Paper 038 / Application 015

PulsarMesh

Unified XNAV, DTN, and Optical Communications for Off-World Navigation and Networking

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Abstract

A galactic civilization needs more than rockets. It needs a shared layer for position, time, trust, and memory. *PulsarMesh* is a proposed off-world navigation-and-network stack that unifies X-ray pulsar navigation (XNAV), delay/disruption-tolerant networking (DTN), optical communications, RF survival links, local beacons, quantum gravimetry, signed ephemerides, and civilizational timekeeping. The grounded claim is that off-world systems should not treat navigation and communications as separate afterthoughts. The speculative claim is that a mature PulsarMesh becomes a chronogeodesic commons: a civilization-scale coordinate ritual anchored by neutron-star clocks, beam lighthouses, and signed memories moving through intermittent light cones. This paper defines a position-time-trust state, a contact-and-observation graph, a bundle-native navigation object, and an evidence program from cislunar testbeds to interplanetary relay swarms. It accepts the hard limits of relativity and intermittent connectivity while proposing an auditable layer that can grow from Moon networks to asteroid industry and eventually interstellar precursor missions.

Contents

1 01 / Problem

Earth-centered command, tracking, and data return do not scale to a galactic civilization. The farther civilization moves from Earth, the more destructive centralized assumptions become: continuous connectivity disappears, light-time dominates, pointing becomes mission-critical, local autonomy becomes mandatory, and position knowledge must survive without terrestrial handholding.

Navigation and networking are usually described separately. A vehicle estimates state; a network moves packets. Off-world, this division is artificial. A contact opportunity is a navigation observation. A navigation fix is a network routing primitive. A clock is an authority object. A relay is both infrastructure and measurement station. An optical downlink is a data path and a precise pointing experiment.

The technical ingredients already exist in early form. BPv7 defines a Bundle Protocol for delay-tolerant environments with intermittent connectivity, large delays, and store-carry-forward operation [8]. NASA/JPL's Deep Space Optical Communications demonstration showed high-rate optical communications from deep space, including a laser signal over roughly Mars-farthest-distance scales and data rates described as up to 100 times higher than radio frequency links [7]. XNAV work around NICER/SEXTANT and later pulse-phase algorithms demonstrates the plausibility of autonomous state estimation from X-ray pulsars [9, 10]. PulsarMesh asks what happens if these are designed as one layer.

Claim 1 (Unified layer claim)**.** Off-world civilization should merge navigation, communications, timing, and provenance into a single position-time-trust layer rather than integrate them as separate mission subsystems.

2 02 / Model

Let each node i have a state

$$z_i(t) = [x_i(t), v_i(t), \tau_i(t), \dot{\tau}_i(t), q_i(t), k_i(t), m_i(t)]^\top, \tag{2.1}$$

where x, v are position and velocity, $\tau, \dot{\tau}$ are clock offset and drift, q is attitude, k is cryptographic/trust state, and m is memory or custody state.

Measurements arrive through heterogeneous channels:

$$Y_t = \{Y_t^{\mathrm{XNAV}}, Y_t^{\mathrm{opt}}, Y_t^{\mathrm{RF}}, Y_t^{\mathrm{grav}}, Y_t^{\mathrm{local}}, Y_t^{\mathrm{crosslink}}\}. \tag{2.2}$$

The estimator is a factor graph over position, time, contact, and trust:

$$p(Z_{0:t}, K_{0:t} \mid Y_{0:t}) \propto \prod_{\phi \in \Phi} \phi(Z_{\partial\phi}, K_{\partial\phi}; Y_{\partial\phi}), \tag{2.3}$$

where K denotes keys, signatures, custody states, and trust assertions.

Definition 1 (Contact-and-observation graph)**.** The PulsarMesh graph is

$$\mathcal{G}_P(t) = (V, E_C(t), E_O(t), E_T(t)), \tag{2.4}$$

where E_C are communication contacts, E_O are navigation observations, and E_T are trust/provenance edges. Each contact edge has capacity, latency, pointing constraints, energy cost, custody semantics, and disruption probability:

$$C_{ij}(t) = \{b_{ij}(t), \ell_{ij}(t), p_{\mathrm{up}}(t), \theta_{ij}(t), E_{ij}(t), \kappa_{ij}(t)\}. \tag{2.5}$$

Definition 2 (Position-time-trust object)**.** A position-time-trust object is a signed bundle payload

$$\mathsf{PTT} = \langle \hat{x}, \hat{v}, \hat{\tau}, \Sigma, \mathcal{O}, \mathcal{E}, \mathcal{K}, \mathcal{R} \rangle, \tag{2.6}$$

where Σ is covariance, $\mathcal{O}$ observations, $\mathcal{E}$ ephemeris context, $\mathcal{K}$ signatures and key state, and $\mathcal{R}$ routing/custody hints.

3 03 / Architecture

3.1 Layer 0: survival links

RF remains the survival layer: low-rate, forgiving, robust, and politically legible. PulsarMesh does not replace RF; it places RF inside a mesh that can prefer optical or crosslink routes when conditions allow.

3.2 Layer 1: optical high-rate fabric

Optical terminals provide high-rate links between orbiters, depots, lunar sites, Mars assets, deep-space relays, and Earth stations. Optical contacts are scheduled, opportunistic, weather-aware, pointing-aware, and energy-aware. The key software object is not a link, but a *contact contract*: a signed prediction of when two nodes can exchange which bundles at what cost and risk.

3.3 Layer 2: Bundle-native memory

BPv7-like bundles are the natural unit for stressed environments because they can carry data through networks where sender and receiver are not simultaneously connected [8]. PulsarMesh adds navigation payloads, custody proofs, time-quality annotations, and route-intent metadata.

3.4 Layer 3: XNAV and beacon fusion

XNAV provides a natural deep-space reference: pulsars are external clocks with sky positions and timing models. Local beacons, optical crosslinks, inter-satellite ranging, star trackers, and RF tracking fill in the gaps. The update equation is:

$$\hat{z}_t^{+} = \hat{z}_t^{-} + K_t \left(y_t - H_t \hat{z}_t^{-} \right), \qquad K_t = P_t^{-} H_t^{\top} (H_t P_t^{-} H_t^{\top} + R_t)^{-1}, \tag{3.1}$$

but the civilized version records every assumption behind H_t and R_t.

3.5 Layer 4: quantum gravimetry and local gravity maps

Cold atom gradiometers can reduce inertial navigation drift by referencing gravity-gradient measurements against maps [17]. On the Moon, Mars, asteroids, and large habitats, gravity maps become local navigation infrastructure. PulsarMesh treats gravimetry as another clock-like field: a way to bind local motion to a durable environmental signature.

3.6 Layer 5: trust, provenance, and civil time

In a delay-tolerant civilization, trust cannot depend on continuous central verification. PulsarMesh therefore binds every position, time, route, and data product to signatures and provenance trails. Civil time is a ledger of clock relationships, not a single privileged clock.

4 04 / The non-negotiable practical spine

Spine	Role in the research program
Fission/fusion baseload	Provides mission-scale energy for dark sites, industrial heat, closed-loop habitats, high-duty robotics, and high-field experiments.
Cryogenic and HTS power routing	Moves high current through modular infrastructure while keeping quench protection, thermal accounting, and magnetic cleanliness visible.
Quantum gravimetry and sensors	Turns gravity gradients, inertial drift, and subtle environmental fields into calibrated infrastructure data rather than anecdote.
Directed-energy logistics	Uses beams, sails, optical links, and high-energy supply gradients to reduce dependence on chemical cargo chains.
Evidence pipeline	Converts every build, test, null, anomaly, and revision into signed artifacts that can be audited and reproduced.

For PulsarMesh, the spine is communicative:

- **Directed-energy sail arrays** double as beam lighthouses, precision timing sources, launchers, and emergency data beacons. Their aperture discipline and phase control can bootstrap optical infrastructure.
- **HTS magnetic infrastructure** supports high-current beam stations, superconducting energy storage, precision attitude systems, low-vibration cryogenic platforms, and radiation shielding around network hubs.
- **Cryogenic power buses** route energy through optical ground/space terminals, X-ray detectors, superconducting sensors, and high-duty relay nodes.
- **Quantum gravimetry** anchors local navigation where sky visibility, RF links, or optical contacts are degraded.
- **Fission/fusion power** supplies dark-side lunar relays, Mars storm-resilient terminals, outer-system nodes, and high-rate computational routing.

5 05 / Claims

Claim 2 (Navigation is a network service)**.** Every node that can estimate its position can improve the network, and every network contact can improve position estimates. PulsarMesh should expose navigation as a signed network service.

Claim 3 (Bundles should carry time quality)**.** A data object moving through a stressed off-world network should carry not merely payload and route metadata, but the quality, provenance, and reference frame of its time and position assertions.

Claim 4 (Optical links require ritual-grade pointing)**.** High-rate optical communications become civilization-grade only when pointing, weather, ephemeris, timing, and custody are handled as one auditable contact ceremony.

Claim 5 (Pulsars are not GPS)**.** Pulsars are not a drop-in replacement for terrestrial GNSS. They are sparse, weak, timing-model-dependent celestial clocks. Their value increases when fused with local beacons, crosslinks, gravity maps, and signed ephemerides.

6 06 / Evidence program

6.1 Phase A: cislunar software testbed

Build a simulator that combines BPv7-like bundle routing, optical contact schedules, RF fallback, clock drift, and navigation-state covariance. The core test is whether routing decisions improve when navigation covariance is visible to the network.

6.2 Phase B: optical contact contract pilot

Use terrestrial and/or orbital optical test data to build signed contact contracts. Each contract declares pointing constraints, power budget, expected rate, weather or occlusion assumptions, and custody semantics.

6.3 Phase C: XNAV replay

Replay public X-ray pulsar data through onboard-constrained estimators. Publish covariance, compute budget, failure modes, and timing-model sensitivity. Negative results are useful if they reveal when XNAV should not be trusted.

6.4 Phase D: lunar relay mesh

Deploy a small Moon-oriented mesh: surface node, orbiter node, Earth gateway, and simulated Mars/asteroid delay. Measure delivery probability, custody latency, time-quality propagation, and position-time-trust consistency.

6.5 Phase E: interplanetary mesh

Add Mars, asteroid, and solar-orbit relays. The exit criterion is not continuous Internet-like connectivity. It is predictable, signed, custody-aware memory flow through intermittent light cones.

7 07 / Chronogeodesic commons

Speculative extension. The mystical layer of PulsarMesh is that civilization learns to pray in coordinates. Every bundle says: here is where I was, here is when I was, here is who touched me, here is the uncertainty of my memory. The galaxy becomes navigable when memory becomes geometric.

Define a chronogeodesic bundle path as a sequence

$$\Gamma = \{(i_k, t_k, z_{i_k}(t_k), K_{i_k}(t_k))\}_{k=0}^{n} \tag{7.1}$$

that respects causal order, contact availability, custody transfer, and trust transitions. Its cost is

$$\mathcal{J}(\Gamma) = \sum_{k=0}^{n-1} \left[\lambda_l \ell_k + \lambda_e E_k + \lambda_u \mathrm{tr}(\Sigma_k) + \lambda_r R_k - \lambda_v V_k\right]. \tag{7.2}$$

A civilization chooses paths not only by latency, but by how much truth survives the journey.

Let $\mathcal{T}_{\text{civil}}$ be a sheaf of local clocks over the network. The global civil time section exists when clock relationships can be glued within tolerance:

$$\Gamma(\mathcal{G}_P, \mathcal{T}_{\text{civil}}) \neq \emptyset. \tag{7.3}$$

When it fails, the network has not merely lost synchronization; it has fractured reality into local truths. PulsarMesh's deeper mission is to keep those truths composable without pretending simultaneity is universal.

Hypothesis 1 (Galactic address hypothesis)**.** A mature off-world network address should include a causal reference frame, a position-time covariance, and a trust context, not merely a node identifier.

8 08 / Implementation objects

Object	Meaning
`PTTBundle`	Signed position-time-trust payload with covariance, frame, observations, and key state.
`ContactContract`	Predicted or measured communication opportunity with rate, latency, energy, pointing, weather, and custody semantics.
`PulsarAlmanac`	Versioned pulsar timing model, sky position, uncertainty, detector constraints, and validity interval.
`GravityTile`	Local gravity or gradient map with uncertainty, source, resolution, and navigation fitness.
`CustodyProof`	Evidence that a bundle was accepted, stored, transformed, forwarded, or intentionally discarded.
`CivilTimePatch`	Signed update to relationships among local clocks, ephemerides, and reference frames.

9 09 / Technology roadmap

Horizon	Milestone	Exit criterion
0–12 months	PulsarMesh simulator	Unified routing/navigation/covariance simulation with BPv7-style bundles.
12–24 months	Contact contract service	Signed contact predictions for optical/RF links with replayable outcomes.
24–48 months	XNAV replay lab	Public-data XNAV estimator with compute, covariance, and failure reports.

48–72 months	Cislunar mesh pilot	Bundle delivery with time-quality and position-quality propagation across intermittent contacts.
72–120 months	Lunar gravity tiles	Quantum-gravimetry-ready data model and local position-fixing experiment.
120+ months	Interplanetary PTT layer	Mars/asteroid relay architecture where route choice uses navigation covariance and trust state.

10 10 / Failure modes

- **GPS nostalgia.** Treating XNAV as a magical replacement for GNSS.
- **Optical fragility.** Ignoring weather, pointing, thermal drift, dust, and acquisition constraints.
- **Security centralization.** Assuming continuous access to Earth-based authorities.
- **Clock arrogance.** Publishing data without time-quality and frame-quality metadata.
- **Covariance denial.** Routing as though position uncertainty is not mission-critical.
- **Protocol fragmentation.** Each mission invents its own dialect and the future cannot compose it.

11 11 / Release

The release bundle should include the LaTeX and PDF, a PulsarMesh object schema, a small DTN/contact simulator, sample PTT bundles, and replay scripts. PulsarMesh should integrate with Orbis Edge for latency-tolerant commands and artifact sync [4].

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