Global Navigation Satellite System
GPS/GLONASS/Galileo

Positioning | Navigation | Timing |
Geo-Fencing

Cell #1

Tall Aviation Obstacle

UAV$_2$

UEs

App I: Traffic Off-loading
Ground Nodes: UEs

App II: Coverage Extension
Ground Nodes: Soil Sensors
Livestock Monitors

UAV$_1$

Base Station (BS-1)
mmWave

UAV$_3$

Ground Nodes: Cellular UEs

No-Fly Zone (NFZ-1)
Power Plant | Transmission Lines

Cell #2

UE

UEs

Base Station (BS-2)
mmWave

App IV: Coverage Extension &
Traffic Off-loading
Ground Nodes: Autonomous Harvesters (x6)

UAV$_4$ UAV$_5$

Virtual Perimeter for
the UAV Fleet

Ground Control Station

Recharge | Data Upload | Policy Download

UAV$_7$ UAV$_9$ UAV$_8$

UAV$_6$ Landing Pad

Cell #3

UEs

UE

UE

Base Station (BS-3)
mmWave

Tall Aviation Obstacle

UAV$_{10}$

App III: Blockage
Ground Nodes: Soil Sensors

No-Fly Zone (NFZ-2)
Wind Farm

Traffic Classes: QoS Details

Traffic Class	ρ	$\delta_{\max}$ s	L bytes	$\tilde{\gamma}$	Example Application
Command & Control	1.0	0.25	256	0.10	Controlling the critical real-time motion of an autonomous harvester
Telemetry	2.0	1.0	256	0.33	Uploading critical mission-sensitive data/parameters from livestock monitoring sensors (aggregated)
File Transfer	3.0	10.0	536	0.67	Uploading non-critical data (eg., operational log) from soil sensors (aggregated)
Image	3.0	5.0	536	0.33	Downloading an image on a cellular UE
Video Buffer	5.0	3.0	536	0.33	Uploading a locally-recorded video from a cellular UE to the cloud for backup
Voice over IP (VoIP)	6.0	0.15	480	0.05	A voice call from a cellular UE over IP
Video Stream	15.0	0.5	1387	0.05	Monitoring the real-time motion of an autonomous harvester

where

- $L \triangleq$ The maximum individual packet length (in bytes) for flows of a certain traffic class;
- $\rho \triangleq$ The priority value (point value) of flows belonging to a specific traffic class;
- $\delta_{\max} \triangleq$ The maximum allowed one-way per-packet latency (in seconds) for flows of a certain traffic class; and
- $\tilde{\gamma} \triangleq$ The post-deadline discounted reward multiplier for flows belonging to a specific traffic class, i.e.,

$$\text{QoS achievement reward additive} = \begin{cases} \rho & \text{if } \delta \leq \delta_{\max}, \\ \rho\tilde{\gamma}^{(\delta - \delta_{\max})} & \text{otherwise.} \end{cases}$$

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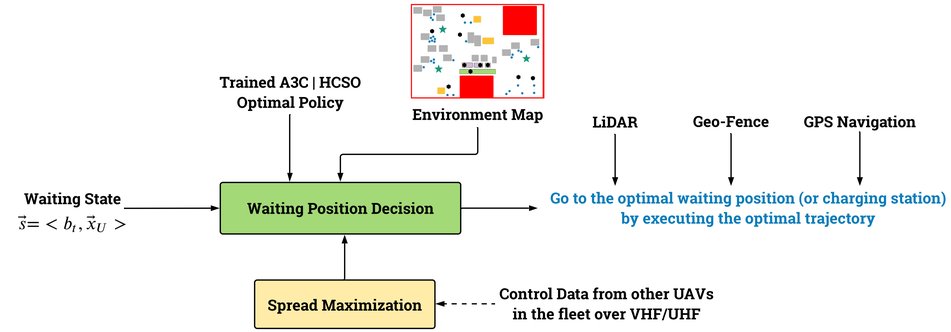
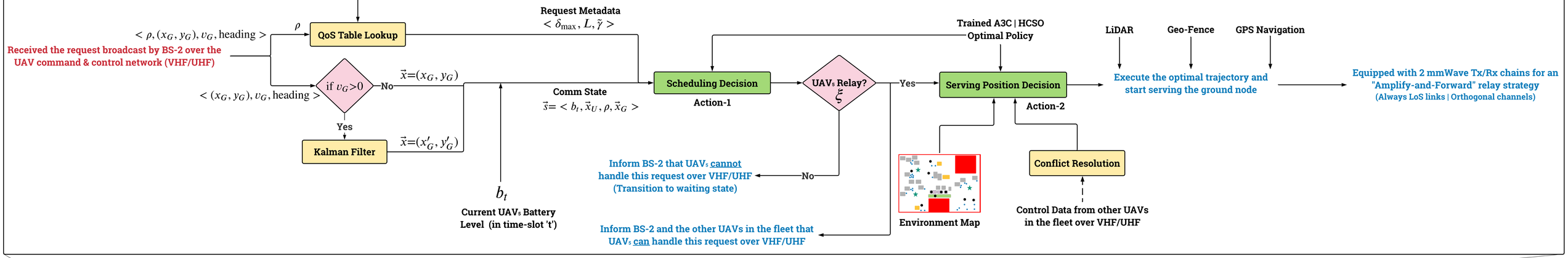
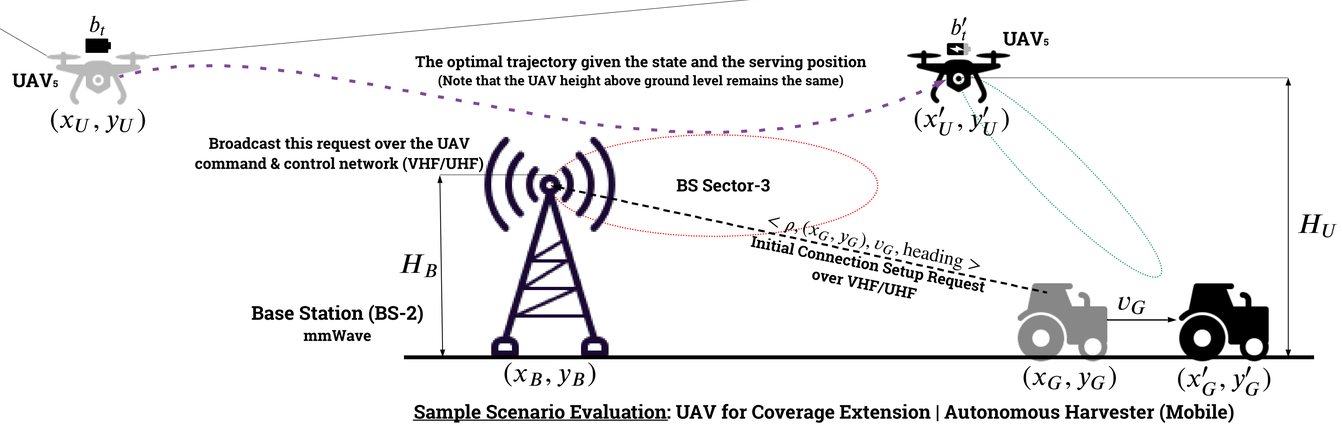
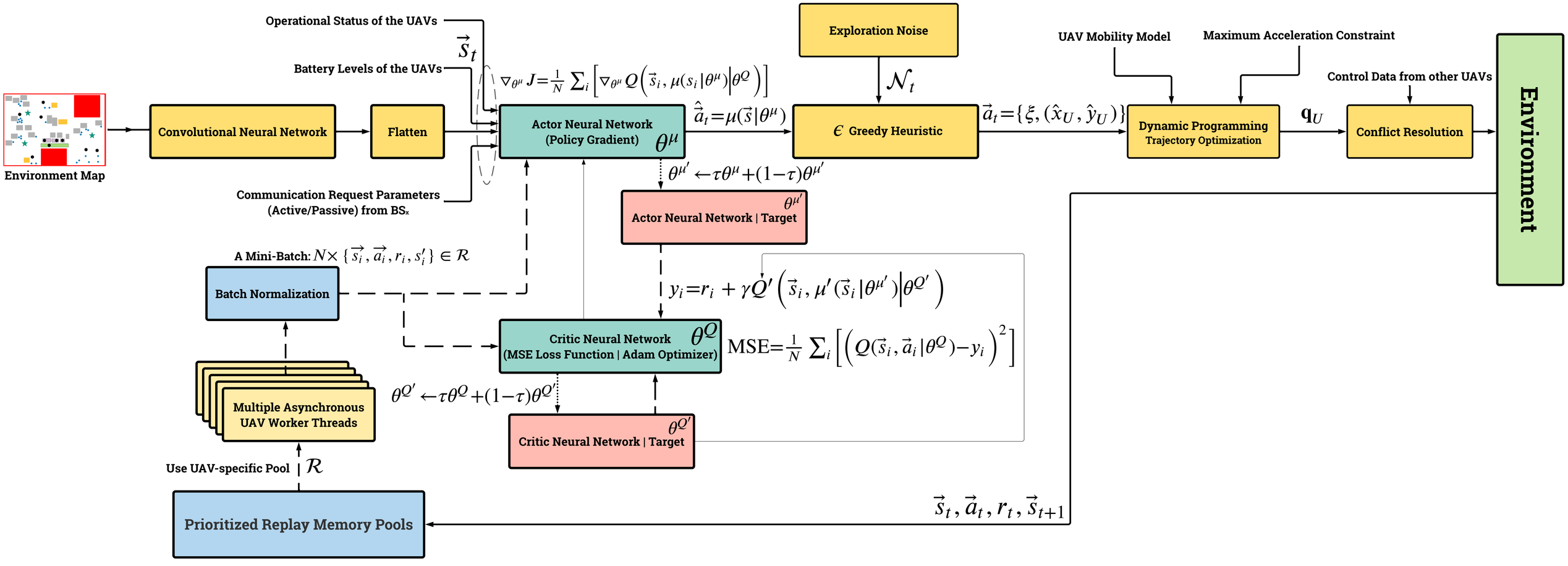
Sequence of operations at UAV$_5$ when a communication request is received from a Ground Node (GN)
(similar operations occur at the other UAVs in the fleet upon receiving a broadcast request from BS-2)







Sample Scenario Evaluation: UAV for Coverage Extension | Autonomous Harvester (Mobile)


Operational Status of the UAVs
$\vec{s}_t$
Battery Levels of the UAVs
Exploration Noise
$\mathcal{N}_t$
UAV Mobility Model
Maximum Acceleration Constraint
Control Data from other UAVs
Environment
Environment Map
Convolutional Neural Network
Flatten
Actor Neural Network (Policy Gradient) θ^{μ}
$\nabla_{\theta^{\mu}} J = \frac{1}{N} \sum_i \left[\nabla_{\theta^{\mu}} Q\left(\vec{s}_i, \mu(s_i|\theta^{\mu})\middle|\theta^{Q}\right)\right]$
$\hat{\vec{a}}_t = \mu(\vec{s}|\theta^{\mu})$
ϵ Greedy Heuristic
$\vec{a}_t = \{\xi, (\hat{x}_U, \hat{y}_U)\}$
Dynamic Programming
Trajectory Optimization
$\mathbf{q}_U$
Conflict Resolution
Communication Request Parameters
(Active/Passive) from BS$_x$
$\theta^{\mu'} \leftarrow \tau\theta^{\mu} + (1-\tau)\theta^{\mu'}$
$\theta^{\mu'}$
Actor Neural Network | Target
A Mini-Batch: $N \times \{\vec{s}_i, \vec{a}_i, r_i, s'_i\} \in \mathcal{R}$
Batch Normalization
$y_i = r_i + \gamma Q'\left(\vec{s}_i, \mu'(\vec{s}_i|\theta^{\mu'})\middle|\theta^{Q'}\right)$
Critic Neural Network θ^{Q}
(MSE Loss Function | Adam Optimizer)
$\text{MSE} = \frac{1}{N} \sum_i \left[\left(Q(\vec{s}_i, \vec{a}_i|\theta^{Q}) - y_i\right)^2\right]$
Multiple Asynchronous
UAV Worker Threads
$\theta^{Q'} \leftarrow \tau\theta^{Q} + (1-\tau)\theta^{Q'}$
$\theta^{Q'}$
Critic Neural Network | Target
Use UAV-specific Pool | $\mathcal{R}$
Prioritized Replay Memory Pools
$\vec{s}_t, \vec{a}_t, r_t, \vec{s}_{t+1}$