Chapter Outline

Communication Modeling and Interference Simulation

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

9.4.1 Channel Characteristics

Textbook: Section 9.1.5.1

9.4.2 Communication Attenuation Modeling

Textbook: Section 9.1.5.2

9.4.3 Communication Loss Models

Textbook: Section 9.1.5.3

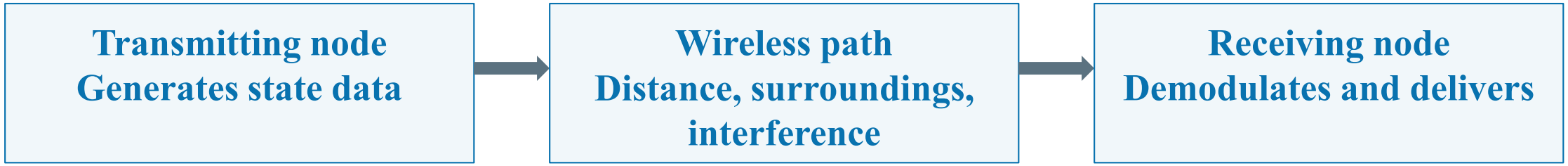
9.4.4 Network Simulation Methods and ns-3

Textbook: Sections 9.1.5.4–9.1.5.5 | ns-3: Network Simulator 3

9.4.1 Channel Characteristics: Channels and Tasks

What Changes Along a Wireless Link?

Channel: the medium and propagation paths that carry signals from transmitter to receiver. Wired channels use cables or optical fiber; wireless channels vary with position, the environment, and other transmissions.



Running example: increase the separation on a 2.4 GHz link. Check whether received power meets the threshold, then decide what network modeling is still needed.

Channel outputs: received power, delay, or response. Packet delivery also depends on modulation / coding, access, retransmissions, and queues.

9.4.1 Channel Characteristics: Propagation Paths

One Signal Can Reach the Receiver Along Multiple Paths

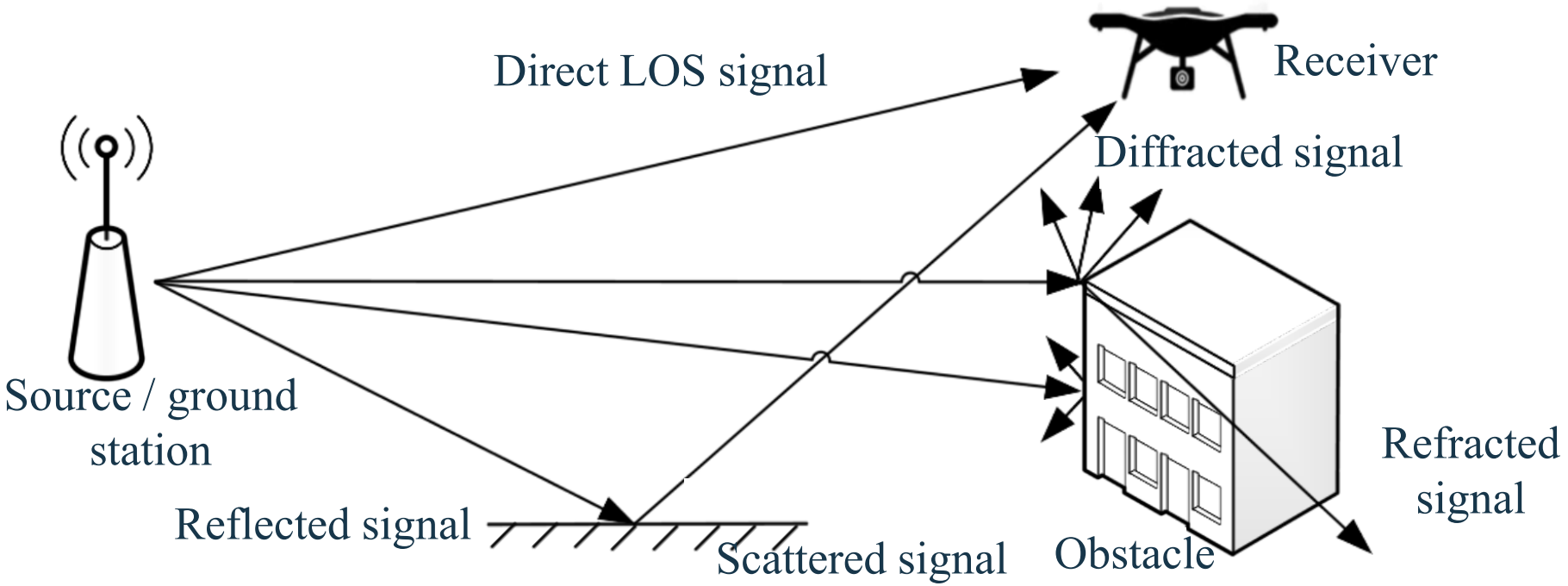


Figure 9.5. Wireless channel propagation characteristics

Line of sight (LOS) has a direct path; non-line of sight (NLOS) has no usable direct sight path.

9.4.1 Channel Characteristics: Reflection, Refraction, and Diffraction

Obstacles Change Signal Direction and Energy Distribution

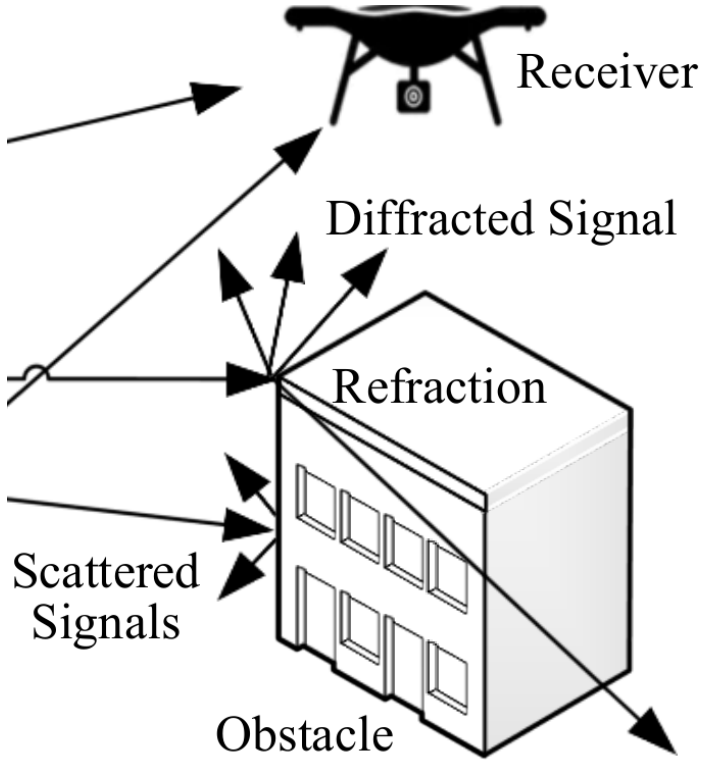


Figure 9.5, detail. Propagation near an obstacle

Reflection and refraction: an interface returns or bends the signal. Material and incidence angle affect its strength.

Diffraction: edges let signals enter a geometric shadow. The effect depends on wavelength and obstacle size.

Scattering and absorption: nonuniform structures redirect energy; absorption in a medium reduces it.

9.4.1 Channel Characteristics: Phenomena and Measurements

Model Power Loss, Phase Changes, and Queuing Separately

Phenomenon	Main change	Inputs and observable outputs
Path loss / shadowing	Average power falls or varies slowly	Distance, frequency, obstacles; measure received power.
Multipath fading	Signals combine with different phases and delays	Path lengths, reflections; measure power / delay distributions.
Co-channel / external interference	Energy beyond the desired signal increases	Concurrent transmissions; measure signal-to-interference-plus-noise ratio (SINR).
Network congestion	Arrival rate exceeds service capacity	Traffic load, queues; measure waiting time and packet loss.

$$t_{\text{prop}} = d/c = 1000/(3 \times 10^8) = 3.33\ \mu s$$

t_{prop}: propagation delay (s); d: distance (m); c: speed of light (m/s). Waiting and processing are not yet included.

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9.4.4 Network Simulation Methods and ns-3

Textbook: Sections 9.1.5.4–9.1.5.5

9.4.2 Communication Attenuation Modeling: Equations 9.1 and 9.2

Free-space Loss Grows with Distance and Frequency

$$L_{\mathrm{fs}} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}(4\pi/c) \tag{9.1}$$

L_{fs}: loss, dB; d: distance, m; f: frequency, Hz; $c \approx 3 \times 10^8$ m/s: speed of light. Enter numerical values in the specified units.

$$L_{\mathrm{fs}} = 32.44 + 20\log_{10}(d_{\mathrm{km}}) + 20\log_{10}(f_{\mathrm{MHz}}) \tag{9.2}$$

Enter d_{km} in km and f_{MHz} in MHz. The textbook rounds the constant to 32.44 for engineering calculations.

Assumptions: antenna far field and an unobstructed, homogeneous medium. Model significant ground reflections, multipath, and weather losses separately.

9.4.2 Communication Attenuation Modeling: Free-Space Example

At 1 km and 2.4 GHz, Free-Space Loss Is About 100.04 dB

$$d_{\mathrm{km}} = 1, \quad f_{\mathrm{MHz}} = 2400$$

$$L_{\mathrm{fs}} = 32.44 + 0 + 67.604 = 100.044\ \mathrm{dB}$$

Conditions	Loss	Relative to 1 km, 2.4 GHz
0.5 km, 2.4 GHz	94.02 dB	Half the distance: 6.02 dB less loss.
2 km, 2.4 GHz	106.06 dB	Doubling distance adds 6.02 dB.
1 km, 4.8 GHz	106.06 dB	Doubling frequency adds 6.02 dB.

Unit check: entering 1000 in the kilometer formula gives 160.04 dB, an error of +60 dB.

9.4.2 Communication Attenuation Modeling: Received Power and Margin

Link Margin Compares Received Power with a Threshold

$$P_r = P_t + G_t + G_r - L_c - L_{\text{total}}$$

P_t, P_r: transmit / receive power, dBm; G_t, G_r: antenna gains, dBi; L_c: total feeder loss, dB; L_{total}: propagation loss, dB.

$$P_r = 20 + 2 + 2 - 2 - 100.04 = -78.04 \text{ dBm}$$

$$M = P_r - S = -78.04 - (-85) = 6.96 \text{ dB}$$

$S = -85$ dBm is the threshold for the receive mode specified in this example; M is power margin. More than 6.96 dB of total additional loss puts this link below threshold. This test does not model packet errors, retransmissions, or queuing.

9.4.2 Communication Attenuation Modeling: Fresnel Zones

An Unobstructed Sight Line Still Needs Fresnel Clearance

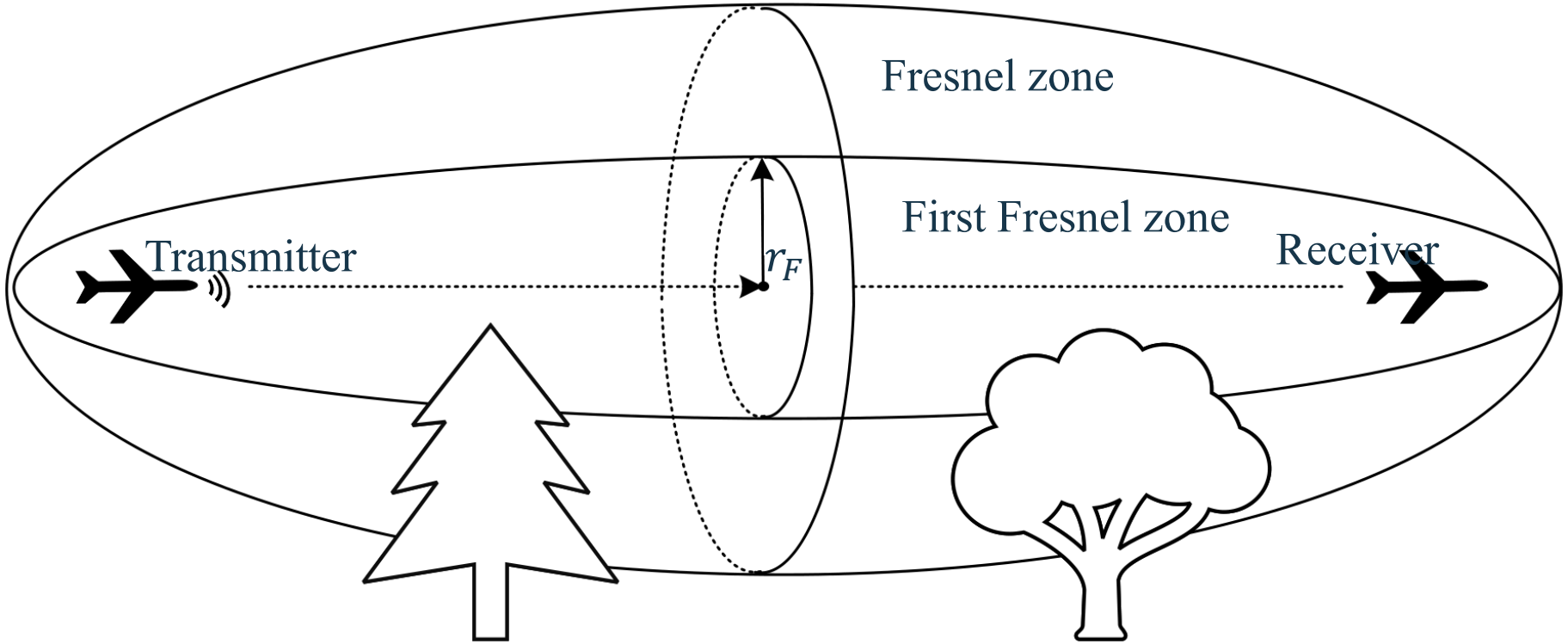


Figure 9.6. Fresnel zones in wireless communication

The first boundary adds half a wavelength to the direct path. Check clearance along the whole link.

9.4.2 Communication Attenuation Modeling: Equation 9.3 and Clearance

The First Fresnel Radius at the 1 km Midpoint Is 5.59 m

$$r_F = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}, \quad n = 1 \tag{9.3}$$

r_F, λ, d_1, d_2 are in m; $\lambda = c/f$. d_1, d_2: along-path distances from the cross-section to each end. Paraxial approximation: radius is much smaller than path length.

Midpoint: each path segment is 500 m

$$r_F = \sqrt{\frac{0.125 \times 500 \times 500}{1000}} = 5.59 \text{ m}$$

$$\lambda = c/f = 0.125 \text{ m}$$

$$0.6 r_F = 3.35 \text{ m}$$

Here, frequency is 2.4 GHz and $c = 3 \times 10^8$ m/s. Clearance is the vertical gap from obstacle top to sight line. The next page illustrates the geometry.

The 60%-radius engineering check does not convert 40% blockage into a fixed dB loss.

9.4.2 Communication Attenuation Modeling: Fresnel Clearance

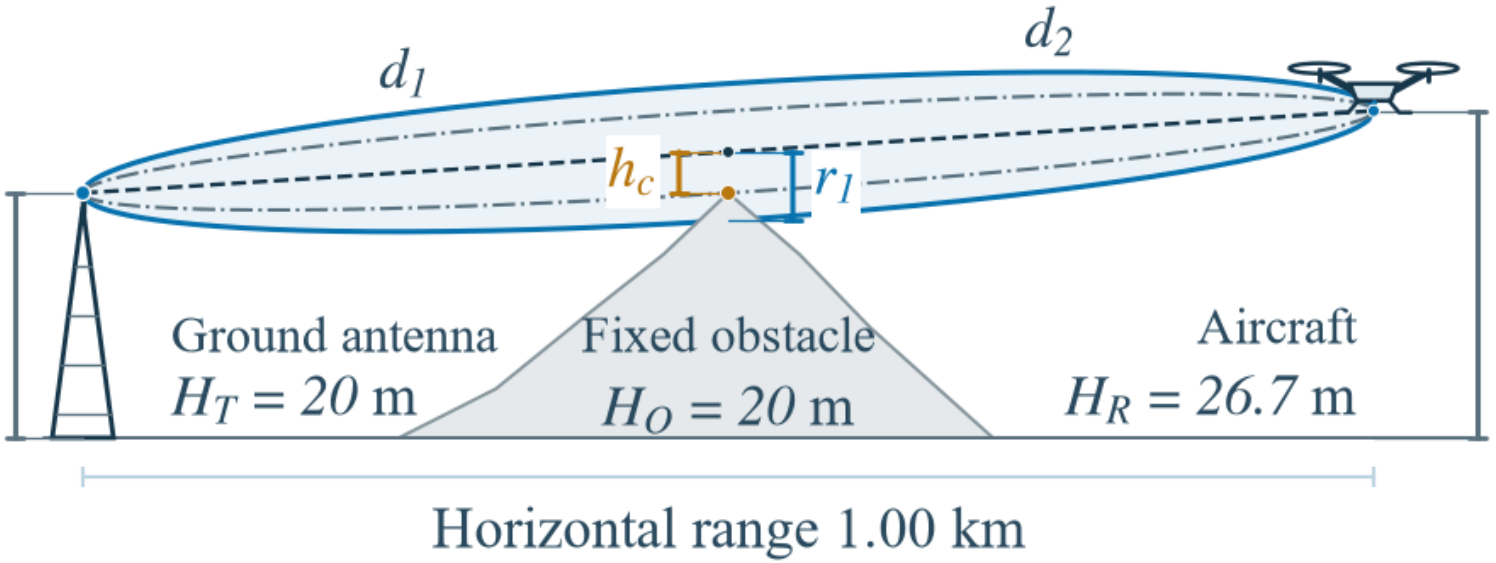
Endpoint Height Changes the Clearance Above an Obstacle

Raising the antenna increases local clearance

$\lambda = 0.125$ m

— First Fresnel zone --- Line of sight –·– $0.6r_1$ reference

Vertical scale enlarged



Radius at obstacle

$r_1 = 5.59$ m

Clearance h_c

$h_c = 3.35$ m

$0.6r_1 = 3.35$ m

$h_c/r_1 = 0.60$

$$r_1 \approx \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}}$$

Fixed terrain; the sight line and Fresnel zone change with endpoint position. Vertical scale exaggerated.

9.4.2 Communication Attenuation Modeling: Equation 9.4 and Knife-Edge Diffraction

Additional Attenuation Needs an Explicit Obstacle Model

$$L_{\text{total}} = L_{\text{fs}} + \Delta L_{\text{Fresnel}} \tag{9.4}$$

All losses are in dB. Compute $\Delta L_{\text{Fresnel}}$ from geometry, wavelength, and a specified diffraction model. The blockage fraction alone does not determine it.

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

h: obstacle-top height relative to sight line (m), positive above and negative below; opposite in sign to clearance. ν: dimensionless diffraction parameter; d_1, d_2, λ in m.

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

Single knife-edge approximation: use this equation for $\nu > -0.78$; below that, this teaching implementation uses 0 dB. J: additional loss, dB. Assumes one isolated thin obstacle; ignores specular reflection and penetration.

9.4.2 Communication Attenuation Modeling: Diffraction and Thresholds

A Higher Obstacle Adds Diffraction Loss and Reduces Margin

Conditions: 1 km, 2.4 GHz, one knife edge at the midpoint; free-space margin 6.96 dB. Keep feeder and antenna parameters fixed.

$$h = 0 \Rightarrow \nu = 0, \quad J(0) = 6.9 + 20\log_{10}(\sqrt{1.01} - 0.1) = 6.03\ \text{dB}$$

Height vs. sight line	Diffraction loss	Margin (dB)	Model result
3.35 m below sight line	0 dB (approx.)	6.96 dB	Meets 60%-radius clearance.
Just touches sight line	6.03 dB	0.92 dB	Above threshold, with little margin.
1 m above sight line	8.22 dB	-1.27 dB	Below the specified receive threshold.

Terrain accuracy, effective Earth curvature, multiple obstacles, and reflections affect predictions; match the propagation model.

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Textbook: Section 9.1.5.3

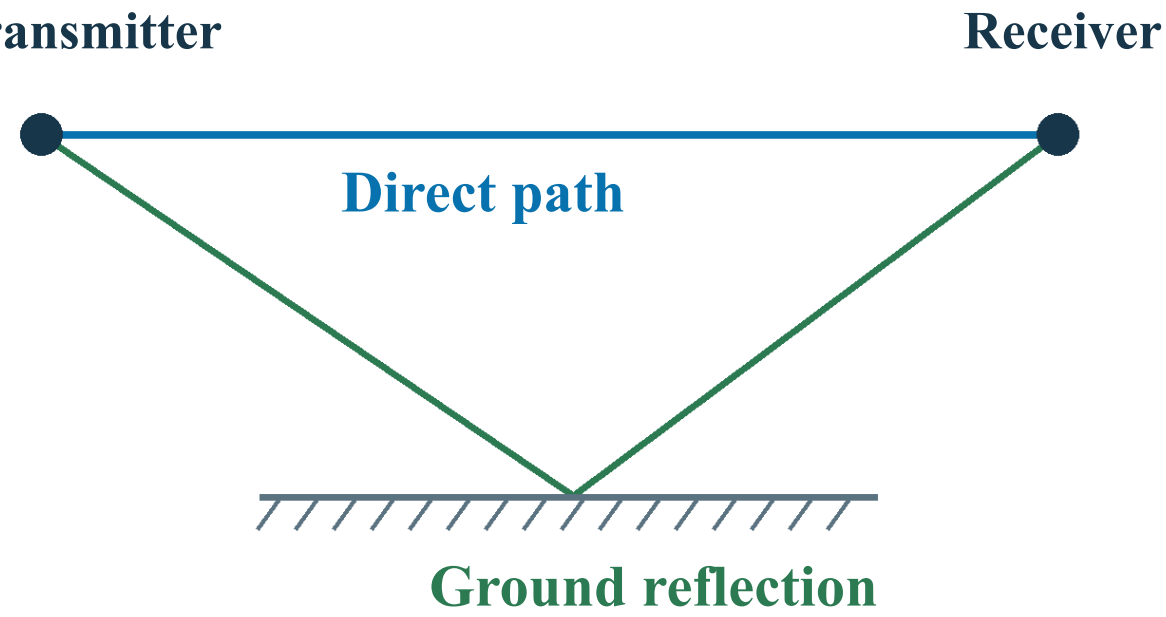
9.4.4 Network Simulation Methods and ns-3

Textbook: Sections 9.1.5.4–9.1.5.5

9.4.3 Communication Loss Models: Geometric Multipath

Different Path Lengths Produce Different Arrival Phases

Direct and ground-reflected paths



Inputs: endpoint positions, terrain, surfaces, materials.
Outputs: amplitude, delay, phase per path.

$$\Delta\tau = \frac{\ell_2 - \ell_1}{c}$$

ℓ_1, ℓ_2: direct and reflected path lengths, m; $\Delta\tau$: delay difference, s. A 1 m path difference gives about 3.33 ns of delay difference.

Geometry suits known scenes, beams, and positioning; path coefficients need electromagnetic modeling or measurement calibration.

9.4.3 Communication Loss Models: Two-Path Example

The Same Amplitudes Can Reinforce or Cancel

$$P_{\text{rel}} = |1 + ae^{-j\Delta\phi}|^2 = 1 + a^2 + 2a\cos\Delta\phi$$

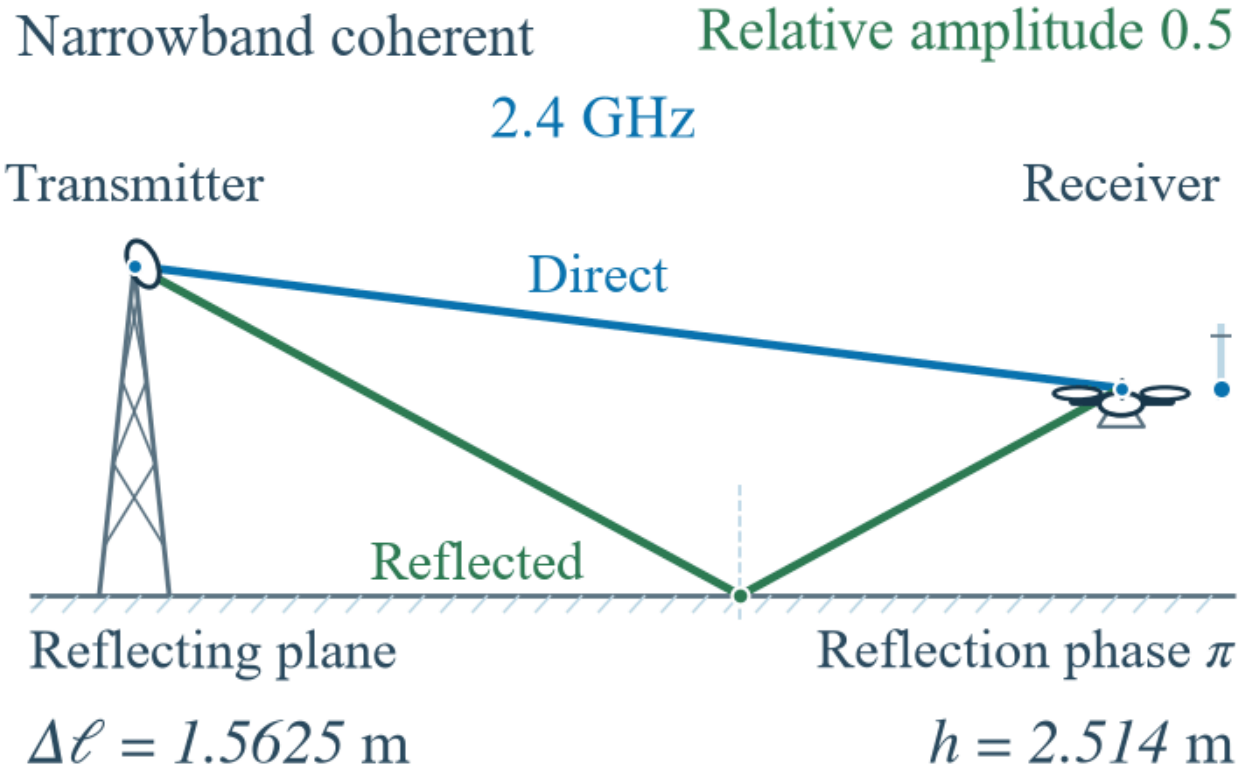
$a = 0.5$: relative path-2 amplitude; $\Delta\phi$: total phase difference including reflection phase, rad; $j^2 = -1$. P_{rel} is a dimensionless linear power ratio relative to the direct path alone. Assumes two coherent, narrowband paths.

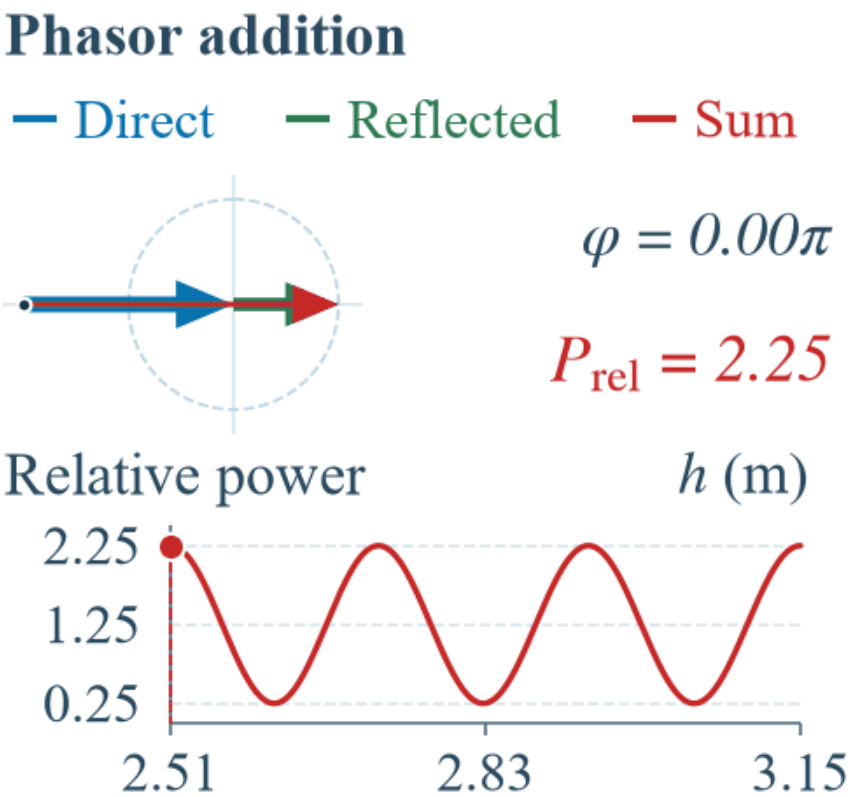
In phase	Quarter-cycle shift	Half-cycle shift
$\Delta\phi = 0$	$\Delta\phi = \pi/2$	$\Delta\phi = \pi$
2.25×	**1.25×**	**0.25×**

At 2.4 GHz, each 0.0625 m increase in path difference adds half a cycle of propagation phase. For wideband signals, compare path delays with symbol duration; intersymbol interference may occur.

9.4.3 Communication Loss Models: Two-Path Interference

Receiver Motion Changes Path Difference, Phase, and Power



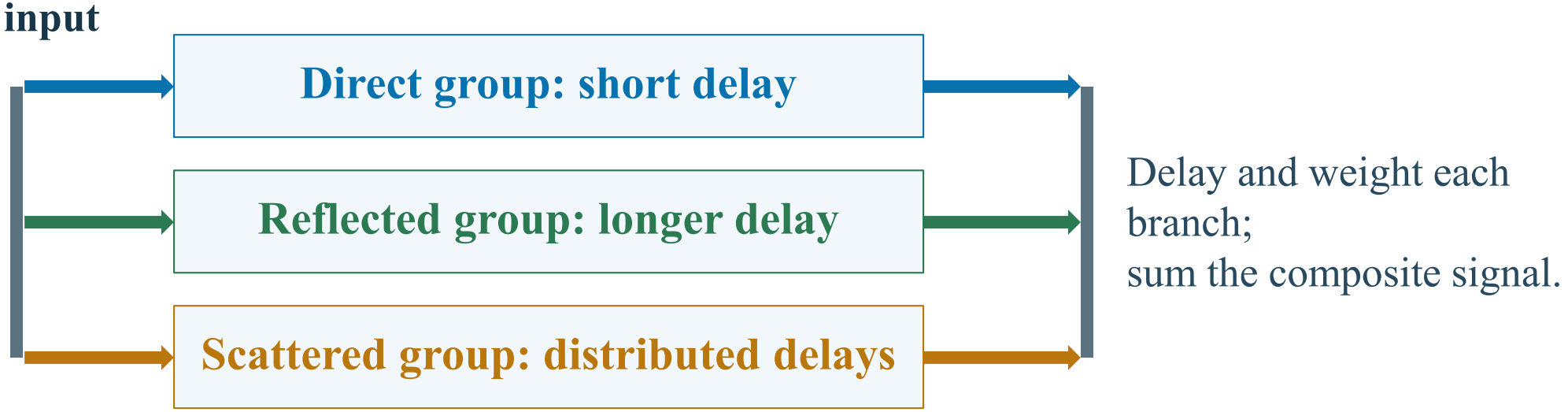


Receiver height changes path difference, phasor angle, and relative power.

9.4.3 Communication Loss Models: Geometric and Statistical Models

Statistical Models Group Multipath into Delay Taps

Tapped delay line (TDL): each tap represents a group of paths. Its delay and complex gain describe arrival time, amplitude, and phase.



Geometry explains scenes but needs detailed inputs; statistics support repeated sampling and scale studies. Rayleigh / Rician: small-scale fading; lognormal shadowing: large-scale variation.

9.4.3 Communication Loss Models: Weather

Rain, Cloud / Fog, and Gases Need Different Models

Medium	Model and inputs	Outputs and limits
Raindrops	P.838: frequency, rain rate, polarization, path elevation.	dB/km × effective rain-path length; higher bands may be more sensitive.
Cloud / fog liquid water	P.840: liquid water content, temperature, frequency.	Cloud / fog attenuation; relative humidity is not liquid water content.
Oxygen / water vapor	P.676: pressure, temperature, water vapor density, and frequency.	Gaseous absorption; treat separately from droplet scattering.

Snow, aerosols, and visible light need other models. P.840 covers cloud / fog liquid water only.

9.4.3 Communication Loss Models: Rain Attenuation Calculation

Rain Loss at 30 GHz Depends on Rain Rate and Path Length

$$\gamma_R = kR^{\alpha}, \quad A_R = \gamma_R \ell_{\text{rain}}$$

γ_R: specific attenuation, dB/km;
R: rain rate, mm/h;
ℓ_{rain}: rain-path length, km; A_R: rain attenuation, dB.

Assume 50 mm/h at 30 GHz, horizontal polarization, and a nearly horizontal path. Coefficients: $k = 0.2403$, $\alpha = 0.9485$. Use the units specified by this equation.

$$\gamma_R = 0.2403 \times 50^{0.9485} \approx 9.82 \text{ dB/km}$$

Uniform rain path	Added attenuation	Interpretation
1.0 km	9.82 dB	Entire segment has the same rain rate.
0.1 km	0.98 dB	Same rain rate, shorter rain-affected path.

9.4.3 Communication Loss Models: Signal, Interference, and Noise

Compare Desired Signal Power with Interference and Noise

$$\mathrm{SINR} = \frac{P_s}{P_I + P_N}$$

Signal-to-interference-plus-noise ratio (SINR): P_s, P_I, P_N are linear powers of the desired signal, interference, and noise, all in mW. Use the same receive bandwidth and time interval; add interference and noise as uncorrelated powers.

$$P_{\mathrm{mW}} = 10^{P_{\mathrm{dBm}}/10}$$

$$\mathrm{SINR}_{\mathrm{dB}} = 10\log_{10}\frac{10^{-7}}{10^{-8} + 10^{-10}} = 9.96\ \mathrm{dB}$$

Given: signal -70 dBm, interference -80 dBm, noise -100 dBm. Without interference, the signal-to-noise ratio is 30 dB. Do not add dBm values directly.

9.4.3 Communication Loss Models: Multiple Users and Resources

Shared Channels Introduce Interference and Access Waits

Mechanism	Signal or packet effect	Modeling and adjustment
Co-channel interference	Signals arrive at the same frequency and time.	Sum received interference power; evaluate SINR.
Adjacent-channel interference	Energy leaks from a nearby band into the receive band.	Include transmit spectrum, filtering, and receiver selectivity.
Random access	Contention, backoff, and overlapping transmissions.	Model access events; Poisson arrivals are one traffic assumption. Collision rate depends on protocol.

Time-division multiple access (TDMA) assigns slots; frequency-division multiple access (FDMA), bands; code-division multiple access (CDMA), user codes. Scheduling reduces overlap at the cost of waits and resource overhead. Analyze queues separately.

9.4.3 Communication Loss Models: External Interference and Robustness

Inject Electromagnetic and Data Faults at Their Own Layers

Injection layer	Teaching-model inputs	What to observe
Received signal	Add broadband random noise, or specify interference power and time window.	SINR, packet errors, and recovery; match bandwidth and waveform assumptions.
Link / network	Select affected links and time intervals; apply packet loss, delay, or resource limits.	Route changes, state freshness, task completion rate, and network overhead.
Data / system	Offline: duplicate, stale, wrong data; separate navigation-observation faults.	Timestamp, sequence, integrity checks; redundant sensing; degraded operation.

Record noise power, packet losses, and data semantics separately, then analyze their effects on the task.

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Textbook: Section 9.1.5.3

9.4.4 Network Simulation Methods and ns-3

Textbook: Sections 9.1.5.4–9.1.5.5

9.4.4 Network Simulation Methods and ns-3: Choosing a Method

Choose a Method for the Phenomenon You Need to Explain

Method	Inputs and outputs	Suitable questions and limits
Python / MATLAB C++	Position, parameters, randomness; power or preset packet loss / delay.	Algorithm / sensitivity checks; add detailed protocol behavior.
3D engine (e.g., Unreal Engine [UE])	Scene meshes and endpoint poses; blockage, distance, normals, materials.	Geometry and spatial relationships; couple to a radio propagation model.
Network simulator (e.g., ns-3)	Nodes, devices, channels, traffic; packet arrivals, delay, queue events.	Access / routing / load; compare protocols. Accuracy: modules and parameters.

Joint modeling: geometry feeds propagation, channel results feed the network, and control uses arriving data.

9.4.4 Network Simulation Methods and ns-3: Complete Simplified Loop

Seven Python Lines Track Separation and Added Loss

2.4 GHz; threshold -85 dBm; transmit power + antenna gains - feeder loss = 22 dBm. Evaluate 0–20 s in 0.1 s steps; add 8 dB from 8 through 12 s.

```
from math import log10
for i in range(201):
    t = i / 10; d = 500 + 50 * t
    extra = 8 if 8 <= t <= 12 else 0
    loss = 32.44 + 20*log10(d/1000) + 20*log10(2400)
    pr = 22 - loss - extra
    print(t, d, round(pr, 2), pr >= -85)
```

Run the complete code in Python: it prints time (s), distance (m), received power (dBm), and the threshold test, then exits. It tests only link power; packets, retries, and queues are not modeled.

9.4.4 Network Simulation Methods and ns-3: Numerical Results

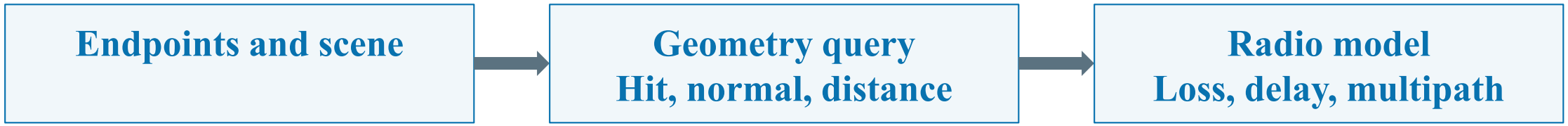
Threshold Margin Is Negative During the added-loss Window

Time (s)	Distance (m)	Added loss (dB)	Received (dBm)	Margin (dB)
0	500	0	-72.02	12.98
8	900	8	-85.13	-0.13
10	1000	8	-86.04	-1.04
12	1100	8	-86.87	-1.87
12.1	1105	0	-78.91	6.09
20	1500	0	-81.57	3.43

41 of 201 samples are below threshold, all from 8 through 12 s. These are numerical-model results; the sample fraction is not packet loss rate or a platform measurement.

9.4.4 Network Simulation Methods and ns-3: Geometry and Radio Parameters

UE Provides Geometry; a Propagation Model Computes Radio Effects

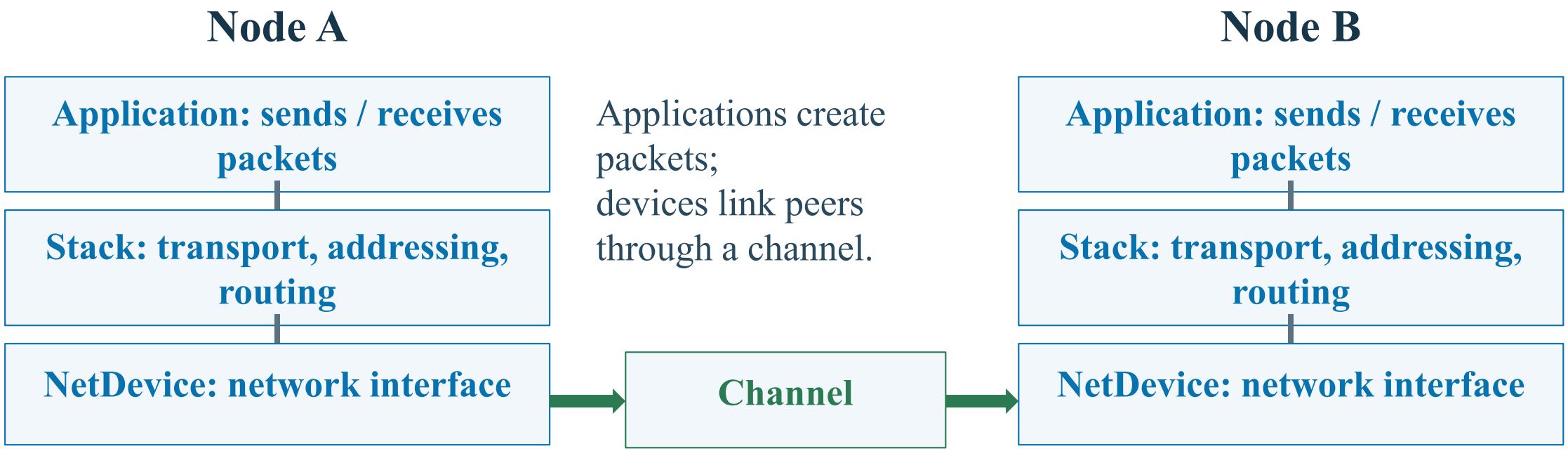


Interface fields	Meaning transferred	Use in this example
Scene and pose	Coordinate frame, units, timestamp.	Convert to one metric frame; establish a 1 km path.
Obstacle and material	Blockage location, height, material ID.	Midpoint roof: 1 m above sight line; define or calibrate material parameters.
Propagation results	Frequency-dependent loss and delay.	Single knife-edge loss: 8.22 dB; pass it to the link or network model.

Collision checks do not give radio loss; model reflection, diffraction, and penetration separately.

9.4.4 Network Simulation Methods and ns-3: Core Objects

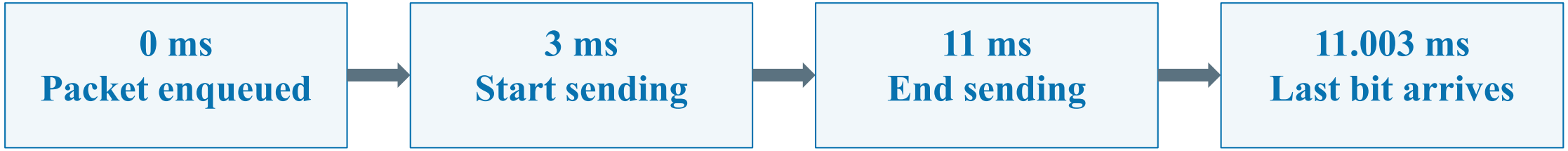
ns-3 Builds Networks from Nodes, Applications, Devices, and Channels



MobilityModel gives position and motion; propagation / reception models determine packet reception. A node may hold multiple NetDevices. Stack: Internet Protocol (IP), Transmission Control Protocol (TCP), User Datagram Protocol (UDP).

9.4.4 Network Simulation Methods and ns-3: Event Time and Delay

Discrete Events Advance to the Next Network State Change



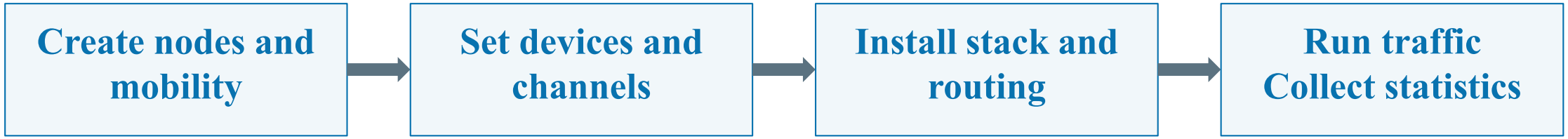
$$T = W + L/R + d/c$$

$W = 3$ ms: queuing; $L = 8000$ bit: bits serialized here; $R = 10^6$ bit/s: rate; $d = 1000$ m; $c = 3 \times 10^8$ m/s. T: total delay; excludes headers, processing, and retransmissions.

$$T = 3 + 8 + 0.00333 = 11.00333 \text{ ms}$$

9.4.4 Network Simulation Methods and ns-3: Configuration Workflow

Control Topology, Traffic, and Measurement Definitions



Layer	Required inputs	Control or vary for comparison
Physical / link	Position, frequency, power, bandwidth; modulation / coding, access, propagation model.	Keep wireless parameters fixed when studying routing.
Network / traffic	Routing, destination, packet size; packet generation rate, start / stop times.	Use equal traffic; compare delivery and overhead.
Repetition / outputs	Random seeds, repeat count; measurement layer and time window.	Report variation; keep inputs and event logs.

9.4.4 Network Simulation Methods and ns-3: Metrics and FlowMonitor

Consistent Metrics for Delivery, Throughput, and Delay

$$\mathrm{PDR} = N_{\mathrm{rx}}/N_{\mathrm{tx}} \qquad Q = 8B_{\mathrm{rx}}/T_{\mathrm{obs}}$$

Packet delivery ratio (PDR) is dimensionless. $N_{\mathrm{tx}}, N_{\mathrm{rx}}$ count sent and received packets of the same flow. B_{rx}: received bytes; T_{obs}: observation time (s); Q: throughput (bit/s).

Recording layer	What is recorded	Interpretation limits
FlowMonitor	IP flow: packets, bytes, delay; mean: received packets only.	Mainly unicast TCP / UDP; IP bytes ≠ application payload.
Application / capture	Sequence, creation / arrival times; PCAP (packet capture), traces, views.	Wireshark: inspect packets; NetAnim, etc.: events and motion.
End time	Stop sending; drain in-flight and queued packets.	Lost / in-flight / cutoff packets; iPerf: compatible live endpoints only.

9.4.4 Network Simulation Methods and ns-3: Reading Materials

Trace How Platform Models Connect to the Message Path

Installed reading root: [installation directory]/RflySimAPIs/9.RflySimComm/

Coarse-grained models and message forwarding

2.AdvExps/e1.CoaGraNetSimExps/1.NetSim4Demo/

Read Readme.pdf, NetworkSimulation.py, and common.py to relate the quality matrix, messages, and forwarding.

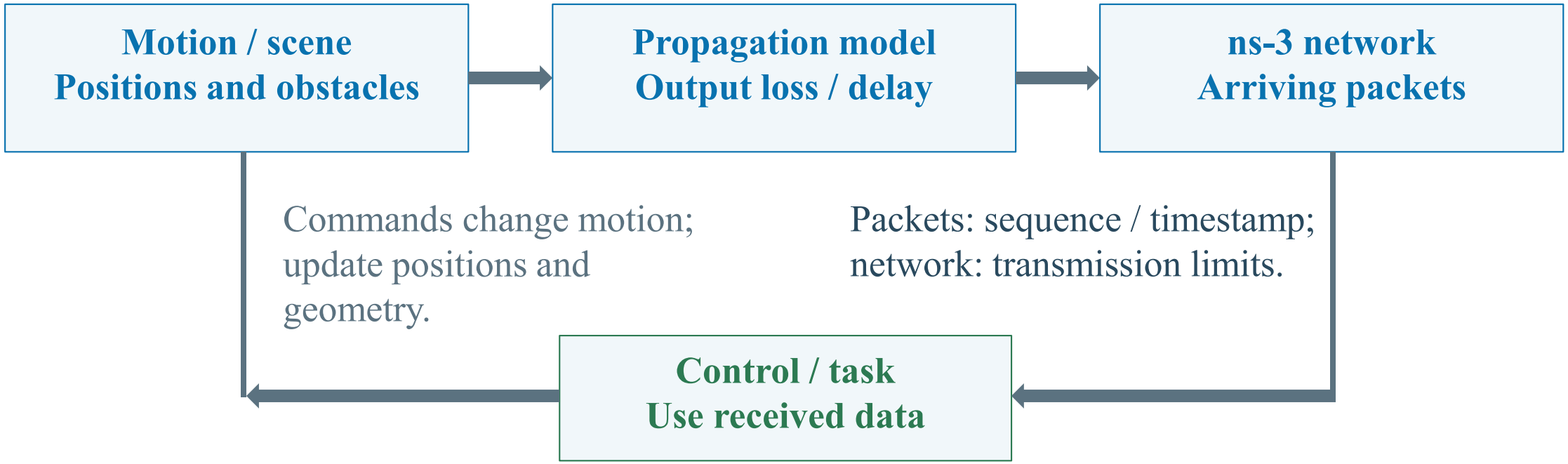
ns-3 dependencies and custom interfaces

0.ApiExps/e6.NS3DepsTestExps/

Read Readme.pdf, RflyNet.cc, and TestSend.py. Check installed documentation for Windows Subsystem for Linux (WSL), ns-3 versions, and custom modules. Run workflow: slide deck 9.7.

9.4.4 Network Simulation Methods and ns-3: Interfaces and Time

Co-Simulation Exchanges Geometry, Channel Data, and Packets



Agree on frames, units (e.g., m/s), update rates, and clocks. Offline simulation need not follow wall-clock time; real-time co-simulation must handle computation lag and buffering.

Exercises and Discussion

Why Can a Viable Link Still Deliver Unusable State?

Given: 1 km, 2.4 GHz; free-space margin 6.96 dB; a midpoint roof 2 m below the sight line. Multiple nodes transmit on the same frequency, and the receiver sometimes reads stale state.

1. Geometry: find the midpoint radius and 60% clearance. Does the roof meet it? Can intrusion fraction directly give a dB loss?

2. Power: with one knife edge, how should height and added loss be defined? What inputs are needed for co-channel interference?

3. Network: choose Python, UE, ns-3, or a combination to separate propagation degradation, access collisions, queue waits, and stale data.

Reference Points

Locate the Cause, Then Choose Models and Evidence

Question	Reference calculation or evidence	Interpretation
Clearance	Radius 5.59 m; 60% is 3.35 m. Actual clearance is only 2 m.	Fails the clearance check; this alone does not give a loss value.
Diffraction / interference	Knife-edge height: -2 m. Interference needs received power, band, and time window.	Diffraction loss ≈1.91 dB; margin ≈5.05 dB. Sum linear interference powers, then find SINR.
Protocol / state	Fix trajectories / traffic; log power, sequences, creation / arrival times, queues, retries.	Python checks the baseline; UE gives geometry; ns-3 explains delivery and waiting.

Check power, packet delivery, and state freshness together; conclusions stay within model assumptions.

9.4.4 Network Simulation Methods and ns-3: References

Consult Official Propagation, Weather, and Protocol References

International Telecommunication Union Radiocommunication Sector (ITU-R): free space P.525 (search same site), diffraction P.526
https://www.itu.int/rec/R-REC-P.526/en

Weather: P.838 rain; P.840 cloud / fog; P.676 gases (search same site)
https://www.itu.int/rec/R-REC-P.838/en

ns-3: tutorial objects and the first experiment
https://www.nsnam.org/docs/release/3.44/tutorial/

ns-3: model assumptions, wireless modules, and FlowMonitor
https://www.nsnam.org/docs/models/

UE: search Traces Overview for geometry-query interfaces
https://dev.epicgames.com/documentation/en-us/unreal-engine

Section Summary

Communication Models Connect Geometry, Power, and Packets

Establish a baseline: combine free-space loss with antenna and feeder budgets to find received power and threshold margin for the specified mode.

Add the environment: Fresnel clearance gives the geometric scale; diffraction, multipath, rain / fog, and gas models give propagation effects.

Explain packets: SINR, access, retransmissions, and queues jointly affect delivery and state freshness. Do not add dBm values directly.

Choose tools: Python computes the baseline, UE supplies geometry, and ns-3 handles events. Align time, units, and coordinates at their interfaces.

Common errors: clearance fraction ≠ fixed loss; threshold sample fraction ≠ packet loss rate; real-time operation ≠ calibration.