Wireless Communications with Unmanned Aerial Vehicles: Opportunities and Challenges

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Outline

❑ Unmanned Aerial Vehicles (UAVs): Introduction

❑ Wireless Communications with UAVs: Overview

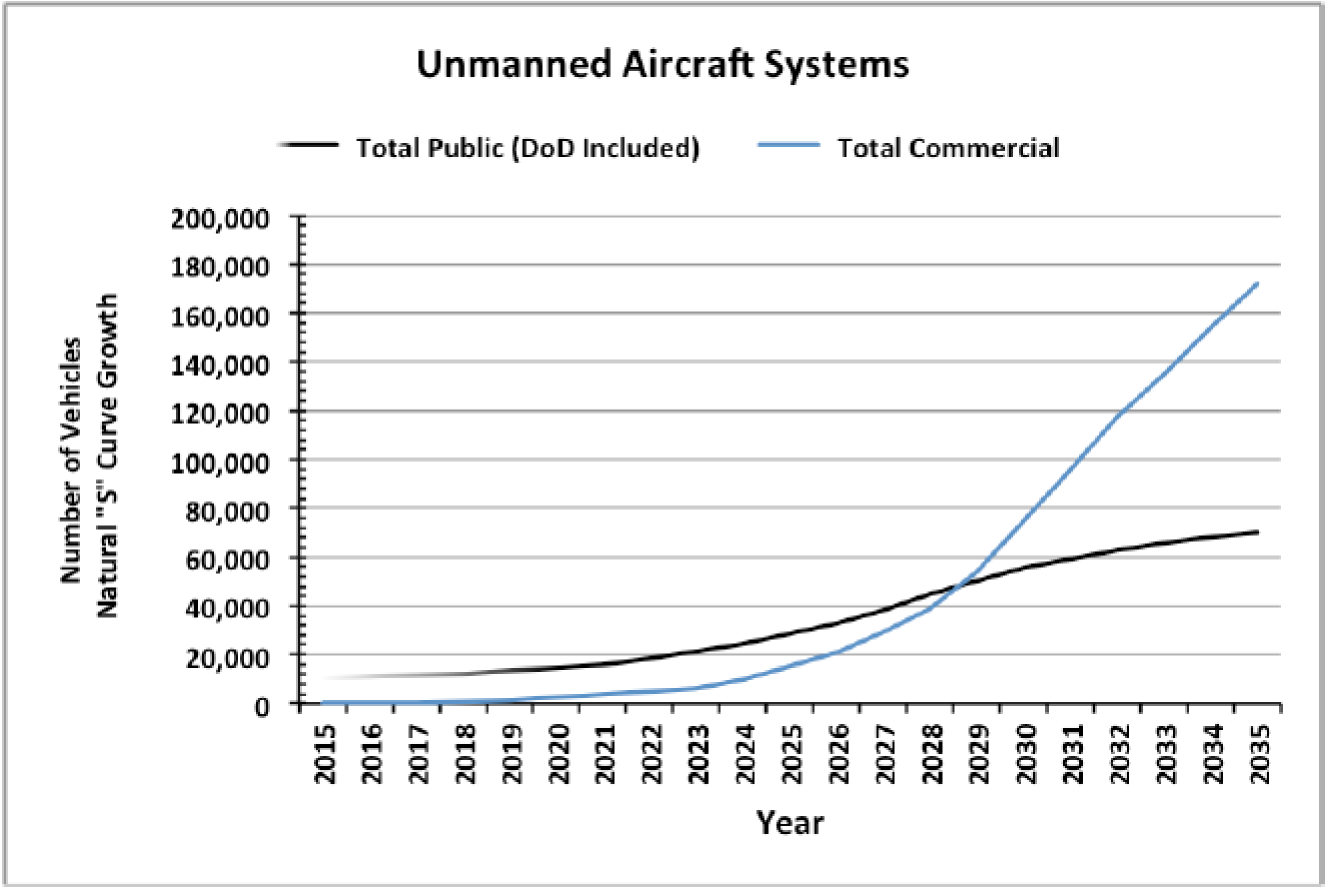
❑ UAV-Enabled Mobile Relaying

❑ Summary and Future Directions

Unmanned Aerial Vehicles

- ☐ Unmanned Aerial Vehicle (UAV): “A **powered**, aerial vehicle that does not carry a human operator,...” [Source: *TheFreeDictionary.com*]
- ☐ A brief history on UAV [Source: *Wikipedia*]
  - ➢ 1916: The earliest attempt at a UAV by A. M. Low
  - ➢ World War I: Hewitt-Sperry Automatic Airplane
  - ➢ 1935: The first scaled remote pilot vehicle was developed
  - ➢ World War II: Nazi Germany produced and used various UAVs
  - ➢ 1959: US Air Force began planning use UAV to reduce pilot loss
  - ➢ 1964: UAVs were firstly used for combat missions in Vietnam War
  - ➢ As of 2012: US army employed 7494 UAVs
- ☐ Applications
  - ➢ Military uses: reconnaissance, armed attacks, targets for military training,…
  - ➢ Civilian uses: Cargo delivery, police operation, powerline and pipeline inspection, agriculture, search and rescue, **communications**,….

Total Unmanned Aircraft Systems Forecast 2015-2035

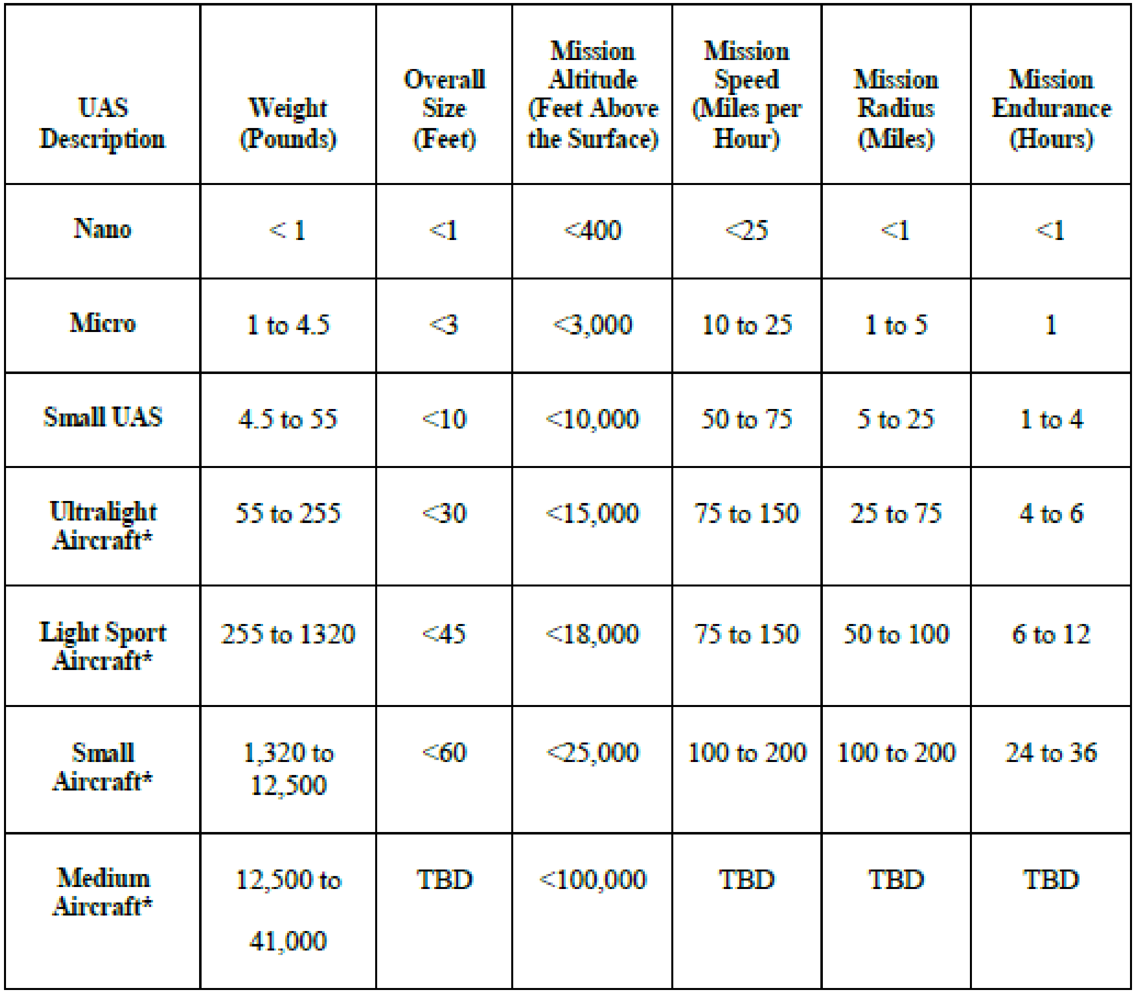


Source: US Department of Transportation, “Unmanned Aircraft System (UAS) Service Demand 2015–2035: Literature Review & Projections of Future Usage,” tech. rep., v.0.1, DOT-VNTSC-DoD-13-01, Sept. 2013.

UAV Classification: Fixed-Wing vs. Rotary-Wing

	Fixed-Wing	**Rotary-Wing**
Mechanism	Lift generated using wings with forward airspeed	Lift generated using blades revolving around a rotor shaft
Advantages	Simpler structure, usually higher payload, higher speed	Can hover, able to move in any direction, vertical takeoff and landing
Limitations	Need to maintain forward motion, need a runway for takeoff and landing	Usually lower payload, lower speed, shorter range

UAV Classification: By Weight



UAS Description	Weight (Pounds)	Overall Size (Feet)	Mission Altitude (Feet Above the Surface)	Mission Speed (Miles per Hour)	Mission Radius (Miles)	Mission Endurance (Hours)
Nano	< 1	<1	<400	<25	<1	<1
Micro	1 to 4.5	<3	<3,000	10 to 25	1 to 5	1
Small UAS	4.5 to 55	<10	<10,000	50 to 75	5 to 25	1 to 4
Ultralight Aircraft*	55 to 255	<30	<15,000	75 to 150	25 to 75	4 to 6
Light Sport Aircraft*	255 to 1320	<45	<18,000	75 to 150	50 to 100	6 to 12
Small Aircraft*	1,320 to 12,500	<60	<25,000	100 to 200	100 to 200	24 to 36
Medium Aircraft*	12,500 to 41,000	TBD	<100,000	TBD	TBD	TBD

Source: US Department of Transportation, "Unmanned Aircraft System (UAS) Service Demand 2015–2035: Literature Review & Projections of Future Usage," tech. rep., v.0.1, DOT-VNTSC-DoD-13-01, Sept. 2013.

UAV Classification: By Control Method

Remote human pilot	Real-time control by remote pilot
Remote human operator	Human provides the flight parameters to invoke the built-in functions for vehicle control
Semi-autonomous	Human controlled initiation and termination, autonomous mission execution
Autonomous	Automated operation after human initiation
Swarm control	Cooperative mission accomplishment via control among the vehicles

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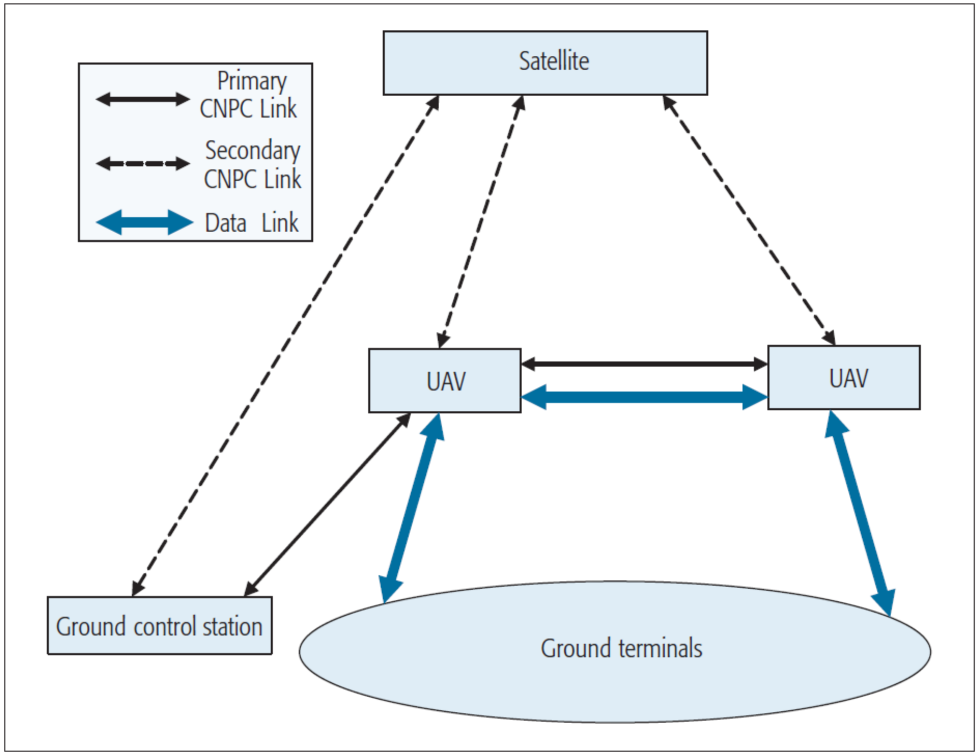
Wireless Communications with UAVs

CNPC: control and non-payload communication



- Main advantages over terrestrial, satellite, or high-altitude platform (HAP)
  - On demand deployment, fast response
  - Low cost
  - More flexible in reconfiguration and movement
  - Short-distance line of sight (LoS) communication

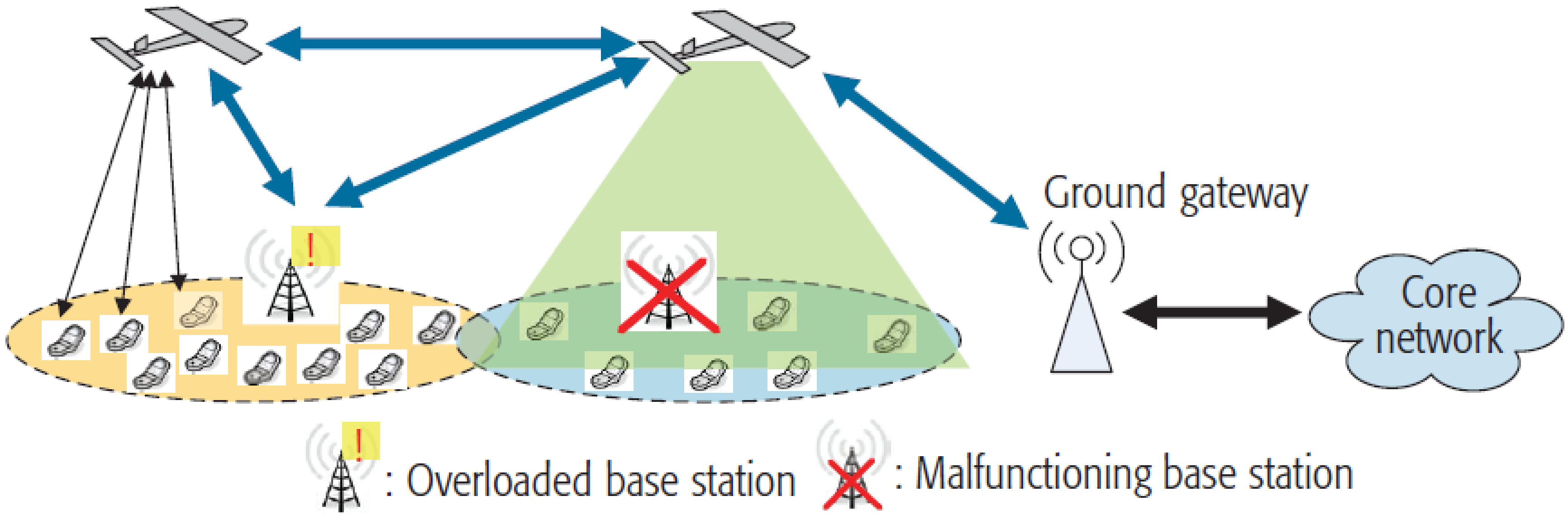
Wireless Communications with UAVs: Typical Use Cases (1)

❑ UAV-aided ubiquitous coverage

- Provide seamless coverage within the serving area
- Application scenarios:
  - ✓ fast service recovery after infrastructure failure
  - ✓ base station offloading at hotspot

❑ UAV-aided relaying

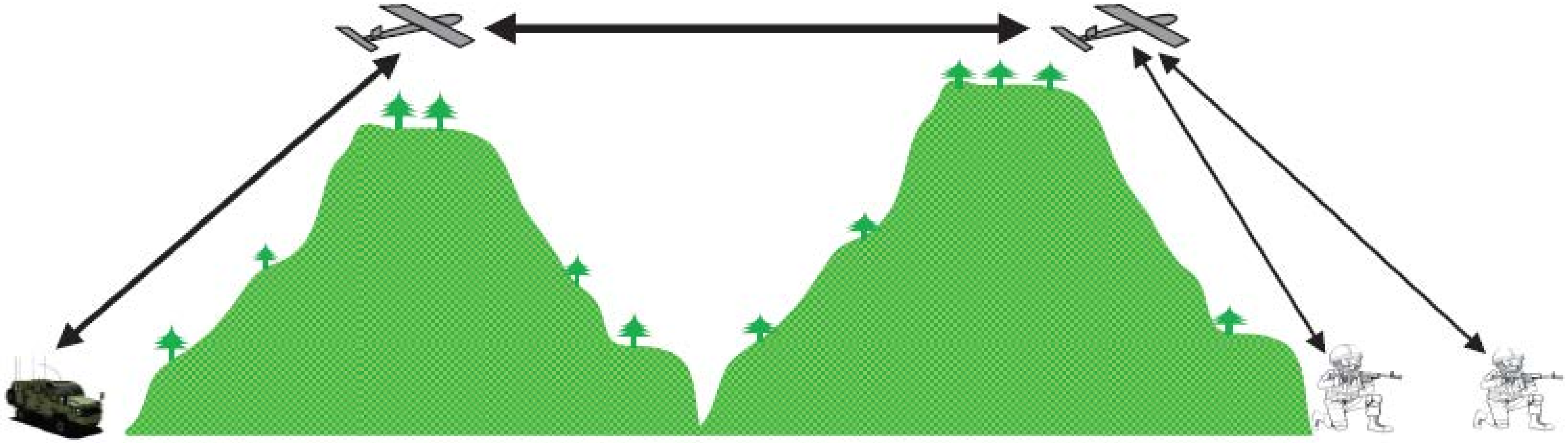
❑ UAV-aided information dissemination/data collection



UAV-aided ubiquitous coverage

Wireless Communications with UAVs: Typical Use Cases (2)

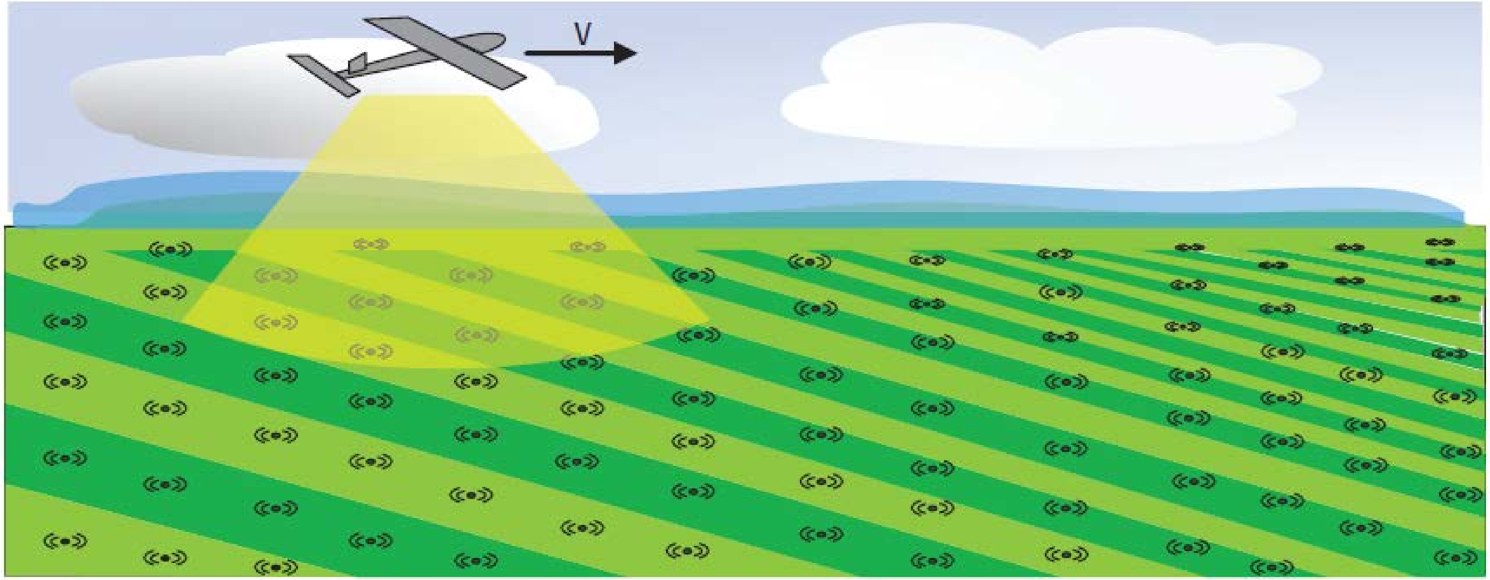
- ❑ UAV-aided ubiquitous coverage
- ❑ **UAV-aided relaying**
  - ➢ Connecting two or more distant users or user groups
  - ➢ Application scenarios:
    - ✓ Military operation, e.g., between frontline and headquarter
    - ✓ Dig data transfer between data centers
- ❑ UAV-aided information dissemination/data collection



UAV-aided relaying

Wireless Communications with UAVs: Typical Use Cases (3)

- ☐ UAV-aided ubiquitous coverage
- ☐ UAV-aided relaying
- ☐ **UAV-aided information dissemination/data collection**
  - ➢ Application scenarios: periodic sensing, information multicasting



UAV-aided information dissemination and data collection

Wireless Communications with UAVs: New Challenges

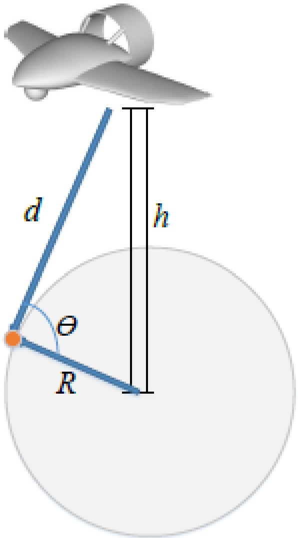
- ☐ Crucial control and non-payload communication (CNPC) link
  - ➢ Support safety-critical functions:
    - ✓ Command and control from ground to UAVs
    - ✓ Aircraft status report from UAVs to ground
    - ✓ Sense-and-avoid information between UAVs
  - ➢ Stringent security and latency requirement, e.g., avoid ghost control
  - ➢ Dedicated spectrum: L-band (960-977 MHz), C-band (5030-5091 MHz)
- ☐ Sparse and intermminent network connectivity: wireless backhaul, highly dynamic environment
- ☐ Size, weight and power (SWAP) constraint
- ☐ UAV swarm operation: inter-UAV coordination, interference mitigation, etc.

Main Channel Characteristics

- UAV-ground channel
  - Usually line-of-sight (LoS) links, but may be occasionally blocked by terrain, buildings, or airframe itself
  - Probabilistic LoS model: LoS probability increases with elevation angle θ

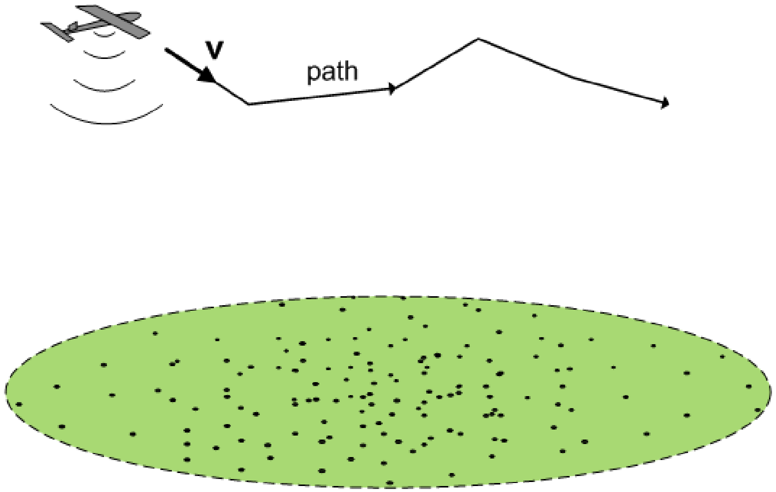
$$\mathrm{P(LOS)} = \frac{1}{1 + \alpha \exp\left(-\beta \left[\frac{180}{\pi}\theta - \alpha\right]\right)}$$

  - Multi-path: usually less scattering than terrestrial channels
  - Rician fading: typical Rician factor 15 dB for L-band and 28 dB for C-band in hilly terrain
  - Two-ray model over desert or sea
- UAV-UAV channel
  - Dominant LoS component
  - High Doppler due to relative movement



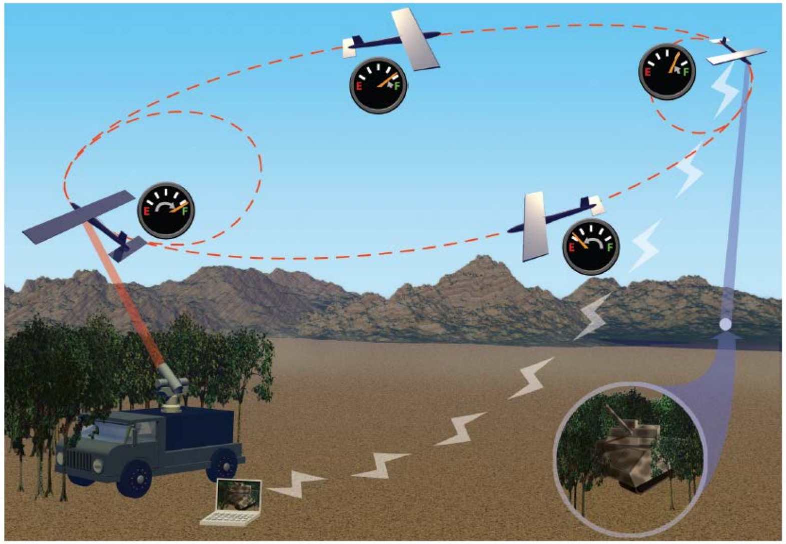
Main Design Considerations (1)

- ☐ UAV deployment and path planning
  - Aimed to shorten average communication distance
  - Challenging in general, various constraints: connectivity, fuel limitation, collision and terrain avoidance, etc.
  - Approximate path optimization with mixed integer linear programming (MILP)
  - UAV deployment for ubiquitous coverage (aerial BS):
    - ✓ Tradeoff in UAV altitude: higher altitude, larger path loss, but also higher probability for LoS link, and vice versa



Main Design Considerations (2)

- ❑ Energy-aware deployment and operation
  - ➢ Sequential energy replenishment via inter-UAV cooperation
  - ➢ Exploit the dynamic load patterns for energy scheduling
  - ➢ Wireless-powered UAVs (by e.g. lasers, microwave beams)
  - ➢ Energy-efficient operation
    - ✓ Energy-efficient mobility: e.g., avoid unnecessary vehicle maneuvering or ascending
    - ✓ Energy-efficient communication: maximize bits/Joule

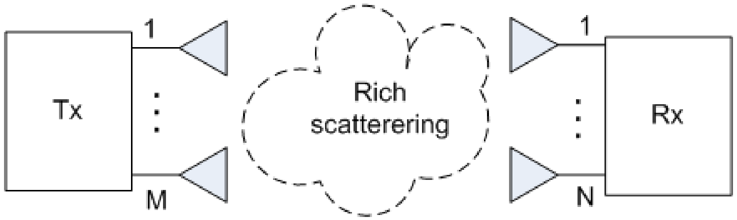


Laser-powered UAV

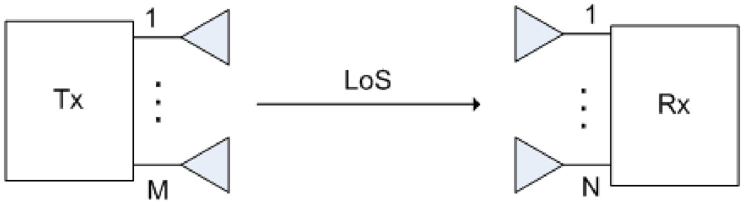
Main Design Considerations (3)

MIMO for UAV

- MIMO: improve spectral efficiency/diversity
- Practical considerations for MIMO in UAV communications
  - Poor scattering environment: limited spatial multiplexing gain
  - High signal processing complexity, high hardware and power consumption costs versus the limited SWAP constraint
  - Acquisition of channel state information (CSI) in UAV systems
- Potential solutions:
  - Achieve spatial multiplexing even in LoS channels
  - Multi-user MIMO
  - Millimeter wave MIMO: reap large MIMO array gain



$$\mathrm{rank}(\mathbf{H}) = \min(M, N)$$

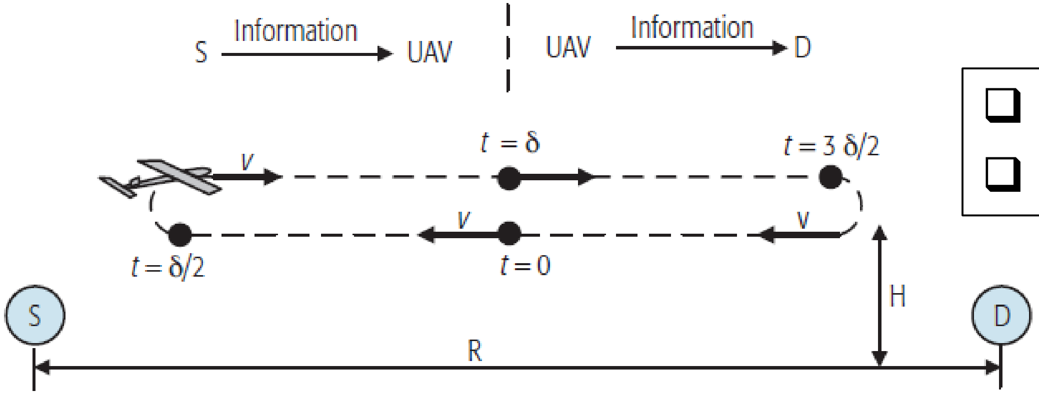


$$\mathrm{rank}(\mathbf{H}) = 1$$

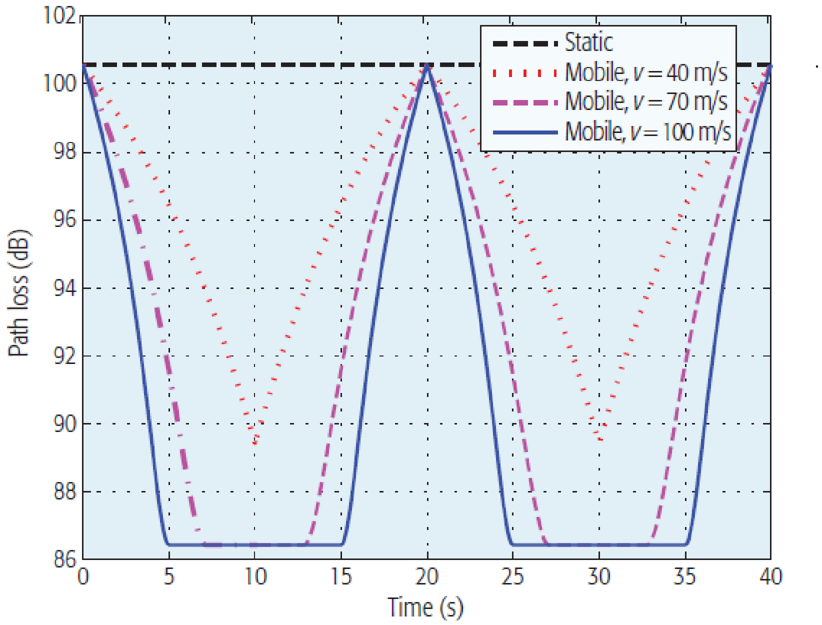
A New Wireless Communication Paradigm: Exploiting the Interplay of UAV Controlled Mobility and Communication

- ☐ UAV-enabled mobile relaying
  - Conventional relay: static, fixed locations due to limited mobility, wired backhauls, etc.
  - Mobile relay: relays mounted on high-speed vehicles, such as UAVs, AGVs
  - Additional degree of freedom for performance enhancement: mobility control, joint communication and movement scheduling
- ☐ D2D-enhanced UAV information dissemination
  - Exploit both D2D communication and UAV controlled mobility
  - Energy saving for UAV and performance enhancement

UAV-Enabled Mobile Relaying: Toy Example

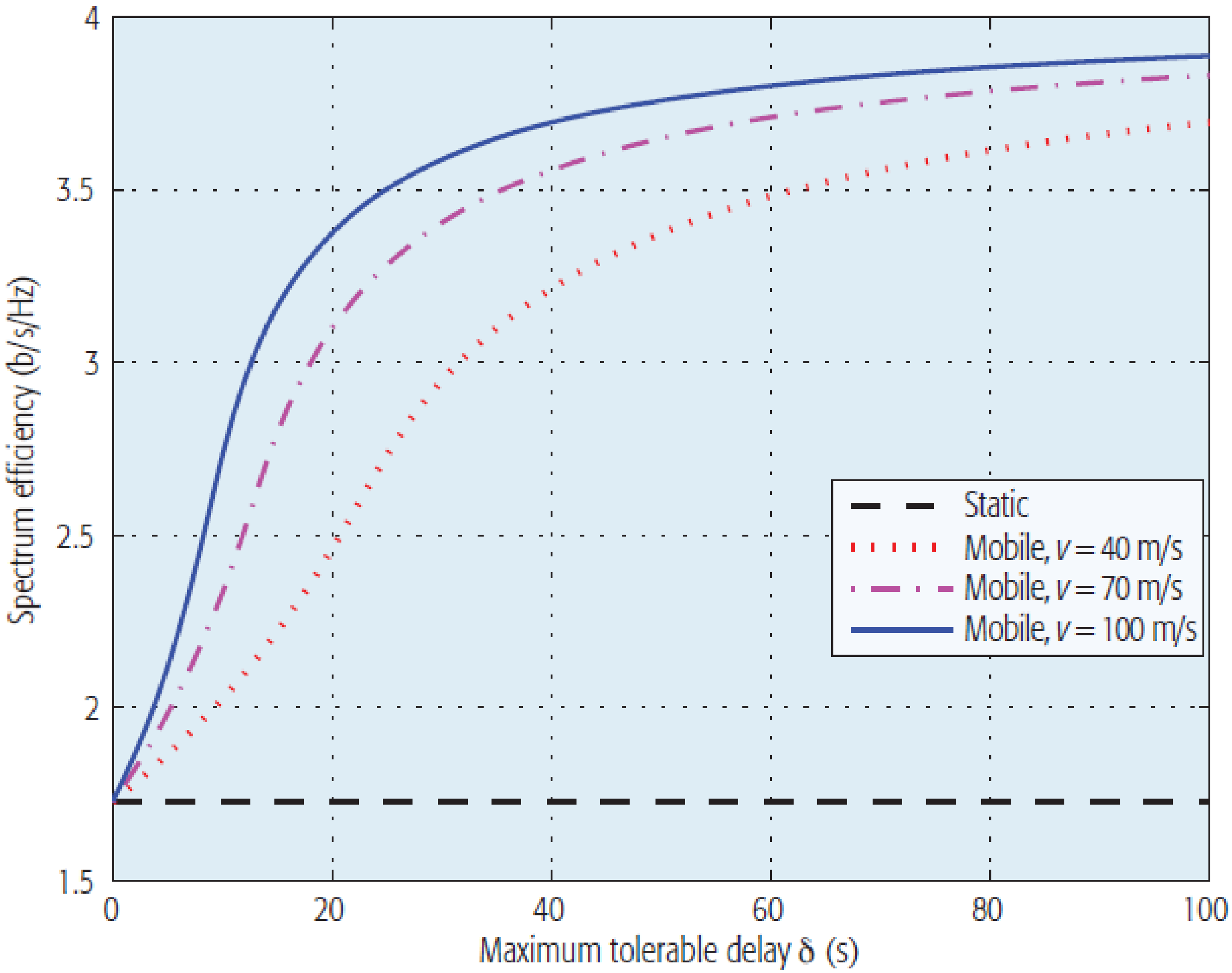


- ☐ UAV closer to source: receiving
- ☐ UAV closer to destination: relaying



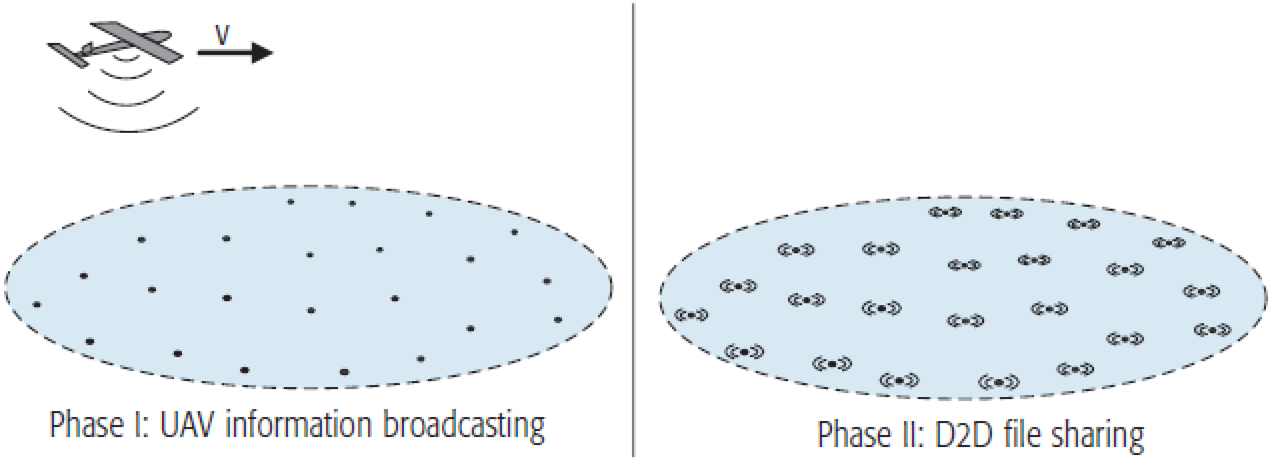
- ☐ Always enjoy smaller path loss than static relaying
- ☐ Better channel in average for higher UAV maximum speed

UAV-Enabled Mobile Relaying : Throughput vs. Delay



D2D Enhanced UAV Information Dissemination

- ☐ Objective: deliver a bulky common file to a massive number of ground terminals scattered in a wide area
- ☐ Direct UAV multicasting: intensive UAV load
- ☐ D2D enhanced information dissemination
  - ➢ Phase I: limited UAV multicasting while flying, each terminal is likely to receive a (different) portion of the file
  - ➢ Phase II: file sharing among ground terminals via D2D
  - ➢ Advantages: offload UAV, saves flying time and energy, enhanced performance
- ☐ Design problem: D2D file sharing and UAV path/speed optimization



Phase I: UAV information broadcasting

Phase II: D2D file sharing

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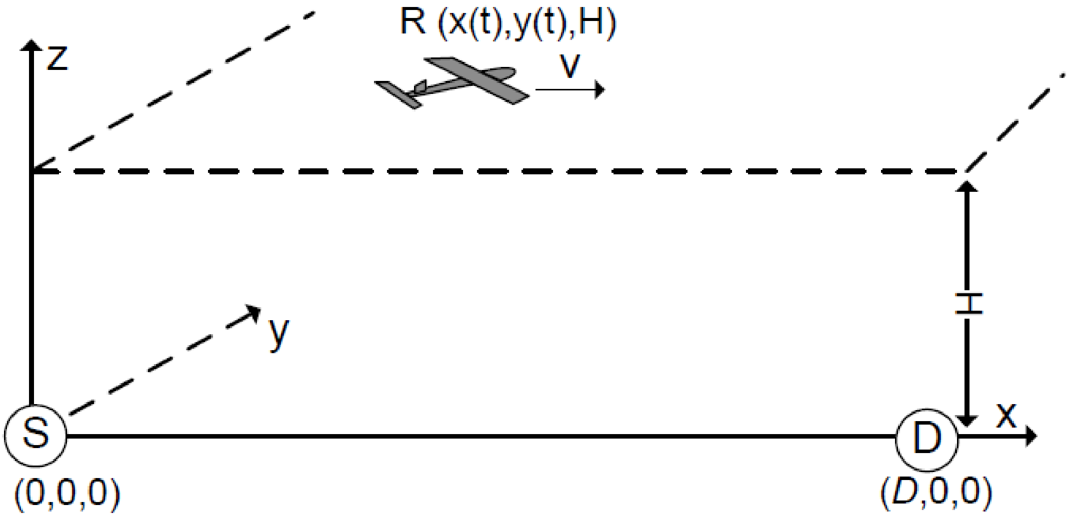
UAV-Enabled Mobile Relaying: Joint Communication and Trajectory Optimization



- Relay moves at a constant altitude *H,* FDD communication
- 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 time-varying (mobility-controlled) channels
- Objective: maximize the end-to-end throughput via joint transmit power/rate allocation and trajectory design

UAV-Enabled Mobile Relaying: Problem Formulation

- ❑ Relay mobility constraints:

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

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

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

Problem Formulation

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

aggregate rate at destination

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

information-causality constraint

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

power constraint

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

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

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

initial location constraint

$$
\left(x[n+1]-x[n]\right)^2+\left(y[n+1]-y[n]\right)^2 \leq V^2, \qquad n=1,\cdots,N-1,
$$

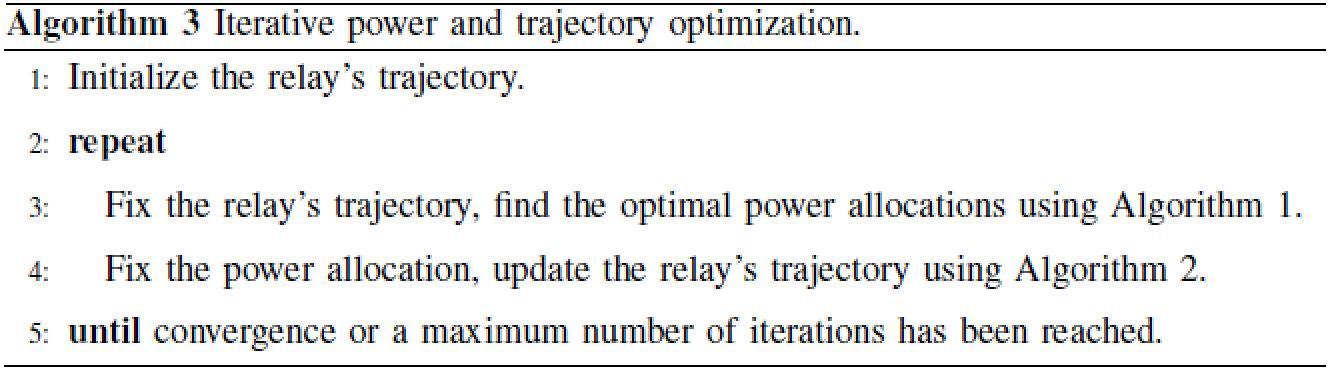
speed constraint

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

final location constraint

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 optimization



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

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

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

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

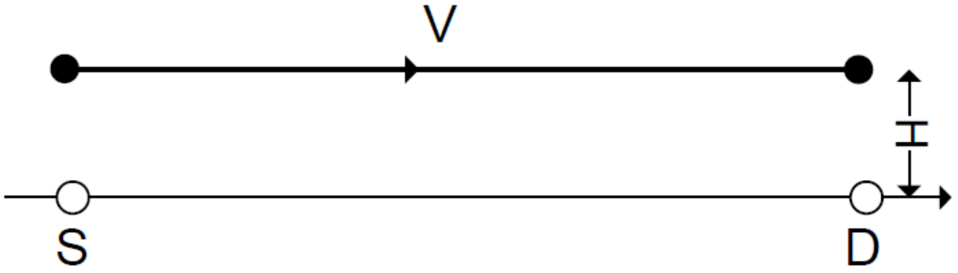
- Staircase waterfilling with non-increasing water level at source
- Staircase waterfilling with non-decreasing water level at relay

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

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

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



Trajectory Optimization with Fixed Power

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

- Successive convex optimization based on rate lower bound
- Main idea: optimize the trajectory incremental in each iteration

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

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

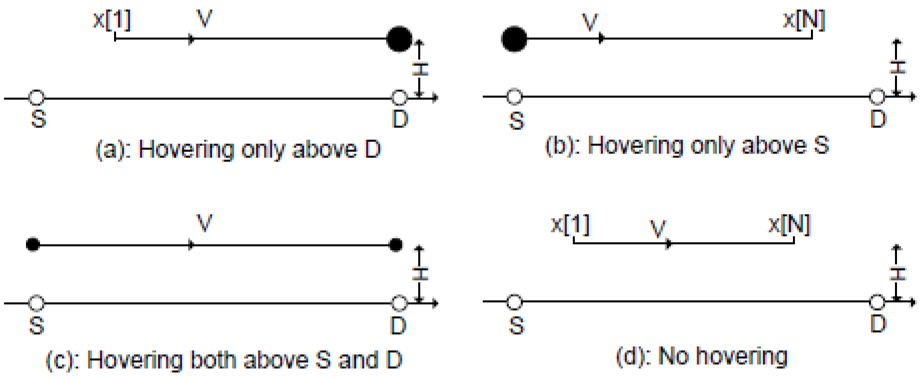
Jointly Optimal Solution with Free Initial/Final Relay Location

- 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

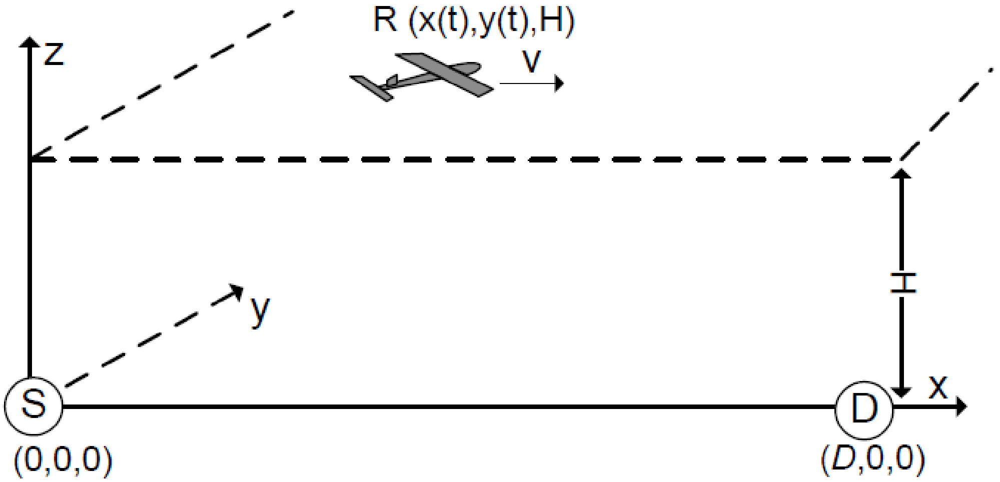
(b): Hovering only above S

(c): Hovering both above S and D

(d): No hovering

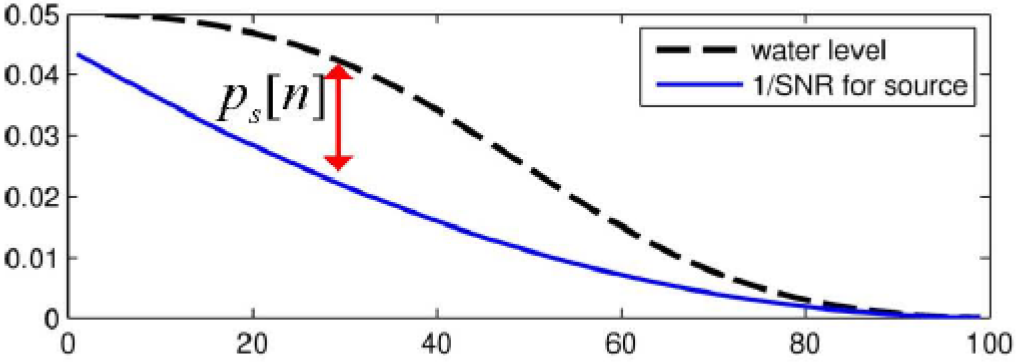
Simulation Setup

- ☐ 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



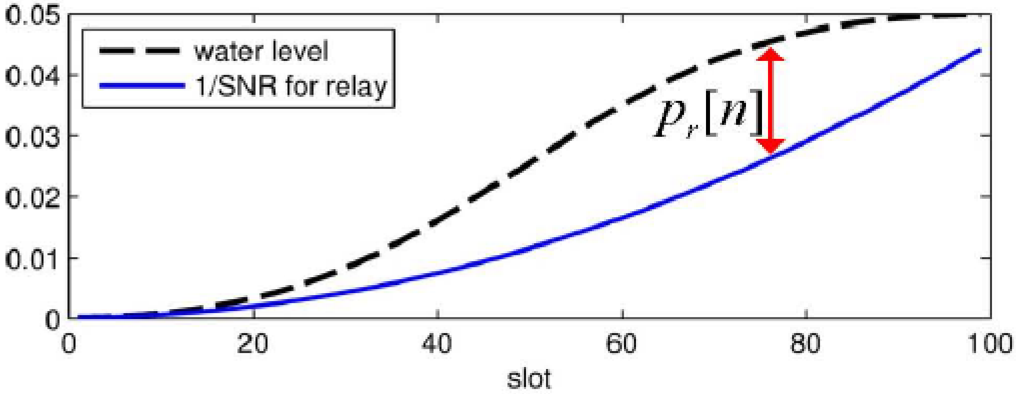
Optimal Power Allocation with Fixed Trajectory

- ☐ 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

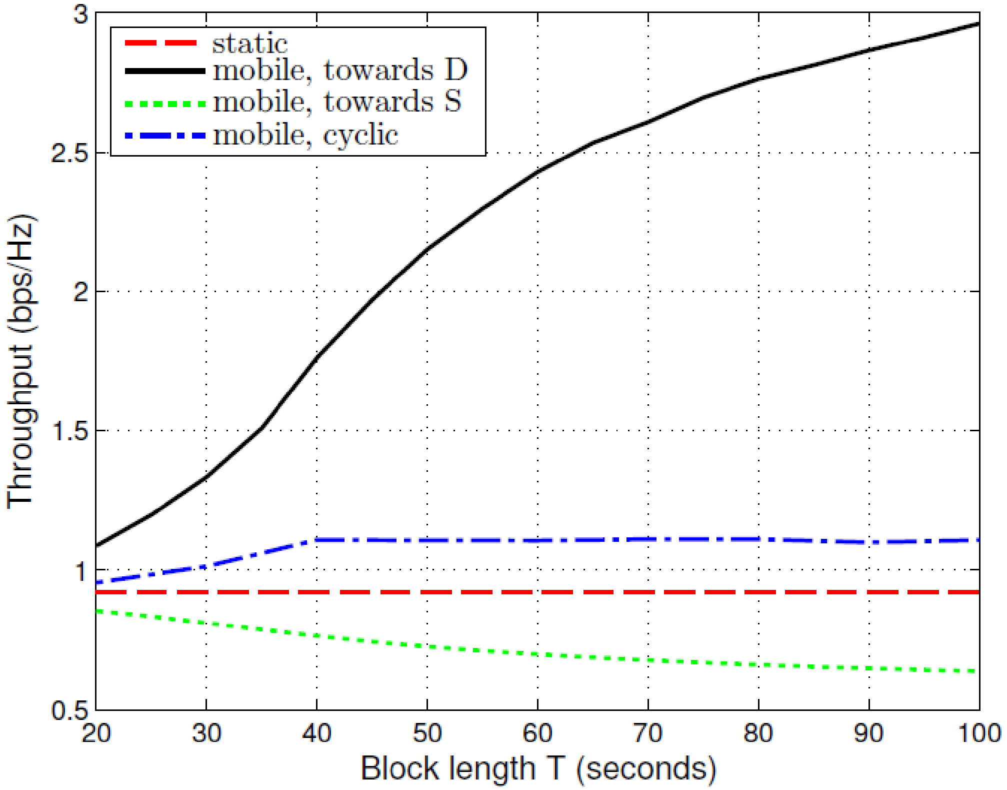
Decreasing water level at source



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

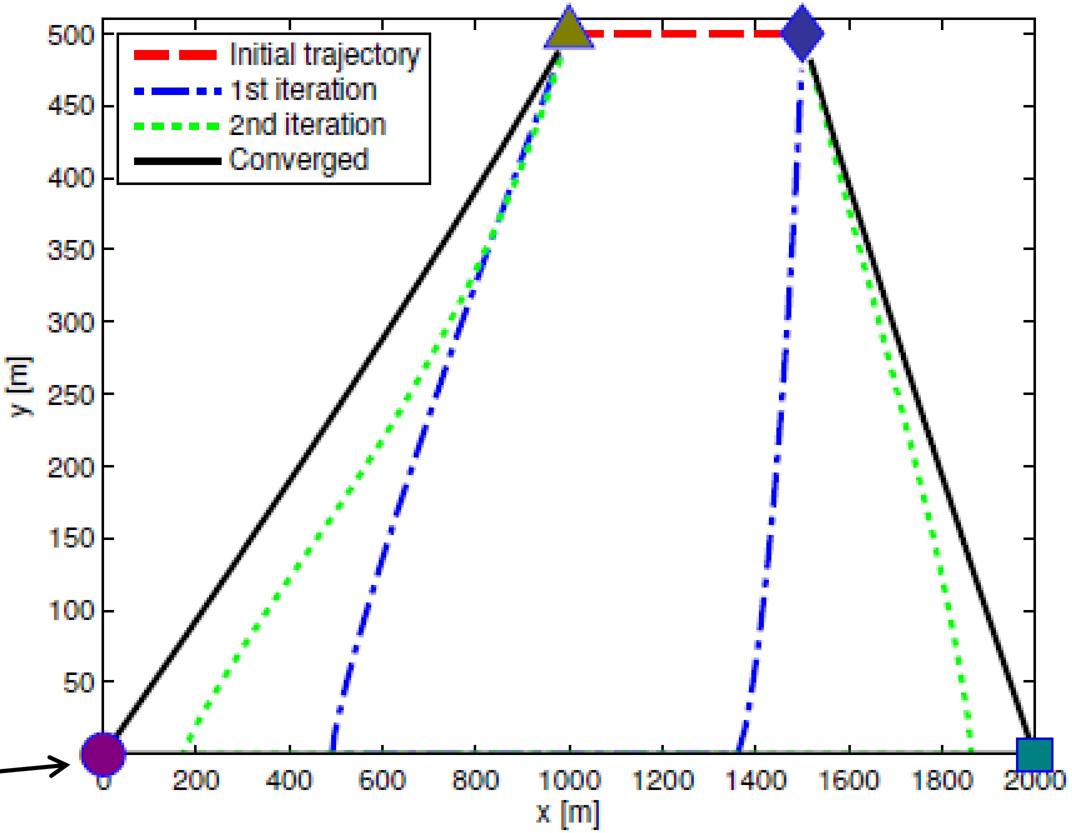
Increasing water level at relay

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



initial relay location

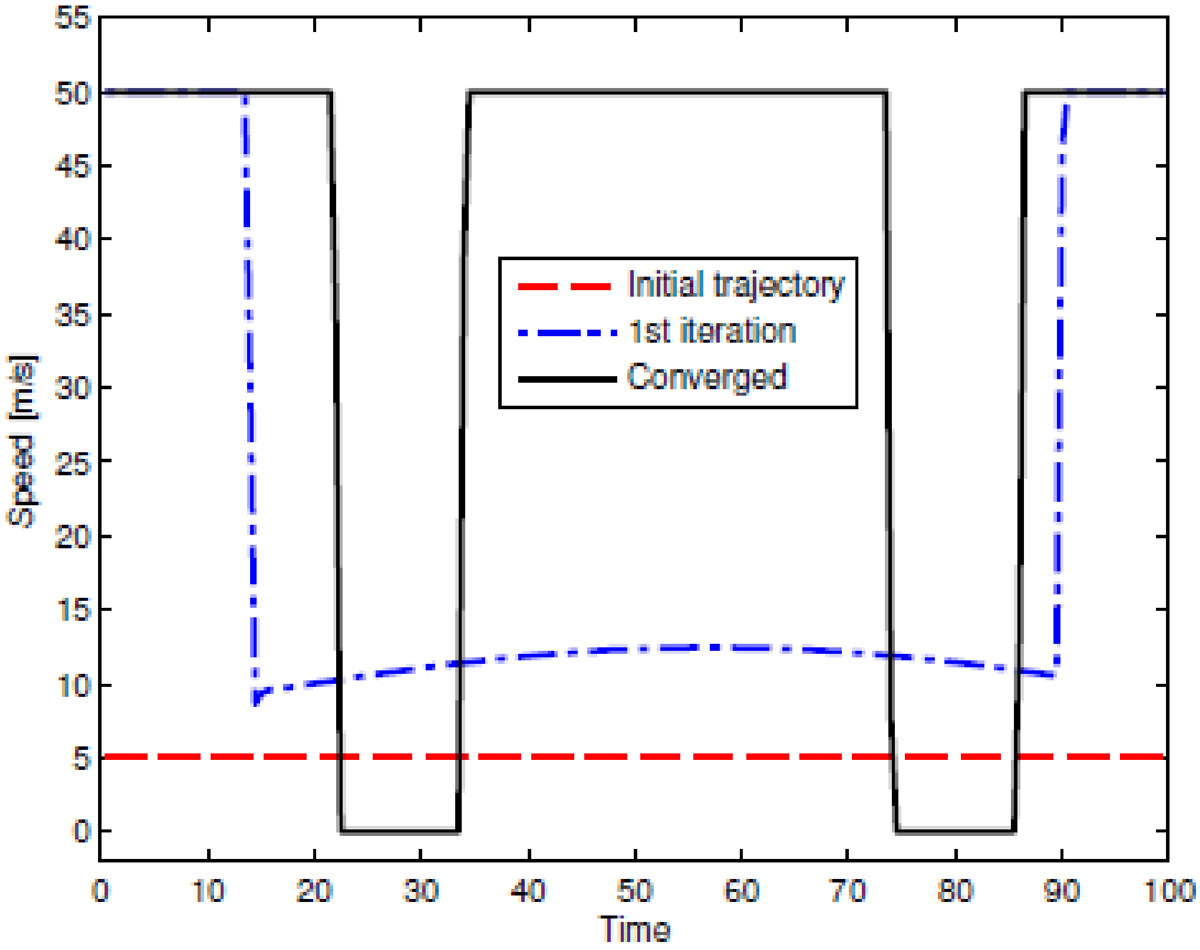
final relay location

source node

destination node

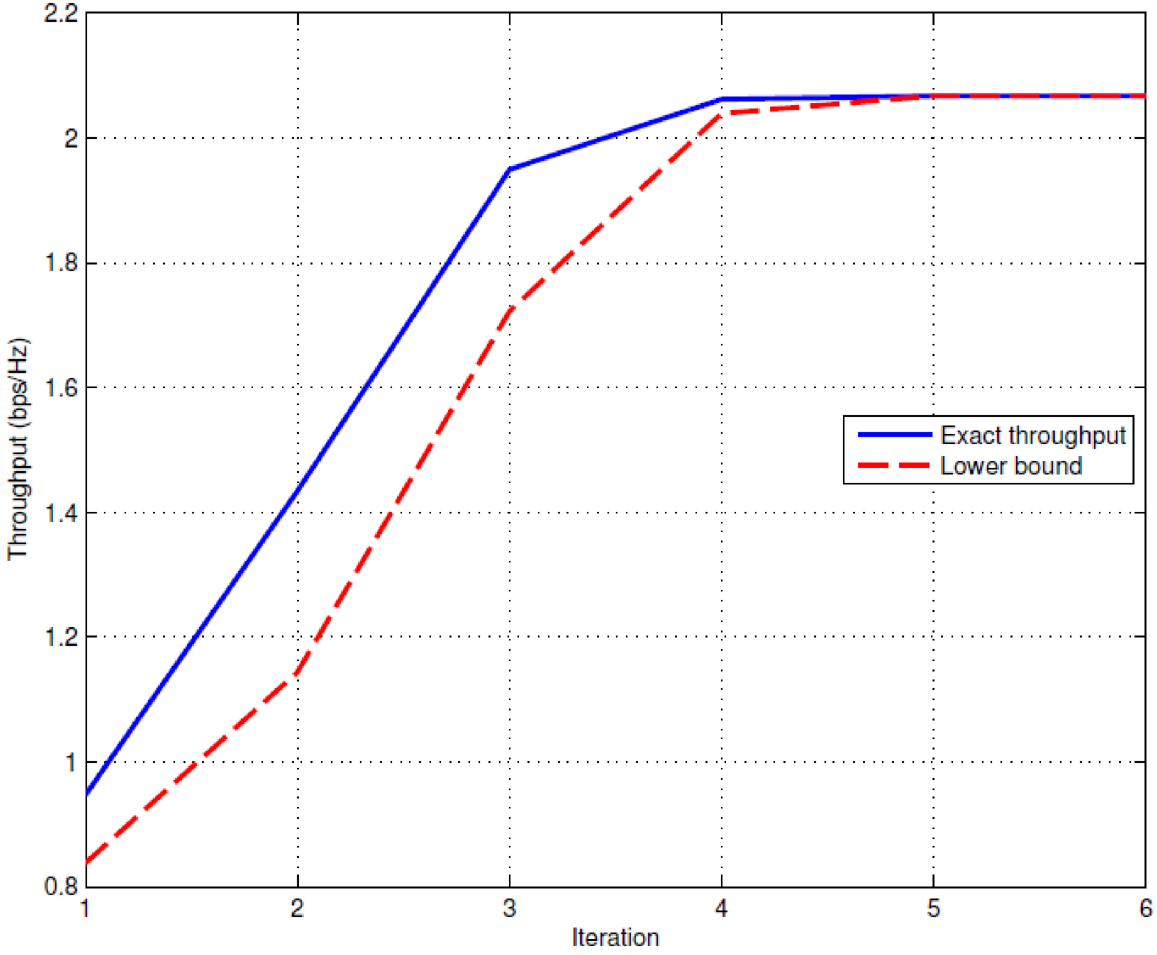
- ❑ Trajectories after different iterations of the proposed successive convex optimization algorithm

Optimized Speed



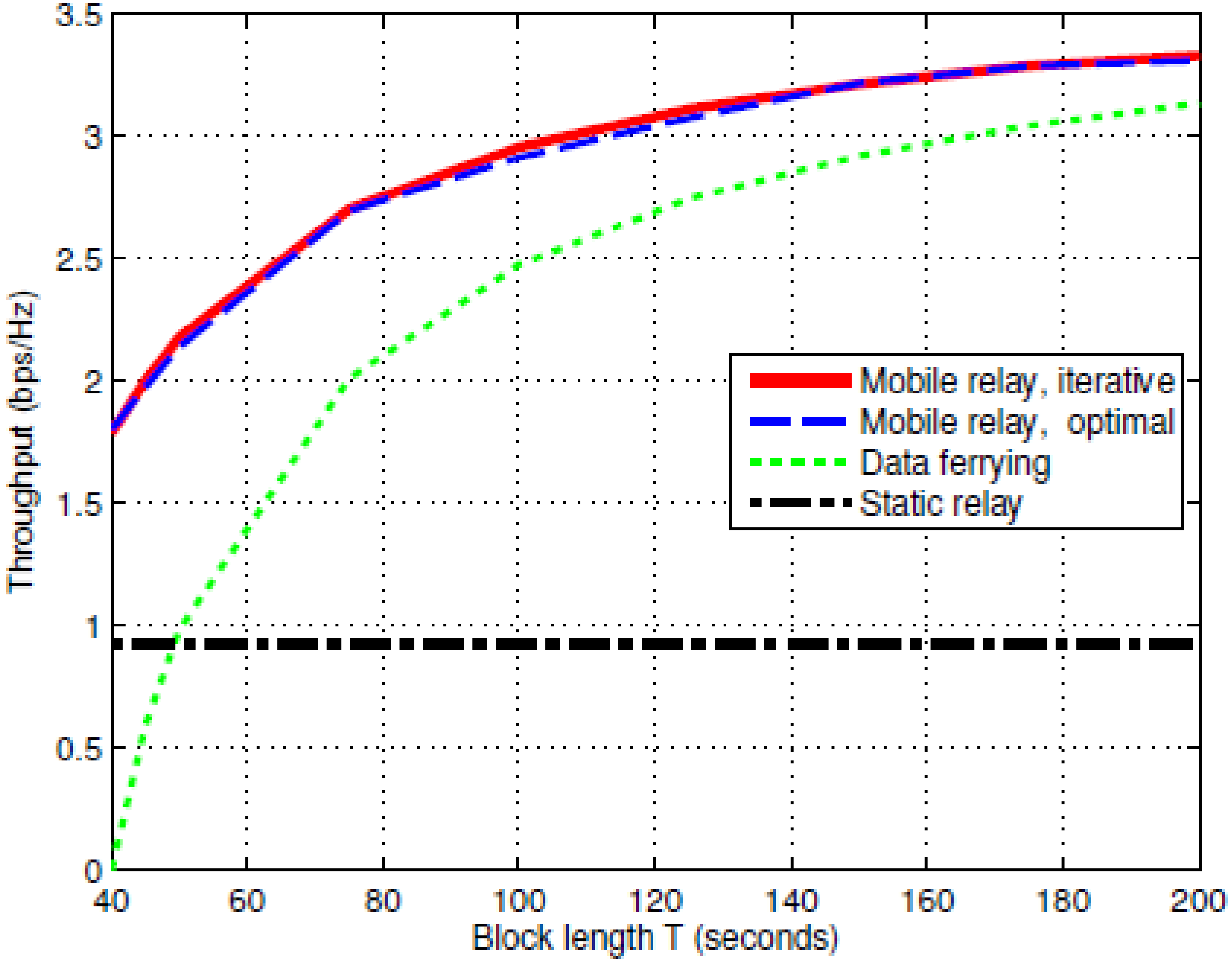
- ❑ Two-level (max. or zero) speed after convergence

Convergence

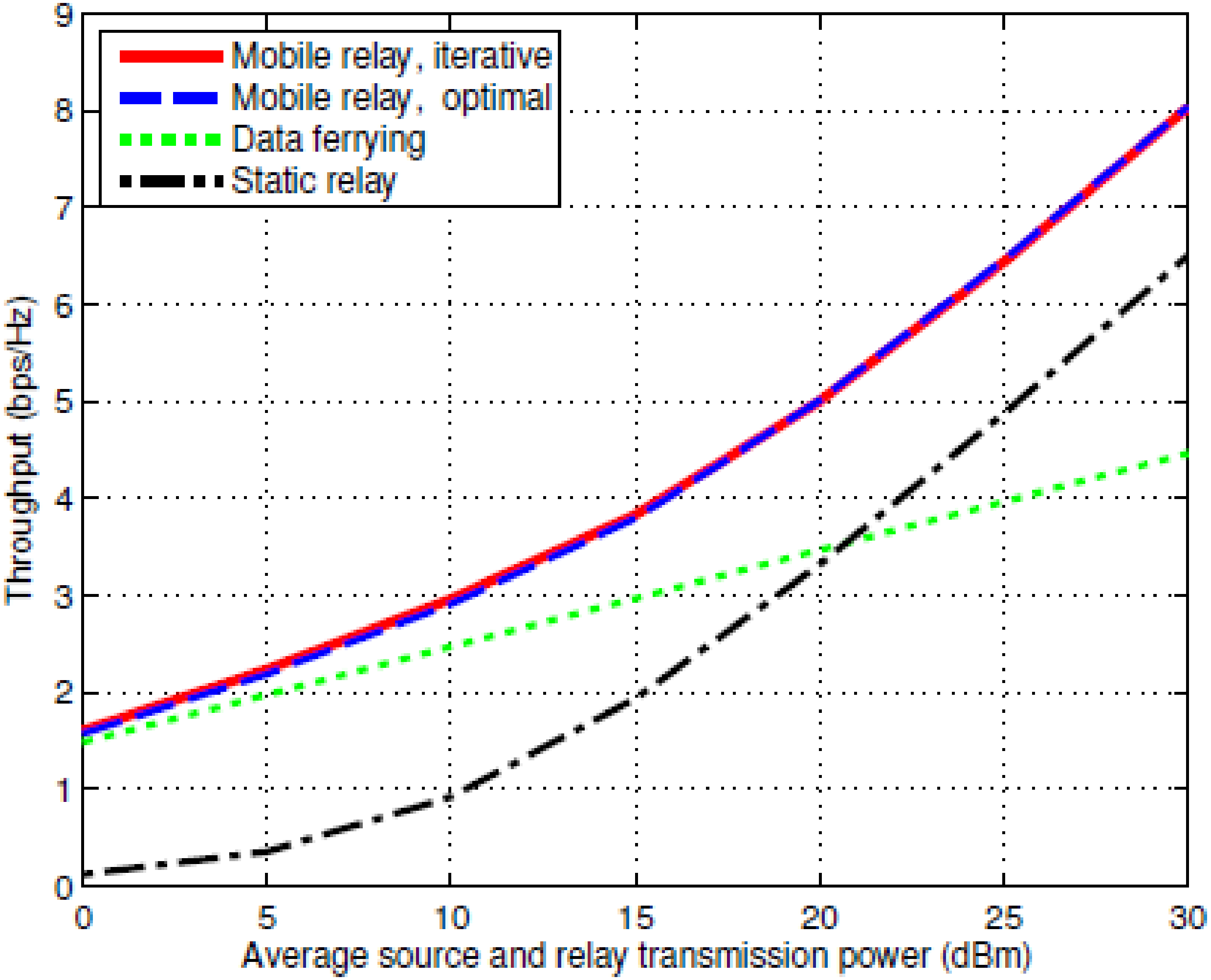


- ❑ Fast convergence for the trajectory optimization algorithm

Joint Power and Trajectory Design via Alternating Optimization



Joint Power and Trajectory Design via Alternating Optimization



Outline

- ❑ Unmanned Aerial Vehicles (UAVs): Introduction
- ❑ Wireless Communications with UAVs: Overview
- ❑ UAV-Enabled Mobile Relaying
- ❑ Summary and Future Directions

Summary

- UAVs have promising applications in future wireless communication
    - On-demand deployment, fast response, cost-effective
    - Flexible in deployment and reconfiguration
    - Short-distance LoS channels
- Three typical use cases
    - UAV-aided ubiquitous coverage
    - UAV-aided relaying
    - UAV-aided information dissemination/data collection
- Main design challenges
    - Crucial control links for safety-critical functions
    - Sparse and intermittent network connectivity
    - Size, weight, and power (SWAP) limitations
    - Swarm operation and coordination
- New opportunities: exploiting UAV controlled-mobility
    - Joint adaptive communication and mobility design
    - Example: joint power and trajectory optimization in UAV-enabled relaying

Future Directions

- UAV swarm operation and communications
- Aerial base station, e.g., mobile LTE BS/relay
- UAV information dissemination/collection
- UAV-ground channel models
- UAV communication with limited buffer size/energy storage
- Throughput-delay trade-off in UAV communications
- UAV deployment/movement optimization
- MIMO communication in UAV
- Wireless-powered/energy-harvesting-enabled UAVs
- Energy-efficient UAV communications
- …..

Reference

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