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

## UAV Classification: Fixed-Wing vs. Rotary-Wing

<table>
<thead>
<tr>
<th></th>
<th><strong>Fixed-Wing</strong></th>
<th><strong>Rotary-Wing</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanism</strong></td>
<td>Lift generated using wings with forward airspeed</td>
<td>Lift generated using blades revolving around a rotor shaft</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>Simpler structure, usually higher payload, higher speed</td>
<td>Can hover, able to move in any direction, vertical takeoff and landing</td>
</tr>
<tr>
<td><strong>Limitations</strong></td>
<td>Need to maintain forward motion, need a runway for takeoff and landing</td>
<td>Usually lower payload, lower speed, shorter range</td>
</tr>
</tbody>
</table>
## UAV Classification: By Weight

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

## UAV Classification: By Control Method

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote human pilot</td>
<td>Real-time control by remote pilot</td>
</tr>
<tr>
<td>Remote human operator</td>
<td>Human provides the flight parameters to invoke the built-in functions for vehicle control</td>
</tr>
<tr>
<td>Semi-autonomous</td>
<td>Human controlled initiation and termination, autonomous mission execution</td>
</tr>
<tr>
<td>Autonomous</td>
<td>Automated operation after human initiation</td>
</tr>
<tr>
<td>Swarm control</td>
<td>Cooperative mission accomplishment via control among the vehicles</td>
</tr>
</tbody>
</table>
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Wireless Communications with UAVs

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

CNPC: control and non-payload 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**
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
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 intermittent 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 $\theta$
    \[
    P(\text{LOS}) = \frac{1}{1 + \alpha \exp(-\beta \left[\frac{180}{\pi} \theta - \alpha\right])}
    \]
  - 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

\[
\text{Rank}(H) = \min(M, N) \quad \text{rank}(H) = 1
\]
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

![Graph showing throughput versus delay for static and mobile relaying at different speeds](image)
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
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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:**

  $$
  (x[1] - x_0)^2 + (y[1] - y_0)^2 \leq V^2, \\
  (x[n + 1] - x[n])^2 + (y[n + 1] - y[n])^2 \leq V^2, \\
  n = 1, \ldots, N - 1, \\
  (x_F - x[N])^2 + (y_F - y[N])^2 \leq V^2,
  $$

  - $V$: 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

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

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

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

(P1) \[
\max_{\{x[n], y[n]\}, \{p_s[n], p_r[n]\}} \sum_{n=2}^{N} \log_2 \left( 1 + p_r[n] \gamma_{rd}[n] \right)
\]
\[
\text{s.t. } \sum_{i=2}^{n} \log_2 \left( 1 + p_r[i] \gamma_{rd}[i] \right) \leq \sum_{i=1}^{n-1} \log_2 \left( 1 + p_s[i] \gamma_{sr}[i] \right), \quad n = 2, \cdots, N,
\]
\[
\frac{1}{N} \sum_{n=1}^{N-1} p_s[n] \leq \bar{P}_s, \quad \frac{1}{N} \sum_{n=2}^{N} p_r[n] \leq \bar{P}_r,
\]
\[
p_s[n] \geq 0, \quad n = 1, \cdots, N - 1,
\]
\[
p_r[n] \geq 0, \quad n = 2, \cdots, N,
\]
\[
(x[1] - x_0)^2 + (y[1] - y_0)^2 \leq V^2,
\]
\[
(x[n+1] - x[n])^2 + (y[n+1] - y[n])^2 \leq V^2,
\]
\[
\quad n = 1, \cdots, N - 1,
\]
\[
(x_F - x[N])^2 + (y_F - y[N])^2 \leq V^2,
\]
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

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**Algorithm 3** Iterative power and trajectory optimization.

1: Initialize the relay's trajectory.
2: repeat
3: Fix the relay’s trajectory, find the optimal power allocations using Algorithm 1.
4: Fix the power allocation, update the relay’s trajectory using Algorithm 2.
5: 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

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

\[
p_s^*[n] = \left[\eta \beta_n - \frac{1}{\gamma_{sr}[n]}\right]^+ \\
p_r^*[n] = \left[\xi \nu_n - \frac{1}{\gamma_{rd}[n]}\right]^+
\]

- 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

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

\[
p_r^*[n] = \left[ \xi - \frac{1}{\gamma_{rd}[n]} \right]^+
\]
Trajectory Optimization with Fixed Power

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

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

\[
R_{s,l+1}[n] \geq R_{s,l+1}^{lb}[n] \triangleq R_{s,l}[n] - a_{s,l}[n] (\delta_l^2[n] + \xi_l^2[n])
\]
\[
- b_{s,l}[n] \delta_l[n] - c_{s,l}[n] \xi_l[n],
\]

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:

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

where \( v[n] \triangleq x[n+1] - x[n] \) 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.

![Diagram showing different scenarios of hovering and movement](image-url)
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

(b): power allocation at relay for trajectory 2

Decreasing water level at source

Increasing water level at relay
Throughput Comparison for Different Trajectories

- Mobile relaying significantly outperforms 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
Two-level (max. or zero) speed after convergence
Fast convergence for the trajectory optimization algorithm
Joint Power and Trajectory Design via Alternating Optimization
Joint Power and Trajectory Design via Alternating Optimization
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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
- .....