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Joint Optimization of Role Switching and Trajectory Planning for Multi-UAV Assisted Uplink Secure Communications

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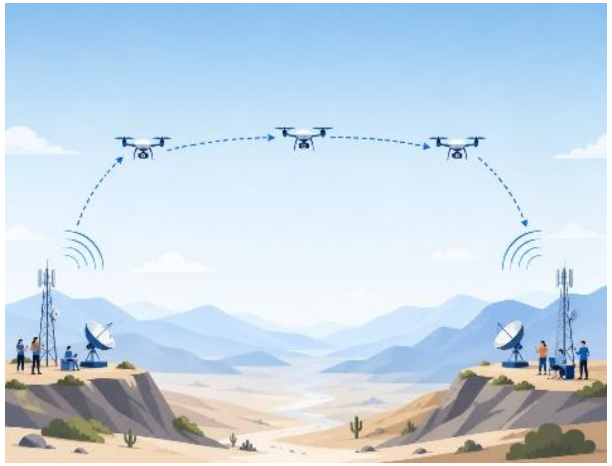
Background

■ The Rise of UAVs in Wireless Communications

- **Flexibility & Mobility:** Act as aerial base stations for rapid, on-demand deployment
- **Line-of-Sight (LoS) Advantage:** Establish reliable links in disaster zones or remote areas with damaged terrestrial infrastructure
- **Key Applications:** Network coverage extension, emergency communications

Infrastructure-limited areas

Emergency communication



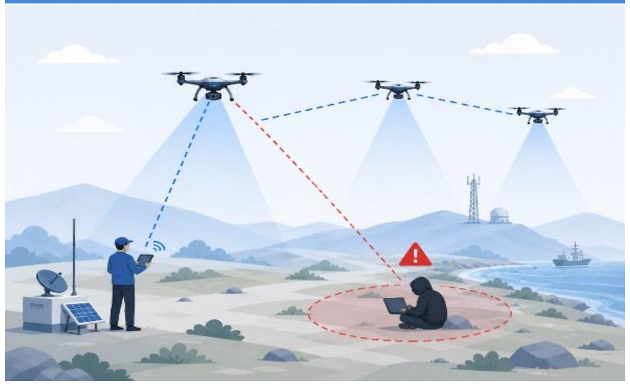
Long-distance communication

Obstructed environments

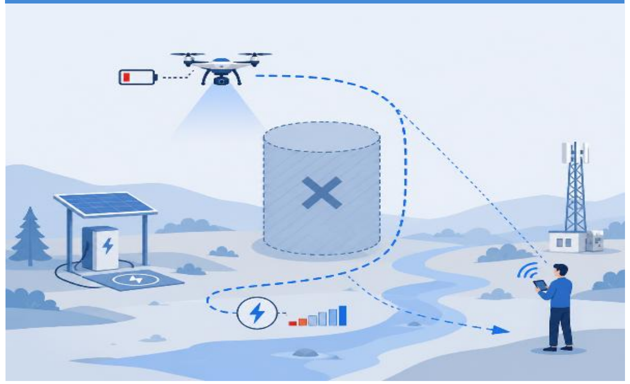
Motivation

- **The Reality: Security is a Major Concern**
  - **Vulnerable Open Environment:** Wireless transmissions are easily intercepted by eavesdroppers, posing significant privacy risks
  - **Limitations of Traditional Security:** Standard encryption methods are computationally expensive and energy-heavy for resource-constrained UAVs
- **Physical Layer Security (PLS)**
  - **Exploiting Channel Properties:** Leverages the inherent randomness of wireless fading channels to enhance security, without heavy encryption overhead
  - **Friendly Jamming:** UAVs can transmit artificial noise to disrupt eavesdropper channels while protecting the legitimate communication link

Eavesdropping threats



Resource constraints



The Challenge

- **Limitations of Existing Approaches**
  - **Fixed Roles:** Limiting operational flexibility
  - **Single-UAV Focus:** Lack robustness and coverage for multi-user, multi-eavesdropper environments
  - **Ignoring Uncertainty:** Eavesdropper locations are often assumed to be perfectly known, which is unrealistic in practice
- **Our Goal：Design a dynamic and robust secure communication strategy for a multi-UAV network**
  - Dynamically switch UAV roles to maximize efficiency
  - Jointly optimize role switching, trajectory, and power allocation
  - Account for uncertainty in eavesdropper locations to ensure worst-case performance

Role inflexibility

Multi-role UAV

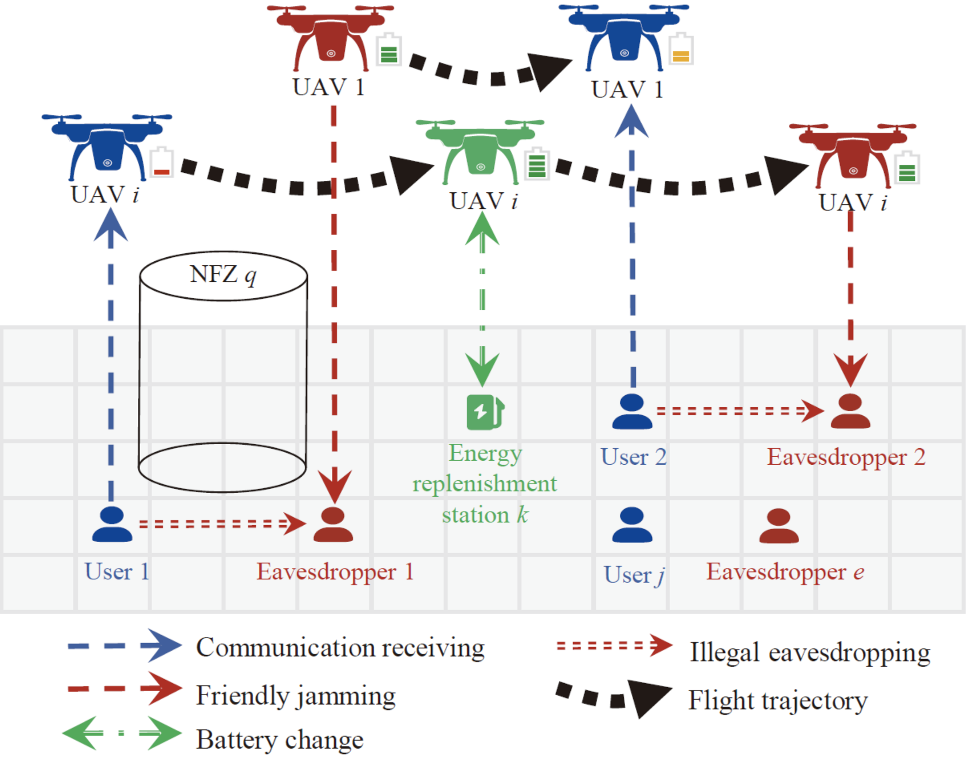
System Model

■ Network Components

- ➢ **Multiple UAVs:** Core agents with dynamic role-switching capabilities
- ➢ **Ground Users & Eavesdroppers:** Legitimate data sources and location-uncertain threats
- ➢ **Energy Stations & No-Fly Zones (NFZ):** Operational lifeline and physical movement constraints

■ Key Features

- ➢ **Dynamic Role Switching:** Per-time-slot adaptation between Collector, Jammer, or Recharger roles
- ➢ **OFDMA Technology:** Guarantees interference-free orthogonal communication for multiple users
- ➢ **Flight trajectory:** UAVs is flying along the grid



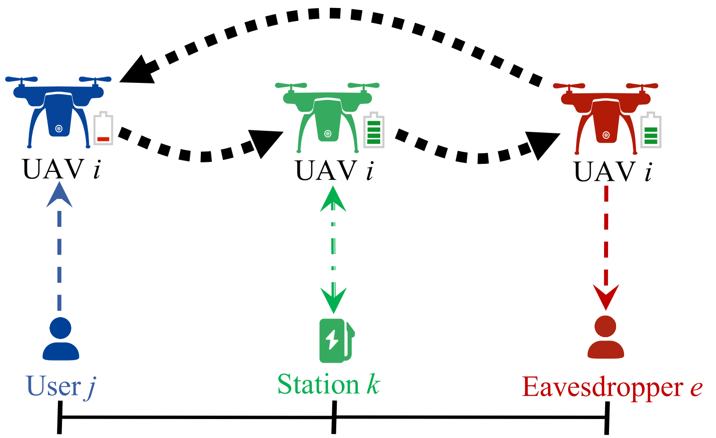
Secure uplink communication

System Model (cont.)

Eavesdroppers position

Actual | Estimated | Estimated error

$$\mathbf{w}_e = \hat{\mathbf{w}}_e + \Delta\mathbf{w}_e \qquad \|\Delta\mathbf{w}_e\|^2 \leq r_{eve}^2$$



Secrecy Capacity

- According to the physical layer security theory:

Communication capacity | Eavesdropping capacity

$$R_{sec}[n] = \frac{1}{J}\left[R_{rec}[n] - R_{wtp}[n]\right]^+, \forall n$$

$$[R]^+ \triangleq \max(R, 0)$$

Energy Consumption

- **Energy consumption of UAV i at n:**

Flighting | Hovering

$$E_i[n] = t_i^{pro}[n]P^{pro}(V) + t_i^{hov}[n]P^{pro}(0), \forall n, i$$

- **Remaining energy of UAV i at n:**

$$E_i^{rem}[n] = (1 - \sum_{k=1}^{K} c_{ik}[n])(E_i^{rem}[n-1] - E_i[n]) + \sum_{k=1}^{K} c_{ik}[n]E_U, \forall n, i$$

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Objective function

- Maximizing the average secrecy capacity across all time slots

$$(\mathcal{P}0): \quad \max_{\mathcal{A},\mathcal{B},\mathcal{C},\mathcal{P},\mathcal{W}} \frac{1}{N}\sum_{n=1}^{N} R_{sec}[n]$$

Optimization variables

Role switching

Comm. reception: $a_{ij}[n] \in \{0,1\}, \forall n, i, j$

Friendly jamming: $b_{ie}[n] \in \{0,1\}, \forall n, i, e$

Energy replenishment: $c_{ik}[n] \in \{0,1\}, \forall n, i, k$

Binary indicators

Power allocation

Tx power of UAVs: $p_i[n], \forall n, i, j$

Tx power of GUs: $p_j[n], \forall n, i, j$

Trajectory planning

Flight trajectory of UAVs:

$\mathbf{w}_i[n], \forall n, i$

Problem Formulation (cont.)

Role switching constraint

$$C1:\begin{cases} \text{I}: \sum_{j=1}^{J} a_{ij}[n] + \sum_{e=1}^{E} b_{ie}[n] \\ \qquad + \sum_{k=1}^{K} c_{ik}[n] \leq 1, \forall n, i \\ \text{II}: \sum_{i=1}^{I} a_{ij}[n] \leq 1, \forall n, j \\ \text{III}: \sum_{i=1}^{I} b_{ie}[n] \leq 1, \forall n, e \\ \text{IV}: \sum_{i=1}^{I} a_{ij}[n] = \sum_{i=1}^{I} \sum_{e=1}^{E} l_{je} b_{ie}[n], \forall n, j \end{cases}$$

Tx power constraint

$$C2:\begin{cases} \text{I}: 0 \leq p_i[n] \leq P_U^{max}, \forall n, i \\ \text{II}: \frac{1}{N} \sum_{n=1}^{N} p_i[n] \leq P_U^{avg}, \forall i \\ \text{III}: 0 \leq p_j[n] \leq P_{GU}^{max}, \forall n, j \\ \text{IV}: \frac{1}{N} \sum_{n=1}^{N} p_j[n] \leq P_{GU}^{avg}, \forall j \end{cases}$$

Flight trajectory constraint

$$C3:\begin{cases} \text{I}: \|\mathbf{w}_i[n] - \mathbf{w}_i[n-1]\|^2 \leq l_{gri}^2, \forall n, i \\ \text{II}: \|\mathbf{w}_i[n] - \mathbf{w}_{i'}[n]\|^2 \geq (d_{saf}^{min})^2, \forall n \neq N, i \neq i' \\ \text{III}: \|\mathbf{w}_i[n] - \mathbf{w}_q\|^2 \geq r_{nfz}^2, \forall n, i, q \\ \text{IV}: \mathbf{w}_i[0] = \mathbf{w}_i^I \quad \mathbf{w}_i[N] = \mathbf{w}_i^F, \forall i \end{cases}$$

Communication distance constraint

$$C4:\begin{cases} \text{I}: a_{ij}[n] \|\mathbf{w}_i[n] - \mathbf{w}_j\|^2 \leq (d_{com}^{max})^2, \forall n, i, j \\ \text{II}: b_{ie}[n] \|\mathbf{w}_i[n] - \mathbf{w}_e\|^2 \leq (d_{com}^{max})^2, \forall n, i, e \end{cases}$$

Energy constraint

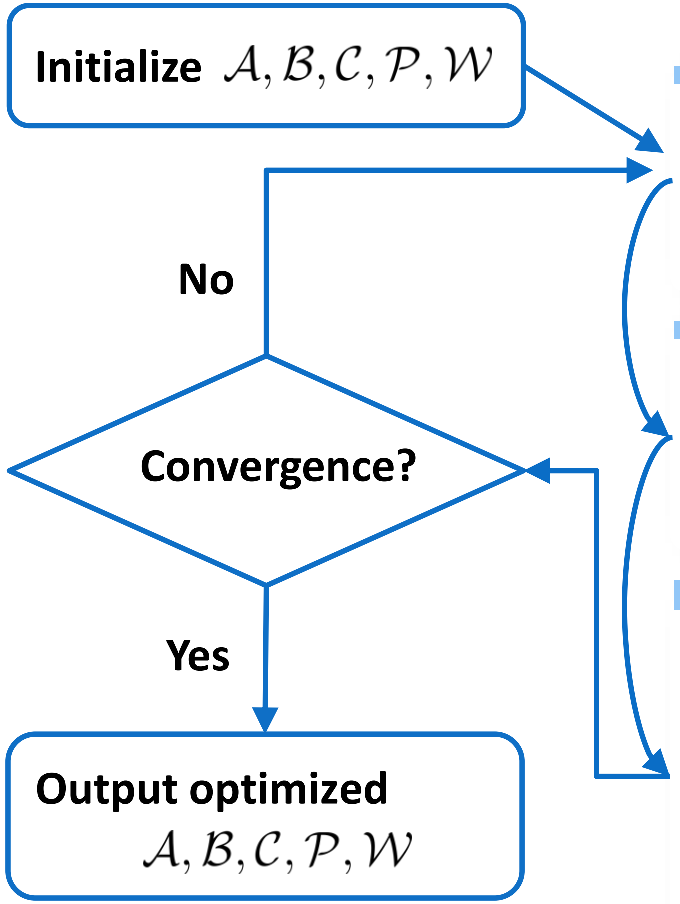
$$C5:\begin{cases} \text{I}: E_i^{rem}[n] \geq \eta E_U, \forall n, i \\ \text{II}: E_i^{rem}[0] = E_U, \forall i \end{cases}$$

Data reception constraint

$$C6: t_{hov}^{min} \sum_{n=1}^{N} \sum_{i=1}^{I} a_{ij}[n] \log_2\left(1 + \frac{p_j[n] g_{ij}[n]}{\sigma^2}\right) \geq D, \forall j$$

This is a complex, non-convex optimization problem due to the variable coupling and non-convex nature

- Iterative framework based on **block coordinate descent (BCD)** and **successive convex approximation (SCA)**



SP1: Role Switching

$$(\mathcal{SP}1): \quad \max_{\mathcal{A},\mathcal{B},\mathcal{C}} \frac{1}{N}\sum_{n=1}^{N}\left(R_{rec}[n]-\hat{R}_{wtp}[n]\right)$$
$$\text{s.t.} \quad \text{C1}, \text{C4}, \text{C5}, \text{C6}$$

SP2: Power Allocation

$$(\mathcal{SP}2'): \quad \max_{\mathcal{P}} \frac{1}{N}\sum_{n=1}^{N}\left(R_{rec}[n]-\hat{R}^{ub}_{wtp}[n]\right)$$
$$\text{s.t.} \quad \text{C2}, \text{C6}$$

SP3: Trajectory Planning

$$(\mathcal{SP}3'): \quad \max_{\mathcal{M},\mathcal{S},\mathcal{T},\mathcal{U}} \frac{1}{N}\sum_{n=1}^{N}\left(R^{lb}_{rec}[n]-\hat{R}^{ub}_{wtp}[n]-c_{ik}[n]u_{ik}[n]\right)$$
$$\text{s.t.} \quad \text{C3}', \text{C4}, \text{C5}, \text{C6}', \text{C7}, \text{C8}$$

$$\text{C7}: \begin{cases} \text{I}: \|\mathbf{w}_i[n]-\mathbf{w}_j\|^2 + H_U^2 \le s_{ij}[n], \forall n,i,j \\ \text{II}: (\|\mathbf{w}_i[n]-\hat{\mathbf{w}}_e\| + r_{eve})^2 + H_U^2 \le t_{ie}[n], \forall n,i,e \\ \text{III}: \|\mathbf{w}_i[n]-\mathbf{w}_k\|^2 \le u_{ik}[n], \forall n,i,k \end{cases} \quad \text{C8}: \begin{cases} \text{I}: 1 \le \mathbf{m}_i[n] \le \frac{l_{sce}}{l_{gri}}, \quad \forall n,i \\ \text{II}: \mathbf{w}_i[n] = \mathbf{m}_i[n]\cdot l_{gri} - \frac{l_{gri}}{2}, \quad \forall n,i \\ \mathbf{m}_i[n] \in \mathbb{Z}, \quad \forall n,i \end{cases}$$

Simulation Setup

■ Comparison Benchmarks

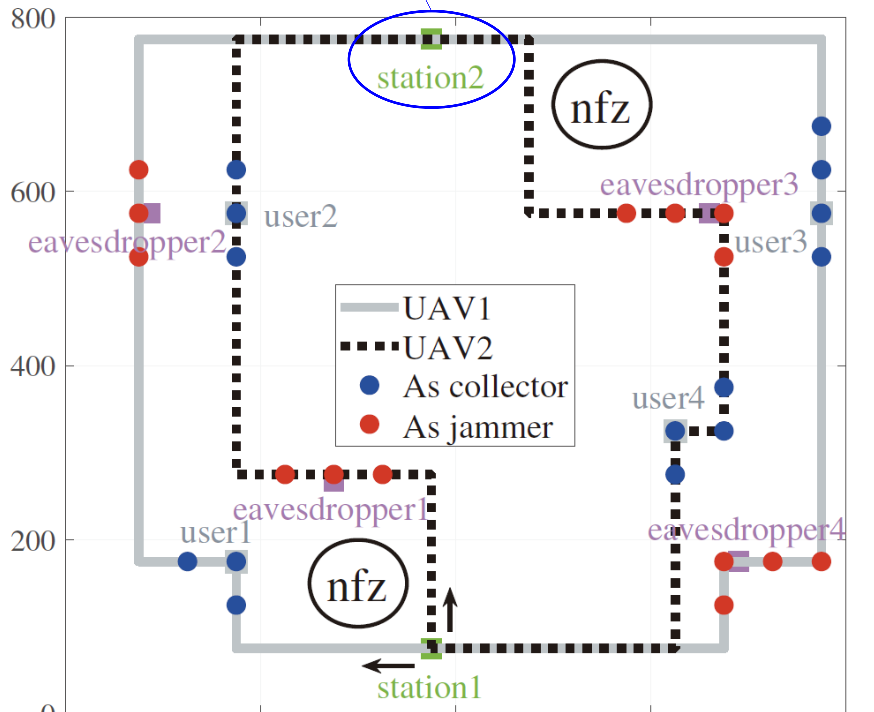
- ➢ **DOFJ (Our Proposal):** Dynamic role switching, joint optimization of power allocation & flight trajectory
- ➢ **DOFJ-NR (Non-Robust):** DOFJ variant that ignores the uncertainty of eavesdropper locations
- ➢ **FR (Fixed-Role):** UAVs are assigned static roles (transmitter or jammer) with no switching
- ➢ **FP (Fixed-Power):** All UAVs and ground users transmit at a constant average power level.
- ➢ **FT (Fixed-Trajectory):** UAVs follow a fixed, pre-defined flight path with no adaptive movement

Parameter	Values
UAV Model	DJI Mini 3 drone
Battery capacity E_U	18.1Wh
Flight speed V	40m/s
Side length of place and grids	800m and 50m
UAV flight altitude H_U	36.4m
Duration of each time slot δt	1.5s，2，3
Channel power gain at a unit distance β_0 ,	-60dB
noise power σ^2	-110dBm
User’s data size D	100B

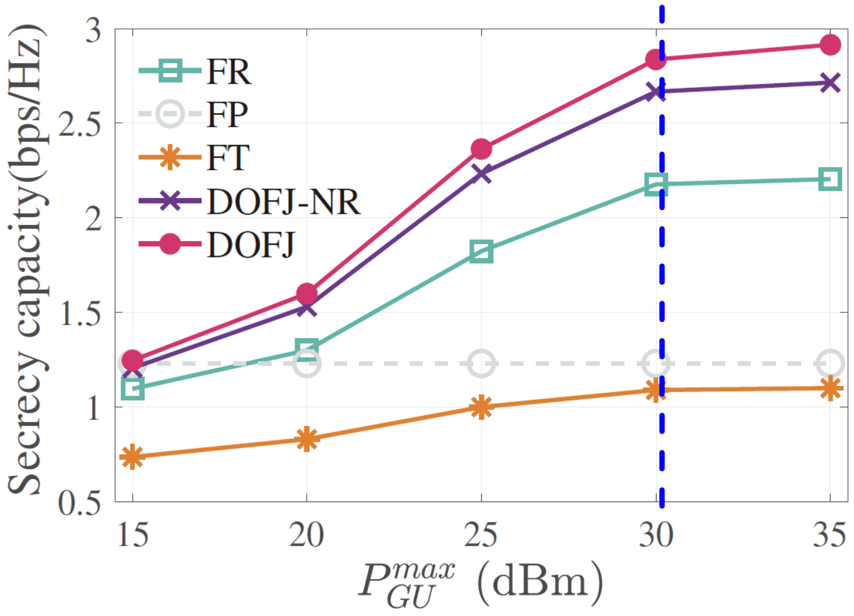
UAV Trajectory Example

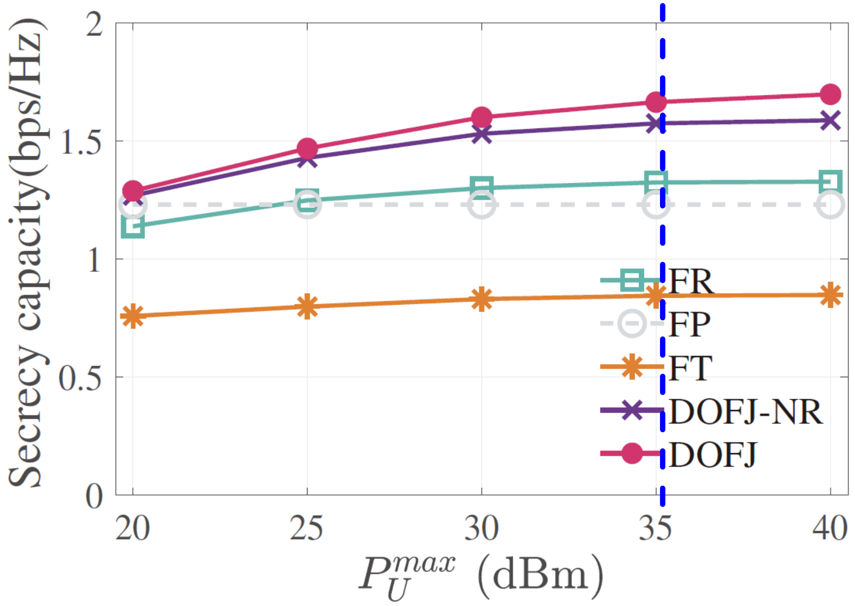
- **Dynamic Path**
  - The UAVs intelligently bypass the no-fly zone while maintaining mission objectives
- **Energy Management**
  - They autonomously visit Station 2 before their batteries deplete, ensuring sustained operation
- **Role Execution**
  - Dynamic role switching shortens UAVs' flight distances
- **Robustness**
  - The trajectory accounts for the uncertain regions of eavesdroppers and enables friendly jammers to approach eavesdroppers more closely

Energy replenishment station



Performance Comparison





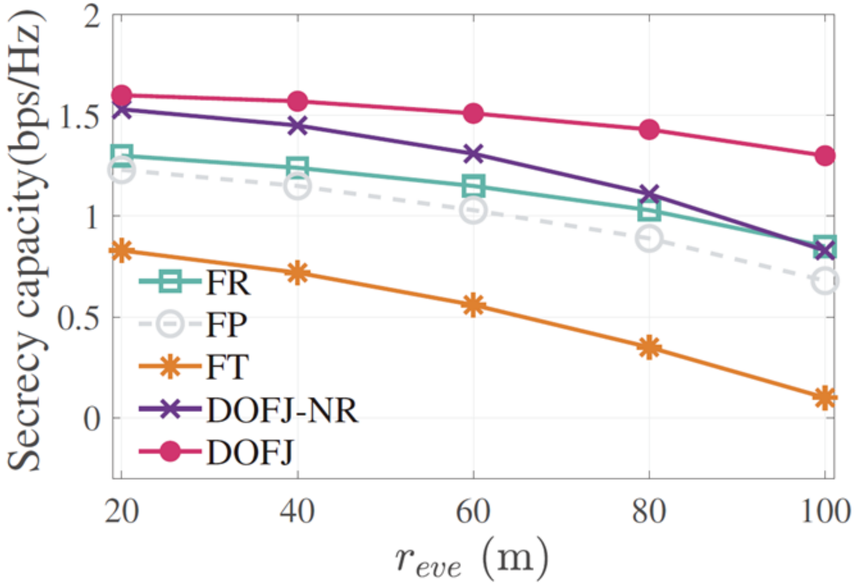
Maximum User Power

- Secrecy capacity saturates at about 30 dBm, with diminishing returns from higher tx power
- The DOFJ maintains a significant and consistent lead across all power levels

Maximum UAV Power

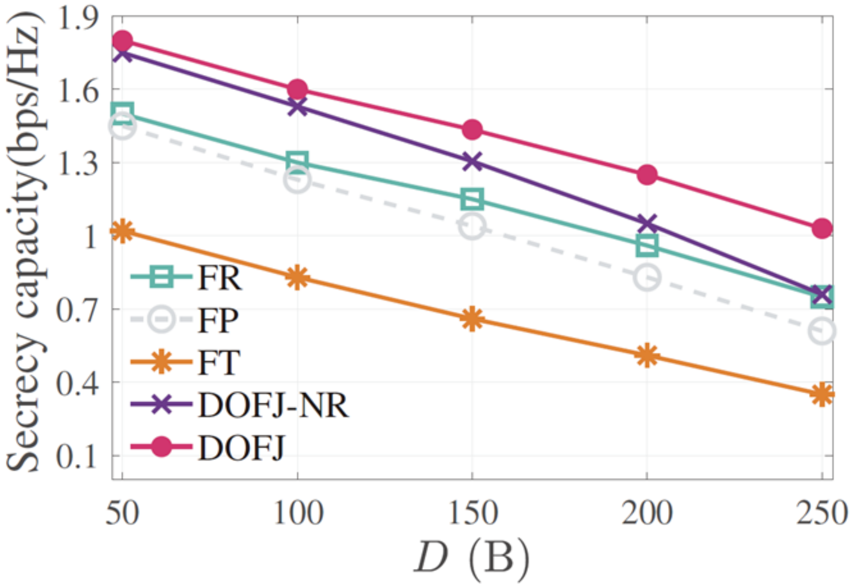
- **Effectiveness:** There is an optimal jamming power level for jamming effectiveness
- **Suppression:** The DOFJ leverage UAV jamming resources to suppress eavesdropper channels and maximize secure communication

Performance Comparison (cont.)



Eavesdropper Uncertainty

- **Predictability:** Secrecy capacity decreases as the uncertainty region of the eavesdropper grows
- **Robustness:** The DOFJ achieves the best performance

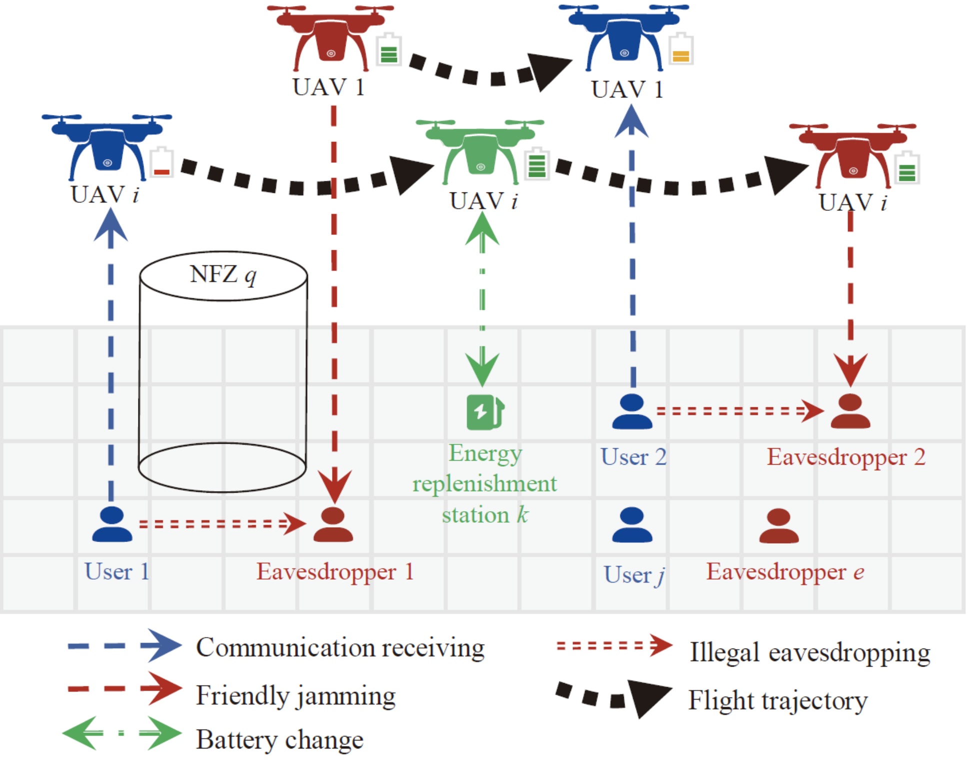


User Data Size

- **Vulnerability:** Larger data collection requirements create more vulnerability
- **Trade-off:** The DOFJ balances the need for large-scale data collection and the maintenance of high security levels

Conclusions

- **Established a multi-UAV assisted uplink secure communication system** with dynamic role switching
- **Formulated a joint optimization problem** to maximize the average secrecy capacity by jointly optimizing UAV role-switching decisions, power allocation, and trajectory planning under practical constraints
- **Developed a BCD- and SCA-based optimization algorithm**, which achieves superior secrecy capacity performance in simulations



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The End

Thank you！

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