Paper #1433

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Multiscale Adaptive Scheduling and Path-Planning for Power-Constrained UAV-Relays via SMDPs

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Motivation

Need for multi-tier/non-terrestrial Radio Access Networks (RANs):

- Sustained device proliferation
- Advanced next-generation RANs promising URLLC services
- Intensive data-driven applications spanning nearly every sector
- Massive OPEX and CAPEX in horizontally scaling terrestrial RANs

R&D emphasis on vertical scaling:

- Unmanned Aerial Vehicles (UAVs);
- High Altitude Platforms (HAPs); and
- Low Earth, Medium Earth, & Geostationary Earth Orbit (LEO, MEO, GEO) satellites

operating cooperatively to offload traffic, extend coverage, and enhance QoS

We will be focusing on UAV-relays augmenting terrestrial networks

3D Mobility & Maneuverability of UAVs are leveraged in:

- Military deployments
- Disaster-Relief
- Precision Agriculture
- URLLC QoS guarantees in Industrial IoT

Why UAVs?

09.23.2020 | **Public Safety** | **First Responders**

Verizon deploys remote network-connected drone during Big Hollow Wildfire

Media contact(s)

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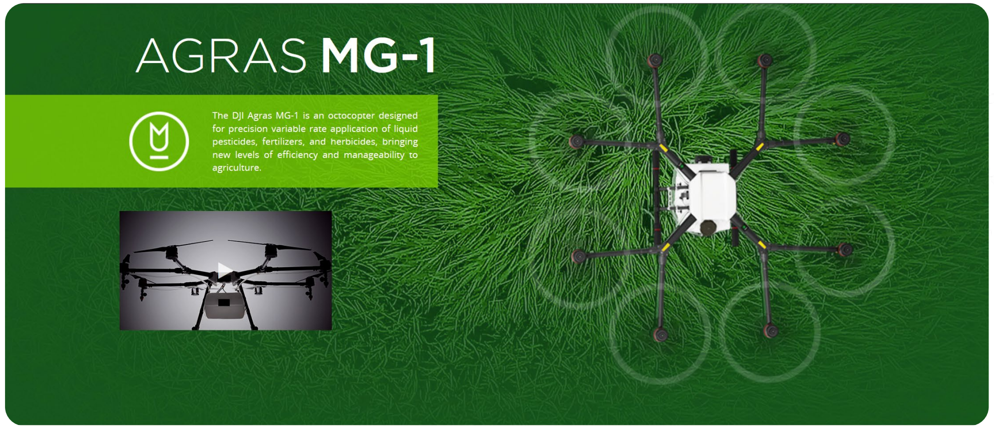
Federal Aviation Administration grants special waiver to allow civilian operations to inspect critical communications infrastructure in the U.S.

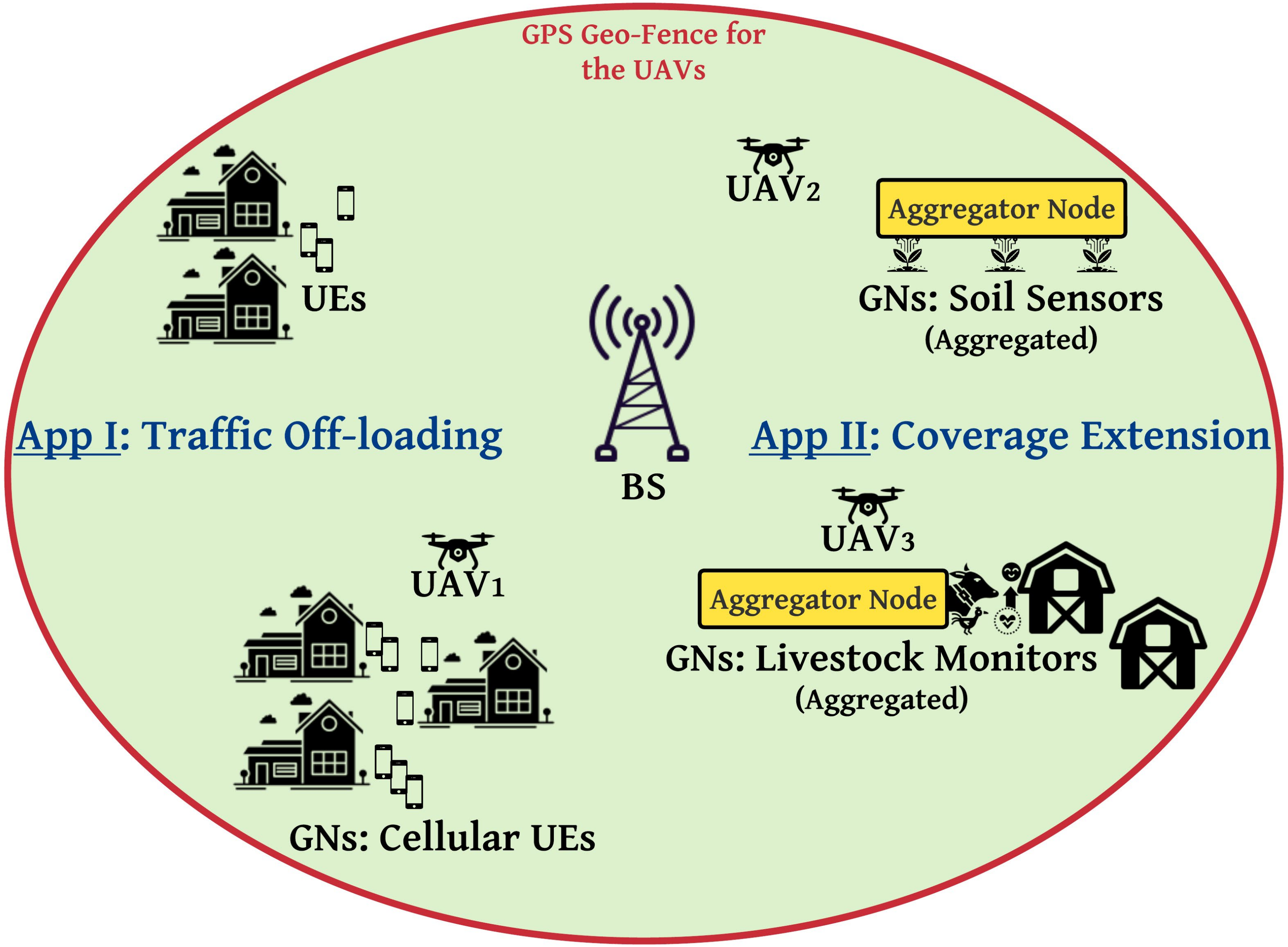
03.08.2019 | **Verizon News Archives**

Robots, drones and sensors are changing the way we farm

By: Suzanne Guillette

This tech brings agriculture into the 21st century



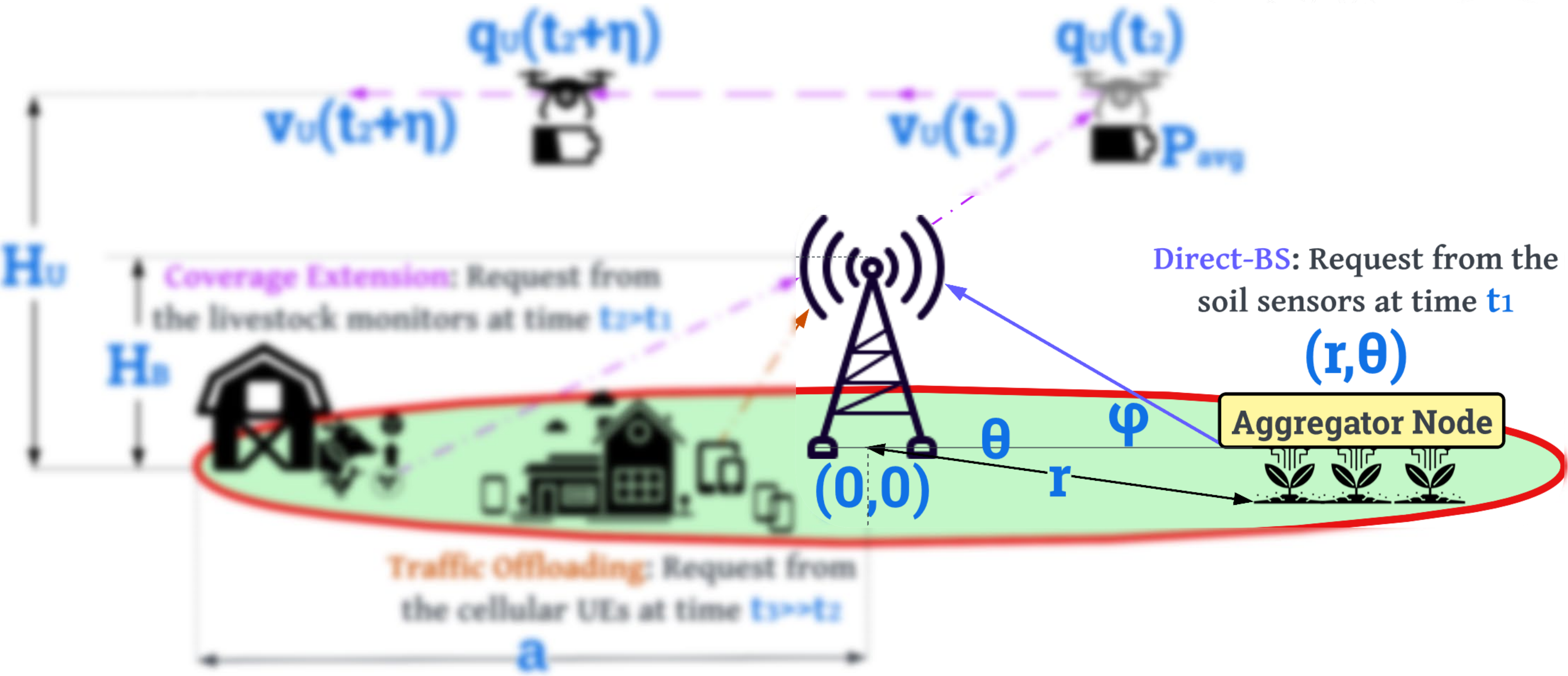


Deployment: Orchestrating a swarm of UAVs serving as cellular relays, augmenting a terrestrial BS

Objective: Optimizing service delays experienced by GNs vs on-board UAV energy constraints

Questions

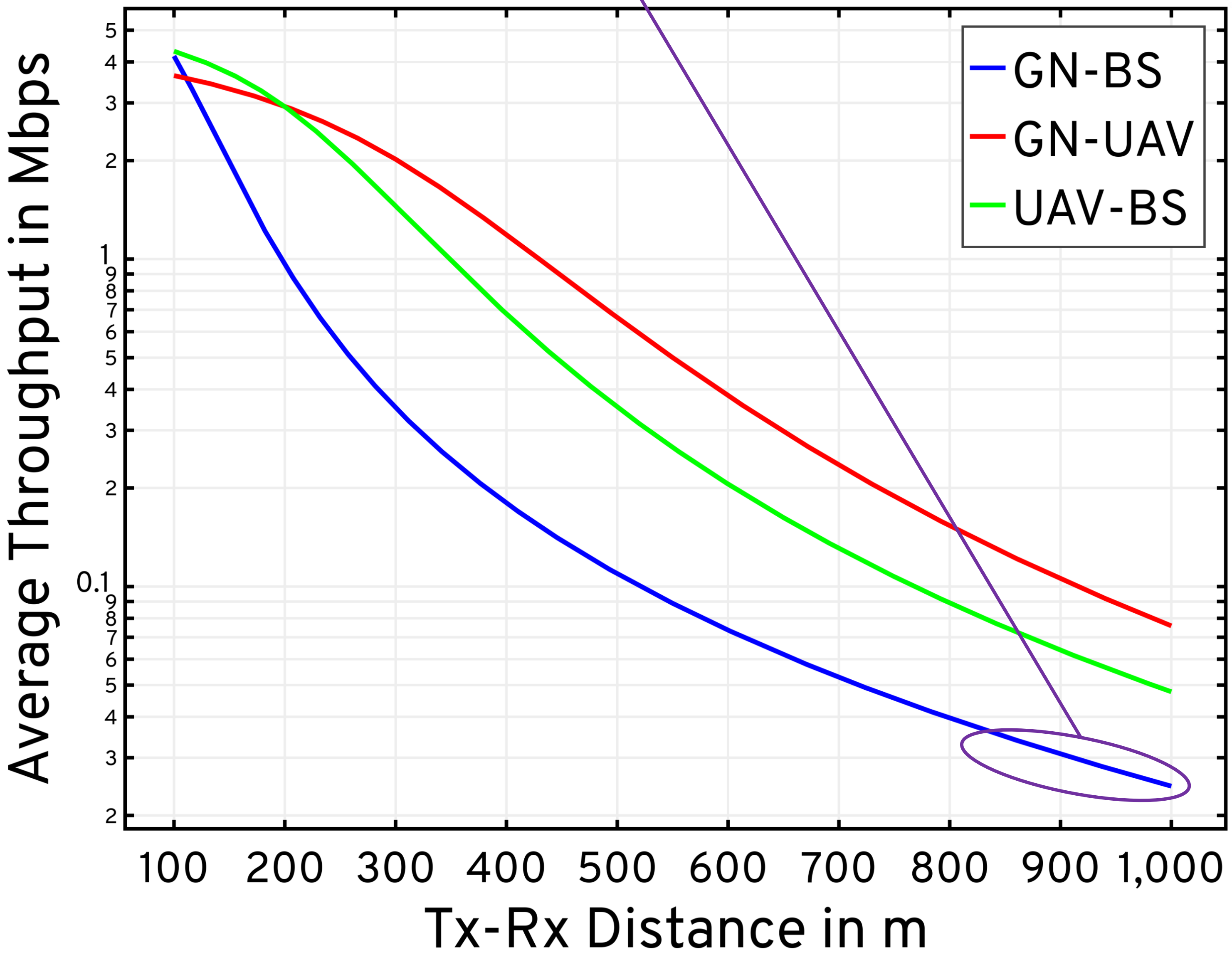
- How do UAV relays assist in improving service latencies in terrestrial networks?



Question setup: GN requests in Precision Agriculture | Service through UAV or BS?

BS height = 60 m | UAV height = 200 m | BW = 1 MHz

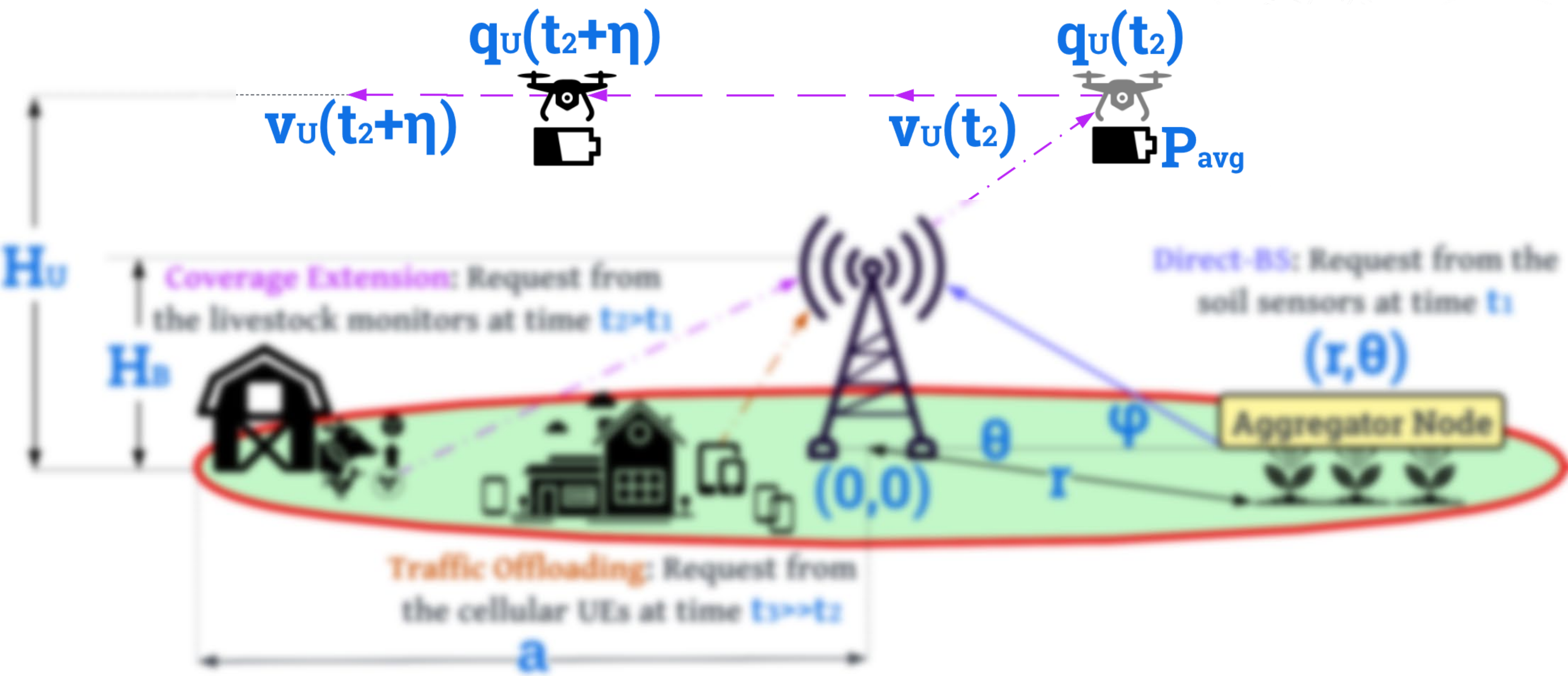
GNs farther away from the BS experience poor path-loss conditions and attenuations due to NLoS propagation (BVLoS/blockages)



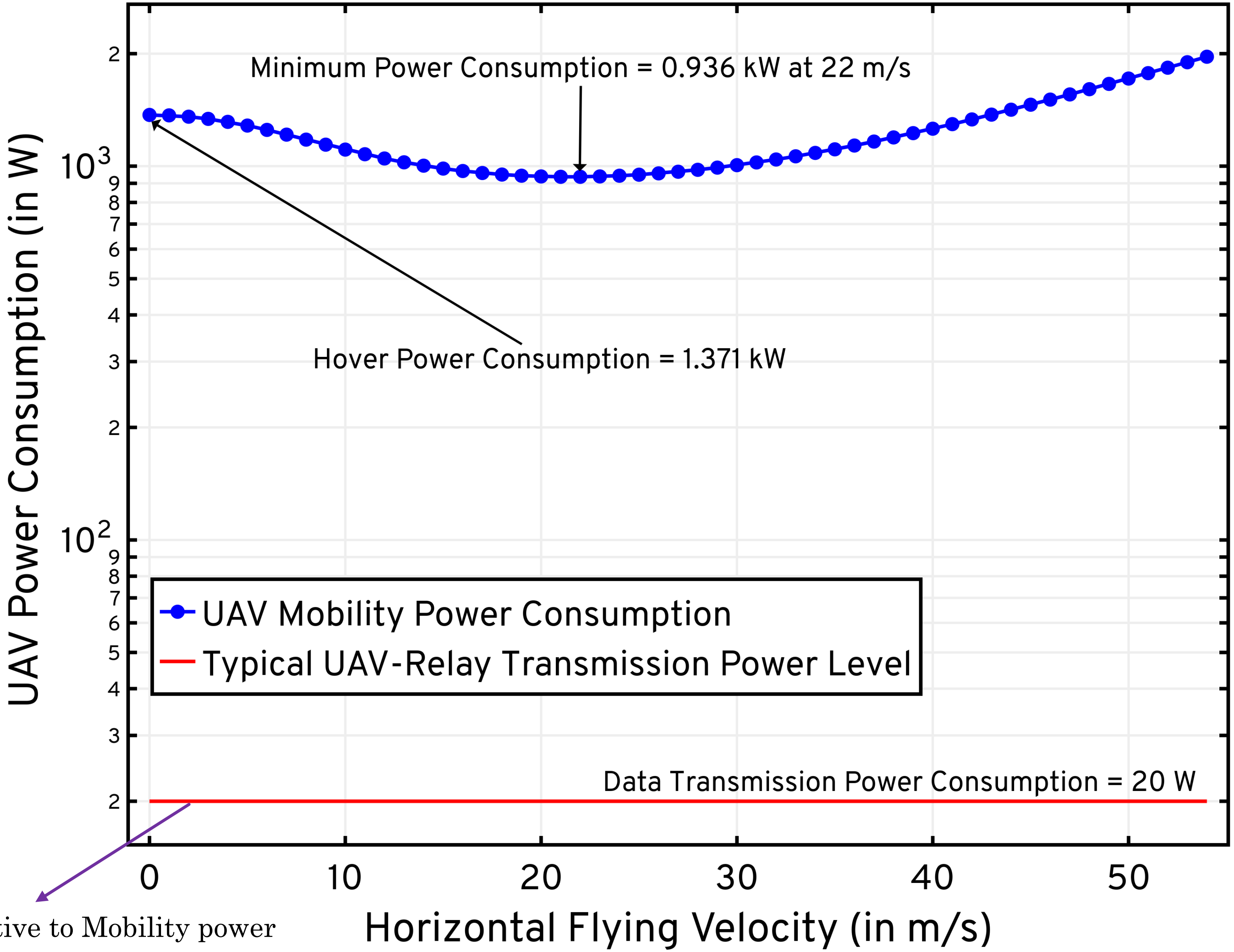
Exploiting LoS performance in GN-UAV-BS communications

Questions

- How do UAV relays assist in improving service latencies in terrestrial networks?
- Why is optimizing the UAV’s mobility important for its battery-life?



Question setup: Relayed Service through UAV | Moving under P_{avg} constraint



Tx power negligible relative to Mobility power

Optimizing UAV Mobility Power Consumption

State-of-the-art: Drawbacks

- Control [1, 2, 3, 4]:
  - Non-adaptive: Deterministic traffic models
  - Approaches rely on Successive Convex Approximation (SCA):
    - Iterative optimization of non-convex problems via convex approximations at a local point
    - Involves prohibitively large policy convergence times

- Channel Model [1,2,3,4]:
  - Inaccurately employ free space path-loss models
  - Fail to exploit the A2G channel characteristics
  - SCA: Approximations in data payload delivery constraints to enforce convexity

[1] Y. Zeng et al., "Energy Minimization for Wireless Communication With Rotary-Wing UAV," IEEE Transactions on Wireless Communications, vol. 18, no. 4, pp. 2329–2345, April 2019.
[2] M. A. Abd-Elmagid and H. S. Dhillon, "Average Peak Age-of-Information Minimization in UAV-Assisted IoT Networks," IEEE Transactions on Vehicular Technology, vol. 68, no. 2, pp. 2003–2008, 2019.
[3[X. Hu et al., "UAV-Assisted Relaying and Edge Computing: Scheduling and Trajectory Optimization," IEEE Transactions on Wireless Communications, vol. 18, no. 10, pp. 4738–4752, 2019
[4] C. You and R. Zhang, "3D Trajectory Optimization in Rician Fading for UAV-Enabled Data Harvesting," IEEE Transactions on Wireless Communications, vol. 18, no. 6, pp. 3192–3207, 2019

State-of-the-art: Drawbacks

- UAV Trajectory Design:
  - Static positioning [1,2,3]
  - SCA [4]: Approximations in mobility model constraints to enforce convexity
  - Restricted Mobility: Fixed forward flying velocity [4] | Impractical path structures [3]
  - Particle Swarm Optimization (PSO) [1,2,3] is inefficient (limited update scope) and computationally intractable

- UAV Deployment:
  - Single UAV deployments are insufficient [1,2,3,4]
  - Centralized swarm control suffers from higher OPEX and CAPEX [5,6]
  - Joint multi-UAV constructions [7,8] lead to prohibitively large solution spaces

[1] H. Shakhatreh et al., "Efficient 3D placement of a UAV using particle swarm optimization," in 2017 8th International Conference on Information and Communication Systems (ICICS), 2017, pp. 258–263.
[2] Z. Yuheng et al., "3-D Deployment Optimization of UAVs Based on Particle Swarm Algorithm," in 2019 IEEE 19th International Conference on Communication Technology (ICCT), 2019, pp. 954–957.
[3] R. K. Patra, P. Muthuchidambaranathan, "Optimisation of Spectrum and Energy Efficiency in UAV-Enabled Mobile Relaying Using Bisection and PSO Method," in 2018 International Conference for Convergence in Technology (I2CT), 2018, pp. 1–7.
[4] M. A. Abd-Elmagid and H. S. Dhillon, "Average Peak Age-of-Information Minimization in UAV-Assisted IoT Networks," IEEE Transactions on Vehicular Technology, vol. 68, no. 2, pp. 2003–2008, 2019.
[5] Q. Wu et al., "Joint Trajectory and Communication Design for Multi-UAV Enabled Wireless Networks," IEEE Transactions on Wireless Communications, vol. 17, no. 3, pp. 2109–2121, 2018.
[6] M. Mozaffari et al., "Efficient Deployment of Multiple Unmanned Aerial Vehicles for Optimal Wireless Coverage," IEEE Communications Letters, vol. 20, no. 8, pp. 1647–1650, 2016.
[7] Q. Hu et al., "Low-Complexity Joint Resource Allocation and Trajectory Design for UAV-Aided Relay Networks With the Segmented Ray-Tracing Channel Model," IEEE Transactions on Wireless Communications, vol. 19, no. 9, pp. 6179–6195, 2020.
[8] A. E. A. A. Abdulla et al., "Toward Fair Maximization of Energy Efficiency in Multiple UAS-Aided Networks: A Game-Theoretic Methodology," IEEE Transactions on Wireless Communications, vol. 14, no. 1, pp. 305–316, Jan 2015.

Our Contributions: Addressing the drawbacks

- Adaptive Control:
  - UAVs relay dynamically-generated traffic from randomly distributed GNs
  - Semi-Markov Decision Process (SMDP) formulation captures temporal irregularities in state transitions
- A2G Channel Model:
  - Accurately model A2G channel characteristics along BS-UAV and GN-UAV links
  - Incorporation of rate-adaptation at all transmitters to maximize system throughput

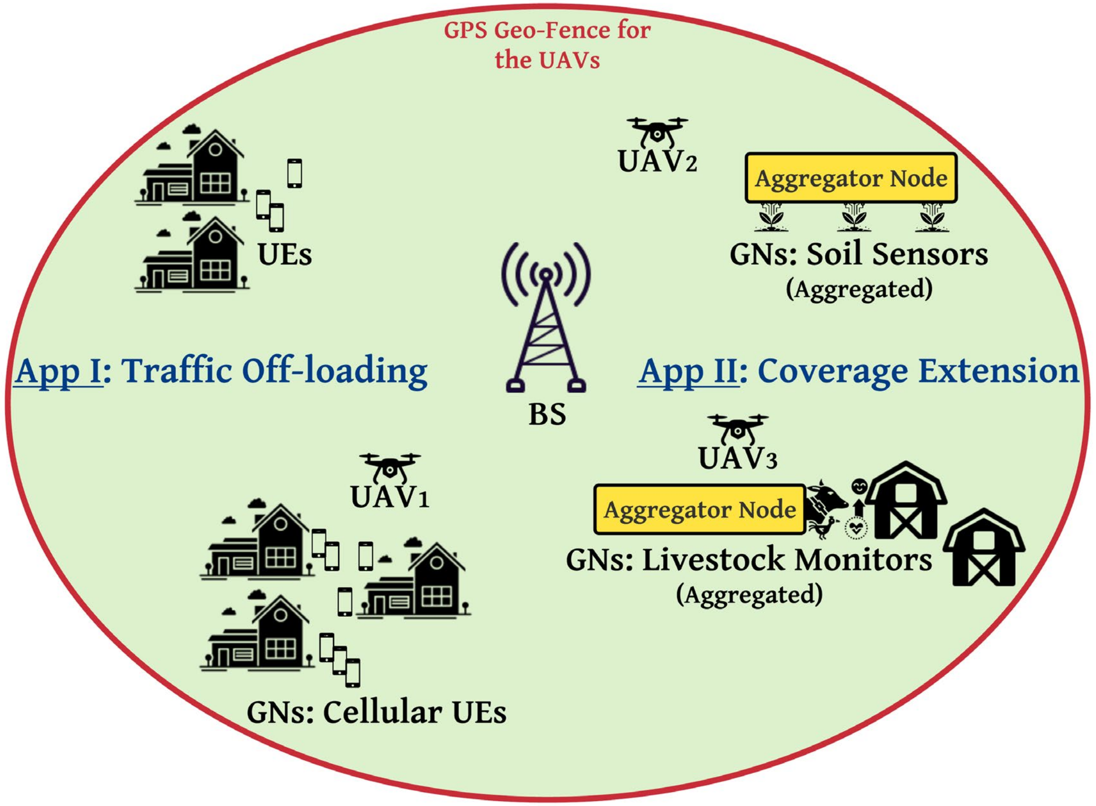
Our Contributions: Addressing the drawbacks

- UAV Trajectory Design:
  - Competitive Swarm Optimization (CSO)
  - Unlike SCA, CSO does not rely on a specific problem structure
  - Unlike PSO, CSO has more efficient updates via pair-wise competition

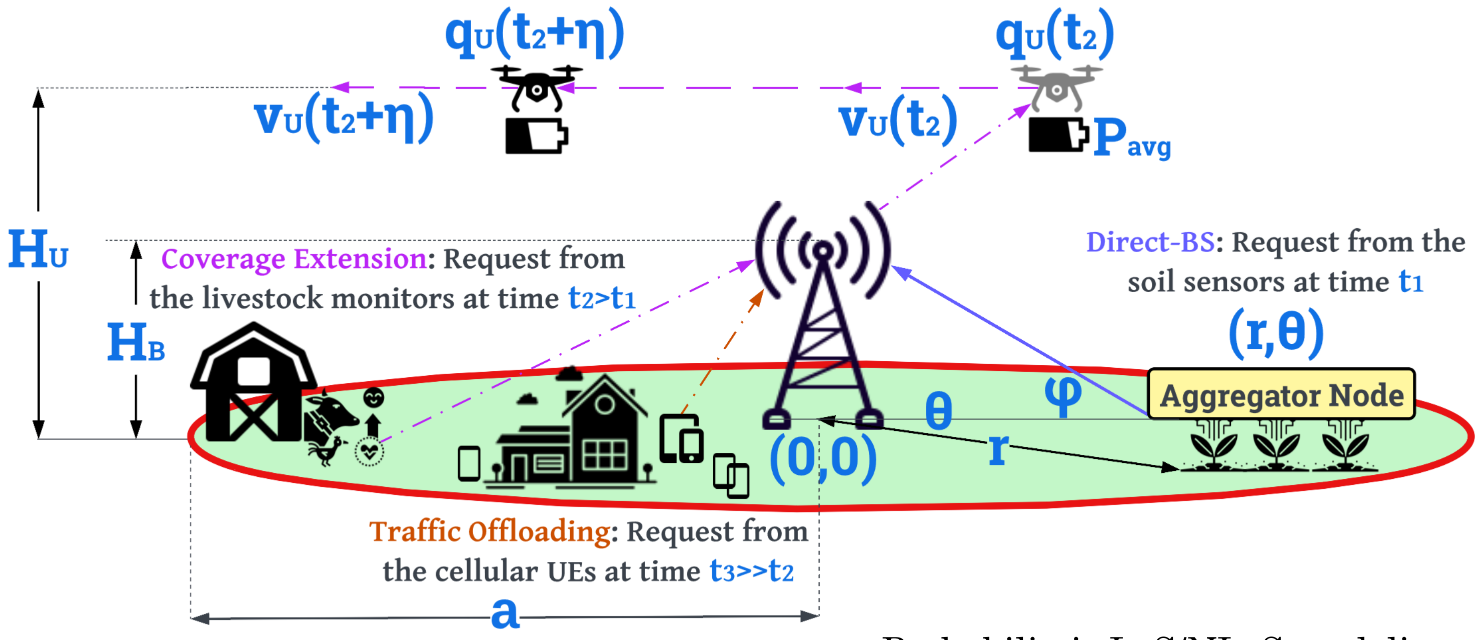
- Distributed Swarm Deployments:
  - Decoupled executions via policy replication across the swarm
  - Overlay a fully-connected mesh network for command & control
  - Multi-UAV heuristics for spread maximization and conflict resolution

System Model: Deployment

- N_U rotary-wing UAV relays assisting a terrestrial BS
- Circular cell of radius a
- GNs generate uplink requests of L bits according to a Poisson process with rate Λ
- BS uses k orthogonal channels (OFDMA)
- Each UAV equipped with one transceiver chain
- Decode & Forward (D&F) strategy



System Model: Channel



- Channel coefficient: $h = \sqrt{\beta} g$
- $\beta = \beta_{\text{LoS}}(d) = \beta_0 d^{-\alpha}$ and $\beta = \beta_{\text{NLoS}}(d) = \kappa\beta_0 d^{-\tilde{\alpha}}$ capture large-scale variations for LoS & NLoS
- φ-dependent $K-$factor, i.e., $K(\varphi) = k_1 \exp(k_2\varphi)$
- g with $E[|g|^2] = 1$ models small-scale fading
- g is modeled as Rician fading for LoS links and as Rayleigh fading for NLoS links

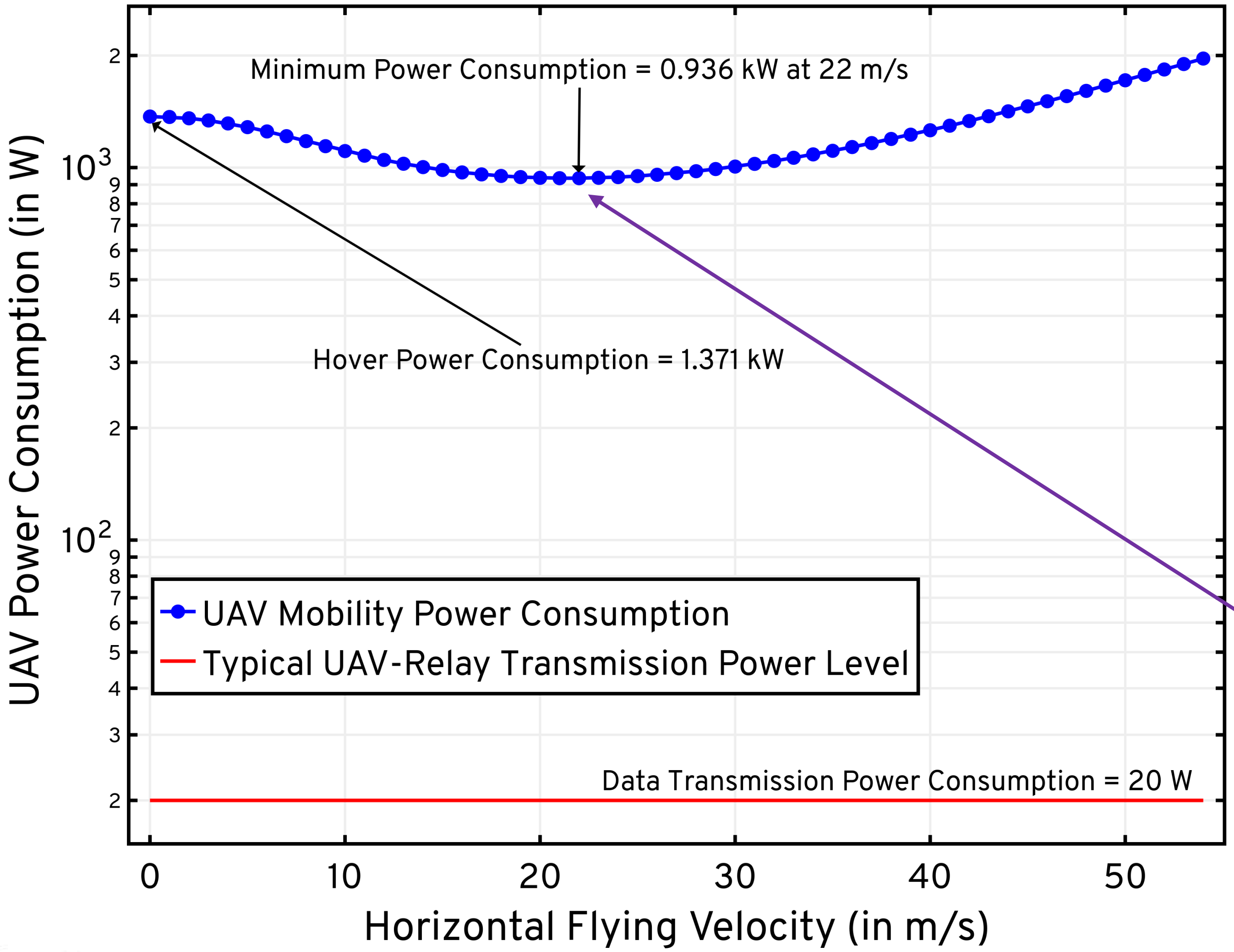
Probabilistic LoS/NLoS modeling

- LoS probability: $P_{\text{LoS}}(\varphi) = \frac{1}{1+z_1 \exp(-z_2[\varphi - z_1])}$
- NLoS probability: $P_{\text{NLoS}}(\varphi) = 1 - P_{\text{LoS}}(\varphi)$

[1] C. You and R. Zhang, “3D Trajectory Optimization in Rician Fading for UAV-Enabled Data Harvesting,” IEEE Transactions on Wireless Communications, vol. 18, no. 6, pp. 3192–3207, 2019.
[2] A. Al-Hourani, S. Kandeepan, and S. Lardner, “Optimal LAP Altitude for Maximum Coverage,” IEEE Wireless Communications Letters, vol. 3, no. 6, pp. 569–572, 2014.
[3] D. Tse and P. Viswanath, Fundamentals of Wireless Communication. Cambridge: Cambridge University Press, 2005.
[4] R. Essaadali and A. Kouki, “A new simple Unmanned Aerial Vehicle doppler effect RF reducing technique,” in MILCOM 2016 - 2016 IEEE Military Communications Conference, 2016, pp. 1179–1183.

Rate Adaptation

- We assume signal degradation via the Doppler effect is well-compensated at the receiver
- The large-scale channel variations vary slowly relative to the rate of Channel State Information (CSI) acquisition
    - At the transmitters, we know the large-scale channel variations ($\beta, K(\varphi)$, LoS/NLoS probabilities)
    - These large-scale variations (β, K) are coordinated over the control network, i.e., CSI feedback
- Not knowing the small-scale variations, we adapt the rate to maximize throughput



System Model: Power

Negligible relative to Mobility power usage

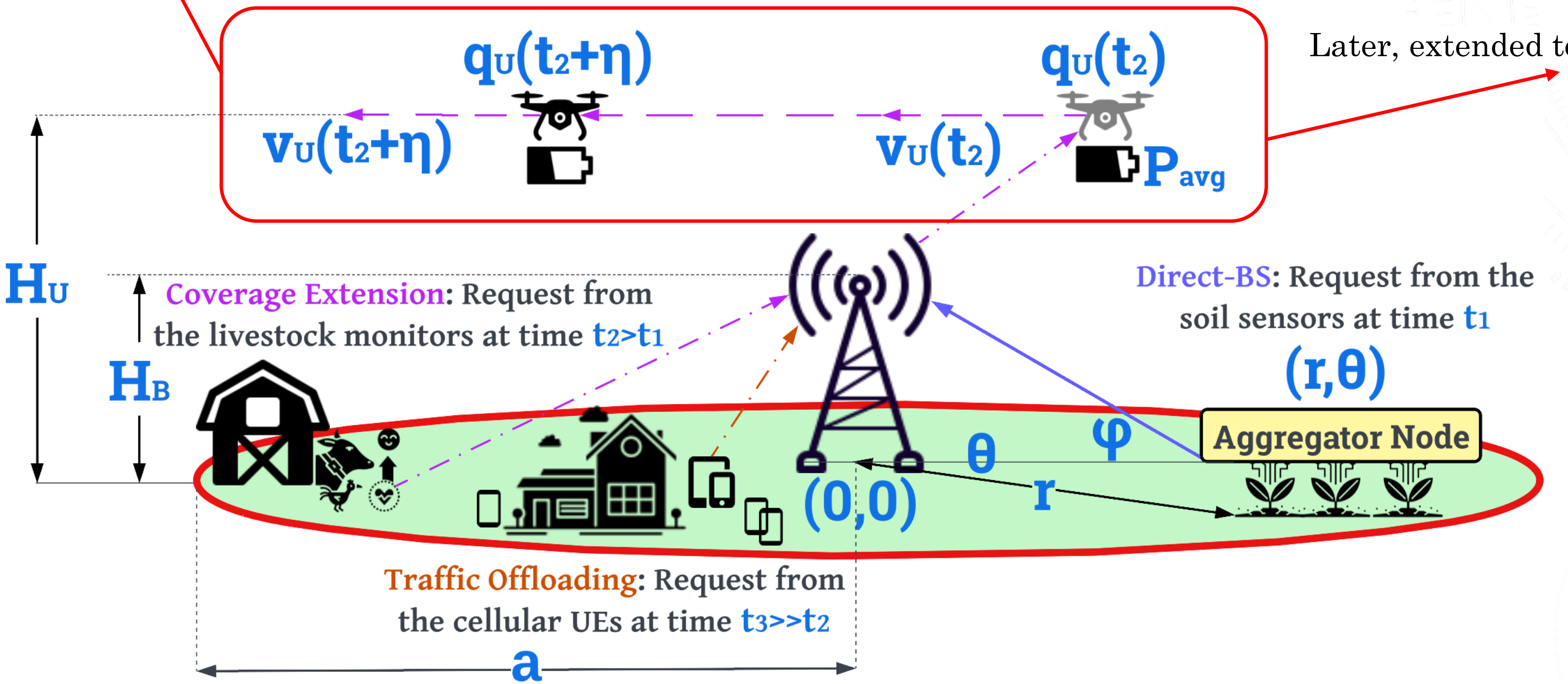
- $P_{U_i}(t) = \boxed{P_{U_i,\mathrm{comm}}(t)} + P_{\mathrm{mob}}\left(v_{U_i}(t)\right)$
- $P_{\mathrm{mob}}(V) = P_1\left(1 + \frac{3V^2}{U_{\mathrm{tip}}^2}\right) + P_2\left(\sqrt{1 + \frac{V^4}{4v_0^4}} - \frac{V^2}{2v_0^2}\right)^{1/2} + P_3V^3$
- P_1, P_2, P_3 are scaling constants
- Dynamic UAV movements are more power-efficient relative to static hovering

[1] Y. Zeng et al., "Energy Minimization for Wireless Communication With Rotary-Wing UAV," IEEE Transactions on Wireless Communications, vol. 18, no. 4, pp. 2329–2345, April 2019.

Restricting our generalized system model to a single UAV to find the optimal control policy

The Single-Agent Specialization

Later, extended to multiple UAVs

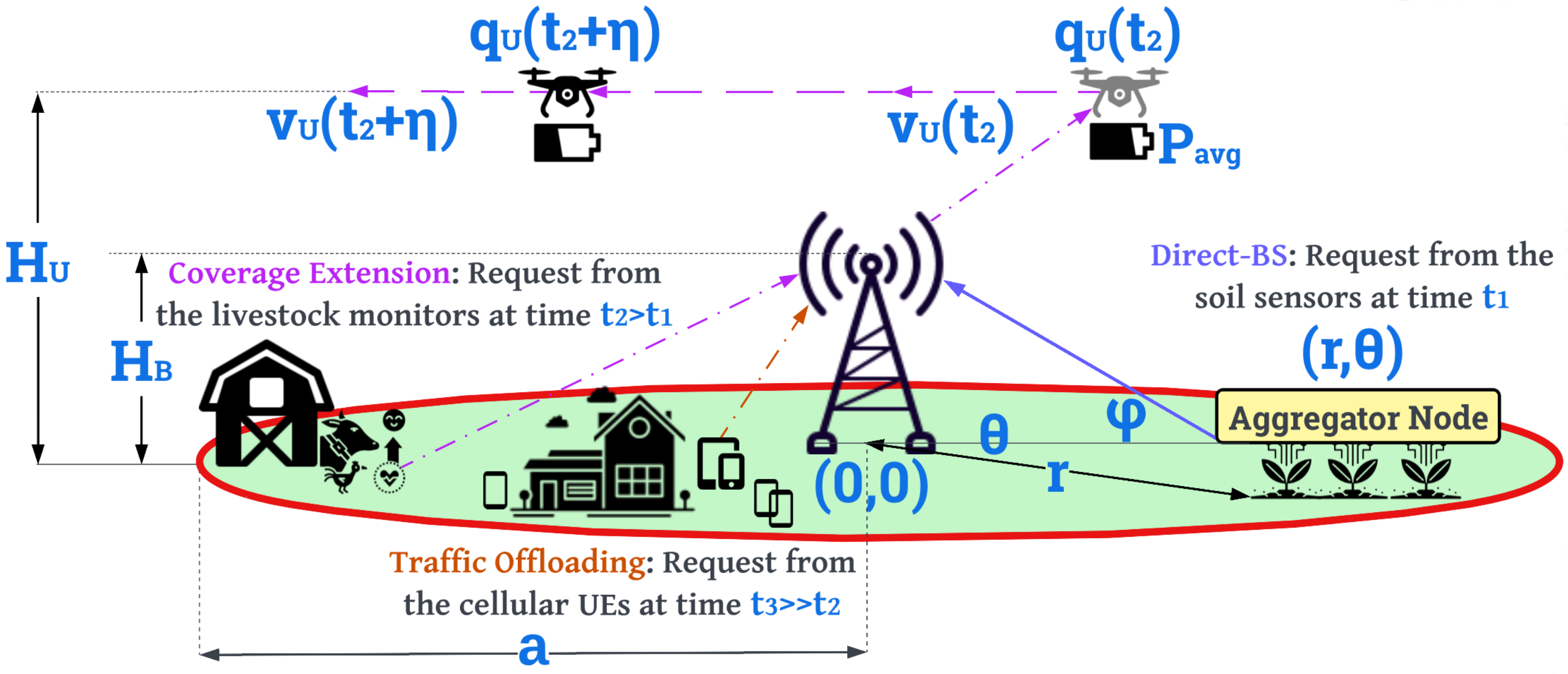


- UAV radius level $r_U(t) \in R_+$ and UAV angular position $\theta_U(t) \in [0,2\pi)$
- Polar coordinate of the UAV at time t: $\boldsymbol{q}_U(t) = \left(r_U(t), \theta_U(t)\right)$
- Effective traffic rate experienced by the UAV $= \Lambda/N_U$ [req/time]

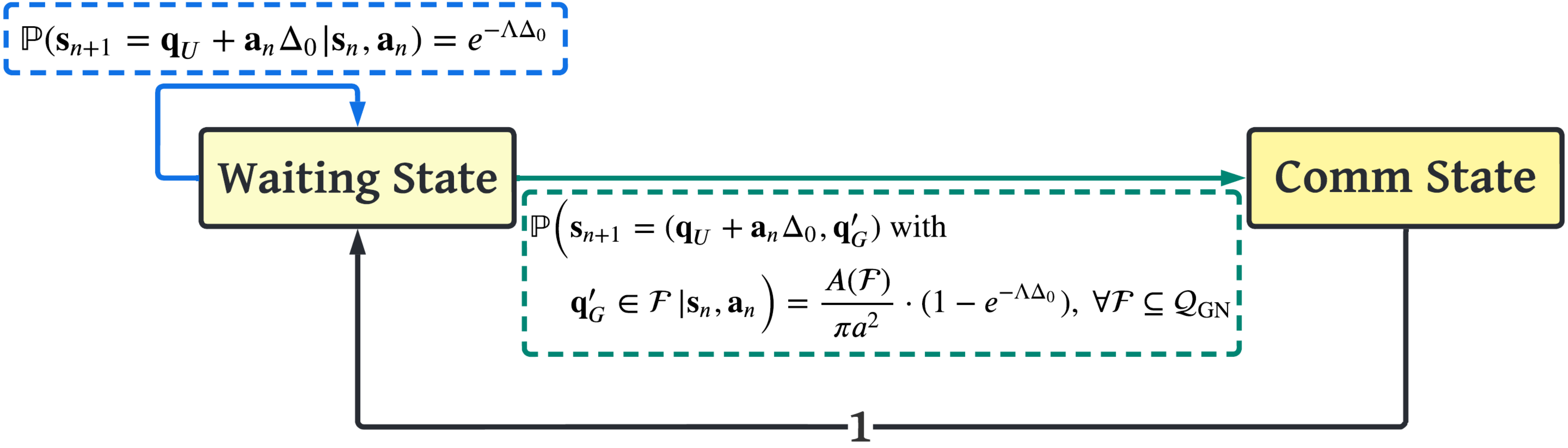
The Optimization Problem

- Minimize the expected average service time for scheduled requests subject to a UAV energy constraint
- Formulate the Lagrangian
- Decoupled into waiting- and communication-state optimization
- Solved via a Semi-Markov Decision Process (SMDP) construction

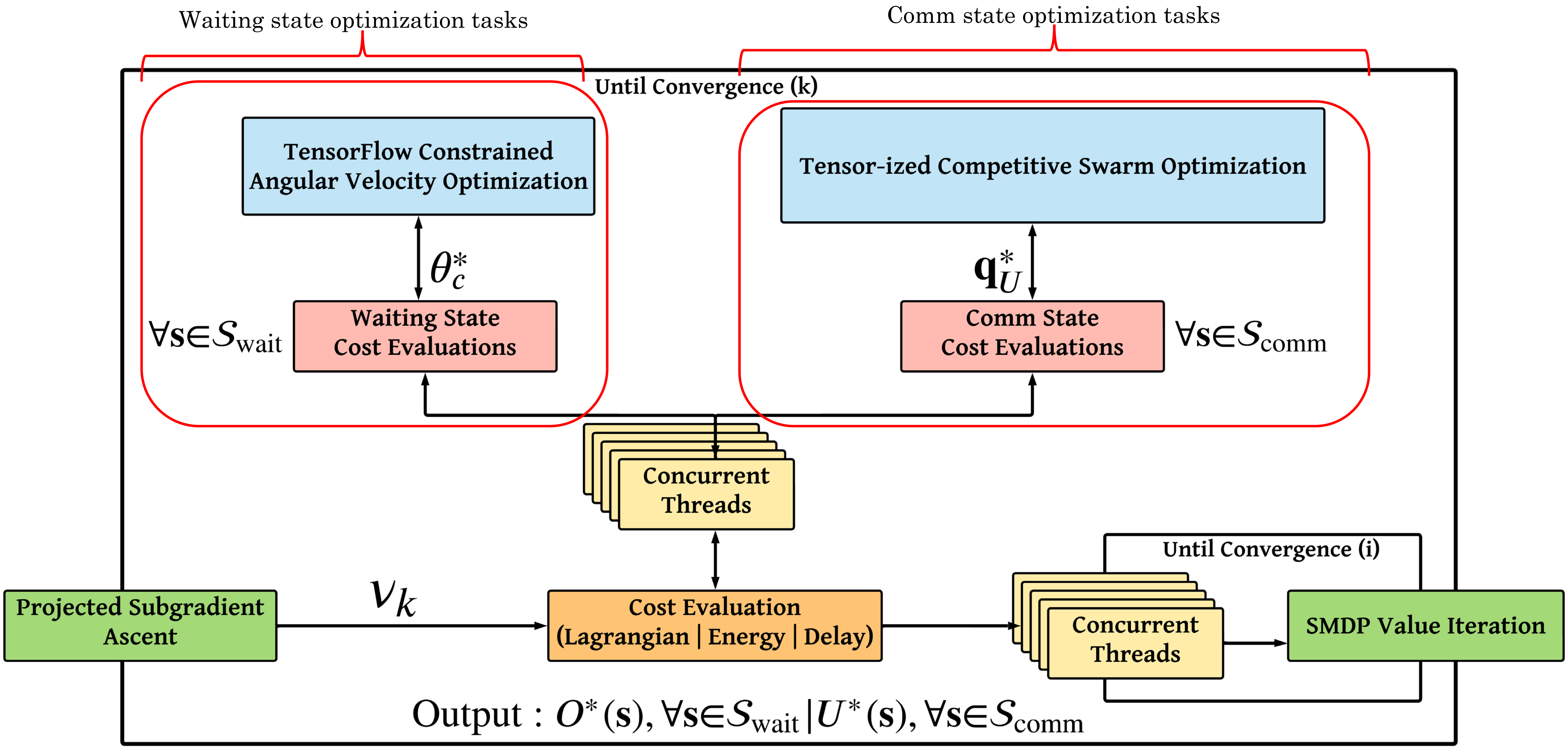
SMDP Formulation: States & Actions



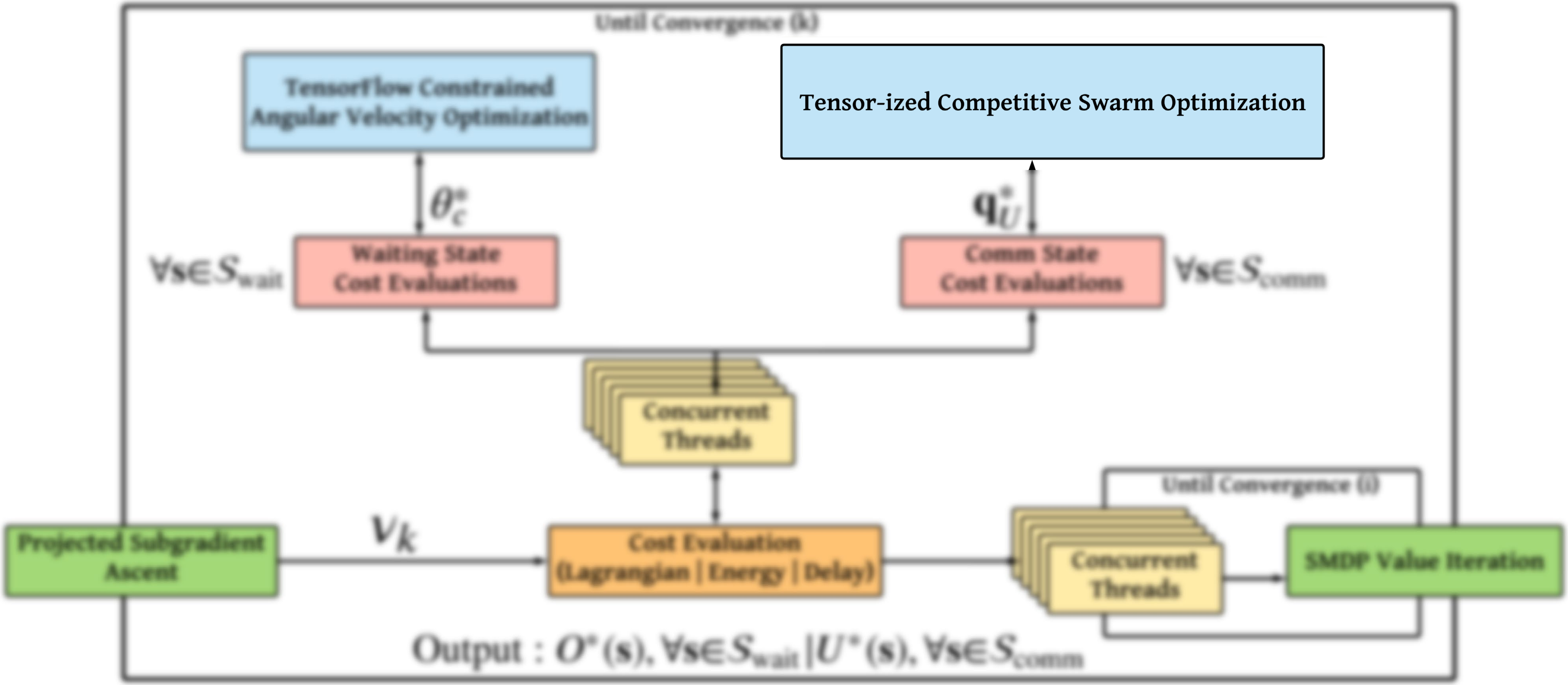
- Waiting states: UAV position $\boldsymbol{q}_U = (r_U, \theta_U)$ | Waiting actions: Radial & Angular velocities v_r, θ_c
- Comm states: UAV and GN positions $(\boldsymbol{q}_U, \boldsymbol{q}_G) = (r_U, \theta_U, r, \theta)$ | Comm actions: Schedule & Trajectory $\xi, \boldsymbol{q}'_U, Q_{\boldsymbol{q}_G}(\boldsymbol{q}_U \to \boldsymbol{q}'_U)$
- Angular symmetry simplifies the multiscale decomposition of our problem



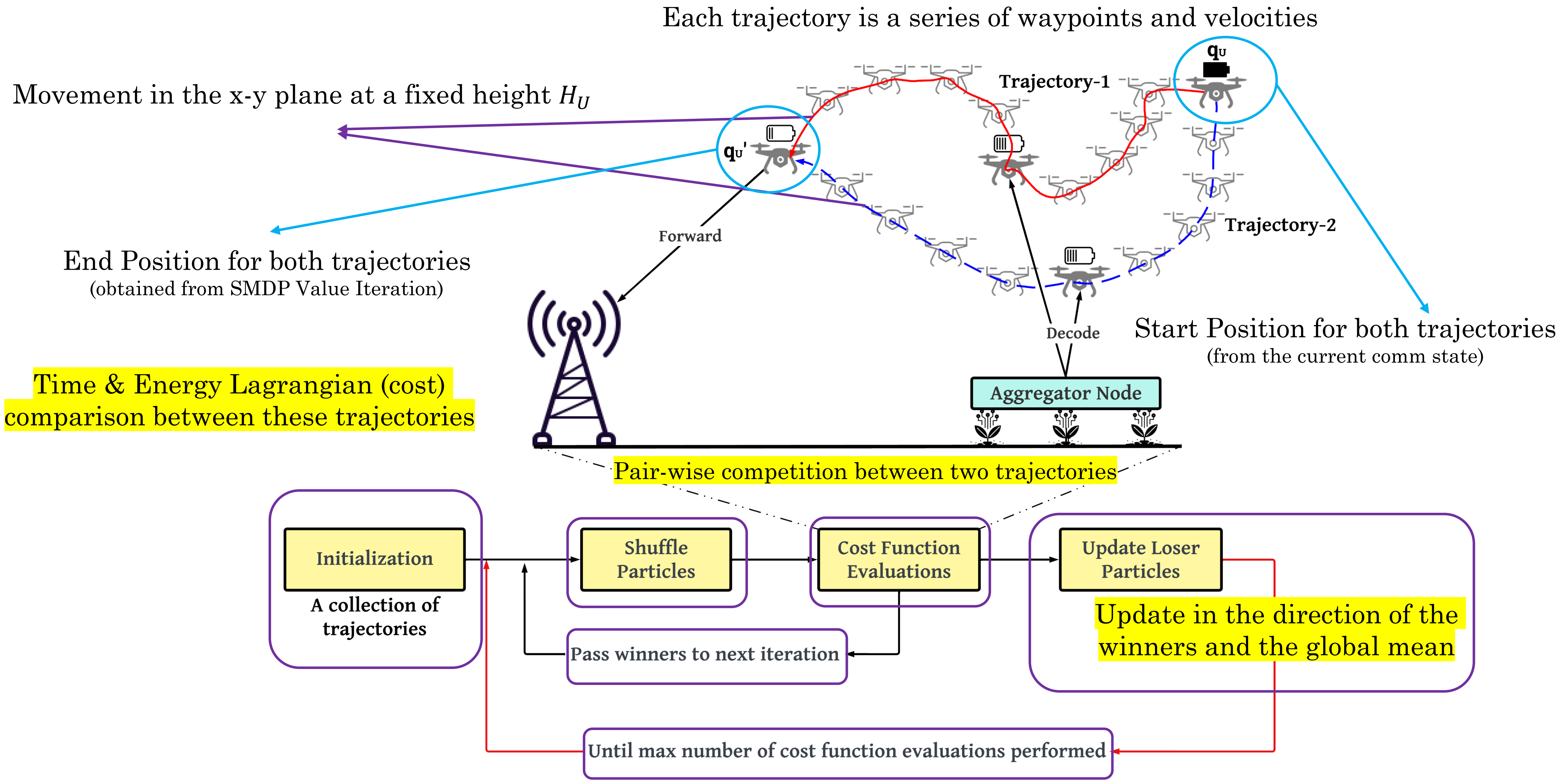
SMDP Formulation: Transition Model



Algorithmic Flow of the single-agent optimization process



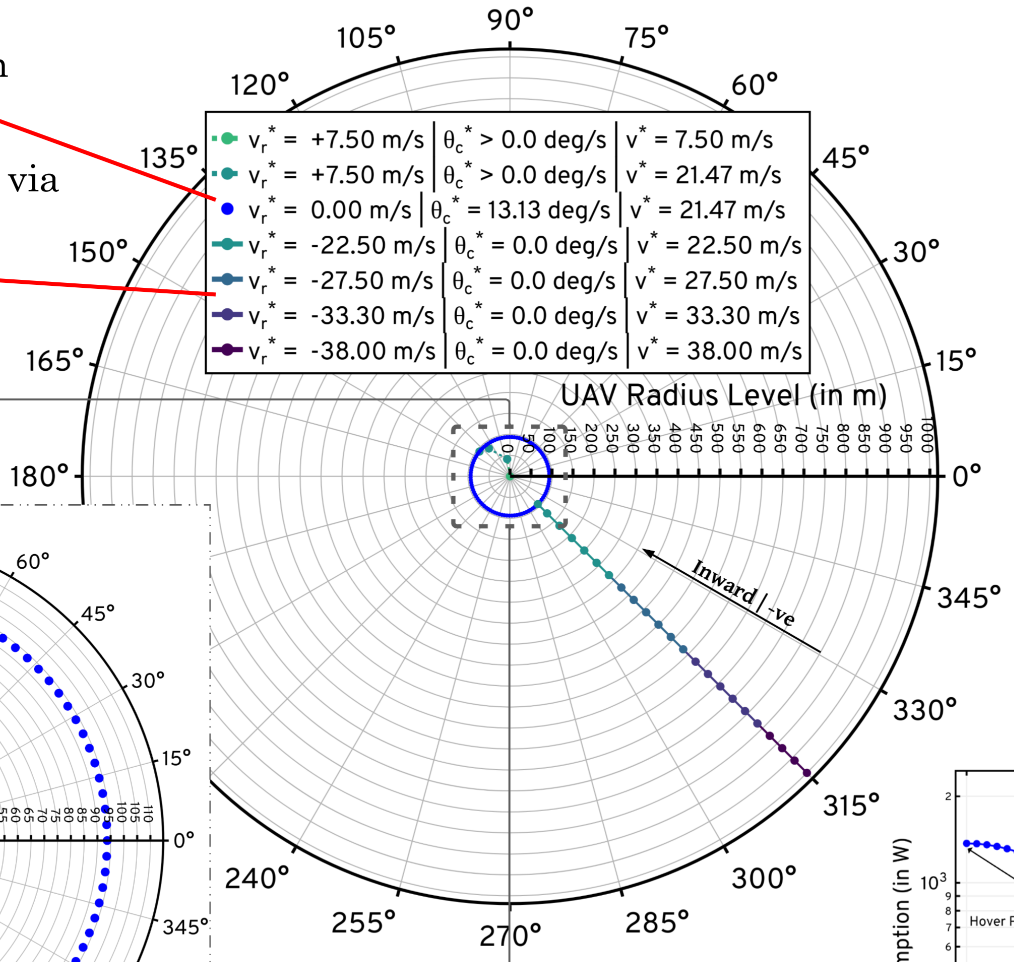
Algorithmic Flow of the single-agent optimization process



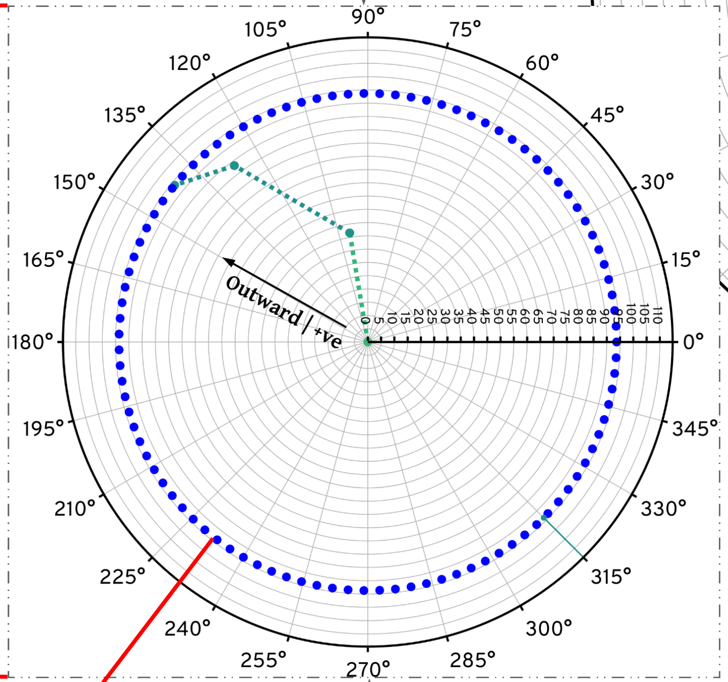
Algorithmic Flow of the CSO Trajectory Design process

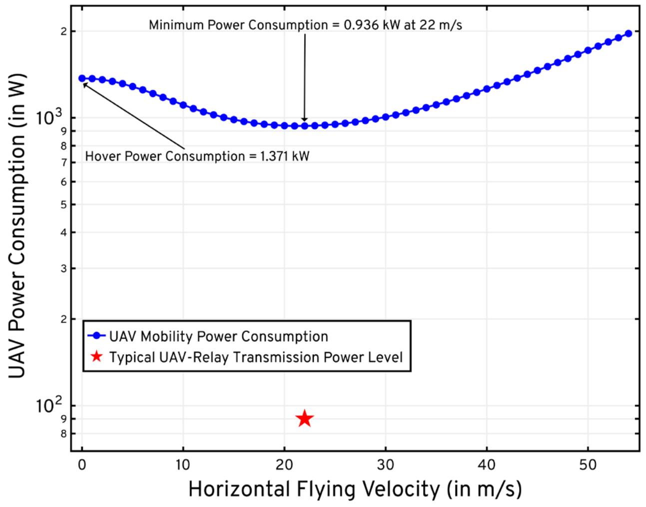
Optimal radial velocity obtained via SMDP Value Iteration

Given this radial velocity action, angular velocity obtained via minimization of mobility power consumption



Zoomed-in version



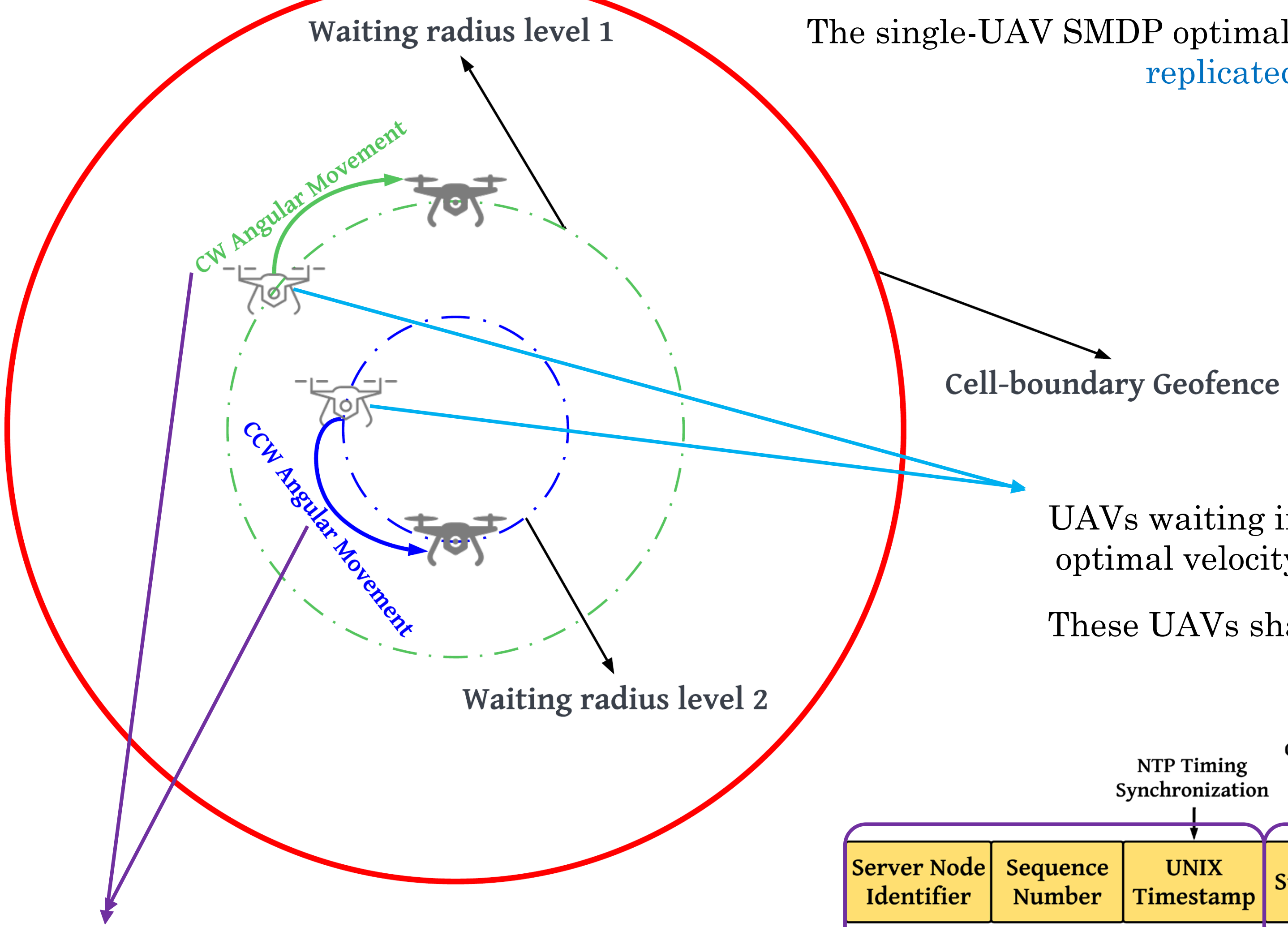


To minimize mobility power consumption, the UAV waits at ~95 m radius level

Optimal Waiting Policy Visualization: $L = 1$ Mb

Extension to UAV Swarms

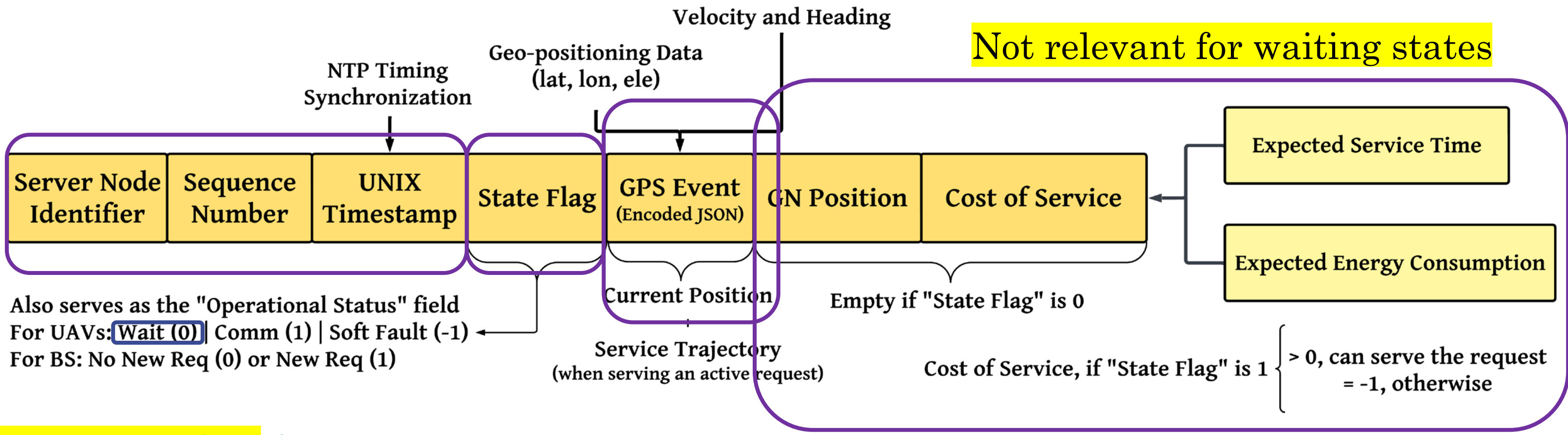
The single-UAV SMDP optimal wait policy is augmented with spread maximization and replicated across all the UAVs in the swarm



UAVs waiting in a particular radius level at the optimal velocity according to the derived policy

These UAVs share control frames amongst each other over the command-and-control network

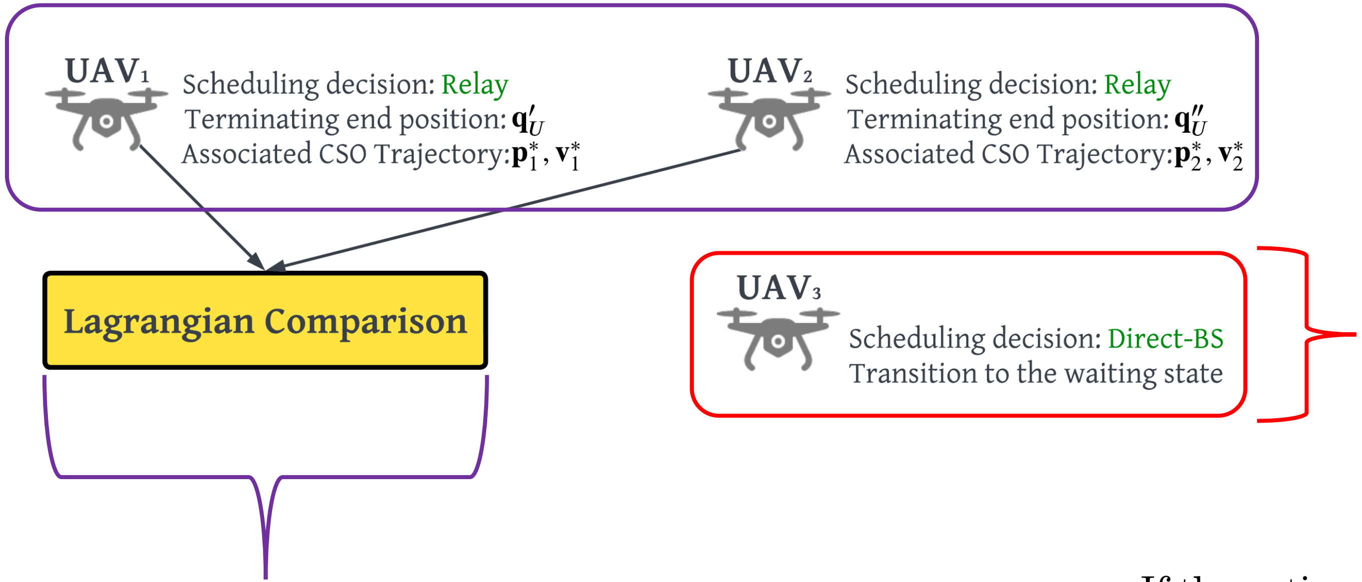
Maximize the angular spread by controlling CW/CCW angular movements



The objective here is to better position and prime the waiting UAVs for potential new requests

Extension to UAV Swarms

The single-UAV SMDP optimal comm policy is augmented with conflict resolution and replicated across all the UAVs in the swarm

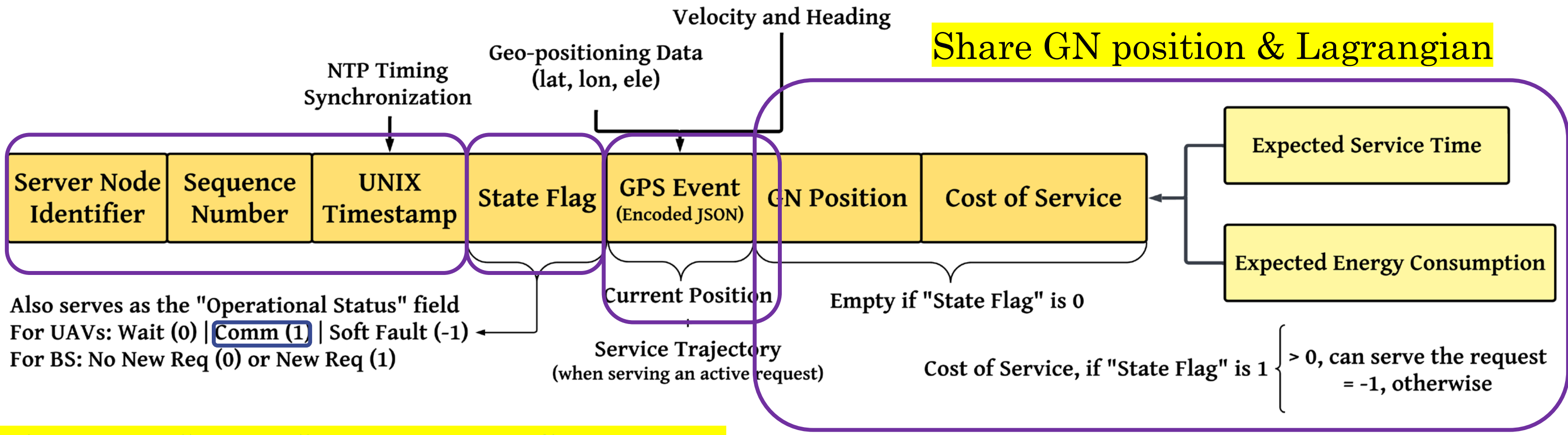


UAVs with "Direct-BS" as their optimal scheduling decision will not take part in the consensus-driven conflict resolution process

Resolve conflict by choosing the node with the smallest Lagrangian (delay & energy cost)

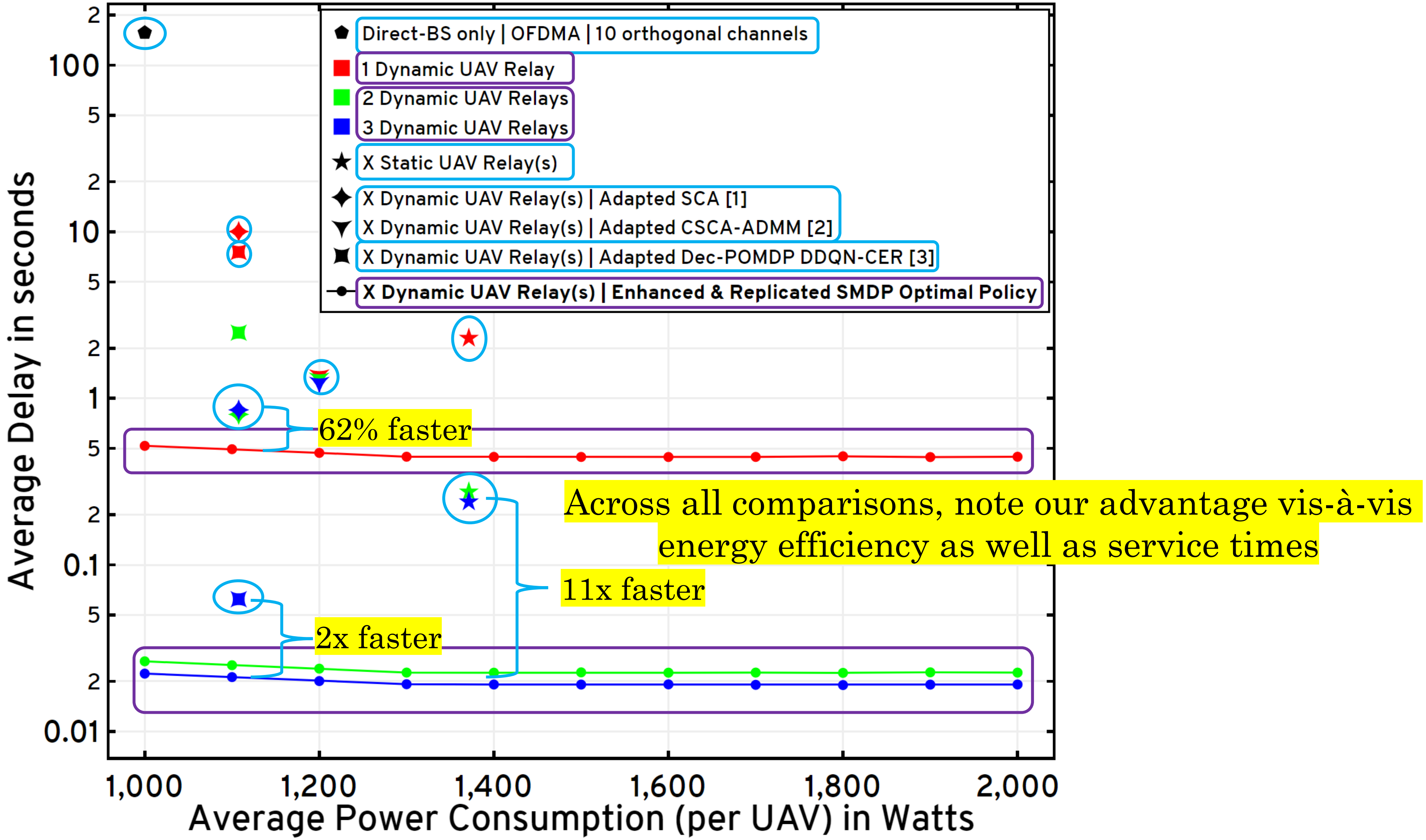
Waiting UAVs enter the comm state when a new request arises from a GN in the cell

If the optimal scheduling action is to provide relayed-service to the GN, then the UAVs share their Lagrangians over the command-and-control network



The objective here is to resolve the conflicts among UAVs that "decide" to serve the GN request

Data Payload Size = 1 Mb | BW = 5 MHz | Arrival Rate = 1 request every minute | 10,000 requests from 300 GNs
BS at (0,0) | BS Height = 80 m | UAV Height = 200 m | UAV Hover Power Consumption = 1.37 kW



Average delay for the GNs versus per-UAV average power constraint

[1] Y. Zeng et al., "Energy Minimization for Wireless Communication With Rotary-Wing UAV," IEEE Transactions on Wireless Communications, vol. 18, no. 4, pp. 2329–2345, April 2019.
[2] Q. Wu et al., "Joint Trajectory and Communication Design for Multi-UAV Enabled Wireless Networks," IEEE Transactions on Wireless Communications, vol. 17, no. 3, pp. 2109–2121, 2018.
[3] H. Bayerlein et al., "Multi-UAV Path Planning for Wireless Data Harvesting With Deep Reinforcement Learning," IEEE Open Journal of the Communications Society, vol. 2, p. 1171–1187, 2021.

Conclusion

- Dynamic traffic | A2G channel model with Rate-Adaptation
- Specialized to single-relay constructions via an SMDP formulation | Trajectory design via CSO
- Supplemented with multi-UAV heuristics: Spread Maximization | Conflict Resolution
- Performance comparisons with relevant schemes in the state-of-the-art as well as with policy-driven heuristics