Chapter Outline

# Exercises and Classroom Discussion

**Chapter 9 Multi-Vehicle Communication and Intelligent Networking**

9.1 Networking Fundamentals

9.2 Hardware and Link Mechanisms

9.3 Software Layers and Protocols

9.4 Channel and Interference Modeling

9.5 RflySim Networking and Simulation

9.6 Protocols and Development Interfaces

9.7 Experiments and Validation

**9.8 Exercises and Classroom Discussion**

## 3 Units in This Section

**9.8.1 Concepts and Engineering Judgment**

Textbook: Sec. 9.4, Questions 1–5

**9.8.2 Link and Routing Calculations**

Textbook: Sec. 9.4, Questions 6–8

**9.8.3 Networking Design and Integrated Validation**

Textbook: Sec. 9.4, Questions 9–10

### 9.8.1 Concepts and Engineering Judgment: Effective Networking

## Q1: Information Sharing and a Star Network

**Q1:** What makes networked communication effective? When do separate point-to-point ground-station links fail to support information sharing?

| Configuration | Sharing for Coordination | Reference Assessment |
|---|---|---|
| **Separate ground-station control**<br>**No state sent to other vehicles** | The task's required cross-node information is not shared. | The question's claim applies only under this assumption |
| **Ground station receives and relays usable state** | A central relay provides an information path | A star network<br>The center limits capacity and resilience |
| **Direct or relayed inter-vehicle sharing** | Distributed paths can serve the task | Check identity, data meaning, freshness, reliability, and authorization |

### 9.8.1 Concepts and Engineering Judgment: Network Scale

# Q2: Larger Swarms Create More Communication Load

**Q2:** Compare communication strategies and clustering choices for small and large swarms.

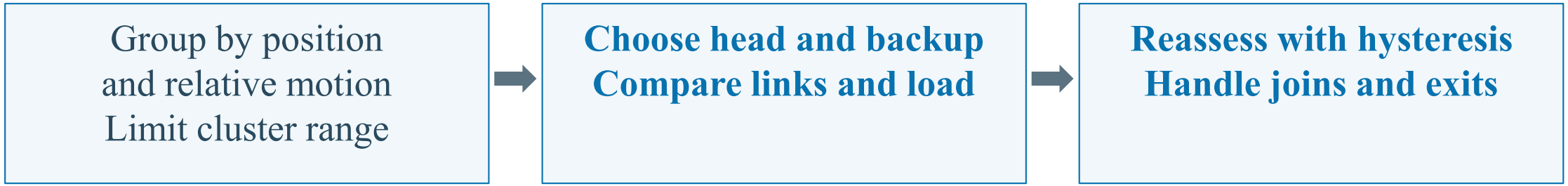
$N$ nodes unicast once per ordered pair per round. The expression counts message copies.

| Aspect | Small-Swarm Option | Large-Swarm Option |
|---|---|---|
| **State exchange** | Direct links or one relay<br>Simple structure | Frequent local updates<br>Cross-cluster summaries and events |
| **Control overhead** | More complete neighbor maintenance may be affordable | Clusters, hierarchical routing, and duplicate suppression |
| **Failure recovery** | A few alternative paths | Backup cluster heads, boundary nodes, and rejoining |

$$N(N-1): \quad 4 \times 3 = 12, \qquad 30 \times 29 = 870$$

### 9.8.1 Concepts and Engineering Judgment: Clustering

## Q2: Forming, Maintaining, and Leaving Clusters




**Membership:** proximity, relative velocity, link quality, and traffic relevance all matter. Test the node-count threshold in the intended scenario.

**Recovery:** use head heartbeats, backup roles, inter-cluster gateways, and a rejoin procedure. Hysteresis reduces repeated boundary switching.

**Evaluation:** compare throughput, tail latency, control overhead, head load, and disconnection duration during reconfiguration.

### 9.8.1 Concepts and Engineering Judgment: Performance Metrics

## Q3: Link Parameters and End-to-End Performance

**Q3:** Explain key communication metrics and the system-level sources of latency.

| Metric Group | Quantities and Units | Effect on the Task |
|---|---|---|
| **Physical and link** | Frequency and bandwidth: Hz<br>Power and threshold: dBm<br>Distance: m | Coverage and usable links depend on antennas, environment, and selected data rate |
| **Data delivery** | Goodput: bit/s<br>Packet rate: packets/s<br>Bit error and packet loss rates | Payload, protocol overhead, and retransmissions share communication resources |
| **Timing and stability** | End-to-end delay, jitter, age of information, and outage duration: s or ms | Information freshness affects control and task recovery |

### 9.8.1 Concepts and Engineering Judgment: Delay Components

## Q3: Decomposing One End-to-End Delay

Timing: message generation to completed reception. Inputs: 1 km, 1,000 B, 10 Mbit/s. After generation: send scheduling 10 ms, processing 2 ms, queueing 8 ms, access/retries 6 ms.

$$d_{\text{tx}} = \frac{8 \times 1000}{10 \times 10^6} = 0.8 \text{ ms}$$

$$d_{\text{prop}} = \frac{1000}{3 \times 10^8} \approx 0.0033 \text{ ms}$$

$$d_{\text{end}} = 10 + 2 + 8 + 6 + 0.8 + 0.0033 \approx 26.8033 \text{ ms}$$

Boundary: generation-to-reception. Align timestamp locations with Section 9.7 before comparing delays.

Count pre-generation sampling wait separately. Reduce queueing, access, and scheduling first.

### 9.8.1 Concepts and Engineering Judgment: Modulation Trade-Offs

# Q4: Modulation Efficiency and Link Conditions

**Q4:** Discuss trade-offs in modulation and anti-jamming techniques.

| Modulation | Benefit | Cost and Conditions |
|---|---|---|
| **Quadrature phase-shift keying QPSK** | 2 bits/symbol. Wider points than 16-QAM at equal mean symbol energy. | Lower spectral efficiency than 16-QAM at the same symbol rate |
| **16-level quadrature amplitude modulation 16-QAM** | 4 bits/symbol<br>Higher theoretical uncoded bit rate at equal symbol rate | Needs higher signal-to-noise ratio and linearity. Errors may rise as the link degrades. |
| **Gaussian minimum-shift keying GMSK** | Continuous phase<br>Approximately constant envelope | Pulse shaping and receiver complexity trade off against spectrum use and errors |

### 9.8.1 Concepts and Engineering Judgment: Anti-Jamming

## Q4: Spreading, Error Control, and Retransmission

| Method | Mechanism | Main Cost |
|---|---|---|
| Frequency hopping (FHSS)<br>Direct sequence (DSSS) | Spread interference effects across frequencies / process a spreading code | Bandwidth, synchronization, and protocol overhead |
| Cyclic redundancy check (CRC) | Detect errors in received data | Detection alone cannot restore erroneous bits |
| Forward error correction (FEC) | Add redundancy to recover a bounded range of errors | Lower code rate, with added decoding cost |
| Automatic repeat request (ARQ) | Retransmit after detected delivery failure | Capacity use, added delay, and a longer delay tail |

LoRa uses chirp spread spectrum (CSS). Balance reliability, goodput, energy use, and latency.

### 9.8.1 Concepts and Engineering Judgment: Protocol Stacks

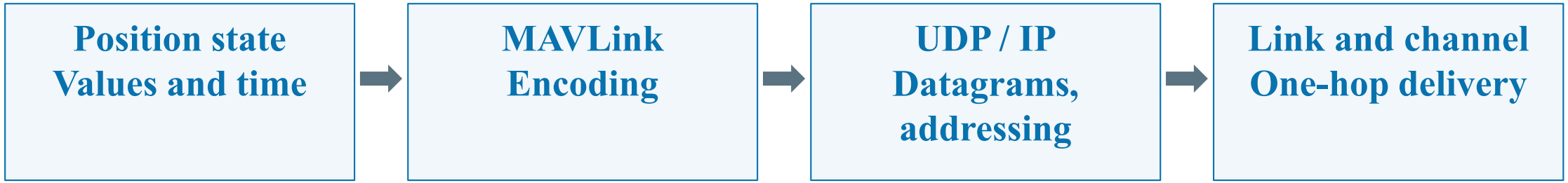
# Q5: The Roles of Common Protocols

Q5: Explain protocol layers. OLSR = Optimized Link State Routing. AODV = Ad hoc On-Demand Distance Vector.

| Layer or Role | Examples | Responsibility |
|---|---|---|
| **Physical / link** | Modulation, radio access, Ethernet | Signals, frames, access, one-hop delivery |
| **Network / routing** | Internet Protocol (IP)<br>OLSR / AODV routing | Addressing and multi-hop paths<br>OLSR maintains routes proactively |
| **Transport** | User Datagram Protocol (UDP)<br>Transmission Control Protocol (TCP) | Datagrams / reliable ordered bytes |
| **Messaging** | Micro Air Vehicle Link (MAVLink)<br>Data Distribution Service (DDS)<br>Message Queuing Telemetry Transport (MQTT) | Fields / publish–subscribe quality of service (QoS) / broker topics |
| **Frameworks / services** | Robot Operating System 2 (ROS 2) / Redis<br>Real Time Streaming Protocol (RTSP) | Applications / data / stream sessions |

### 9.8.1 Concepts and Engineering Judgment: A Concrete Stack

# Q5: Following One State Message




Receiver: receive a frame, extract the UDP payload, parse the MAVLink fields, and use the position and time.

DDS variant: the application agrees on a Topic and type. Matching writers and readers distribute samples over the implementation's configured transport.

**Message format, distribution, and routing have distinct jobs. Trace faults along the data path.**

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Textbook: Sec. 9.4, Questions 9–10

### 9.8.2 Link and Routing Calculations: Path Loss and Margin

# Q6: Link-Budget Inputs and Assumptions

**Q6:** Calculate free-space path loss and evaluate the communication link margin.

| Parameter | Teaching Value | Assumption or Meaning |
|---|---|---|
| **Frequency and distance** | 2.4 GHz / 1 km | Free space and line of sight<br>No additional loss yet |
| **Transmit power / antenna gains** | 20 dBm / 5 dBi at each end | Assume matched antenna direction and polarization |
| **Feeder losses** | 1 dB at each end | Count transmitter and receiver feeders separately |
| **Receiver threshold / required margin** | −85 dBm / 10 dB | Threshold tied to the selected rate and error requirement |

### 9.8.2 Link and Routing Calculations: Eqs. (9.1)–(9.2)

## Q6: Free-Space Loss, Units, and Substitution

$$L_{\mathrm{fs}} = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right), \qquad \lambda = \frac{c}{f}$$

Eq. (9.1): distance d and wavelength use the same length unit. c is propagation speed and f is frequency. This model excludes blockage, reflection, and interference.

$$L_{\mathrm{fs}} = 32.44 + 20\log_{10}(d_{\mathrm{km}}) + 20\log_{10}(f_{\mathrm{MHz}})$$

$$L_{\mathrm{fs}} = 32.44 + 20\log_{10}(1) + 20\log_{10}(2400) \approx 100.04\ \mathrm{dB}$$

Unit check: 2.4 GHz = 2400 MHz. Eq. (9.2)' s constant depends on its specified units.

### 9.8.2 Link and Routing Calculations: The Complete Budget

# Q6: Received Power and Available Margin

Units: transmit/received power in dBm, antenna gain in dBi, feeder/path losses in dB. The receiver threshold depends on the selected mode.

$$P_r = P_t + G_t + G_r - L_t - L_r - L_{\text{fs}}$$

$$P_r = 20 + 5 + 5 - 1 - 1 - 100.04 = -72.04\ \text{dBm}$$

$$M = P_r - P_{\text{sens}} = -72.04 - (-85) = 12.96\ \text{dB}$$

Required margin: 10 dB, leaving 2.96 dB reserve. This meets the stated assumptions. Also assess attitude, polarization, feeder changes, blockage, and interference.

### 9.8.2 Link and Routing Calculations: Budget Limits

# Q6: Sensitivity to Distance and Additional Loss

| Condition | Total Path Loss | Margin over [illegible] | 10 dB Reserve? |
|---|---|---|---|
| **0.5 km** | 94.02 dB | 18.98 dB | Yes |
| **1 km** | 100.04 dB | 12.96 dB | Yes |
| **2 km** | 106.06 dB | 6.94 dB | No |
| **1 km + 6 dB blockage loss** | 100.04 + 6 dB | 6.96 dB | No |

$$L_{\text{total}} = L_{\text{fs}} + \Delta L_{\text{Fresnel}} \quad \text{(Textbook Eq. 9.4)}$$

### 9.8.2 Link and Routing Calculations: The First Fresnel Zone

# Q7: Clearance Extends beyond the Direct Line

**Q7:** Derive and calculate the first Fresnel-zone radius, then justify an obstacle-clearance criterion.

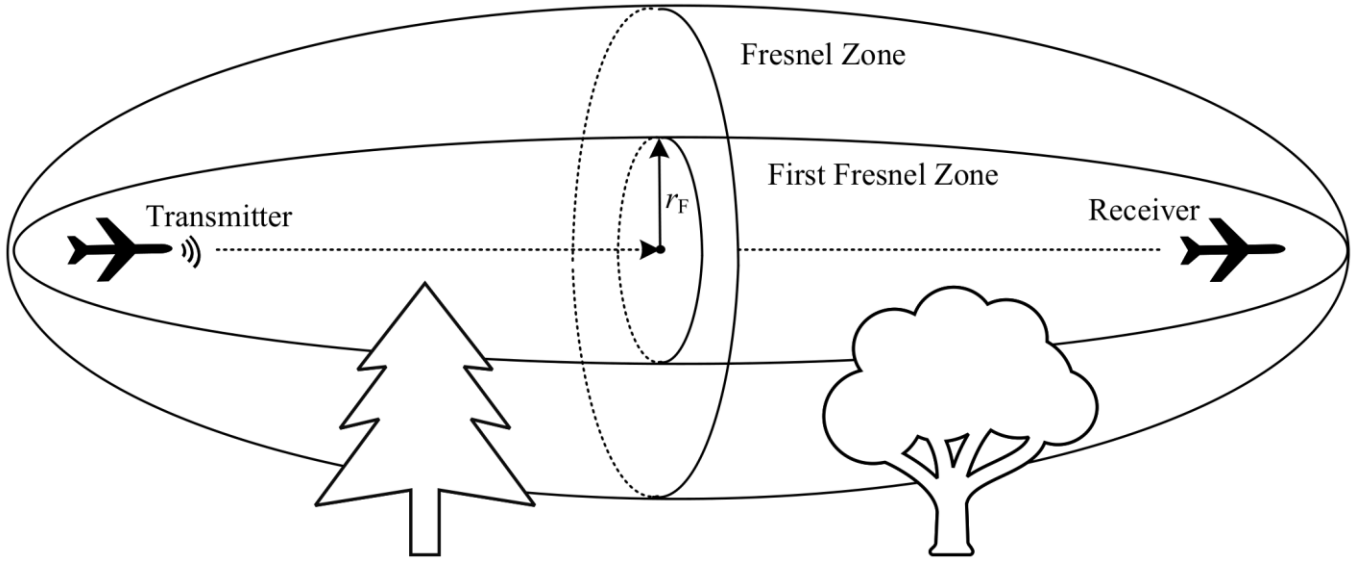



Figure 9.6: Fresnel zone in wireless communication

**Definition:** the first-zone boundary adds half a wavelength to the direct path.

**Inputs:** frequency, endpoint distance, and obstacle position and height.

**Outputs:** local zone radius, clearance ratio, and diffraction risk.

### 9.8.2 Link and Routing Calculations: Small-Radius Approximation

## Q7: Deriving the First-Zone Radius

Let $d_1, d_2$ be the distances from the cross-section to the endpoints, $r$ the radial distance, and $\lambda$ the wavelength, all in m.

$$\Delta = \sqrt{d_1^2 + r^2} + \sqrt{d_2^2 + r^2} - (d_1 + d_2)$$

$$\Delta \approx \frac{r^2}{2d_1} + \frac{r^2}{2d_2} = \frac{\lambda}{2}$$

$$r_1 = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}} \qquad (r_1 \ll d_1, d_2)$$

Eq. (9.3), zone order 1: the radius must be much smaller than both endpoint distances.

### 9.8.2 Link and Routing Calculations: Numerical Example

## Q7: Radius and Clearance for a 1 km Link

Use 2.4 GHz over 1 km. Start at the midpoint, 500 m from either end.

$$\lambda = \frac{3 \times 10^8}{2.4 \times 10^9} = 0.125 \text{ m}$$

$$r_1 = \sqrt{\frac{0.125 \times 500 \times 500}{1000}} = \sqrt{31.25} \approx 5.59 \text{ m}$$

$$h_{\text{clear,screen}} = 0.6 r_1 \approx 3.35 \text{ m}$$

Screening criterion: keep the obstacle at least 3.35 m below the direct line. A 0.6-radius clearance is a common screen, followed by terrain and propagation assessment.

At 100 m from the transmitter, the radius is about 3.35 m. Recalculate along the path.

### 9.8.2 Link and Routing Calculations: Obstacle Clearance

# Q7: Assessing and Improving an Obstructed Link

Example: the midpoint direct line is 12 m above flat ground. First-zone radius: 5.59 m. Screen for at least 3.35 m clearance.

| Height | Direct-Line Clearance | Clearance Ratio | Reference Assessment |
|---|---|---|---|
| **8 m** | 4 m | 0.716 | Passes this geometric screen |
| **9 m** | 3 m | 0.537 | Below 0.6 radius<br>Assess diffraction |
| **13 m** | −1 m | −0.179 | Direct path blocked<br>Estimate additional loss |

9 m obstacle: raise both ends about 0.36 m or one end about 0.72 m, then add reserve.

### 9.8.2 Link and Routing Calculations: Geometry to Loss

# Q7: A Single Knife-Edge Diffraction Example

Single-knife-edge model: $h = 1$ m above the direct line, 500 m to each endpoint, wavelength 0.125 m.

$$\nu = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \approx 0.253$$

$\nu$: dimensionless obstruction parameter. $J$: added diffraction loss in dB. $M$: remaining link margin.

$$J(\nu) \approx 6.9 + 20\log_{10}\left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1\right)$$

$$J(0.253) \approx 8.22\ \text{dB}, \qquad M \approx 12.96 - 8.22 = 4.74\ \text{dB}$$

The approximation applies for $\nu > -0.78$. Including this loss in Eq. (9.4) leaves less than the 10 dB reserve. Multiple obstacles need another model.

### 9.8.2 Link and Routing Calculations: The ETX Model

# Q8: From Delivery Probability to Expected Attempts

**Q8:** Build a route-selection model using expected transmission count (ETX), test an example, and analyze its validity.

Let $d_f, d_r \in (0,1]$ be forward-data and reverse-acknowledgment success probabilities. Assume independence, stationarity, and consistent retry conditions.

$$p = d_f d_r, \qquad E = 1 + (1-p)E \quad \Rightarrow \quad E = \frac{1}{p}$$

$p$ is success probability per attempt. $E$ counts expected attempts up to success, including the first.

$$\mathrm{ETX}(u,v) = \frac{1}{d_f d_r}, \qquad C(P) = \sum_{(u,v)\in P} \mathrm{ETX}\,(u,v)$$

Dimensionless ETX adds hop costs to form route cost. See textbook Eqs. (9.6)–(9.7).

### 9.8.2 Link and Routing Calculations: Worked Route Comparison

# Q8: Direct Delivery versus Two Hops

| Candidate Link | Forward Success | Reverse Success | Hop ETX |
|---|---|---|---|
| A→C | 0.4 | 0.8 | 3.125 |
| A→B | 0.9 | 0.9 | 1.2346 |
| B→C | 0.9 | 0.9 | 1.2346 |

$$C(A \to C) = 3.125 > \frac{1}{0.81} + \frac{1}{0.81} \approx 2.469 = C(A \to B \to C)$$

ETX selects A→B→C for fewer expected attempts, without guaranteeing minimum delay.

### 9.8.2 Link and Routing Calculations: Route Computation

# Q8: Recovering the Next Hop with Dijkstra's Algorithm

| Step | Settled Nodes | Tentative Cost to B | Tentative Cost to C |
|---|---|---|---|
| **Initialize** | A | 1.2346, predecessor A | 3.125, predecessor A |
| **Settle B, relax C** | A、B | 1.2346 | 2.4691, predecessor B |
| **Settle C** | A、B、C | Unchanged | Optimal path settled |

Route: destination C, next hop B, total ETX about 2.469. Treat a link with zero success probability as unavailable.

### 9.8.2 Link and Routing Calculations: Sensitivity and Implementation

# Q8: When the Route Model Remains Useful

Let all forward and reverse success probabilities on the two-hop route equal $s$. Compare with direct ETX = 3.125.

$$2/s^2 < 3.125 \quad \Rightarrow \quad s > 0.8$$

| Changed Condition | Effect on the Decision |
|---|---|
| **Time-varying success rates** | Balance estimator noise and response. Stale statistics can select the wrong route. |
| **Low rates or long queues** | Lower ETX can still mean more delay. Add capacity and delay constraints. |
| **Correlated loss / finite retries** | The stationary independent geometric model becomes inaccurate. Record actual delivery and cost. |
| **Protocol implementation** | ns-3 3.43 implements baseline RFC 3626 OLSR. Check source and configuration separately for ETX extensions. |

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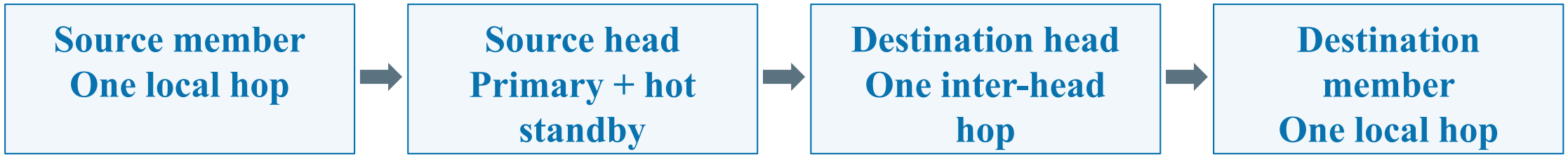
**9.8.3 Networking Design and Integrated Validation**

Textbook: Sec. 9.4, Questions 9–10

### 9.8.3 Networking Design and Integrated Validation: Assumptions

# Q9: A Reference Design for 30 UAVs

**Q9:** Design clustering and quality-of-service (QoS) policies for 30 unmanned aerial vehicles (UAVs), balancing stability and efficiency while keeping critical-command delay strictly below 100 ms.




Example: 5 clusters of 6 UAVs. Choose heads by links, relative motion, energy, and load. Use hysteresis and minimum residence time for boundary changes.
Conditions: ≤3 hops, admitted traffic within capacity, at most one controlled switchover.
Persistent partitions are outside the 100 ms guarantee.

### 9.8.3 Networking Design and Integrated Validation: Capacity

## Q9: Traffic Budget and Admission

Assume 100 B at 50 Hz per UAV, one destination delivery per message, at most 3 hops, and a provisional factor of 2 for protocol overhead and bounded retries.

$$R_{\text{payload}} = 30 \times 100 \times 50 \times 8 = 1.2\ \text{Mbit/s}$$

$$R_{\text{air,budget}} \leq 1.2 \times 3 \times 2 = 7.2\ \text{Mbit/s}$$

$$7.2 < 0.7 \times 20 = 14\ \text{Mbit/s}$$

Assume 20 Mbit/s usable capacity in one contention domain. Admit at most 70%, leaving reserve. Recalculate for extra destination copies or video and check peak head load.

### 9.8.3 Networking Design and Integrated Validation: QoS

# Q9: Queues and Policies for Each Traffic Type

| Traffic | Reference Handling | Purpose |
|---|---|---|
| **Critical commands** | Reliable delivery, acknowledgment, sequence IDs. Bound retries, reject expired commands, and handle repeats idempotently. | Know delivery status Limit late or repeated execution |
| **Periodic state** | Shallow KEEP_LAST history Set Deadline / Lifespan for the task | Detect missing updates Avoid a backlog of old state |
| **Images and logs** | Rate limits, lower priority, bounded queues. Reduce rate or drop replaceable content under congestion. | Protect control traffic's capacity and queue access |

Fast DDS 3.6.2/3.7.0.1 marks LatencyBudget for future implementation. This policy alone cannot guarantee end-to-end timing.

### 9.8.3 Networking Design and Integrated Validation: Timing Budget

# Q9: A Strict 100 ms Limit Needs a Defensible Bound

| Stage | Bound | Required Condition |
|---|---|---|
| **Application scheduling + encoding** | 10 + 5 ms | High priority and bounded execution |
| **Queueing over the complete path** | 10 ms | Admission control, priority queues, bounded bursts |
| Access/send/retries<br>Up to 3 hops | 3×12 = 36 ms | Per-hop service bound<br>Bounded retries |
| **Relay + destination processing** | 5 + 9 ms | Bounded relay and consumer tasks |
| **One controlled switchover** | 15 ms | Ready standby<br>Bounded switch time |

$$D_{\text{bound}} = 10 + 5 + 10 + 36 + 5 + 9 + 15 = 90 \text{ ms}$$

Including an extra 3 ms timing-error bound gives 93 ms, still below 100 ms.

### 9.8.3 Networking Design and Integrated Validation: Conditions

## Q9: Failure Handling and Acceptance Scope

**Stability:** synchronize required state to the hot standby. Use hysteresis for changes and track critical-command sequence numbers and deadlines through route changes.

**Strict criterion:** worst-case generation-to-consumption delay plus timing error is below 100 ms, with no lost or late critical commands. The 95th percentile (P95) cannot replace a maximum bound.

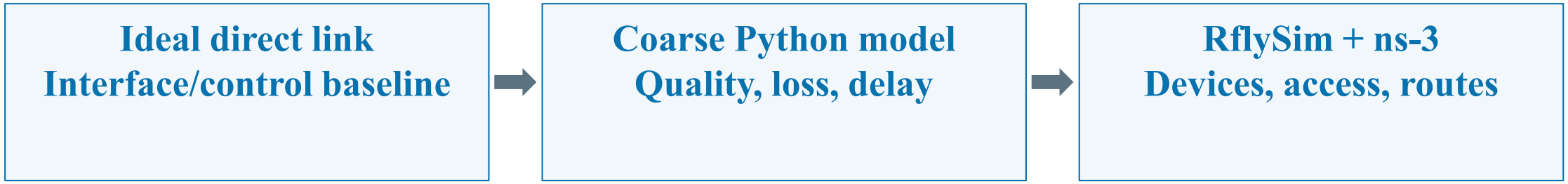
**Stress cases:** test maximum admitted load, longest allowed range, and one switchover. Overload, partitions, or a second fault require readmission or degradation.

**Conclusion:** five clusters form a testable design. The timing commitment holds only within the proven component bounds and operating assumptions.

### 9.8.3 Networking Design and Integrated Validation: Co-Simulation

# Q10: What to Compare across Simulation Stages

**Q10:** Build a joint RflySim and ns-3 simulation, run a complete test workflow, and explain differences between the results at each stage.




Common metrics: per-packet delivery, P95/maximum delay, age of information, outage duration, and following error. List internal model statistics separately.

### 9.8.3 Networking Design and Integrated Validation: Setup

# Q10: Entry Points and Prerequisites

Parent directory: [installation directory]/RflySimAPIs/9.RflySimComm/. Read each example's Readme.pdf first.

| Purpose | Relative Directory | Entry Point |
|---|---|---|
| **Minimal state path** | 0.ApiExps/e1.RflyNetAPIExps/<br>1.P2PSendData/ | SITLRun2MavlinkFull.bat<br>Run UAV2Ctrl.py, then UAV1Ctrl.py |
| **Coarse-model comparison** | 2.AdvExps/e1.CoaGraNetSimExps/<br>1.NetSim4Demo/ | SITLRun4MavlinkFull.bat<br>Then PythonRunALL.bat |
| **ns-3 dependency test** | 0.ApiExps/e6.NS3DepsTestExps/ | RflyNet.cc / TestSend.py |
| **Control co-simulation** | 3.CustExps/e2.NS3_UAVCommExps/<br>4.NS3-Ctrl/ | OneScript.bat<br>Full edition or above only |

### 9.8.3 Networking Design and Integrated Validation: Integration

# Q10: Mapping Motion to the Network Model

| RflySim Side | ns-3 Side | Check |
|---|---|---|
| **Vehicle ID and traffic source/target** | Node and application endpoint | Send one sequenced message between two fixed nodes |
| **Position, velocity, timestamp** | MobilityModel and event time | Check trajectory units and directions point by point |
| **Traffic bytes and frequency** | Application and send events | Compare generated count and payload size |
| **Interface input and model output** | NetDevice / Channel / routing | Log packet entry into and exit from the model |
| **Control input and task error** | Arrival sequence and packet events | Align network changes with control error in the same time window |

### 9.8.3 Networking Design and Integrated Validation: Test Workflow

# Q10: From Preparation to Shutdown

**Prepare:** freeze versions, reference trajectories, and traffic. The custom case needs the Full edition or above, RflySim-20.04, a custom ns-3.33 tree, and its routing modules.

**Launch:** the entry extracts/copies source, runs sudo configuration/build steps, and starts processes. Check build exit status, node mapping, UDP transfer, and control inputs.

**Record:** warm up, then start a common window. Log source/target ID, sequence, bytes, generation/reception/use times, position, and control error.

**Finish:** stop traffic, drain as agreed, then use Ctrl+C on this run's control, model, and interface. Locate hangs by process ID, save logs, and restore the working copy.

### 9.8.3 Networking Design and Integrated Validation: Test Matrix

# Q10: Changing One Network Factor at a Time

| Test | Change | Fixed Conditions / Sampling |
|---|---|---|
| **A: Ideal baseline** | Remove artificial network degradation | 4 vehicles: same reference, initial state, controller, 100 B at 50 Hz |
| **B: Range degradation** | Change only distance or model-quality parameter | Same message and reference-generation rules |
| **C: Contention and routing** | Add background traffic or link changes in ns-3 | Record device, channel, and routing configuration |
| **D: Recovery and faults** | One traceable link break or node departure | Define fault time, recovery criterion, and drain period |

Suggested: 10 s warm-up, 60 s measurement, agreed draining, 10 repeats per case.

### 9.8.3 Networking Design and Integrated Validation: Illustrative Data

# Q10: Recalculating Metrics from Example Records

Common basis: one source–destination pair, 3,000 messages of 100 B over 60 s, deduplicated and drained. All values below are illustrative, not measurements.

| Example Case | Received | Loss Rate | Goodput | P95 Delay |
|---|---|---|---|---|
| **Direct-link example** | 2,997 | 0.1% | 39,960 bit/s | 5 ms |
| **Coarse-model example** | 2,850 | 5.0% | 38,000 bit/s | 35 ms |
| Detailed model Example | 2,790 | 7.0% | 37,200 bit/s | 60 ms |

$$G_{\text{example}} = \frac{2790 \times 100 \times 8}{60} = 37200 \text{ bit/s}$$

### 9.8.3 Networking Design and Integrated Validation: Explaining Results

# Q10: Diagnosing Differences and Completing the Test

| Observed Difference | Possible Cause | Further Check |
|---|---|---|
| **Longer delay tail** | Queueing, access contention, retries, scheduling | Fix the link, vary only traffic load, inspect queue events |
| **Much higher packet loss** | Channel errors, full queues, no route | Group drops by reason and time |
| **Similar communication Larger control error** | Stale state, frame/clock mismatch, bypass | Trace the actual control input by sequence number |
| **Persistent coarse/detailed gap** | Contention/routing omitted by the coarse model | Toggle one mechanism while holding other settings fixed |

Completion: reproducible settings, no bypass, recalculable metrics, explained differences. Validate deployment separately.

Exercises and Discussion

# Discussion: Why More Reliable Messages Can Be Older

1. Ordered retransmission of historical state reduces loss but increases age of information. Is that necessarily better for following control?

2. Should critical task commands and 50 Hz position state use the same history depth, retransmission, and expiry policies?

3. When load doubles or a cluster head leaves, how should admission, rate limits, and degradation change to retain a defensible delay commitment?

Reference Points

# Discussion: Deadlines, Reliability, and Message Meaning

| Topic | Reference Reasoning |
| --- | --- |
| **Reliable but stale** | Filter periodic state by freshness and compare age with task error. Recovering expired state can grow queues and delay newer samples. |
| **Commands and state** | Commands: acknowledgment, sequence, idempotence, deadlines. State: shallow history, expiry filtering, missing-update detection. |
| **Load / head failure** | Prioritize critical traffic and rate-limit other flows. Recheck capacity, paths, and timing after standby takeover. |
| **Evidence scope** | Passing a stated case supports that case. A strict limit also needs upper-bound analysis and runtime validation. |

Chapter Summary

# Chapter Summary: Communication Limits Available Information

**Concepts:** effective networking provides the information a task needs. Links, message formats, distribution, and routing serve different roles.

**Methods:** budget traffic, path loss and margin, Fresnel clearance, and ETX routes, then compare tests using the same metric definitions.

**Pitfalls:** update rate differs from network delay. Lower ETX need not mean lower latency. QoS settings and averages alone cannot prove a strict bound.

**Next:** Chapter 10, Swarm Collaboration and Game-Theoretic Confrontation, examines coordinated action with stale, missing, and uncertain information.