

Resource-Aware Raft for UAV Swarms via Online Q-Learning: A Systems-Level Adaptive Timeout Controller

Supplementary Material

I. ADDITIONAL EXPERIMENTAL FIGURES (EXPERIMENTAL SETUP)

This appendix supplements Sec. V with compact visual diagnostics. All figures use the bins/actions and guardrails defined in Secs. III–IV; each plot aggregates 25 seeds unless noted. Filenames correspond to the artifact package.

A. Election Timeout Usage

What it shows. Fig. 1 summarizes how often the controller selects each election-timeout lattice value $T_e \in \{200, \dots, 500\}$ ms across S1–S5 and swarm sizes N .

Why it matters. T_e governs leader turnover; longer timeouts reduce split votes but may delay failover.

Key observation. Under harsher RTT/loss (S3) and dense contention (S4), usage shifts toward the upper half of the lattice, reflecting the guardrails’ bias for stability under Eq. 8; in stable S1, the mass centers near the nominal baseline.

B. Heartbeat Interval Usage

What it shows. Fig. 2 reports the distribution of heartbeat intervals $T_h \in \{50, 75, 100, 125, 150\}$ ms.

Why it matters. T_h trades commit responsiveness against control overhead and energy.

Key observation. The controller favors shorter T_h in mobile/harsh regimes (S2/S3/S5) to accelerate detection and recovery, while relaxing to longer T_h in S1 to curb overhead, consistent with the composite cost function in Sec. III.

C. Step-Cost Time Series

What it shows. Fig. 3 plots the windowed step-cost c_t over time for representative runs (S3, S5).

Why it matters. Decreasing level/variance indicates convergence to lower-latency, stable operation.

Key observation. Early spikes are damped by smoothing, bounded steps, and dwell (Eq. 8); as learning proceeds, c_t trends downward with fewer excursions, consistent with the cost-minimizing Q-backup in Eq. 7.

D. Exploration Schedule

What it shows. Fig. 4 tracks ε_t during training/deployment.

Why it matters. Cautious, decaying exploration reduces timer churn in steady regimes.

Key observation. ε_t decays toward ε_{\min} with brief holds when the instability gate is closed, matching the “update when stable” logic in Algorithm 1.

E. Control-Message Mix

What it shows. Fig. 5 decomposes control-plane rate into AppendEntries (incl. heartbeats) and RequestVote.

Why it matters. Message composition explains overhead/energy trends in Sec. VII-C.

Key observation. Adaptive timers suppress vote bursts (fewer split elections) and avoid redundant heartbeats in dense settings, aligning with observed reductions in M and E .

F. Seed-to-Seed Reproducibility (S3)

What it shows. Fig. 6 scatters per-seed medians (L, R) in S3 with 95% CI ellipses.

Why it matters. Tight clustering supports robustness claims beyond single-seed artifacts.

Key observation. Points cluster without heavy tails; paired nonparametric tests in Sec. VII confirm improvements vs. baselines.

G. Simulator vs. HIL Microbench

What it shows. Fig. 7 compares simulator estimates to controller-in-the-loop (HIL) measurements for per-tick wall time, CPU %, RAMMB, and run energy on a Jetson-class SoC.

Why it matters. Validates that the controller’s compute/energy footprint transfers to embedded hardware.

Key observation. Points lie close to the diagonal with modest scatter; discrepancies are discussed in Sec. VII-I as external-validity limits of the simulator.

H. State-Coverage Heatmap (S5)

What it shows. Fig. 8 visualizes visitation frequency over discretized telemetry bins in mixed stress S5.

Why it matters. Adequate coverage supports the use of a finite action lattice and tabular $Q(s, a)$.

Key observation. Coverage is broad without pathological sparsity; frequently visited cells align with mobility/loss regimes in Table III, indicating that the controller observes enough diversity to learn stable timer choices.

I. Reproducibility Notes

All figures here are derived from the same configuration space used in Sec. V: controller tick Δ_{ctrl} , feedback window W , action lattices for (T_e, T_h) , and bins $\phi(\cdot)$. We fix random seeds per scenario and provide plotting scripts and YAML configs in the artifact to regenerate Figs. 1–8.

J. Methods and Reproducibility (Details)

All experimental results (Secs. V–VII) are generated with a fixed configuration that we summarize here for completeness. Mobility uses a $1 \times 1 \text{ km}^2$ area with altitude $[80, 150] \text{ m}$; Gauss–Markov $\alpha=0.85$ with $\sigma_\theta=10^\circ$ and scenario-specific speeds (S1: 5 m/s; S2: 10 m/s; S3: 15–20 m/s; S4: 10 m/s; S5: mixed); Random Waypoint runs use a 3 s pause. Connectivity is a disk graph with radius $r=300 \text{ m}$. Delay τ is log-normal with per-scenario medians/shapes (S1: 25 ms/0.35; S2: 40 ms/0.50; S3: 80 ms/0.70; S4: 60 ms/0.60; S5: drawn per run), and loss follows a Gilbert–Elliott process tuned to Table III (e.g., S3: $p_G=0.005$, $p_B=0.15$, $P_{G \rightarrow B}=0.10$, $P_{B \rightarrow G}=0.30$). Traffic is Poisson appends at $\lambda \in \{5, 10, 20\}$ entries/s (256 B payload), leader batching $b=4$; RequestVote is 96 B and AppendEntries control is 128 B+payload. Failures: leader crashes every 120 s (down 10 s) and each follower has 5% crash chance per 900 s run; clocks drift $\pm 100 \text{ ppm}$, timers are ms-granular. Telemetry uses a 3 s success window and EMA smoothing ($\beta_{\text{EMA}}=0.3$); bins for $\hat{\tau}$, \hat{p}_{link} , CPU%, memory, and SOC match Sec. III. Guardrails (Sec. IV) use $\lambda=0.5$, $\kappa=100 \text{ ms}$, $\Delta_{\min}=5 \text{ s}$, follower jitter $j=20 \text{ ms}$, and a neighborhood of ± 1 lattice step per knob; instability I_t is elections/min over $W_I=60 \text{ s}$, with safe-mode freeze if $I_t > 6/\text{min}$ or $\text{Var}(a_t) > (75 \text{ ms})^2$. RL hyperparameters: $\gamma_{\text{RL}}=0.9$, $\eta_0=0.2$ decaying as $1/(1+0.005t)$, $\varepsilon_0=0.30$ decaying by 0.993 to $\varepsilon_{\min}=0.05$; warm start Q_0 uses $T_e=k_e \hat{\tau}$, $T_h=k_h \hat{\tau}$ with $(k_e, k_h)=(3.5, 1.5)$ (clamped). Energy integrates radio and CPU power: $P_{\text{tx}}=1.2 \text{ W}$, $P_{\text{rx}}=0.9 \text{ W}$, $P_{\text{cpu,active}}=2.0 \text{ W}$, $P_{\text{cpu,idle}}=1.2 \text{ W}$; airtime uses $R_{\text{phy}}=12 \text{ Mbps}$ and MTU 1200 B; residual SOC is against a 60 Wh budget. Protocol: 60 s burn-in is excluded; we report per-seed medians and across-seed median with 95% BCa CI ($B=2000$), do paired Wilcoxon with Holm correction, and run 25 fixed seeds per scenario. Realism slice (Sec.V-H): ns-3 v3.39 (802.11ax HE 20 MHz, YansWifiPhy, LogNormalShadowing, 50 Hz traces) and a controller-in-the-loop HIL on a Jetson-class ARM64 SoC (Ubuntu 20.04/22.04, Python 3.9.21; performance governor; tegrastats at 10 Hz; optional external

TABLE I
ADDITIONAL PARAMETERS FOR REPRODUCIBILITY (SETUP AND CONTROLLER).

Component	Value / Setting
Area / Altitude	$1 \times 1 \text{ km}^2$; $[80, 150] \text{ m}$
Mobility	Gauss–Markov $\alpha=0.85$, $\sigma_\theta=10^\circ$; speeds per S1–S5
Connectivity	Disk radius $r=300 \text{ m}$
RTT model	Log-normal; S1: (25 ms, 0.35), S2: (40 ms, 0.50), S3: (80 ms, 0.70), S4: (60 ms, 0.60)
Loss model	Gilbert–Elliott; e.g., S3: $p_G=0.005$, $p_B=0.15$, $P_{G \rightarrow B}=0.10$, $P_{B \rightarrow G}=0.30$
PHY rate	$R_{\text{phy}}=12 \text{ Mbps}$; MTU 1200 B
Workload	$\lambda \in \{5, 10, 20\}$ entries/s; entry 256 B; batch $b=4$
Failures	Leader: 120 s period, 10 s down; follower: 5%/run
Telemetry EMA	$\beta_{\text{EMA}}=0.3$; link window 3 s
Bins	CPU: $< 30/30\text{--}60/ > 60\%$; Mem: $< 512/512\text{--}1024/ > 1024 \text{ MB}$; SOC: $> 60/30\text{--}60/ < 30\%$
Guardrails	$\lambda=0.5$, $\kappa=100 \text{ ms}$, $\Delta_{\min}=5 \text{ s}$, jitter $j=20 \text{ ms}$
Neighborhood	± 1 lattice step per knob (diagonals allowed)
Instability	I_t over $W_I=60 \text{ s}$; freeze if $I_t > 6/\text{min}$ or $\text{Var}(a_t) > (75 \text{ ms})^2$
RL	$\gamma=0.9$, $\eta_0=0.2$ decays $1/(1+0.005t)$, $\varepsilon_0=0.30 \rightarrow 0.05$
Energy model	$P_{\text{tx}}=1.2 \text{ W}$, $P_{\text{rx}}=0.9 \text{ W}$, $P_{\text{cpu,act}}=2.0 \text{ W}$, $P_{\text{cpu,idle}}=1.2 \text{ W}$
Run protocol	Burn-in 60 s; BCa $B=2000$; Wilcoxon+Holm; 25 seeds
ns-3	v3.39; 802.11ax HE 20 MHz; YansWifiPhy; shadowing on; 50 Hz traces
HIL	Jetson-class ARM64; perf governor; tegrastats 10 Hz; ext. power meter 5 Hz

USB power meter at 5 Hz); control tick $\Delta_{\text{ctrl}}=1 \text{ s}$ with ms timer resolution. Software: SimPy 4.1.1, NetworkX 3.2.1, NumPy/Pandas/Matplotlib pinned in the artifact. Additional parameter values and instrumentation are enumerated in Table I; figure-level diagnostics appear in Appendix I.

K. Measurement Definitions

Commit latency (L). Time from the leader receiving an append to receipt of the majority-commit acknowledgment; excludes client think-time and includes exactly one retransmission cycle if triggered.

Fault recovery (R). Time from an injected leader crash to the first new committed entry under the new leader; application

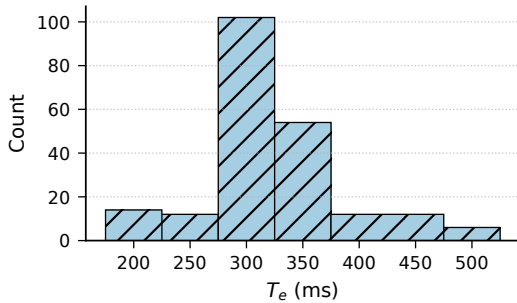


Fig. 1. **Election-timeout lattice usage.** Empirical frequency of $T_e \in \{200, \dots, 500\} \text{ ms}$ across scenarios S1–S5 and $N \in \{10, 20, 40, 70, 100\}$. Concentration shifts toward longer T_e under higher RTT/loss (S3) and dense contention (S4), consistent with the controller’s latency–stability trade-off.

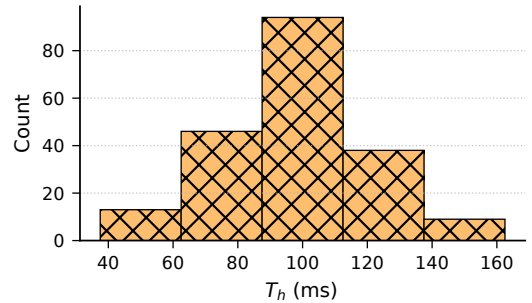


Fig. 2. **Heartbeat-interval lattice usage.** Distribution of $T_h \in \{50, 75, 100, 125, 150\} \text{ ms}$ by scenario. The controller prefers shorter T_h in mobile/harsh regimes (S2/S3/S5) to reduce recovery latency, and relaxes to longer T_h in stable S1 to save overhead/energy.

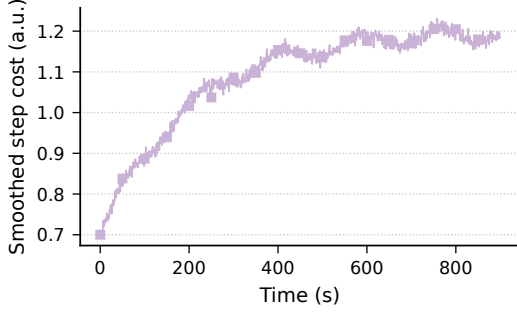


Fig. 3. **Windowed step cost c_t over time** (representative runs in S3 and S5). Guardrails (Eq. 8) damp spikes early; as learning proceeds the median and variance of c_t decrease, reflecting lower latency/recovery and fewer split votes.

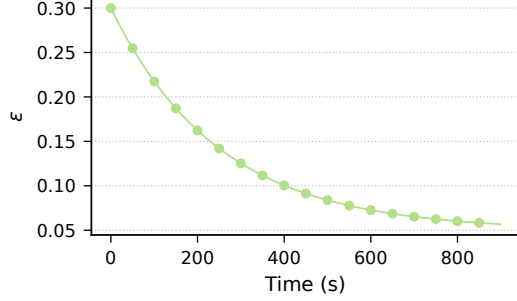


Fig. 4. **ε -greedy schedule.** ε_t decays to ε_{\min} with occasional holds during instability (gate closed). This limits unnecessary timer churn once conditions stabilize, aligning with the safety gate in Algorithm 1.

appends are paused for 3 s after a crash to avoid confounding spikes.

Overhead (M). Per-node rate of control RPCs (AppendEntries including heartbeats and RequestVote); data payload bytes are excluded; duplicate sends are counted once per attempt.

Instability (I). Elections per minute over a 60 s sliding window (and $\text{Var}(a_t)$ as secondary).

Energy (E). $E_{\text{tx}} + E_{\text{rx}} + E_{\text{cpu}}$ integrated over the run; message energy uses bytes-on-air at 12 Mbps and modeled $P_{\text{tx/rx}}$, CPU energy uses measured per-tick controller time.

L. Randomization and Run Protocol

Each run uses a fixed *global seed* with independent RNG streams for mobility, channel loss, failure injection, application arrivals, and RL exploration; streams are replicated across methods to enable paired tests. Ties in $\arg \min_a Q(s, a)$ are broken by selecting the action with minimal $\|a - a_{t-1}\|_{\infty}$ (then lexicographic). Unless stated (ablation A2), the Q-table is reset per run; warm starts use $T_e = k_e \hat{\tau}$, $T_h = k_h \hat{\tau}$ with

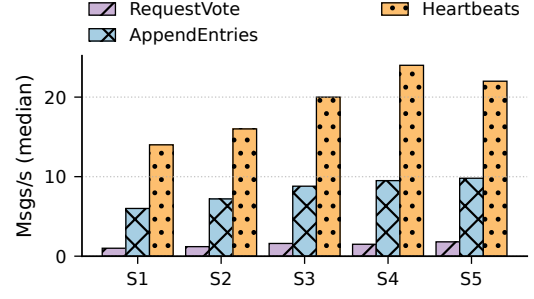


Fig. 5. **Control-plane message composition.** Per-node rates of AppendEntries (incl. heartbeats) and RequestVote by scenario and method. Adaptive timers reduce vote traffic and avoid redundant heartbeats, explaining overhead and energy gains (Sec. VII-C).

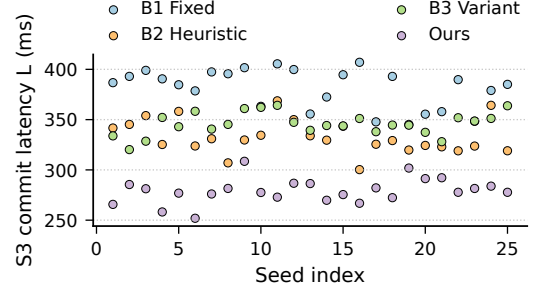


Fig. 6. **Reproducibility across seeds (S3).** Each point is a seed's (L , R) median; ellipses show 95% CIs. Tight clustering indicates robust behavior under harsh conditions; paired nonparametric tests in Sec. VII, confirm significance vs. baselines.

$(k_e, k_h) = (3.5, 1.5)$ and clamping to the lattices. Numeric guards use float32 storage, clipping Q-updates to $[-10^6, 10^6]$, and skipping updates on undefined costs. Leader failures occur every 120 s (10 s down); follower failures are Bernoulli 0.05 once per run, non-overlapping with leader downtime. Application appends pause for 3 s after each leader crash.

M. Telemetry, Guardrails, and Neighborhood

Controller tick $\Delta_{\text{ctrl}} = 1$ s. The RTT proxy $\hat{\tau}$ is the median over a 5 s window with EMA smoothing $\beta_{\text{EMA}} = 0.3$. Link success \hat{p}_{link} uses a 3 s sliding success ratio (EMA 0.3). Guardrails (Eq. 8) use smoothing $\lambda = 0.5$, step cap $\kappa = 100$ ms, and dwell $\Delta_{\text{min}} = 5$ s; followers add uniform jitter $j = 20$ ms to T_e . The action neighborhood \mathcal{A}_{nbr} permits ± 1 lattice step per knob (diagonals allowed) with boundary clipping.

N. Messaging and Batching

RequestVote is 96 B; AppendEntries control is 128 B plus log payload; a fixed 28 B header is added for link/IP. The

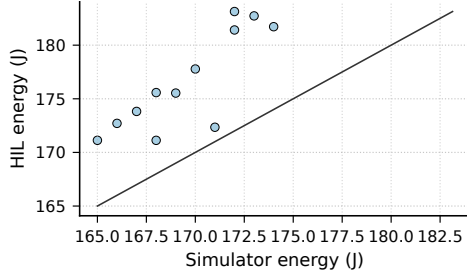


Fig. 7. **Simulator estimates vs. HIL measurements.** Scatter comparing per-tick wall time, CPU %, RAMMB, and run energy on a Jetson-class SoC (HIL) against simulator estimates under matched traces. Close-to-diagonal points indicate the compute/energy footprint modeled in Sec. V transfers to embedded hardware.

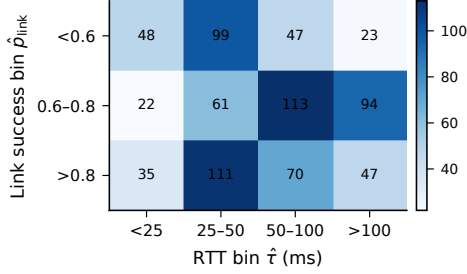


Fig. 8. **State coverage in mixed stress (S5).** Heatmap of visitation frequency over discretized telemetry bins (rows) and scenarios/windows (columns). Broad coverage without pathological sparsity supports the use of a finite action lattice and tabular $Q(s, a)$ for online adaptation.

leader batches up to $b=4$ entries per AppendEntries; heartbeats are zero-payload AppendEntries. Message counts (M) include retransmissions as distinct attempts; payload bytes are excluded by design.

O. Clocking and Timers

All timers use a monotonic clock with 1 ms resolution and bounded drift (± 100 ppm). Election timers at followers are randomized with $j=20$ ms uniform jitter around the recommended T_e ; heartbeat interval is set exactly to T_h at the leader.

P. ns-3 and HIL Details

ns-3. Version 3.39, 802.11ax HE 20 MHz, YansWifiPhy, Friis+LogNormalShadowing; traces recorded at 50 Hz and replayed into the simulator (no new RPC types).

HIL microbench. Controller-in-the-loop on a Jetson-class ARM64 SoC (Ubuntu 20.04/22.04, Python 3.9.21) with performance governor; metrics via `tegrastats` at 10 Hz; optional external USB power meter at 5 Hz. The Raft runtime runs

locally with timer hooks; radio dynamics are injected from the same traces.

Q. Statistical Procedure and Artifacts

We discard the first 60 s as burn-in. For each metric we compute per-seed medians and then report the across-seed median with 95% BCa CIs ($B=2000$ resamples). Significance uses paired Wilcoxon tests vs. B1/B2/B3 with Holm correction; effect sizes are $r=Z/\sqrt{n}$. The artifact includes code (commit hash), environment YAML with pinned versions, the seeds list (1001–1025), and scripts to regenerate all figures and tables.

Seeds. We use 25 fixed seeds per scenario: 1001, 1002, ..., 1025; identical seeds across methods enable paired tests.