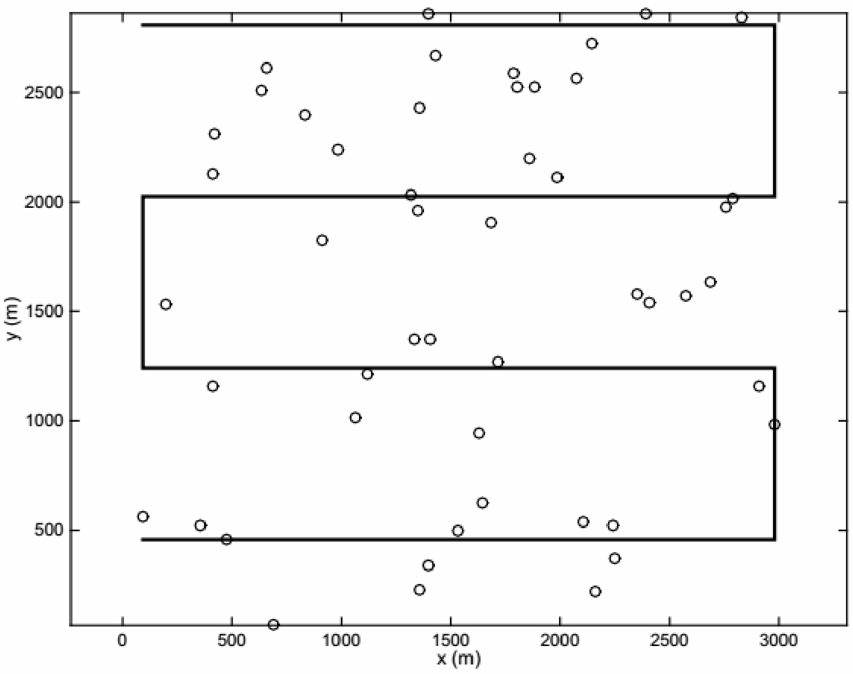
UAV-Enabled Multicasting

- ☐ UAV-enabled multicasting with random linear network coding: common information for multiple ground nodes
- ☐ Applications: public safety communication, emergency response, video streaming, intelligent transportation systems
- ☐ Minimize mission completion time, while satisfying target file recovery probability (each ground node needs to have a minimum "contact" duration with the UAV)
- ☐ Optimal trajectory design is challenging (NP-hard):
  - ➢ virtual BS placement for waypoint design
  - ➢ travelling salesman for visiting order
  - ➢ linear programming for optimal speed

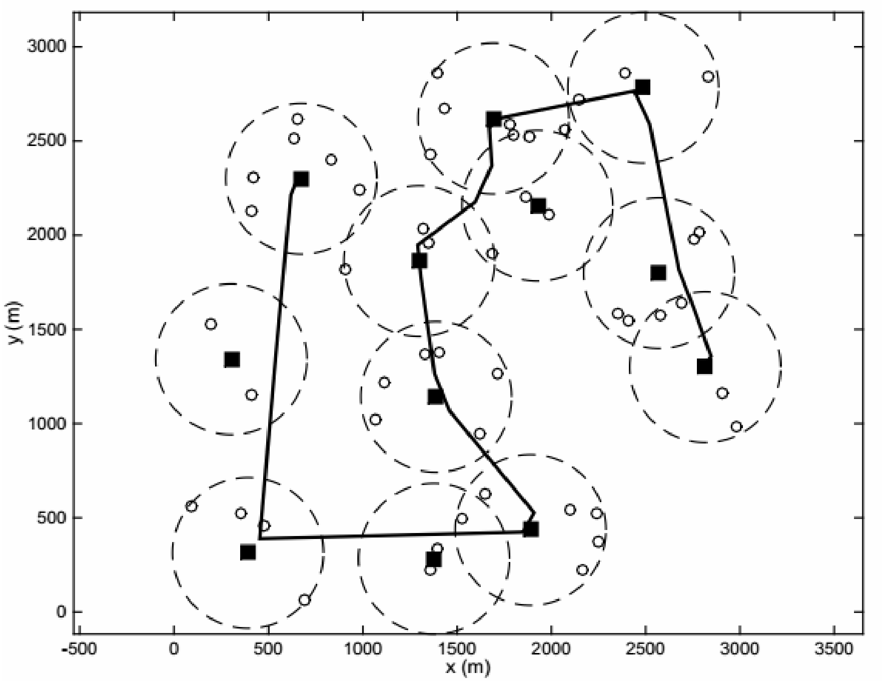


Y. Zeng, X. Xu, and R. Zhang, "Trajectory design for completion time minimization in UAV-enabled multicasting", *IEEE Trans. Wireless Commun.*, to appear

UAV-Enabled Multicasting: Optimized Trajectory



Benchmark: strip-based trajectory
Total traveling distance: 13.9 km
Required time: 279 s

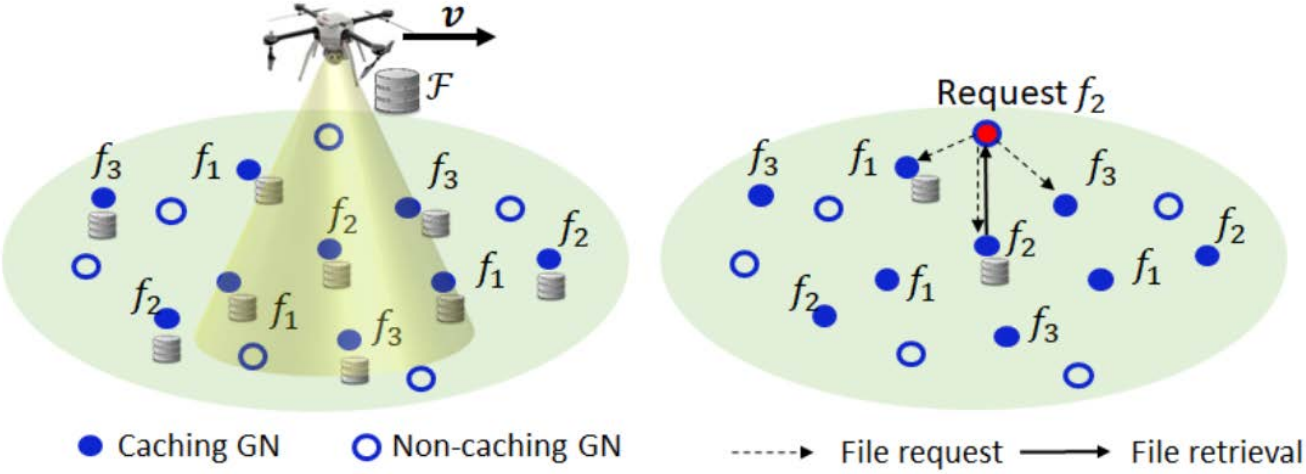


Optimized trajectory
Total traveling distance: 8.1 km
Required time: 173.5 s

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

UAV Communications with Caching

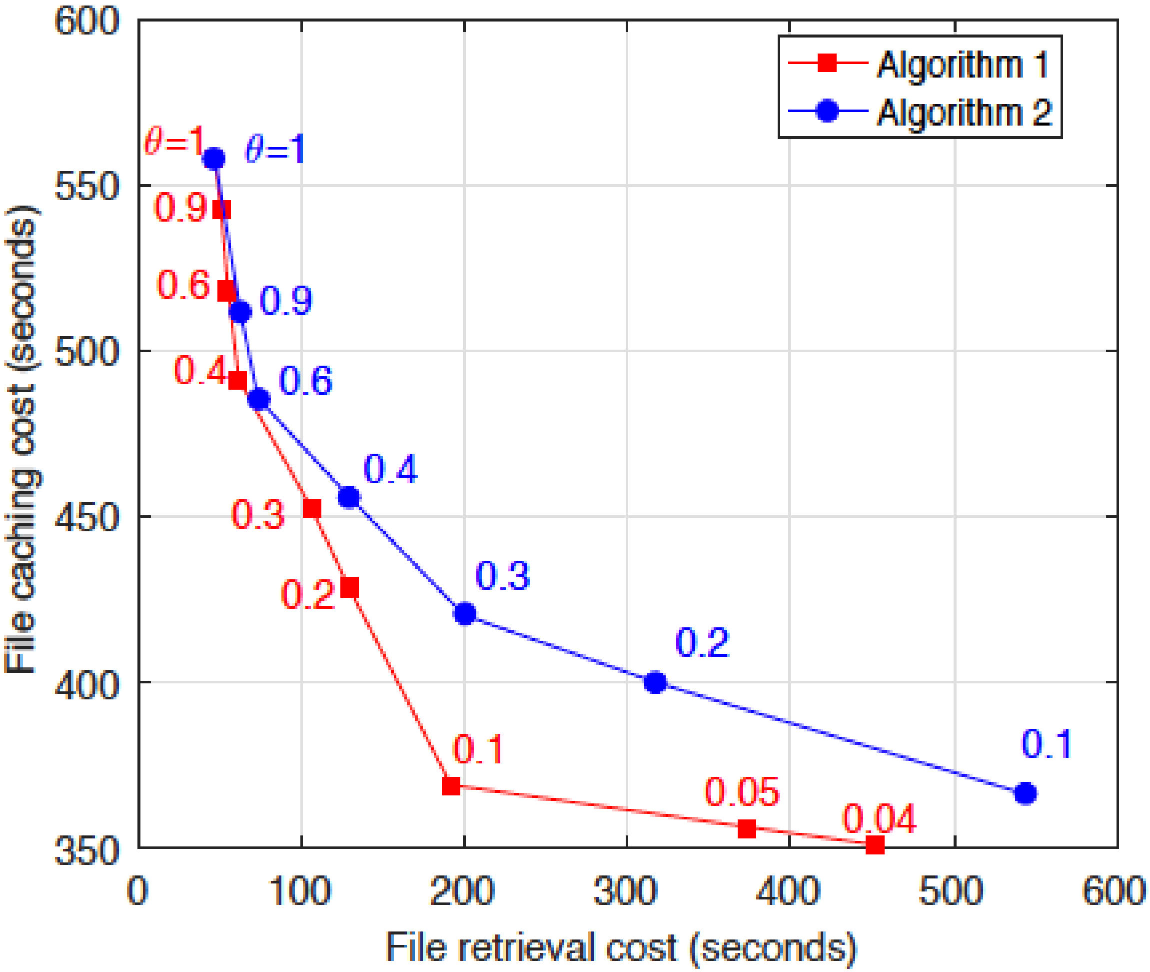
- Critical issue in UAV communication: limited UAV endurance (e.g., ~30mins)
- Proposed solution: exploiting ground user caching
- Phase 1: UAV caches files to the selected ground users
- Phase 2: D2D file sharing among ground users
- Fundamental trade-off in file caching time and file retrieval time: joint trajectory and caching design



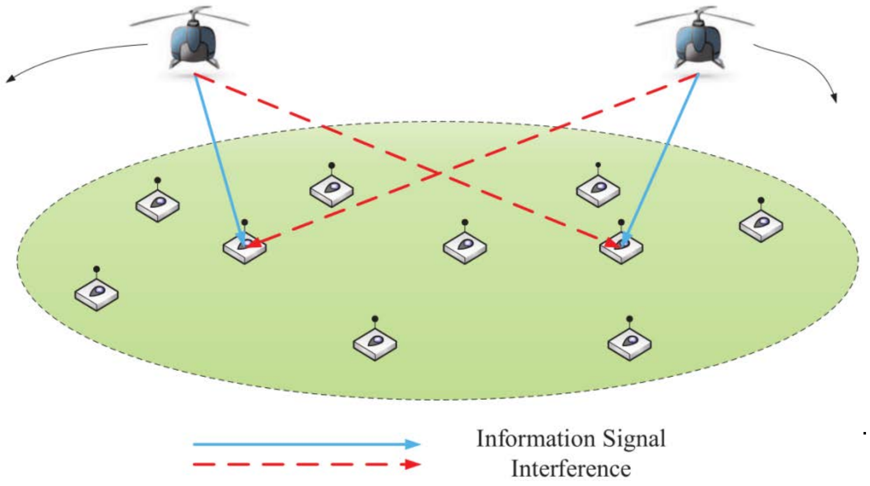
(a) File caching phase (b) File retrieval phase

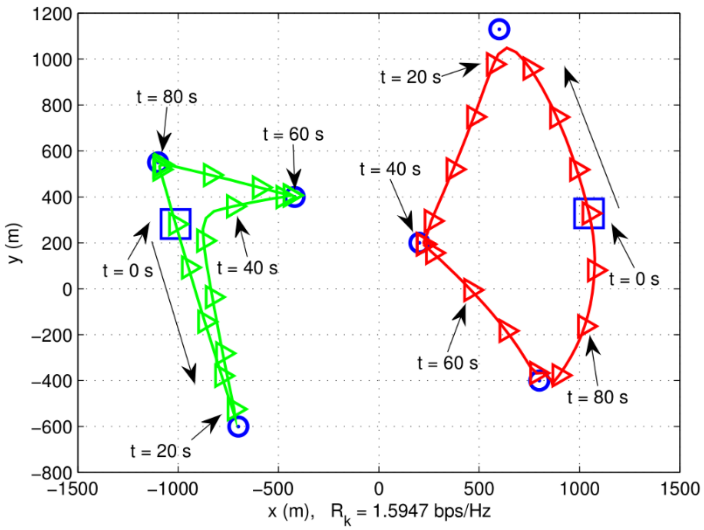
X. Xu, Y. Zeng, Y. L. Guan, and R. Zhang, "Overcoming endurance issue: UAV-enabled communications with proactive caching," *IEEE JSAC,* accepted

UAV Communications with Caching



Multi-UAV Enabled Networks with Coordination





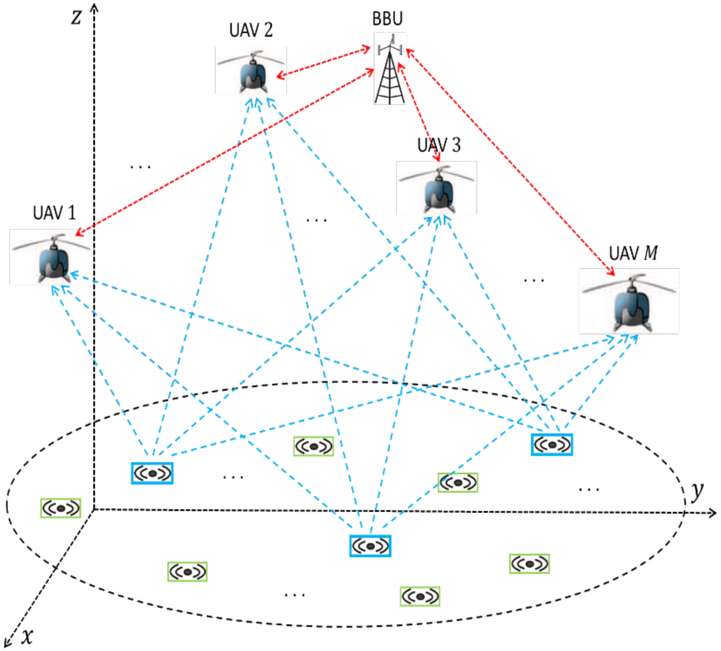
(a) Optimized UAV trajectories without power control.

- Multiuser downlink communication: broadcast channel (BC) + interference channel (IFC)

- New Interference-mitigation approach: coordinated trajectory design (more details in Part 2)

Q. Wu, Y. Zeng, and R. Zhang, "Joint Trajectory and Communication Design for Multi-UAV Enabled Wireless Networks," *IEEE Trans. Wireless Commun.*, Mar. 2018

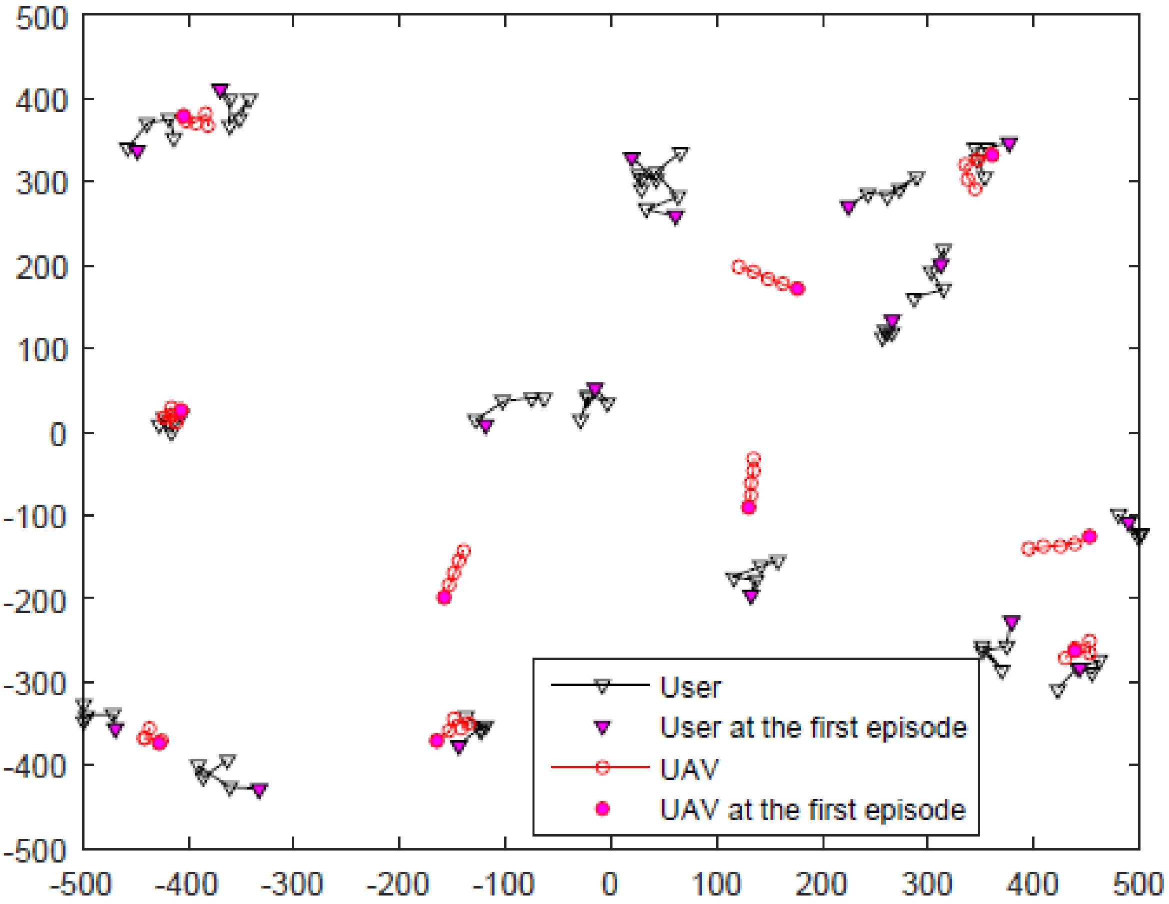
UAV-enabled CoMP



- ☐ CoMP in the sky: multi-UAV cooperation
- ☐ LoS channel with random phase
- ☐ Moving users
- ☐ Joint UAV trajectory and beamforming design

L. Liu, S. Zhang, and R. Zhang, "CoMP in the sky: UAV placement and movement optimization for multi-user communications," submitted to *IEEE Trans. Wireless Commun.*, 2018.

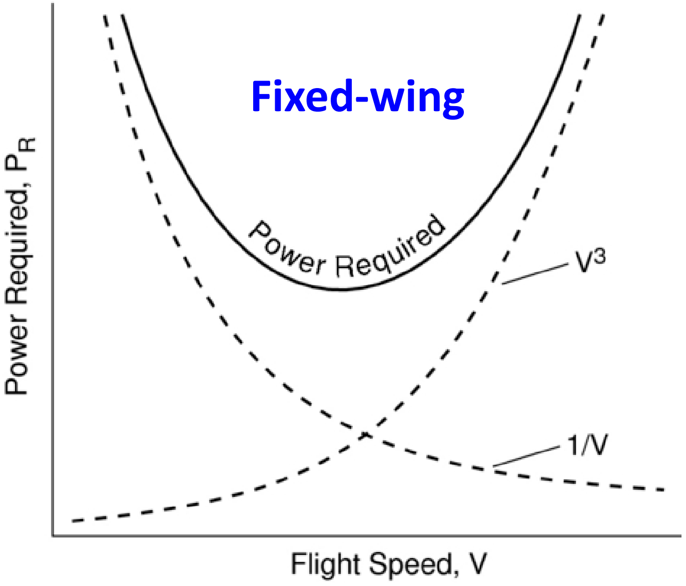
UAV-enabled CoMP: Joint Trajectory Optimization

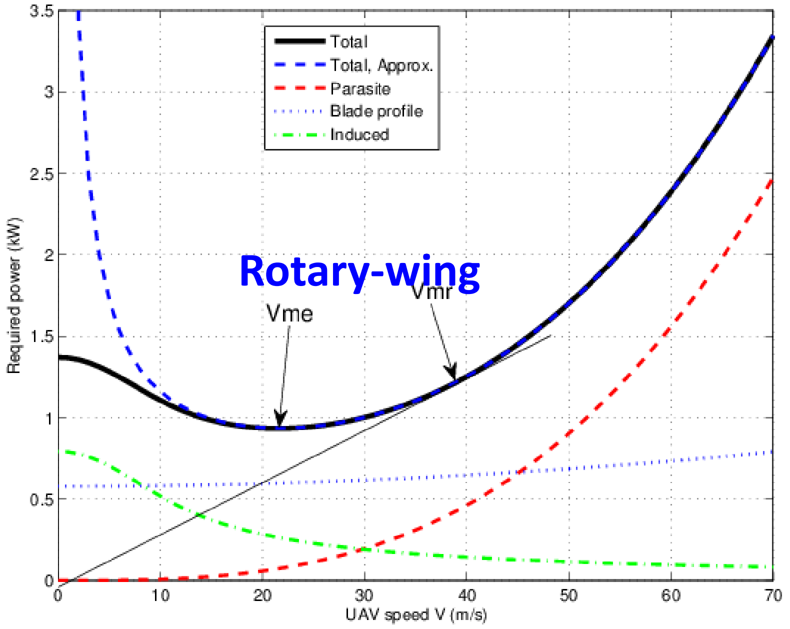


L. Liu, S. Zhang, and R. Zhang, "CoMP in the sky: UAV placement and movement optimization for multi-user communications," submitted to *IEEE Trans. Wireless Commun.*, 2018.

Energy-Efficient UAV Communications

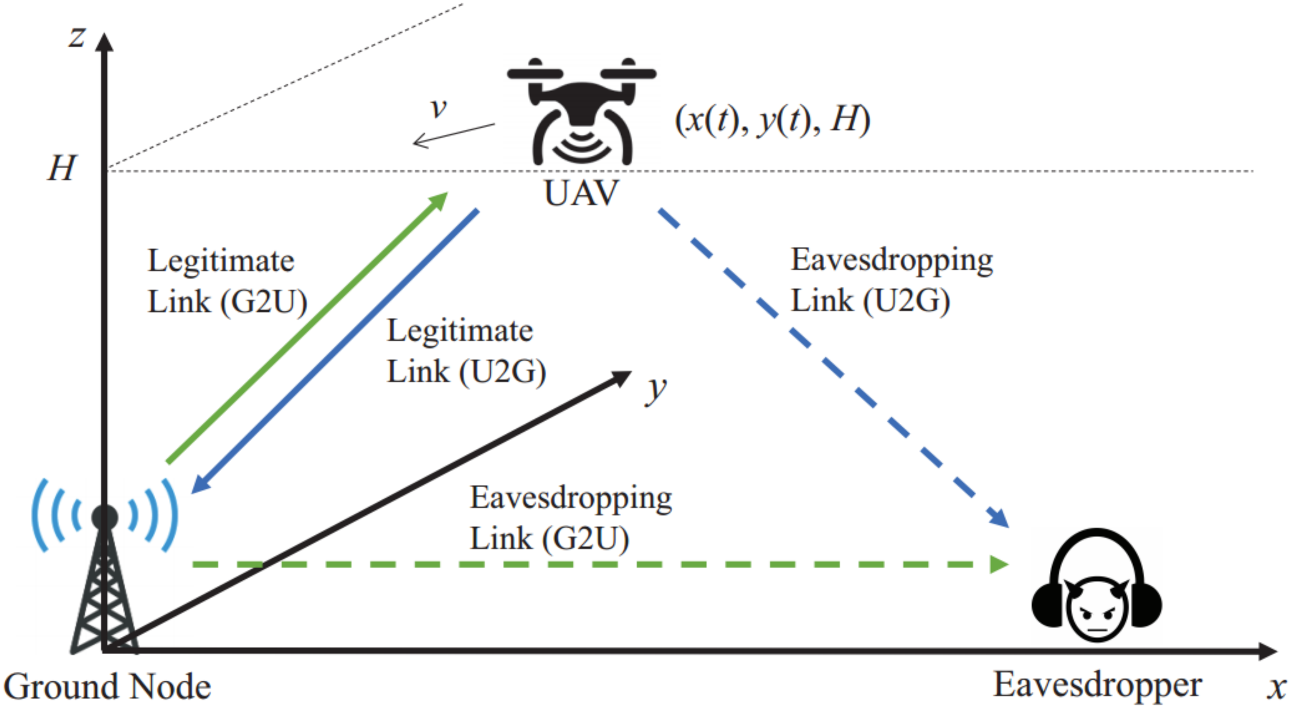
- **Limited onboard energy**: critical issue in UAV communications
- UAV energy consumption: Propulsion energy >> Communication energy
- New rate-energy trade-off via UAV trajectory design (more in Part 2)





Y. Zeng and R. Zhang, "Energy-Efficient UAV Communication with Trajectory Optimization," *IEEE Trans. Wireless Commun.*, June 2017.

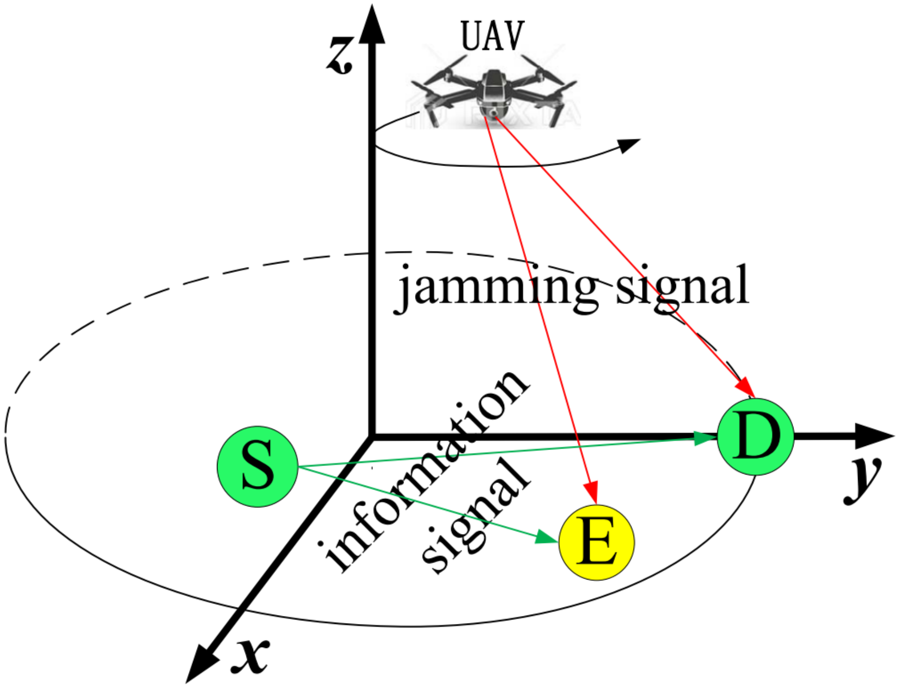
Secure UAV-Ground Communications



- ☐ Physical layer security via joint transmit power control and trajectory design

G. Zhang, Q. Wu, M. Cui, and R. Zhang, “Securing UAV communications via trajectory optimization,” IEEE Globecom, Dec. 2017.

UAV-assisted Jamming

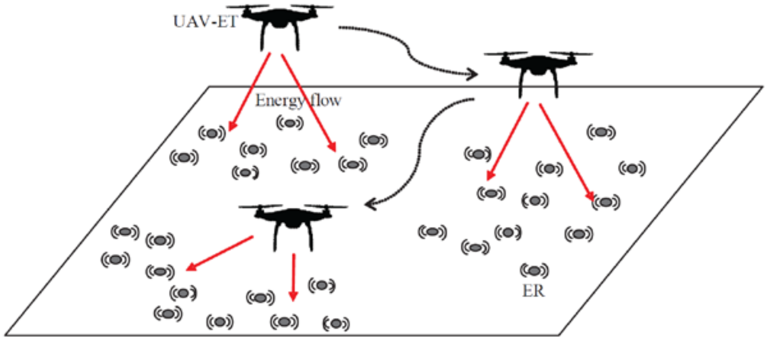


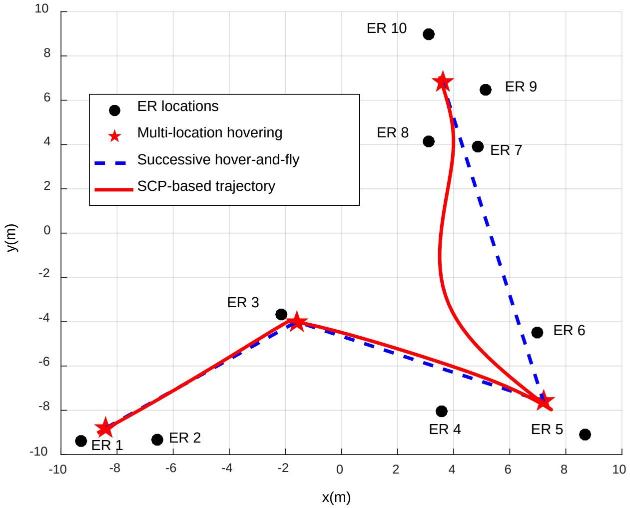
- ☐ Opportunistic UAV jamming to assist in secure terrestrial communication

A. Li, Q. Wu, and R. Zhang, “UAV-enabled cooperative jamming for improving secrecy of ground wiretap channel,” submitted to IEEE Wireless Communications Letters.

UAV-Enabled Wireless Power Transfer (WPT)

- A UAV-mounted mobile energy transmitter (ET) is dispatched to deliver wireless energy to a set of on-ground energy receivers (ERs)
    - Facilitate large-scale implementation of future WPT systems with improved energy transfer efficiency
- Optimize UAV trajectory to maximize the minimum received energy among all ERs
- Main techniques:
    - Multi-location hovering by ignoring the maximum UAV speed constraints
    - Successive hover-and-fly via travelling salesman and successive convex programming (SCP)





J. Xu, Y. Zeng, and R. Zhang, “UAV-enabled wireless power transfer: Trajectory design and energy optimization,” submitted to IEEE Transactions on Wireless Communications.

Promising Research Directions

- ☐ New use cases for UAV-assisted terrestrial communications
- ☐ New protocols for aerial communication platform
- ☐ Channel measurement and modelling for UAV-ground and UAV-UAV links
- ☐ Multi-UAV cooperative communication/interference management
- ☐ UAV-aided information dissemination/data collection/offloading
- ☐ UAV communication with limited buffer size/energy/wireless backhaul
- ☐ Throughput-delay trade-off in UAV communications
- ☐ Physical-layer security in UAV-ground communications
- ☐ Energy-efficient joint communication and trajectory optimization
- ☐ UAV-ground energy/throughput trade-off
- ☐ UAV BS/relay 3D placement and dynamic movement
- ☐ UAV and ground BS coexistence and spectrum sharing
- ☐ MIMO/massive MIMO/mmWave for UAV-assisted communications
- ☐ UAV meets wireless power/energy harvesting/caching/edge computing, etc.
- ☐ …..

Outline

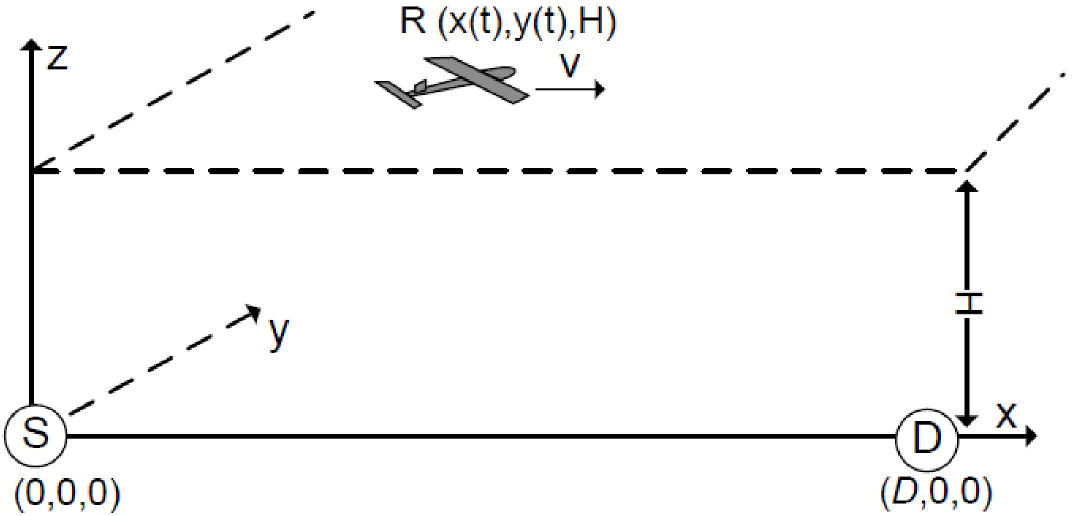
- ☐ Part 1: Overview
  - ➢ Introduction
  - ➢ Integrating UAVs into 5G and Beyond: Two Paradigms
    - ☐ Cellular-Connected UAVs
    - ☐ UAV-Assisted Terrestrial Communications

- ☐ Part 2: Case Study
  - ➢ UAV-enabled mobile relaying
  - ➢ Multi-UAV enabled wireless network
  - ➢ Energy-efficient UAV communication
  - ➢ Cellular-connected UAV: QoS-aware trajectory design

Case Study I: UAV-Enabled Mobile Relaying

Y. Zeng, R. Zhang, and T. J. Lim, “Throughput maximization for UAV-enabled mobile relaying systems,” *IEEE Trans. Commun.,* Dec. 2016.

System Model



- ☐ UAV-enabled relay moves at a constant altitude *H*
- ☐ Relay mobility constraints: (i) Maximum speed; (ii) Initial and final location
- ☐ S-R and R-D channels vary with the relay location (x(t),y(t))
- ☐ Adaptive rate/power transmission by source and relay based on the predictable channels
- ☐ Problem: maximize throughput via joint power allocation and trajectory design

Problem Formulation

- Relay mobility constraints:

$$\boxed{\begin{aligned} \left(x[1]-x_0\right)^2+\left(y[1]-y_0\right)^2 &\leq V^2, \\ \left(x[n+1]-x[n]\right)^2+\left(y[n+1]-y[n]\right)^2 &\leq V^2, \\ n=1,\cdots,N-1&, \\ \left(x_F-x[N]\right)^2+\left(y_F-y[N]\right)^2 &\leq V^2, \end{aligned}}$$

V : maximum speed

n: slot index

(x_0, y_0) : initial location;

(x_F, y_F) : final location

- Channel model: assume line of sight (LoS), perfect Doppler compensation

$$R_s[n] = \log_2\left(1+\frac{p_s[n]\gamma_0}{H^2+x^2[n]+y^2[n]}\right) \qquad R_r[n] = \log_2\left(1+\frac{p_r[n]\gamma_0}{H^2+(D-x[n])^2+y^2[n]}\right),$$

- Information-causality constraints at UAV: only information that has been received from the source can be forwarded to the destination

$$R_r[1]=0,\ \sum_{i=2}^{n} R_r[i] \leq \sum_{i=1}^{n-1} R_s[i],\ n=2,\cdots,N.$$

Problem Formulation

$$(\mathrm{P1}): \max_{\substack{\{x[n],y[n]\},\\ \{p_s[n],p_r[n]\}}} \sum_{n=2}^{N} \log_2\left(1+p_r[n]\gamma_{\mathrm{rd}}[n]\right)$$

aggregate rate at destination

$$\text{s.t.} \sum_{i=2}^{n} \log_2\left(1+p_r[i]\gamma_{\mathrm{rd}}[i]\right) \le \sum_{i=1}^{n-1} \log_2\left(1+p_s[i]\gamma_{\mathrm{sr}}[i]\right),$$

$$n=2,\cdots,N,$$

information-causality constraint

$$\frac{1}{N}\sum_{n=1}^{N-1} p_s[n] \le \bar{P}_s, \quad \frac{1}{N}\sum_{n=2}^{N} p_r[n] \le \bar{P}_r,$$

power constraint

$$p_s[n] \ge 0, \;\; n=1,\ldots,N-1,$$

$$p_r[n] \ge 0, \;\; n=2,\ldots,N,$$

$$(x[1]-x_0)^2+(y[1]-y_0)^2 \le V^2,$$

initial location constraint

$$(x[n+1]-x[n])^2+(y[n+1]-y[n])^2 \le V^2,$$

$$n=1,\cdots,N-1,$$

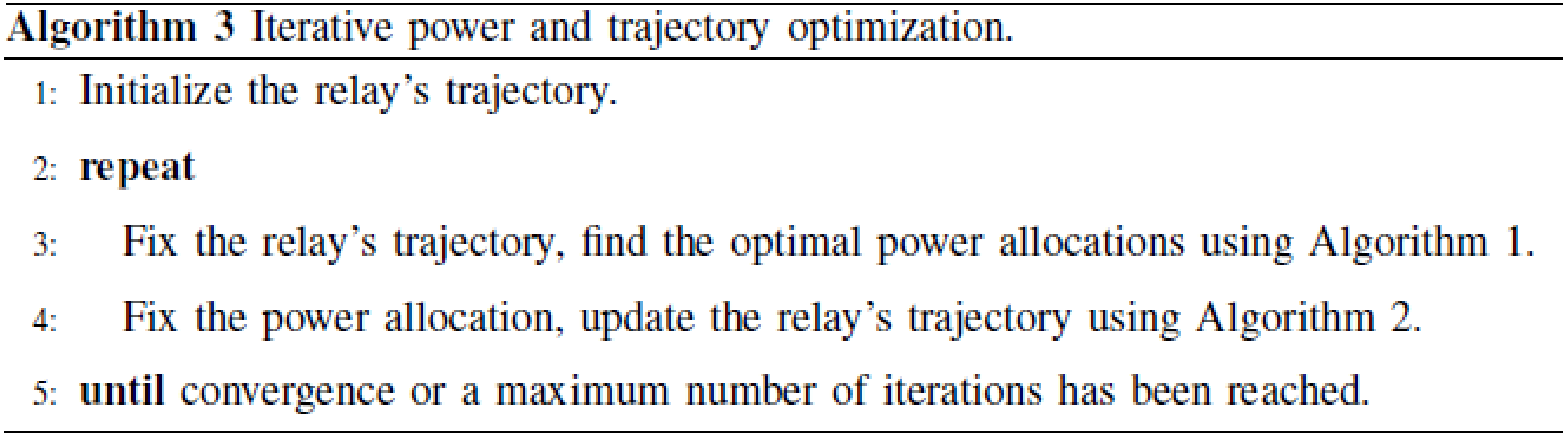
speed constraint

$$(x_F-x[N])^2+(y_F-y[N])^2 \le V^2,$$

final location constraint

Proposed Alternating Power and Trajectory Optimization

- (P1) is not jointly convex w.r.t. power and relay trajectory
- Can be approximately solved with alternating optimization
- Fix trajectory, power allocation is convex
- Fix power, trajectory optimization is still non-convex, but can be approximately solved by successive convex approximation (SCA)



Algorithm 3 Iterative power and trajectory optimization.

```
Initialize the relay's trajectory.
repeat
    Fix the relay's trajectory, find the optimal power allocations using Algorithm 1.
    Fix the power allocation, update the relay's trajectory using Algorithm 2.
until convergence or a maximum number of iterations has been reached.
```

Optimal Power Allocation with Fixed Trajectory

- E.g., UAVs primarily deployed for surveillance, opportunistic relaying
- For any fixed trajectory, power allocation is convex

$$
\begin{aligned}
\text{(P1.1)}: \quad & \max_{\substack{\{p_s[n]\}_{n=1}^{N-1},\\ \{p_r[n], R_r[n]\}_{n=2}^{N}}} \quad \sum_{n=2}^{N} R_r[n] \\
\text{s.t.} \quad & \sum_{i=2}^{n} R_r[i] \le \sum_{i=1}^{n-1} \log_2\left(1 + p_s[i]\gamma_{\rm sr}[i]\right), n = 2, \cdots, N \\
& R_r[n] \le \log_2\left(1 + p_r[n]\gamma_{\rm rd}[n]\right), n = 2, \cdots, N \\
& \sum_{n=1}^{N-1} p_s[n] \le E_s, \ \sum_{n=2}^{N} p_r[n] \le E_r, \\
& p_s[n] \ge 0, \ \ n = 1, ..., N-1, \\
& p_r[n] \ge 0, \ \ n = 2, ..., N,
\end{aligned}
$$

$$
p_s^\star[n] = \left[\eta\beta_n - \frac{1}{\gamma_{\rm sr}[n]}\right]^+
$$

$$
p_r^\star[n] = \left[\xi\nu_n - \frac{1}{\gamma_{\rm rd}[n]}\right]^+
$$

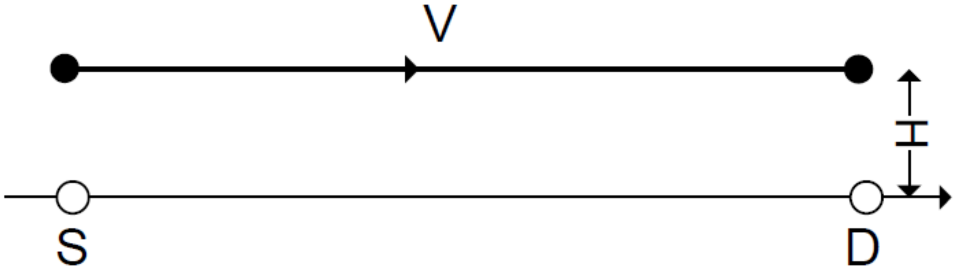
- Staircase waterfilling with non-increasing water level at source
- Staircase waterfilling with non-decreasing water level at relay

Unidirectional Trajectory From Source to Destination

- ❑ Special trajectory case: UAV moves unidirectionally from source to destination
- ❑ Optimal power allocation reduces to classic WF with constant water levels

$$p_s^*[n] = \left[\eta - \frac{1}{\gamma_{\mathrm{sr}}[n]}\right]^+$$

$$p_r^*[n] = \left[\xi - \frac{1}{\gamma_{\mathrm{rd}}[n]}\right]^+$$



Trajectory Optimization with Fixed Power

$$
\begin{aligned}
\text{(P1.2)}: \quad & \max_{\substack{\{x[n],y[n]\}_{n=1}^N\\ \{R_r[n]\}_{n=2}^N}} \sum_{n=2}^{N} R_r[n] \\
\text{s.t.} \; & \sum_{i=2}^{n} R_r[i] \le \sum_{i=1}^{n-1} \log_2\left(1+\frac{\gamma_s[i]}{H^2+x^2[i]+y^2[i]}\right), \\
& \qquad\qquad\qquad\qquad n=2,\cdots,N, \\
& R_r[n] \le \log_2\left(1+\frac{\gamma_r[n]}{H^2+(D-x[n])^2+y^2[n]}\right), \\
& \qquad\qquad\qquad\qquad n=2,\cdots,N, \\
& \left(x[1]-x_0\right)^2+\left(y[1]-y_0\right)^2 \le V^2, \\
& \left(x[n+1]-x[n]\right)^2+\left(y[n+1]-y[n]\right)^2 \le V^2, \\
& \qquad\qquad\qquad\qquad n=1,\cdots,N-1, \\
& \left(x_F-x[N]\right)^2+\left(y_F-y[N]\right)^2 \le V^2,
\end{aligned}
$$

- Successive convex approximation (SCA) based on rate lower bound
- Main idea: optimize the trajectory incremental in each iteration

$$
\begin{aligned}
R_{s,l+1}[n] \ge R^{\mathrm{lb}}_{s,l+1}[n] \triangleq\; & R_{s,l}[n] - a_{s,l}[n]\left(\delta_l^2[n]+\xi_l^2[n]\right) \\
& - b_{s,l}[n]\delta_l[n] - c_{s,l}[n]\xi_l[n],
\end{aligned}
$$

Lower bound is concave w.r.t. incremental $\delta_l[n], \xi_l[n]$

- SCA has then been extensively used for UAV trajectory optimization

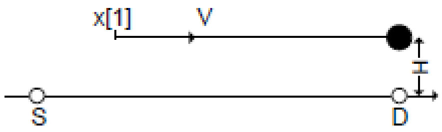
Jointly Optimal Solution with Free Initial/Final Relay Location

- If no constraint on the relay’s initial/final location, jointly optimal power and trajectory can be analytically obtained

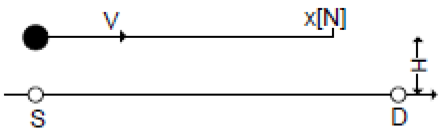
$$v[n] = \begin{cases} V, & \textit{if } 0 < x[n] < D, \\ 0, & \textit{if } x[n] = D, \\ V \textit{ or } 0, & \textit{if } x[n] = 0, \end{cases}$$

$$\textit{where } v[n] \triangleq x[n+1] - x[n] \textit{ is the velocity at slot } n.$$

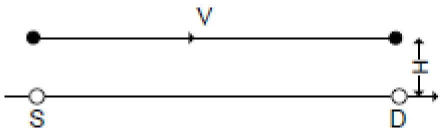
- Two-level (max. or zero) speed is optimal: hovering only above source and/or destination, and move at maximum speed in between



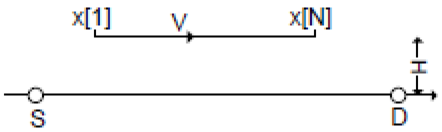
(a): Hovering only above D



(b): Hovering only above S



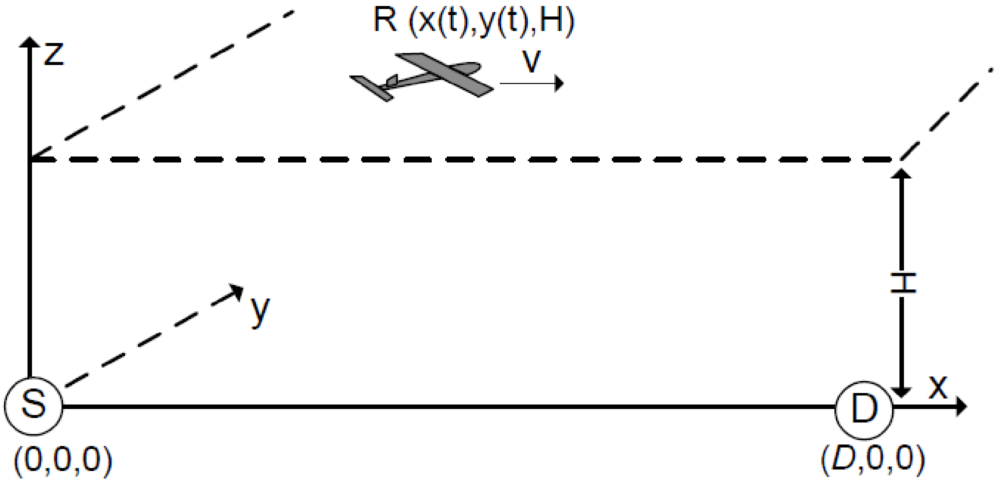
(c): Hovering both above S and D



(d): No hovering

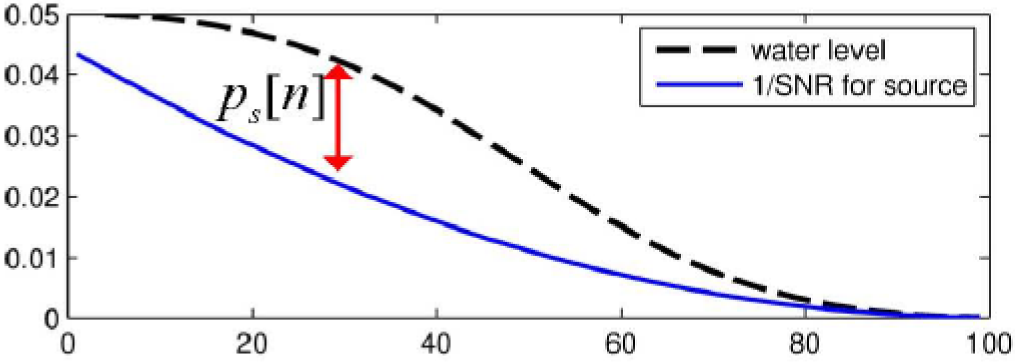
Simulation Setup

- ☐ Source and destination separated by D=2000 m
- ☐ Maximum UAV speed: 50 m/s
- ☐ Source and relay average transmission power: 10 dBm
- ☐ Simulation scenarios:
  - ➢ Optimized power with fixed trajectory
  - ➢ Optimized trajectory with fixed power
  - ➢ Jointly optimized power and trajectory



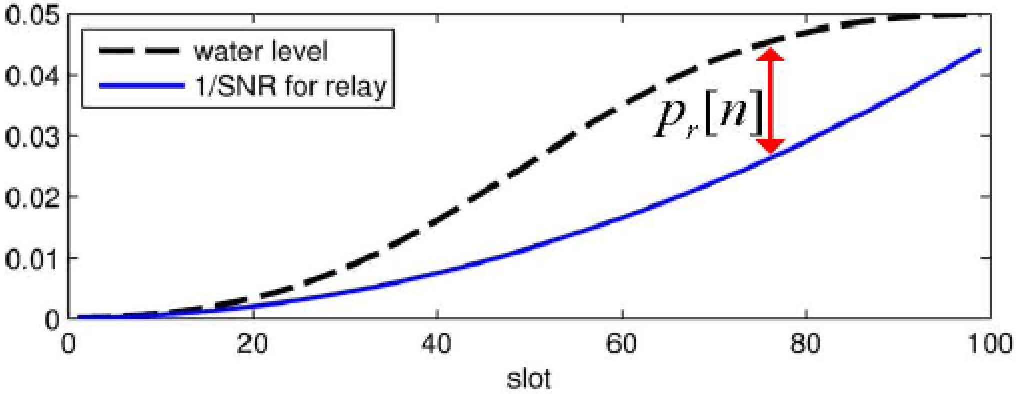
Optimal Power Allocation with Fixed Trajectory

- Trajectory 1: unidirectionally towards destination
- Trajectory 2: unidirectionally towards source
- Trajectory 3: cyclic between source and destination



(a): power allocation at **source** for trajectory 2

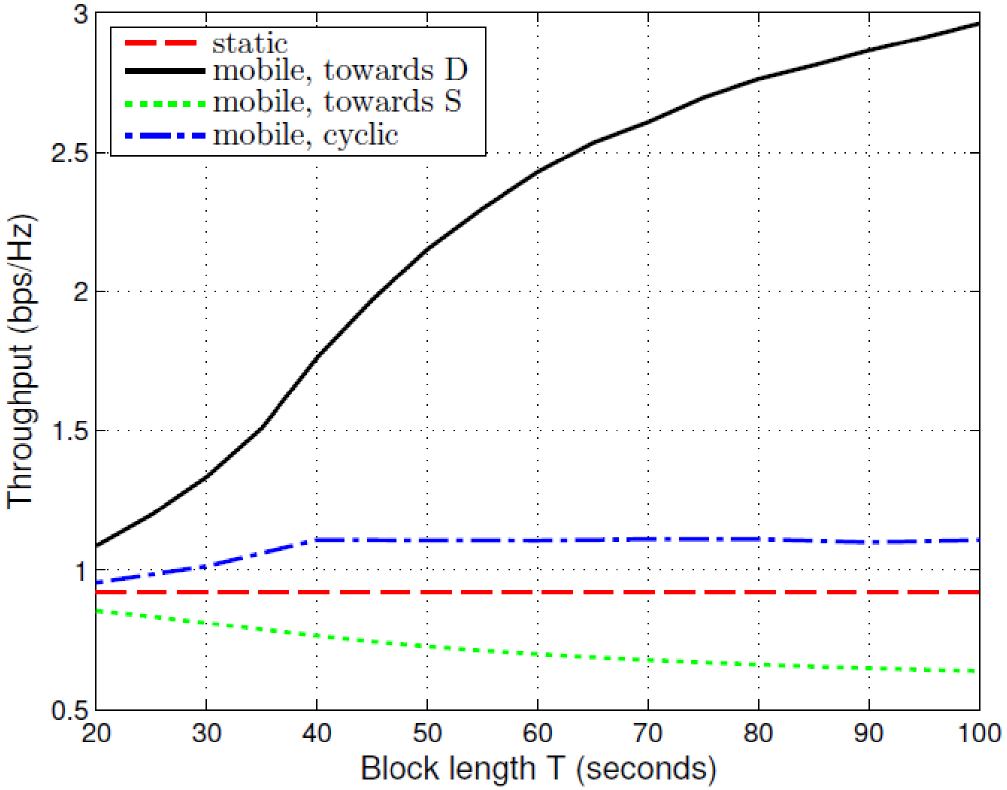
Decreasing water level at source



(b): power allocation at **relay** for trajectory 2

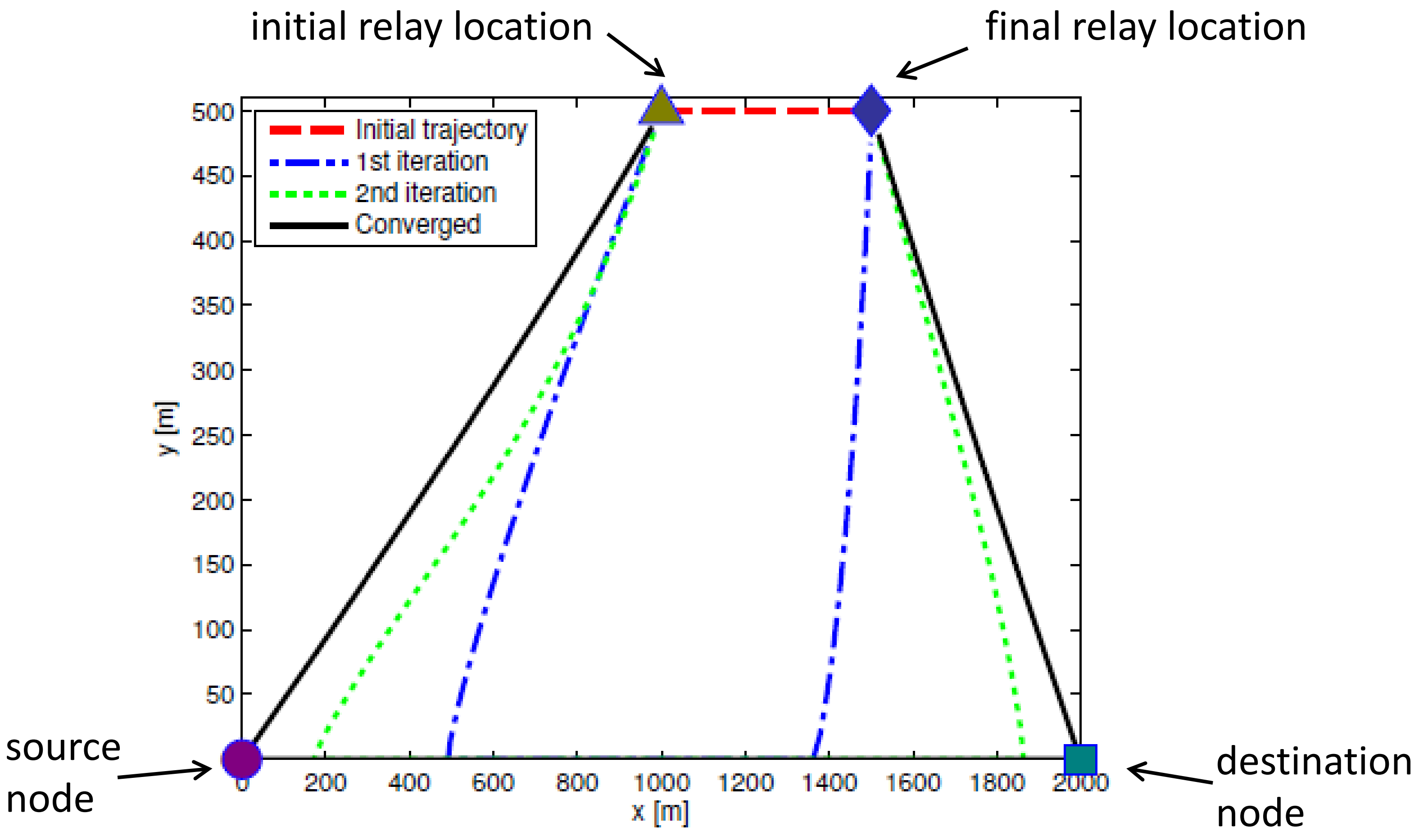
Increasing water level at relay

Throughput Comparison for Different Trajectories



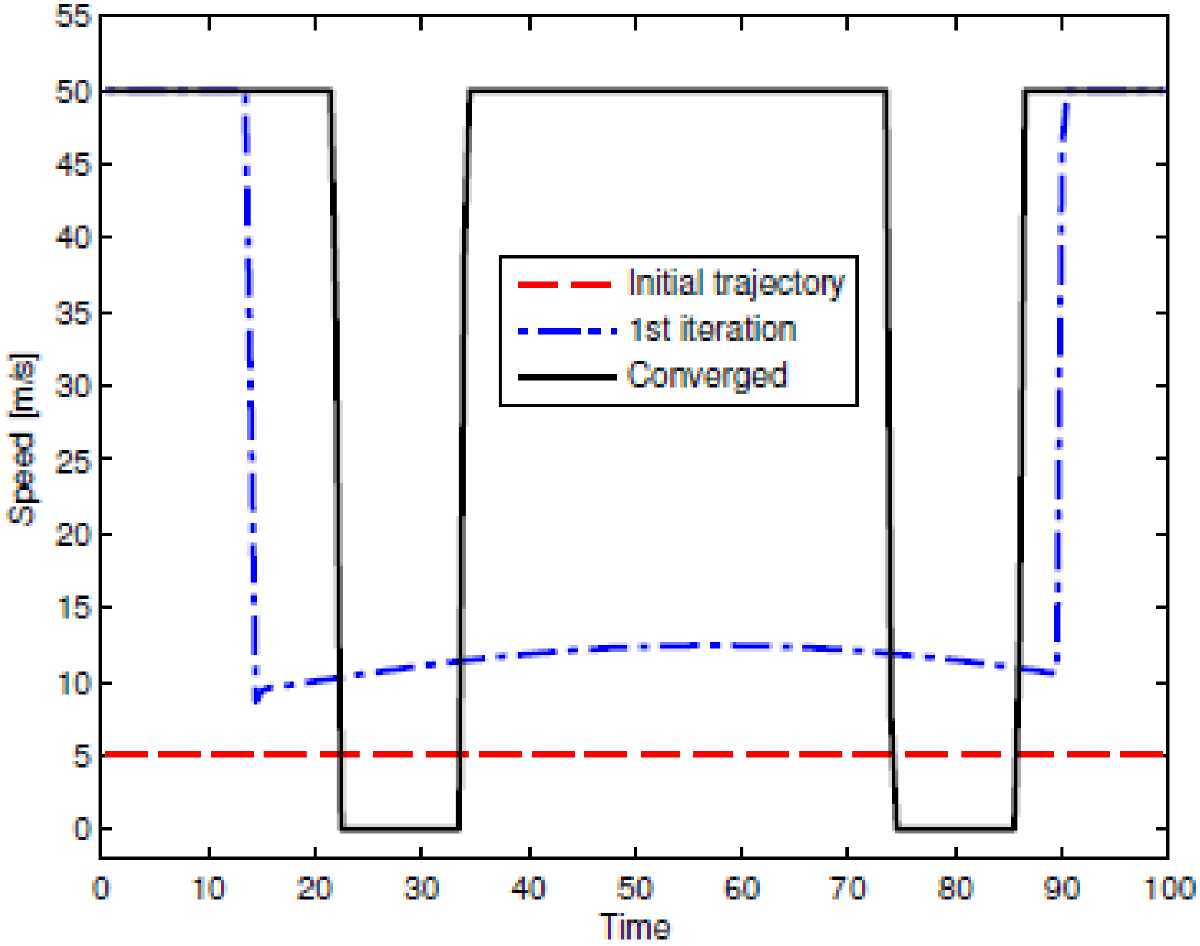
- ☐ Mobile relaying significantly outforms static relaying, if UAV trajectory is properly designed
- ☐ With inappropriate flying path, mobile relaying may even perform worse than static relaying

Optimized Trajectory with Fixed Constant Power Allocation



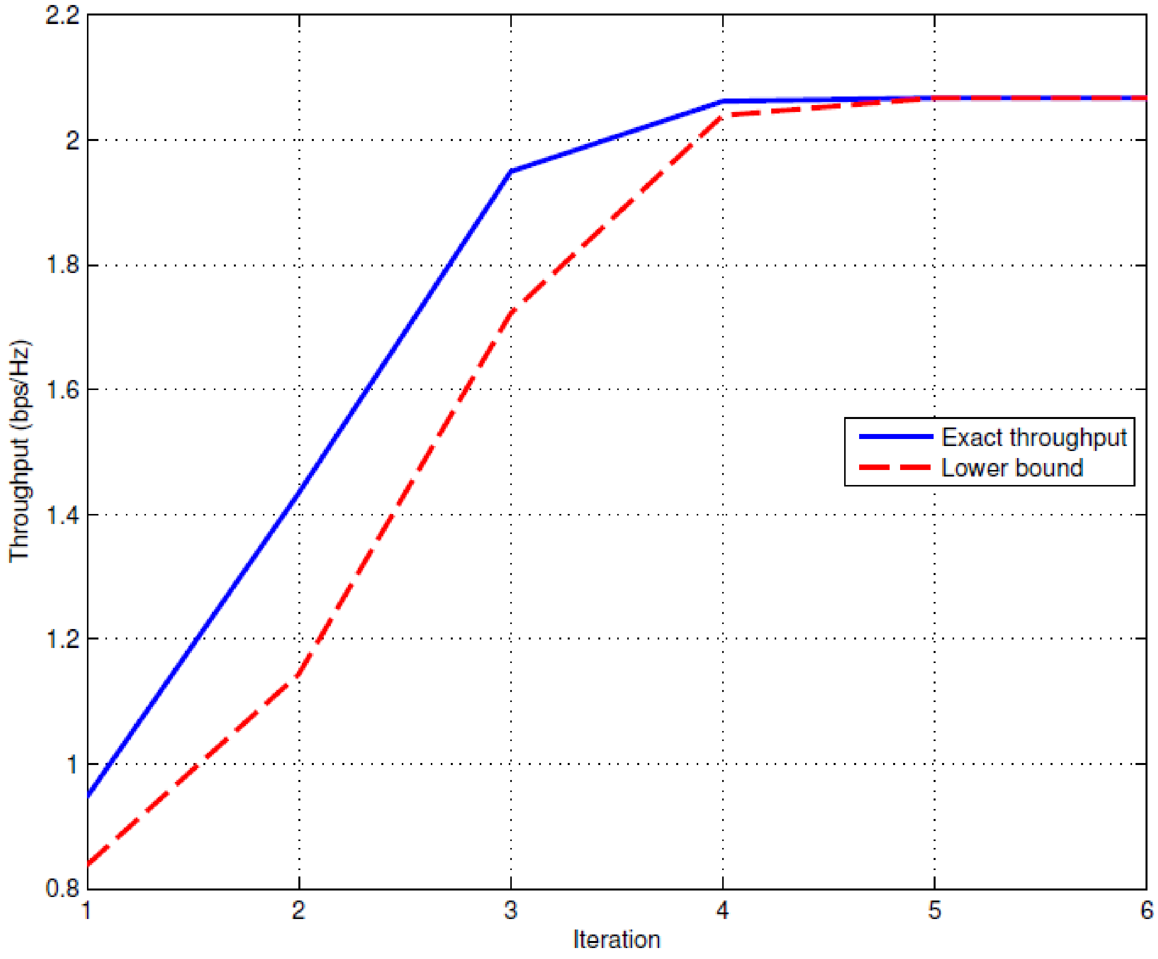
- ❑ Trajectories after different iterations of the proposed successive convex optimization algorithm

Optimized Speed



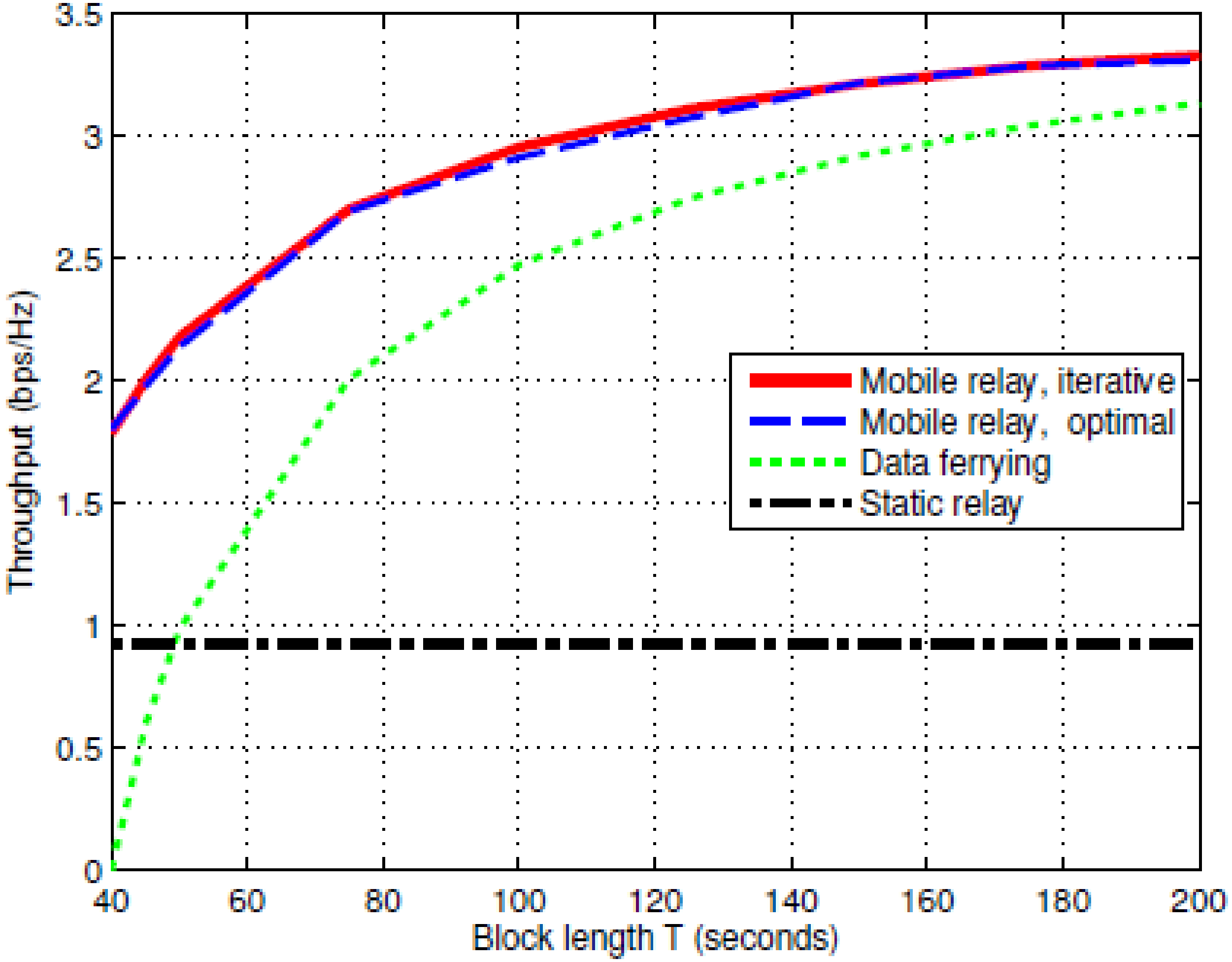
- ☐ Two-level (max. or zero) speed after convergence

Convergence

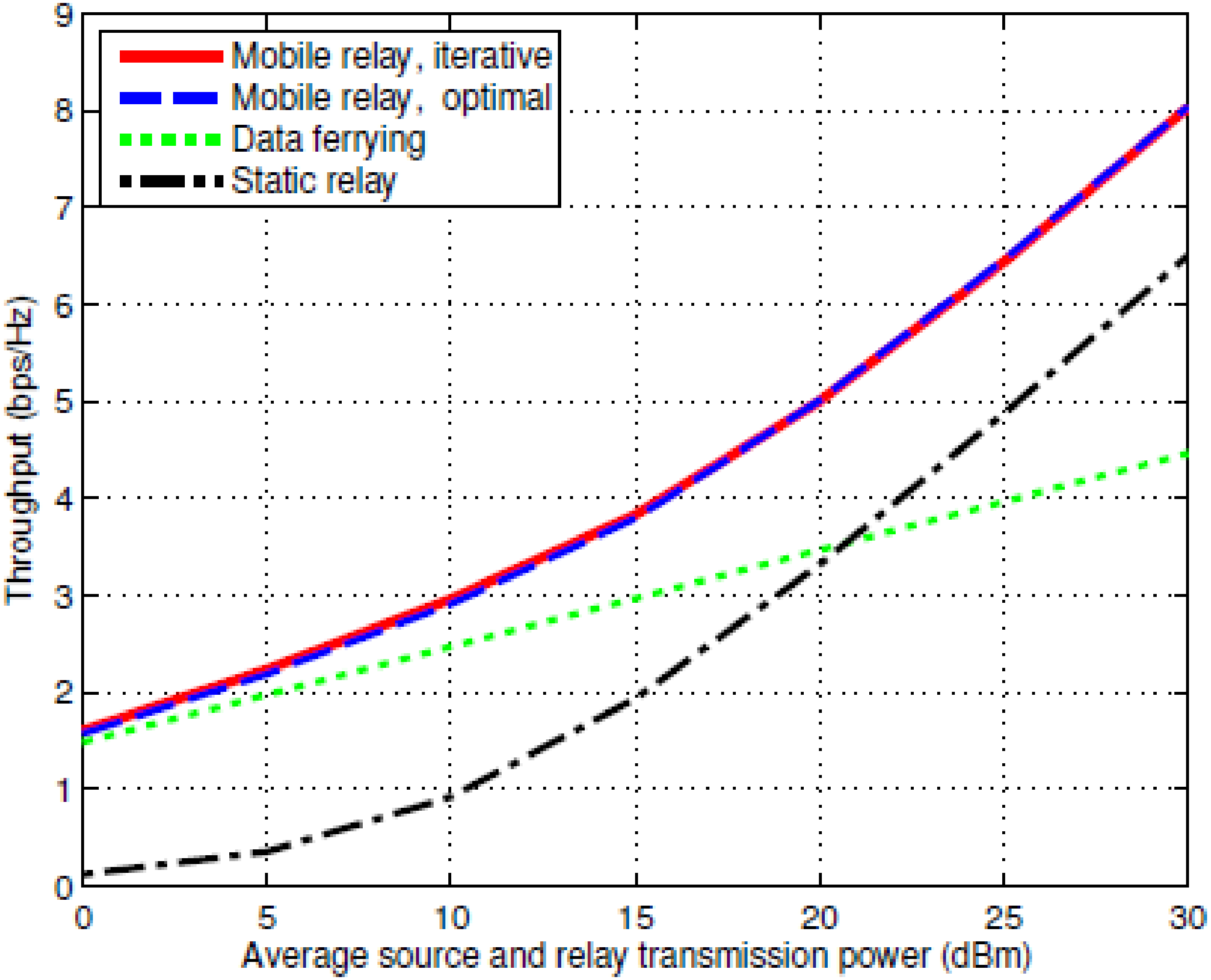


- ❑ Fast convergence for the trajectory optimization algorithm

Joint Power and Trajectory Design via Alternating Optimization



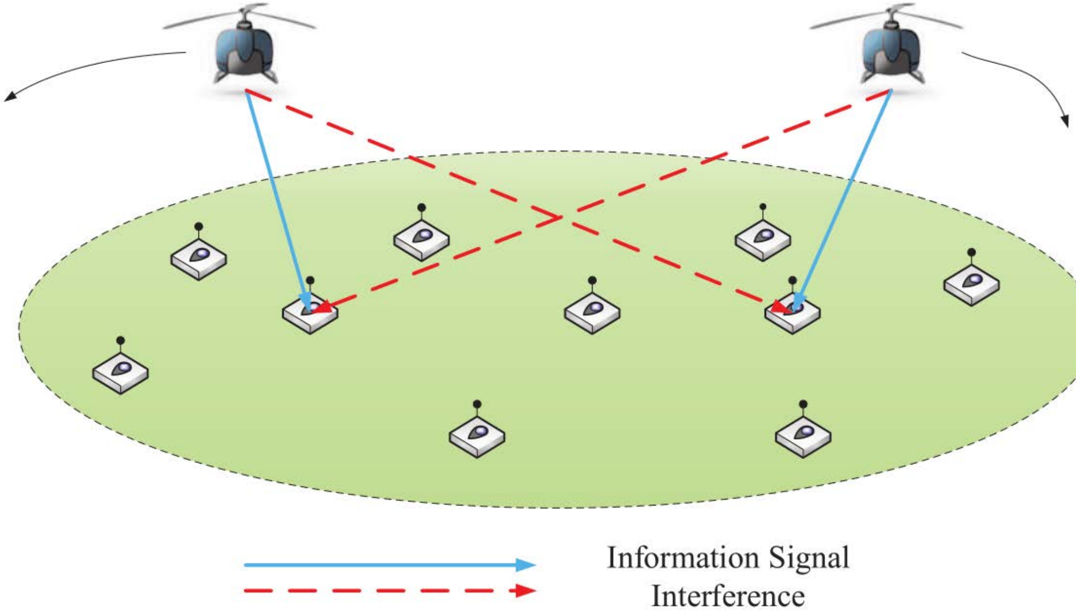
Joint Power and Trajectory Design via Alternating Optimization



Case Study II: Multi-UAV Enabled Wireless Network

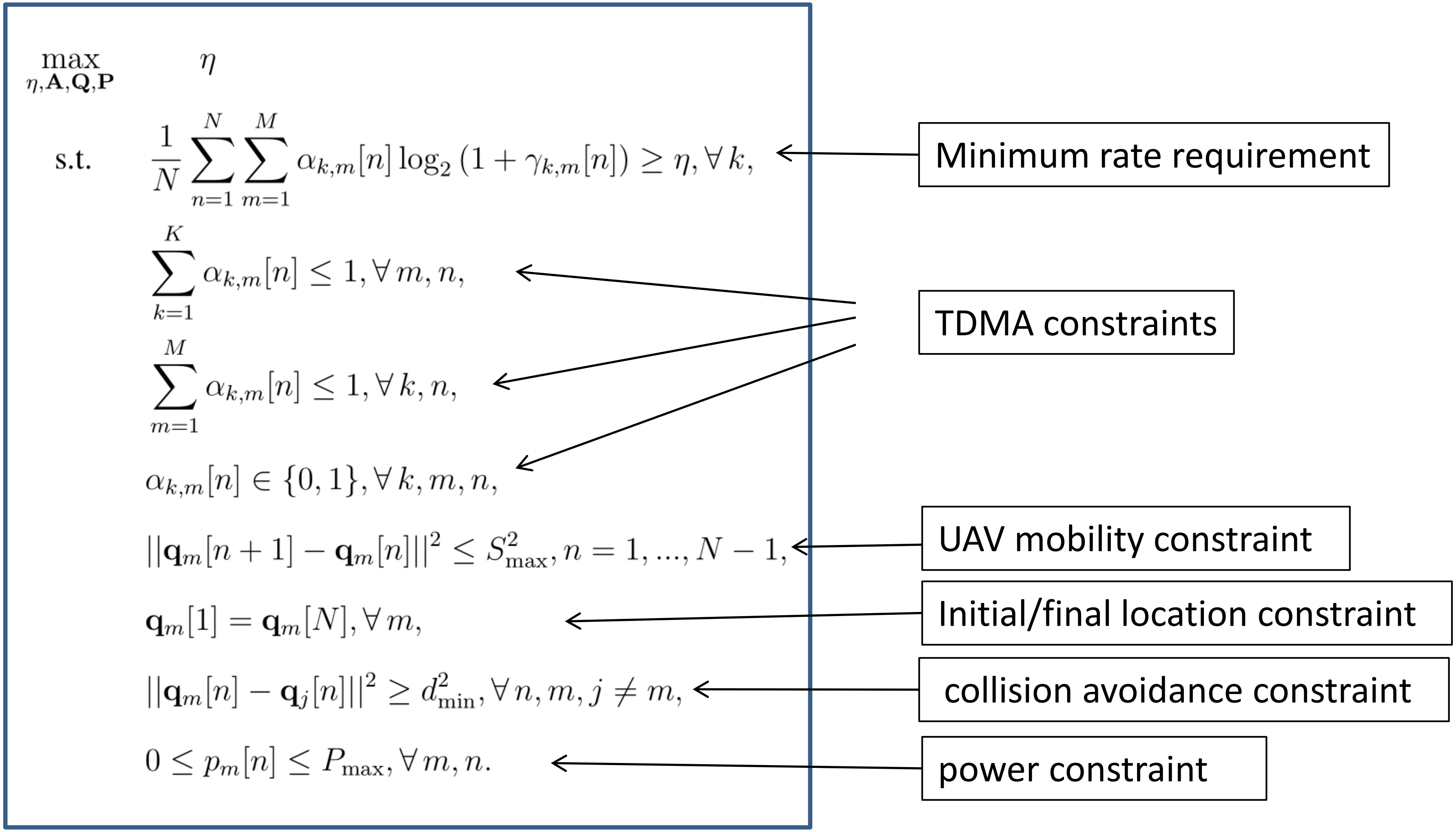
Q. Wu, Y. Zeng, and R. Zhang, “Joint trajectory and communication design for multi-UAV enabled wireless networks,” *IEEE Trans. Wireless Commun.,* Mar. 2018.

System Model



- ☐ Multi-UAV spectrum sharing, interference channel (IFC)+broadcast channel (BC)
- ☐ TDMA for user communication scheduling
- ☐ Problem: maximize the minimum average rate via joint user scheduling and transmit power control as well as UAV trajectory design

Problem Formulation



$$
\begin{aligned}
\max_{\eta,\mathbf{A},\mathbf{Q},\mathbf{P}} \quad & \eta \\
\text{s.t.} \quad & \frac{1}{N}\sum_{n=1}^{N}\sum_{m=1}^{M}\alpha_{k,m}[n]\log_2\left(1+\gamma_{k,m}[n]\right) \geq \eta, \forall\, k, \\
& \sum_{k=1}^{K}\alpha_{k,m}[n] \leq 1, \forall\, m, n, \\
& \sum_{m=1}^{M}\alpha_{k,m}[n] \leq 1, \forall\, k, n, \\
& \alpha_{k,m}[n] \in \{0,1\}, \forall\, k, m, n, \\
& ||\mathbf{q}_m[n+1]-\mathbf{q}_m[n]||^2 \leq S_{\max}^2, n=1,...,N-1, \\
& \mathbf{q}_m[1]=\mathbf{q}_m[N], \forall\, m, \\
& ||\mathbf{q}_m[n]-\mathbf{q}_j[n]||^2 \geq d_{\min}^2, \forall\, n, m, j \neq m, \\
& 0 \leq p_m[n] \leq P_{\max}, \forall\, m, n.
\end{aligned}
$$

Minimum rate requirement

TDMA constraints

UAV mobility constraint

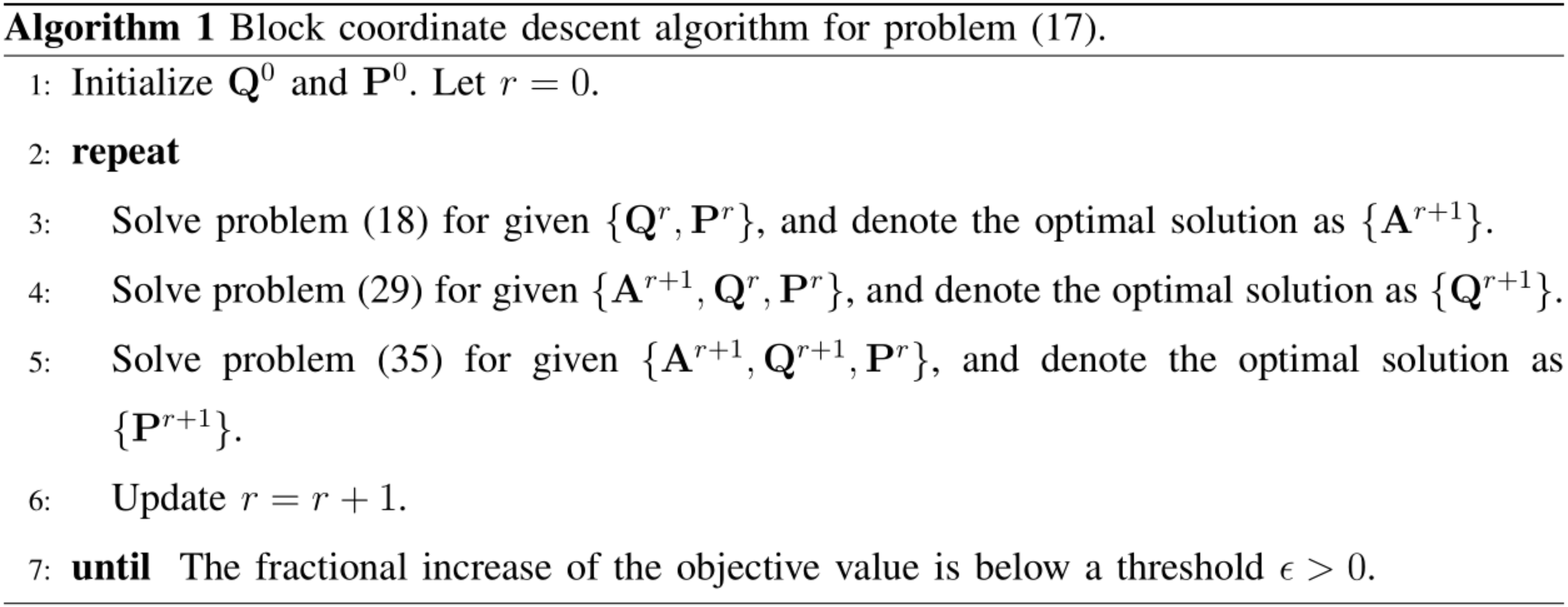
Initial/final location constraint

collision avoidance constraint

power constraint

Proposed Solution

Block coordinate descent algorithm



Algorithm 1 Block coordinate descent algorithm for problem (17).

```
Initialize $\mathbf{Q}^0$ and $\mathbf{P}^0$. Let $r = 0$.
repeat
    Solve problem (18) for given $\{\mathbf{Q}^r, \mathbf{P}^r\}$, and denote the optimal solution as $\{\mathbf{A}^{r+1}\}$.
    Solve problem (29) for given $\{\mathbf{A}^{r+1}, \mathbf{Q}^r, \mathbf{P}^r\}$, and denote the optimal solution as $\{\mathbf{Q}^{r+1}\}$.
    Solve problem (35) for given $\{\mathbf{A}^{r+1}, \mathbf{Q}^{r+1}, \mathbf{P}^r\}$, and denote the optimal solution as $\{\mathbf{P}^{r+1}\}$.
    Update $r = r + 1$.
until The fractional increase of the objective value is below a threshold $\epsilon > 0$.
```

Proposed Solution: Sub-problem 1

User Scheduling and Association Optimization

$$
\begin{aligned}
\max_{\eta, \mathbf{A}} \quad & \eta \\
\text{s.t.} \quad & \frac{1}{N}\sum_{n=1}^{N}\sum_{m=1}^{M}\alpha_{k,m}[n]\log_2\left(1+\gamma_{k,m}[n]\right) \geq \eta, \forall\, k, \\
& \sum_{k=1}^{K}\alpha_{k,m}[n] \leq 1, \forall\, m, n, \\
& \sum_{m=1}^{M}\alpha_{k,m}[n] \leq 1, \forall\, k, n, \\
& 0 \leq \alpha_{k,m}[n] \leq 1, \forall\, k, m, n.
\end{aligned}
$$

- ☐ Continuous relaxation on binary variables
- ☐ Linear program

Proposed Solution: Sub-problem 2

UAV Trajectory Optimization

$$
\begin{aligned}
\max_{\eta,\mathbf{Q}} \quad & \eta \\
\text{s.t.} \quad & \frac{1}{N}\sum_{n=1}^{N}\sum_{m=1}^{M}\alpha_{k,m}[n]\log_2\left(1+\frac{\frac{p_m[n]\rho_0}{H^2+||\mathbf{q}_m[n]-\mathbf{w}_k||^2}}{\sum_{j=1,j\neq m}^{M}\frac{p_j[n]\rho_0}{H^2+||\mathbf{q}_j[n]-\mathbf{w}_k||^2}+\sigma^2}\right)\geq\eta,\forall\, k, \\
& ||\mathbf{q}_m[n+1]-\mathbf{q}_m[n]||^2\leq S_{\max}^2, n=1,\ldots,N-1, \\
& \mathbf{q}_m[1]=\mathbf{q}_m[N],\forall\, m, \\
& ||\mathbf{q}_m[n]-\mathbf{q}_j[n]||^2\geq d_{\min}^2,\forall\, n,m,j\neq m.
\end{aligned}
$$

- Successive convex approximation

Proposed Solution: Sub-problem 3

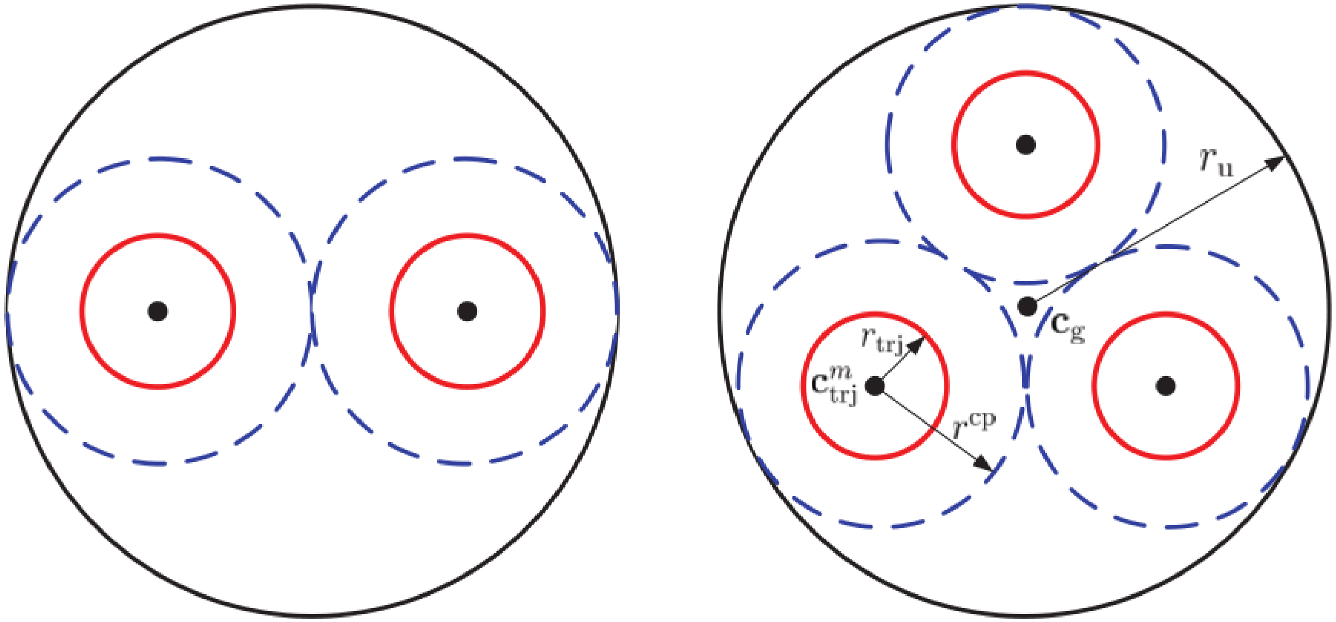
Transmit Power Control

$$
\begin{aligned}
\max_{\eta,\mathbf{P}} \quad & \eta \\
\text{s.t.} \quad & \frac{1}{N}\sum_{n=1}^{N}\sum_{m=1}^{M}\alpha_{k,m}[n]\log_2\left(1+\frac{p_m[n]h_{k,m}[n]}{\sum_{j=1,j\neq m}^{M}p_j[n]h_{k,j}[n]+\sigma^2}\right)\geq \eta, \forall\, k, \\
& 0 \leq p_m[n] \leq P_{\max}, \forall\, m, n.
\end{aligned}
$$

- ☐ Successive convex approximation

Simulation Results

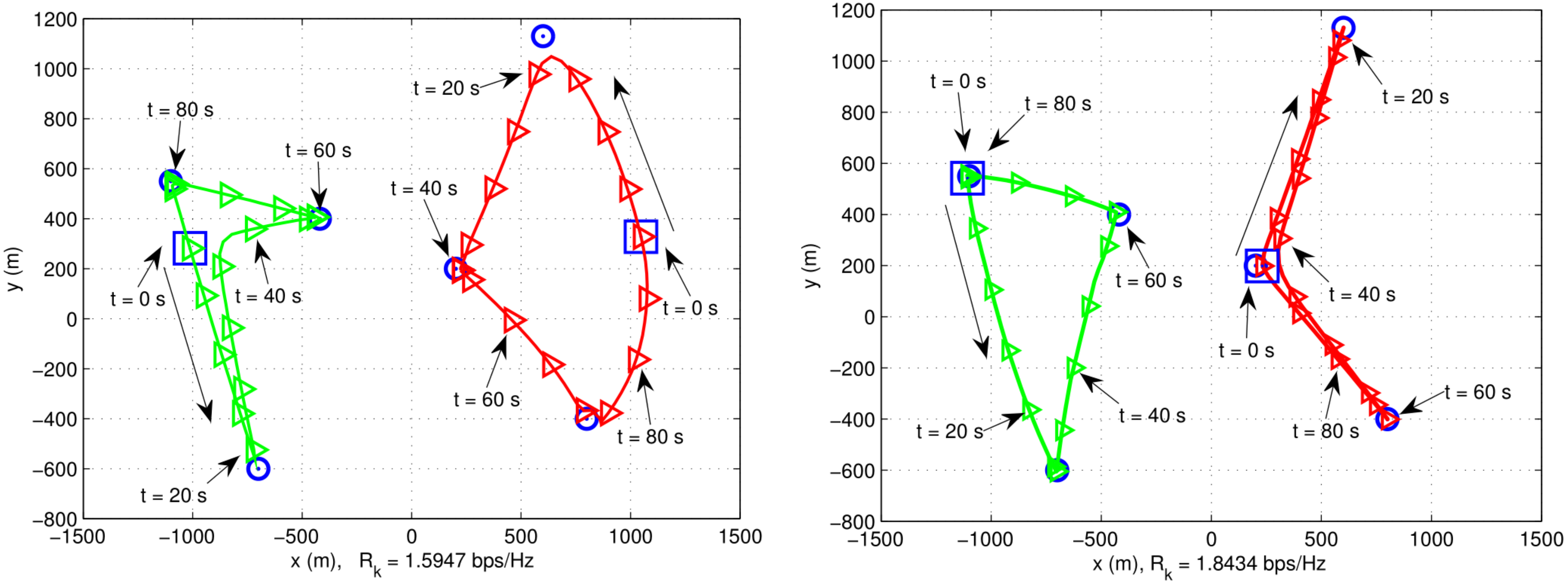
UAV trajectory initialization scheme



- ☐ Circle packing
- ☐ Avoid interference
- ☐ Cover as much area as possible

Simulation Results

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

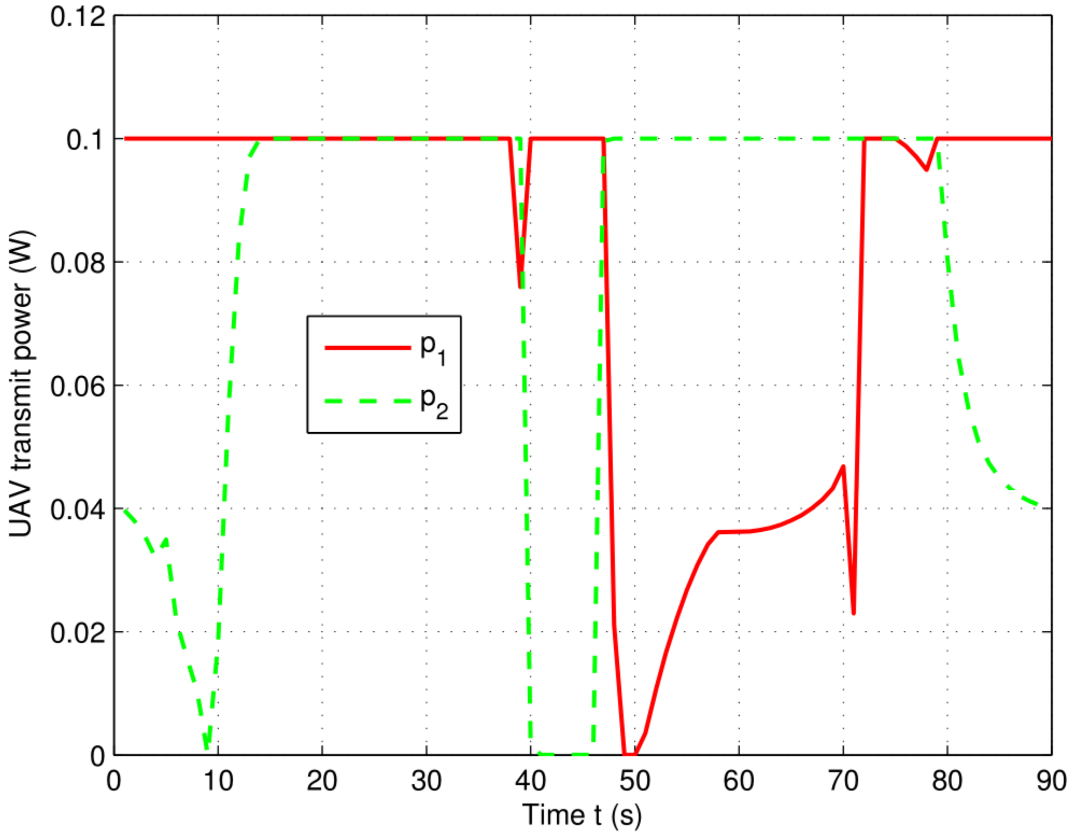


(a) Optimized UAV trajectories without power control.

(b) Optimized UAV trajectories with power control.

Simulation Results

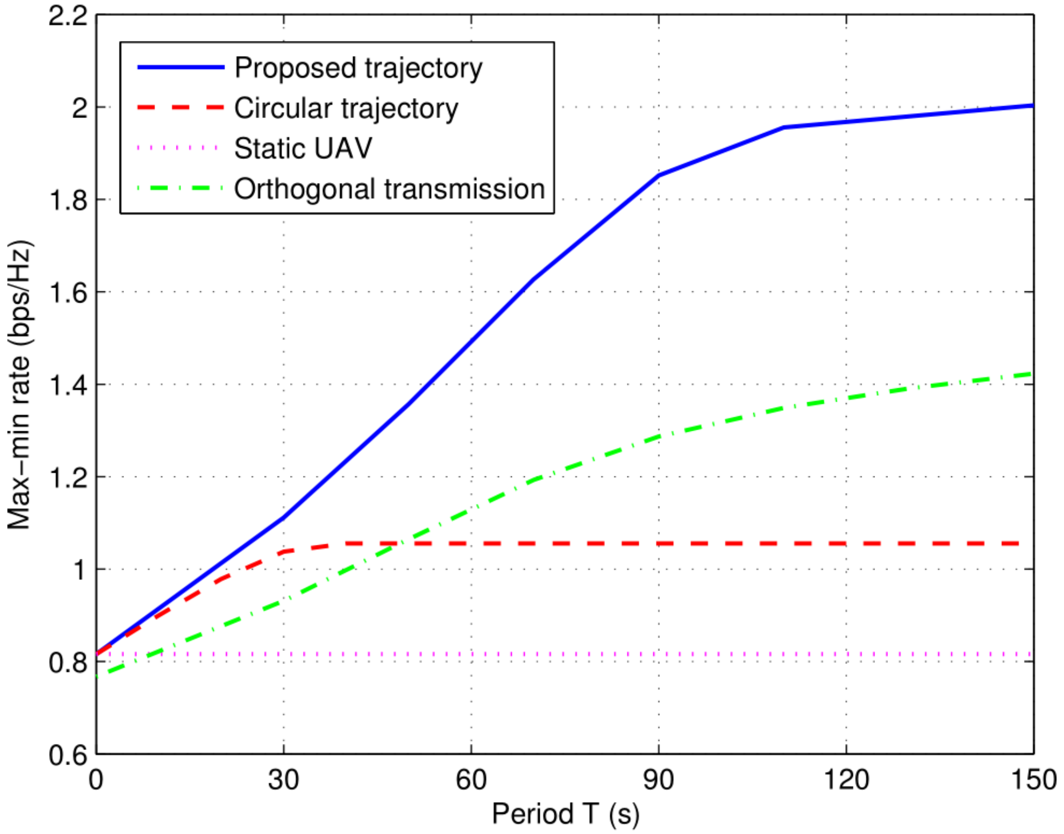
Power control under optimized UAV trajectory



- ❑ Full-power transmission for large inter-UAV distance
- ❑ Small/zero power for small inter-UAV distance

Simulation Results

Throughput-delay tradeoff



- ❑ Longer flight period achieves higher max-min throughput
- ❑ Longer flight period implies larger user delay on average

Case Study III: Energy-Efficient UAV Communication

Y. Zeng and R. Zhang, “Energy-efficient UAV communication with trajectory optimization,” *IEEE Trans. Wireless Commun.*, June 2017.

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

Energy-Efficient UAV Communications

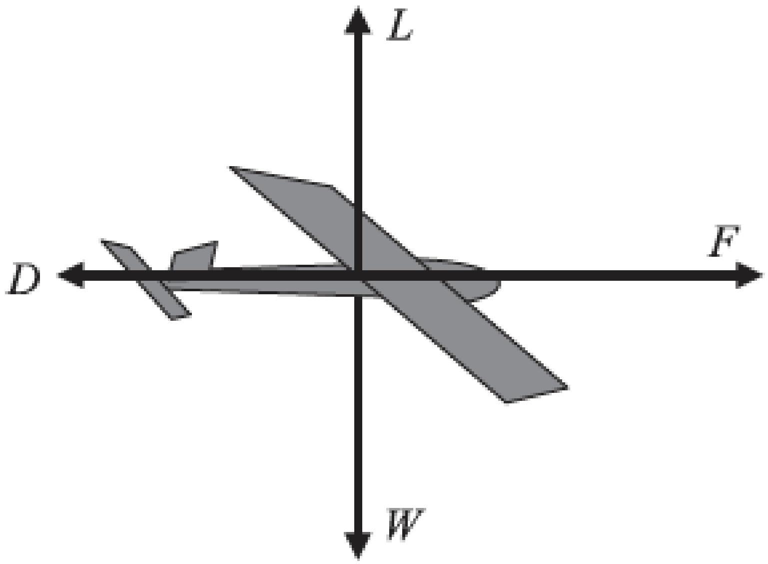
- ☐ **Energy**: critical issue for UAV, finite endurance
- ☐ UAV energy consumption:
  - ➢ Communication energy: signal transmission/reception/processing and circuitry (extensively studied in existing literature)
  - ➢ **Propulsion energy:** maintain UAV aloft and mobile (important but with only limited work, rigorous mathematical model is needed)
- ☐ UAV energy model
  - ➢ Depend on UAV type: fixed-wing vs. rotary-wing
  - ➢ A function of UAV speed, acceleration
- ☐ Energy-efficient UAV communications:
  - ➢ Maximize energy efficiency (bits/Joule), or equivalently
  - ➢ Minimize energy expenditure subject to throughput constraint
  - ➢ Maximize throughput subject to energy constraint

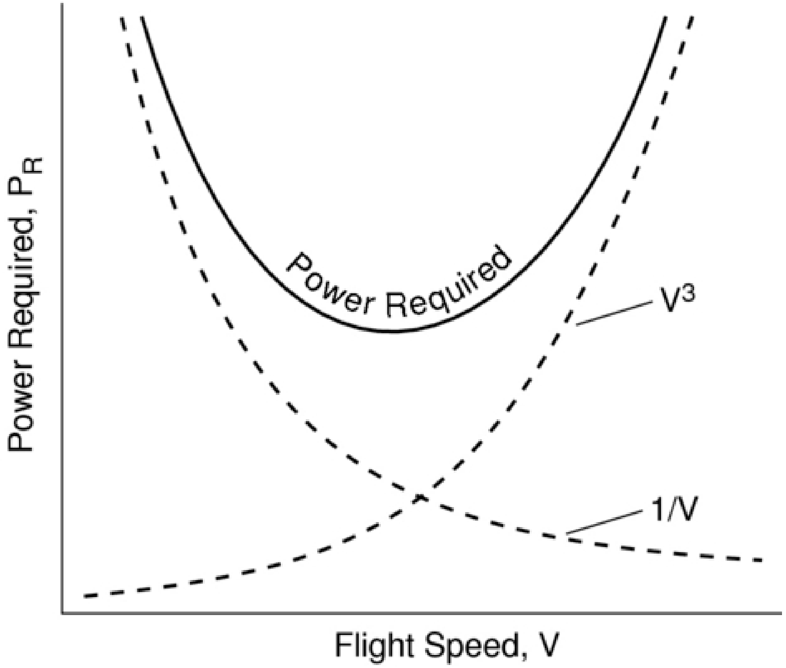
UAV Energy Model (Fixed-Wing)

- ❑ Forces on UAV: weight (W), lift (L), drag (D), and thrust (F)
- ❑ Fixed-wing propulsion energy (Straight and level flight)

$$\bar{E}_{\mathrm{SLF}}(V) = T\left(c_1 V^3 + \frac{c_2}{V}\right)$$

- ❑ Convex function: first decreasing then increasing with speed

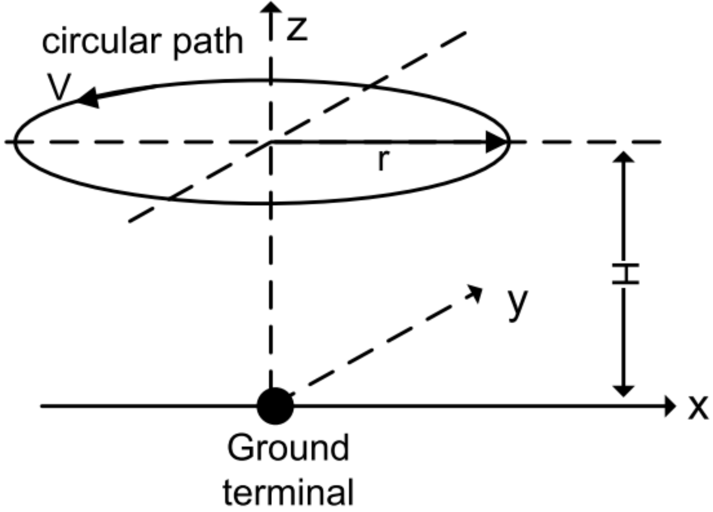




Energy-Efficient UAV Communication with Circular Flight

- ☐ Circular trajectory with radius r and speed v
- ☐ Communication rate: $\bar{R}_{\text{cir}}(r) = TB\log_2\left(1 + \frac{\gamma_0}{H^2 + r^2}\right).$
- ☐ UAV energy consumption: $\bar{E}_{\text{cir}}(V, r) = T\left[\left(c_1 + \frac{c_2}{g^2 r^2}\right)V^3 + \frac{c_2}{V}\right].$
- ☐ Smaller *r*: higher rate, but also more energy consumption
- ☐ Maximize energy efficiency (bits/Joule)

$$\text{EE}_{\text{cir}}(V, r) = \frac{\bar{R}_{\text{cir}}(r)}{\bar{E}_{\text{cir}}(V, r)} = \frac{B\log_2\left(1 + \frac{\gamma_0}{H^2+r^2}\right)}{\left(c_1 + \frac{c_2}{g^2 r^2}\right)V^3 + \frac{c_2}{V}}.$$



Trajectory Optimization for Energy Efficiency Maximization

- ☐ UAV energy model with general trajectory:

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

- ☐ Aggregate throughput as a function of UAV trajectory

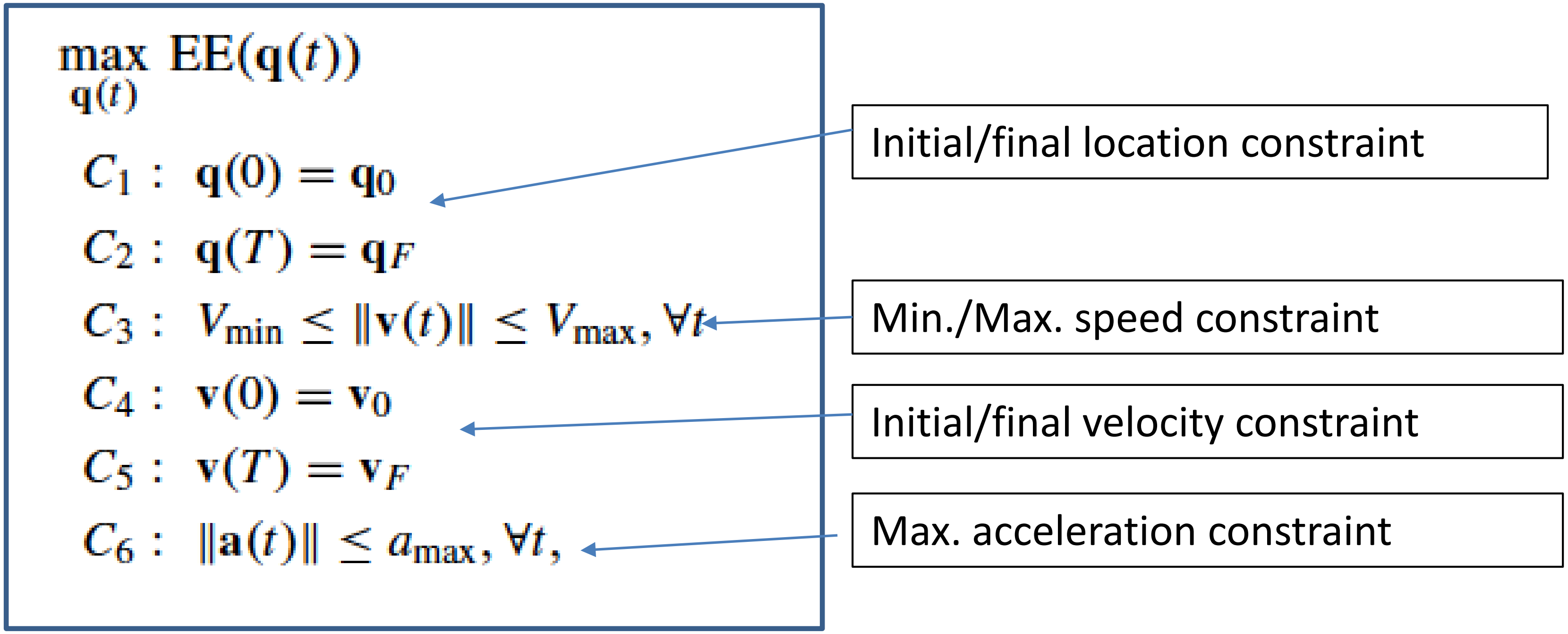
$$\bar{R}(\mathbf{q}(t)) = \int_0^T B\log_2\left(1+\frac{\gamma_0}{H^2+\|\mathbf{q}(t)\|^2}\right)dt.$$

- ☐ Energy efficiency in bits/Joule:

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

Trajectory Optimization for Energy Efficiency Maximization

- Maximize energy efficiency in bits/Joule via trajectory optimization



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

Initial/final location constraint

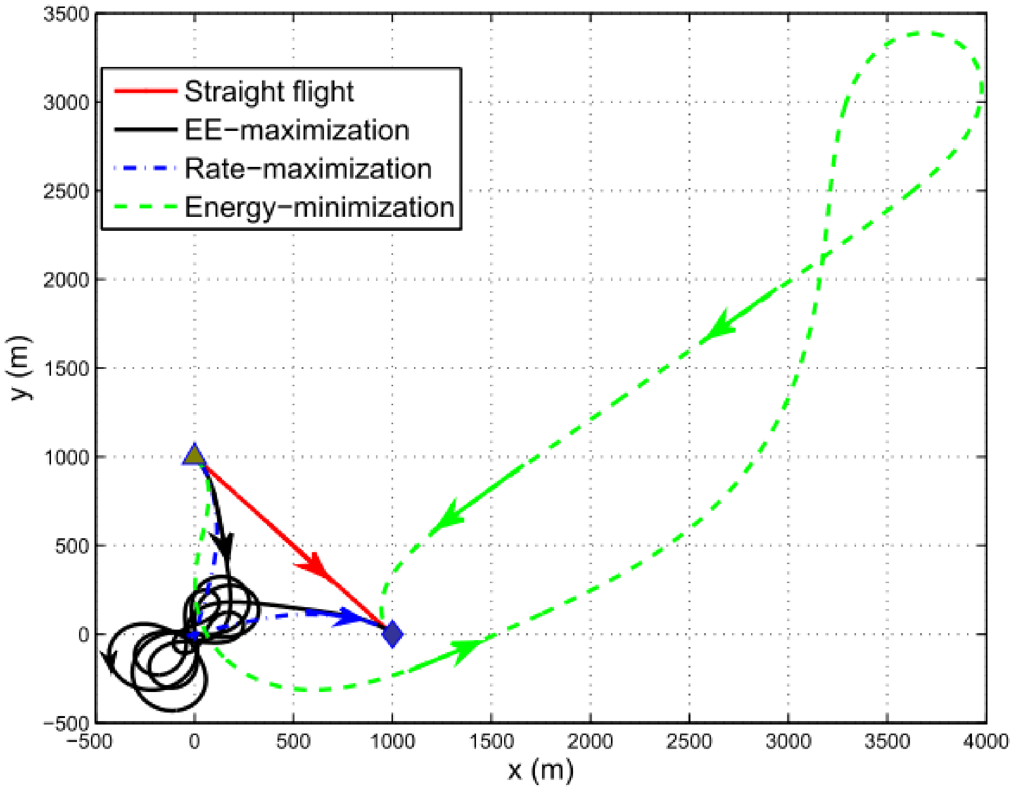
Min./Max. speed constraint

Initial/final velocity constraint

Max. acceleration constraint

- Non-convex, infinite number of variables
- Main techniques: time discretization and Successive Convex Approximation (SCA)

Simulation Results



- ☐ 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

UAV Energy Model (Rotary-Wing)

- Rotary-wing propulsion power

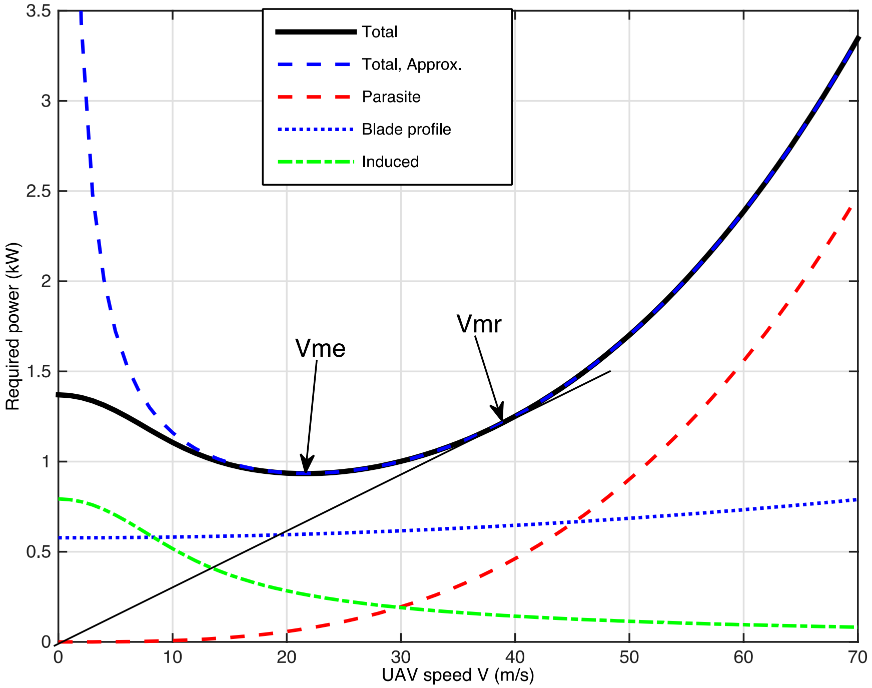
$$P(V) = \underbrace{P_0\left(1+\frac{3V^2}{U_{\text{tip}}^2}\right)}_{\text{blade profile}} + \underbrace{P_i\left(\sqrt{1+\frac{V^4}{4v_0^4}}-\frac{V^2}{2v_0^2}\right)^{1/2}}_{\text{induced}} + \underbrace{\frac{1}{2}d_0\rho s A V^3}_{\text{parasite}},$$

- Non-convex function: first decreasing then increasing with speed
- Maximum-endurance (me) speed
- Maximum-range (mr) speed

$$V_{\text{me}} = \arg\min_{V\geq 0} P(V)$$

$$V_{\text{mr}} = \arg\min_{V\geq 0} E_0(V) \triangleq \frac{P(V)}{V}$$

Energy per unit distance



Energy Minimization with Rate Constraint

- ☐ UAV communicates with multiple users, each has a throughput requirement
- ☐ Minimize UAV energy, via joint trajectory design and communication scheduling

$$
\begin{aligned}
\text{(P1)}: \min_{T_t,\{\mathbf{q}(t)\},\{\lambda_k(t)\}} \quad & E(T_t,\{\mathbf{q}(t)\},\{\lambda_k(t)\}) \\
\text{s.t.} \quad & \bar{R}_k(T_t,\{\mathbf{q}(t)\},\{\lambda_k(t)\}) \geq \tilde{Q}_k, \ \forall k \in \mathcal{K}, \\
& \|\dot{\mathbf{q}}(t)\| \leq V_{\max}, \ \forall t \in [0, T_t], \\
& \mathbf{q}(0) = \mathbf{q}_I, \ \mathbf{q}(T_t) = \mathbf{q}_F, \\
& \lambda_k(t) \in \{0,1\}, \ \forall k \in \mathcal{K}, \ t \in [0, T_t], \\
& \sum_{k=1}^{K} \lambda_k(t) \leq 1, \ \forall t \in [0, T_t],
\end{aligned}
$$

UAV energy

Throughput constraint

Max. speed constraint

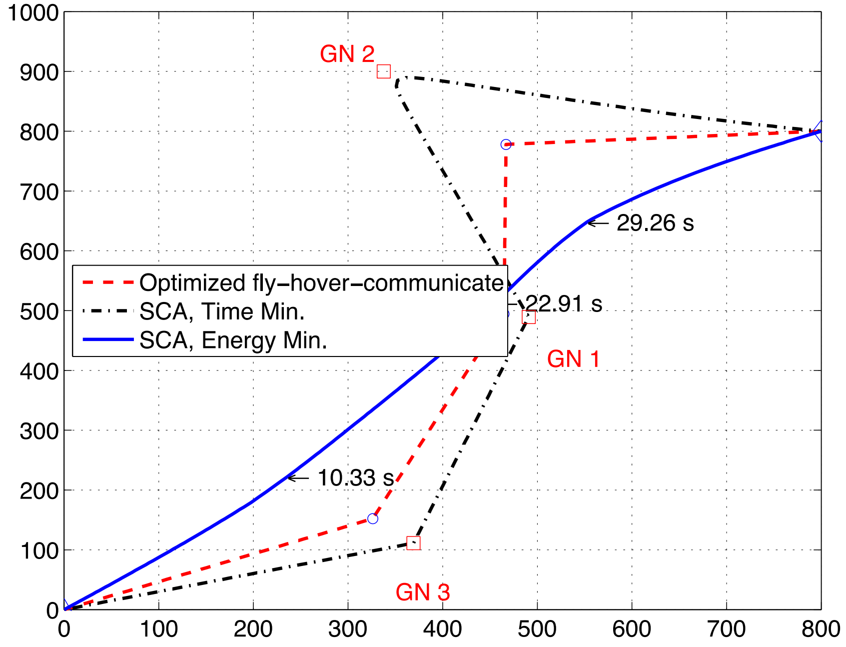
Initial/final location constraint

Scheduling variables

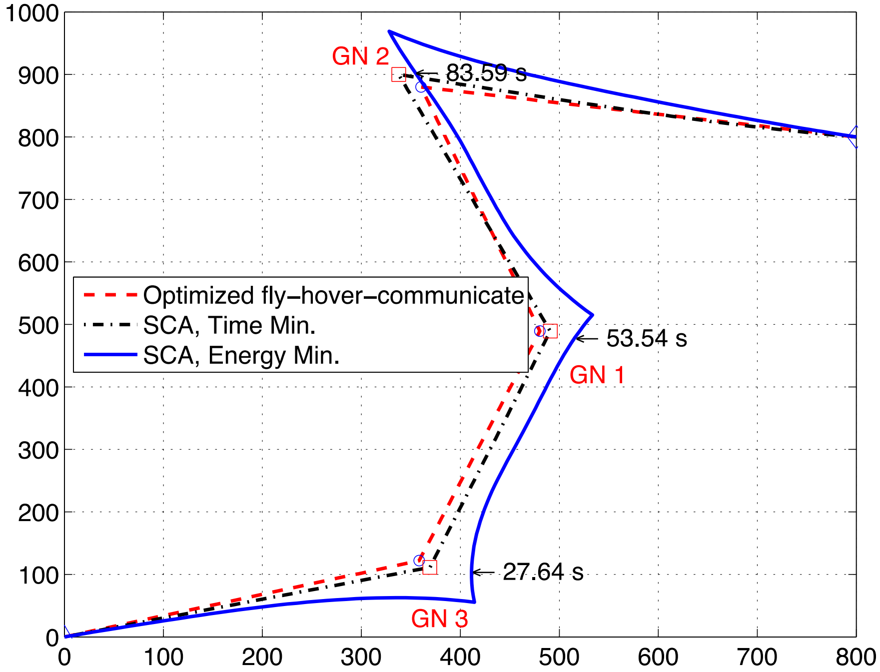
Proposed Solutions

- ☐ The problem is non-convex, infinite number of optimization variables
- ☐ Solution 1: Fly-hover-communicate protocol
  - ➢ Communication only while hovering
  - ➢ Optimize hovering locations, visiting order, and flying speed
  - ➢ Optimal speed: maximum-range speed
  - ➢ Convex optimization to find hovering locations, and Travelling salesman with neighborhood (TSPN) to find visiting order
- ☐ Solution 2: Joint design
  - ➢ Path discretization (vs. time discretization)
  - ➢ Successive convex approximation (SCA)

Simulation Results



Target throughput: 50 Mbits



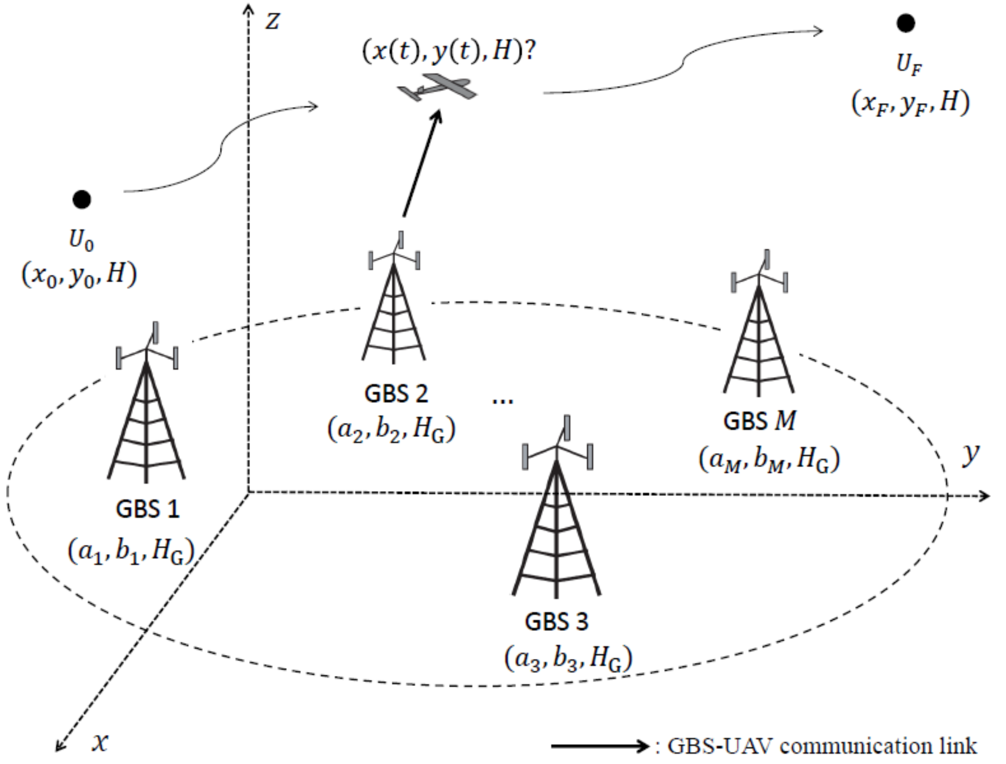
Target throughput: 200 Mbits

Case Study IV: Cellular-Connected UAV: QoS-Aware Trajectory Design

S. Zhang, Y. Zeng, and R. Zhang, “Cellular-enabled UAV communication: Trajectory optimization under connectivity constraint,” to appear *in IEEE Int. Conf. Commun. (ICC),* May 2018 [Online]. Available: https://arxiv.org/abs/1710.11619.

System Model

- ☐ Setup: A cellular-enabled UAV communication system with one UAV and $M \geq 1$ ground base stations (GBSs).



- ➢ UAV altitude: H
- ➢ GBS altitude: H_G
- ➢ Horizontal location of mth GBS: $\boldsymbol{g}_m \in \mathbb{R}^2$
- ➢ Horizontal location of UAV at time t: $\boldsymbol{u}(t) \in \mathbb{R}^2, 0 \leq t \leq T$, with T denoting mission completion time
- ➢ UAV and each GBS assumed to be equipped with one single antenna (effectively).

- ☐ UAV mission: Fly between a pair of pre-determined initial location U_0 and final location U_F.
- ☐ Downlink GBS-UAV communication (assumed to be interference-free): UAV associate with one GBS at each time instant.

System Model

- ☐ Channel model: Assumed to be line-of-sight (LoS), perfect Doppler compensation.

  - ➢ Channel power gain between mth GBS and UAV at time t:

$$|h_m(t)|^2 = \frac{\beta_0}{d_m^2(t)} = \frac{\beta_0}{(H-H_{\rm G})^2 + \|\boldsymbol{u}(t) - \boldsymbol{g}_m\|^2}, \quad m \in \mathcal{M}$$

β_0: channel power gain at reference distance $d_0 = 1$ m

- ☐ UAV should associate with closest GBS at each time instant to maximize channel power gain.

- ☐ SNR at UAV receiver: $\rho(t) = \dfrac{\gamma_0}{(H-H_{\rm G})^2 + \min\limits_{m\in\mathcal{M}} \|\boldsymbol{u}(t) - \boldsymbol{g}_m\|^2}$

γ_0: reference SNR at $d_0 = 1$ m

- ☐ QoS metric: Quality-of-connectivity specified by receiver SNR (delay-sensitive communication, e.g., command & control signal transmission).

- ☐ QoS requirement: A minimum SNR $\bar{\rho}$ needs to be achieved at any time instant during mission.

$$\rho(t) \geq \bar{\rho}, \quad 0 \leq t \leq T$$

  - ➢ Equivalently:

$$\min_{m\in\mathcal{M}} \|\boldsymbol{u}(t) - \boldsymbol{g}_m\| \leq \bar{d}, \quad 0 \leq t \leq T \qquad \bar{d} \triangleq \sqrt{\frac{\gamma_0}{\bar{\rho}} - (H-H_{\rm G})^2}$$

Problem Formulation

- Objective: Optimize UAV trajectory to minimize mission completion time, subject to UAV initial and final location constraints, quality-of-connectivity constraint, and maximum UAV speed constraint.

$$\text{(P1)} \quad \min_{T,\{\boldsymbol{u}(t),\ 0\leq t\leq T\}} \quad T \longrightarrow \text{Mission completion time}$$

$$\text{s.t.} \quad \boldsymbol{u}(0) = \boldsymbol{u}_0 \longrightarrow \text{UAV initial location constraint}$$

$$\boldsymbol{u}(T) = \boldsymbol{u}_F \longrightarrow \text{UAV final location constraint}$$

$$\min_{m\in\mathcal{M}} \|\boldsymbol{u}(t) - \boldsymbol{g}_m\| \leq \bar{d}, \quad 0 \leq t \leq T \rightarrow \text{Quality-of-connectivity constraint}$$

$$\|\dot{\boldsymbol{u}}(t)\| \leq V_{\max}, \quad 0 \leq t \leq T. \longrightarrow \text{Maximum UAV speed constraint}$$

- (P1) is non-convex and difficult to solve, since:

1. Quality-of-connectivity constraint is non-convex in general.
2. Trajectory $\boldsymbol{u}(t)$ is a continuous function of t, thus (P1) involves infinite # of variables.

Feasibility of (P1)

$$\boxed{\begin{aligned}
\text{Find}\quad & T, \{\boldsymbol{u}(t),\ 0 \le t \le T\} \\
\text{s.t.}\quad & \boldsymbol{u}(0) = \boldsymbol{u}_0 \\
& \boldsymbol{u}(T) = \boldsymbol{u}_F \\
& \min_{m \in \mathcal{M}} \|\boldsymbol{u}(t) - \boldsymbol{g}_m\| \le \bar{d}, \quad 0 \le t \le T \\
& \|\dot{\boldsymbol{u}}(t)\| \le V_{\max}, \quad 0 \le t \le T.
\end{aligned}}$$

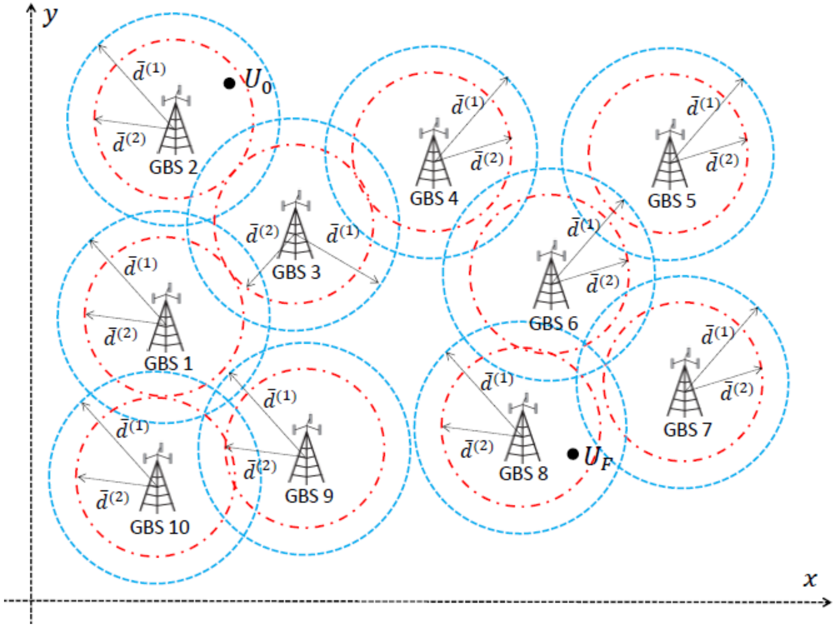
- Proposition: (P1) is feasible if and only if there exists a *GBS-UAV association sequence* $\boldsymbol{I} = [I_1, \ldots, I_N]^T$, that satisfies the following conditions:

$$\|\boldsymbol{u}_0 - \boldsymbol{g}_{I_1}\| \le \bar{d}$$

$$\|\boldsymbol{u}_F - \boldsymbol{g}_{I_N}\| \le \bar{d}$$

$$\|\boldsymbol{g}_{I_{i+1}} - \boldsymbol{g}_{I_i}\| \le 2\bar{d}, \quad i = 1, \ldots, N-1$$

$$I_i \in \mathcal{M}, \quad i = 1, \ldots, N.$$



Feasibility Check of (P1): A Graph Connectivity Based Approach

- ❑ Graph construction: undirected weighted graph $G = (V, E)$
- ❑ Vertex set: $V = \{U_0, G_1, ..., G_M, U_F\}$
- ❑ Edge set:

$$\begin{aligned} E = & \{(U_0, G_m) : \|\boldsymbol{u}_0 - \boldsymbol{g}_m\| \leq \bar{d},\ m \in \mathcal{M}\} \\ & \cup \{(G_m, G_n) : \|\boldsymbol{g}_m - \boldsymbol{g}_n\| \leq 2\bar{d},\ m, n \in \mathcal{M}, m \neq n\} \\ & \cup \{(U_F, G_m) : \|\boldsymbol{u}_F - \boldsymbol{g}_m\| \leq \bar{d},\ m \in \mathcal{M}\}. \end{aligned}$$

> ➢ An edge (U_0, G_m) or (G_m, U_F) exists if and only if U_0 or U_F is covered by GBS m
> ➢ An edge (G_m, G_n) exists if and only if the coverage areas of GBSs m and n overlap

- ❑ Weight of each edge:

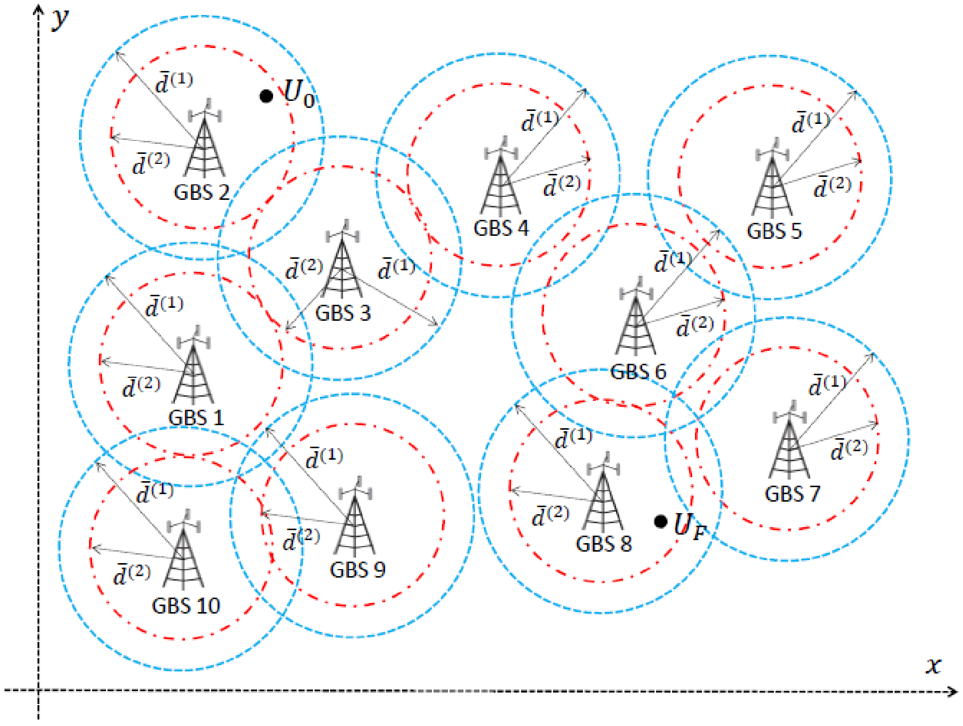
$$W(U_0, G_m) = \|\boldsymbol{u}_0 - \boldsymbol{g}_m\|,$$

$$W(U_F, G_m) = \|\boldsymbol{u}_F - \boldsymbol{g}_m\|,$$

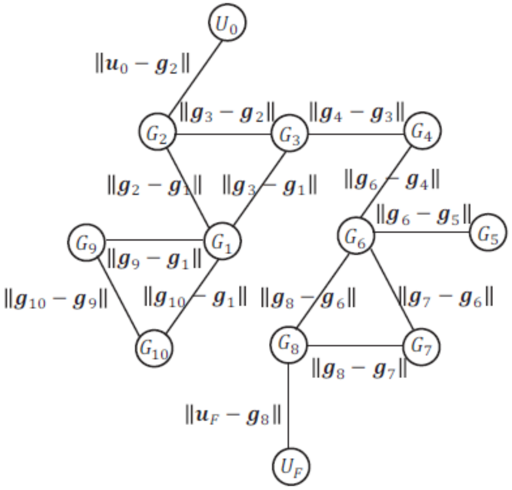
$$W(G_m, G_n) = \|\boldsymbol{g}_m - \boldsymbol{g}_n\|, \quad m, n \in \mathcal{M}, m \neq n$$

Feasibility of (P1): An Example

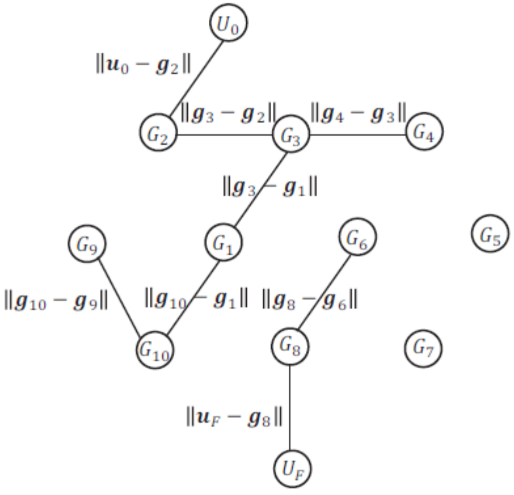
- (P1) is feasible if and only if U_0 and U_F are connected in the constructed graph G.
- Feasibility (graph connectivity) check: existing graph theory based algorithms (e.g., breadth-first search).
- Overall complexity: $\mathcal{O}(M^2)$.



(a) Horizontal locations of U_0, U_F and $M = 10$ GBSs



(b) Graph G with $\bar{d} = \bar{d}^{(1)}$: Feasible case



(c) Graph G with $\bar{d} = \bar{d}^{(2)}$: Infeasible case

Proposed Solution - Reformulation

- ❑ GBS-UAV association sequence $\boldsymbol{I} = [I_1, \ldots, I_N]^T$: UAV first associated with GBS I_1 for time T_1, then GBS I_2 for time T_2, etc., and finally GBS I_N for time T_N.
- ❑ Handover location: horizontal location of UAV where it is handed over from GBS I_i to GBS I_{i+1}

$$\boldsymbol{u}^i \triangleq \boldsymbol{u}\left(\sum_{j=1}^{i} T_j\right), \quad i = 1, \ldots, N-1 \qquad \boldsymbol{u}^0 \triangleq \boldsymbol{u}(0) = \boldsymbol{u}_0 \qquad \boldsymbol{u}^N \triangleq \boldsymbol{u}(T) = \boldsymbol{u}_F$$

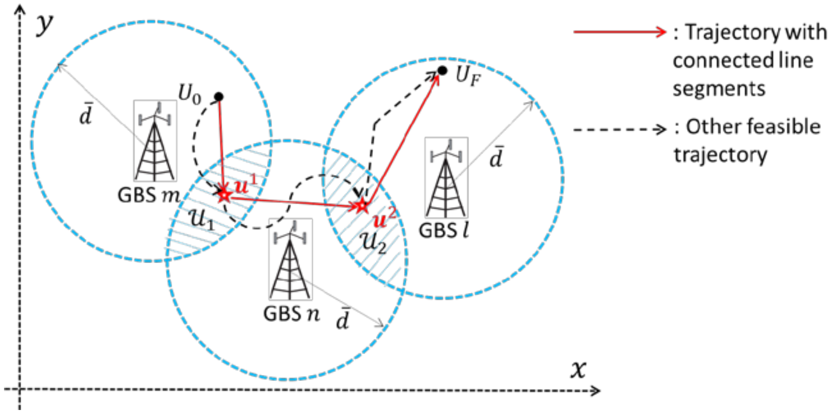
- ❑ Proposition: The optimal solution to (P1) satisfies the following conditions

$$\boldsymbol{u}(t) = \boldsymbol{u}^{i-1} + \left(t - \sum_{j=1}^{i-1} T_j\right) V_{\max} \frac{\boldsymbol{u}^i - \boldsymbol{u}^{i-1}}{\|\boldsymbol{u}^i - \boldsymbol{u}^{i-1}\|}, \quad t \in \left[\sum_{j=1}^{i-1} T_j, \sum_{j=1}^{i} T_j\right], \ i = 1, \ldots, N$$

$$T = \sum_{i=1}^{N} \frac{\|\boldsymbol{u}^i - \boldsymbol{u}^{i-1}\|}{V_{\max}}.$$

$$T_i = \frac{\|\boldsymbol{u}^i - \boldsymbol{u}^{i-1}\|}{V_{\max}}, \quad i = 1, \ldots, N$$

- ❑ With the optimal UAV trajectory, the UAV should fly from U_0 to U_F by following a path consisting of only connected line segments with maximum speed.



Proposed Solution - Reformulation

- Equivalent reformulation: Joint GBS-UAV association sequence and handover location optimization to minimize total flying distance.

$$
\begin{aligned}
\text{(P3)} \quad \min_{\boldsymbol{I}, \{\boldsymbol{u}^i\}_{i=0}^{N}} \quad & \sum_{i=1}^{N} \|\boldsymbol{u}^i - \boldsymbol{u}^{i-1}\| \\
\text{s.t.} \quad & \boldsymbol{u}^0 = \boldsymbol{u}_0 \\
& \boldsymbol{u}^N = \boldsymbol{u}_F \\
& \|\boldsymbol{u}^i - \boldsymbol{g}_{I_i}\| \le \bar{d}, \quad i = 1, \ldots, N \\
& \|\boldsymbol{u}^{i-1} - \boldsymbol{g}_{I_i}\| \le \bar{d}, \quad i = 1, \ldots, N \\
& \|\boldsymbol{u}_0 - \boldsymbol{g}_{I_1}\| \le \bar{d} \\
& \|\boldsymbol{u}_F - \boldsymbol{g}_{I_N}\| \le \bar{d} \\
& \|\boldsymbol{g}_{I_{i+1}} - \boldsymbol{g}_{I_i}\| \le 2\bar{d}, \quad i = 1, \ldots, N-1 \\
& I_i \in \mathcal{M}, \quad i = 1, \ldots, N.
\end{aligned}
$$

Each ith handover location should lie in the coverage areas of GBSs I_i and I_{i+1}

Feasibility constraints on GBS-UAV association sequence

Proposed Solution

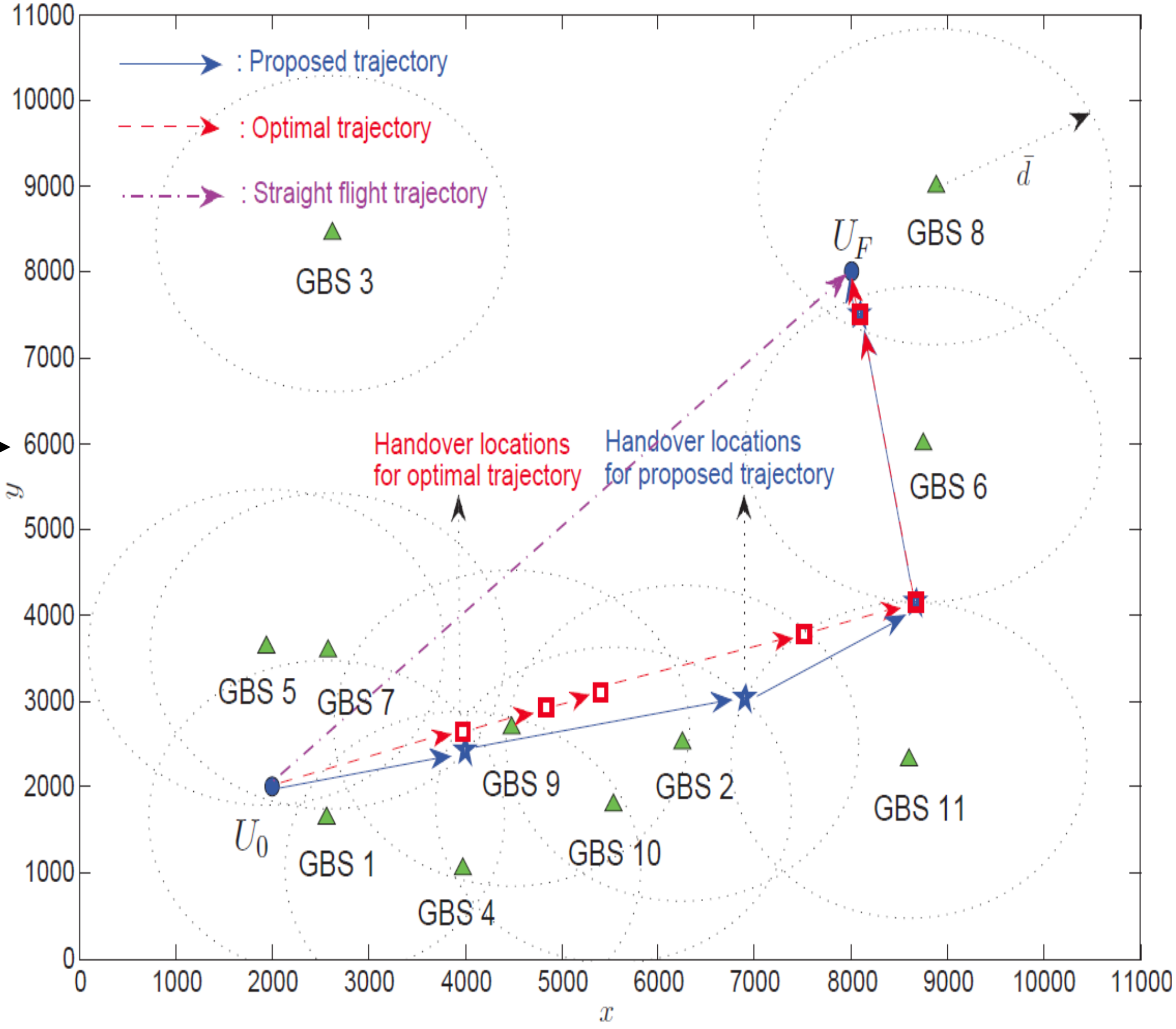
- ☐ **Step 1**: Assume UAV sequentially flies above its associated GBSs $I_1, \ldots, I_N$. Find the GBS-UAV association sequence that minimizes the flying distance under this strategy.
  - ➢ Equivalent to finding the shortest path from U_0 to U_F in graph G constructed previously, can be solved via Dijkstra algorithm with complexity $\mathcal{O}(M^2)$.
- ☐ **Step 2**: Handover location optimization with obtained GBS-UAV association sequence is a convex optimization problem, can be solved efficiently via CVX.
- ☐ **Overall complexity**: Polynomial over M (# of GBSs)
- ☐ Can be modified to find the optimal solution by exhaustively searching for the optimal GBS-UAV association sequence.

Simulation Setup

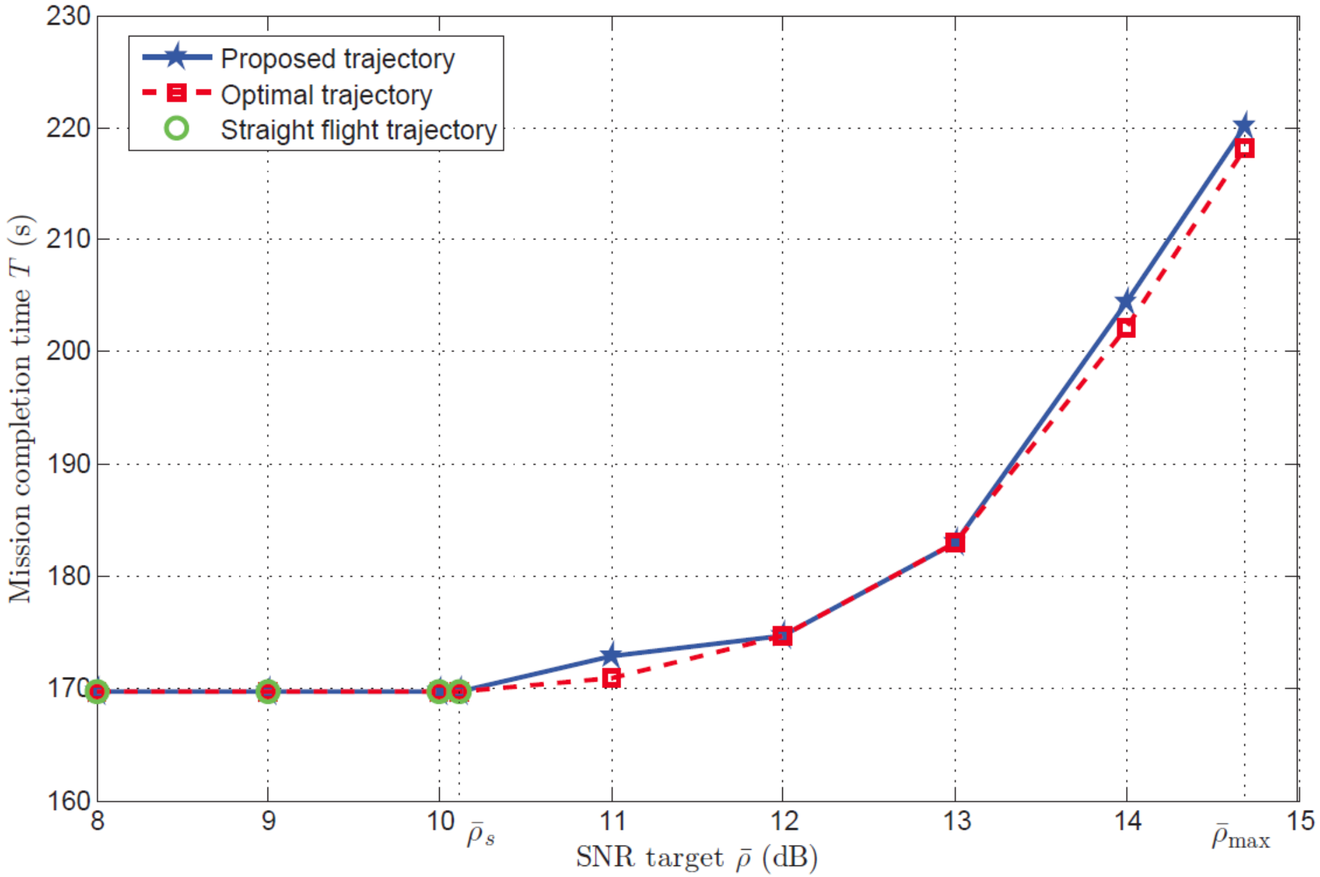
- ☐ $M = 11$ GBSs uniformly randomly distributed in a 10 km x 10 km square region
- ☐ UAV altitude: $H = 90$ m; GBS height: $H_G = 12.5$ m
- ☐ Maximum speed of UAV: $V_{\max} = 50$ m/s
- ☐ Reference SNR at distance $d_0 = 1$ m: $\gamma_0 = \frac{P\beta_0}{\sigma^2} = 80$ dB
- ☐ Benchmark trajectories:
  - ➢ Straight flight trajectory: UAV flies from U_0 to U_F in a straight line with maximum speed $V_{\max}$
  - ➢ Optimal trajectory: Optimal solution to (P1), by solving (P3) via exhaustive search over all feasible GBS-UAV associations

Illustration of Trajectory Designs with $\bar{\rho} = \bar{\rho}_{\max}$

- ❑ **Maximum achievable SNR target $\bar{\rho}_{\max}$ for proposed trajectory and optimal trajectory**: increase $\bar{\rho}$ and check feasibility of (P1) until it becomes infeasible.
  - ➢ $\bar{\rho}_{\max} = 14.69$ dB ⟶
- ❑ Proposed trajectory similar to optimal trajectory.
- ❑ Straight flight trajectory cannot satisfy the given SNR target.



Mission Completion Time versus SNR Target



- ☐ Proposed trajectory design achieves near-optimal performance.
- ☐ Maximum SNR target for straight flight trajectory is 4.57 dB lower than the proposed and optimal trajectory designs (10.12 dB versus 14.69 dB).

Conclusions

- ❑ Integrating UAVs into 5G and beyond: a new and promising paradigm to embrace the forthcoming IoD (internet-of-drones) era

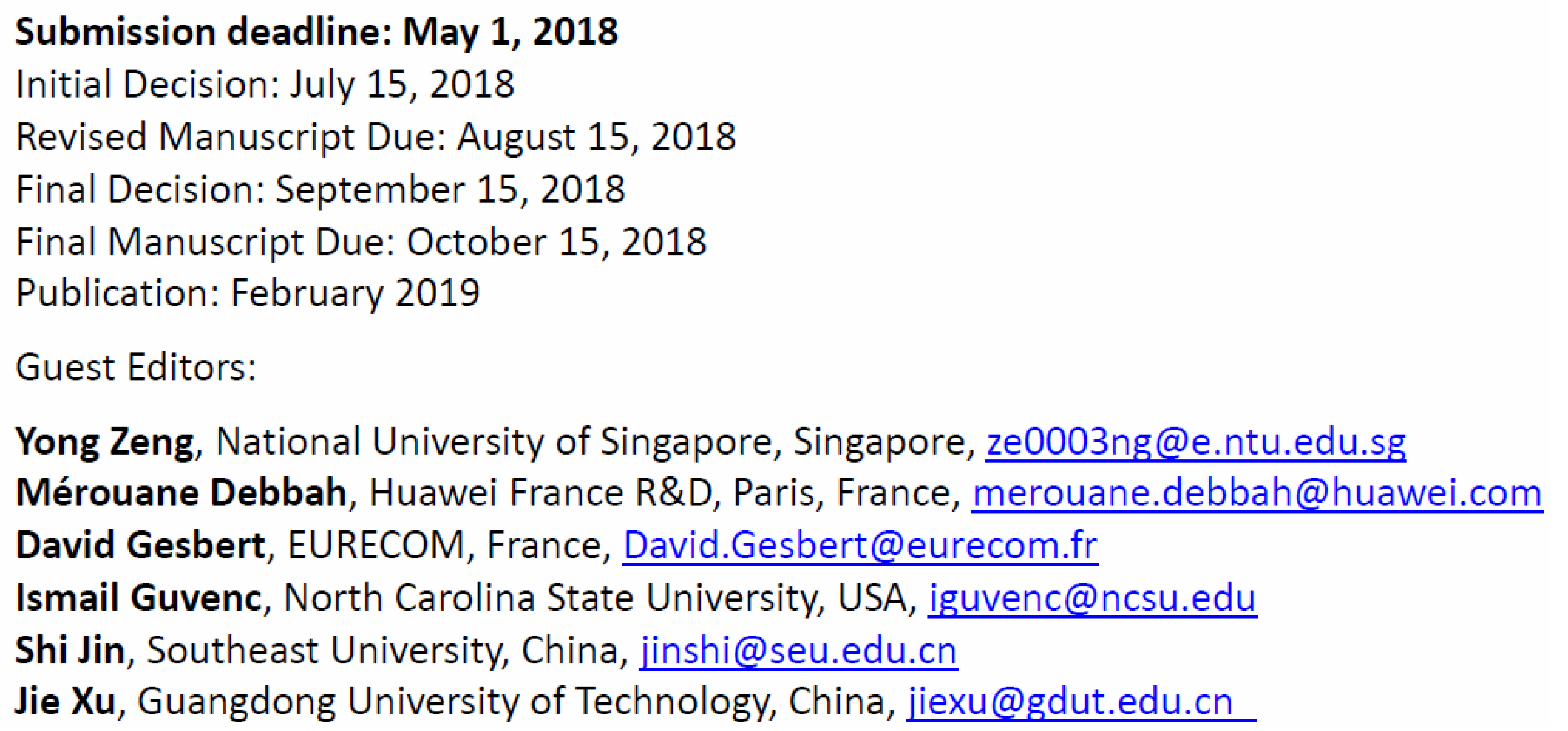
- ❑ Cellular-Connected UAVs: UAV as aerial user
  - ➢ 3D aerial coverage
  - ➢ Aerial-terrestrial interference management
  - ➢ Communication-aware trajectory design

- ❑ UAV-Assisted Terrestrial Communications: UAV as BS/relay
  - ➢ 3D BS/relay placement, movement control
  - ➢ Exploit UAV controlled-mobility for enhanced communication
  - ➢ New throughput-delay, rate-energy trade-offs

- ❑ Much more to be done…

IEEE Wireless Communications Magazine “Integrating UAVs into 5G and Beyond”

CFP: IEEE Wireless Communications Special Issue on Integrating UAVs into 5G and Beyond



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Thank You

Q & A ?