Chapter Outline

Software Layering and Communication Protocols

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

4 Units in This Section

9.3.1 Network Layering

Textbook: Section 9.1.4, item 1

9.3.2 Communication Protocols and Software Roles

Textbook: Section 9.1.4, item 2

9.3.3 Network Topologies and Routing Protocols

Textbook: Section 9.1.4, item 3

9.3.4 Routing Trends and Selection

Textbook: Section 9.1.4, item 4

9.3.1 Network Layering: Responsibilities

A State Message Needs Three Kinds of Agreement

Message meaning Position / units / time	→	Endpoint delivery Host / program	→	Hop-by-hop transfer Next hop / signal

Message protocol: Defines fields and their meaning. Middleware also manages data discovery, matching, and distribution.

Network and transport: Internet Protocol (IP) addresses hosts and forwards packets. User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) deliver data to programs by port.

Link and physical layers: Each hop packages data into frames and sends signals over radio, copper cable, or optical fiber.

9.3.1 Network Layering: Figure 9.3 and Layer Mapping

Open Systems Interconnection (OSI) and TCP/IP

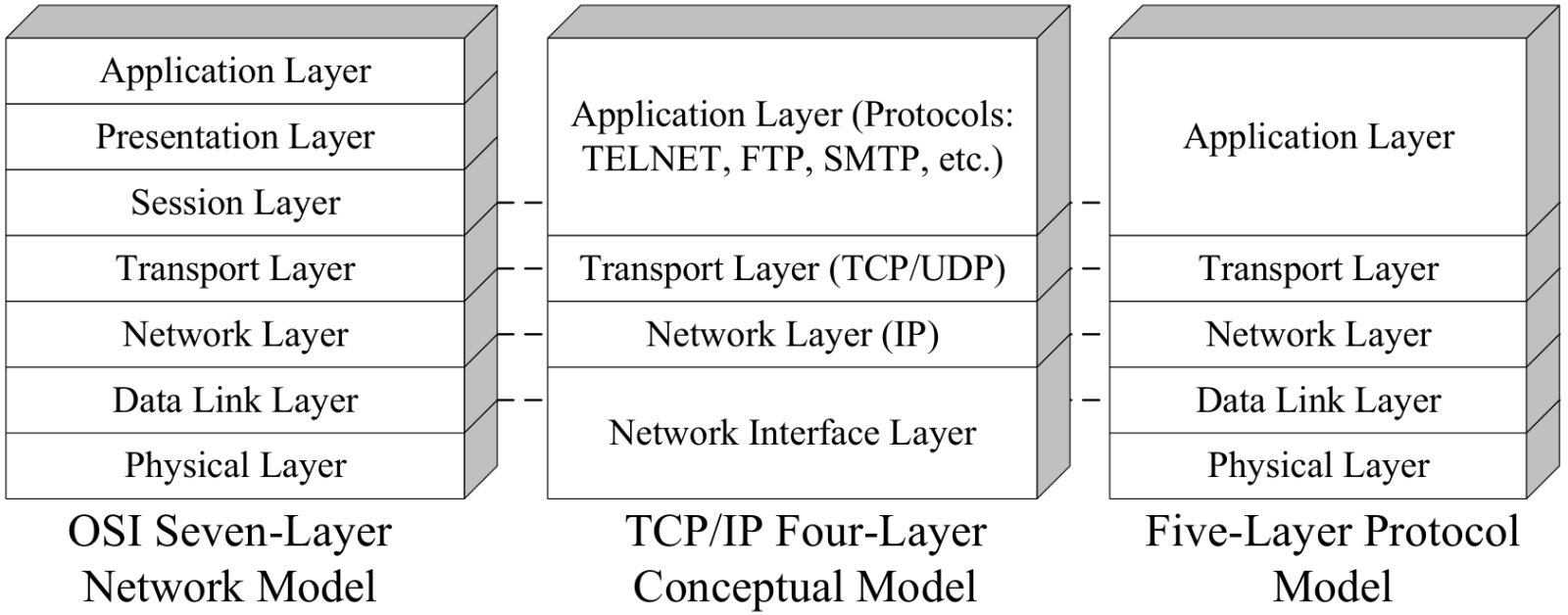


Figure 9.3 Network Layering Model

OSI maps roles; TCP/IP describes the practical stack. The five-layer view separates link and physical.

9.3.1 Network Layering: Physical, Link, Network, Transport, Application

What Each of the Five Layers Does

Layer	Core responsibility	Unmanned-system example
Application	Message meaning, encoding, sessions	State fields, task commands, video sessions
Transport	Ports and end-to-end delivery semantics	UDP datagrams; TCP reliable, ordered byte stream
Network	Logical addressing and forwarding across networks	IP addresses, routing tables, next hops
Data link	Frame transfer between adjacent nodes	Ethernet / Wi-Fi frames; Point-to-Point Protocol (PPP) links
Physical	Bits to electrical, optical, or radio signals	Modulation, bands, power, transceivers

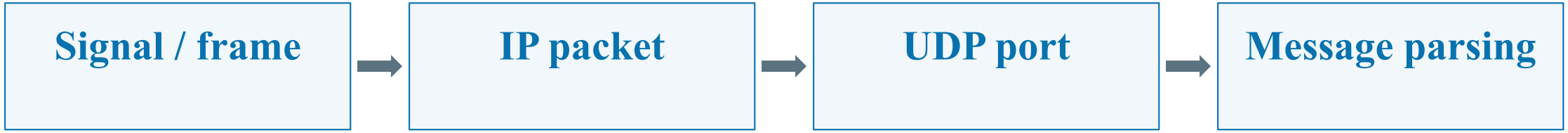
9.3.1 Network Layering: From Application Message to Link Frame

The Sender Encapsulates Data Layer by Layer

Application message	Node ID, timestamp, position, and velocity
UDP datagram	UDP header: Source / destination ports + application message
IP packet	IP header: Source / destination IP addresses + UDP datagram
Current-hop link frame	Link header / check + IP packet; then modulate into a signal

9.3.1 Network Layering: Decapsulation and Address Scope

The Receiver Recovers the Message Layer by Layer



Identifier	What it locates	Scope and limits
Link address	Link endpoint on the current hop	Routing changes the link encapsulation
IP address + port	Host network endpoint + transport endpoint	A port is not a vehicle ID
Node ID in the message	A specific vehicle or component	Application-defined; also usable over serial

9.3.1 Network Layering: Transport Tradeoffs

UDP and TCP Offer Different Delivery Semantics

Aspect	UDP: User Datagram Protocol	TCP: Transmission Control Protocol
Data boundaries	Individual datagrams	Ordered byte stream; application defines framing
Reliability	No built-in acknowledgments, retries, or ordering	Sequence numbers, acknowledgments, retries, flow / congestion control
Latency cost	Low overhead; the application handles loss	Missing earlier data delays later delivery
Common uses	Frequent state updates; streams that can discard old samples	Files, configuration, and sessions that prioritize integrity

UDP does not ensure low latency; TCP does not ensure deadlines. Task commands still need application acknowledgments and deduplication.

9.3.1 Network Layering: Debugging by Layer

Locate a Fault by Its Layer

Observed symptom	Check first	What to inspect
No connection on this hop	Physical / link	Power, band, modulation Medium access and neighbors
Local traffic works; cross-network traffic fails	Network	Addresses, routing table, next hop Network Address Translation (NAT)
Host receives packets; application does not	Transport and host configuration	Protocol, port, bind address, filtering
Bytes arrive; values or timing are wrong	Application meaning	Field layout, units, byte order Protocol version and clocks

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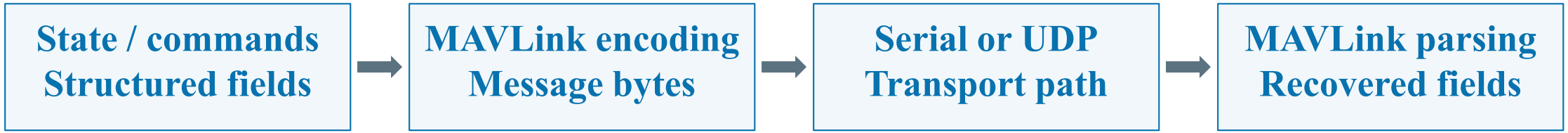
Textbook: Section 9.1.4, item 3

9.3.4 Routing Trends and Selection

Textbook: Section 9.1.4, item 4

9.3.2 Communication Protocols and Software Roles: Lightweight Messages

MAVLink Defines Message Formats



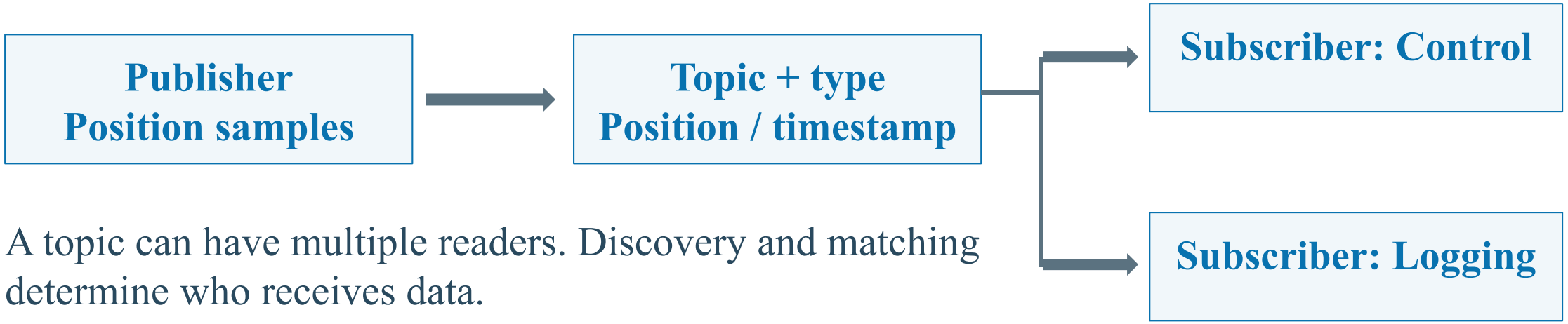
Example: Micro Air Vehicle Link (MAVLink) carries autopilot heartbeats and position. The ground station updates its display by message type and vehicle ID.

Input / output: The encoder takes fields and type definitions. The parser takes received bytes and produces structured messages.

Adjacent layers: UDP still needs IP and a link. A MAVLink system ID cannot replace an IP address.

9.3.2 Communication Protocols and Software Roles: Publish-Subscribe Middleware

Data Distribution Service (DDS) Matches Topic Endpoints



A topic can have multiple readers. Discovery and matching determine who receives data.
Quality of service (QoS) policies include reliability and history depth.

Example: A controller and logger read the position topic. Each reader configures its own buffer depth and data-freshness requirements.

9.3.2 Communication Protocols and Software Roles: Framework and Middleware

ROS 2 Organizes Applications; Middleware Communicates

ROS 2 nodes
Perception / control

→

RMW interface
Middleware abstraction

→

DDS, for example
Discovery / distribution

ROS 2 construct	Simple use	Communication result
Topic	Publish position and sensor data	Subscribers receive a stream of samples
Service	Request a parameter or state once	Receive one response
Action	Start a task that takes time	Progress feedback and final result

ROS 2 = Robot Operating System 2; RMW = ROS Middleware. ROS 2 is a framework. MAVLink, DDS, and ROS 2 work separately or through adapters.

9.3.2 Communication Protocols and Software Roles: Remote Publish-Subscribe

MQTT Distributes Topic Messages Through a Broker

Unmanned node
Publishes state
→
Broker server
Forwards by topic
→
Monitor / task app
Subscribes to topics

QoS level	Delivery per leg	Engineering implications
0	At most once	No acknowledged retry; messages may be lost
1	At least once	Duplicates: Deduplicate or use idempotent operations (repeats leave the result unchanged)
2	Exactly once (protocol delivery)	More exchanges; action execution still needs confirmation

Message Queuing Telemetry Transport (MQTT) sets QoS separately on each broker leg. Reachability and session settings still affect delivery.

9.3.2 Communication Protocols and Software Roles: Storage and Publish-Subscribe

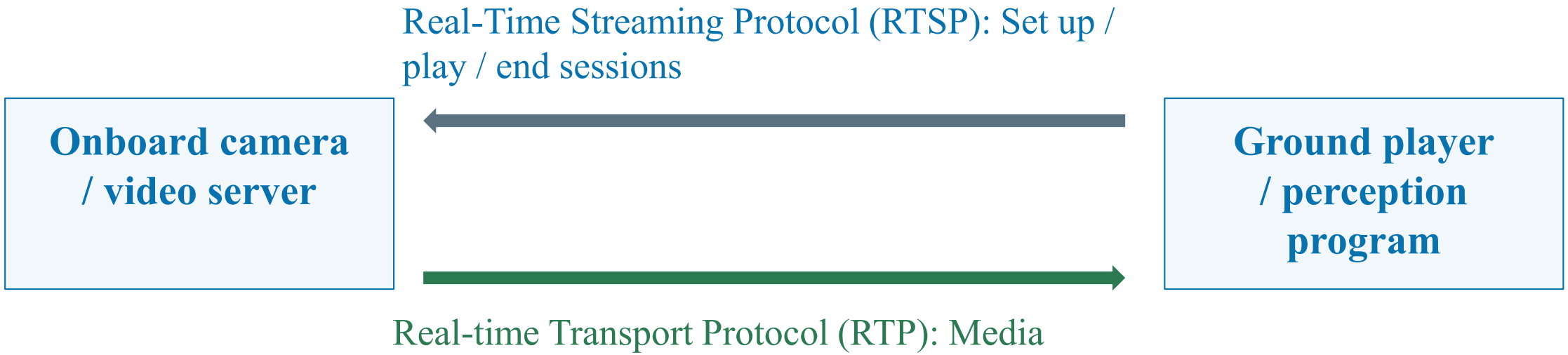
Redis Supports Shared Data and Messaging

Use	Input / output	Example and limits
Shared key-value data	Write state; read the currently stored value	Simulation writes position; monitor reads Handle stale data and concurrent access
Pub/Sub channels	Publish events; connected subscribers receive them	State-update broadcasts No automatic replay after disconnection
Streams	Append entries; read stored records	An option when replay and consumer acknowledgments are needed

Storage, live notifications, and reliable queues have different semantics.

9.3.2 Communication Protocols and Software Roles: Video Sessions and Media

RTSP Controls Sessions; Media Uses Its Own Path



Input / output: RTSP requests get responses. RTP carries video. RTP Control Protocol (RTCP) reports statistics.

Example: Set up a camera session, then read video frames continuously. Position and commands keep their own message paths.

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9.3.3 Network Topologies and Routing Protocols: Figure 9.4 Overview

Point-to-Point and Networked Communication

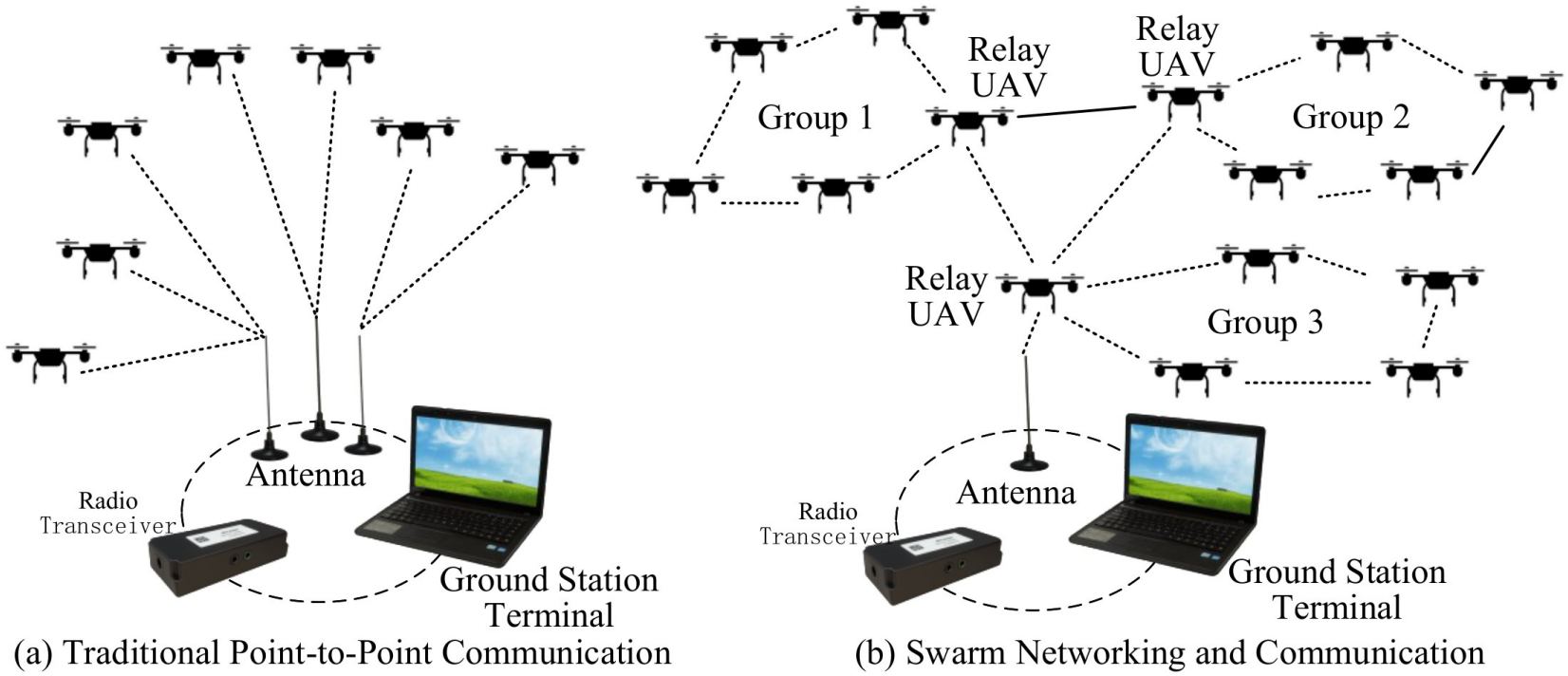
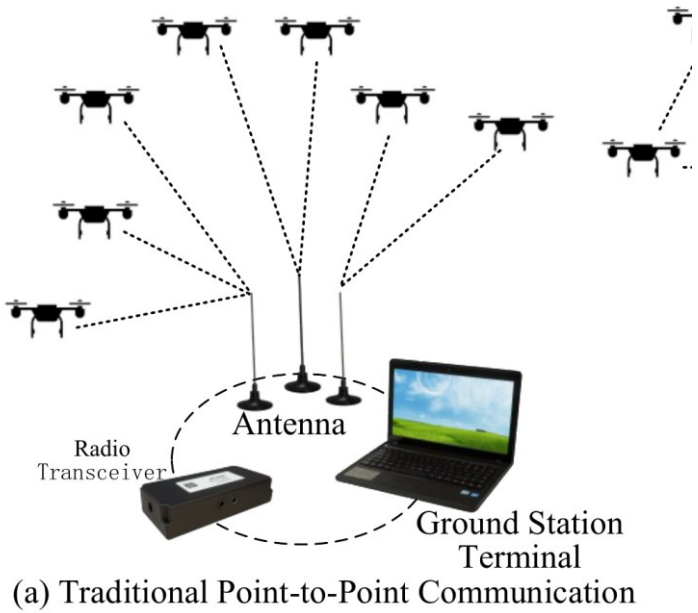


Figure 9.4 Point-to-Point and Networked Communication

Identify central or relay forwarding. Topology alone does not specify the routing protocol.

9.3.3 Network Topologies and Routing Protocols: Figure 9.4, Left Detail

Sharing Between Aircraft Depends on Ground Forwarding



Connections: Wireless links converge at the ground receiving system.

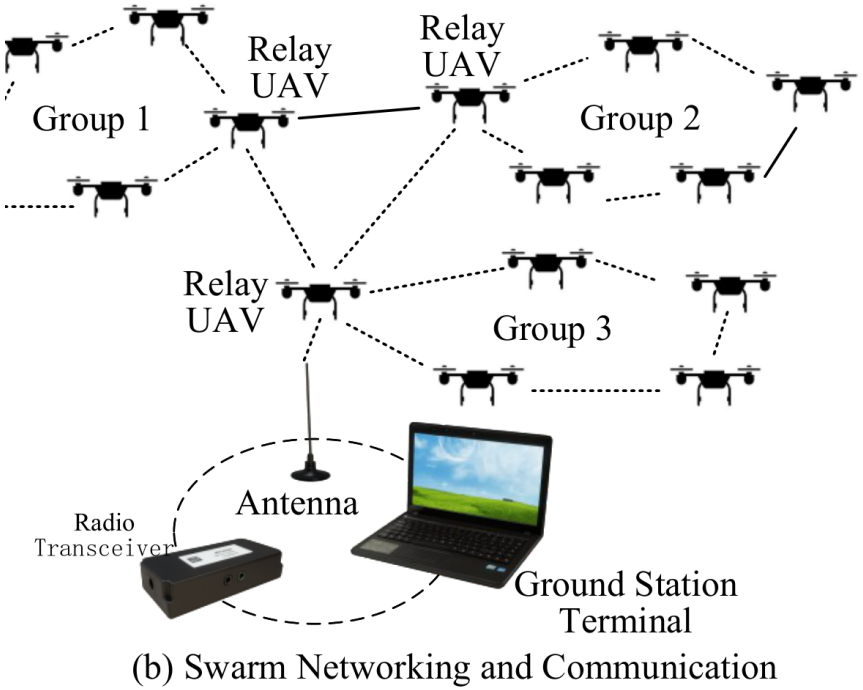
Sharing: Reachability between nodes depends on whether the ground system forwards data.

Tradeoffs: Central management is convenient. Central load, failures, and coverage limit the scope of cooperation.

Figure 9.4(a) Traditional Point-to-Point Communication

9.3.3 Network Topologies and Routing Protocols: Figure 9.4, Right Detail

Groups and Relays Form Multi-Hop Paths



(b) Swarm Networking and Communication

Figure 9.4(b) Networked Communication

Within a group: Local nodes exchange state.

Between groups: Relays forward across groups.

Constraints: Motion can invalidate paths. A relay can become a capacity bottleneck.

9.3.3 Network Topologies and Routing Protocols: Flying Ad Hoc Networks

Links in Flying Ad Hoc Networks Keep Changing

Network type	Mobility and connectivity	Routing concerns
Mobile ad hoc network (MANET)	Mobile nodes without fixed infrastructure	Neighbor changes, partitions, maintenance overhead
Vehicular ad hoc network (VANET)	Movement constrained by roads	Traffic density, intersections, obstructions, speed
Flying ad hoc network (FANET)	3D motion; changing heading and altitude	Link lifetime, state freshness Load and energy

FANET refers specifically to flying ad hoc networks. Other unmanned vehicles can draw on their routing methods.

9.3.3 Network Topologies and Routing Protocols: Message Recipients

Unicast, Multicast, and Broadcast Define Recipients

Mode	Recipient set	Unmanned-system example
Unicast	One destination endpoint	Send parameters to one vehicle
Multicast	Endpoints that joined a specified group	Publish state to members of the same mission
Broadcast	All endpoints in a defined broadcast domain	Neighbor discovery or local state publication

Recipient scope, topology, and routing are independent choices that can be combined.

9.3.3 Network Topologies and Routing Protocols: Routing and Forwarding

Routing Builds Information; Forwarding Uses It

Control messages
Discovery / updates

→

Path information
Table / source route

→

Packet forwarding
Choose the next hop

Strategy	When path information is built	Main cost
Proactive	Maintain updates with or without data traffic	Ongoing maintenance; information can still age
Reactive / on demand	Start discovery when data needs to be sent	First-packet wait; rediscovery after a break
Hybrid / position-assisted	Combine methods using organization or available positions	Needs topology, positioning, or implementation support

9.3.3 Network Topologies and Routing Protocols: Proactive Protocols

OLSR and DSDV Maintain Routes in Advance

Aspect	OLSR	DSDV
Full name	Optimized Link State Routing	Destination-Sequenced Distance-Vector Routing
State maintained	Neighbor and topology information	Distance / next hop to each destination
Key mechanism	Hello discovers neighbors. Multipoint relays (MPRs) reduce redundant forwarding.	Sequence numbers identify newer routes. Periodic and triggered updates.
Tradeoffs	Routes ready for use; topology control uses capacity	Direct table lookup; changes increase update overhead

Proactive maintenance often suits continuous data exchange. Fast motion still requires balancing update intervals and control overhead.

9.3.3 Network Topologies and Routing Protocols: Reactive Protocols

AODV and DSR Discover Routes on Demand

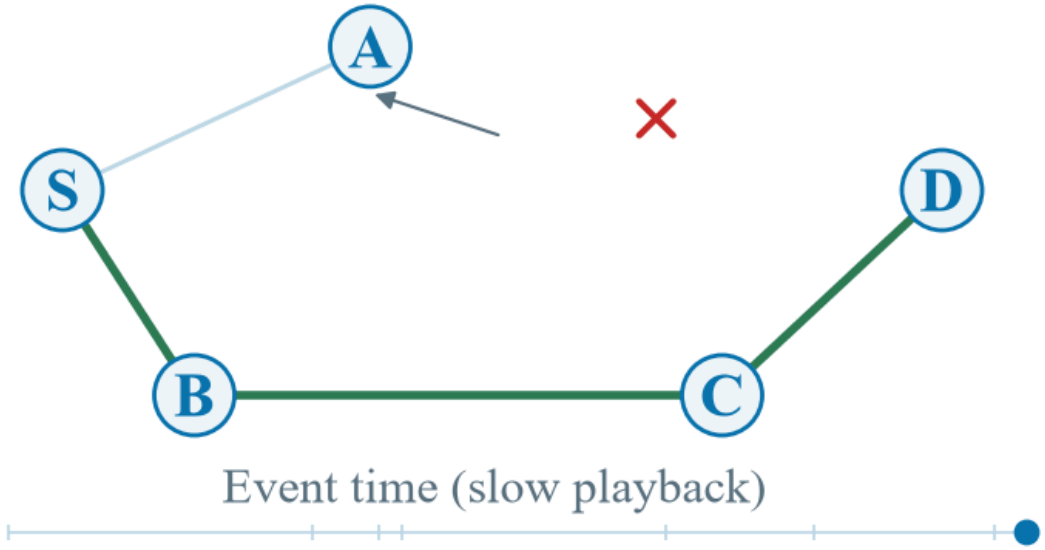
Data to send
No valid path yet
→
Route Request (RREQ)
Route Reply (RREP)
→
Send data
Maintain broken paths

Aspect	AODV	DSR
Full name	Ad hoc On-Demand Distance Vector Routing	Dynamic Source Routing
Path representation	Nodes store next hops. Sequence numbers help reject stale routes.	Packets carry a source route. Nodes may also cache paths.
Main cost	Discovery wait and maintenance after a break	Longer paths require larger source-route headers

9.3.3 Network Topologies and Routing Protocols: AODV Route Maintenance

AODV Builds a Replacement Route After a Link Break

AODV: recovery takes detection and message exchanges



Local route at S

To D: next hop B

Old packet lost: 1

DATA

New data reached D

t = 12.4

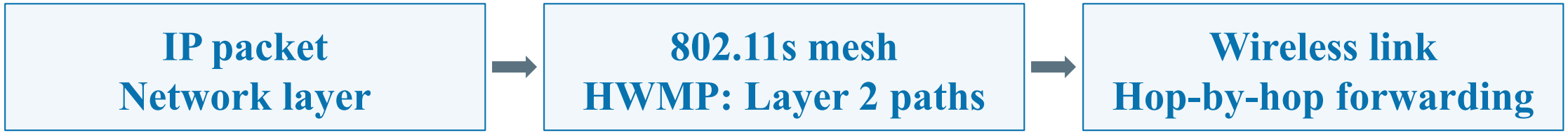
New data arrives via S-B-C-D

AODV route-recovery schematic. RERR = Route Error message.

Here, the link layer detects failure; no local repair. S resumes after a Route Reply.

9.3.3 Network Topologies and Routing Protocols: Hybrid Path Selection

HWMP Selects Layer 2 Mesh Paths



Layer 2 mechanism: Hybrid Wireless Mesh Protocol (HWMP) discovers paths on demand. A configured root also enables proactive maintenance.

Deployment requirements: The adapter, driver, and mesh configuration must support the functions, and the nodes must interoperate.

Layer boundary: HWMP selects paths within a mesh. OLSR and AODV typically route at the IP layer; the two layers need not run in sequence.

9.3.3 Network Topologies and Routing Protocols: Position-Assisted Routing

Greedy Perimeter Stateless Routing (GPSR)



Example: B is A's reachable neighbor closest to D and is closer than A, so choose B.
Assume valid neighbor and destination positions from positioning and a location service.

Condition	Forwarding action	Limits
A closer neighbor exists	Greedy forwarding	Geometric distance alone does not ensure minimum latency
No closer neighbor exists	Perimeter recovery around a local minimum	Classic recovery depends on planarization. 3D extensions require a separate design.

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Textbook: Section 9.1.4, item 4

9.3.4 Routing Trends and Selection: Latency, Reliability, and Load

Path Selection Starts with Mission Constraints

Candidate path (assumed)	End-to-end latency	Delivery success rate
A directly to C	40 ms	92%
A to B, then to C	10 + 15 = 25 ms	98% × 99% = 97.02%

$$p_{\text{path}} = p_{AB}p_{BC} = 0.98 \times 0.99 = 0.9702$$

Teaching thresholds: Latency ≤30 ms, success ≥95%. Choose A-B-C.
p_{path}, p_{AB}, and p_{BC}: Success probabilities of the full path, A-B, and B-C, respectively.
Assume independent hops, no retransmission. Latencies exclude route-discovery waiting.

9.3.4 Routing Trends and Selection: Demand, Link State, Position, Prediction

Motion Prediction Supports Earlier Route Maintenance

Design direction	Information used	Benefit / cost
On-demand discovery	Current traffic demand	Less idle maintenance; initial discovery takes time
Link-state updates	Neighbors and link quality	Fresher paths; periodic updates use capacity
Position assistance	GNSS, vision, or fused positioning	Fewer next-hop candidates; depends on position accuracy and freshness
Dynamic-state prediction	Velocity, heading, trajectory Kalman / learned models	Ant-colony / particle-swarm path search Prediction errors can trigger wrong switches

GNSS = Global Navigation Satellite System. Predict link lifetime to switch early; use path search to compare routes.

9.3.4 Routing Trends and Selection: Emerging Designs

Energy, Hierarchy, and Intermittent Connectivity

Direction	How forwarding changes	Scope and limits
Energy awareness	Use relays with more energy; rotate the load	May increase distance, hop count, or latency
Hierarchy / clustering	Local cluster exchange; heads forward between groups	Cluster-head load and elections Failure recovery
Delay-tolerant networking (DTN)	Store and carry data; forward at the next contact	Intermittent links For data that can wait

9.3.4 Routing Trends and Selection: A Short Decision Sequence

Route Choices Change with Conditions

Time	Candidate paths / given performance	Threshold-based choice
0 s	A-B-C: 25 ms, 97.02% A-C: 40 ms, 92%	Choose A-B-C
2 s	A-B-C: 45 ms, 97% A-D-C: 28 ms, 96%	Switch to A-D-C
4 s	Every available path exceeds 30 ms or has a success rate below 95%	Constraints unmet Degrade or change the mission

Also record discovery wait, control traffic, received signal strength indicator (RSSI), throughput, energy use, and node load.

Exercises and Discussion

Select Software and Routing for Three Traffic Types

Task 1: Frequent state updates may discard old samples, logs must be complete, and video must be continuous. Which path would you use for each?

Task 2: How do proactive versus on-demand routing tradeoffs change between continuous state exchange and occasional remote requests?

Discuss: TCP receipt = command executed? Clustered diagram = OLSR? Coordinates = guaranteed GPSR operation in 3D?

Suggested Answers

Explain Each Choice Using Its Traffic Requirements

Question	Possible choice	Required conditions
Three traffic types	State: MAVLink, DDS, etc. Logs: TCP or other reliable transport Video: RTSP session + RTP media	State timestamps and expiry policy Log integrity; video encoding and buffering
Routing mechanism	Continuous: Consider proactive. Occasional: Consider on demand.	Weigh control overhead, first-packet wait, and topology changes.
Three claims	None follows automatically	Execution acknowledgment; actual protocol settings; fresh positions and 3D adaptation.

Section Summary

Design Message Meaning, Delivery, and Paths Separately

Messages and software: Fields, units, discovery, and distribution must match. Tools can work independently or in combination.

Delivery and timing: Reliable ordering, fresh data, and command execution are different requirements. Define a criterion for each.

Routing and networking: Choose recipient scope, topology, and maintenance separately. Path quality depends on the mission and current conditions.

Common errors: DDS and UDP occupy different layers. ROS 2 is a framework, not one protocol. HWMP selects Layer 2 mesh paths.