

Advanced Mars communications: networks, DTN and operations

Understand how a radio link becomes an interplanetary network that stores, prioritizes and forwards data through delay, occultation and disruption.

Before starting — Prerequisites: modules 00 to 28 are recommended depending on the topic. Every important symbol is defined at first use.

Mastery objectives

- explain quantities, units, assumptions and uncertainty
- repeat simple calculations without a black box
- identify interfaces, limits and degraded modes
- turn the result into an operational or architecture decision

1. A link is not yet a network

A link budget answers a physical question: can the received signal carry bits with enough margin? A network solves a larger problem: which flows move, through which relays, at what time, with what priority, and what happens when a complete end-to-end path does not exist.

On Mars, habitat, rover, EVA suit, relay orbiter, surface antenna and Earth form several segments. A robust architecture must keep local operations alive when the Earth link is unavailable.

2. Delay creates a different operational discipline

Radio propagation is limited by the speed of light. Earth–Mars delay therefore varies strongly with geometry. Even with an excellent link, real-time conversation does not exist. The system must separate decisions that can wait for the ground from decisions that must be made locally.

This changes procedure design. An emergency message should be useful without ten rounds of clarification. It should include context, current state, actions already taken and the next planned decision.

3. DTN: store now, forward when the next link exists

DTN means Delay/Disruption Tolerant Networking. The key mechanism is store-and-forward: a node keeps data when the next hop is unavailable and forwards it when contact returns. The network does not assume a permanent end-to-end connection.

That model fits orbiters that periodically pass above a base, temporary ground-station outages or a relay hidden by geometry. Data also needs lifetime and priority: science telemetry can wait; a critical alarm should not.

4. Contact plans, queues and capacity

An interplanetary network is planned around contact windows. Each window has duration, useful data rate and sometimes interruption probability. Data rate multiplied by duration gives theoretical capacity, but protocol overhead, retransmission and margin reduce what is delivered.

If producers create data faster than the network drains it, the problem becomes a queue. Backlog age can become an operational metric as important as instantaneous throughput.

5. Traffic classes: safety, command, maintenance, science and comfort

Not all traffic has the same consequence. A Mars architecture should define classes such as crew emergency, critical command, system-health telemetry, maintenance, science, nonurgent video and comfort traffic. Losing a relay should trigger a known service degradation.

Priority is not just a router number. It needs policy: what can be deleted, compressed, delayed or rerouted, and who is authorized to change that policy during a crisis?

6. Redundancy and independent paths

Two antennas powered by the same electrical bus are not independent paths. Resilience must follow common causes: power, pointing, software, terrestrial weather for optical links, relay orbit, spectrum and ground-network availability.

A settlement should at least maintain autonomous local networking, multiple surface-to-orbit options and procedures for operating when Earth disappears from the network for hours or days.

7. Command integrity and security

More autonomy makes command authenticity more important. The system must distinguish a valid command from corrupted, replayed or unauthorized traffic. Security must also avoid making degraded operation impossible.

Architecture therefore needs documented key management, time assumptions, logging and recovery procedures after loss of a trusted node.

8. Worked example: drain a data backlog

A rover accumulates 18 Gbit. One relay pass provides 2.0 Mbit/s for 45 minutes. Raw contact capacity is $2.0 \times 10^6 \text{ bit/s} \times 2,700 \text{ s} = 5.4 \times 10^9 \text{ bits}$, or 5.4 Gbit.

At 75% useful efficiency, delivered capacity is $5.4 \times 0.75 = 4.05 \text{ Gbit}$. After one pass, $18 - 4.05 = 13.95 \text{ Gbit}$ remain. The calculation shows why a mission must manage data production, not merely own a fast radio.

9. Engineering calculation: why an Earth–Mars conversation cannot drive an emergency

Quantities. Let d be transmitter-to-receiver distance in kilometres, c the speed of electromagnetic propagation in vacuum, 299,792.458 km/s, and t propagation time in seconds. The relationship is $t = d / c$: distance is divided by speed because the unknown is the time required to cover that distance.

Teaching assumption. Take an Earth–Mars distance of 225,000,000 km. Then $t = 225,000,000 \text{ km} / 299,792.458 \text{ km/s} \approx 750.5 \text{ s}$. Since $60 \text{ s} = 1 \text{ min}$, $750.5 / 60 \approx \mathbf{12.5 \text{ min one way}}$. A question sent from Mars followed by an immediate Earth reply therefore requires at least about 25 min of propagation before human analysis and decision time are added.

Physical meaning. This number rules out the mental model of an Earth operator continuously “driving” a Mars rover. It forces goal-based commanding, local procedures, systems able to reject hazardous actions, and networking able to retain messages while a link is unavailable. DTN is therefore not merely a communications feature; it is a direct consequence of interplanetary geometry.

Order-of-magnitude check. At roughly 300,000 km/s, light covers about 18 million kilometres per minute. A distance of a few hundred million kilometres should therefore produce a delay of several to a few tens of minutes, consistent with 12.5 min for this selected assumption.

Progressive exercise

A base produces 12 Gbit/day of telemetry and science. Two 30-minute contacts at 1.5 Mbit/s are available each day at 80% efficiency. Compute useful daily capacity and determine whether backlog grows. Then propose a traffic-priority policy.

Detailed correction — worked mission case

Reasoned correction

Each contact lasts 1,800 s. Two contacts at 1.5 Mbit/s provide $2 \times 1,800 \times 1.5 = 5,400$ Mbit gross. At 80% efficiency, useful daily capacity is only 4,320 Mbit, or 4.32 Gbit. The base generates 12 Gbit/day, so backlog grows by 7.68 Gbit every day. A sound policy first reserves capacity for commands, alarms, vehicle health and critical telemetry, then sends compact science summaries, and finally bulk data that can tolerate delay. DTN priorities and expiration times should preserve that operational order across interrupted contacts.

Mini-project

Design the network for a Mars base with three rovers, one relay orbiter and two surface antennas. Define traffic classes, local storage, contact plan, 48-hour Earth-loss operation, software-update strategy and recovery after relay loss.

Associated calculators

Apply this module with:

- Simplified Earth–Mars link-budget calculator

Primary sources and pathways

- NASA SCA_N — Services and Scheduling
- NASA — Delay/Disruption Tolerant Networking
- NASA — DTN Overview

FR ↔ EN parity matrix

Transmission time	Temps de transmission
Net queue drain time	Vidage net d'une file
Contact capacity	Capacité d'un contact
One-way light time	Temps lumière aller simple
Total operational latency	Latence opérationnelle totale
Two-link path success	Succès d'un chemin à deux liaisons

Mars-network foundations and mission reasoning

This English communications module matches the French teaching standard by separating propagation delay, radio-link performance and network scheduling before asking the learner to size capacity or prioritize traffic.

Four concepts to master first

latency

Definition. Latency is the time required for information to reach its destination; Earth–Mars links are dominated by light-time propagation.

Mission example. A rover emergency cannot be joystick-driven from Earth when a command and response may require many minutes.

Pitfall. Do not confuse latency with low data rate: a link can have high throughput and still have long delay.

Mental check. Separate propagation delay, processing delay, queueing and contact scheduling when analysing an operation.

Evidence

Use timestamped send and receive records plus the geometric Earth-Mars distance to separate propagation delay from processing and queueing delays.

Decision use

If latency exceeds the decision horizon, move the function to local autonomy or use time-tagged commands rather than waiting for Earth-in-the-loop control.

bandwidth

Definition. Bandwidth in this operational context represents how much information a link can carry under stated conditions.

Mission example. A science camera can produce data faster than a Mars relay can immediately transmit it, forcing storage and prioritisation.

Pitfall. Peak physical-layer rate is not the same as useful delivered application throughput.

Mental check. Account for coding, protocol overhead, contact duration, pointing losses and retransmission policy.

Evidence

Use the allocated channel width, modulation/coding assumptions and measured or predicted useful data rate for the contact.

Decision use

If available capacity cannot carry required traffic, reduce data generation, compress or reprioritise products, or schedule additional contacts.

DTN

Definition. Delay/Disruption Tolerant Networking stores and forwards bundles across links that may be delayed or temporarily unavailable.

Mission example. An orbiter can accept rover data, hold it through occultation and forward it during a later Earth contact.

Pitfall. DTN does not remove latency; it makes disrupted paths operationally usable.

Mental check. Check custody, priority, expiration and storage capacity for the mission data classes.

Evidence

Use bundle logs showing storage, forwarding, priority, custody and expiry through an interrupted-contact test.

Decision use

If bundles cannot survive the planned disruption pattern, change routing, storage allocation or expiry policy before relying on the network operationally.

link budget

Definition. A link budget combines transmitter power, antenna gains, path losses, pointing losses and receiver performance to estimate received margin.

Mission example. A large dish can compensate for part of the enormous Mars free-space loss, but only if pointing and system noise remain within assumptions.

Pitfall. Do not add quantities expressed in incompatible linear and decibel units.

Mental check. Trace every gain and loss from transmitter output to required receiver threshold and preserve a margin for uncertainty.

Evidence

Use the complete transmitter-to-receiver budget with power, gains, path loss, pointing losses, noise assumptions and required signal-to-noise threshold.

Decision use

A negative or fragile link margin requires more gain, power, coding, contact time or a different geometry before the link is considered dependable.

Calculation laboratory

Use each communication relation as a capacity or margin audit. Convert bits and seconds consistently, distinguish linear and logarithmic quantities, and finish by checking whether the contact plan can carry the required traffic.

Canonical quantitative mini-lessons

This block is the module quantitative reference; exercise values are pedagogical and must be replaced by mission data before any real decision.

Transmission time

$$t_{tx} = D / R_{\text{useful}}$$

1 — Concrete question

What does “ $t_{tx} = D / R_{\text{useful}}$ ” compute in “Transmission time”?

2 — Intuition without symbols

Required time depends on the amount to send and the rate actually available to useful data.

3 — Quantities

t_{tx} : transmission time [s]; D: data quantity [Mb]; R_{useful} : useful data rate [Mb/s]

4 — Formula

$$t_{tx} = D / R_{\text{useful}}$$

5 — Read aloud

Read “ $t_{tx} = D / R_{\text{useful}}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

t_{tx} : transmission time [s]; D: data quantity [Mb]; R_{useful} : useful data rate [Mb/s]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

t_{tx} [s]; D [Mb]; R_{useful} [Mb/s]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division relates a quantity to a coherent capacity, duration or reference.

11 — Assumptions

Numerator and denominator must describe the same scenario and the denominator must remain positive.

12 — Independent check

Multiplying the result by the denominator should reconstruct the numerator.

13 — Numerical case

With $D = 1200$ Mb, $R_{\text{useful}} = 20$ Mb/s: $t_{tx} = 1200 / 20 = 60$ s.

14 — Why the calculation works

Division relates a quantity to a coherent capacity, duration or reference.

15 — Verification

Multiplying the result by the denominator should reconstruct the numerator.

16 — Mental estimate

Comparing numerator and denominator scales predicts the result.

17 — Interpretation

Do not start a transfer when its duration exceeds the available contact window.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls as the denominator rises.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $D = 800$ Mb, $R_{\text{useful}} = 10$ Mb/s: $t_{\text{tx}} = 800 / 10$?

Detailed guided correction — open after trying

With $D = 800$ Mb, $R_{\text{useful}} = 10$ Mb/s: $t_{\text{tx}} = 800 / 10 = 80$ s. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $D = 450$ Mb, $R_{\text{useful}} = 15$ Mb/s: $t_{\text{tx}} = 450 / 15$?

Autonomous correction — open after trying

With $D = 450$ Mb, $R_{\text{useful}} = 15$ Mb/s: $t_{\text{tx}} = 450 / 15 = 30$ s. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Do not start a transfer when its duration exceeds the available contact window.

Net queue drain time

$$t_{\text{drain}} = Q / (R_{\text{out}} - R_{\text{in}})$$

1 — Concrete question

What does “ $t_{\text{drain}} = Q / (R_{\text{out}} - R_{\text{in}})$ ” compute in “Net queue drain time”?

2 — Intuition without symbols

A queue shrinks only when service rate exceeds the rate still feeding it.

3 — Quantities

t_{drain} : drain time [s]; Q : initial backlog [Mb]; R_{out} : service rate [Mb/s]; R_{in} : arrival rate [Mb/s]

4 — Formula

$$t_{\text{drain}} = Q / (R_{\text{out}} - R_{\text{in}})$$

5 — Read aloud

Read “ $t_{\text{drain}} = Q / (R_{\text{out}} - R_{\text{in}})$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

t_{drain} : drain time [s]; Q : initial backlog [Mb]; R_{out} : service rate [Mb/s]; R_{in} : arrival rate [Mb/s]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

t_{drain} [s]; Q [Mb]; R_{out} [Mb/s]; R_{in} [Mb/s]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division relates a quantity to a coherent capacity, duration or reference.

11 — Assumptions

Numerator and denominator must describe the same scenario and the denominator must remain positive.

12 — Independent check

Multiplying the result by the denominator should reconstruct the numerator.

13 — Numerical case

With $Q = 600$ Mb, $R_{\text{out}} = 20$ Mb/s, $R_{\text{in}} = 5$ Mb/s: $t_{\text{drain}} = 600 / (20 - 5) = 40$ s.

14 — Why the calculation works

Division relates a quantity to a coherent capacity, duration or reference.

15 — Verification

Multiplying the result by the denominator should reconstruct the numerator.

16 — Mental estimate

Comparing numerator and denominator scales predicts the result.

17 — Interpretation

If net service becomes zero or negative, reduce generation or increase capacity before the next contact.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls as the denominator rises.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $Q = 900$ Mb, $R_{\text{out}} = 30$ Mb/s, $R_{\text{in}} = 10$ Mb/s: $t_{\text{drain}} = 900 / (30 - 10)$?

Detailed guided correction — open after trying

With $Q = 900$ Mb, $R_{\text{out}} = 30$ Mb/s, $R_{\text{in}} = 10$ Mb/s: $t_{\text{drain}} = 900 / (30 - 10) = 45$ s. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $Q = 240$ Mb, $R_{\text{out}} = 12$ Mb/s, $R_{\text{in}} = 4$ Mb/s: $t_{\text{drain}} = 240 / (12 - 4)$?

Autonomous correction — open after trying

With $Q = 240$ Mb, $R_{\text{out}} = 12$ Mb/s, $R_{\text{in}} = 4$ Mb/s: $t_{\text{drain}} = 240 / (12 - 4) = 30$ s. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

If net service becomes zero or negative, reduce generation or increase capacity before the next contact.

Contact capacity

$$C_{\text{contact}} = R_{\text{useful}} \times t_{\text{contact}}$$

1 — Concrete question

What does " $C_{\text{contact}} = R_{\text{useful}} \times t_{\text{contact}}$ " compute in "Contact capacity"?

2 — Intuition without symbols

Total window capacity is the useful rate sustained over usable contact time.

3 — Quantities

C_{contact} : transferable data [Mb]; R_{useful} : useful data rate [Mb/s]; t_{contact} : contact duration [s]

4 — Formula

$$C_{\text{contact}} = R_{\text{useful}} \times t_{\text{contact}}$$

5 — Read aloud

Read " $C_{\text{contact}} = R_{\text{useful}} \times t_{\text{contact}}$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

C_{contact} : transferable data [Mb]; R_{useful} : useful data rate [Mb/s]; t_{contact} : contact duration [s]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

C_{contact} [Mb]; R_{useful} [Mb/s]; t_{contact} [s]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Multiplication converts a rate, fraction or specific quantity into a total.

11 — Assumptions

Factors must belong to the same scenario and their units must combine correctly.

12 — Independent check

Dividing the result by a non-zero factor should recover the product of the others.

13 — Numerical case

With $R_{\text{useful}} = 15$ Mb/s, $t_{\text{contact}} = 300$ s: $C_{\text{contact}} = 15 \times 300 = 4500$ Mb.

14 — Why the calculation works

Multiplication converts a rate, fraction or specific quantity into a total.

15 — Verification

Dividing the result by a non-zero factor should recover the product of the others.

16 — Mental estimate

Estimating each factor separately quickly predicts product scale.

17 — Interpretation

Keep margin for retries and priority traffic instead of filling a window to theoretical capacity.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

A relative change in one factor transfers directly to the product when the others stay fixed.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $R_{\text{useful}} = 8$ Mb/s, $t_{\text{contact}} = 600$ s: $C_{\text{contact}} = 8 \times 600$?

Detailed guided correction — open after trying

With $R_{\text{useful}} = 8$ Mb/s, $t_{\text{contact}} = 600$ s: $C_{\text{contact}} = 8 \times 600 = 4800$ Mb. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $R_{\text{useful}} = 25$ Mb/s, $t_{\text{contact}} = 120$ s: $C_{\text{contact}} = 25 \times 120$?

Autonomous correction — open after trying

With $R_{\text{useful}} = 25$ Mb/s, $t_{\text{contact}} = 120$ s: $C_{\text{contact}} = 25 \times 120 = 3000$ Mb. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Keep margin for retries and priority traffic instead of filling a window to theoretical capacity.

One-way light time

$$t_{\text{ow}} = d / c$$

1 — Concrete question

What does “ $t_{\text{ow}} = d / c$ ” compute in “One-way light time”?

2 — Intuition without symbols

Even a perfect signal remains limited by light-travel time.

3 — Quantities

t_{ow} : one-way delay [s]; d: propagation distance [km]; c: speed of light [km/s]

4 — Formula

$$t_{ow} = d / c$$

5 — Read aloud

Read " $t_{ow} = d / c$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

t_{ow} : one-way delay [s]; d: propagation distance [km]; c: speed of light [km/s]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

t_{ow} [s]; d [km]; c [km/s]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division relates a quantity to a coherent capacity, duration or reference.

11 — Assumptions

Numerator and denominator must describe the same scenario and the denominator must remain positive.

12 — Independent check

Multiplying the result by the denominator should reconstruct the numerator.

13 — Numerical case

With $d = 225000000$ km, $c = 299792$ km/s: $t_{ow} = 225000000 / 299792 = 750.52$ s.

14 — Why the calculation works

Division relates a quantity to a coherent capacity, duration or reference.

15 — Verification

Multiplying the result by the denominator should reconstruct the numerator.

16 — Mental estimate

Comparing numerator and denominator scales predicts the result.

17 — Interpretation

Urgent decisions must be locally delegable when one-way delay exceeds the dynamics of the problem.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls as the denominator rises.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $d = 56000000$ km, $c = 299792$ km/s: $t_{ow} = 56000000 / 299792$?

Detailed guided correction — open after trying

With $d = 56000000$ km, $c = 299792$ km/s: $t_{ow} = 56000000 / 299792 = 186.8$ s. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $d = 400000000$ km, $c = 299792$ km/s: $t_{ow} = 400000000 / 299792$?

Autonomous correction — open after trying

With $d = 400000000$ km, $c = 299792$ km/s: $t_{ow} = 400000000 / 299792 = 1334.26$ s. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Urgent decisions must be locally delegable when one-way delay exceeds the dynamics of the problem.

Total operational latency

$$t_{\text{total}} = t_{\text{ow}} + t_{\text{queue}} + t_{\text{tx}}$$

1 — Concrete question

What does “ $t_{\text{total}} = t_{\text{ow}} + t_{\text{queue}} + t_{\text{tx}}$ ” compute in “Total operational latency”?

2 — Intuition without symbols

Operational response adds propagation, queueing and transmission; reducing one term does not remove the others.

3 — Quantities

t_{total} : total latency [s]; t_{ow} : propagation delay [s]; t_{queue} : queue delay [s]; t_{tx} : transmission time [s]

4 — Formula

$$t_{\text{total}} = t_{\text{ow}} + t_{\text{queue}} + t_{\text{tx}}$$

5 — Read aloud

Read “ $t_{\text{total}} = t_{\text{ow}} + t_{\text{queue}} + t_{\text{tx}}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

t_{total} : total latency [s]; t_{ow} : propagation delay [s]; t_{queue} : queue delay [s]; t_{tx} : transmission time [s]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

t_{total} [s]; t_{ow} [s]; t_{queue} [s]; t_{tx} [s]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Addition combines delays or contributions that accumulate in the same operational chain.

11 — Assumptions

Contributions must use a common unit and the same system boundary.

12 — Independent check

Removing one term from the total should recover the sum of the others.

13 — Numerical case

With $t_{\text{ow}} = 750$ s, $t_{\text{queue}} = 40$ s, $t_{\text{tx}} = 60$ s: $t_{\text{total}} = 750 + 40 + 60 = 850$ s.

14 — Why the calculation works

Addition combines delays or contributions that accumulate in the same operational chain.

15 — Verification

Removing one term from the total should recover the sum of the others.

16 — Mental estimate

Adding dominant terms first gives a robust order of magnitude.

17 — Interpretation

Compare total latency with the function’s acceptable delay before selecting network architecture.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The total changes linearly with each term when the others stay fixed.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $t_{\text{ow}} = 187$ s, $t_{\text{queue}} = 20$ s, $t_{\text{tx}} = 80$ s: $t_{\text{total}} = 187 + 20 + 80$?

Detailed guided correction — open after trying

With $t_{\text{ow}} = 187$ s, $t_{\text{queue}} = 20$ s, $t_{\text{tx}} = 80$ s: $t_{\text{total}} = 187 + 20 + 80 = 287$ s. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $t_{\text{ow}} = 1334$ s, $t_{\text{queue}} = 15$ s, $t_{\text{tx}} = 30$ s: $t_{\text{total}} = 1334 + 15 + 30$?

Autonomous correction — open after trying

With $t_{ow} = 1334$ s, $t_{queue} = 15$ s, $t_{tx} = 30$ s: $t_{total} = 1334 + 15 + 30 = 1379$ s. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Compare total latency with the function's acceptable delay before selecting network architecture.

Two-link path success

$$P_{path} = P_{link1} \times P_{link2}$$

1 — Concrete question

What does " $P_{path} = P_{link1} \times P_{link2}$ " compute in "Two-link path success"?

2 — Intuition without symbols

Two serial links must both succeed for the complete path to succeed.

3 — Quantities

P_{path} : path success probability [sans dimension]; P_{link1} : link one success [sans dimension]; P_{link2} : link two success [sans dimension]

4 — Formula

$$P_{path} = P_{link1} \times P_{link2}$$

5 — Read aloud

Read " $P_{path} = P_{link1} \times P_{link2}$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

P_{path} : path success probability [sans dimension]; P_{link1} : link one success [sans dimension]; P_{link2} : link two success [sans dimension]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

P_{path} [sans dimension]; P_{link1} [sans dimension]; P_{link2} [sans dimension]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Multiplication converts a rate, fraction or specific quantity into a total.

11 — Assumptions

Factors must belong to the same scenario and their units must combine correctly.

12 — Independent check

Dividing the result by a non-zero factor should recover the product of the others.

13 — Numerical case

With $P_{link1} = 0.98$ sans dimension, $P_{link2} = 0.97$ sans dimension: $P_{path} = 0.98 \times 0.97 = 0.9506$.

14 — Why the calculation works

Multiplication converts a rate, fraction or specific quantity into a total.

15 — Verification

Dividing the result by a non-zero factor should recover the product of the others.

16 — Mental estimate

Estimating each factor separately quickly predicts product scale.

17 — Interpretation

Add a genuinely independent path when the result does not meet the traffic class requirement.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

A relative change in one factor transfers directly to the product when the others stay fixed.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $P_{\text{link1}} = 0.95$ sans dimension, $P_{\text{link2}} = 0.9$ sans dimension: $P_{\text{path}} = 0.95 \times 0.9$?

Detailed guided correction — open after trying

With $P_{\text{link1}} = 0.95$ sans dimension, $P_{\text{link2}} = 0.9$ sans dimension: $P_{\text{path}} = 0.95 \times 0.9 = 0.855$. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $P_{\text{link1}} = 0.999$ sans dimension, $P_{\text{link2}} = 0.99$ sans dimension: $P_{\text{path}} = 0.999 \times 0.99$?

Autonomous correction — open after trying

With $P_{\text{link1}} = 0.999$ sans dimension, $P_{\text{link2}} = 0.99$ sans dimension: $P_{\text{path}} = 0.999 \times 0.99 = 0.989$. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Add a genuinely independent path when the result does not meet the traffic class requirement.

Mission reasoning

Delay changes operations

Mars communications design is an operations problem as much as a radio problem. Long one-way light time rules out continuous terrestrial control. Vehicles and habitats need local autonomy, time-tagged commands and procedures that can continue when Earth is silent. Teams should classify actions by whether they can wait for approval, require local authority or must happen automatically.

Contact plans and store-and-forward

Orbiters create intermittent opportunities rather than permanent links. A rover may accumulate science data, transmit to a relay during a short pass and rely on that orbiter to forward later. Contact plans therefore manage time, data volume, priorities and storage. A network can have excellent instantaneous rate yet still build backlog if daily production exceeds useful scheduled capacity.

DTN priority and expiration

Not every bundle deserves the same treatment. Command acknowledgements, alarms and vehicle health can have high priority and short relevance windows, while bulk imagery can tolerate delay. DTN supports such distinctions through priority, expiration and custody mechanisms. Mission design must prevent low-value bulk traffic from consuming the storage or contact time needed for safety-critical information.

Link margin and graceful degradation

A link budget is never a single magic number. Pointing error, weather at the Earth station, equipment temperature, antenna availability and coding mode all change margin. Operations should define what happens as margin falls: lower rate, stronger coding, reduced payload, alternate relay or stored backlog. Graceful degradation is safer than designing one brittle nominal rate.

Communications practice — size the link or queue before revealing the answer

Exercise A — Latency reasoning

Explain why increasing antenna gain does not eliminate the fundamental Earth–Mars command delay.

Detailed correction — Exercise A

Antenna gain can improve received signal strength and support a higher data rate or margin, but electromagnetic propagation still cannot exceed the speed of light. The geometric light-time delay remains.

Separate propagation physics from radio performance: antenna gain may improve link margin or data rate, but Earth-Mars light time remains distance divided by the speed of light.

Exercise B — Transmission time

A rover must send 1.8 Gbit at a useful rate of 3 Mbit/s. Estimate transmission time in minutes.

Detailed correction — Exercise B

1.8 Gbit = 1,800 Mbit. Time = $1,800/3 = 600$ s = 10 min. This assumes the 3 Mbit/s rate is already net useful throughput and remains available for the full interval.

Convert 1.8 Gbit and 3 Mbit/s to consistent units before dividing; the result is 600 s, or 10 min, before any additional protocol or contact-window losses.

Exercise C — Daily backlog

A base generates 12 Gbit/day but scheduled useful capacity is 9 Gbit/day. What happens after four days if generation and capacity remain constant?

Detailed correction — Exercise C

Backlog grows by 3 Gbit/day, so after four days it reaches 12 Gbit. The network needs prioritisation, extra contacts, compression or reduced generation before storage fills.

Track the daily balance explicitly: generating 12 Gbit and delivering 9 Gbit adds 3 Gbit of backlog per day, so four unchanged days accumulate 12 Gbit.

Exercise D — DTN priority

Rank emergency telemetry, command acknowledgements, compressed science summaries and raw high-resolution imagery for a severely limited contact.

Detailed correction — Exercise D

Emergency telemetry and command acknowledgements normally come first because they protect command authority and vehicle health. Compact science summaries may follow, with bulk raw imagery last unless a specific science event changes mission priority.

Rank traffic by operational consequence and expiry, not by file size alone; emergency telemetry and command acknowledgement normally outrank science products that can wait for later contacts.

Exercise E — Link-budget discipline

A spreadsheet mixes transmitter power in watts with antenna gains in dB and subtracts them directly. What is wrong?

Detailed correction — Exercise E

Linear and logarithmic quantities cannot be combined by direct addition or subtraction without conversion. A dB link budget must express compatible power levels and gains/losses in the logarithmic convention, with clear reference units such as dBW or dBm where required.

Do not mix linear watts with logarithmic dB by direct addition or subtraction; convert quantities into a consistent representation before assembling the link budget.

Interactive beginner glossary

Use the interactive terms to understand what happens to information between generation and delivery. Each definition should clarify delay, storage, priority, reliability or radio-link performance.

- latency — Latency is the elapsed time between sending information and its useful arrival or response. For Earth–Mars links, propagation delay alone can reach many minutes.

- **light time** — Light time is the propagation time imposed by distance divided by the speed of light. No antenna, coding scheme or higher transmitter power can remove this geometric delay.
- **bandwidth** — Bandwidth is the range of frequencies available to a communication channel. It constrains achievable data rate together with received-signal condition, coding and modulation.
- **data rate** — Data rate is the amount of digital information transferred per unit time, commonly expressed in bit/s, kbit/s or Mbit/s.
- **throughput** — Throughput is the useful application data successfully delivered per unit time after accounting for coding, retransmissions, protocol overhead and unavailable contact periods.
- **contact window** — A contact window is an interval during which two communication nodes have suitable geometry and link conditions to exchange data.
- **relay** — A relay is an intermediate node that receives data and forwards it toward its destination, extending coverage or creating an alternate path when direct communication is unavailable.
- **orbiter** — An orbiter is a spacecraft operating around a planetary body. Around Mars it can act as a relay between surface assets and Earth while also performing science and navigation support.
- **store and forward** — Store-and-forward means a node can retain data locally when the next link is unavailable and transmit it later when a suitable contact becomes available.
- **DTN** — Delay/Disruption Tolerant Networking (DTN) is a networking approach designed for long delays and intermittent links by storing data between contacts instead of assuming a continuous end-to-end connection.
- **bundle** — A bundle is a self-contained unit of data used by DTN's Bundle Protocol, carrying payload and routing/lifetime information so it can survive store-and-forward transfer.
- **custody** — Custody is a reliability mechanism in which a DTN node accepts responsibility for retaining a bundle until another node has safely accepted it or the bundle expires.
- **priority** — Priority ranks traffic so limited contact time and storage are used first for information with greater operational urgency or value.
- **expiration** — Expiration is the time after which queued data is no longer worth forwarding, preventing obsolete bundles from consuming storage and communication capacity.
- **backlog** — Backlog is queued data waiting for transmission. It grows when data generation exceeds delivered throughput and shrinks only when later capacity exceeds incoming traffic.
- **compression** — Compression reduces the number of bits required to represent information. Lossless methods preserve all information; lossy methods trade some fidelity for a larger size reduction.
- **coding** — Channel coding adds structured check information so the receiver can detect or correct transmission errors, improving reliability at the cost of extra transmitted bits.
- **protocol overhead** — Protocol overhead is the fraction of transmitted bits used for headers, addressing, framing, acknowledgements or other control information rather than the useful payload.
- **link budget** — A link budget accounts for transmitter power, antenna gains, propagation losses and receiver requirements to estimate received signal level and communication margin.
- **transmitter power** — Transmitter power is the radio-frequency power delivered by the transmitter before antenna gain. Increasing it can improve received signal strength but costs electrical power and thermal capacity.
- **antenna gain** — Antenna gain describes how strongly an antenna concentrates transmitted or received energy in a direction compared with an isotropic reference.
- **free-space loss** — Free-space path loss is the geometric spreading of radio energy as a wave propagates over distance. It rises strongly with distance and frequency.
- **pointing loss** — Pointing loss is the reduction in received signal caused when transmitting or receiving antennas are not perfectly aligned with the intended direction.
- **receiver noise** — Receiver noise is unwanted random electrical energy in the receiving system that competes with the desired signal and limits detectability.
- **signal-to-noise ratio** — Signal-to-noise ratio compares useful received signal power with noise power. Higher values generally support more reliable or faster communication.
- **link margin** — Link margin is the amount by which the predicted received signal performance exceeds the minimum required performance after all stated gains, losses and uncertainties are included.

- ground station — A ground station is a terrestrial facility with antennas, radios, timing and network systems used to communicate with spacecraft or planetary assets.
- time-tagged command — A time-tagged command carries an execution time so a remote system can perform an approved action later without waiting for a real-time command from Earth.
- autonomy — Communication autonomy is the ability of a Mars asset to queue, prioritize, route and act on information locally when Earth contact is delayed or interrupted.
- disruption — A disruption is a temporary loss of a communication path caused by geometry, obstruction, weather, equipment state, interference or scheduled unavailability.

Operational depth: from calculation to mission decision

End-to-end throughput matters

Radio specifications often quote peak physical-layer rate, but mission planners need end-to-end useful throughput. Coding overhead, protocol headers, retransmissions, pointing acquisition, scheduled contact time and priority traffic all reduce the volume available for science or maintenance files. A network budget therefore begins with daily information generation and traces how much survives each bottleneck. If production exceeds delivery for long enough, storage fills even when every individual radio works exactly as specified.

Contact geometry as infrastructure

Mars communications depend on orbital geometry. A relay that is excellent during one pass may disappear behind the planet minutes later. Surface terrain can block line of sight, and Earth itself may be unavailable during solar conjunction. Mission architecture therefore treats contacts as scheduled infrastructure. Critical functions need local autonomy and enough storage to survive expected gaps. Additional orbiters improve availability only when their orbits and ground support create genuinely complementary contact opportunities.

DTN and information value

Delay-tolerant networking lets the system store data when no end-to-end path exists. That capability becomes powerful only when information value is encoded operationally. A vehicle-health alarm should not wait behind gigabytes of raw imagery. Bundles can carry priority, expiration and custody rules so the network preserves information that still matters. Mission planners should define these classes before launch and test them during disrupted contacts, including failure of a relay or unexpected growth of backlog.

Link budgets across changing modes

A Mars link budget changes with distance, antenna pointing, weather at Earth stations, transmitter temperature and coding mode. One nominal margin is therefore not enough. Operations need thresholds for switching data rates, choosing alternate ground stations or deferring bulk traffic. If a low-margin mode is expected, the network should degrade gracefully rather than abruptly losing command. The best link plan links every margin state to an operational response and a prediction of delivered useful data.

Conjunction and communications autonomy

Solar conjunction can severely restrict or interrupt Earth–Mars communications. The settlement must therefore enter a known autonomy posture before the disruption: command sequences are preloaded, nonessential risky activities are reduced, storage is checked and local decision authority is explicit. When communication resumes, reconciliation procedures compare what Earth expected with what Mars actually did. This is a network problem, an operational-governance problem and a data-integrity problem at the same time.

Final mission assurance note

Communications planning should include recovery after a missed contact. If an orbiter pass is lost because of pointing, weather at the ground station or spacecraft safe mode, the network needs enough storage and a rule for rescheduling data. Priority queues should be tested with realistic backlog rather than empty buffers. Teams should also verify clock synchronisation because expiration times, contact plans and time-tagged commands depend on a shared time reference. A network that transports bits correctly but applies the wrong time semantics can still produce an operational failure.

Mission integration note

Network verification should also include message meaning, not just successful delivery. A command that arrives intact but too late can be operationally wrong, while duplicated or reordered messages can create ambiguity unless protocols are designed for idempotence and sequence control. Engineers should test what happens when a packet is delayed across a mode transition, when an acknowledgement is lost, or when the same command is received twice. This is especially important with store-and-forward relays because delivery order may differ from transmission order. Robust operations therefore pair transport reliability with clear command validity windows, sequence numbers and state reconciliation.

Additional operational assurance

Communications resilience also depends on ground architecture. Mars links can be technically healthy while one terrestrial station is unavailable because of maintenance, local weather or equipment failure. Multiple geographically separated ground stations improve availability, but handover and routing must be exercised rather than assumed. Mission planning should know which services can move between stations, how authentication is preserved and how priorities are reconciled after a disruption. This makes the communications chain a true end-to-end service extending from a Mars application through relays and deep-space links to terrestrial networks, operators and archives.

Last readiness check

A final planning check is storage autonomy. Backlog capacity should cover the longest credible communications interruption plus the data generated during recovery. If storage is nearly full before the outage begins, the network is already operating without resilience and must shed or compress lower-priority data before critical telemetry competes for space.

Service restoration after disruption

After communications recover, operations must reconcile state rather than assume continuity. Teams compare queued commands, acknowledgements, telemetry gaps, bundle custody and local autonomous actions before returning to the nominal plan. This prevents a delayed command from being executed after Mars has already solved the problem locally, and it ensures that Earth databases reflect the actual spacecraft or settlement state before the next decision cycle begins.

Operational review checklist

Before accepting a communications result, separate geometric light time from transmission time, useful payload from protocol overhead, and generated data from delivered throughput. Then state the operational consequence for backlog or command timing.

Plan explicitly for interrupted links: orbit geometry, pointing loss, equipment outages or full contact loss must not make the architecture collapse. A robust network stores, prioritizes and forwards data according to mission consequence.