ACCUSTOM

Adaptive **C**ontrol & **C**oordination of **U**AV **S**warms for **T**raffic **O**ffloading in **M**IMO ecosystems

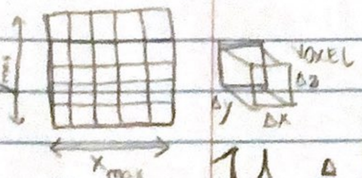
DEPLOYMENT MODEL

- U rotary-wing UAVs.
- G Ground Nodes (GNs) deployed uniformly at random across the deployment site.
- Deployment site tessellated into a cuboidal grid world.

$(x_{max}, y_{max}, z_{max})$ — length, breadth, height

$(\Delta x, \Delta y, \Delta z)$ — size of each voxel

TOTAL NUMBER OF VOXELS $V = n_x \cdot n_y \cdot n_z$.



$n_x = \frac{x_{max}}{\Delta x}$ (number of voxels in x-dir), $n_y = \frac{y_{max}}{\Delta y}$ (number of voxels in y-dir), $n_z = \frac{z_{max}}{\Delta z}$ (number of voxels in z-dir)

$\mathcal{U} \triangleq \{1, 2, 3, \ldots, U\}$ (Set of UAVs) and $\mathcal{G} \triangleq \{1, 2, 3, \ldots, G\}$.

Rectangular/Cartesian representation of positions:

At time t: For a UAV $u \in \mathcal{U}$: $p_u'(t) = [x_u', y_u', z_u']$, where

$$0 \leq x_u' \leq x_{max}, \quad 0 \leq y_u' \leq y_{max}, \quad 0 \leq z_u' = H_u' \leq z_{max}$$

For a GN $g \in \mathcal{G}$: $p_g'(t) = [x_g', y_g', z_g']$, where

GN doesn't necessarily have to be at ground level

$$0 \leq x_g' \leq x_{max}, \quad 0 \leq y_g' \leq y_{max}, \quad 0 \leq z_g' = H_g' \leq z_{max}.$$

Approximated (Voxel-based) representation of positions:

At time t: For a UAV $u \in \mathcal{U}$: $\underbrace{p_u'(t)}_{[x_u', y_u', z_u']} \in \mathcal{V}_j$, $j \in \{1, 2, 3, \ldots, V\}$ if

$$x_{j,min} \leq x_u' < x_{j,max}, \quad y_{j,min} \leq y_u' < y_{j,max}, \text{ and } z_{j,min} \leq z_u' < z_{j,max};$$

where $\mathcal{V}_j \in \mathcal{V}$, $\mathcal{V}_j \triangleq \{[x_j, y_j, z_j] : x_{j,min} \leq x_j < x_{j,max}, y_{j,min} \leq y_j < y_{j,max}, z_{j,min} \leq z_j < z_{j,max}\}$, Set of voxels: $\mathcal{V} \triangleq \{ \mathcal{V}_1, \mathcal{V}_2, \mathcal{V}_3, \ldots, \mathcal{V}_V \}$, with each voxel represented by its bounds in the x-, y-, and z-directions.

Then, $p'_u(t)$ can be approximated by the centroid of the voxel cuboid to which it belongs, i.e.,

$$p'_u(t) \approx p_u(t) = \left[\underbrace{\frac{\sum_{j'=1}^{8} x_{j'}}{8}}_{x_u}, \underbrace{\frac{\sum_{j'=1}^{8} y_{j'}}{8}}_{y_u}, \underbrace{\frac{\sum_{j'=1}^{8} z_{j'}}{8}}_{z_u = H_u} \right], \text{ where}$$

$\left\{ [x_{j'}, y_{j'}, z_{j'}], j' = 1, 2, 3, \ldots, 8 \right\} \subseteq \mathcal{V}_j$ represents the corners/vertices of the cuboid.

- Similar approximated (voxel-based) representation is used for $p_g(t)$. $[x_g, y_g, z_g = H_g]$
- This approximated notation is employed henceforth in our development.

UAV COLLISION AVOIDANCE: $p_{u_1}(t) \neq p_{u_2}(t)$, for $u_1, u_2 \in \{1, 2, 3, \ldots, U\}$, $u_1 \neq u_2$, at any time t.

NO GN OVERLAP: $p_{g_1}(t) \neq p_{g_2}(t)$, for $g_1, g_2 \in \{1, 2, 3, \ldots, G\}$, $g_1 \neq g_2$, at any time t.

STATIC GNs: $p_g(t) = p_g = [x_g, y_g, z_g]$, for any $g \in \{1, 2, 3, \ldots, G\}$, $\forall t$.

Stationary GNs

DEPOT TAKEOFF & LANDING & CHARGING ZONE: $\mathcal{F}'' \triangleq \left\{ [x'_i, y'_i, z'_i] : 0 \leq x'_i < x_f, \; 0 \leq y'_i < y_f, \; 0 \leq z'_i \leq z_f \right\}$.

in cartesian coordinate system (non-voxel based)

end x-coordinate of the depot

end y-coordinate of the depot

end z-coordinate of the depot

collection of voxels in the depot

$\mathcal{F}' = \{ \mathcal{V}_i, i = 1, 2, 3, \ldots, V_f : 0 \leq x_{i,min} < x_{i,max} < x_f, \; 0 \leq y_{i,min} < y_{i,max} < y_f, \; 0 \leq z_{i,min} < z_{i,max} < z_f \}$.

in approximate (voxel-based) coordinate system

number of voxels in the depot

NFZs & unavoidable obstacles:

- Under a similar cartesian and voxel-based representation:

let $$\underset{\substack{(\text{/mathcal\{Z\}}) \\ (\text{CARTESIAN REPR})}}{\mathcal{Z}''} \approx \underset{(\text{VOXEL-BASED REPR})}{\mathcal{Z}} = \left\{ \left[\underbrace{\frac{\sum_{i'=1}^{8} x_{i'}}{8}}_{x_i}, \underbrace{\frac{\sum_{i'=1}^{8} y_{i'}}{8}}_{y_i}, \underbrace{\frac{\sum_{i'=1}^{8} z_{i'}}{8}}_{z_i} \right] : [x_{i'}, y_{i'}, z_{i'}] \in \mathcal{V}_i, \forall \mathcal{V}_i \in \mathcal{Z}' \right\}. \quad (3)$$

- $p_u(t) \notin \mathcal{Z}, \forall u \in \mathcal{U}, \forall t$ and $p_g \notin \mathcal{Z}, \forall g \in \mathcal{G}$. The set of voxels corresponding to $\mathcal{Z}''$

- Finally, the depot can be denoted in terms of its voxel centroids as:

$$\mathcal{F}'' \approx \mathcal{F} = \left\{ \left[\underbrace{\frac{\sum_{i'=1}^{8} x_{i'}}{8}}_{x_i}, \underbrace{\frac{\sum_{i'=1}^{8} y_{i'}}{8}}_{y_i}, \underbrace{\frac{\sum_{i'=1}^{8} z_{i'}}{8}}_{z_i} \right] : [x_{i'}, y_{i'}, z_{i'}] \in \mathcal{V}_i, \forall \mathcal{V}_i \in \mathcal{F}' \right\}.$$

Thus, $p_u(t) \in \mathcal{F}, \forall t \in [0, t_{u,init}], \forall u \in \mathcal{U}$;

$p_u(t) \in \mathcal{F}, \forall t \geq t_{u,term}, \forall u \in \mathcal{U}$, and

$p_u(t) \in \mathcal{F}, \forall t \in [t_{u,chrg}, t_{u,chrg} + \tau_{u,chrg}], \forall u \in \mathcal{U}$;

where $t_{u,init}$ and $t_{u,term}$ are the arbitrary mission start and mission end times of a UAV $u \in \mathcal{U}$, respectively -- determined dynamically by the Upper Agent in our HRL framework;

also, $t_{u,chrg}$ is the time at which a UAV $u \in \mathcal{U}$ comes in for recharging, while $\tau_{u,chrg}$ is the amount of time spent recharging: both these parameters are determined dynamically by the Upper Agent (DQN) or the Lower Agent (mTSP) in our HRL framework.

- Note that, UAV-UAV collision avoidance applies here in the depot voxels as well, i.e., $\underbrace{p_{u_1}(t)}_{\text{voxelized}} \neq \underbrace{p_{u_2}(t)}_{\text{voxelized}}, \forall u_1, u_2 \in \mathcal{U}, u_1 \neq u_2, \forall t \in [0, \infty)$.

... (Two UAVs [and also two GNs] cannot occupy the same voxel) ...

- A UAV u has A_u antennas arranged in a rectangular planar array. To enforce heterogeneity in the comm system design of the UAVs, A_{u_1} may or may not be equal to A_{u_2}, for two distinct UAVs $u_1, u_2 \in \mathcal{U}$.

- Similarly, a GN g has A_g antennas arranged in a rectangular planar array. To enforce heterogeneity, A_{g_1} may or may not be equal to A_{g_2}, for two distinct GNs $g_1, g_2 \in \mathcal{G}$.

COMMUNICATION MODEL

$g \in \mathcal{G}$

- Each GN generates a traffic offloading request, according to a Poisson process with rate Λ requests per unit time. Each request involves a header constituting the following fields:

(a) Traffic class identifier $\quad$ (b) Traffic priority value X_g $\quad$ (c) Traffic max allowed latency $\delta_{g,max}$

(d) Traffic payload size ϑ_g $\quad$ (e) Post-deadline discount factor γ_g

REQUEST

$\langle$class, X_g, $\delta_{g,max}$, ϑ_g, $\gamma_g\rangle$

GN $g \in \mathcal{G}$

$[x_g, y_g, z_g]$, $z_g = H_g$ (can be zero)

- If δ_{gu} is the amount of time taken by GN $g \in \mathcal{G}$ to offload its data payload to UAV $u \in \mathcal{U}$ (based on UAV positioning, A2G channel conditions, and MIMO beamforming design), then the reward received by the UAV is $\Omega_{gu} = X_g \gamma_g^{(\delta_{gu} - \delta_{g,max})}$.

- A UAV $u \in \mathcal{U}$ can serve multiple GNs simultaneously.

- A GN $g \in \mathcal{G}$ should only be associated with one UAV. Once associated with a UAV $u \in \mathcal{U}$, the GN's current request should be fully served by UAV u.

SIGNAL MODEL

TRANSMITTED SIGNAL

For GN $g \in \mathcal{G}$, at time t:

$$\underline{x}_g = \Phi_g \underline{s}_g, \quad \underline{x}_g \in \mathbb{C}^{A_g \times 1}, \quad \underline{s}_g \in \mathbb{C}^{A_g \times 1} \text{ with } \mathbb{E}\left[\underline{s}_g^H \underline{s}_g\right] = 1.$$

Transmitted signal from GN g to its serving UAV u

linear precoding matrix applied at GN g

Transmit symbol vector

$\Phi_g \in \mathbb{C}^{A_g \times A_g}$

(Simplicity of notation: we omit the t variable here...)

- The signal received at $\overset{\text{serving}}{\text{UAV}}$ u as a result is:

Signal received at UAV u at time t $y_u \in \mathbb{C}^{A_u \times 1}$

$$y_u = \underbrace{\sum_{g \in \mathcal{G}_u}}_{\text{The set of GNs being served by UAV } u \text{ at time } t} H_{gu} \underline{x}_g + \underline{w}_u ,$$

where $H_{gu} \in \mathbb{C}^{A_u \times A_g}$ is the channel between GN g and UAV u obtained from our channel estimation procedure (Wireless Insite ray-tracing + site partitioning & MLE + radio map generation), and $z_u \in \mathbb{C}^{A_u \times 1}$ is the AWGN noise vector with $\underline{w}_u \sim \mathcal{CN}(\underline{0}, BN_0 I_{A_u})$.

- B is the predetermined bandwidth allocated to each UAV prior to mission start, N_0 is the noise power spectral density, and I_{A_u} is the identity matrix of dimension $A_u \times A_u$.

CHANNEL MODEL

The channel gain between GN g Tx ANT m and $\overset{\text{serving}}{\text{UAV}}$ u Rx ANT n is given by:

$$\underset{\text{(in dB)}}{h_{mn}} = \overset{\text{avg. channel gain at ref. dist. of 1m}}{\beta_{mn}} - 10 \overset{\text{pathloss exponent}}{\alpha_{mn}} \log_{10} d_{mn} + \xi_{mn} + \lambda_{mn},$$

with $\xi_{mn} \sim \underbrace{\mathcal{N}}_{\text{GAUSSIAN}}(0, \sigma^2_{SF,mn})$ and $\lambda_{mn} \sim \underbrace{\mathcal{CN}}_{\text{RICE}}\left(\underbrace{\frac{K_{mn}}{\sqrt{K_{mn}+1}}}_{\mu_{SSF,mn}}, \underbrace{\frac{1}{K_{mn}+1}}_{\sigma^2_{SSF,mn}}\right)$;

for shadow-fading

for small-scale fading

$$d_{mn} = \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2 + (z_m - z_n)^2}.$$

3D Euclidean distance

see channel modeling document

... for estimating $\beta, \alpha, \sigma^2_{SF}, \mu_{SSF}, \sigma^2_{SSF}$ ...

!

UAV ENERGY MODEL :

- For a rotary-wing UAV $u \in \mathcal{U}$, its mobility energy consumption upon executing an arbitrary horizontal (2D) trajectory is given by:

$$E_{horz}\Big(\underbrace{\{p_u(\tau), v_{u,horz}(\tau)\}_{\tau=t_{u,init}}^{\tau=t_{u,term}}}_{Q_{u,horz}}\Big) =$$

horizontal velocity of UAV u in τ

$$\underbrace{\int_{t_{u,init}}^{t_{u,term}} C_0\left(1 + C_1 v^2_{u,horz}(\tau)\right) d\tau}_{\text{blade profile component}} + \underbrace{\int_{t_{u,init}}^{t_{u,term}} C_4 v^3_{u,horz}(\tau)\, d\tau}_{\text{parasitic component}} +$$

induced energy consumption component

$$\left\{ \int_{t_{u,init}}^{t_{u,term}} C_2 \sqrt{1 + \frac{a^2_{u,\perp}(\tau)}{g^2}} \left(\sqrt{1 + \frac{a^2_{u,\perp}(\tau)}{g^2} + \frac{v^4_{u,horz}(\tau)}{C_3^2}} - \frac{v^2_{u,horz}(\tau)}{C_3} \right)^{1/2} d\tau \right. +$$

$$\underbrace{\frac{1}{2} m_u \left(v^2_{u,horz}(t_{u,term}) - v^2_{u,horz}(t_{u,init}) \right)}_{\text{change in kinetic energy}}, \text{ where}$$

$$\underbrace{a^2_{u,\perp}(\tau)}_{\text{UAV's centrifugal acceleration horizontally in } \tau} \triangleq \sqrt{\underbrace{a^2_{u,horz}(\tau)}_{\text{UAV's horizontal acceleration in } \tau} - \frac{\left(a_{u,horz}(\tau)\, v_{u,horz}(\tau)\right)^2}{v^2_{u,horz}(\tau)}}, \quad \forall \tau \in [t_{u,init}, t_{u,term}];$$

$$\rightarrow a_{u,horz}(t) = \frac{d v_{u,horz}(\tau)}{d\tau}$$

C_0, C_1, C_2, C_3, and C_4 are constants that depend on the UAV weight $m_u g$, rotor disc area, air density, etc.

(REFERENCE PAPER)

- Similarly, for vertical movements of a rotary-wing UAV $u \in \mathcal{U}$, its contribution to the overall mobility energy consumption is:

$$E_{vert}\Big(\underbrace{\left[p_u(\tau), v_{u,vert}(\tau)\right]_{\tau=t_{u,init}}^{\tau=t_{u,term}}}_{Q_{u,vert}}\Big) =$$

$$\int_{t_{u,init}}^{t_{u,term}} C_0\left(1 + C_1 v_{u,vert}^2(\tau)\right) d\tau \; +$$

$$\int_{t_{u,init}}^{t_{u,term}} x(\tau) C_2 \left(\sqrt{x^2(\tau) + \frac{v_{u,vert}^4(\tau)}{C_3^2}} - \frac{v_{u,vert}^2(\tau)}{C_3}\right)^{1/2},$$

where $v_{u,vert}(\tau)$ is the vertical velocity component in τ; $C_0, C_1, C_2,$ and C_3 are constants that depend on UAV weight $m_u g$, rotor disc area, air density, etc., and

(REFERENCE PAPER) $\quad x(\tau) = \sqrt{1 + \frac{\left(\rho_u d_{0,u} s_u A_u v_{u,vert}^2(\tau) + 2 m_u a_{u,vert}(\tau)\right)^2}{4(m_u g)^2}}$, with

ρ being the air density, $d_{0,u}$ is the fuselage drag ratio of UAV $u \in \mathcal{U}$, s_u is the rotor solidity factor of UAV u, A_u is the rotor disc area of UAV u, and $a_{u,vert}(\tau)$ is the vertical acceleration component in τ.
↳ $a_{u,vert}(\tau) = \frac{d v_{u,vert}(\tau)}{d\tau}$.

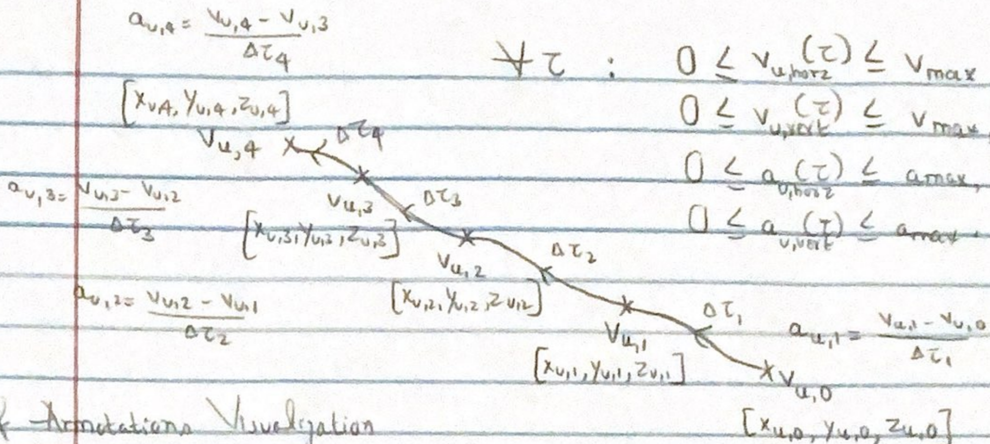
∴ Finally, the overall mobility energy consumption of the UAV $u \in \mathcal{U}$ under its optimal 3D trajectory determined by LCSO is given by,

$$E_{3D}\Big(\underbrace{\left[p_u(\tau), \vec{v}_u(\tau)\right]_{\tau=t_{u,init}}^{\tau=t_{u,term}}}_{Q_u}\Big) = E_{horz}\left(\left[p_u(\tau), v_{u,horz}(\tau)\right]_{\tau=t_{u,init}}^{\tau=t_{u,term}}\right) + E_{vert}\left(\left[p_u(\tau), v_{u,vert}(\tau)\right]_{\tau=t_{u,init}}^{\tau=t_{u,term}}\right),$$

where $v_{u,horz}(\tau) = \left|\vec{v}_u(\tau)\right| \cos \angle \vec{v}_u(\tau)$ and

$v_{u,vert}(\tau) = \left|\vec{v}_u(\tau)\right| \sin \angle \vec{v}_u(\tau)$.

$$\forall \tau : \quad 0 \le v_{u,horz}(\tau) \le v_{max}, \quad 0 \le v_{u,vert}(\tau) \le v_{max}, \quad 0 \le a_{u,horz}(\tau) \le a_{max}, \text{ and } \quad 0 \le a_{u,vert}(\tau) \le a_{max}.$$



Trajectory & Annotations Visualization

- Since the UAVs are only receiving traffic from the GNs and are not themselves involved in any multi-antenna Tx processes, we can safely ignore the communication energy consumption of a UAV (used to only operate Rx chains, order of 1-10 W, negligible) relative to its mobility energy consumption (order of 1000 W).

- The UAVs harvest traffic from the GNs they're serving according to a MOVE-AND-RECEIVE protocol. Here, signal degradation effects due to Doppler shifts brought on by the UAV's motion towards and/or away from a transmitting GN are compensated using the UAV comm subsystem architecture ("Phase Locked Loop [PLL] enabled RF-based adaptive Doppler compensation") proposed in [CITED PAPER].