

AETHERIX — Examiner Handout

Interplanetary Communication Network for Mars Mission Support

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Live Demo: matx104.github.io/AETHERIX | **Repository:** github.com/matx104/AETHERIX

The Challenge

Problem	Impact
Earth-Mars distance: 54.6M — 401M km	3 — 22 min one-way light-time
Current RF data rates: 0.5 — 6 Mbps	Severely limited science data return
Solar conjunction (every 780 days)	2-week complete communication blackout
TCP/IP requires low-latency RTT	Fails at 6 — 44 min round-trip times

The Solution: AETHERIX Architecture

Five-Tier Network (241 nodes)

- Earth Ground** (5 nodes) — 3 DSN (Goldstone, Madrid, Canberra) + MOC + SOC
- Earth Orbital** (51 nodes) — 3 GEO relays + 48 LEO laser satellites
- Deep Space Transit** (8 nodes) — Lagrange point relays (ES-L4, ES-L5) + transfer orbit sats + quantum repeaters
- Mars Orbital** (4 nodes) — 2 areostationary + 1 polar + 1 orbiter
- Mars Surface** (170 nodes) — Bases, rovers, drones, sensor networks

Core Technologies

Technology	Function	Standard
Bundle Protocol v7	Store-and-forward delay-tolerant networking	RFC 9171, CCSDS 734.2-B-1
RL Routing	Q-learning agents replace static Contact Graph Routing	Custom (demo implementation)
Optical Links (1550 nm)	2 — 200 Mbps data rates (10-100× over RF)	CCSDS 141.0-B-1
QKD Security	BB84/E91 quantum key distribution + post-quantum crypto	ETSI QKD, NIST FIPS 203/204

Key Innovations

- RL-based autonomous routing** — Agents learn optimal forwarding from experience, adapt to link failures in seconds (vs hours for manual replanning)
- Lagrange relay constellation** — Maintains 50-70% availability during solar conjunction blackouts
- Hybrid optical/RF** — Optical primary for throughput (200 Mbps peak), RF backup for reliability (>99% combined availability)
- Quantum-secured links** — QKD for key exchange (information-theoretic security) + CRYSTALS-Kyber/Dilithium for post-quantum signatures

Performance Comparison

Metric	Current (MRO)	AETHERIX	Improvement
Downlink rate	0.5 — 6 Mbps	2 — 200 Mbps	10-100×
Daily data volume	5 — 10 GB	50 — 100 GB	10-20×
Availability	60 — 75%	> 95% (target)	+20-35%
Routing	Static (CGR)	RL-adaptive	Autonomous
Security	AES-256 (classical)	QKD + PQC	Future-proof

Key Equations

- Free-Space Path Loss:** $FSPL = 20 \times \log_{10}(4\pi d/\lambda)$ dB
- Link Budget:** $Pr = Pt + Gt + Gr - FSPL - Latm - Lpoint$
- RL Reward:** $R = \alpha(\text{delivery}) - \beta(\text{delay}) - \gamma(\text{hops}) - \delta(\text{drops}) - \epsilon(\text{energy})$
- QBER Threshold:** $QBER < 11\% \rightarrow \text{secure}; QBER \geq 11\% \rightarrow \text{abort}$

Standards Compliance

Standard	Description
CCSDS 734.0-G-1	DTN Architecture (Green Book — rationale)
CCSDS 734.2-B-1	Bundle Protocol Specification
RFC 9172	Bundle Protocol Security (BPSec)
CCSDS 141.0-B-1	Optical Communications Physical Layer
CCSDS 142.0-B-2	Space Link Identification (LNIS v5)
RFC 9171	Bundle Protocol Version 7
RFC 5326	Licklider Transmission Protocol

Implementation Status

Component	Location	Status
Optical Link Budget Calculator	<code>src/infrastructure/</code>	Complete
Hybrid Optical/RF Link Model	<code>src/infrastructure/</code>	Complete
Simulation Framework	<code>src/simulation/</code>	Complete
RL Routing Agent (Q-learning)	<code>src/routing/</code>	Complete
BPv7 Forwarding Engine (BFS fallback)	<code>src/routing/</code>	Complete
LTP Convergence Layer	<code>src/routing/</code>	Complete
Policy Engine	<code>src/routing/</code>	Complete
BB84/E91 QKD Simulation	<code>src/security/</code>	Complete
Quantum Repeater Chains	<code>src/security/</code>	Complete
Privacy Amplification (Toeplitz)	<code>src/security/</code>	Complete
CASCADE Error Correction	<code>src/security/</code>	Complete
Orbital Mechanics / Contact Windows	<code>src/orbital/</code>	Complete
Topology Generator (241 nodes)	<code>src/orbital/</code>	Complete
Training Pipeline	<code>src/simulation/</code>	Complete
Multi-Agent Federation	<code>src/simulation/</code>	Complete
Scenario Runner	<code>src/simulation/</code>	Complete
Interactive Web Platform	<code>docs/</code>	Live
Test Suite (643 tests)	<code>tests/</code>	Complete

Demonstrated Simulation Results

All numbers below are generated by python run_simulation.py (seed-fixed, reproducible):

Module	Metric	Result
3 — RL Training	Forward decisions	713 / 800 (89%)
4 — Failure & Recovery	Reward (optical CLOSED → ES-L4 OPEN)	−1.438 → −0.201 (7× improvement)
6 — Radiation	Raw SEUs / residual	37,159 → 186 (200× reduction)
6 — Radiation	TMR reliability gain (p=1e-4)	3,334×
6 — Radiation	TID margin (RAD750 200 krad)	2,127×

Note: Delivery ratios of 1.3–6.4% in the demo simulator reflect the proof-of-concept scope (small contact windows, conservative link budgets). The >95% availability and 10–100× data-rate figures are **design targets** derived from link-budget capability (2–200 Mbps) and Lagrange-relay conjunction coverage, not measured end-to-end results.

Key References

Industry & Scientific [1]–[20] — every entry links to its source:

Ref	Source
[1]	NASA Mars Relay Network / MRO Ka-band (0.5–6 Mbps baseline)
[2]	CCSDS 734.2-B-1 — CCSDS Bundle Protocol Specification (Sept 2015)
[3]	JPL Horizons ephemeris system (Earth–Mars geometry)
[4]	NASA DSOC / Psyche (2023 deep-space optical demonstration)
[5]	CCSDS 141.0-B-1 — Optical Communications Physical Layer (Aug 2019)
[6]	CCSDS 131.0-B-5 — TM Synchronization and Channel Coding
[7]	CCSDS 121.0-B-3 — Lossless Data Compression
[8]	CCSDS 122.0-B-2 — Image Data Compression
[9]	IETF RFC 9171 — Bundle Protocol Version 7
[10]	IETF RFC 5326 — Licklider Transmission Protocol (LTP)
[11]	IETF RFC 7242 — TCP Convergence Layer
[12]	IETF RFC 4838 — Delay-Tolerant Networking Architecture
[13]	Bennett & Brassard, 1984 — BB84 Quantum Key Distribution
[14]	Ekert, 1991 — E91 Entanglement-based QKD
[15]	Shor & Preskill, 2000 — QBER < 11% security threshold proof
[16]	NIST FIPS 203 — ML-KEM (post-quantum key encapsulation)
[17]	NIST FIPS 204 — ML-DSA (post-quantum signatures)
[18]	BAE Systems RAD750 — radiation-hardened processor
[19]	ESA / Cobham LEON3FT — fault-tolerant processor
[20]	IETF RFC 4838 §3.1 — DTN design challenges

Project Source [A1]–[A8] — every entry links to the file on GitHub:

Ref	Module	Verifiable by
[A1]	src/routing/rl_agent.py	Q-learning agent, reward function
[A2]	src/orbital/topology.py	5-tier, 241-node topology, BFS routing
[A3]	run_simulation.py	7-module integration suite
[A4]	src/infrastructure/link_budget.py	Optical link budget (1550 nm, 2–200 Mbps)
[A5]	src/security/qkd.py	BB84, E91, quantum repeater, QBER
[A6]	src/computing/radiation.py	SEU/TID model, TMR, ECC, scrubbing
[A7]	src/routing/prioritization.py	Deadline-aware QoS scheduler
[A8]	run_simulation.py Module 4	Failure/recovery reward demonstration

Full 70+ reference list in references/REFERENCES.md.