Intelligent Unmanned System Control Practice

Chapter 9 Multi-Vehicle Communication and Intelligent Networking

Author: Xunhua Dai, Central South University

Website: https://faculty.csu.edu.cn/daixunhua

Email: dai.xh@csu.edu.cn

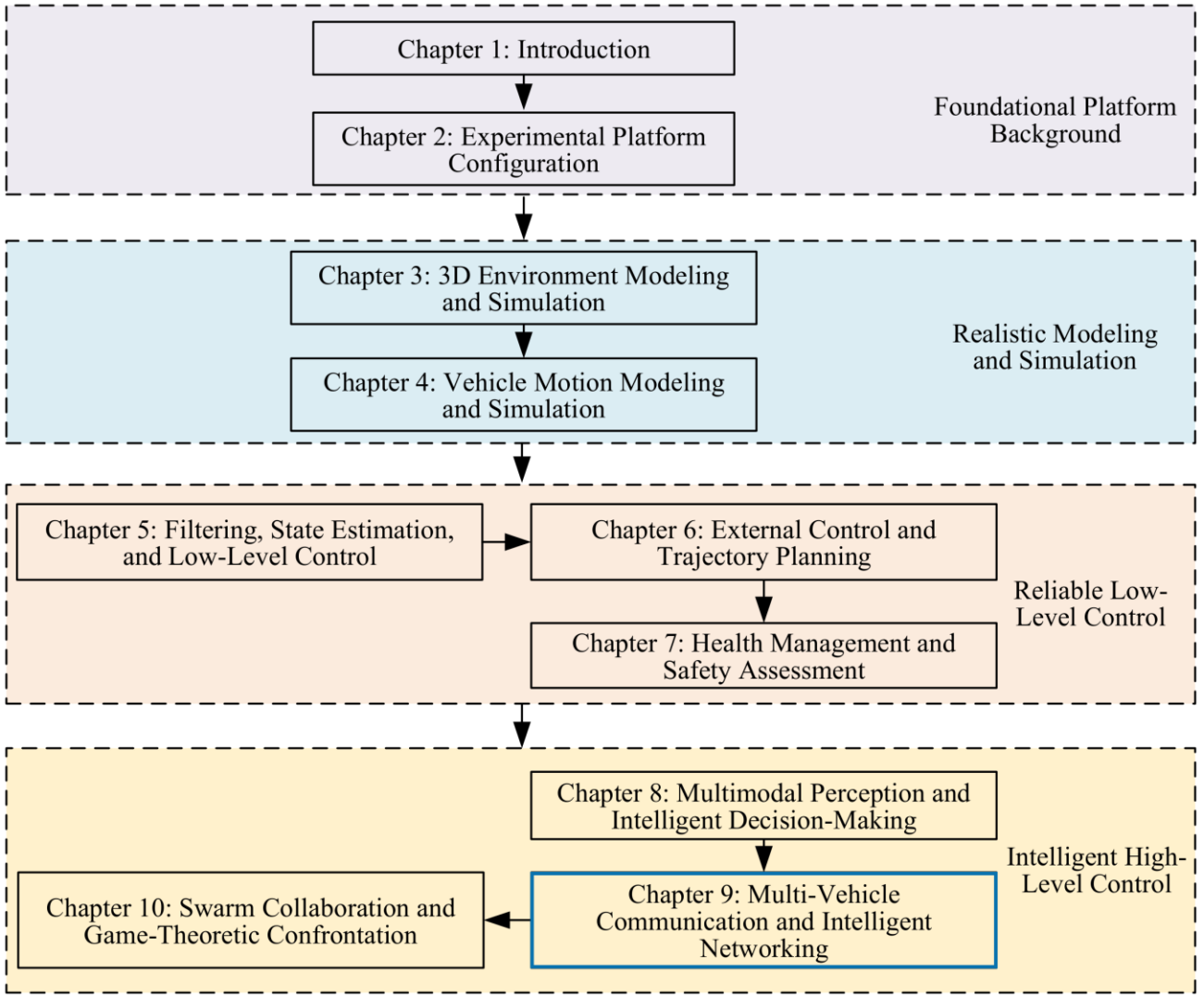
RflySim: http://rflysim.com

Companion Paper



Dai, Xunhua, Jinhu Tu, and Quan Quan. "RflySim ToolChain: a rapid development and validation toolchain for intelligent unmanned swarm systems." Journal of Systems Engineering and Electronics 36.4 (2025): 1077-1093.

Textbook is coming soon...



Chapter Learning Objectives

What You Can Do After Chapter 9

1. Explain which data a task requires nodes to exchange and how timely it must be
2. Select hardware and protocols for the traffic load, range, and environment
3. Calculate link loss and routing cost, and explain when the models apply
4. Design and evaluate multi-vehicle communication tests along RflySim data paths

Chapter Outline

Networked Communication Fundamentals and Requirements

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

9.1.1 Concept and Role of Networked Communication

Textbook: Section 9.1.1.1

9.1.2 Typical Application Scenarios

Textbook: Section 9.1.1.2

9.1.3 Communication and Cooperative Control

Textbook: Section 9.1.2

9.1.4 Optimization and Future Directions

Textbook: Section 9.1.1.3–9.1.1.5

9.1.1 Concept and Role of Networked Communication: Cooperative tasks

Individual Sensing and Shared Task Information



Information to share: Target position, observation time, coordinate frame, and confidence.

Tasks to coordinate: Who verifies the target, who continues the inspection, and how actions change when the target is updated.

Capabilities define what vehicles can do; information sharing broadens cooperation.

9.1.1 Concept and Role of Networked Communication: Basic concepts

Nodes, Links, and Networks in a Communication System

Concept	Meaning	Inspection example
Node	An entity that sends, receives, or forwards information	Vehicle, ground station, or relay node
Link	A communication connection between adjacent nodes	A wireless connection between A and B
Network	Nodes and links organized to exchange data	A sends its state to C through a relay
Networked communication	Establishing and maintaining information exchange among nodes	Node discovery and path maintenance

Wired, wireless, or mixed: Choose by motion range and deployment environment.

9.1.1 Concept and Role of Networked Communication: Information roles

Four Information Categories Support Different Cooperative Tasks

Information	Typical content	Questions to consider
Environmental perception	Images, point clouds, target positions	Are raw data needed? Are coordinate frames consistent?
State and intent	Position, velocity, planned path	Use the latest position; check plan versions and conflicts
Tasks and commands	Waypoints, task assignments, acknowledgments	Track receipt, progress, and completion by task identifier (ID).
Health and anomalies	Heartbeats, link quality, fault reports	Is the node faulty, or is the link temporarily down?

A periodic heartbeat reports a node is online; its position sample may still be stale.

9.1.1 Concept and Role of Networked Communication: Message delivery

A State Message Travels from Sampling to Reception

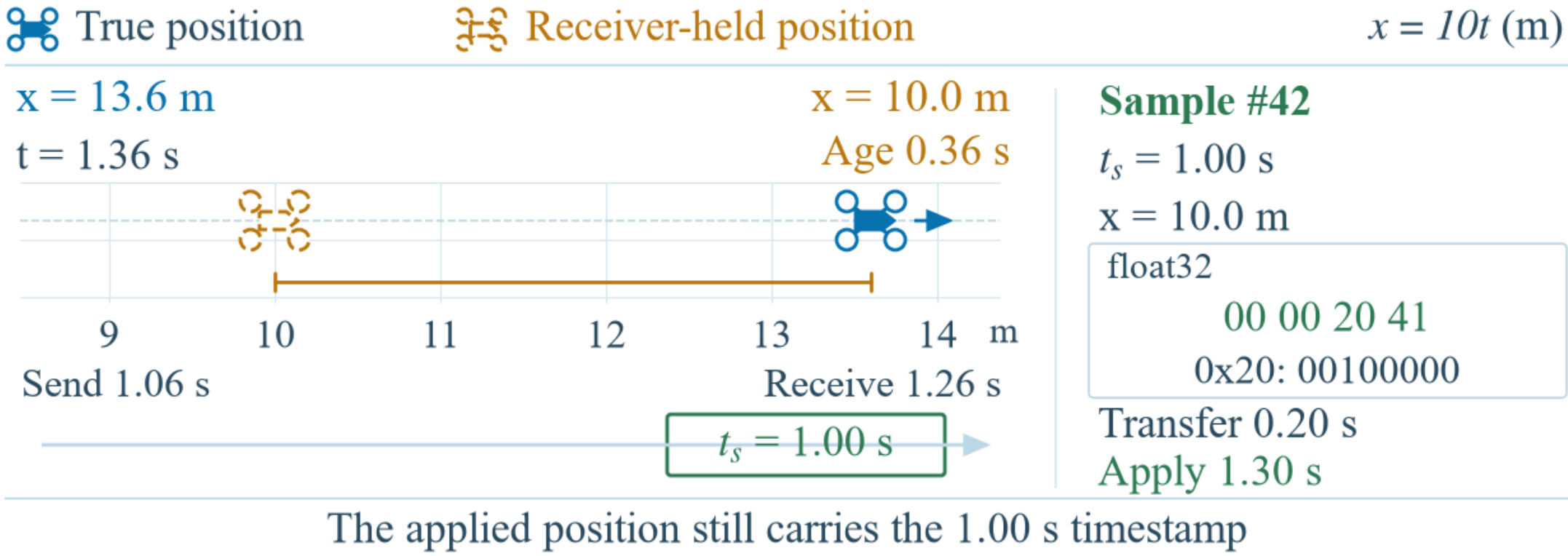


Figure: The message carries position and time at sampling; the vehicle keeps moving before it arrives.

9.1.1 Concept and Role of Networked Communication: Message conventions

The Receiver Needs the Source and Sampling Time of Each Value

Field	Example	Purpose
Sender / type	Node 2 / position state	Identify the sender and how to parse the message
Sequence / sample time	105 / 12.400 s	Detect reordering and duplicates; assess sample validity
Frame / units	North-East-Down (NED), m	Avoid mixing directions, origins, or units
State values	Position (m), velocity (m/s)	Provide inputs for neighbor estimation and cooperative calculations

Timestamps need a common time reference; NED coordinates need a common origin.

9.1.1 Concept and Role of Networked Communication: Communication and tasks

Local Sharing and Coordinated Action Are Separate Steps



Can messages reach the target node?

Are meaning and time interpreted consistently?

How are tasks divided and changes handled?

Star, mesh, and clustered topologies describe connections; centralized and distributed architectures describe computation and decision roles.

Connectivity enables cooperation; task rules determine how the information is used.

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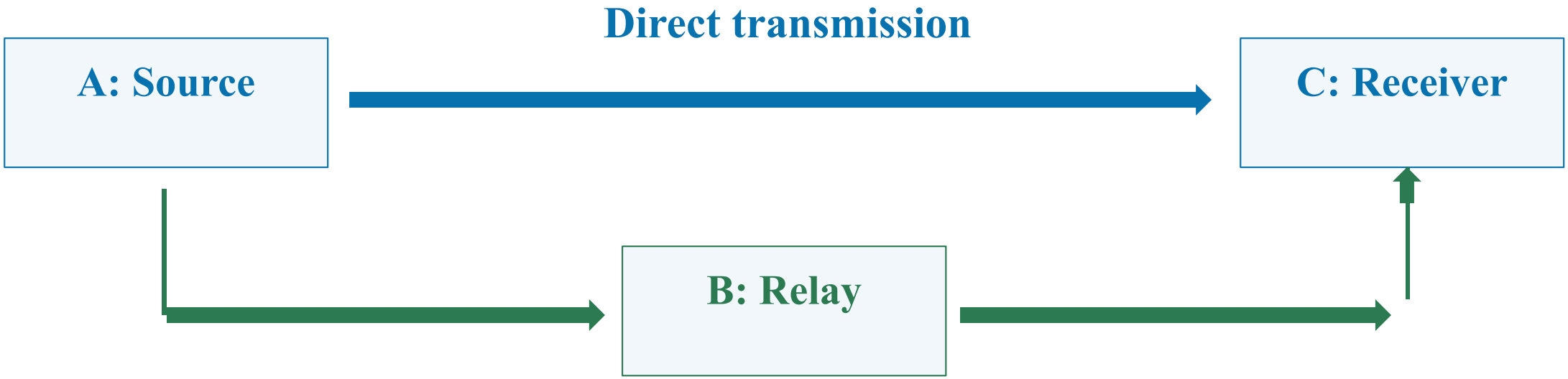
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9.1.2 Typical Application Scenarios: Small-scale paths

Three Nodes Can Connect Directly or Through a Relay



A relays to C through B; a B–C outage invalidates this path.
Switch to A–C only if reachable; otherwise find a path or wait for recovery.
Relaying adds overhead but may improve per-hop link quality.

9.1.2 Typical Application Scenarios: Small-scale objectives

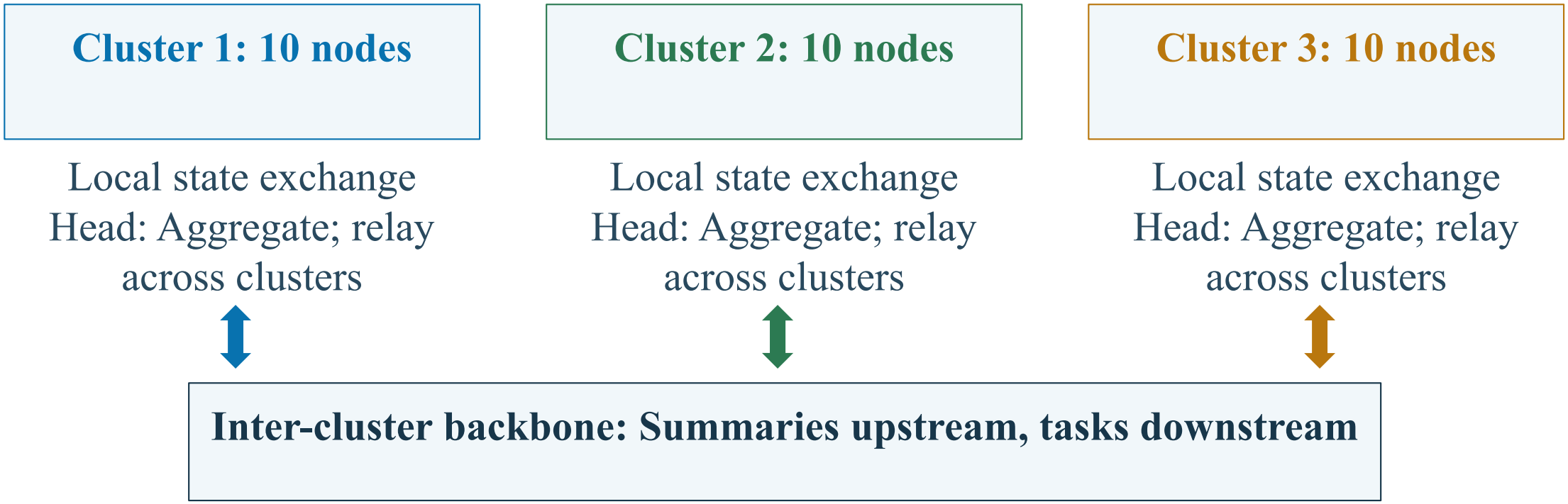
Latency, Energy Use, and Load Balancing Can Conflict

Objective	Observable metrics	Possible cost
Timely response	End-to-end delay and timeout rate	More frequent updates consume link capacity
Lower energy use	Energy for sending, receiving, and retransmitting	More hops or longer waiting times
Share the load	Forwarding packet rate and queue length at each node	An alternate path may be slower

Example: Direct path: 5 ms queuing + 10 ms sending = 15 ms.
Two hops: 2 ms queuing + 4 ms sending per hop = 12 ms (other times omitted).

9.1.2 Typical Application Scenarios: Large-scale organization

Clusters Separate Local Sharing from Inter-Cluster Forwarding



Example: 3 clusters × 10 nodes; benefits depend on traffic and topology.

9.1.2 Typical Application Scenarios: Cluster head management

Rotating Cluster Heads Redistributes Load at a Cost

Method	Change in workload	Considerations
Rotate cluster heads	Other nodes take over aggregation and forwarding	Election and state-transfer cost; more charge need not mean less load.
Deputy heads / multiple levels	Share work or replace a failed node	Additional coordination overhead
Adjust members / summarize data	Redistribute traffic or reduce the amount sent	Topology changes and information loss

Low-Energy Adaptive Clustering Hierarchy (LEACH): Probabilistic head rotation.
Hybrid Energy-Efficient Distributed Clustering (HEED): Select heads by residual energy and communication cost.
Particle swarm optimization (PSO): Search cluster designs by energy, distance, and load.

9.1.2 Typical Application Scenarios: Topology and architecture

Topology and Control Roles Can Be Designed Together

Topology	Message paths	Possible computation roles
Star	Nodes exchange information through a hub	Hub plans tasks, or only forwards data
Mesh	Multi-hop paths update when links change	Local computation, or centralized task planning
Clustered	Local exchange; backbone links clusters	Local autonomy combined with higher-level coordination

Draw message paths and decision locations separately.

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9.1.3 Communication and Cooperative Control: Timeliness

Update Interval and Network Delay Are Different Time Quantities

Event	Time	Meaning of the interval
Sample and send t_{sample}	100 ms	100 ms since the previous sample
Receive the sample	140 ms	40 ms delivery delay for this sample
Control program uses it t_{use}	150 ms	Sample age: 50 ms; held for 10 ms after reception

$$\Delta_{\text{age}} = t_{\text{use}} - t_{\text{sample}} = 150 - 100 = 50\,\text{ms}$$

Δ_{age} is the sample age; clocks share a time reference, and each sample is sent immediately.

9.1.3 Communication and Cooperative Control: Delay and loss

The Same Motion Can Yield Different Received Information

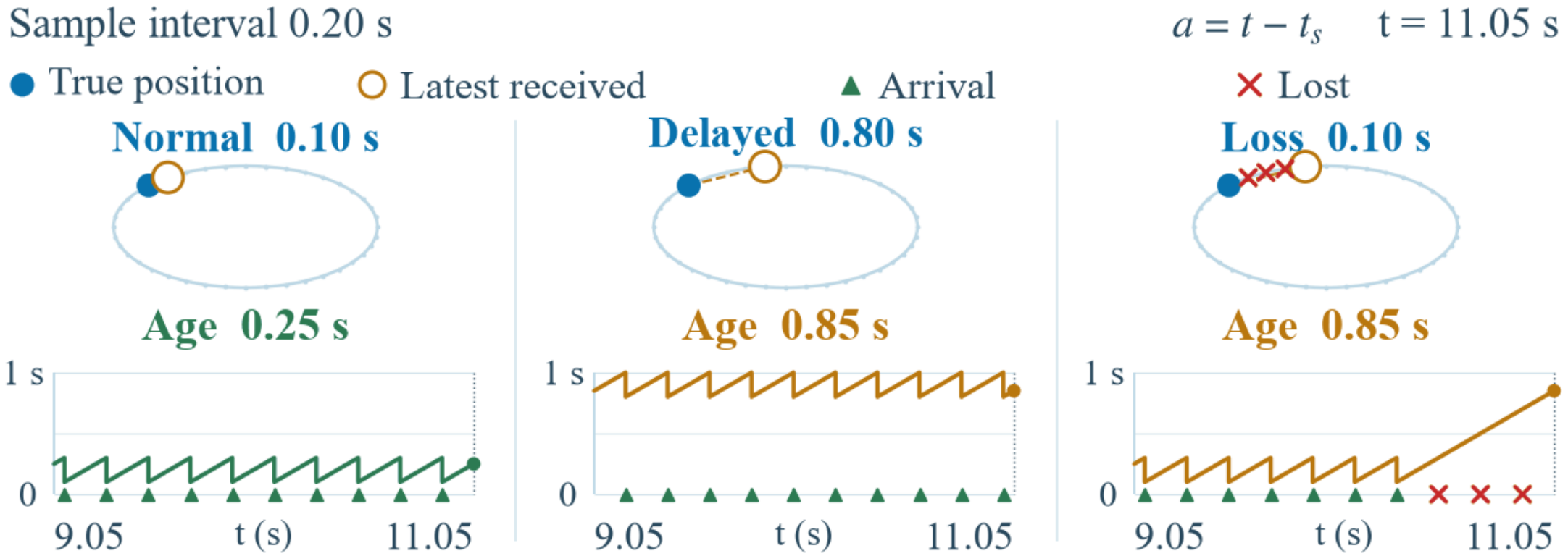


Figure: Data age grows while waiting; a new sample reduces age, usually without bringing it to zero.

9.1.3 Communication and Cooperative Control: State prediction

Holding an Old Position versus short-term Prediction

1-D motion: Position $x(t_s) = 20\,\text{m}$; velocity $v(t_s) = 10\ \text{m/s}$.
t_s: sample time; t: use time; sample age $\Delta t = t - t_s = 0.2\,\text{s}$.

$$\hat{x}(t) = x(t_s) + v(t_s)\Delta t = 20 + 10 \times 0.2 = 22\,\text{m}$$

Constant velocity: $\hat{x}(t)$ is predicted position; Δx_{hold} is the old-position error.

$$\Delta x_{\text{hold}} = v\Delta t = 2\,\text{m}$$

With unknown constant acceleration $a = 2\ \text{m/s}^2$, the prediction residual is $e = x(t) - \hat{x}(t)$:

$$e = \frac{1}{2}a(\Delta t)^2 = \frac{1}{2} \times 2 \times 0.2^2 = 0.04\,\text{m}$$

At 30 m/s, 1 s of staleness implies 30 m of uniform motion, not actual control error.

9.1.3 Communication and Cooperative Control: Traffic budget

Traffic Depends on Node Count, Message Size, and Rate

Nodes $N = 4$; publication rate per node $f = 50$ Hz; payload length $L = 100$ B; 1 B = 8 bit.

$$R = NfL \times 8 = 4 \times 50 \times 100 \times 8 = 160\,\text{kbit/s}$$

R: Network-wide payload rate; all 4 nodes can reach each other in one hop.

Transmission method	Payload rate	Additional work
Broadcast once per sample	160 kbit/s	Receivers share one transmission
Unicast to each of 3 neighbors	480 kbit/s	Sender copies the message for each recipient

Payload only; include headers, contention, and retransmissions in the link budget.

9.1.3 Communication and Cooperative Control: Worked example

Reception Records Reveal Packet Loss and Stale Information

Control use time	Latest sample time	Sample age	Held position
50 ms	0 ms	50 ms	0 m
150 ms	100 ms	50 ms	1 m
250 ms	100 ms	150 ms	1 m
350 ms	300 ms	50 ms	3 m

Start at 0 m, move at 10 m/s; sample and send at 0, 100, 200, 300 ms.
Arrivals: 40, 140, lost, 340 ms. Three of four arrive; the third use holds an old sample.

9.1.3 Communication and Cooperative Control: Loss patterns

Consecutive Losses Create Longer Gaps at the Same Loss Rate

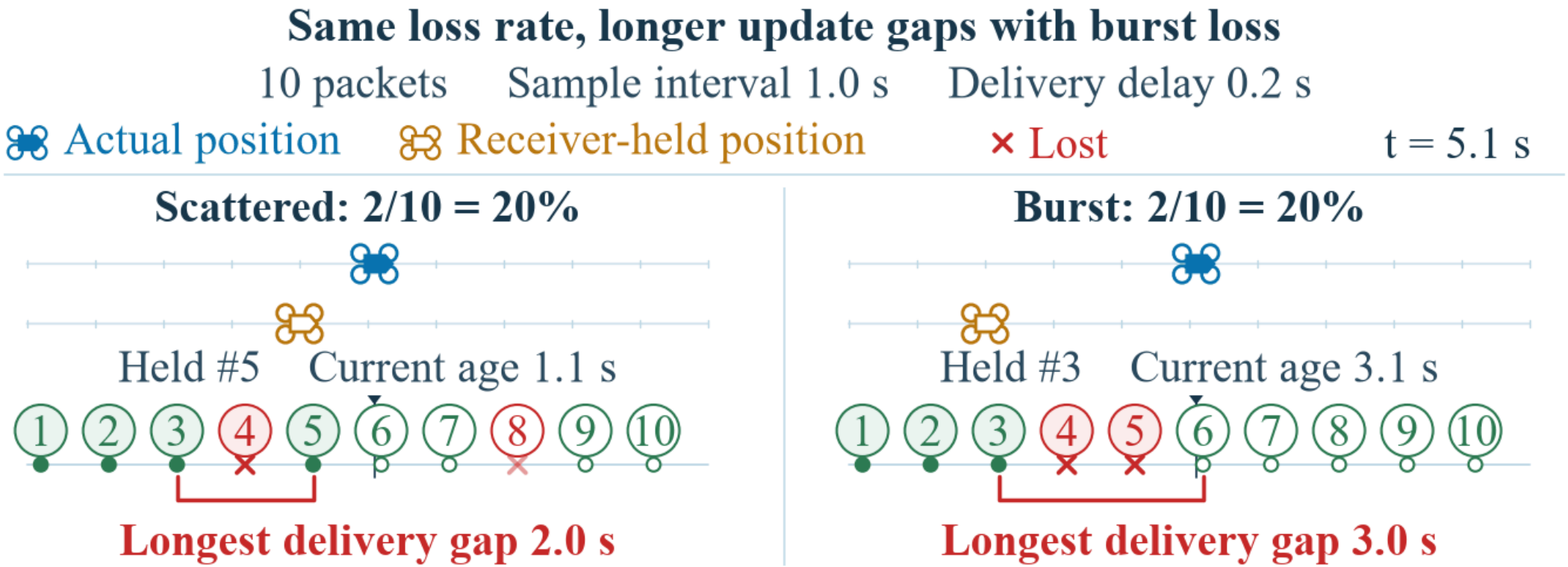


Figure: Equal send and loss counts can give different maximum waits for new information.

9.1.3 Communication and Cooperative Control: Communication and control

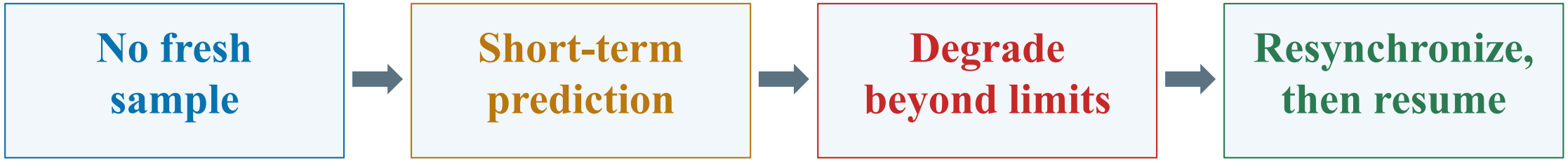
Allocate Limited Communication Resources to Useful Information

Adjustment	Method	Engineering tradeoff
Message content	Send key states or target summaries	Reduce load, but potentially lose information
Update timing	Periodic or event-triggered (e.g., state change > threshold)	Balance average traffic, bursts, and timeliness
Resource allocation	Priorities, paths, retransmission limits	Higher priority can make other flows wait

Deliver useful information to the nodes that need it, in time to use it.

9.1.3 Communication and Cooperative Control: Failure and robustness

Prediction, Degraded Operation, and Recovery After an Outage



Network: Try alternate links and rebuild paths to shorten the remaining outage.

Node: When information age or prediction error exceeds a task threshold, stop actions that depend on remote information and maintain safe separation.

Short-term prediction has limits; after link recovery, check task states again.

9.1.3 Communication and Cooperative Control: Limited communication

Nearby Sensing Can Supplement Wireless Information

Information source	What it provides	Limits
Last sample and motion prediction	A short-term estimate of neighbor state	Errors grow with stronger maneuvers and longer gaps
Vision / point clouds / acoustics	Local relative position and motion	Visibility, range, occlusion, and noise
Agreed lights, sounds, or actions	A small amount of task state or intent	Agreed encoding, recognition, and mutual observability

Local sensing can still support nearby cooperation and collision avoidance when global synchronization fails.

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9.1.4 Optimization and Future Directions: Problems and optimization

Five Changing Constraints Shape Network Design

Problem	Possible mechanisms	Validation metrics
Topology changes	Neighbor discovery and path rebuilding	Discovery and recovery time
Limited resources	Summaries, scheduling, lightweight designs	Effective throughput, queues, energy use
Packet loss and delay	Retransmission, redundancy, freshness checks	Delivery ratio, delay distribution, information age
Forgery and tampering	Authentication, integrity, access control	Can invalid messages be detected and rejected?
Obstructions and interference	Alternate links, interference mitigation, degraded operation	Reachability and task completion

9.1.4 Optimization and Future Directions: Optimization choices

Redundancy Expands Choices but Consumes Resources

Multiple paths and redundant links: More chances of an available alternative, with more maintenance and transmission overhead.

Lightweight cross-layer design: Less repeated processing; application timeliness guides scheduling, with stronger interface coupling.

Interference mitigation and energy efficiency: Adjust frequency, coding, or power; benefits depend on interference and link conditions.

Extra resources should yield measurable task benefits, beyond more communication.

9.1.4 Optimization and Future Directions: Security and privacy

Distinguish Error Checks, Authentication, and Confidentiality

Goal	Question	Typical mechanism
Transmission error detection	Did random errors change the data?	Check codes, e.g., cyclic redundancy check (CRC)
Source and integrity	Is the source trusted? Was the message altered?	Message authentication, identity and permission management
Confidentiality and replay protection	Was information exposed? Was an old message reused?	Encryption, counters, or time constraints

Security protects data and identity; safety also depends on control strategies and task risks.

9.1.4 Optimization and Future Directions: Cross-domain architecture

Space-air-sea-ground Networks Connect Different Coverage Areas

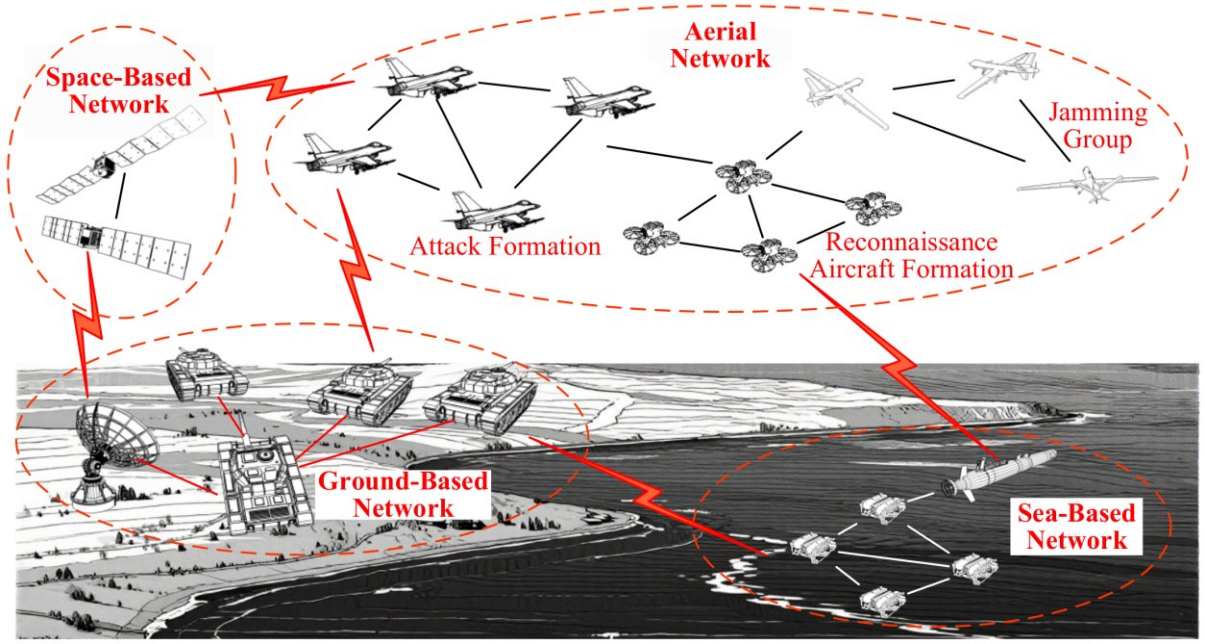


Figure 9.1 Concept of an Integrated Space-Air-Sea-Ground Communication Network System

Space and air: Wide-area coverage and mobile relays.

Ground and sea: Ground tasks, surface nodes, and underwater nodes.

Across domains: Coordinate interfaces, timeliness, and resources across different links.

9.1.4 Optimization and Future Directions: Enabling technologies

Cross-domain Cooperation Must Accommodate Delay and Bandwidth

Technology	Role	Effect on the task
Heterogeneous link integration	Gateways connect different media and protocols	Wider coverage, with added conversion and management
Routing and scheduling	Choose paths and resources by timeliness needs	Handle critical messages separately from bulk data
Common data conventions	Agree on identity, time, coordinates, and meaning	Interpret the same state across platforms

$$t = \frac{d}{c} = \frac{10^7}{3 \times 10^8} \approx 0.033\,\text{s} = 33\,\text{ms}$$

One-way path $d = 10^7$ m
Vacuum light speed $c \approx 3 \times 10^8$ m/s
t: Propagation delay only.

9.1.4 Optimization and Future Directions: RflySim validation

Simulation Links Network Conditions with Task Performance



Controlled comparison: Fix the task, initial state, reference trajectory, and message settings; vary one network condition.

Record and evaluate: Delay, packet loss, reachability, and throughput, alongside task error or completion time.

Software-in-the-loop (SITL; SIL in the textbook) provides a repeatable baseline. Hardware-in-the-loop (HITL; HIL in the textbook) and real vehicles test effects beyond the model.

9.1.4 Optimization and Future Directions: Simulated delivery

Communication Conditions Affect Algorithms Through Delivered Messages

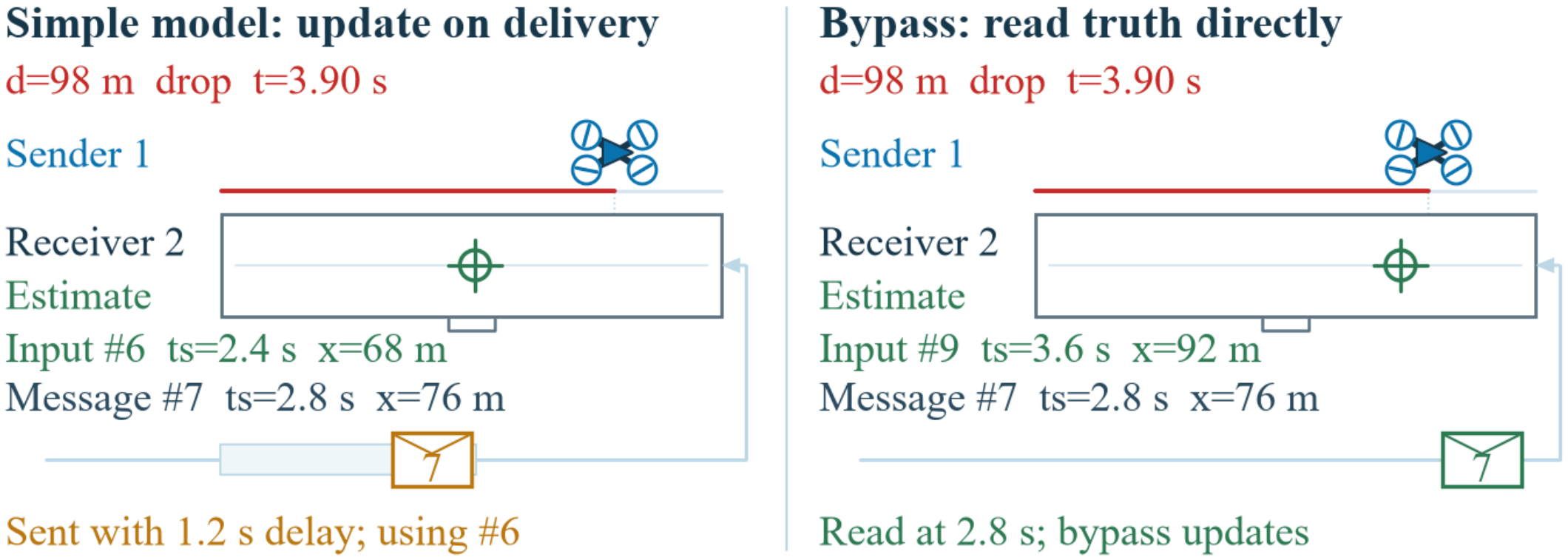


Figure: Compare modeled delivery and direct ground-truth access at the algorithm input.

Exercises and Discussion

Why Can More Information Fail to Improve Cooperation?

Question 1: Which tasks favor frequent sharing of full images, and which favor target summaries on demand?

Question 2: Heartbeats arrive, but position has not updated for 1 s. What should you check first?
With equal loss counts, do consecutive and scattered losses pose the same risk?

Calculate: Each of 4 nodes unicasts a 100 B payload at 50 Hz to each of its 3 peers. Find the network-wide transmission rate.

Approach: Identify task information, then assess timeliness, traffic, and outage handling.

Key Answer Points

Explain Communication Choices Through Task Requirements

Select information: Original images preserve detail; summaries reduce data volume. Let the task determine the required fields.

Check freshness: Inspect sampling time, sequence numbers, and coordinate conventions. Distinguish a responsive link from a stale state.

Assess risk: Consecutive losses can extend information gaps. Check reachability, the longest outage, and task thresholds before choosing prediction, degraded operation, or path rebuilding.

$$R = 4 \times 50 \times 100 \times 8 \times 3 = 480\,\text{kbit/s}$$

Payload only; headers, acknowledgments, and retransmissions add overhead.

Section Summary

Communication Requirements Guide Hardware and Protocol Design

Concept: Nodes and links form a communication network; cooperative algorithms use the information it delivers.

Method: Define data content, update rate, acceptable age, and outage handling for the task.

Common confusions: Update interval differs from delivery delay; topology alone does not determine computation roles.

Define task communication requirements before comparing device parameters.