

AETHERIX

Autonomous Extraterrestrial High-throughput Enhancing Routing and Inter-planetary eXchange

EDUQUAL LEVEL 6 — TOPIC 59

Building an Interplanetary Communication Network with DTN, Quantum Communication, and Space-Based Infrastructure for Mars Mission Support

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[Live Showcase](#)

[Source Code](#)

What We'll Cover

01 The Challenge

Why space breaks the internet

02 DTN & BPv7

Store-and-forward with custody

03 Architecture

System modules & protocol stack

04 Topology

241 nodes, 5 tiers, two worlds

05 Link Budget

1550nm optical analysis

06 Data Flow & RL

End-to-end journey, adaptive routing

07 Quantum Security

BB84/E91 + repeater chains

08 Orbital & Doppler

Contact windows, synodic period

09 Radiation Hardening

SEU, TMR, ECC, FDIR

10 Data Prioritization

QoS, compression, preemption

11 Trade-offs & Failure

Design choices, conjunction recovery

12 Performance & Q&A

vs current systems, live demo

What is AETHERIX & Why It Matters

What is AETHERIX?

- An architecture for **delay-tolerant networking (DTN)** between Earth and Mars
- Replaces static Contact Graph Routing with **reinforcement-learning** routing
- Secures links with **Quantum Key Distribution** (BB84 & E91 + repeaters)
- Hybrid **optical/RF** links across a 5-tier, 241-node topology
- Working proof-of-concept: 33 Python modules, 643 tests, 15 browser demos

The Problem

- **TCP/IP breaks** — 3–22 min one-way delay; 6–44 min round trip
- Current Mars links: **0.5–6 Mbps**, 60–75% availability [1]
- **Solar conjunction**: ~2-week blackout every 26 months
- Static routing can't adapt to dynamic contact schedules
- Classical key exchange is infeasible across interplanetary distance

AETHERIX addresses every one: DTN store-and-forward, AI-driven routing, quantum-secured keys, and hybrid optical/RF links with Lagrange-relay conjunction coverage.

Why Space Breaks the Internet

Earth → Mars

Closest approach	54.6 million km
Farthest distance	401 million km
Distance range	7.3× variation
One-way light time	3 – 22 minutes
Synodic period	779.94 days (26 months)

Why TCP/IP Fails

TCP/IP expects	Deep-space reality
RTT < 200 ms	6 – 44 min RTT
Always connected	Scheduled contacts only
End-to-end path	No simultaneous route
ACKs in seconds	ACKs take minutes–hours

“TCP/IP assumes the network is fast, reliable, and always connected. Deep space is none of those things.”

Delay-Tolerant Networking — The Postal Service of Space



BPv7

Store & forward with custody (RFC 9171)

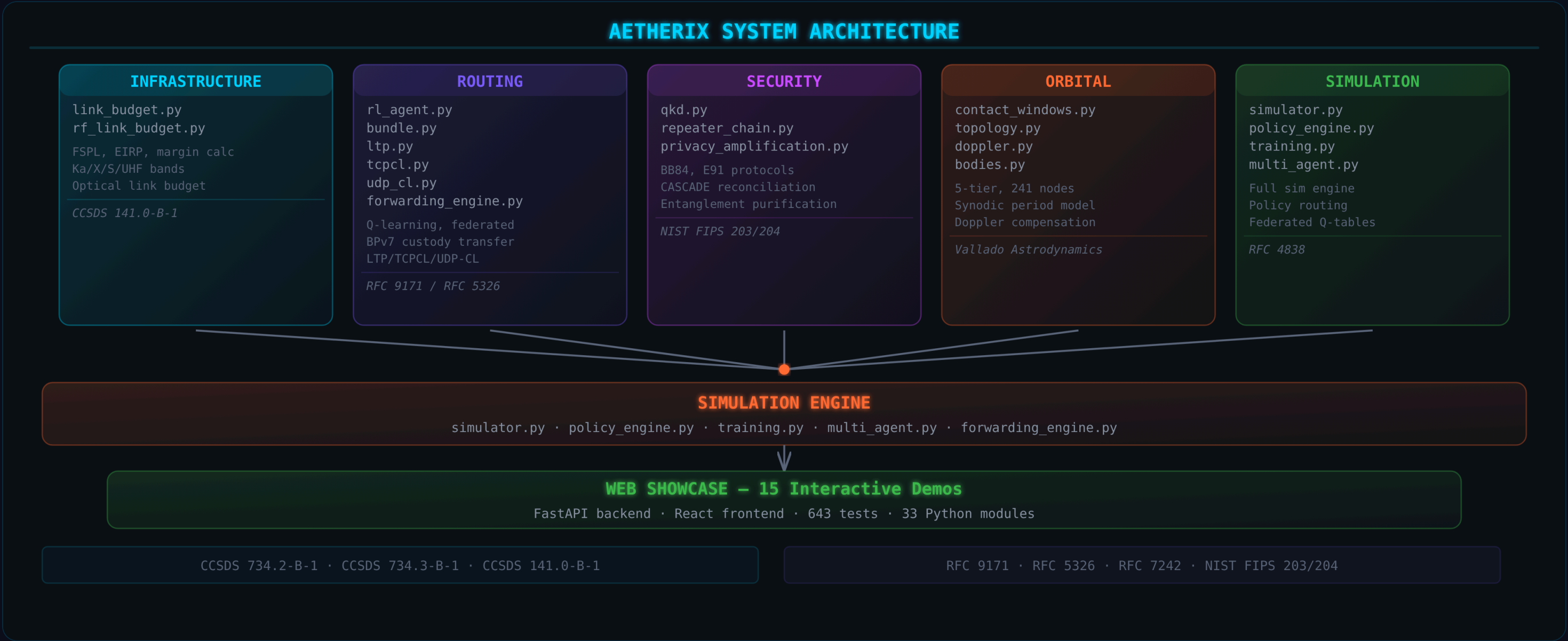
RL

Multi-agent federated Q-learning

QKD

BB84 & E91 + repeater chains

Each node takes **custody** of the bundle and forwards it one hop closer when a contact window opens — no continuous end-to-end connection is ever required.



Source modules → simulation engine → web showcase. Every module is independently tested.

Protocol Stack

- **Application** — science data, commands, telemetry
- **Bundle Protocol v7** — custody, fragmentation, TTL, priority
- **Convergence** — LTP (deep space), TCPCL (Earth), UDP-CL (optical ISL)
- **Physical** — optical 1550 nm / Ka-band RF

Custody transfer = each node takes legal responsibility, then the previous custodian frees its buffer.

Priority Classes (P0–P4)

P0 EMERGENCY	Life-critical alerts, abort
P1 URGENT	Nav corrections, hazards
P2 NORMAL	Telemetry, science, commands
P3 LOW	Software updates, bulk files
P4 BULK	Background sync, archival

Protocol Stack — BPv7 over Three Convergence Layers

AETHERIX PROTOCOL STACK



Application → BPv7 (custodv) → LTP / TCPCL / UDP-CL → optical 1550 nm / Ka-band RF.

Tier Breakdown (matches topology.py)

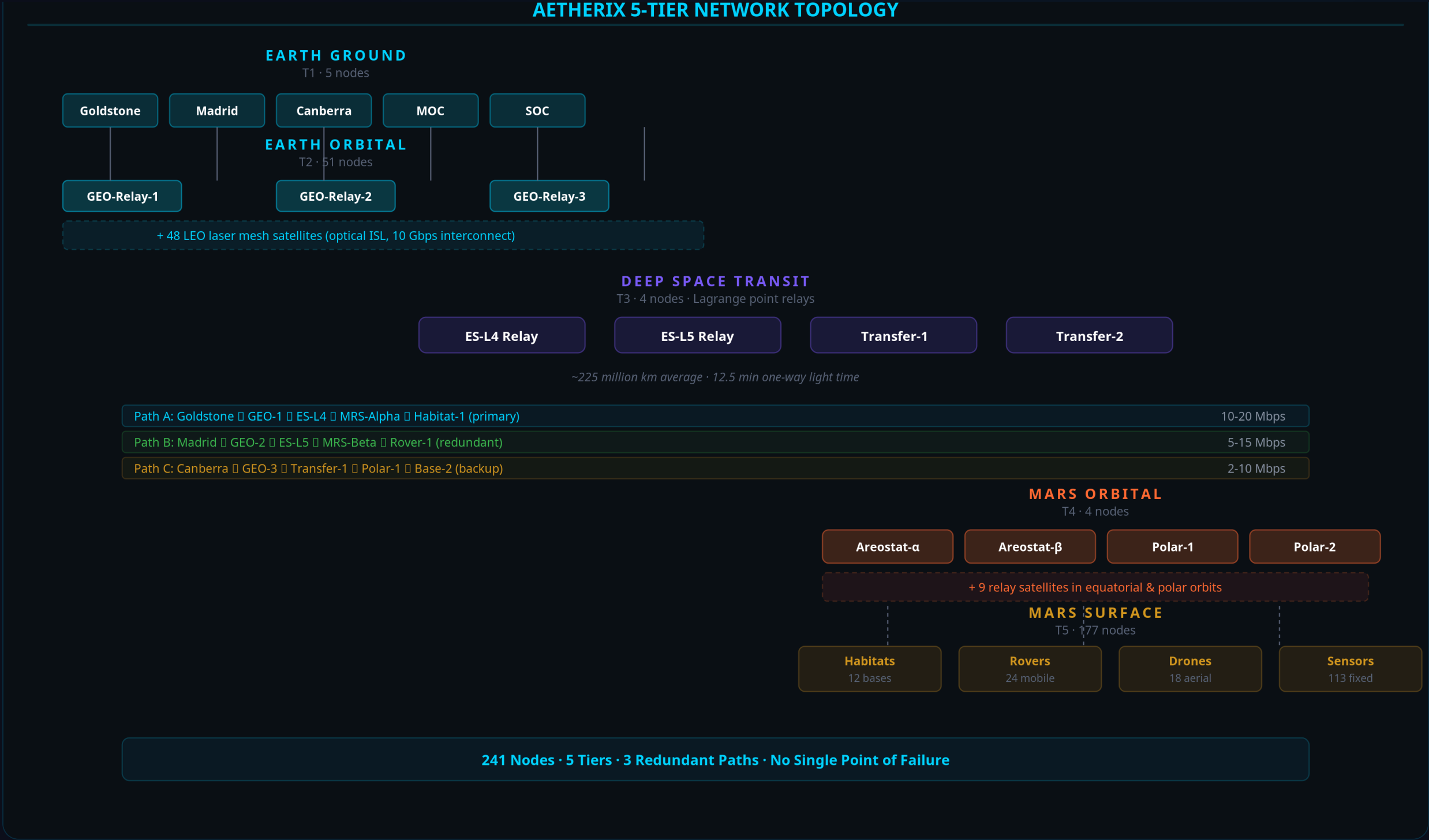
Tier	Nodes	Assets
T1 Earth Ground	5	3 DSN (Goldstone, Madrid, Canberra) + MOC + SOC
T2 Earth Orbital	51	3 GEO + 48 LEO laser mesh
T3 Deep Space	4	ES-L4, ES-L5 + 2 transfer-orbit relays
T4 Mars Orbital	4	2 areostationary + 1 polar + 1 orbiter
T5 Mars Surface	177	2 bases, 5 rovers, 10 drones, 160 sensors
Total	241	

Link Characteristics

Link	Rate	Type
Earth ↔ Deep Space	100 Mbps	1550 nm optical
Deep Space ↔ Mars	2–200 Mbps	distance-dependent
Mars Orbit ↔ Surface	2 Mbps	UHF / X-band
LEO inter-satellite	10 Gbps	optical ISL

3 redundant paths · no single point of failure · Lagrange relays for conjunction coverage.

5-Tier Network Diagram



Optical Communications — 1550 nm

100–200

Mbps at closest approach

10–20

Mbps at average distance

2–5

Mbps at farthest point

Rates above are **capability targets** for a coded DSOC-class link [4], not measured throughput.

Key Equations

- $FSPL = 20 \cdot \log_{10}(4\pi d/\lambda)$
- $Gain = 10 \cdot \log_{10}(\eta \cdot (\pi D/\lambda)^2)$
- $P_r = P^t + G^t + G_r - FSPL$

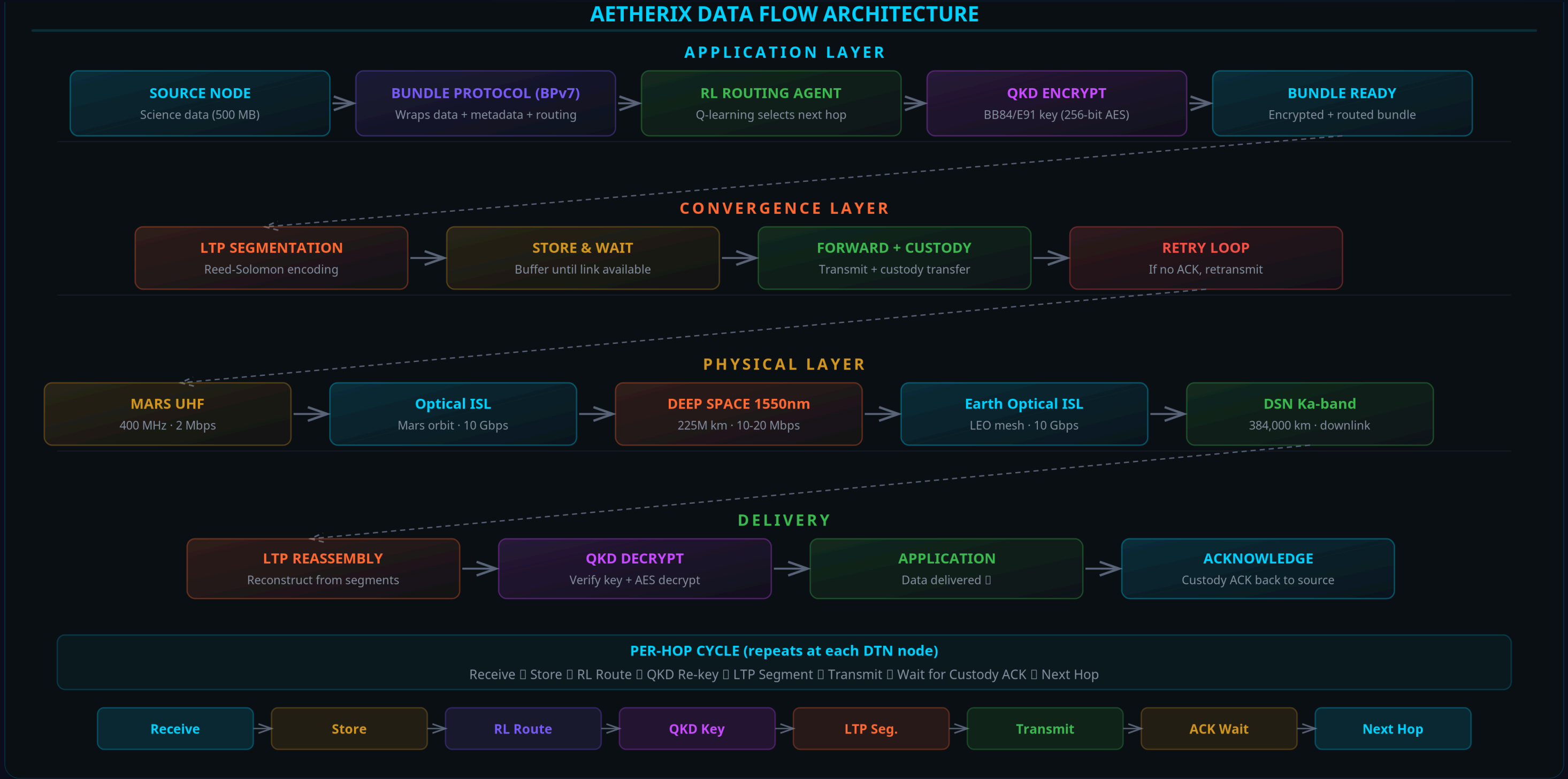
Rate degrades with distance squared — 10–100× capability over the RF baseline (**target**).

Computed margins [A4] are a **conservative uncoded photon-counting budget**: +4.31 / +3.33 / +3.08 dB at 55M / 225M / 401M km. It excludes SCPPM coding gain and high-order PPM photon efficiency (≈13 dB), so it is a floor, not a rate prediction.

Configuration

Wavelength	1550 nm (telecom heritage)
Tx power	5 W
Tx aperture	22 cm
Rx aperture	5.0 m (Hale-class ground)

End-to-End Bundle Journey — Mars to Earth



Contact Graph Routing (baseline)

- Pre-computed contact plans required
- Cannot adapt to unexpected link failures
- Re-plans on a stale schedule
- No learning from historical performance

AETHERIX RL Agent

- **State:** node, neighbours, link quality, buffer
- **Actions:** forward | store | drop | split
- **Reward:** $R = \alpha(\text{delivery}) - \beta(\text{delay}) - \gamma(\text{hops}) - \delta(\text{drops}) - \epsilon(\text{energy})$
- ϵ -greedy, decay 0.995; $\alpha=1.0$, $\delta=10.0$ (drops forbidden)
- Q-table + federated aggregation — every value auditable

713/800

forward decisions [A3]

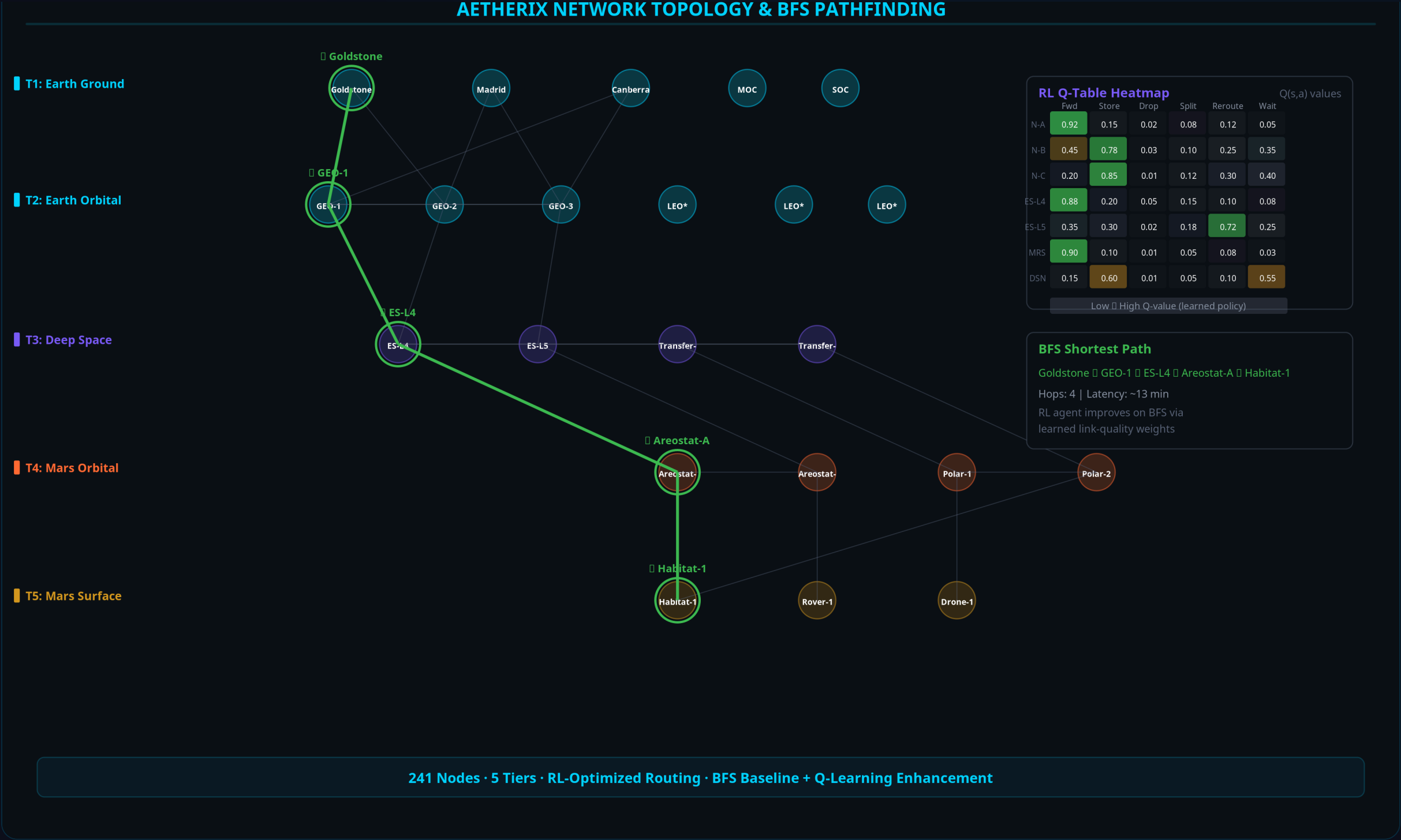
seconds

recovery vs hours

Q-table

human-auditable policy

Network Topology Graph — BFS + RL Routing



BB84 Protocol

- 1. Alice sends random polarised photons (H/V, D/A) [13]
- 2. Bob measures in random bases
- 3. Public reconciliation — keep matching bases
- 4. Estimate QBER from a sampled subset
- 5. Privacy amplification (universal hashing)
- 6. **QBER < 11% → SECURE** key established [15]

Post-Quantum & Deployment

- ML-KEM (FIPS 203) — key encapsulation [16]
- ML-DSA (FIPS 204) — digital signatures [17]
- Hybrid classical + quantum key exchange

Phase	Protocol	Key rate
1 — LEO	BB84	1–10 kbps
2 — GEO	BB84 + E91	10–100 kbps
3 — Mars	E91 + repeaters	1+ kbps

Contact Windows & Doppler Compensation

Mars Parameters

Semi-major axis	1.524 AU
Synodic period	779.94 days
Distance range	54.6M – 401M km
Areostationary alt.	17,032 km
Doppler (Ka, max)	±2.1 MHz @ 24 km/s

Contact Windows

Window	Avail.	Duration	Rate
Optimal	99%	8–12 hrs	100–200 Mbps
Good	95%	6–8 hrs	20–100 Mbps
Fair	85%	4–6 hrs	5–20 Mbps
Blackout	0%	2–4 wks	—

Radiation-Hardened Computing

Effects & Mitigation

Effect	Mitigation
SEU (bit flip)	SECDED ECC
MBU (adjacent bits)	Bit interleaving
SEL (latch-up)	Current limit + power-cycle
TID (cumulative dose)	Rad-hard parts (RAD750) [18]

Defense-in-Depth

1. TMR — 3 replicas + majority voter
2. SECDED (39,32) ECC — correct 1, detect 2
3. Memory scrubbing before 2nd upset
4. FDIR + watchdog → isolate → reload
5. SAFE-MODE after recovery budget exhausted

37,159

raw upsets

200×

protection factor

3,334×

TMR gain

2,127×

RAD750 TID margin

Priority Tiers

Tier	Class	Examples
P0	Emergency	Health, collision, faults
P1	Mission-critical	Command ACKs, time-sensitive sci
P2	High	Routine telemetry, scheduled sci
P4	Bulk	Housekeeping, files, SW images

Three Levers

- **Compression:** Rice $\approx 3\times$ [7], wavelet $\approx 10\times$ [8]
- **Deadline-aware preemptive QoS** [A7] — strict priority, earliest deadline
- **BPv7 fragmentation** [9] — send what fits, defer rest, link never idle

5/6

items delivered

100%

link utilisation (target)

41%

SW update fragmented

P0

emergency preempts

IMPACT

Performance vs Current Systems

Metric	Current (MRO) [1]	AETHERIX [A4]	Note
Downlink rate	0.5–6 Mbps	2–200 Mbps	10–100× capability
Availability	60–75%	>95%	design target
Routing	Static (CGR)	RL-adaptive	autonomous [A1]
Security	AES-256	QKD + PQC	future-proof [16][17]
Scalability	5–10 assets	241 nodes	10–100× [A2]
Conjunction	Blackout	L4/L5 relay (target)	+50–70% (target) [A8]

Demonstrated results and design **targets** are labelled separately — the 10–100× figure is a physics-derived capability from the link budget, not a measured throughput.

33

Python modules

643

tests (37 files)

15

interactive demos

5

routing policies

Core Modules

- Link Budget · RL Agent · QKD
- Bundle Protocol · Topology · Simulation
- Radiation · Prioritization · Doppler

All physics is real — no mocked data.

Standards Compliance

RFC 9171	Bundle Protocol v7
RFC 4838 / 5326 / 7242	DTN / LTP / TCPCL
RFC 9172	BPsec (security)
CCSDS 734.2 / 734.3	Bundle Protocol / SABR
CCSDS 141.0-B-1	Optical comms physical

Trade-off Analysis — Why These Choices

Decision	Choice	Rationale vs alternative
Optical vs RF	Hybrid 1550 nm + Ka fallback [4]	10–100× throughput [A4]; RF survives clouds & corona
Routing	Custom Q-learning, not ION-DTN CGR [A1]	Adapts to live state; CGR re-plans on stale schedule
RL model	Q-tables now, DQN later	Every value auditable; trains in seconds
Reward weights	$\alpha=1.0$, $\delta=10.0$, ϵ -decay 0.995 [A1]	Drop penalty 10× delivery — forbids bundle loss

Each choice sacrifices peak theoretical performance for **auditability and reproducibility** — exactly what a defence and a research artefact require. DSOC heritage: NASA flew optical + RF side-by-side on Psyche [4].

Autonomous solar-conjunction link-blackout survival

Path	Band	Quality	Status	Reward [A8]
Direct Mars → Earth	1550 nm optical	0.05	CLOSED	−1.438
Mars → ES-L4 → Earth	Ka-band RF	0.65	OPEN	−0.201
Mars → ES-L5 → Earth	Ka-band RF	0.60	OPEN	−0.201

How AETHERIX Recovers (automatically)

1. Detect — optical Q-value collapses ($q < 0.3$)
2. Re-route — agent picks highest-Q: ES-L4 (Ka-band)
3. Prioritise — P0 forwarded on best link; P4 stored & deferred

Why Lagrange Relays

- ES-L4 / ES-L5 sit 60° ahead/behind Earth
- Keep line-of-sight to Mars around the solar limb
- Direct: 0% at conjunction → via L4/L5: 50–70% retained [A8]

Throughput drops (optical → RF) but no mission-critical data is lost. Run live: `python run_simulation.py --module 4`

Problem Solved

TCP/IP can't work at interplanetary distances.

What We Built

BPv7 · RL Routing · QKD · Optical/RF Hybrid.

10–100×

target speedup ♦

>95%

availability (target)

RL

adaptive routing [A1]

QKD

quantum security [13][15]

Demonstrated: 241-node topology, RL routing, QKD, 200× radiation reduction. ♦ Targets are labelled as targets, never measured results.

Three-layer attribution: [N] industry · [AN] this project · every entry links to its source

[1] NASA JPL, Mars Relay Network User's Guide, 2024.

[2] CCSDS, Bundle Protocol Spec., 734.2-B-1, 2015.

[3] JPL Horizons, Earth–Mars Ephemeris, 2025.

[4] NASA, Deep Space Optical Comm. (DSOC), Psyche, 2024.

[5] CCSDS, Optical Comm. Physical Layer, 141.0-B-1, 2019.

[6] CCSDS, TM Synchronization & Channel Coding, 131.0-B-5, 2023.

[7] CCSDS, Lossless Data Compression, 121.0-B-3, 2020.

[8] CCSDS, Image Data Compression, 122.0-B-2, 2017.

[9] IETF, Bundle Protocol Version 7, RFC 9171, 2022.

[10] IETF, Licklider Transmission Protocol, RFC 5326, 2008.

[11] IETF, DTN TCP Convergence Layer, RFC 7242, 2014.

[12] IETF, DTN Architecture, RFC 4838, 2007.

[13] Bennett & Brassard, Quantum Cryptography, 1984.

[14] Ekert, Bell's-Theorem Cryptography, PRL 67, 1991.

[15] Shor & Preskill, Security of BB84, PRL 85, 2000.

[16] NIST, Module-Lattice KEM, FIPS 203, 2024.

[17] NIST, Module-Lattice Signature, FIPS 204, 2024.

[18] BAE Systems, RAD750 Rad-Hard PowerPC, 2024.

[19] ESA/Gaisler, LEON3FT Processor, 2023.

[20] IETF, RFC 4838 §3.1, 2007 (DTN challenges).

M. A. Tariq, AETHERIX, github.com/matx104/AETHERIX (2025) · each links to the source file

Design & Code

- [\[A1\]](#) RL Routing Agent — `src/routing/rl_agent.py`
- [\[A2\]](#) Network Topology — `src/orbital/topology.py`
- [\[A3\]](#) End-to-End Simulation — `run_simulation.py` Module 3
- [\[A4\]](#) Optical Link Budget — `src/infrastructure/link_budget.py`

Security, Resilience & QoS

- [\[A5\]](#) QKD Protocols — `src/security/qkd.py`
- [\[A6\]](#) Radiation Hardening — `src/computing/radiation.py`
- [\[A7\]](#) Data Prioritization — `src/routing/prioritization.py`
- [\[A8\]](#) Failure & Recovery — `run_simulation.py` Module 4

Three-layer attribution: Layer A industry baseline [1]–[20] · Layer B design decision [A1]–[A8] · Layer C demonstrated result (e.g. radiation 200× [A6]). Design targets are labelled as such, never as measured results.

THANK YOU

Questions?

10–100×

target speedup ♦

>95%

availability (target)

RL

adaptive routing

QKD

quantum security

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matx104.github.io/AETHERIX · github.com/matx104/AETHERIX