Joint Trajectory and Communication Design for UAV/Drone-enabled Wireless Networks

Qingqing Wu and Rui Zhang

APCC, 2017
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Outline

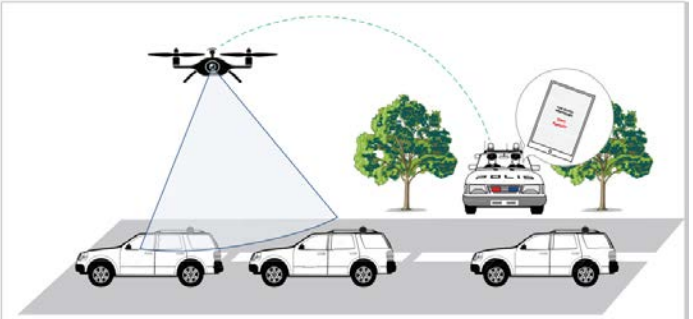
- Introduction
  - UAV applications and future trend
  - UAV-enabled/assisted terrestrial communication
- Cyclical Multiple Access and Throughput-Delay Trade-off
- Joint Trajectory and Communication Design with/without Delay Consideration
- Conclusions

UAV: Whose Time is Coming

- To create more than **100,000 new jobs** in US alone over the next 10 years (Source: SDI analysis)
- **Numerous applications**: military, traffic control, cargo delivery, precise agriculture, video streaming, aerial inspection, rescue and search,…





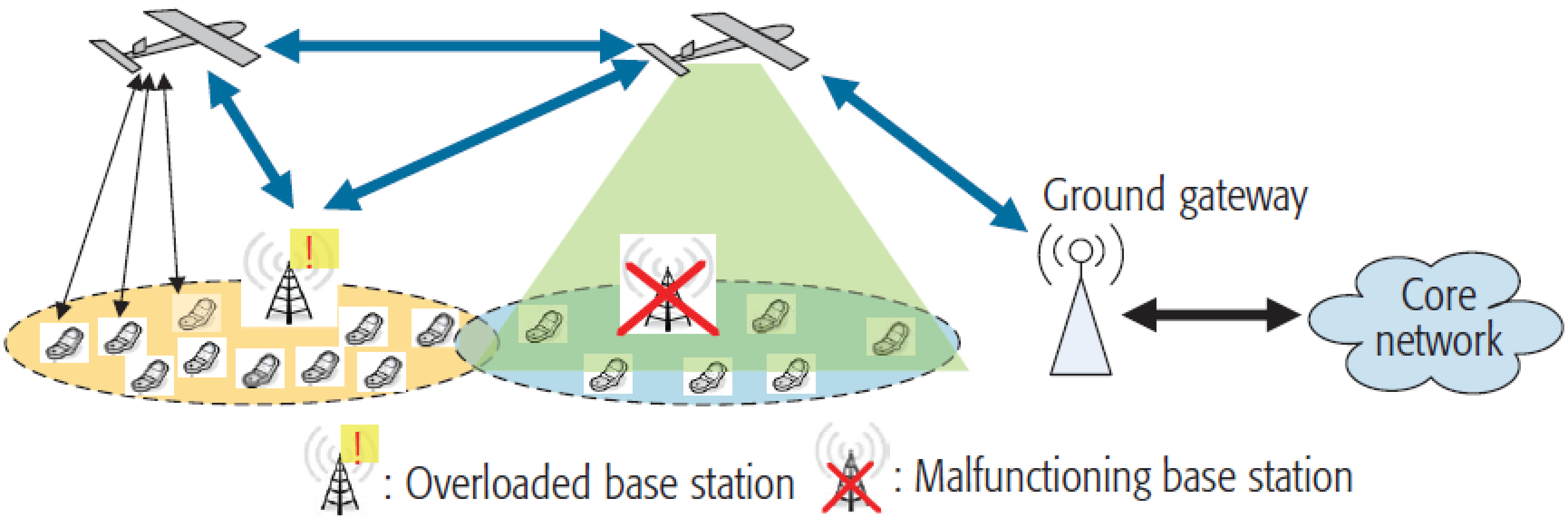


Wireless Connection from the Sky: Candidate Solutions

- Satellite: very high altitude
- High-altitude platform (HAP) ~20km
  - Google loon project
- Low-altitude platform (LAP): below a few km
  - Helikite (EU ABSOLUTE project)
  - UAV/drone
- Advantages of UAV-enabled/assisted terrestrial 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

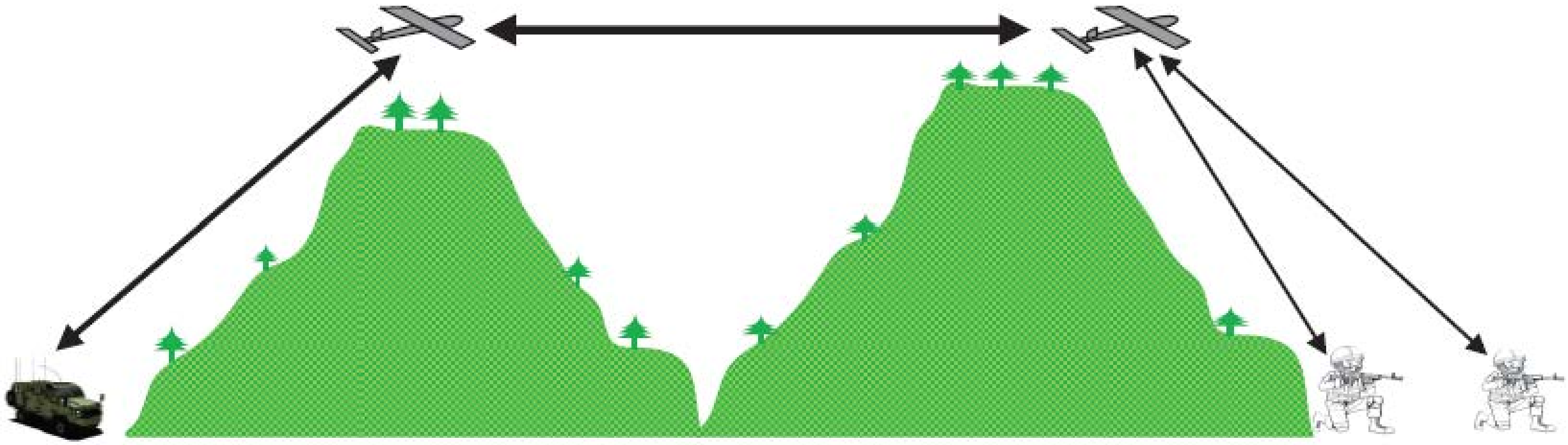
- Provide seamless coverage within the serving area
- Application scenarios:
  - fast service recovery after natural disaster
  - BS offloading at hotspot



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

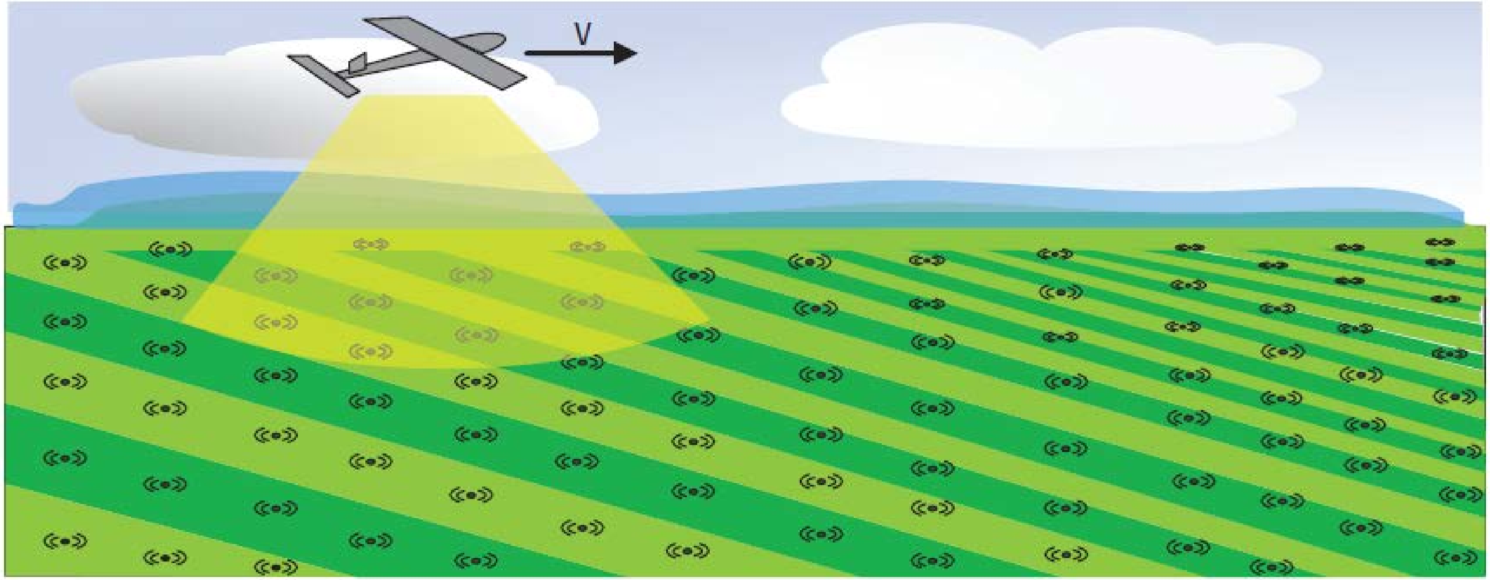
- ❑ Connecting two or more distant users or user groups
- ❑ Application scenarios:
  - ➢ Military network, e.g., between frontline and headquarter
  - ➢ Big data transfer between distant data centers



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
  - Video multicasting/broadcasting



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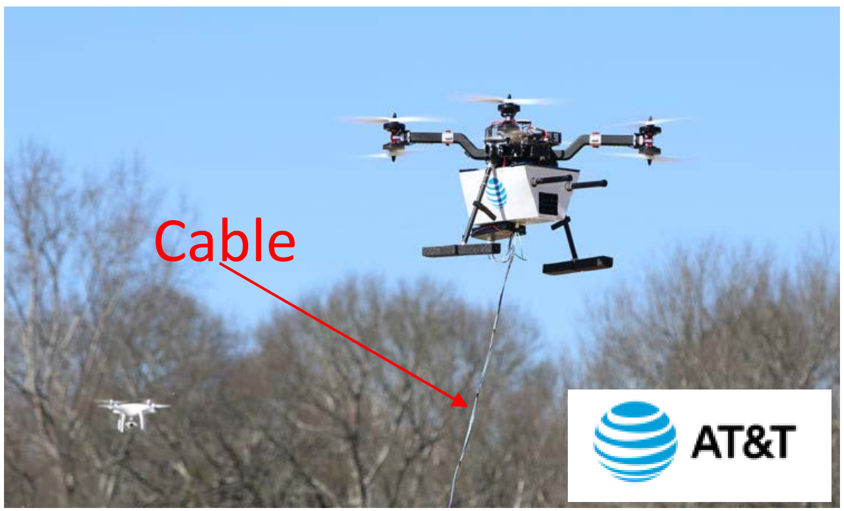
UAV-mounted Aerial BSs: Two Practical Realizations

- Tethered UAVs: UAVs connected with ground platform by cables (for power and/or data backhaul)
  - Examples: AT&T's "flying cell-on-wings (COWs)", Facebook's "Tether-Tenna", EE's "Air Masts"
- Untethered UAVs: Wireless, free-fly drones
  - Examples: Nokia's flying-cell (F-Cell) and Facebook's Aquila



AT&T's flying COW

Nokia's F-Cell

Source: http://www.zdnet.com/article/at-t-completes-its-first-flying-cow-test-flight/
https://www.fiercewireless.com/tech/nokia-bell-labs-uses-drone-to-deliver-breakthrough-f-cell-to-office-rooftop

UAV-Enabled/Assisted Terrestrial Communications: New Design Considerations

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

UAV-Enabled/Assisted Communications: Recent Results

- Overview [ZengZhangLimComM16], [YalinizComMag16]
- UAV as quasi-stationary BS/relay
  - 2D/3D BS placement [YalinizICC16], [MozaffariCL16], [KalantariVTC16], [LyuZengZhangLimCL17]
  - Optimal altitude with adjustable beamwidth [HeZhangZengZhangCL17]
  - Performance analysis [MozaffariTWC16], [ZhangZhangJSAC16]
  - Radio map reconstruction [ChenGesbertICC17], [ChenYatnalliGesbertICC17]
- UAV as mobile BS/relay
  - Trajectory optimization [HanTVT09], [JiangJSAC12], [ZengZhangLimTcom16], [ZengXuZhangTWC17]
  - Joint resource allocation and trajectory optimization [ZengZhangLimTcom16], [WuZengZhangTWC17] With delay consideration [WuZhangTCOM17]
  - Throughput-delay trade-off [LyuZengZhangWCL16]
  - Hybrid UAV and ground BSs [LyuZengZhangTWC17]
- Energy-efficient UAV communications
  - UAV propulsion energy [ZengZhangTWC17]
  - UAV transmission energy [MozaffariICC16]
  - Energy of ground nodes [MozaffariGlobecom16], [ZhanZengZhangWCL17]
  - Energy trade-off between UAV and ground nodes [YangWuZengZhangTVT17]

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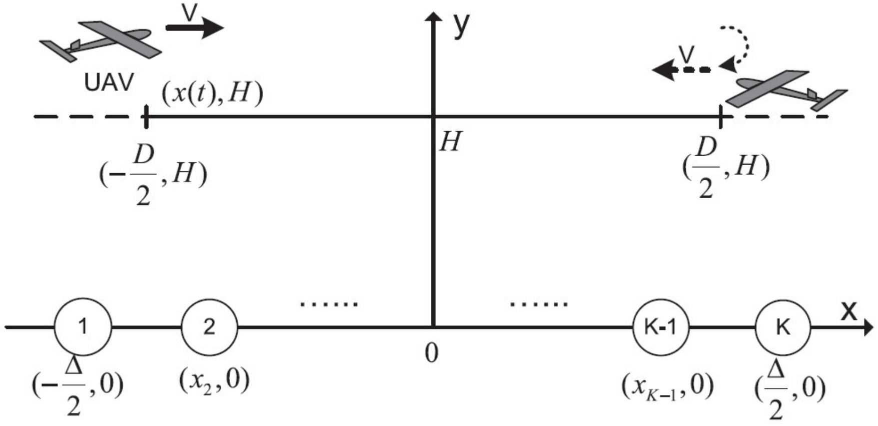
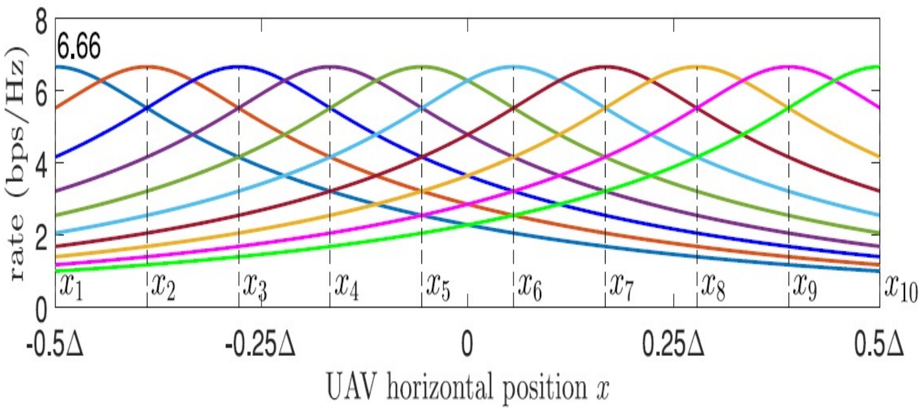
UAV-enabled Multiuser Network: Cyclical Multiple Access

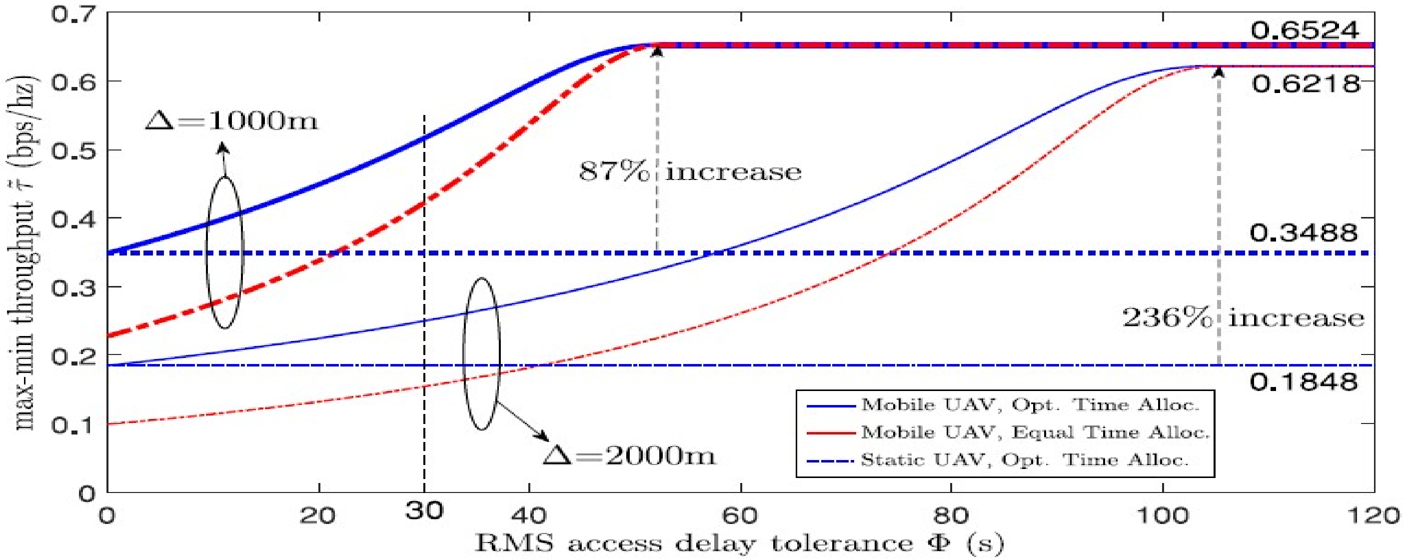




❑ Cyclical Multiple Access (CMA)

- UAV flies following a certain trajectory to serve ground mobile terminals (MTs) in a periodic manner
- Cyclically varying pattern of each UAV-MT channel: better communication link when the UAV flies close to an MT
- Time-division based cyclical multiple access: schedule the nearby MTs from the current UAV position to communicate with the UAV
- Optimize time allocation to maximize the minimum throughput of all MTs

A New Fundamental Throughput-Delay Trade-off



❑ Throughput-Delay Trade-off

- Access delay: each MT needs to wait for the UAV to fly nearby to be served again
- More delay tolerance leads to larger throughput gain, since the UAV can traverse a longer distance to visit more (distant) MTs
- Suitable for delay-tolerant applications with high throughput demand

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

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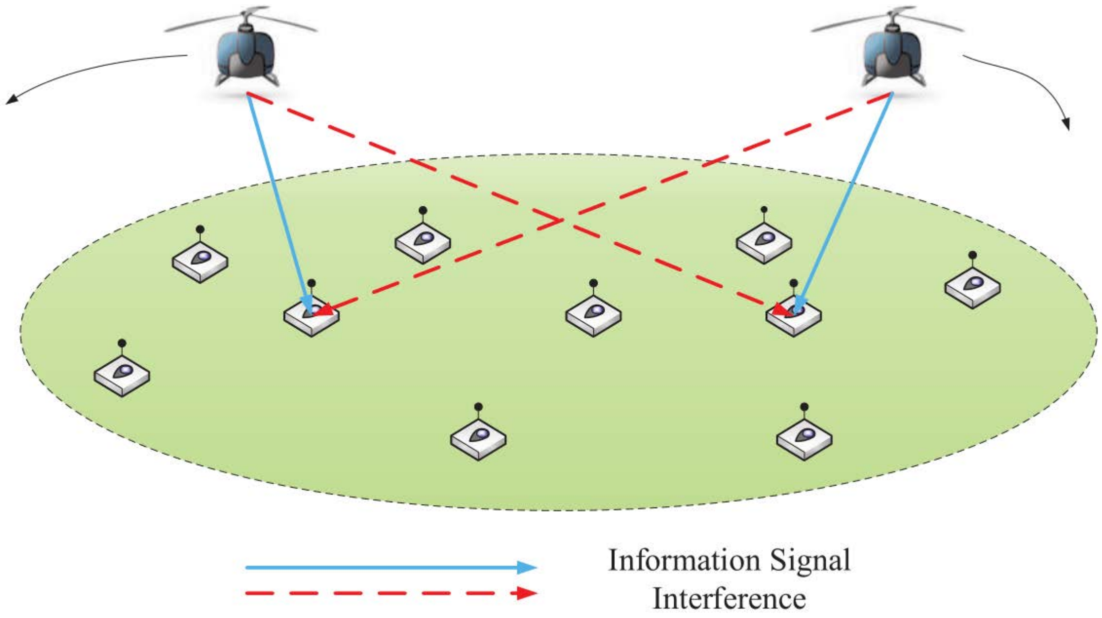
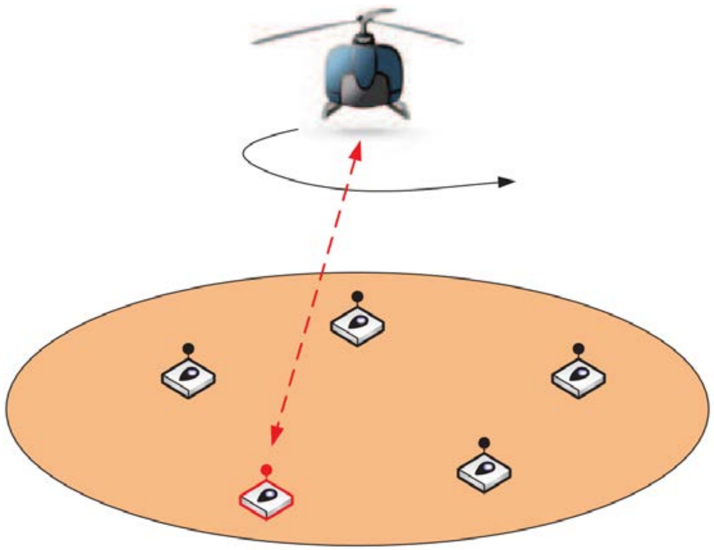
Multi-UAV Enabled Networks with Cooperative Design

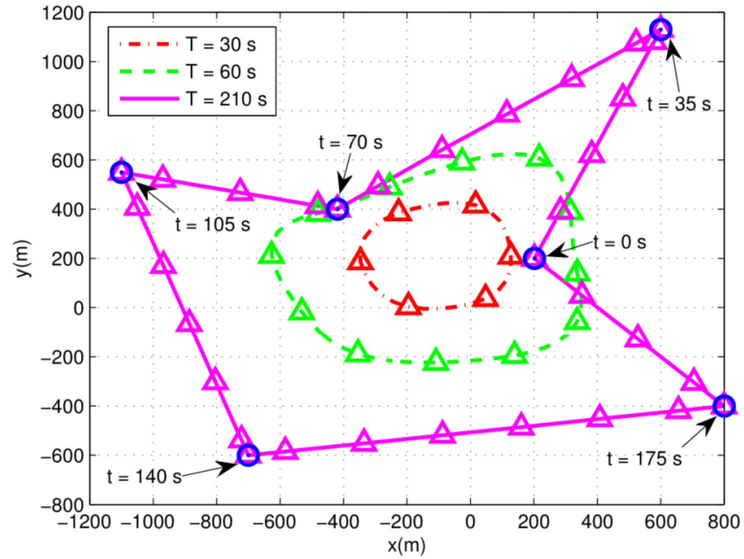


- Multi-UAV spectrum sharing, broadcast channel (BC) + interference channel (IFC)
- Cyclical TDMA for user scheduling
- Objective: maximize the minimum average rate of all ground users via joint user scheduling, power control, and UAV trajectory design

Q. Wu, Y. Zeng, and R. Zhang, “Joint Trajectory and Communication Design for Multi-UAV Enabled Wireless Networks,” submitted to *IEEE Trans. Wireless Commun.*, 2017

Special Case: A Single UAV



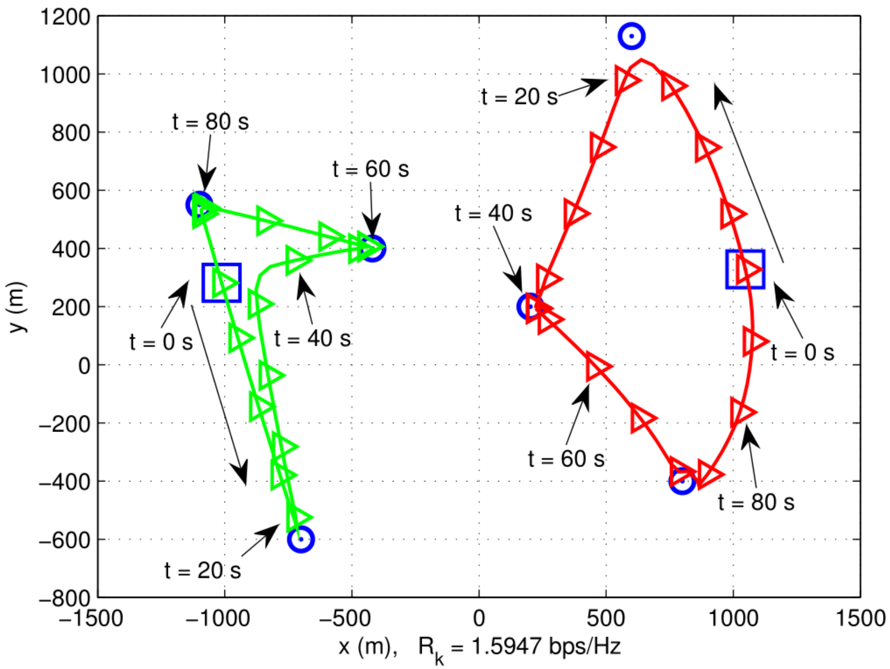


- Singe UAV, multiple-access channel (MAC), fixed transmit power
- Objective: maximize the minimum average rate of all users via joint user scheduling and trajectory design
- With period *T* (access delay) increases, UAV converges to hover-fly-hover trajectory

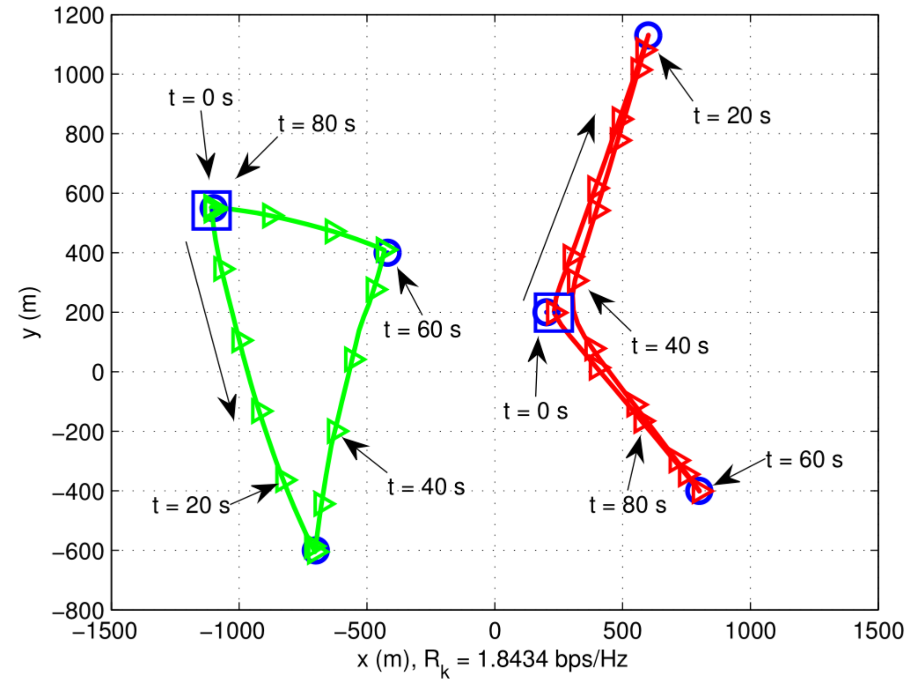
Q. Wu, Y. Zeng, and R. Zhang, “Joint trajectory and communication design for UAV-enabled multiple access,” in *Proc. IEEE Globecom*, 2017, [Online] https://arxiv.org/abs/1704.01765.

Multi-UAV Trajectories Without versus With Power Control

New Interference-mitigation approach: cooperative trajectory design



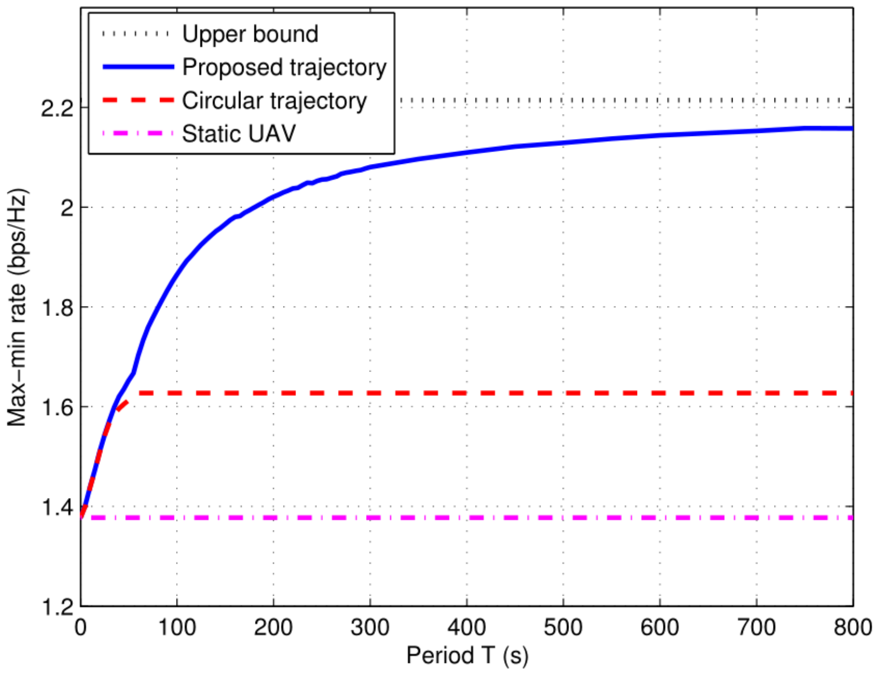
(a) Optimized UAV trajectories without power control.



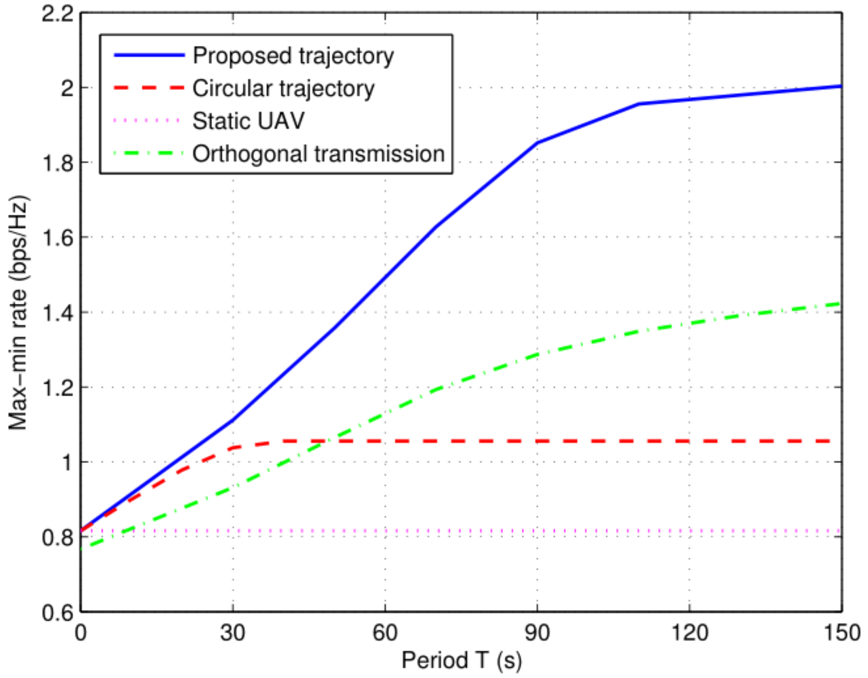
(b) Optimized UAV trajectories with power control.

Throughput-Delay Trade-off

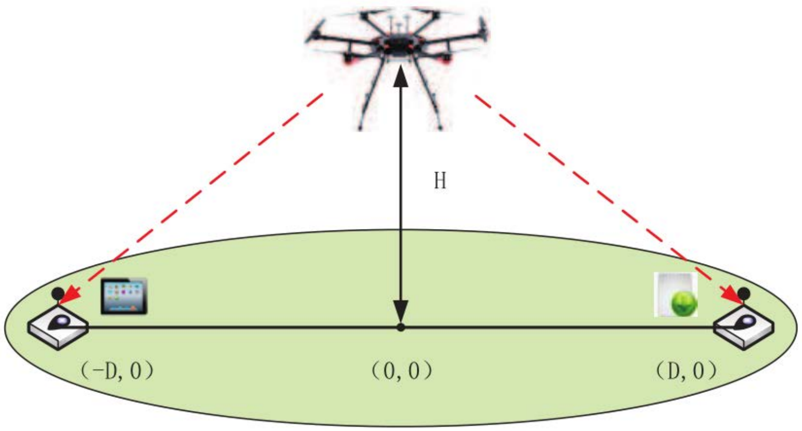
a single UAV

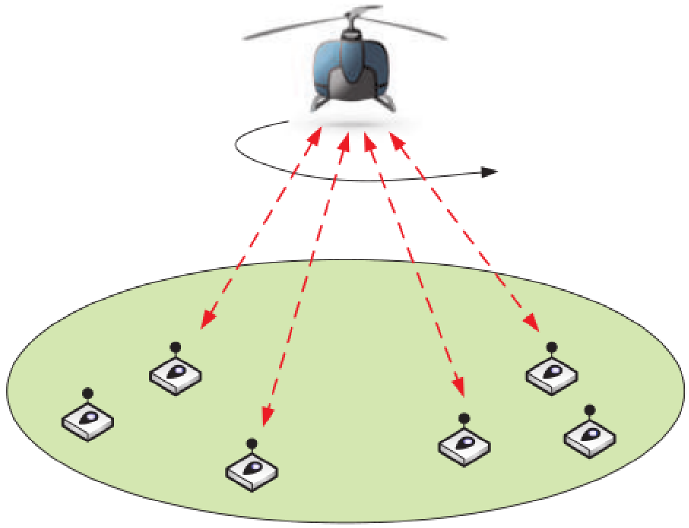


two UAVs



Delay-Constrained Throughput Maximization in UAV-Enabled OFDMA Systems





- Downlink BC, OFDMA
- Objective: maximize the minimum average rate of all users via joint bandwidth and transmit power allocation, and UAV trajectory optimization
- Delay-tolerant traffic vs. delay-constrained traffic: minimum-rate ratio (MRR) constraint per user

Q. Wu and R. Zhang, "Throughput Maximization in UAV-Enabled Multiuser OFDM Systems with Delay Consideration," submitted to *IEEE Trans. Commun.*, 2017 (Conference version: invited paper, APCC, 2017)

Delay-Constrained Throughput Maximization

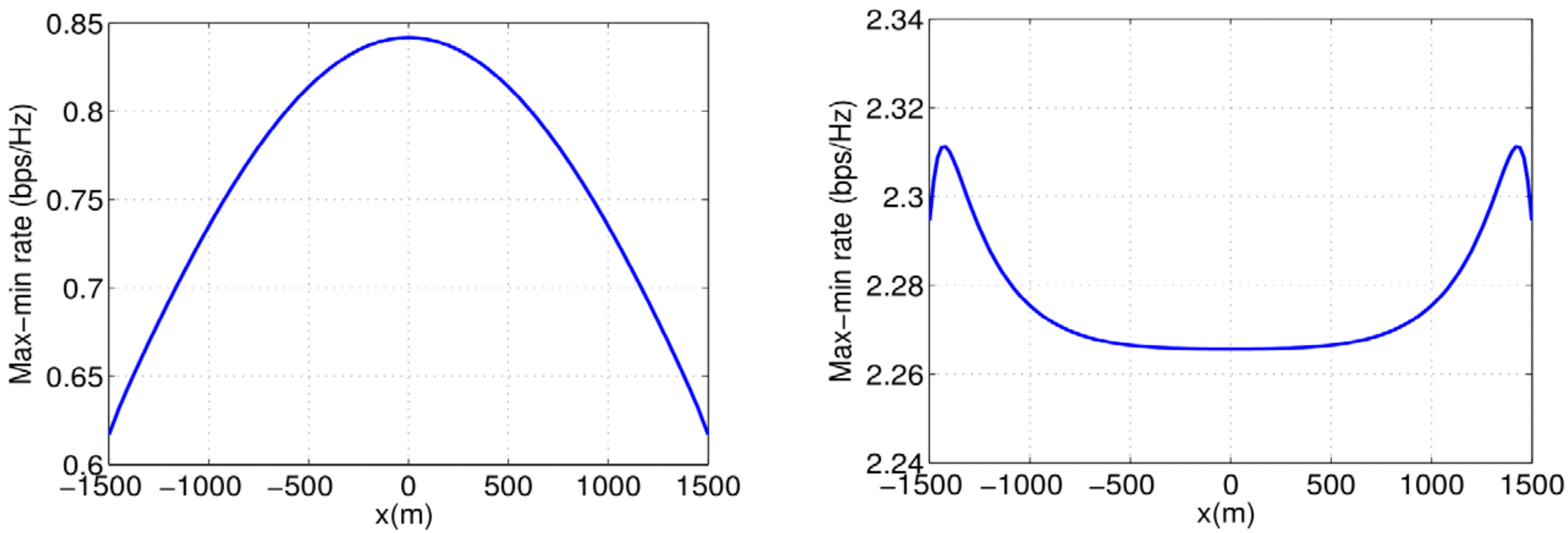
$$
\begin{aligned}
\max_{\eta,\mathbf{A},\mathbf{P},\mathbf{Q}} \quad & \eta \\
\text{s.t.} \quad & R_k \geq \eta, \forall k, \\
& r_k[n] \geq \theta_k R_k, \forall k, n, \\
& \sum_{k=1}^{2} p_k[n] \leq P_{\max}, \forall n, \\
& p_k[n] \geq 0, \forall k, n, \\
& \sum_{k=1}^{2} \alpha_k[n] \leq 1, \forall n, \\
& 0 \leq \alpha_k[n] \leq 1, \forall k, n, \\
& ||\mathbf{q}[n+1] - \mathbf{q}[n]||^2 \leq S_{\max}^2, \\
& \qquad n = 1, ..., N-1, \\
& \mathbf{q}[1] = \mathbf{q}[N].
\end{aligned}
$$

Proposed solution: *Parameter-assisted* block coordinate descent algorithm

- minimum-rate ratio (MRR) constraint per user ($r_k[n] \geq \theta_k R_k$)
- power constraint ($\sum_{k=1}^{2} p_k[n] \leq P_{\max}$)
- bandwidth constraint ($\sum_{k=1}^{2} \alpha_k[n] \leq 1$)
- speed constraint ($||\mathbf{q}[n+1] - \mathbf{q}[n]||^2 \leq S_{\max}^2$)
- Initial/final location constraint ($\mathbf{q}[1] = \mathbf{q}[N]$)

Delay-Constrained Throughput Maximization

- Θ_1=1 or Θ_2=1
  - Remaining static is the optimal UAV trajectory
  - Counterintuitive: middle location (x=0) may not achieve the maximum equal rate for high SNR



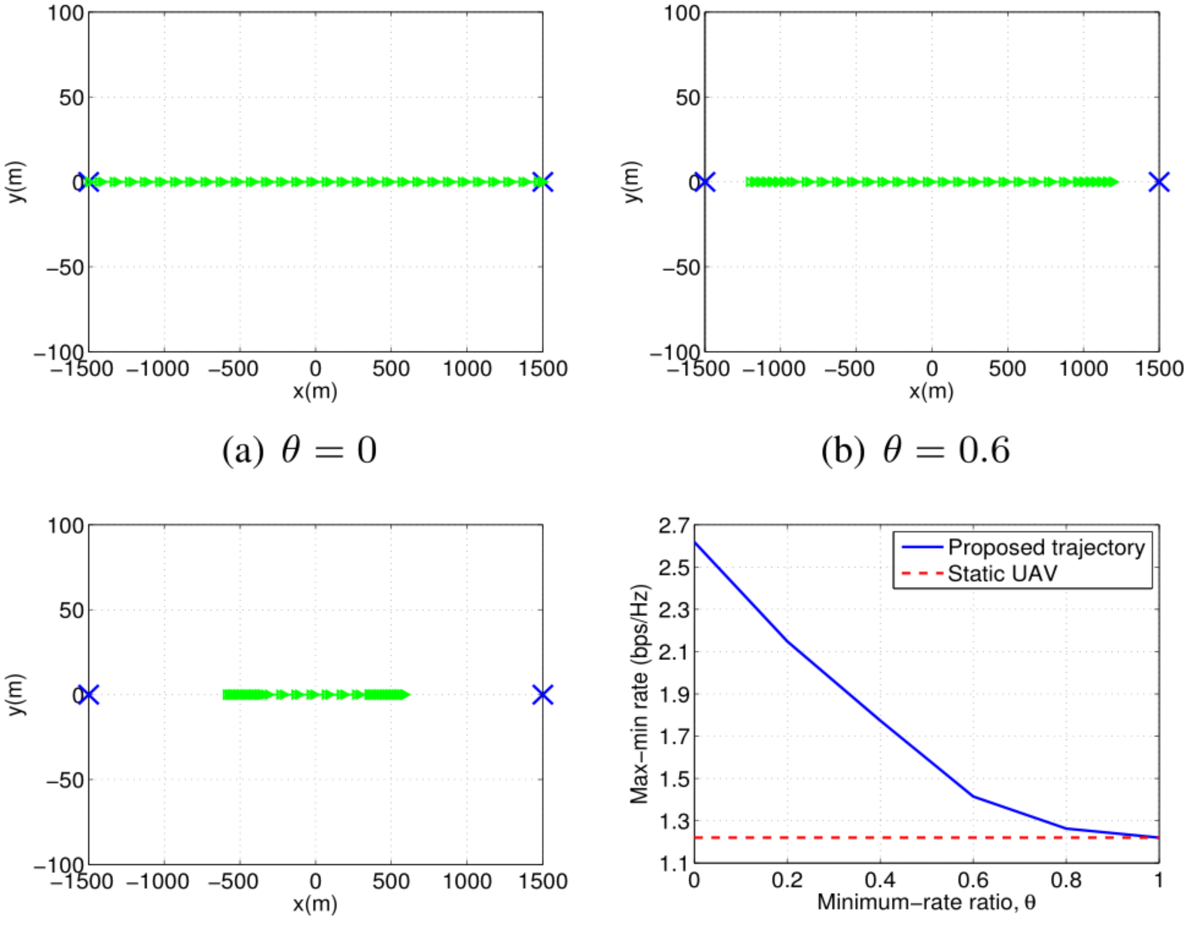
(a) $P_{\max} = 0.05W$.

(b) $P_{\max} = 0.5W$.

- Θ_1= Θ_2=0 and $T \rightarrow \infty$
  - Hover-fly-hover is the optimal UAV trajectory

Trajectory and Max-min Rate versus MRR

- Homogeneous case, $\Theta_1 = \Theta_2 = \Theta$

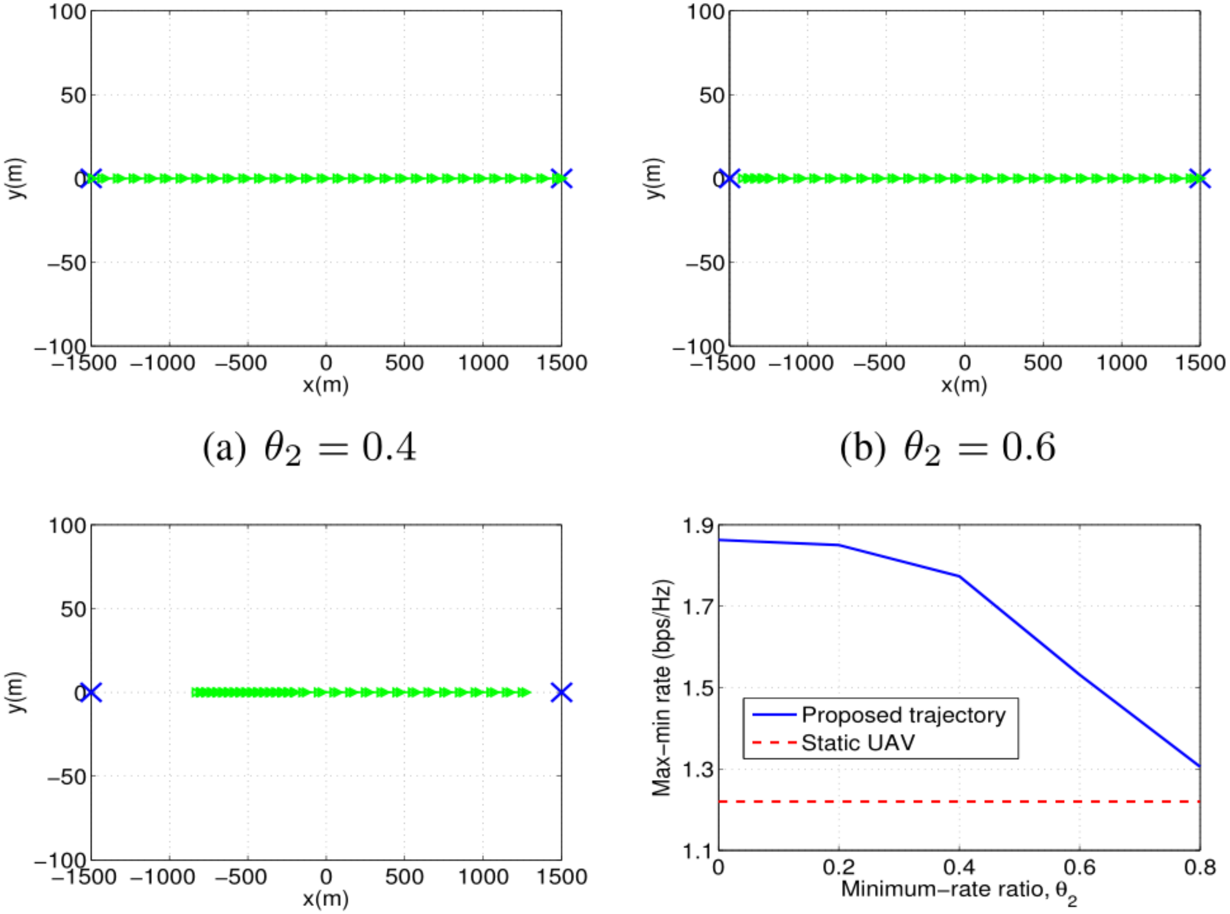


(a) $\theta = 0$ (b) $\theta = 0.6$

(c) $\theta = 0.8$ (d) Max-min rate

Trajectory and Max-min Rate versus MRR

- Heterogeneous case, $\Theta_1 = 0.4$, vary Θ_2

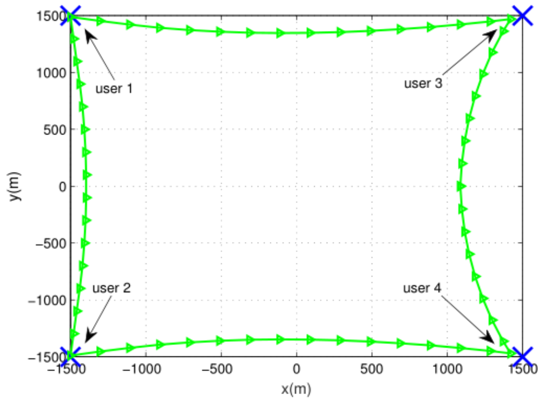


(a) $\theta_2 = 0.4$ (b) $\theta_2 = 0.6$

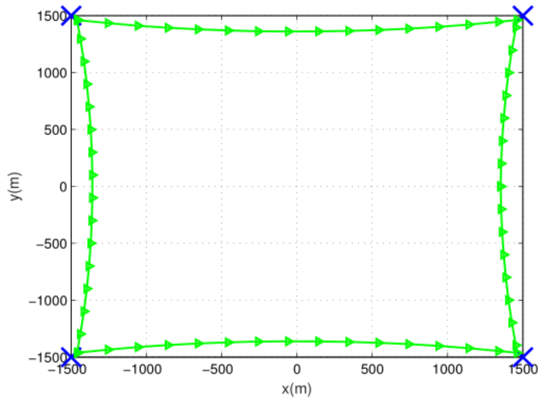
(c) $\theta_2 = 0.8$ (d) Max-min rate

Multiuser Scenario: Optimal UAV Trajectory versus MMR

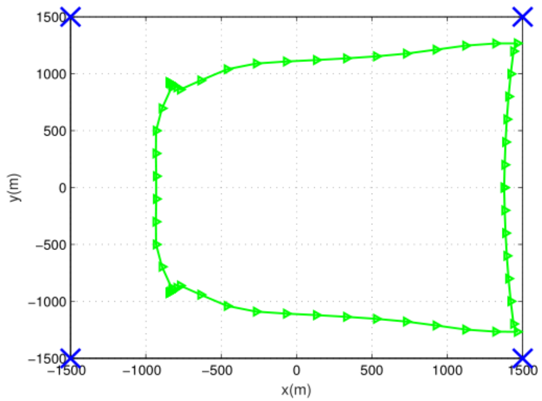
- Heterogeneous case, $\Theta_1 = \Theta_2 = 0.4$, vary $\Theta_3 = \Theta_4$



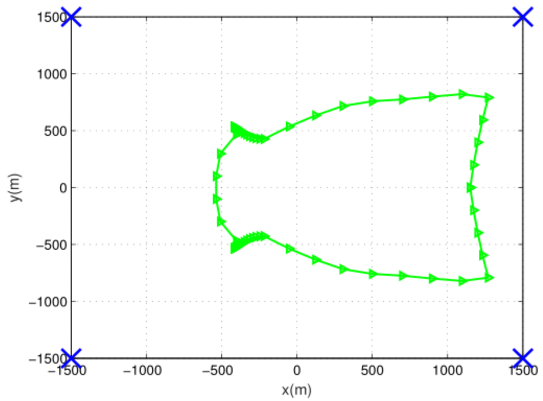
(a) $\theta_3 = \theta_4 = 0$



(b) $\theta_3 = \theta_4 = 0.4$



(c) $\theta_3 = \theta_4 = 0.6$



(d) $\theta_3 = \theta_4 = 0.8$

Conclusions

- Joint UAV trajectory and communication design: a new and promising paradigm to enhance wireless system performance

- UAV-enabled multiuser communication: Cyclical Multiple Access
  - Exploit UAV mobility to schedule nearby users to communicate
  - Opportunistic transmission enhances system throughput, but results in long access delay: a fundamental throughput-delay trade-off

- Rate maximization with minimum-rate ratio (MRR) constraint
  - Flexibly adjust delay-tolerant versus delay-constrained traffic per user
  - Throughput gain due to UAV mobility decreases as delay (MRR) constraint increases: optimal UAV trajectory finally converges to a stationary point (i.e., static UAV)

ICC2018 Workshop on "Integrating UAVs into 5G"

WELCOME TO ICC2018 WORKSHOP ON "INTEGRATING UAVS INTO 5G"

May 20, 2018, Kansas City, MO, USA

WORKSHOP CO-CHAIRS:

- **Yong Zeng**, National University of Singapore, Singapore, elezeng@nus.edu.sg
- **Jie Xu**, Guangdong University of Technology, China, jiexu@gdut.edu.cn

KEYNOTE SPEAKER:

- **Rui Zhang,** National University of Singapore, Singapore

CONFIRMED AUTHORS FOR INVITED PAPERS:

- **David Gesbert**, EURECOM, France
- **Robert W. Heath Jr.**, The University of Texas at Austin, USA
- **Halim Yanikomeroglu**, Carleton University, Canada

CALL FOR PAPERS:

http://icc2018.ieee-icc.org/workshop/integrating-uavs-5g/call-papers

DEADLINES:

- Paper Submission Deadline: **January 3, 2018**
- Acceptance Notification: February 21, 2018
- Final Paper submission: March 5, 2018

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Thank You

Q & A ?