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

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Motivation: Non-Terrestrial Augmentations of Conventional Networks

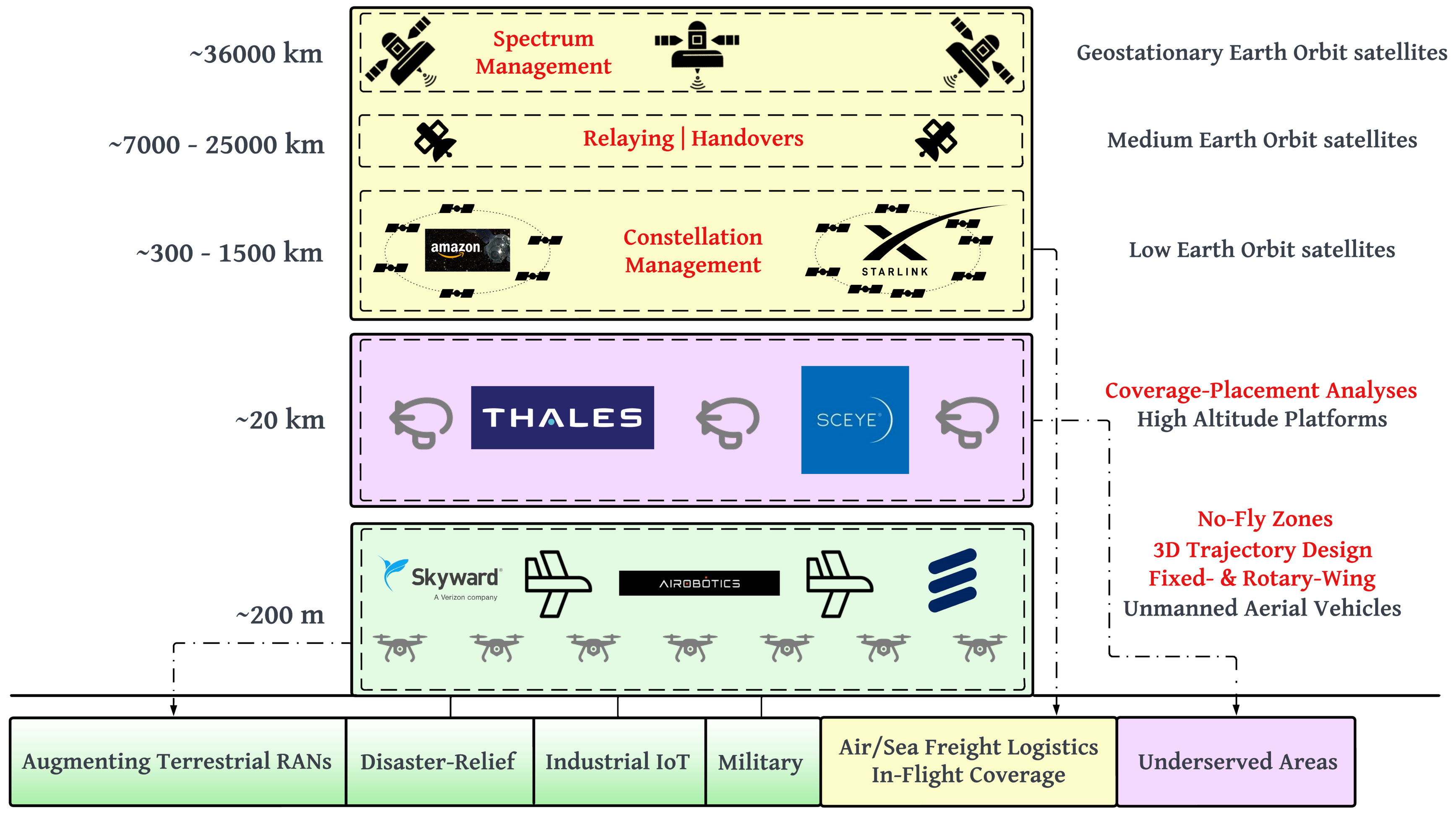

Figure 1. An envisioned illustration of the multi-tiered augmentation hierarchy of non-terrestrial networks.

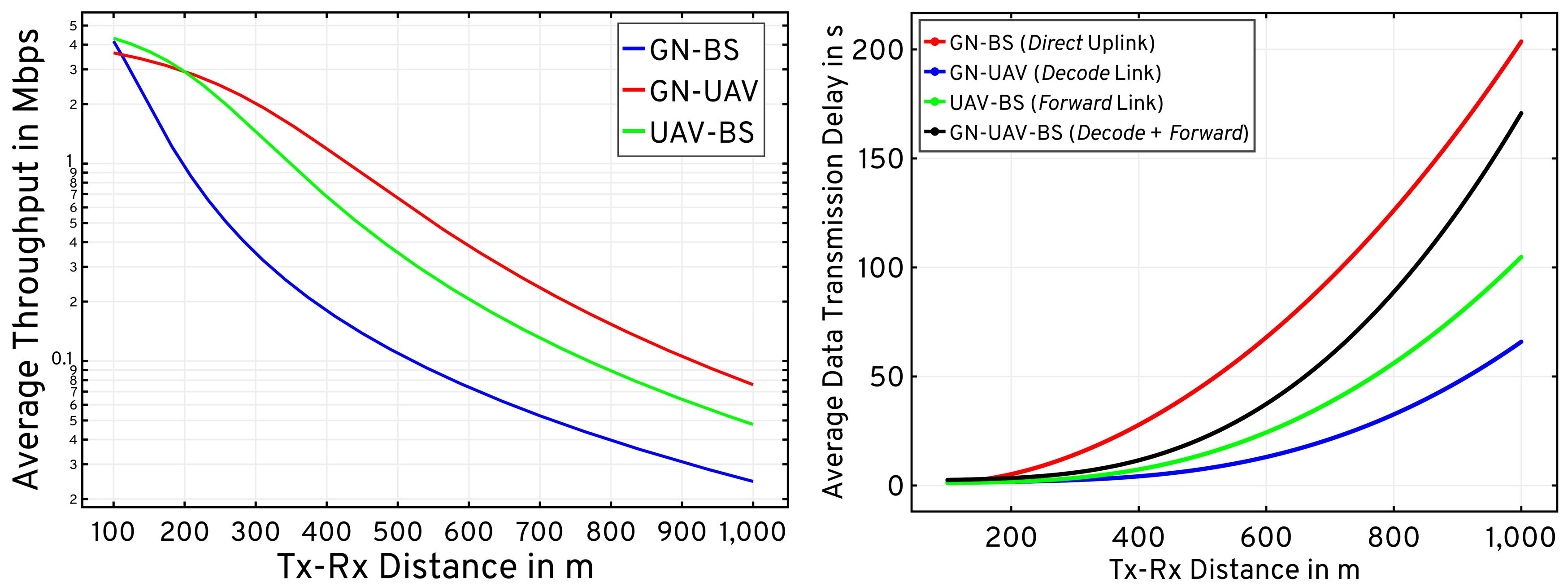

Figure 2. The throughput and delay gains associated with exploiting the guaranteed LoS capabilities of UAV links.

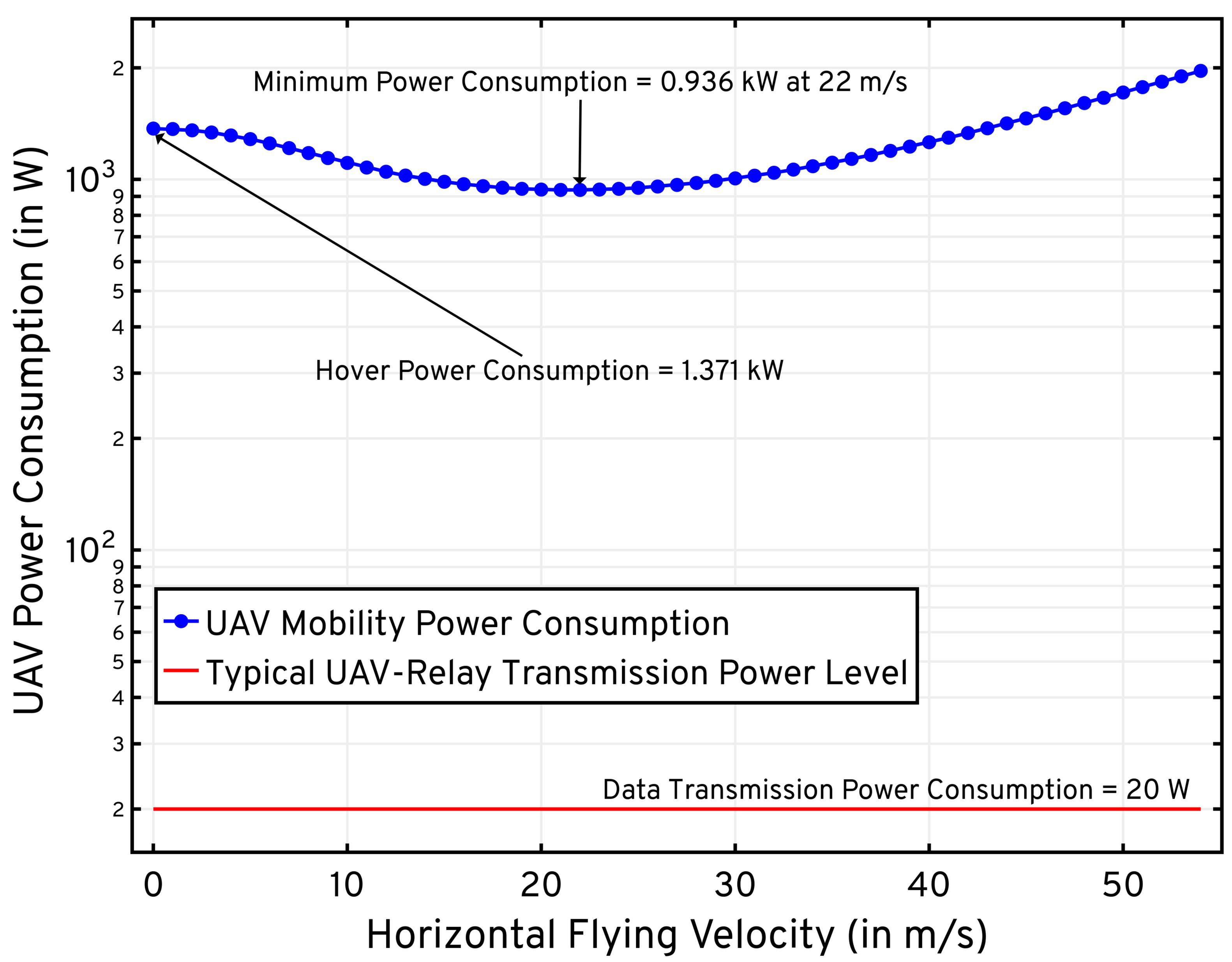

Figure 3. A depiction of the mobility power consumption of a rotary-wing UAV as a function of its horizontal flying velocity.

Deployment Model: UAV-Relays in Precision Agriculture

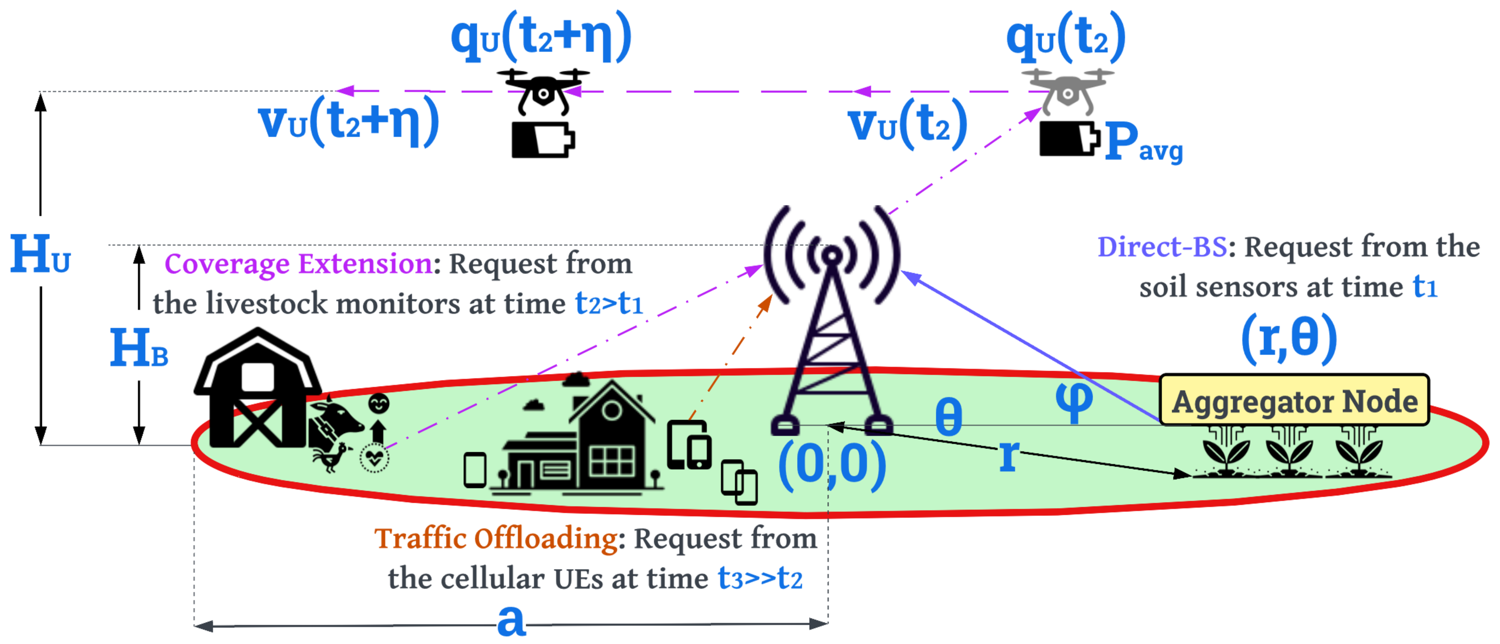

Figure 4. The specialized deployment model for a single UAV, which is later extended to UAV swarms.

Policy Computation: Rate Adaptation | SMDP Formulation | Algorithms

UAV Mobility Power Model: $P_{\text{mob}}(V) = P_1\left(1+\frac{3V^2}{U_{\text{tip}}^2}\right) + P_2\left(\sqrt{1+\frac{V^4}{4v_0^4}}-\frac{V^2}{2v_0^2}\right)^{1/2} + P_3V^3$

A2G Channel Model (with Rate Adaptation):

$$P_{\text{LoS}}(\varphi) = \frac{1}{1+z_1\cdot\exp\left(-z_2\left[\varphi-z_1\right]\right)},\quad P_{\text{NLoS}}(\varphi) = 1-P_{\text{LoS}}(\varphi); C(h) = B\cdot\log_2\left(1+\frac{|h|^2P}{\sigma^2\Gamma}\right)$$

$$P_{\text{out}}(\Upsilon,\beta,K) = 1-Q_1\left(\sqrt{2K},\sqrt{2(K+1)u(\Upsilon,\beta)}\right); u(\Upsilon,\beta)\triangleq\sigma^2\Gamma(2^{\Upsilon/B}-1)/(\beta P)$$

$$R(\Upsilon,\beta,K) = \Upsilon\cdot(1-P_{\text{out}}(\Upsilon,\beta,K)) = \Upsilon\cdot Q_1\left(\sqrt{2K},\sqrt{2(K+1)u(\Upsilon,\beta)}\right)$$

$$\text{With } Z\triangleq\sqrt{\frac{2\beta P}{\sigma^2\Gamma}u(\Upsilon,\beta)},\ \Upsilon = B\log_2\left(1+\frac{1}{2}Z^2\right)\triangleq f(Z) \text{ and } \Upsilon^*(\beta,K) = f(Z^*(\beta,K))$$

$$Z^*(\beta,K)\triangleq\arg\min_{Z\geq 0} -\ln f(Z)-\ln Q_1\left(\sqrt{2K},\sqrt{\frac{(K+1)\sigma^2\Gamma}{\beta P}}Z\right)\quad\text{[Bisection Method]}$$

$$\bar{R}(d,\varphi)\triangleq P_{\text{LoS}}(\varphi)\cdot R^*(\beta_{\text{LoS}}(d),K(\varphi))+P_{\text{NLoS}}(\varphi)\cdot R^*(\beta_{\text{NLoS}}(d),0)$$

Two-Stage Decision Framework | A Semi-Markov Decision Process (SMDP) formulation

- Waiting states ($s\in\mathcal{S}_{\text{wait}}$):
  - Outer decision | Optimal UAV radial velocity (v_r^*) | **SMDP Value Iteration**
  - Inner decision | Optimal UAV angular velocity (θ_c^*) | **Solve**

$$\ell_\nu^*(s;v_r) = \min_{\theta_c}\nu\left(P_{\text{mob}}\left(\sqrt{v_r^2+r_U^2\cdot\theta_c^2}\right)-P_{\text{avg}}\right)\Delta_0 \text{ s.t. } \sqrt{v_r^2+r_U^2\cdot\theta_c^2}\leq V_{\max}.$$

- Communication states ($s\in\mathcal{S}_{\text{comm}}$):
  - Outer decision | Optimal UAV end position $[(\hat{r}_U^*,\hat{\theta}_U^*)]$ | **SMDP Value Iteration**
  - Inner decision I | Optimal scheduling strategy (ξ^*) | **Pick the minimizing action between**

$$\ell_\nu^*(s;r_U,0) = L/\bar{R}_{GB}(r) \text{ and } \ell_\nu^*(s;\hat{r}_U,1) = \min_{\Delta,\mathbf{q}_U,t_p}(1-\nu P_{\text{avg}})\Delta+\nu\int_0^\Delta P_{\text{mob}}\left(\sqrt{r_U'(\eta)^2+r_U^2(\eta)\cdot\theta_U'(\eta)^2}\right)\mathrm{d}\eta$$

s.t. data payload, max velocity, and start & end position constraints

  - Inner decision II | Optimal trajectory | **Competitive Swarm Optimization (CSO)**

$$\mathbf{p}^*,\mathbf{v}^* = \underset{\mathbf{p},\mathbf{v}\in[V_{\text{low}},V_{\max}]^M}{\text{argmin}}(1-\nu P_{\text{avg}})\sum_{m=0}^{M-1}\frac{\|\mathbf{x}_{m+1}-\mathbf{x}_m\|_2}{v_m}+\nu\sum_{m=0}^{M-1}\frac{\|\mathbf{x}_{m+1}-\mathbf{x}_m\|_2}{v_m}P_{\text{mob}}(v_m)$$

s.t. data payload, max velocity, and start & end position constraints

- Competitive Swarm Optimization | Loser particle updates in the $(k+1)$-th iteration:

$$\mathbf{u}_{j_{\text{los}}}(k+1) = r_{j,1}(k)\mathbf{u}^l+r_{j,2}(k)\left(\mathbf{p}^w-\mathbf{p}^l\right)+\omega\cdot r_{j,3}(k)\left(\bar{\mathbf{p}}(k)-\mathbf{p}^l\right),$$

$$\mathbf{w}_{j_{\text{los}}}(k+1) = r_{j,1}(k)\mathbf{w}^l+r_{j,2}(k)\left(\mathbf{v}^w-\mathbf{v}^l\right)+\omega\cdot r_{j,3}(k)\left(\bar{\mathbf{v}}(k)-\mathbf{v}^l\right),$$

$$\mathbf{p}_{j_{\text{los}}}(k+1) = \mathbf{p}^l+\mathbf{u}_{j_{\text{los}}}(k+1),\quad \mathbf{v}_{j_{\text{los}}}(k+1) = \left[\mathbf{v}^l+\mathbf{w}_{j_{\text{los}}}(k+1)\right]^{[V_{\text{low}},V_{\max}]}.$$

Multi-agent heuristics for optimal policy enhancement:

- **Spread Maximization**: UAV i determines the index of its closest peer $j^*=\text{argmin}_{j\in\mathcal{L}}|\theta_i-\theta_j|$, then determines its direction of angular motion as $\rho^*=\text{argmax}_{\rho\in\{+1,-1\}}\left|[\theta_i+\delta\rho\theta_c^*]^{[0,2\pi)}-\theta_{j^*}\right|$.
- **Consensus-driven Conflict Resolution**: For a request at (r,θ), if $\frac{L}{\bar{R}_{GB}(r)}<\hat{f}(\mathbf{p}_i^*,\mathbf{v}_i^*),\forall i\in\mathcal{L}'$, then direct-BS service; else, the GN request is relayed through UAV $i^*=\text{argmin}_{i\in\mathcal{L}'}\hat{f}(\mathbf{p}_i^*,\mathbf{v}_i^*)$.

Numerical Evaluations: Optimal Waiting Policy | Delay-Power Analyses

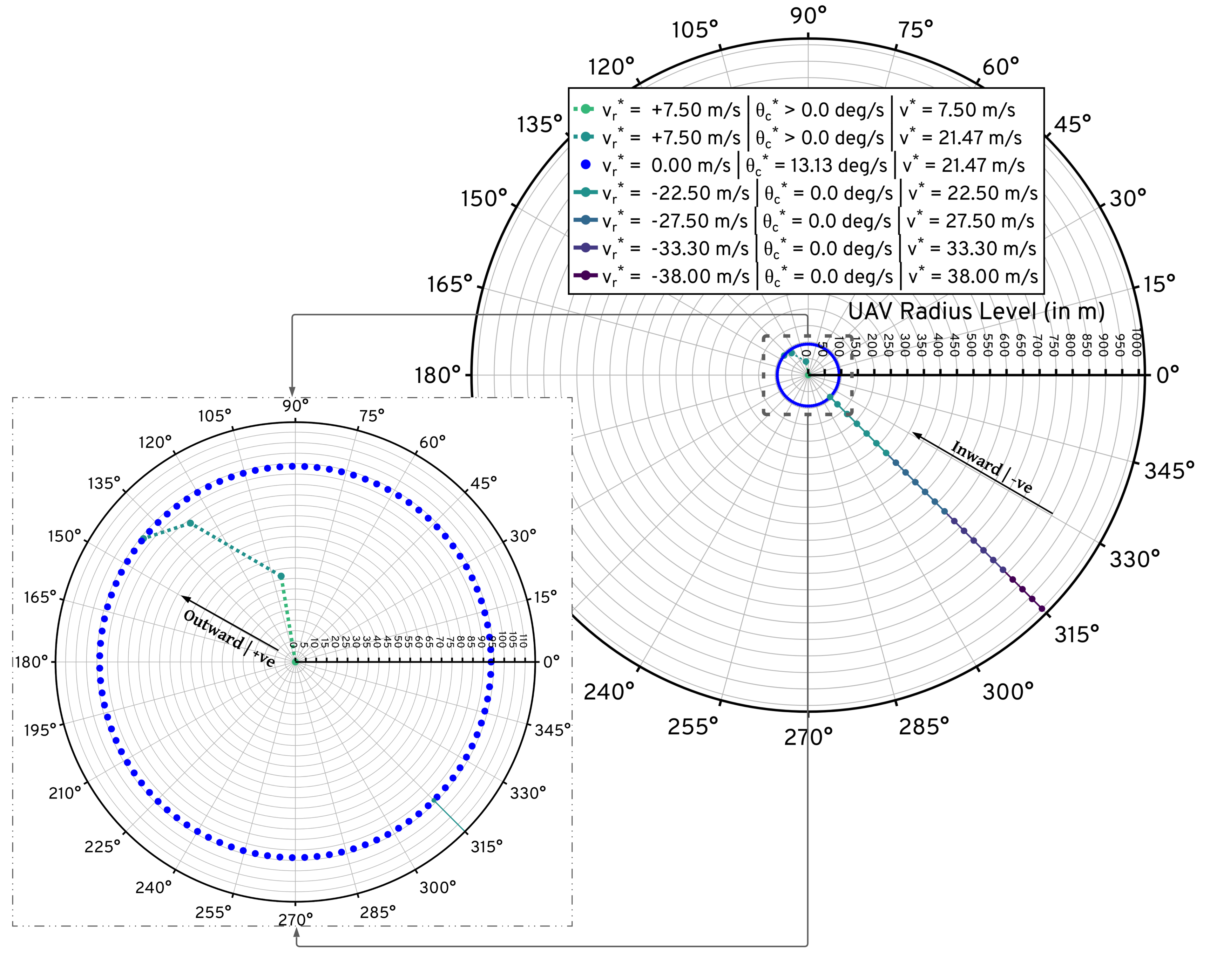

Figure 5. The optimal waiting state policy for our single-agent specialization under L=1Mb data payloads.

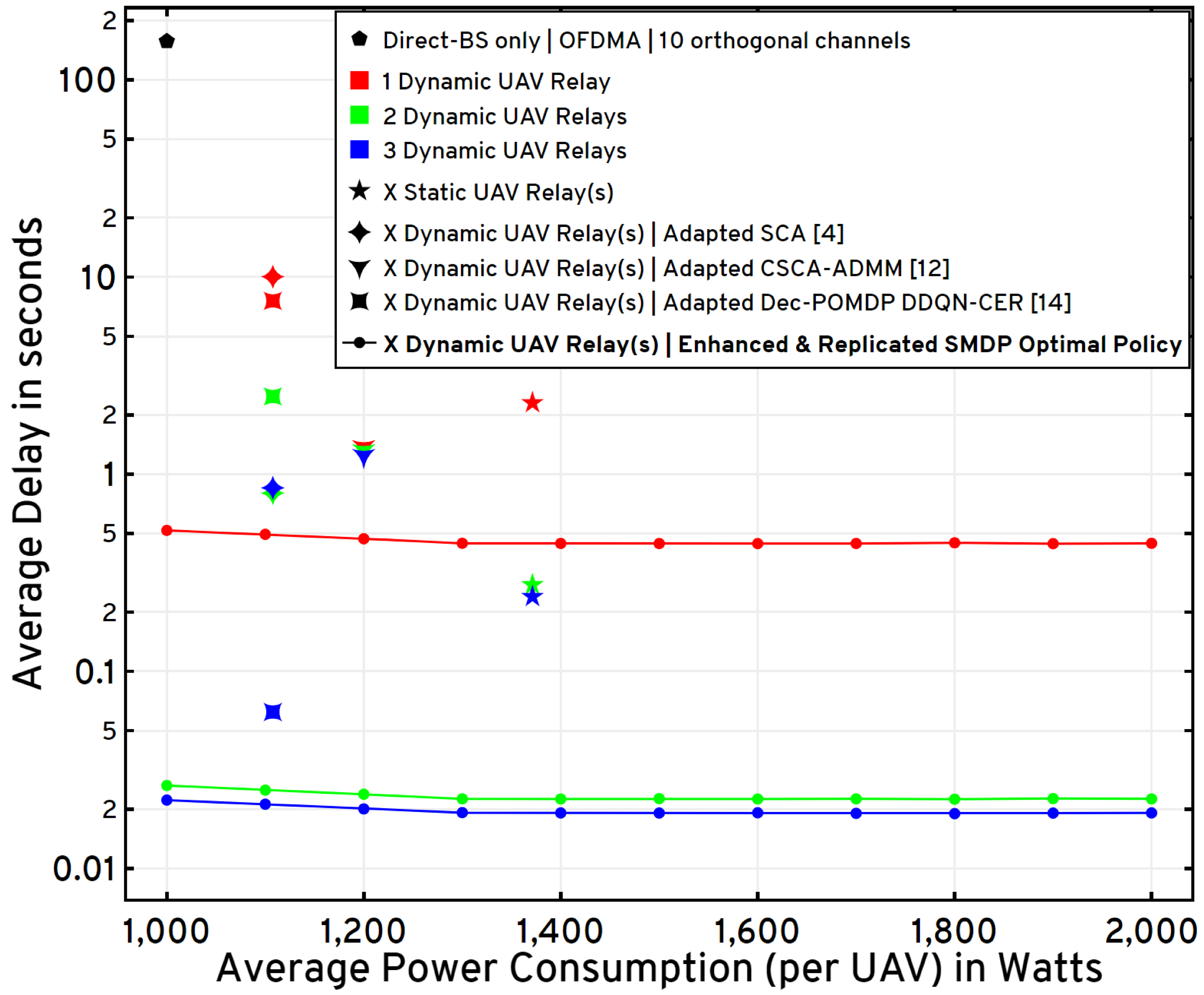

Figure 6. The delay-power performance of our UAV-relay swarm orchestration framework under L=1Mb payloads for different values of the per-UAV P_{avg}: comparisons with BS & static-UAV heuristics and against the state-of-the-art.

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