NEXUS Protocol

Complete Specification

Version 1.0 — Design Complete, Pre-Implementation

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NEXUS Protocol

A Decentralized Capability Marketplace Over Transport-Agnostic Mesh

NEXUS is a decentralized network where every resource — bandwidth, compute, storage, connectivity — is a discoverable, negotiable, verifiable, payable capability. Nodes participate at whatever level their hardware allows. Nothing is required except a cryptographic keypair.

Vision

Strengthen Communities

The internet was supposed to connect people. Instead, it routed everything through distant data centers owned by a handful of corporations. NEXUS reverses this: communication within a community is **free, direct, and unstoppable**. Trusted neighbors relay for each other at zero cost. The economic layer only activates when traffic crosses trust boundaries — just like the real world.

Democratize Communication

A village with no ISP should still be able to communicate. A country under internet shutdown should still have a mesh. A community that can't afford $30/month per household should be able to share one uplink across a neighborhood. NEXUS makes communication infrastructure a commons, not a product.

One Decentralized Computer

Every device on the network — from a $30 solar relay to a GPU workstation — contributes what it can. Storage, compute, bandwidth, and connectivity are pooled into a single capability marketplace. Your phone delegates AI inference to a neighbor's GPU. Your Raspberry Pi stores data for the mesh. No single point of failure, no single point of control. The network **is** the computer.

Share Hardware, Save Money

Most hardware sits idle most of the time. A home internet connection averages less than 5% utilization. A desktop GPU sits unused 22 hours a day. NEXUS turns idle capacity into shared infrastructure: you earn when others use your resources, and you pay when you use theirs. The result is that communities need far less total hardware to achieve the same capabilities.

Why NEXUS?

The internet depends on centralized infrastructure: ISPs, cloud providers, DNS registrars, certificate authorities. When any of these fail — through censorship, natural disaster, or economic exclusion — people lose connectivity entirely.

NEXUS is designed for a world where:

- A village with no internet can still communicate internally over LoRa radio
- A country with internet shutdowns can maintain mesh connectivity between citizens
- A community can run its own local network and bridge to the wider internet through any available uplink
- Every device — from a $30 solar-powered relay to a GPU workstation — contributes what it can and pays for what it needs

Core Principles

1. Transport Agnostic

Any medium that can move bytes is a valid link. The protocol never assumes IP, TCP, or any specific transport. It works from 500 bps radio to 10 Gbps fiber. A single node can bridge between multiple transports simultaneously.

2. Capability Agnostic

Nodes are not classified into fixed roles. A node advertises what it can do. What it cannot do, it delegates to a neighbor and pays for the service. Hardware determines capability; the market determines role.

3. Partition Tolerant

Network fragmentation is not an error state — it is expected operation. A village on LoRa **is** a partition. A country with internet cut **is** a partition. Every protocol layer functions correctly during partitions and converges correctly when partitions heal.

4. Anonymous by Default

Packets carry no source address. A relay node knows which neighbor handed it a packet, but not whether that neighbor originated it or is relaying it from someone else. Identity is a cryptographic keypair — not a name, not an IP address, not an account. Human-readable names are optional and self-assigned. You can use the network, earn NXS, host content, and communicate without ever revealing who you are.

5. Free Local, Paid Routed

Direct neighbors communicate for free. You pay only when your packets traverse other people's infrastructure. This mirrors real-world economics — talking to your neighbor costs nothing, sending a letter across the country does.

6. Layered Separation

Each layer depends only on the layer below it. Applications never touch transport details. Payment never touches routing internals. Security is not bolted on — it is structural.

Protocol Stack Overview

NEXUS is organized into seven layers, each building on the one below:

Layer	Name	Purpose
0	Physical Transport	Wraps existing transports (LoRa, WiFi, cellular, etc.) behind a uniform interface
1	Network Protocol	Identity, addressing, routing, and gossip
2	Security	Encryption, authentication, and privacy
3	Economic Protocol	NXS token, stochastic relay rewards, CRDT ledger, trust neighborhoods
4	Capability Marketplace	Capability advertisement, discovery, agreements, and verification
5	Service Primitives	NXS-Store, NXS-DHT, NXS-Pub, NXS-Compute
6	Applications	Messaging, social, voice, naming, forums

How It Works — A Simple Example

1. **Alice** has a Raspberry Pi with a LoRa radio and WiFi. She's in a rural area with no internet.
2. **Bob** has a gateway node 5 km away with a cellular modem providing internet access.
3. **Carol** is somewhere on the internet and wants to message Alice.

Here's what happens:

- Carol's message is encrypted end-to-end for Alice's public key
- It routes through the internet to Bob's gateway
- Bob relays it over LoRa to Alice (earning a small NXS fee)
- Alice's device decrypts and displays the message
- Bob's relay cost is paid automatically through a bilateral payment channel

No central server. No accounts. No subscriptions. Just cryptographic identities and a marketplace for capabilities.

Next Steps

- **Understand the protocol**: Start with Physical Transport and work up the stack
- **Explore the economics**: Learn how NXS tokens and stochastic relay rewards enable decentralized resource markets
- **See the real-world impact**: Understand how NEXUS affects existing economics and how participants earn
- **See the hardware**: Check out the reference designs for building NEXUS nodes
- **Read the full spec**: The complete protocol specification covers every detail

Frequently Asked Questions

Plain-language answers. No jargon.

The Basics

What is NEXUS?

NEXUS is a network that lets devices talk to each other directly — without relying on a phone company, an ISP, or a cloud server. Your phone, laptop, or a cheap radio module can join the mesh and communicate with anyone nearby. Think of it like a community-owned telephone system that nobody controls.

How do I join?

Install the app (or flash a device) and create an account. That's it. Your account is just a cryptographic key — no email, no phone number, no sign-up form. You're on the network immediately.

What device do I need?

Anything from a $30 solar-powered radio relay to a smartphone to a full computer. The network adapts to what your device can do. Low-power devices relay text messages; powerful devices can host websites and run computations.

Is it free?

Talking to your friends and neighbors: always free. You mark people as "trusted" (like adding a contact), and all communication between trusted people costs nothing.

Reaching strangers or distant nodes: costs a tiny amount of NXS (the network's internal token). You earn NXS automatically by helping relay other people's traffic — so for most people, the system is self-sustaining. You earn by participating, and you spend by using.

Do I need to buy tokens?

No. You earn NXS by relaying traffic for others, which happens automatically in the background. The more your device helps the network, the more you earn. You can start using the network with zero tokens — free communication between trusted peers works immediately.

Finding Things

How do I find what's happening in my city?

Your device automatically discovers nearby nodes and their content. Here's how, from closest to furthest:

1. **Friends' feeds**: You follow people. Their posts show up on your device automatically, newest first. No algorithm choosing what you see — just a chronological feed.
2. **Neighborhood activity**: Your community has a label (like `mumbai-mesh` or `portland-mesh`). Subscribe to it and you'll see all local activity — forum posts, marketplace listings, wiki edits, new websites — from everyone in that community.
3. **Nearby nodes**: Your device constantly hears announcements from nearby nodes. You can browse what services and content exist within a few hops, like walking down a street and reading shop signs.
4. **Search**: If you want something specific that isn't nearby, you can search the wider network. It's slower and may cost a small amount, but you can find anything that anyone has published.

How do I find my friends?

By their name. Everyone can pick a name scoped to their community — like `alice@portland-mesh` or `ravi@mumbai-mesh`. Type it in and you're connected. You can also use private nicknames ("Mom", "Work") that only exist on your device.

If you're physically near someone, your devices will discover each other automatically over radio or WiFi — no names needed.

Is there a "feed" like Instagram or Twitter?

Yes, but better. You follow people and see their posts in chronological order. There is:

- **No algorithm** deciding what you see
- **No ads** injected into your feed
- **No central server** storing your social graph
- **No one** who can ban you from the network

On a good connection you get full images and video. On a weak radio link, you get text and tiny image previews. The app adapts automatically.

Can I browse websites?

Yes. People host websites on NEXUS just like on the regular internet, but without needing a server or domain name. You visit them by name (`mysite@portland-mesh`) or by direct link. Popular sites load fast because copies are cached throughout the network automatically.

Communication

How do I message someone?

Open the messaging app, pick a contact, type your message. It's end-to-end encrypted — only you and the recipient can read it. If they're offline, the network holds the message and delivers it when they come back online (like email, but encrypted).

Can I make voice calls?

Yes, on connections with enough bandwidth. WiFi and cellular links support real-time voice. On slow radio links, voice isn't practical — use text messaging instead.

Can I send photos and videos?

Yes. The app adapts to your connection:

Connection	What you can send/receive
WiFi or cellular	Photos, videos, full media
Moderate radio link	Compressed images, text
Slow radio (LoRa)	Text only, with tiny image previews

You never need to think about this — the app handles it automatically.

What happens when I'm moving around?

Your device automatically handles roaming. It constantly listens for nearby nodes on all its radios (WiFi, Bluetooth, LoRa) and connects to the best one available — no manual switching required.

- **Walk into a cafe with a NEXUS WiFi node?** Your device connects in under a second.
- **Walk out of WiFi range?** Traffic shifts to LoRa automatically. Apps adapt (images become text previews).
- **Visit the same cafe tomorrow?** Your device remembers it and reconnects instantly — no setup.
- **On a voice call while moving?** The call hands off between nodes with less than a second of interruption. Quality may change (WiFi → LoRa = high-fidelity → walkie-talkie) but the call

doesn't drop.

Think of it like your phone switching between cell towers — except there's no phone company, no SIM card, and no monthly bill.

Community

How do communities form?

You mark people as trusted. They mark you as trusted. When a group of people all trust each other, that's a community. Nobody "creates" it or "runs" it — it emerges from real-world relationships.

Optionally, you can all label yourselves with the same community name (like `portland-mesh`) so newcomers can find you.

Can I run a local forum?

Yes. A forum is just a shared space where community members post. A moderator contract enforces whatever rules your community agrees on. Different forums can have different rules — there's no platform-wide content policy.

Can I sell things on a local marketplace?

Yes. Post a listing (text, photos, price), and it's visible to your neighborhood. Buyers contact you directly. Payment can happen in person, through an external service, or through NXS escrow (the network holds the payment until both sides confirm the deal).

Can I host a website or blog?

Yes, and it's much simpler than traditional hosting:

Traditional web	NEXUS
Rent a server	Not needed — content lives in the mesh
Buy a domain name ($10–50/year)	Pick a name for free (`myblog@mumbai-mesh`)
Get an SSL certificate	Not needed — everything is encrypted and verified automatically
Pay for traffic spikes	Visitors pay their own relay costs, not you

You pay only for storage (tiny amounts of NXS), and popular content gets cheaper because it's cached everywhere.

Privacy and Safety

Is it private?

Yes. Messages are end-to-end encrypted. Social posts can be public or neighborhood-only. There is no central server with a copy of your messages, your contacts, or your browsing history. Your identity is a cryptographic key — you never need to provide your real name.

Can someone spy on my messages?

No. End-to-end encryption means only the sender and recipient can read a message. Relay nodes carry encrypted blobs they cannot decrypt. Even your direct neighbors don't know if a packet originated from you or if you're just relaying it for someone else.

Can someone shut down the network?

No single point of failure. There's no server to seize, no company to shut down, no domain to block. As long as any two devices can reach each other — by radio, WiFi, Bluetooth, or anything else — the network works.

Economy

How does money work on NEXUS?

NXS is the network's internal token. Think of it like arcade tokens — they're valuable inside the arcade (network services), but they're not meant for trading on an exchange.

- **You earn NXS** by relaying traffic, storing data, or providing other services
- **You spend NXS** when your messages cross through untrusted infrastructure
- **Talking to friends is always free** — NXS only matters at trust boundaries

What's it worth in real money?

NXS has no official exchange rate with any fiat currency. Its value comes from what it buys on the network — relay time, storage space, compute. The prices of these services float based on supply and demand, like any market. But you never need to convert NXS to dollars — it's a closed-loop system.

Can I get rich from NXS?

That's not the point. NXS is designed to be spent on services, not hoarded or traded. There's no ICO, no pre-mine, no exchange listing. You earn it by contributing, you spend it by consuming. The goal is a functioning economy, not a speculative asset.

Compared to What I Use Now

How is this different from the regular internet?

	Regular Internet	NEXUS
Works without ISP	No	Yes — radio, WiFi, anything
Works during internet shutdown	No	Yes — local mesh continues
Free local communication	No — you pay your ISP	Yes — trusted peers are free
Your data on a corporate server	Yes (Google, Meta, etc.)	No — data stays on your devices and your community's mesh
Can be censored	Yes — ISPs, DNS, app stores	Extremely difficult — no central control point
Needs an account	Email, phone number, ID	Just a cryptographic key (anonymous)

Can NEXUS replace my internet connection?

It depends on where you live.

In a **dense area** (apartment building, neighborhood, campus) where many nodes run WiFi, the mesh delivers 10–300 Mbps per hop — comparable to cable internet. Add a few shared internet uplinks (Starlink, fiber, cellular) and the community mesh handles distribution. Most people would save 50–75% on connectivity costs. You can browse, stream, video call — normal internet use.

In a **rural or remote area** with only LoRa radio coverage, NEXUS delivers 0.3–50 kbps — enough for text messaging, basic social feeds, and push-to-talk voice, but not video streaming or modern web browsing. Here, NEXUS isn't replacing your internet — it's providing communication where there was none, or sharing one expensive satellite connection across an entire village.

Your situation	What NEXUS does
Dense urban, many WiFi nodes	Replaces individual ISP subscriptions — share uplinks, save money
Suburban, mixed WiFi + LoRa	Supplements your connection — free local communication, shared backup uplink

Rural, LoRa only	Provides communication where there is none — text, voice, local services
No infrastructure at all	Only option that works — $30 solar radio nodes, no towers needed

The key insight: NEXUS doesn't compete with Starlink or cellular on raw speed. It **uses** them as transport — one Starlink dish becomes a shared community gateway. The mesh handles the local distribution and economics. Everyone gets internet access; the gateway operator earns; residents save.

How is this different from Signal or WhatsApp?

Signal and WhatsApp need internet access and rely on central servers for delivery. NEXUS works without internet, stores messages across the mesh (not one company's servers), and the network itself is decentralized. Nobody can block your access because there's nothing to block.

How is this different from Bitcoin?

Bitcoin is money designed for global financial transactions. NXS is an internal utility token for paying network services. They share some concepts (cryptographic keys, no central authority) but serve completely different purposes. NXS is more like "bus tokens for the network" than a cryptocurrency.

Layer 0: Physical Transport

NEXUS requires a transport layer that provides transport-agnostic networking over any medium supporting at least a half-duplex channel with ≥5 bps throughput and ≥500 byte MTU. The transport layer is a swappable implementation detail — NEXUS defines the interface it needs, not the implementation.

Transport Requirements

The transport layer must provide:

- **Any medium is a valid link**: LoRa, WiFi, Ethernet, serial, packet radio, fiber, free-space optical
- **Multiple simultaneous interfaces**: A node can bridge between transports automatically
- **Announce-based routing**: No manual configuration of addresses, subnets, or routing tables
- **Mandatory encryption**: All traffic is encrypted; unencrypted packets are dropped as invalid
- **Sender anonymity**: No source address in packets
- **Constrained-link operation**: Functional at ≥5 bps

Current Implementation: Reticulum

The current transport implementation uses the Reticulum Network Stack, which satisfies all requirements above and is proven on links as slow as 5 bps. NEXUS extends it with CompactPathCost annotations on announces and an economic layer above.

Reticulum is an implementation choice, not an architectural dependency. NEXUS extensions are carried as opaque payload data within Reticulum's announce DATA field — a clean separation that allows the transport to be replaced with a clean-room implementation in the future without affecting any layer above.

Participation Levels

Not all nodes need to understand NEXUS extensions. Three participation levels coexist on the same mesh:

Level	Node Type	Understands	Earns NXS	Marketplace
L0	Transport-only	Wire protocol only	No	No
L1	NEXUS Relay	L0 + CompactPathCost + stochastic rewards	Yes (relay only)	No
L2	Full NEXUS	Everything	Yes	Yes

L0 nodes relay packets and forward announces (including NEXUS extensions as opaque bytes) but do not parse economic extensions, earn rewards, or participate in the marketplace. They are zero-cost hops from NEXUS's perspective. This ensures the mesh works even when some nodes run the transport layer alone.

L1 nodes are the minimum viable NEXUS implementation — they parse CompactPathCost, run the VRF relay lottery, and maintain payment channels. This is the target for ESP32 firmware.

L2 nodes implement the full protocol stack including capability marketplace, storage, compute, and application services.

Implementation Strategy

Platform	Implementation
Raspberry Pi, desktop, phone	Rust implementation (primary)
ESP32, embedded	Rust `no_std` implementation (L1 minimum)

All implementations speak the same wire protocol and interoperate on the same network.

Supported Transports

Transport	Typical Bandwidth	Typical Range	Duplex	Notes
LoRa (ISM band)	0.3-50 kbps	2-15 km	Half	Unlicensed, low power, high range. RNode as reference hardware.
WiFi Ad-hoc	10-300 Mbps	50-200 m	Full	Ubiquitous, short range
WiFi P2P (directional)	100-800 Mbps	1-10 km	Full	Point-to-point backbone links
Cellular (LTE/5G)	1-100 Mbps	Via carrier	Full	Requires carrier subscription
Ethernet	100 Mbps-10 Gbps	Local	Full	Backbone, data center
Serial (RS-232, AX.25)	1.2-56 kbps	Varies	Half	Legacy radio, packet radio
Fiber	1-100 Gbps	Long haul	Full	Backbone
Bluetooth/BLE	1-3 Mbps	10-100 m	Full	Wearables, phone-to-phone

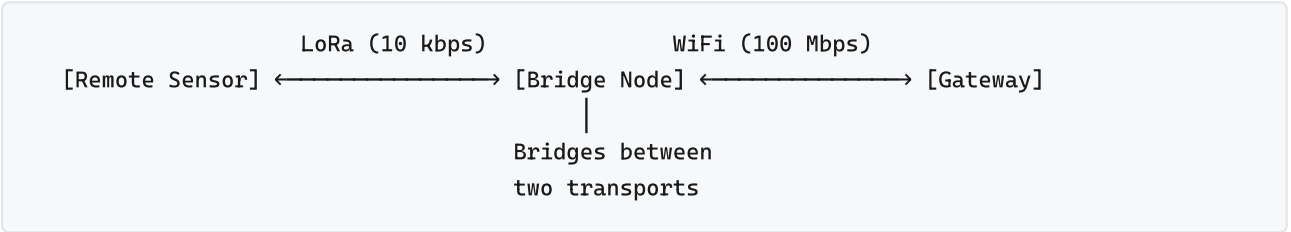
A node can have **multiple interfaces active simultaneously**. The network layer selects the best interface for each destination based on cost, latency, and reliability.

Multi-Interface Bridging

A node with both LoRa and WiFi interfaces automatically bridges between the two networks. Traffic arriving on LoRa can be forwarded over WiFi and vice versa.

The bridge node is where bandwidth characteristics change dramatically — and where the capability marketplace becomes valuable. A bridge node can:

- Accept low-bandwidth LoRa traffic from remote sensors
- Forward it over high-bandwidth WiFi to a local network
- Earn relay rewards for the bridging service
- Advertise its bridging capability to nearby nodes



Bandwidth Ranges and Their Implications

The 20,000x range between the slowest and fastest supported transports (500 bps to 10 Gbps) has profound implications for protocol design:

- **All protocol overhead must be budgeted.** Gossip, routing updates, and economic state consume bandwidth that could carry user data. On a 1 kbps LoRa link, every byte matters.
- **Data objects carry minimum bandwidth requirements.** A 500 KB image declares `min_bandwidth: 10000` (10 kbps). LoRa nodes never attempt to transfer it — they only propagate its hash and metadata.
- **Applications adapt to link quality.** The protocol provides link metrics; applications decide what to send based on available bandwidth.

NAT Traversal

Residential nodes behind NATs (common for WiFi and Ethernet interfaces) are handled at the transport layer. The Reticulum transport uses its link establishment protocol to traverse NATs — an outbound connection from behind the NAT establishes a bidirectional link without requiring port forwarding or STUN/TURN servers.

For nodes that cannot establish outbound connections (rare), the announce mechanism still propagates their presence. Traffic destined for a NATed node is routed through a neighbor that

does have a direct link — functionally equivalent to standard relay forwarding. No special NAT-awareness is needed at the NEXUS protocol layers above transport.

What NEXUS Adds Above Transport

The transport layer provides packet delivery, routing, and encryption. NEXUS adds everything above:

Extension	Purpose
CompactPathCost on announces	Enables economic routing — cheapest, fastest, or balanced path selection
Stochastic relay rewards	Incentivizes relay operators without per-packet payment overhead
Capability advertisements	Makes compute, storage, and connectivity discoverable and purchasable
CRDT economic ledger	Tracks balances without consensus or blockchain
Trust graph	Enables free communication between trusted peers
Congestion control	CSMA/CA, per-neighbor fair sharing, priority queuing, backpressure

These extensions ride on top of the transport's existing gossip and announce mechanisms, staying within the protocol's bandwidth budget.

Layer 1: Network Protocol

The network protocol handles identity, addressing, routing, and state propagation across the mesh. It uses Reticulum as the transport foundation and extends it with cost-aware routing and economic state gossip.

Identity and Addressing

NEXUS uses Reticulum's identity model. Every node has a cryptographic identity generated locally with no registrar:

```
NodeIdentity {
    keypair: Ed25519Keypair,            // 256-bit, generated locally
    public_key: Ed25519PublicKey,        // 32 bytes
    destination_hash: [u8; 16],         // truncated hash of public key
    x25519_public: X25519PublicKey,      // derived via RFC 7748 birational map
}
```

Destination Hash

The destination hash is the node's address — 16 bytes (128 bits), derived from the public key. This provides:

- **Flat address space**: No hierarchy, no subnets, no allocation authority
- **Self-assigned**: Any node can generate an address without asking permission
- **Negligible collision probability**: 2^128 possible addresses
- **Pseudonymous**: The hash is not linked to a real-world identity unless the owner publishes that association

A single node can generate **multiple destination hashes** for different purposes (personal identity, service endpoints, anonymous identities). Each is derived from a separate Ed25519 keypair.

Packet Format

NEXUS uses the Reticulum packet format:

```
[HEADER 2 bytes] [ADDRESSES 16/32 bytes] [CONTEXT 1 byte] [DATA 0–465 bytes]
```

Header flags encode: propagation type (broadcast/transport), destination type (single/group/plain/link), and packet type (data/announce/link request/proof). Maximum overhead

per packet: 35 bytes.

Critical property (inherited from Reticulum): The source address is **NOT** in the header. Packets carry only the destination. Sender anonymity is structural.

NEXUS Extension: Compact Path Cost

NEXUS extends announces with a constant-size cost summary that each relay updates in-place as it forwards the announce:

```
CompactPathCost {
    cumulative_cost: u16,    // log₂-encoded µNXS/byte (2 bytes)
    worst_latency_ms: u16,   // max latency on any hop in path (2 bytes)
    bottleneck_bps: u8,      // log₂-encoded min bandwidth on path (1 byte)
    hop_count: u8,           // number of relays traversed (1 byte)
}
// Total: 6 bytes (constant, regardless of path length)
```

Each relay updates the running totals as it forwards:

- `cumulative_cost += my_cost_per_byte` (re-encoded to log scale)
- `worst_latency_ms = max(existing, my_measured_latency)`
- `bottleneck_bps = min(existing, my_bandwidth)`
- `hop_count += 1`

Log encoding for cost: `encoded = round(16 × log₂(value + 1))`. A u16 covers the full practical cost range with ~6% precision per step.

Log encoding for bandwidth: `encoded = round(8 × log₂(bps))`. A u8 covers 1 bps to ~10 Tbps with ~9% precision.

The CompactPathCost is carried in the announce DATA field using a TLV envelope:

```
NexusExtension {
    magic: u8 = 0x4E,           // 'N' — identifies NEXUS extension presence
    version: u8,                 // extension format version
    path_cost: CompactPathCost,  // 6 bytes
    extensions: [{               // future extensions via TLV pairs
        type: u8,
        length: u8,
        data: [u8; length],
    }],
}
// Minimum size: 8 bytes (magic + version + path_cost)
```

Nodes that don't understand the `0x4E` magic byte forward the DATA field as opaque payload. NEXUS-aware nodes parse and update it.

Why No Per-Relay Signatures

Earlier designs signed each relay's cost annotation individually (~84 bytes per relay hop). This is unnecessary for three reasons:

1. **Routing decisions are local.** You select a next-hop neighbor. You only need to trust your neighbor's cost claim — and your neighbor is already authenticated by the link-layer encryption.
2. **Trust is transitive at each hop.** Your neighbor trusts *their* neighbor (link-authenticated), who trusts *their* neighbor, and so on. No node needs to verify claims from relays it has never communicated with.
3. **The market enforces honesty.** A relay that inflates path costs gets routed around. A relay that deflates costs loses money on every packet. Economic incentives are a cheaper and more robust enforcement mechanism than cryptographic proofs for cost claims.

The announce itself remains signed by the destination node (proving authenticity of the route). The path cost summary is trusted transitively through link-layer authentication at each hop — analogous to how BGP trusts direct peers, not every AS along the path.

Routing

Routing is destination-based with cost annotations, formalized as **greedy forwarding on a small-world graph**. Each node maintains a routing table:

```
RoutingEntry {
    destination: DestinationHash,
    next_hop: InterfaceID + LinkAddress, // which interface, which neighbor

    // From CompactPathCost (6 bytes in announce)
    cumulative_cost: u16,                // log₂-encoded μNXS/byte
    worst_latency_ms: u16,              // max latency on path
    bottleneck_bps: u8,                 // log₂-encoded min bandwidth
    hop_count: u8,                      // relay count

    // Locally computed
    reliability: u8,                     // 0-255 (0=unknown, 255=perfect) - avoids FP on
ESP32

    last_updated: Timestamp,
    expires: Timestamp,
}
```

Small-World Routing Model

NEXUS routing is based on the **Kleinberg small-world model**, adapted for a physical mesh with heterogeneous transports. This provides a formal basis for routing scalability.

The Network as a Small-World Graph

The destination hash space `[0, 2^128)` forms a **ring**. The circular distance between two addresses is:

```
ring_distance(a, b) = min(|a − b|, 2^128 − |a − b|)
```

The physical mesh naturally provides two types of links, matching Kleinberg's model:

- **Short-range links** (lattice edges): LoRa, WiFi ad-hoc, BLE — these connect geographically nearby nodes, forming an approximate 2D lattice determined by physical proximity.
- **Long-range links** (Kleinberg contacts): Directional WiFi, cellular, internet gateways, fiber — these connect distant nodes, providing shortcuts across the ring.

Kleinberg's result proves that greedy forwarding achieves **O(log² N) expected hops** when long-range link probability follows `P(u→v) ∝ 1/d(u,v)^r` with clustering exponent `r` equal to the network dimension. The distribution of real-world backbone links (many local WiFi, fewer city-to-city, even fewer intercontinental) naturally approximates this harmonic distribution.

Greedy Forwarding with Cost Weighting

At each hop, the current node selects the neighbor that minimizes a scoring function:

```
score(neighbor) = α · norm_ring_distance(neighbor, destination)
                + β · norm_cumulative_cost(neighbor)
                + γ · norm_worst_latency(neighbor)
```

Where `norm_*` normalizes each metric to `[0, 1]` across the candidate set. The weights α, β, γ are derived from the per-packet `PathPolicy`:

```
PathPolicy: enum {
    Cheapest,                          // α=0.1, β=0.8, γ=0.1
    Fastest,                           // α=0.1, β=0.1, γ=0.8
    MostReliable,                      // maximize delivery probability
    Balanced(cost_weight, latency_weight, reliability_weight),
}
```

Pure greedy routing (α=1, β=0, γ=0) guarantees **O(log² N) expected hops**. Cost and latency weighting trades path length for economic efficiency — a path may take more hops if each hop is

cheaper or faster.

Applications specify their preferred policy:

- **Voice traffic** uses `Fastest` — latency matters most
- **Bulk storage replication** uses `Cheapest` — cost efficiency matters most
- **Default** is `Balanced` — a weighted combination of all factors

With N nodes where each has O(1) long-range links (typical for relay nodes), expected path length is **O(log² N)**. Backbone nodes with O(log N) connections reduce this to **O(log N)**.

Why NEXUS Does Not Need Location Swapping

Unlike Freenet/Hyphanet, which uses location swapping to arrange nodes into a navigable topology, NEXUS does not need this mechanism:

1. **Destination hashes are self-assigned** — each node's position on the ring is fixed by its Ed25519 keypair.
2. **Announcements build routing tables** — when a node announces itself, it creates routing table entries across the mesh that function as navigable links.
3. **Multi-transport bridges are natural long-range contacts** — a node bridging LoRa to WiFi to internet inherently provides the long-range shortcuts that make the graph navigable.

The announcement propagation itself creates the navigable topology. Each announcement that reaches a distant node via a backbone link creates exactly the kind of long-range routing table entry that Kleinberg's model requires.

Path Discovery

Path discovery works via announcements:

1. A node announces its destination hash to the network, signed with its Ed25519 key
2. The announcement propagates through the mesh via greedy forwarding, with each relay updating the CompactPathCost running totals in-place (no per-relay signatures — link-layer authentication is sufficient)
3. Receiving nodes record the path (or multiple paths) and select based on the scoring function above
4. Multiple paths are retained and scored — the best path per policy is used, with fallback to alternatives on failure

Announce Propagation Rules

Announces are **event-driven with periodic refresh**, not purely periodic:

```
Announce triggers:
  - First boot / new identity: immediate announce
  - Interface change: announce on new interface within 1 gossip round
  - Cost change > 25%: re-announce with updated CompactPathCost
  - Periodic refresh: every 30 minutes (1,800 seconds)
  - Forced refresh: on peer request (pull-based for constrained links)
```

Hop limit: Announces carry a `max_hops` field (u8, default 128). Each relay decrements by 1; announces at 0 are not forwarded. This prevents unbounded propagation in large meshes while ensuring $O(\log^2 N)$ reachability.

Expiry: Routing entries expire at `last_updated + announce_interval × 3` (default 90 minutes). If no refresh is received, the entry is marked stale (still usable at lower priority) for one additional interval, then evicted. On memory pressure, LRU eviction removes the least-recently-used stale entries first, then lowest-reliability active entries.

Link failure detection: If a direct neighbor misses 3 consecutive gossip rounds (3 minutes) without response, the link is marked down. All routing entries using that neighbor as next-hop are immediately marked stale (not deleted — the neighbor may return). After 10 missed rounds, entries are evicted.

Gossip Protocol

All protocol-level state propagation uses a common gossip mechanism:

```
GossipRound (every 60 seconds with each neighbor):

1. Exchange state summaries (bloom filters of known state)
2. Identify deltas (what I have that you don't, and vice versa)
3. Exchange deltas (compact, only what's new)
4. Apply received state via CRDT merge rules
```

Gossip Bloom Filter

State summaries use a compact bloom filter to identify deltas without exchanging full state:

```
GossipFilter {
    bits: [u8; N],          // N scales with known state entries
    hash_count: 3,          // 3 independent hash functions (Blake3-derived)
    target_fpr: 1%,         // 1% false positive rate (tolerant — FP only causes redundant
delta)
}
```

Known state entries	Filter size	FPR

100	120 bytes	~1%
1,000	1.2 KB	~1%
10,000	12 KB	~1%

On constrained links (below 10 kbps), the filter is capped at 256 bytes — entries beyond the filter capacity are omitted (pull-only mode for Tiers 3-4 handles this). False positives are harmless: they cause a delta item to not be requested, but the item will be caught in the next round when the bloom filter is regenerated.

New node joining: A node with empty state sends an all-zeros bloom filter. The neighbor detects maximum divergence and sends a prioritized subset of state (Tier 1 first, then Tier 2, etc.) spread across multiple gossip rounds to avoid link saturation.

A single gossip round multiplexes all protocol state:

- Routing announcements (with cost annotations)
- Ledger state (settlements, balances)
- Trust graph updates
- Capability advertisements
- DHT metadata
- Pub/sub notifications

Bandwidth Budget

Total protocol overhead targets **≤10% of available link bandwidth**, allocated by priority tier:

```
Gossip Bandwidth Budget (per link):

  Tier 1 (critical):  Routing announcements         — up to 3%
  Tier 2 (economic):  Payment + settlement state     — up to 3%
  Tier 3 (services):  Capabilities, DHT, pub/sub     — up to 2%
  Tier 4 (social):    Trust graph, names               — up to 2%
```

On constrained links (< 10 kbps), the budget adapts automatically:

- Tiers 3–4 switch to **pull-only** (no proactive gossip — only respond to requests)
- Payment batching interval increases from 60 seconds to **5 minutes**
- Capability advertisements limited to **Ring 0 only** (direct neighbors)

Link type	Routing	Payment	Services	Trust/Social	Total
1 kbps LoRa	~1.5%	~0.5%	pull-only	pull-only	~2%
50 kbps LoRa	~2%	~2%	~1%	~1%	~6%

10+ Mbps WiFi	~1%	~1%	~2%	~2%	~6%

This tiered model ensures constrained links are never overwhelmed by protocol overhead, while higher-bandwidth links gossip more aggressively for faster convergence.

Congestion Control

User data has three layers of congestion control. Protocol gossip is handled separately by the bandwidth budget.

Link-Level Collision Avoidance (CSMA/CA)

On half-duplex links (LoRa, packet radio), mandatory listen-before-talk:

```
LinkTransmit(packet):
  1. CAD scan (LoRa Channel Activity Detection, ~5ms)
  2. If channel busy:
       backoff = random(1, 2^attempt) × slot_time
       slot_time = max_packet_airtime for this link
                   (~200ms at 1 kbps for 500-byte MTU)
  3. Max 7 backoff attempts → drop packet, signal congestion upstream
  4. If channel clear → transmit
```

On full-duplex links (WiFi, Ethernet), the transport handles collision avoidance natively — this layer is a no-op.

Per-Neighbor Token Bucket

Each outbound link enforces fair sharing across neighbors:

```
LinkBucket {
    link_id: InterfaceID,
    capacity_tokens: u32,        // link_bandwidth_bps × window_sec / 8
    tokens: u32,                 // current available (1 token = 1 byte)
    refill_rate: u32,            // bytes/sec = measured_bandwidth × (1 −
protocol_overhead)
    per_neighbor_share: Map<NodeID, u32>,
}
```

Fair share is `link_bandwidth / num_active_neighbors` by default. Neighbors with active payment channels get share weighted proportionally to channel balance — paying for bandwidth earns proportional priority.

When a neighbor exceeds its share, packets are queued (not dropped). If the queue exceeds a depth threshold, a backpressure signal is sent.

Priority Queuing

Four priority levels for user data, scheduled with strict priority and starvation prevention (P3 guaranteed at least 10% of user bandwidth):

Priority	Traffic Type	Examples	Queue Policy
P0	Real-time	Voice (Codec2), interactive control	Tail-drop at 500ms deadline
P1	Interactive	Messaging, DHT lookups, link establishment	FIFO, 5s max queue time
P2	Standard	Social posts, pub/sub, NXS-Name	FIFO, 30s max queue time
P3	Bulk	Storage replication, large file transfer	FIFO, unbounded patience

Within a priority level, round-robin across neighbors. On half-duplex links, preemption occurs at packet boundaries only.

Backpressure Signaling

When an outbound queue exceeds 50% capacity, a 1-hop signal is sent to upstream neighbors:

```
CongestionSignal {
    link_id: u8,              // which outbound link is congested
    severity: enum {
        Moderate,             // reduce sending rate by 25%
        Severe,               // reduce by 50%, reroute P2/P3 traffic
        Saturated,            // stop P2/P3, throttle P1, P0 only
    },
    estimated_drain_ms: u16,  // estimated time until queue drains
}
// Total: 4 bytes
```

Dynamic Cost Response

Congestion increases the effective cost of a link. When queue depth exceeds 50%:

```
effective_cost = base_cost × (1 + (queue_depth / queue_capacity)²)
```

The quadratic term ensures gentle increase at moderate load and sharp increase near saturation. The updated cost propagates in the next gossip round's CompactPathCost, causing upstream nodes to naturally reroute traffic to less-congested paths. This is a local decision — no protocol extension beyond normal cost updates.

Time Model

NEXUS does not require global clock synchronization. Time is handled through three mechanisms:

Logical Clocks

Packet headers carry a **Lamport timestamp** incremented at each hop. Used for ordering events and detecting stale routing entries. If a node receives a routing announcement with a lower logical timestamp than one already in its table for the same destination, the older announcement is discarded.

Neighbor-Relative Time

During link establishment, nodes exchange their local monotonic clock values. Each node maintains a `clock_offset` per neighbor. Relative time between any two direct neighbors is accurate to within RTT/2.

Used for: agreement expiry, routing entry TTL, payment channel batching intervals.

Epoch-Relative Time

Epochs define coarse time boundaries. "Weekly" means approximately **10,000 settlement batches after the previous epoch** — not wall-clock weeks. The epoch trigger is settlement count, not elapsed time.

The "30-day grace period" for epoch finalization is defined as **4 epochs after activation**, tolerating clock drift of up to 50% without protocol failure.

All protocol `Timestamp` fields are `u64` values representing milliseconds on the node's local monotonic clock (not wall-clock). Conversion to neighbor-relative or epoch-relative time is performed at the protocol layer.

Layer 2: Security

Security in NEXUS is structural, not bolted on. Every layer of the protocol incorporates cryptographic protections. There is no trusted infrastructure — no certificate authorities, no trusted servers, no DNS.

Threat Model

NEXUS assumes the worst:

- **Open network**: Any node can join. Nodes may be malicious.
- **Hostile observers**: All link-layer traffic may be monitored (especially radio).
- **No trusted infrastructure**: No certificate authorities, no trusted servers, no DNS.
- **State-level adversaries**: Governments may control internet gateways and operate nodes within the mesh.

NEXUS does **not** attempt to defend against:

- **Global traffic analysis**: A sufficiently powerful adversary monitoring all links simultaneously can correlate traffic patterns. Opt-in onion routing mitigates this for individual packets but does not defeat a global adversary.
- **Physical compromise**: If an adversary physically captures a node, they obtain its private key and all local state.

Encryption Model

Link-Layer Encryption (Hop-by-Hop)

Every link between two nodes is encrypted using a session key derived from X25519 Diffie-Hellman key exchange:

```
Link establishment:
  1. Alice and Bob exchange X25519 ephemeral public keys
  2. Both derive shared_secret = X25519(my_ephemeral, their_ephemeral)
  3. session_key = Blake2b(shared_secret || alice_pub || bob_pub)
  4. All traffic on this link encrypted with ChaCha20-Poly1305(session_key)
     Nonce: 64-bit counter (zero-padded to 96 bits), incremented per packet
     Counter is per session_key — reset to 0 on each key rotation
     No nonce reuse risk: key rotation occurs well before 2^64 packets
  5. Keys rotated periodically (every 1 hour of local monotonic time, or
     max(1 MB, bandwidth_bps × 60s) of data, whichever first — this scales
     the data threshold to ~1 minute of link capacity, preventing excessive
```

```
    rotation on fast links). "1 hour" is measured by each node's local
    monotonic clock independently — no synchronization needed. Either side
    of the link can initiate rotation; the peer accepts and derives a new
    session key via fresh ephemeral key exchange
```

This prevents passive observers from reading packet contents or metadata beyond the cleartext header fields needed for routing.

End-to-End Encryption (Data Payloads)

Data packets are encrypted by the sender for the destination using the destination's public key. Relay nodes **cannot** read the payload:

```
E2E encryption for a message to Bob:
  1. Alice generates ephemeral X25519 keypair
  2. shared_secret = X25519(alice_ephemeral, bob_x25519_public)
  3. payload_key = Blake2b(shared_secret || alice_ephemeral_pub)
  4. encrypted_payload = ChaCha20-Poly1305(payload_key, plaintext)
  5. Packet contains: alice_ephemeral_pub || encrypted_payload
  6. Bob derives the same payload_key and decrypts
```

This provides **forward secrecy per message** — each message uses a unique ephemeral key. Compromise of one message's key does not compromise any other message.

What Relay Nodes Can See

Visible	Hidden
Destination hash	Source address
Hop count	Payload contents
Packet size	Application-layer data
Timing	Sender identity

Authentication

Node identity is **self-certifying**. A node proves it owns a destination hash by signing with the corresponding Ed25519 private key. No certificates, no PKI, no trust hierarchy.

- **Payment channels**: Both parties sign every state update. Forgery requires the other party's private key.
- **Capability agreements**: Both provider and consumer sign. Neither can forge the other's commitment.

- **Announcements**: Path announcements are signed by the announcing node. Relay nodes update the CompactPathCost running totals (not individually signed — link-layer authentication at each hop is sufficient). Malicious relays can lie about costs, but the economic model disincentivizes this — overpriced nodes are routed around, underpriced nodes lose money.

Privacy

Sender Anonymity

Packets do not carry source addresses. A relay node knows which neighbor sent it a packet, but not whether that neighbor originated the packet or is relaying it from someone else.

Recipient Privacy

Destination hashes are pseudonymous. A hash is not linked to a real-world identity unless the user chooses to publish that association (e.g., via NXS-Name).

Traffic Analysis Resistance

Basic protections (always active):

- Link-layer encryption prevents content inspection
- Variable-rate padding on LoRa links obscures traffic patterns
- No source address in packet headers

Onion Routing (Opt-In)

For high-threat environments where an adversary monitors multiple links simultaneously, per-packet layered encryption is available as an opt-in privacy upgrade via `PathPolicy.ONION_ROUTE`:

```
Onion-routed packet (3-hop default):
  1. Sender selects 3 intermediate relays (at least 1 outside trust neighborhood)
  2. Wraps message in 3 encryption layers (outermost = first relay)
  3. Each layer: 16-byte nonce + 16-byte Poly1305 tag = 32 bytes overhead
  4. Each relay decrypts one layer, reads next-hop destination, forwards
  5. Final relay decrypts innermost layer and delivers to destination

Overhead: 32 bytes × 3 hops = 96 bytes
Usable payload on LoRa (465 max): 369 bytes (~79% efficiency)
```

Key properties:

- **Stateless**: No circuit establishment, no relay-side state. Each packet is independently routable

- **Opt-in**: Enabled per-packet via `PathPolicy.ONION_ROUTE` with configurable hop count (default 3)
- **Cover traffic**: Optional constant-rate dummy packets (1/minute, off by default) for timing analysis resistance on high-threat links
- **Not for voice**: The payload overhead and additional latency make onion routing unsuitable for real-time voice. Recommended for text messaging in high-threat scenarios

Key Rotation

- **Long-lived keys** (Ed25519 identity): Used only for signing, never for encryption
- **Ephemeral keys**: Used for encryption, discarded after use
- Compromise of an ephemeral key does not compromise past or future communications

Sybil Resistance

An attacker can generate unlimited identities (Sybil attack). NEXUS mitigates this through economic mechanisms rather than identity verification:

1. **Payment channel deposits**: Opening a channel requires visible balance. Sybil nodes with no balance cannot participate in the economy.
2. **Reputation accumulation**: Reputation is earned through verified service delivery over time. New identities start with zero reputation. Creating many identities dilutes rather than concentrates reputation.
3. **Trust graph**: A Sybil attacker needs real social relationships to gain trust. Trusted peers vouch economically — they absorb the debts of nodes they trust, making trust costly to extend.
4. **Proof of service**: Stochastic relay rewards use a VRF-based lottery that produces exactly one verifiable outcome per (relay, packet) pair. A node can only earn by actually delivering packets, and cannot grind for favorable lottery outcomes.
5. **Transitive credit limits**: Even if a Sybil node gains one trust relationship, transitive credit is capped at 10% per hop and rate-limited for new relationships.

Reputation

Reputation is a **locally computed, per-neighbor score** — not a global value. There is no network-wide reputation database. Each node maintains its own view of how reliable its peers are.

Reputation State

```
PeerReputation {
    node_id: NodeID,
    relay_score: u16,       // 0–10000 (fixed-point, 2 decimal places)
```

```
    storage_score: u16,     // 0-10000
    compute_score: u16,     // 0-10000
    total_interactions: u32, // number of completed agreements
    failed_interactions: u32,// number of failed/disputed agreements
    first_seen_epoch: u64,  // how long we've known this peer
    last_updated: Timestamp,
}
```

How Reputation Is Earned

Each completed capability agreement adjusts the relevant score:

```
On agreement completion:
  if successful:
    score += (10000 - score) / 100   // diminishing returns — harder to gain at higher
scores
  if failed:
    score -= score / 10              // 10% penalty per failure — fast to lose

New nodes start at score = 0. A node with zero interactions
has zero reputation — not negative, just unknown.
```

How Reputation Is Used

- **Credit line sizing**: Nodes extend larger credit lines to higher-reputation peers
- **Capability selection**: When multiple providers offer the same capability, the consumer considers reputation alongside cost and latency
- **Storage agreement duration**: Nodes with higher storage scores get offered longer storage contracts
- **Epoch consensus**: Epoch proposals from higher-reputation nodes are preferred when competing proposals conflict

Properties

- **Local only**: Each node computes its own reputation scores. No gossip of reputation values — this prevents reputation manipulation by flooding the network with fake endorsements
- **First-hand primary**: Scores are based primarily on direct interactions. First-hand experience always takes precedence over third-party information
- **No global score**: There is no way to ask "what is node X's reputation?" There is only "what is my experience with node X?" This makes reputation Sybil-resistant — an attacker can't inflate a score without actually providing good service to the scoring node

Trust-Weighted Referrals

When a node has no direct experience with a peer, it can query trusted neighbors for their first-hand scores. Referrals help new nodes bootstrap but are tightly bounded to limit manipulation:

- **1-hop only**: Only direct trusted peers can provide referrals. No transitive gossip — a referral from a friend-of-a-friend is not accepted. This limits the manipulation surface to corruption of your direct trusted peers
- **Weight formula**: `referral_weight = trust_score_of_referrer / max_score × 0.3` — even a maximally trusted referrer's opinion carries only 30% of direct experience weight
- **Capped at 50%**: A referred reputation score cannot exceed 5000 (50% of max). A referral alone cannot make a peer fully trusted — direct interaction is required to reach higher scores
- **Overwritten by experience**: Referral scores are advisory. After the first few direct interactions, first-hand experience overwrites the referral entirely
- **Expiry**: Referral scores expire after 500 gossip rounds (~8 hours at 60-second intervals) without refresh from the referrer
- **Anti-collusion**: Since only 1-hop referrals are accepted and each is capped, a colluding cluster must corrupt your direct trusted peers to manipulate scores — which already breaks the trust model regardless of reputation

Key Management

Operation	Method
Generation	Ed25519 keypair from cryptographically secure random source on first boot
Storage	Private key encrypted at rest (ChaCha20-Poly1305 with user passphrase, or hardware secure element)
Recovery	Social recovery via Shamir's Secret Sharing — split key into N shares, recover with K-of-N
Revocation	No global revocation mechanism (intentional — no infrastructure that can be coerced into revoking keys)

The absence of a revocation mechanism is a deliberate tradeoff. A user who loses their key loses their identity and balance, but no authority can forcibly revoke anyone's identity.

Key Compromise Advisory

While there is no revocation, a node that detects its key has been compromised can broadcast an advisory:

```
KeyCompromiseAdvisory {
    compromised_key: Ed25519PublicKey,
    new_key: Ed25519PublicKey,          // optional migration target
    sequence: u64,                      // monotonic counter — prevents replay of old
```

```
advisories
    evidence: enum {
        SignedByBoth(sig_old, sig_new), // proves control of both keys
        SignedByOldOnly(sig_old),       // can only prove old key ownership
    },
    timestamp: u64,
}
```

The `sequence` field is monotonically increasing per compromised key. Receiving nodes only accept an advisory if its sequence is strictly greater than any previously seen advisory for the same `compromised_key`. This prevents an attacker from replaying an old advisory to override a newer one.

This is **advisory, not authoritative**. Receiving nodes may:

- Flag the old identity as potentially compromised
- Require re-authentication for high-value operations
- Accept the new key if evidence includes both signatures (strongest proof)

Conflict resolution: An attacker holding the stolen key could issue a counter-advisory claiming the legitimate owner's *new* key is compromised. Receiving nodes resolve conflicting advisories as follows:

1. `SignedByBoth` **always wins over** `SignedByOldOnly` — proving control of both keys is strictly stronger evidence than proving control of only one
2. **Multiple** `SignedByOldOnly` **advisories cancel out** — if two different advisories both signed only by the old key claim different new keys, both are suspect. Receiving nodes flag the old identity as compromised but accept neither new key automatically.
3. **Trust-weighted resolution** — if the advisory is vouched for by trusted peers (who can attest to knowing the real owner), it is weighted more heavily

This does not prevent an attacker from continuing to use the stolen key. It provides a mechanism for the legitimate owner to signal compromise and begin migration — strictly better than no mechanism at all. The `SignedByBoth` evidence type is the only reliable migration path; users should generate their new keypair **before** the old one is exposed whenever possible.

Cryptographic Primitives Summary

Purpose	Algorithm	Key Size
Identity / Signing	Ed25519	256-bit (32-byte public key)
Key Exchange	X25519 (Curve25519 DH)	256-bit
Identity Hashing	Blake2b	256-bit

Content Hashing	Blake3	256-bit
Symmetric Encryption	ChaCha20-Poly1305	256-bit key, 96-bit nonce
Address Derivation	Blake2b truncated	128-bit (16-byte destination hash)
Relay Lottery (VRF)	ECVRF-ED25519-SHA512-TAI (RFC 9381)	Reuses Ed25519 keypair; 80-byte proof

Hash Algorithm Split

NEXUS uses two hash algorithms for distinct purposes:

- **Blake2b** — Identity derivation and key derivation. Chosen for compatibility with the Ed25519/X25519 ecosystem and its proven security margin. Used in: `destination_hash`, `session_key` derivation.
- **Blake3** — Content addressing and general hashing. Chosen for speed (3x faster than Blake2b on general data) and built-in Merkle tree support for streaming verification. Used in: `DataObject` hash, contract hash, DHT keys, `ChannelState` hash.

Both produce 256-bit outputs. The protocol never mixes them — identity operations use Blake2b, data operations use Blake3.

Ed25519 to X25519 Conversion

X25519 public keys are derived from Ed25519 public keys using the birational map defined in **RFC 7748 Section 4.1**: the Ed25519 public key (a compressed Edwards point) is converted to Montgomery form by computing `u = (1 + y) / (1 - y) mod p`, where `y` is the Edwards y-coordinate and `p = 2^255 - 19`. This is a standard, well-analyzed transformation used by libsodium, OpenSSL, and other major cryptographic libraries.

NXS Token

NXS is the unit of account for the NEXUS network. It is not a speculative asset — it is the internal currency for purchasing capabilities from nodes outside your trust network.

Properties

```
NXS Properties:
  Smallest unit: 1 μNXS (micro-NXS)
  Initial distribution: Proof-of-service mining only (no ICO, no pre-mine)
  Supply ceiling: 2^64 μNXS (~18.4 × 10^18 μNXS, asymptotic — never reached)
```

Supply Model

NXS has an **asymptotic supply ceiling** with **decaying emission**:

Phase	Epoch Range	Emission Per Epoch
Bootstrap	0–99,999	10^12 μNXS (1,000,000 NXS)
Halving 1	100,000–199,999	5 × 10^11 μNXS
Halving 2	200,000–299,999	2.5 × 10^11 μNXS
Halving N	N × 100,000 – (N+1) × 100,000 − 1	10^12 × 2^(−N) μNXS
Tail	When halved reward is below floor	0.1% of circulating supply / estimated epochs per year

```
Emission formula:
  epoch_reward(e) = max(
    10^12 >> (e / 100_000),              // discrete halving (bit-shift)
    circulating_supply * 0.001 / E_year  // tail floor
  )

  E_year = trailing 1,000-epoch moving average of epoch frequency
  Halving is epoch-counted, not wall-clock (partition-safe)
  At ~1 epoch per 10 minutes: 100,000 epochs ≈ 1.9 years
```

The theoretical ceiling is 2^64 μNXS, but it is never reached — tail emission asymptotically approaches it. The initial reward of 10^12 μNXS/epoch yields ~1.5% of the supply ceiling minted in the first halving period, providing strong bootstrap incentive. Discrete halving every 100,000 epochs is epoch-counted (no clock synchronization needed) and trivially computable via bit-shift on integer-only hardware.

The tail ensures ongoing proof-of-service rewards exist indefinitely, funding relay and storage operators. In practice, lost keys (estimated 1–2% of supply annually) offset tail emission, keeping effective circulating supply roughly stable after year ~10.

Typical Costs

Operation	Cost
Expected relay cost per packet	~5 µNXS
Relay lottery payout (on win)	~500 µNXS (5 µNXS ÷ 1/100 win probability)
Expected cost: 1 KB message, 5 hops	~~75 µNXS~~ (3 packets × 5 µNXS × 5 hops)
1 hour of storage (1 MB)	~50 µNXS
1 minute of compute (contract execution)	~30–100 µNXS

The relay lottery pays out infrequently but in larger amounts. Expected value per packet is the same: `500 µNXS × 1/100 = 5 µNXS`. See Stochastic Relay Rewards for the full mechanism.

Economic Architecture

NEXUS has a simple economic model: **free between friends, paid between strangers.**

Free Tier (Trust-Based)

- Traffic between trusted peers is **always free**
- No tokens, no channels, no settlements needed
- A local mesh where everyone trusts each other has **zero economic overhead**

Paid Tier (NXS)

- Traffic crossing trust boundaries triggers stochastic relay rewards
- Relay nodes earn NXS probabilistically — same expected income, far less overhead
- Settled via CRDT ledger

Genesis and Bootstrapping

The bootstrapping problem — needing NXS to use services, but needing to provide services to earn NXS — is solved by separating free-tier operation from the paid economy:

Free-Tier Operation (No NXS Required)

- **Trusted peer communication is always free** — no tokens needed

- **A local mesh works with zero tokens in circulation**
- The protocol is fully functional without any NXS — just limited to your trust network

Proof-of-Service Mining (NXS Genesis)

The stochastic relay lottery serves a dual purpose: it determines who earns and how much, while the **funding source** depends on the economic context:

1. **Minting (subsidy)**: Each epoch, the emission schedule determines how much new NXS is minted. This is distributed proportionally to relay nodes based on their accumulated VRF lottery wins during that epoch — proof that they actually forwarded packets. Minting dominates during bootstrap and decays over time per the emission schedule.

2. **Channel debit (market)**: When a relay wins the lottery and has an open payment channel with the upstream sender, the reward is debited from that channel. The sender pays directly for routing. This becomes the dominant mechanism as NXS enters circulation and channels become widespread.

Both mechanisms coexist. As the economy matures, channel-funded relay payments naturally replace minting as the primary income source for relays, while the decaying emission schedule ensures the transition is smooth.

```
Relay compensation per epoch:
  Epoch mint pool: max(10^12 >> (epoch / 100_000), tail_floor)
    → new supply created (not transferred from a pool)
    → halves every 100,000 epochs; floors at 0.1% annual inflation

  Relay R's mint share: epoch_mint_pool × (R_wins / total_wins_in_epoch)
    → proportional to verified VRF lottery wins
    → a relay with 10% of the epoch's wins gets 10% of the mint pool

  Channel revenue: sum of lottery wins debited from sender channels
    → direct payment, no new supply created

  Total relay income = mint share + channel revenue
```

Bootstrap Sequence

1. Nodes form local meshes (free between trusted peers, no tokens)
2. Gateway nodes bridge to wider network
3. Non-trusted traffic triggers stochastic relay lottery (VRF-based)
4. Lottery wins accumulate as service proofs; epoch minting distributes NXS to relays
5. Relay nodes open payment channels and begin spending NXS on services
6. Senders with NXS fund relay costs via channel debits; minting share decreases

7. Market pricing emerges from supply/demand

Trust-Based Credit

Trusted peers can vouch for each other by extending transitive credit. Each node configures the credit line it extends to its direct trusted peers (e.g., "I'll cover up to 1000 μNXS for Alice"). A friend-of-a-friend gets 10% of that direct limit — backed by the vouching peer's NXS balance. If a credited node defaults, the voucher absorbs the debt. This provides an on-ramp for new users without needing to earn NXS first.

Free direct communication works immediately with no tokens at all. NXS is only needed when your packets traverse untrusted infrastructure.

Why One Global Currency

NXS is a single global unit of account, not a per-community token. This is a deliberate design choice.

The Alternative: Per-Community Currencies

If each isolated community minted its own token, connecting two communities would require a currency exchange — someone to set an exchange rate, provide liquidity, and settle trades. On a mesh network of 50–500 nodes, there is not enough trading volume to sustain a functioning exchange market. The complexity (order books, matching, dispute resolution) vastly exceeds what constrained devices can support.

How One Currency Works Across Partitions

When two communities operate in isolation:

1. **Internally**: Both communities communicate free between trusted peers — no NXS needed
2. **Independently**: Each community mints NXS via proof-of-service, proportional to actual relay work. The CRDT ledger tracks balances independently on each side
3. **On reconnection**: The CRDT ledger merges automatically (CRDTs guarantee convergence). Both communities' NXS is valid because it was earned through real work, not printed arbitrarily

NXS derives its value from **labor** (relaying, storage, compute), not from community membership. One hour of relaying in Community A is roughly equivalent to one hour in Community B. Different hardware costs are reflected in **market pricing** — nodes set their own per-byte charges — not in separate currencies.

Price Discovery Without Fiat

NXS has no fiat exchange rate by design. Its "purchasing power" floats based on supply and demand for services:

```
Abundant relay capacity + low demand → relay prices drop (in μNXS)
Scarce relay capacity + high demand  → relay prices rise (in μNXS)
```

Users don't need to know what 1 μNXS is worth in dollars. They only need to know: "Can I afford this service?" — and the answer is usually yes, because they earn NXS by providing services to others. The economy is circular, not pegged to an external reference.

Economic Design Goals

- **No speculation**: NXS is for purchasing services, not for trading. There is no fiat exchange rate by design.
- **No pre-mine**: All NXS enters circulation through proof-of-service
- **Hoarding-resistant**: NXS has no external exchange value, so accumulating it has no purpose beyond purchasing network services. Tail emission (0.1% annual) mildly dilutes idle holdings. Lost keys (~1–2% annually) permanently remove supply. The economic incentive is to spend NXS on services, not to sit on it.
- **Partition-safe**: The economic layer works correctly during network partitions and converges when they heal
- **Minimal overhead**: Stochastic rewards reduce economic bandwidth overhead by ~10x compared to per-packet payment
- **Communities first**: Trusted peer communication is free. The economic layer only activates at trust boundaries.

Stochastic Relay Rewards

Relay nodes are compensated through **probabilistic micropayments** rather than per-packet accounting. This dramatically reduces payment overhead on constrained radio links while providing the same expected income over time.

Why Not Per-Packet Payment?

Per-packet payment requires a channel state update for every batch of relayed packets. Even batched, this consumes significant bandwidth on LoRa links. The insight: relay rewards don't need to be deterministic — they can be probabilistic, like mining, achieving the same expected value with far less overhead.

How Stochastic Rewards Work

Each relayed packet is checked against a **VRF-based lottery**. The relay computes a Verifiable Random Function output over the packet, producing a deterministic but unpredictable result that anyone can verify:

```
Relay reward lottery (VRF-based):
  1. Relay computes: (vrf_output, vrf_proof) = VRF_prove(relay_private_key, packet_hash)
  2. Check: vrf_output < difficulty_target
  3. If win: reward = per_packet_cost × (1 / win_probability)
  4. Expected value per packet = reward × probability = per_packet_cost ✓
  5. Verification: VRF_verify(relay_public_key, packet_hash, vrf_output, vrf_proof)
```

Why VRF, not a random nonce? If the relay chose its own nonce, it could grind through values until it found a winner for every packet, extracting the maximum reward every time. The VRF produces exactly **one valid output** per (relay key, packet) pair — the relay cannot influence the lottery outcome. The proof lets any party verify the result without the relay's private key.

The VRF used is **ECVRF-ED25519-SHA512-TAI** (RFC 9381), which reuses the relay's existing Ed25519 keypair. VRF proof size is 80 bytes, included only in winning lottery claims (not in every packet).

Example

Parameter	Value
Per-packet relay cost	5 µNXS
Win probability	1/100

Reward per win	500 μNXS
Expected value per packet	5 μNXS (same)
Channel updates needed	1 per ~100 packets (vs. every batch)

A relay handling 10 packets/minute triggers a channel update approximately once every 10 minutes — a **10x reduction** in payment overhead compared to per-minute batching.

Adaptive Difficulty

The win probability adjusts based on traffic volume. Each relay computes its own difficulty locally based on its observed traffic rate — no global synchronization needed:

```
Difficulty adjustment:
  target_updates_per_minute = 0.1  (one channel update per ~10 minutes)
  observed_packets_per_minute = trailing 5-minute moving average

  win_probability = target_updates_per_minute / observed_packets_per_minute
  win_probability = clamp(win_probability, 1/10000, 1/5)  // bounds

  difficulty_target = MAX_VRF_OUTPUT × win_probability

Traffic tiers (approximate):
  High-traffic links (>100 packets/min):   ~1/1000 probability, larger rewards
  Medium-traffic links (10-100 packets/min): ~1/100 probability
  Low-traffic links (<10 packets/min):     ~1/10 probability, smaller rewards

  Reward on win = per_packet_cost × (1 / win_probability)
  Expected value per packet = per_packet_cost (always, regardless of difficulty)
```

Low-traffic links use higher win probability to reduce variance — a relay handling only a few packets per hour will still receive rewards regularly. The difficulty is computed independently by each relay per-link, so different links on the same node may have different difficulties.

Bilateral Payment Channels

Rewards are settled through bilateral channels between direct neighbors. Unlike Lightning-style multi-hop payment routing, NEXUS uses simple per-hop channels:

- Only two parties need to coordinate
- Both parties are direct neighbors (by definition)
- No global coordination needed

Channel State

```
ChannelState {
    channel_id: [u8; 16],       // truncated Blake3 hash (16 bytes)
    party_a: [u8; 16],          // destination hash (16 bytes)
    party_b: [u8; 16],          // destination hash (16 bytes)
    balance_a: u64,             // party A's current balance (8 bytes)
    balance_b: u64,             // party B's current balance (8 bytes)
    sequence: u64,              // monotonically increasing (8 bytes)
    sig_a: Ed25519Signature,    // party A's signature (64 bytes)
    sig_b: Ed25519Signature,    // party B's signature (64 bytes)
}
// Total: 16 + 16 + 16 + 8 + 8 + 8 + 64 + 64 = 200 bytes
```

Channel Lifecycle

1. **Open**: Both parties agree on initial balances. Both sign the opening state.
2. **Update**: On each lottery win, the balance shifts by the reward amount. Channel updates are infrequent — only triggered by wins.
3. **Settle**: Either party can request settlement. Both sign a `SettlementRecord` that is gossiped to the network and applied to the CRDT ledger.
4. **Dispute**: If one party submits an old state, the counterparty can submit a higher-sequence state within a **2,880 gossip round challenge window** (~48 hours at 60-second rounds). The higher sequence always wins.
5. **Abandonment**: If a channel has no updates for **4 epochs**, either party can unilaterally close with the last mutually-signed state. This prevents permanent fund lockup.

Multi-Hop Payment

When Alice sends a packet through Bob → Carol → Dave, each relay independently runs the VRF lottery:

```
Alice ──→ Bob ──→ Carol ──→ Dave
           │        │
        lottery?  lottery?
```

A lottery win triggers compensation through one or both mechanisms:

1. **Channel debit** (if a channel exists with the upstream sender): Bob's win debits Alice's channel with Bob; Carol's win debits Bob's channel with Carol. This is the steady-state mechanism once NXS is circulating.
2. **Mining proof** (always): The VRF proof is accumulated as a service proof entitling the relay to a share of the epoch's minting reward. This is the dominant income source during bootstrap and provides a baseline subsidy that decays over time.

Most packets trigger no channel update at all. Each hop is independent — no end-to-end payment coordination.

Efficiency on Constrained Links

Metric	Value
State update size	200 bytes
Average updates per hour (1/100 prob, 10 pkts/min)	~6
Bandwidth overhead at 1 kbps LoRa	~0.3%
Compared to per-minute batching	**~8x reduction**

The stochastic model fits within Tier 2 (economic) of the gossip bandwidth budget even on the most constrained links.

Trusted Peers: Free Relay

Nodes relay traffic for trusted peers for free — no lottery, no channel updates. The stochastic reward system only activates for traffic between non-trusted nodes. This mirrors the real world: you help your neighbors for free, but charge strangers for using your infrastructure.

CRDT Ledger

The global balance sheet in NEXUS is a CRDT-based distributed ledger. Not a blockchain. No consensus protocol. No mining. CRDTs (Conflict-free Replicated Data Types) provide automatic, deterministic convergence without coordination — exactly what a partition-tolerant network requires.

Why Not a Blockchain?

Blockchains require global consensus: all nodes must agree on the order of transactions. This is fundamentally incompatible with NEXUS's partition tolerance requirement. When a village mesh is disconnected from the wider network for days or weeks, it must still process payments internally. CRDTs make this possible.

Account State

```
AccountState {
    node_id: NodeID,
    total_earned: GCounter,      // grow-only, per-node entries, merge = pointwise max
    total_spent: GCounter,       // grow-only, same structure
    // Balance = earned - spent (derived, never stored)
    settlements: GSet<SettlementHash>,  // dedup set
}
```

How GCounters Work

A GCounter (grow-only counter) is a CRDT that can only increase. Each node maintains its own entry, and merging takes the pointwise maximum:

- Node A says "Node X has earned 100" and Node B says "Node X has earned 150"
- Merge result: "Node X has earned 150" (the higher value wins)
- This works regardless of the order updates arrive

Balance is always derived: `balance = total_earned - total_spent`. It is never stored directly.

Settlement Flow

```
SettlementRecord {
    channel_id: [u8; 16],
    party_a: [u8; 16],
```

```
    party_b: [u8; 16],
    amount_a_to_b: i64,          // net transfer (negative = B pays A)
    final_sequence: u64,         // channel state sequence at settlement
    sig_a: Ed25519Signature,
    sig_b: Ed25519Signature,
}
// settlement_hash = Blake3(channel_id || party_a || party_b || amount || sequence)
// Signatures are over the settlement_hash (sign-then-hash, not hash-then-sign)

Settlement flow:
1. Alice and Bob settle their payment channel (SettlementRecord signed by both)
2. SettlementRecord is gossiped to the network
3. Each receiving node validates:
   - Both signatures verify against the settlement_hash
   - settlement_hash is not already in the GSet (dedup)
   - Neither party's derived balance goes negative after applying
   - If any check fails: silently drop (do not gossip)
4. If valid and new:
   - Increment party_a's spent / party_b's earned (or vice versa)
   - Add settlement_hash to GSet
   - Gossip forward to neighbors
5. Convergence: O(log N) gossip rounds
```

Settlement validation is performed by **every node** that receives the record. This is cheap (two Ed25519 signature verifications + one Blake3 hash + one GSet lookup) and ensures no node relies on a single validator. Invalid settlements are dropped silently — no penalty, no gossip.

Gossip Bandwidth

With stochastic relay rewards, settlements happen far less frequently than under per-packet payment — channel updates only trigger on lottery wins. This dramatically reduces the volume of settlement records the CRDT ledger must gossip.

- Baseline gossip: proportional to settlement frequency (~100-200 bytes per settlement)
- On constrained links (< 10 kbps): batching interval increases, reducing overhead further
- Fits within **Tier 2 (economic)** of the gossip bandwidth budget

Double-Spend Prevention

Double-spend prevention is **probabilistic, not perfect**. Perfect prevention requires global consensus, which contradicts partition tolerance. NEXUS mitigates double-spending through multiple layers:

1. **Channel deposits**: Both parties must have visible balance to open a channel
2. **Credit limits**: Based on locally-known balance
3. **Reputation staking**: Long-lived nodes get higher credit limits

4. **Fraud detection**: Overdrafts are flagged network-wide; the offending node is blacklisted
5. **Economic disincentive**: For micropayments, blacklisting makes cheating unprofitable — the cost of losing your identity and accumulated reputation exceeds any single double-spend gain

Partition Minting and Supply Convergence

When the network is partitioned, each partition independently runs the emission schedule and mints NXS proportional to local relay work. On merge, the GCounter merge (pointwise max per account) preserves individual balance correctness — no one loses earned NXS. However, **total minted supply across all partitions exceeds what a single-partition emission schedule would have produced.**

```
Example:
  Epoch 5 emission schedule: 1000 NXS total
  Partition A (60% of nodes): mints 1000 NXS to its relays
  Partition B (40% of nodes): mints 1000 NXS to its relays
  On merge: total minted in epoch 5 = 2000 NXS (not 1000)
```

This is an accepted tradeoff of partition tolerance — the alternative (coordinated minting) requires global consensus, which is incompatible with the design. The overminting is bounded:

1. **Proportional to partition count**: Two partitions produce at most 2x; three produce at most 3x. Prolonged fragmentation into many partitions is rare in practice.
2. **Detectable on merge**: When partitions heal, nodes can observe that multiple epoch proposals exist for the same epoch number. Post-merge epochs resume normal single-emission-schedule minting.
3. **Self-correcting over time**: The emission schedule decays geometrically. A one-time overmint during a partition is a fixed quantity that becomes negligible relative to total supply. The asymptotic ceiling is unchanged — it is just approached slightly faster.
4. **Offset by lost keys**: The estimated 1-2% annual key loss rate dwarfs partition minting overshoot in most scenarios.

The protocol does not attempt to "claw back" overminted supply. The cost of the mechanism (requiring consensus) exceeds the cost of the problem (minor temporary supply inflation during rare partitions).

Relay Compensation Tracking

Relay minting rewards are computed during epoch finalization. Each relay accumulates VRF lottery win proofs during the epoch and includes them in its epoch acknowledgment:

```
RelayWinSummary {
    relay_id: NodeID,
    win_count: u32,                    // number of VRF lottery wins this epoch
    sample_proofs: Vec<VRFProof>,      // subset of proofs (up to 10) for spot-checking
    total_wins_hash: Blake3Hash,       // Blake3 of all win proofs (verifiable if
challenged)
}
```

The epoch proposer aggregates win summaries from gossip and includes total win counts in the epoch snapshot. Mint share for each relay is `epoch_reward × (relay_wins / total_wins)`. Full proof sets are not gossiped (too large) — only summaries with spot-check samples. Any node can challenge a relay's win count during the 4-epoch grace period by requesting the full proof set. Fraudulent claims result in the relay's minting share being redistributed and the relay's reputation being penalized.

Epoch Compaction

The settlement GSet grows without bound. The Epoch Checkpoint Protocol solves this by periodically snapshotting the ledger state.

```
Epoch {
    epoch_number: u64,
    timestamp: u64,

    // Frozen account balances at this epoch
    account_snapshot: Map<NodeID, (total_earned, total_spent)>,

    // Bloom filter of ALL settlement hashes included
    included_settlements: BloomFilter,

    // Active set: defines the 67% threshold denominator
    active_set_hash: Blake3Hash,    // hash of sorted NodeIDs active in last 2 epochs
    active_set_size: u32,           // number of nodes in the active set

    // Acknowledgment tracking
    ack_count: u32,
    ack_threshold: u32,             // 67% of active_set_size
    status: enum { Proposed, Active, Finalized, Archived },
}
```

Epoch Triggers

An epoch is triggered when **any** of these conditions is met:

Trigger	Threshold	Purpose

Settlement count	≥ 10,000 batches	Standard trigger for large meshes
GSet memory	≥ 500 KB	Protects constrained devices (ESP32 has ~520 KB usable RAM)
Small partition	≥ max(200, active_set_size × 10) settlements AND ≥ 1,000 gossip rounds since last epoch	Prevents stagnation in small partitions

The small-partition trigger ensures a 20-node village doesn't wait months for an epoch. At 200 settlements (the minimum), the GSet is ~6.4 KB — well within ESP32 capacity. The 1,000 gossip round floor (roughly 17 hours at 60-second intervals) prevents epochs from firing too rapidly in tiny partitions with bursty activity.

Epoch Proposer Selection

Eligibility requirements adapt to partition size:

1. The node has processed ≥ min(10,000, current epoch trigger threshold) settlement batches since the last epoch
2. The node has direct links to ≥ min(3, active_set_size / 2) active nodes
3. No other epoch proposal for this `epoch_number` has been seen

In a 20-node partition, a node needs only 3 direct links (not 10) and 200 processed settlements (not 10,000) to propose.

Conflict resolution: If multiple proposals for the same `epoch_number` arrive, nodes ACK the one with the **highest settlement count** (most complete state). Ties broken by lowest proposer `destination_hash`.

Epoch proposals are rate-limited to one per node per epoch period. Proposals that don't meet eligibility are silently ignored.

Epoch Lifecycle

1. **Propose**: An eligible node proposes a new epoch with a snapshot of current state. The proposal includes an `active_set_hash` — a Blake3 hash of the sorted list of NodeIDs in the active set, as observed by the proposer. This fixes the denominator for the 67% threshold.

Active set definition: A node is in the active set if it appears as `party_a` or `party_b` in at least one `SettlementRecord` within the last 2 epochs. Relay-only nodes (that relay packets but never settle channels) are not in the active set — they participate in the economy via mining proofs, not via epoch consensus. This keeps the active set small and the 67% threshold meaningful. 2. **Acknowledge**: Nodes compare against their local state. If they've seen the same or more settlements, they ACK. If they have unseen settlements, they gossip those first. A node ACKs the

proposal's `active_set_hash` — even if its own view differs slightly, it agrees to use the proposer's set as the threshold denominator for this epoch. 3. **Activate**: At 67% acknowledgment (of the active set defined in the proposal), the epoch becomes active. Nodes can discard individual settlement records and use only the bloom filter for dedup. If a significant fraction of nodes reject the active set (NAK), the proposer must re-propose with an updated set after further gossip convergence. 4. **Verification window**: During the grace period (4 epochs after activation), any node can submit a **settlement proof** — the full `SettlementRecord` — for any settlement it believes was missed. If the settlement is valid (signatures check) and NOT in the epoch's bloom filter, it is applied on top of the snapshot. 5. **Finalize**: After the grace period, previous epoch data is fully discarded. The bloom filter is the final word.

Late Arrivals After Compaction

When a node reconnects after an epoch has been compacted, it checks its unprocessed settlements against the epoch's bloom filter:

- **Present in filter**: Already counted, discard
- **Absent from filter**: New settlement, apply on top of snapshot. If within the verification window, submit as a settlement proof.

Bloom Filter Sizing

Data	Size
1M settlement hashes (raw)	~32 MB
Bloom filter (0.01% false positive rate)	~2.4 MB
Target epoch frequency	~10,000 settlement batches
Per-node storage target	Under 5 MB

The false positive rate is set to **0.01% (1 in 10,000)** rather than 1%, because false positives cause legitimate settlements to be silently treated as duplicates. At 0.01%, the expected loss is negligible (~1 settlement per 10,000), and the verification window provides a recovery mechanism for any that are caught.

Construction: The bloom filter uses `k = 13` hash functions derived from Blake3:

```
Bloom filter hash construction:
  For each settlement_hash and index i in [0, k):
    h_i = Blake3(settlement_hash || i as u8) truncated to 32 bits
    bit_position = h_i mod m  (where m = total bits in filter)

  Bits per element: m/n = -ln(p) / (ln2)² ≈ 19.2 bits at p = 0.0001
  k = -log₂(p) ≈ 13.3, rounded to 13
```

```
  For 10,000 settlements: m = 192,000 bits = 24 KB
  For 1M settlements: m = 19.2M bits ≈ 2.4 MB
```

The Merkle tree over the account snapshot also uses Blake3 (consistent with all content hashing in NEXUS). Leaf nodes are `Blake3(NodeID || total_earned || total_spent)`, and internal nodes are `Blake3(left_child || right_child)`.

Critical retention rule: Both parties to a settlement **must retain the full `SettlementRecord`** until the epoch's verification window closes (4 epochs after activation). If both parties discard the record after epoch activation (believing it was included) and a bloom filter false positive caused it to be missed, the settlement would be permanently lost. During the verification window, each party independently checks that its settlements are reflected in the snapshot; if any are missing, it submits a settlement proof. Only after the window closes may the full record be discarded.

Snapshot Scaling

At 1M+ nodes, the flat `account_snapshot` is ~32 MB — too large for constrained devices. The solution is a **Merkle-tree snapshot** with sparse views.

Full snapshot (backbone/gateway nodes only): The account snapshot is stored as a sorted Merkle tree keyed by NodeID. Only nodes that participate in epoch consensus need the full tree. At 1M nodes and 32 bytes per entry, this is ~32 MB — feasible for nodes with SSDs.

Sparse snapshot (everyone else): Constrained devices store only:

- Their own balance
- Balances of direct channel partners
- Balances of trust graph neighbors (Ring 0-2)
- The Merkle root of the full snapshot

For a typical node with ~50 relevant accounts: 50 × 32 bytes = 1.6 KB.

On-demand balance verification: When a constrained node needs a balance it doesn't have locally (e.g., to extend credit to a new node), it requests a Merkle proof from any capable peer:

```
BalanceProof {
    node_id: NodeID,
    total_earned: u64,
    total_spent: u64,
    merkle_siblings: Vec<Blake3Hash>,  // path from leaf to root
    epoch_number: u64,
}
// Size: ~640 bytes for 1M nodes (20 tree levels × 32-byte hashes)
```

The constrained node verifies the proof against the Merkle root it already has. This proves the balance is in the snapshot without storing the full 32 MB.

Constrained Node Epoch Summary

LoRa nodes and other constrained devices don't participate in epoch consensus. They receive a compact summary from their nearest capable peer:

```
EpochSummary {
    epoch_number: u64,
    merkle_root: Blake3Hash,               // root of full account snapshot
    my_balance: (u64, u64),                // (total_earned, total_spent)
    partner_balances: Vec<(NodeID, u64, u64)>, // channel partners + trust neighbors
    bloom_segment: BloomFilter,            // relevant portion of settlement bloom
}
```

Typical size: under 5 KB for a node with 20-30 channel partners.

Trust & Neighborhoods

Communities in NEXUS are **emergent, not declared**. There are no admin-created "zones" to join, no governance to negotiate, no artificial boundaries between groups. Instead, communities form naturally from a trust graph — just like in the real world.

The Trust Graph

Each node maintains a set of trusted peers:

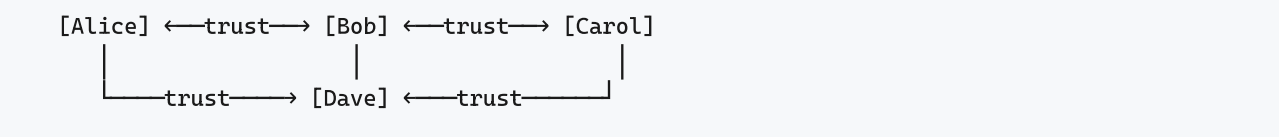
```
TrustConfig {
    // Peers I trust — relay their traffic for free
    trusted_peers: Set<NodeID>,

    // What I charge non-trusted traffic
    default_cost_per_byte: u64,

    // Per-peer cost overrides (discount for friends-of-friends, etc.)
    cost_overrides: Map<NodeID, u64>,

    // Optional self-assigned label (purely informational)
    community_label: Option<String>,    // e.g., "portland-mesh"
}
```

Adding a trusted peer is the only social action in NEXUS. Everything else — free local communication, community identity, credit lines — emerges from the trust graph.

Trust relationships are **asymmetric and revocable at any time**. Removing a node from `trusted_peers` immediately ends free relay for that node and downgrades any stored data from "trusted peer" to normal priority in the garbage collection policy. Cost overrides are unidirectional — they apply to outbound traffic pricing from the configuring node only.

How Communities Emerge

When a cluster of nodes all trust each other, a **neighborhood** forms:



Alice, Bob, Carol, and Dave are a neighborhood. No one "created" it. No one "joined" it. It exists because they trust each other.

Properties

- **No admin**: Nobody runs the neighborhood. It has no keys, no governance, no admission policy.
- **No fragmentation**: The trust graph is continuous. There are no hard boundaries between communities — neighborhoods overlap naturally when people have friends in multiple clusters.
- **No UX burden**: You just mark people as trusted. The same action you'd take when adding a contact.
- **Fully decentralized**: There is nothing to attack, take over, or censor.

Free Local Communication

Traffic between trusted peers is **always free**. A relay node checks its trust list:

```
Relay decision:
  if sender is trusted AND destination is trusted:
    relay for free (no lottery, no channel update)
  else if sender is trusted:
    relay for free (helping a friend send outbound)
  else:
    relay with stochastic reward lottery
```

Note the asymmetry: a relay helps its trusted peers **send** traffic for free, but does not relay free traffic from strangers just because the destination is trusted. Without this rule, an untrusted node could route unlimited free traffic through you to any of your trusted peers, shifting relay costs onto you without compensation.

This means a village mesh where everyone trusts each other operates with **zero economic overhead** — no tokens, no channels, no settlements. The economic layer only activates for traffic crossing trust boundaries.

Trust-Based Credit

When a node needs NXS (e.g., to reach beyond its trusted neighborhood), its trusted peers can vouch for it:

```
Transitive credit:
  Direct trust:           full credit line (set by trusting peer)
  Friend-of-friend (2 hops): 10% of direct credit line
  3+ hops of trust:        no credit (too diluted)

  If a credited node defaults, the vouching peer absorbs the debt.
  This makes trust economically meaningful — you only trust people
  you'd lend to.
```

The credit line is **rate-limited** for safety:

Trust Distance	Max Credit Rate
Direct trusted peer	Configurable by trusting node
Friend-of-friend	10% of direct limit
Beyond 2 hops	No transitive credit

Community Labels

Nodes can optionally self-assign a `community_label` string:

```
Alice sets:  community_label = "portland-mesh"
Bob sets:    community_label = "portland-mesh"
Carol sets:  community_label = "portland-mesh"
```

This label is:

- **Self-assigned** — no one approves it, no authority enforces uniqueness
- **Not authoritative** — it carries no protocol-level privileges (it cannot grant access, waive fees, or modify trust)
- **Not unique** — multiple disjoint clusters can use the same label
- **Used by services** — NXS-Name scopes human-readable names by label, NXS-Pub supports `Neighborhood(label)` subscriptions, and NXS-DHT uses labels for content scoping
- **Useful for discovery** — "find nodes labeled 'portland-mesh' near me"

Community labels enable human-readable naming and discovery without any of the governance overhead of explicit zones.

Comparison: Zones vs. Trust Neighborhoods

Aspect	Explicit Zones (old)	Trust Neighborhoods (current)
Creation	Someone creates a zone	Emerges from mutual trust
Joining	Request + approval	Mark someone as trusted
Governance	Admin keys, voting	None needed
Boundaries	Hard, declared	Soft, overlapping
Free communication	Within zone boundary	Between any trusted peers
Naming	`alice@zone-name`	`alice@community-label`

Sybil resistance	Admission policy	Trust is social and economic (you absorb their debts)
UX complexity	Create, join, configure	Add contacts

Sybil Mitigation

The trust graph provides natural Sybil resistance:

1. **Trust has economic cost**: Vouching for a node means absorbing its potential debts. Sybil identities with no real relationships get no credit.
2. **Rate limiting**: Even if a malicious node gains one trust relationship, transitive credit is capped at 10% per hop.
3. **Reputation**: A node's usefulness as a relay/service provider is what earns trust over time. Creating many identities dilutes reputation rather than concentrating it.
4. **Local detection**: A node's trust graph is visible to its peers. A node trusting an unusual number of new, unproven identities is itself suspicious.

Real-World Parallels

Real World	NEXUS Trust
Talk to your neighbor for free	Free relay between trusted peers
Lend money to a friend	Transitive credit via trust
Wouldn't lend to a stranger	No credit without trust chain
Communities aren't corporations	Neighborhoods have no admin
You belong to multiple groups	Trust graph is continuous, not partitioned
Reputation builds over time	Trust earned through reliable service

Real-World Economics

NEXUS doesn't exist in a vacuum. It interacts with the existing internet economy — ISPs, cloud providers, and the people who pay for connectivity today. This page examines what happens when a mesh network meets existing infrastructure economics.

The Apartment Building Scenario

Consider a typical apartment building in Denmark:

```
Current model:
  50 apartments × 200 kr/month = 10,000 kr/month to ISPs
  Average utilization per connection: <5%
  Each apartment has its own router, its own subscription, its own bill

NEXUS model:
  2–3 gateway nodes with internet subscriptions = 400–600 kr/month to ISPs
  Gateway nodes share internet via WiFi mesh to all 50 apartments
  Other 47 apartments pay gateway operators in NXS
  ISP revenue from building: drops ~94%
```

Why This Works

Residential internet connections are massively over-provisioned. A 1 Gbps connection serving one household averages under 50 Mbps actual usage, and most of that is concentrated in evening hours. The infrastructure exists to handle peak load, but sits idle the vast majority of the time.

With NEXUS, 2-3 well-placed gateway nodes with good internet connections can serve an entire building. The gateway operators earn NXS from the other residents — effectively becoming micro-ISPs within their building.

What Happens to ISPs?

NEXUS doesn't kill ISPs. It restructures them.

Today	With NEXUS
ISPs sell per-household subscriptions	ISPs sell per-building or per-community connections
Revenue depends on subscriber count	Revenue depends on bandwidth sold
Last-mile infrastructure to every apartment	Last-mile to building entry point; mesh handles internal distribution
ISPs handle per-customer support	Gateway operators handle local support

ISPs own the customer relationship	The community owns its own network

The key insight: **ISPs already don't want to be last-mile providers.** Last-mile infrastructure (running cable to every apartment) is their most expensive, lowest-margin business. NEXUS handles last-mile distribution through the mesh, letting ISPs focus on what they're actually good at — backbone transit and peering.

ISPs would likely respond by:

1. Offering **building connections** — one fat pipe per building at a higher bandwidth tier
2. Pricing by **bandwidth consumed**, not by connection count
3. Becoming **backbone providers** to NEXUS gateway operators
4. Running their own **NEXUS backbone nodes** to earn routing fees

The Math for Gateway Operators

```
Gateway operator costs:
  Internet subscription: 200 kr/month
  Hardware (Pi 4 + LoRa + modem): ~300 kr one-time (~25 kr/month amortized over 1 year)
  Total: ~225 kr/month

Gateway operator revenue:
  ~47 apartments paying for shared internet
  If each pays 50 kr/month equivalent in NXS: 2,350 kr/month
  After subtracting costs: ~2,125 kr/month profit

Resident savings:
  Was paying: 200 kr/month
  Now paying: ~50 kr/month in NXS
  Saving: 150 kr/month (75% reduction)
```

Both sides win. Gateway operators earn significant income from hardware they'd have anyway. Residents save money. The only loser is the ISP's per-household billing model — which was always an artifact of last-mile economics, not actual cost.

How You Earn on NEXUS

Every node earns proportionally to the value it provides:

Relay Earnings

The simplest way to earn. Any node that forwards packets for non-trusted traffic participates in the stochastic relay lottery. More traffic through your node = more lottery wins = more NXS.

```
Relay earnings estimate (at ~5 μNXS expected reward per packet):
  Minimal relay (ESP32 + LoRa): ~5,000–50,000 μNXS/month
    → ~30–300 packets/day, zero operating cost (solar powered)

  Community bridge (Pi Zero + WiFi): ~50,000–500,000 μNXS/month
    → Bridges LoRa to WiFi, moderate traffic

  Gateway (Pi 4 + cellular): ~500,000–5,000,000 μNXS/month
    → Internet uplink, high-value traffic

  Backbone (mini PC + directional WiFi): 5,000,000+ μNXS/month
    → High-throughput transit between mesh segments
```

Storage Earnings

Nodes with disk space earn by storing data for the network via NXS-Store:

- Store popular content that others request frequently
- Host replicated data for availability
- Cache content for faster local access

Compute Earnings

Nodes with CPUs or GPUs earn by executing contracts and offering inference via NXS-Compute:

- Run NXS-Byte contracts for constrained nodes
- Offer WASM execution for heavier workloads
- Provide ML inference (speech-to-text, translation, image generation)

Gateway Earnings

The highest-value service. Internet gateway operators earn from:

- HTTP proxy services
- DNS relay
- Bridge traffic between mesh and internet
- All of the above, plus relay/storage/compute earnings

What Makes a Node Valuable?

The marketplace naturally prices capabilities based on scarcity and utility:

Factor	Effect on Earnings
Connectivity	More links = more routing traffic = more relay earnings

Location	Strategic position (bridge between clusters) = higher routing value
Uptime	24/7 availability = more agreements, better reputation
Storage capacity	More disk = more storage contracts
Compute power	GPU = high-value inference contracts
Internet access	Gateway capability = premium pricing
Trust network size	More trusted peers = higher credit lines, more routing

Broader Economic Implications

For Developing Regions

In areas with no ISP at all, NEXUS enables community networks from scratch:

1. One satellite or cellular connection serves an entire village via mesh
2. The gateway operator earns from the community
3. Community members earn by relaying for each other and for outsiders
4. Economic activity within the mesh is free (trusted peers)
5. External connectivity costs are shared, not per-household

For Urban Areas

In cities where internet is available but expensive:

1. Shared internet connections reduce per-household costs by 50-75%
2. Local services (storage, compute, messaging) run on the mesh with no cloud dependency
3. Community infrastructure becomes an income source, not a cost center

For Censorship-Resistant Communication

When governments control the internet:

1. The mesh operates independently of ISP infrastructure
2. Even if internet gateways are shut down, local communication continues
3. Gateway nodes with satellite uplinks or VPN tunnels become high-value — and the market prices them accordingly

Layer 4: Capability Marketplace

The capability marketplace is the unifying abstraction of NEXUS. Every node advertises what it can do. Every node can request capabilities it lacks. The marketplace matches supply and demand through local, bilateral negotiation — no central coordinator.

This is the layer that makes NEXUS a **distributed computer** rather than just a network.

The Unifying Abstraction

In NEXUS, there are no fixed node roles. Instead:

- A node with a LoRa radio and solar panel advertises: "*I can relay packets 24/7*"
- A node with a GPU advertises: "*I can run Whisper speech-to-text*"
- A node with an SSD advertises: "*I can store 100 GB of data*"
- A node with a cellular modem advertises: "*I can route to the internet*"

Each of these is a **capability** — discoverable, negotiable, verifiable, and payable.

Capability Advertisement

Every node broadcasts its capabilities to the network:

```
NodeCapabilities {
    node_id: NodeID,
    timestamp: Timestamp,
    signature: Ed25519Signature,

    // ── CONNECTIVITY ──
    interfaces: [{
        medium: TransportType,
        bandwidth_bps: u64,
        latency_ms: u32,
        reliability: u8,            // 0-255 (avoids FP on constrained devices)
        cost_per_byte: u64,
        internet_gateway: bool,
    }],

    // ── COMPUTE ──
    compute: {
        cpu_class: enum { Micro, Low, Medium, High },
        available_memory_mb: u32,
        nxs_byte: bool,             // can run basic contracts
        wasm: bool,                 // can run full WASM
```

```
        cost_per_cycle: u64,
        offered_functions: [{
            function_id: Hash,
            description: String,
            cost_structure: CostStructure,
            max_concurrent: u32,
        }],
    },

    // ── STORAGE ──
    storage: {
        available_bytes: u64,
        storage_class: enum { Volatile, Flash, SSD, HDD },
        cost_per_byte_day: u64,
        max_object_size: u32,
        serves_content: bool,
    },

    // ── AVAILABILITY ──
    uptime_pattern: enum {
        AlwaysOn, Solar, Intermittent, Scheduled(schedule),
    },
}
```

No Special Protocol Primitives

Heavy compute like ML inference, transcription, translation, and text-to-speech are **not protocol primitives**. They are compute capabilities offered by nodes that have the hardware to run them.

A node with a GPU advertises `offered_functions: [whisper-small, piper-tts]`. A consumer requests execution through the standard compute delegation path. The protocol is agnostic to what the function does — it only cares about discovery, negotiation, verification, and payment.

Emergent Specialization

Nodes naturally specialize based on hardware and market dynamics:

Hardware	Natural Specialization	Earns From	Delegates
ESP32 + LoRa + solar	Packet relay, availability	Routing fees	Everything else
Raspberry Pi + LoRa + WiFi	Compute, LoRa/WiFi bridge	Compute delegation, bridging	Bulk storage
Mini PC + SSD + Ethernet	Storage, DHT, HTTP proxy	Storage fees, proxy fees	Nothing
Phone (intermittent)	Consumer, occasional relay	Relaying while moving	Almost everything

GPU workstation	Heavy compute (inference, etc.)	Compute fees	Nothing

Capability Chains

Delegation cascades naturally:

```
Node A (LoRa relay)
  └── delegates compute to → Node B (Raspberry Pi)
      └── delegates storage to → Node C (Mini PC + SSD)
          └── delegates connectivity to → Node D (Gateway)
```

Each link is a bilateral agreement with its own payment channel. No central coordination required.

Capability Discovery

Discovery uses concentric rings to minimize bandwidth while ensuring nodes can find the capabilities they need. Most needs are satisfied locally — physically close nodes are cheapest and fastest.

Discovery Rings

Ring 0 — Direct Neighbors

```
Scope: Nodes directly connected via any transport
Update frequency: Every gossip round (60 seconds)
Detail level: Full capability exchange
Cost: Free (direct neighbor communication)
```

This is the most detailed and most frequently updated view. A node knows exactly what its immediate neighbors can offer.

Ring 1 — 2-3 Hops

```
Scope: Nodes reachable in 2–3 hops
Update frequency: Every few minutes
Detail level: Summarized capabilities, aggregated by type
Example: "There's a WASM node 2 hops away, cost ~X"
```

Capabilities are summarized to reduce gossip bandwidth. Instead of full advertisements, nodes share aggregated summaries using `CapabilitySummary` records:

```
CapabilitySummary {
    type: u8,           // matches beacon bitfield (0=relay, 1=gateway, 2=storage, etc.)
    count: u8,          // number of providers of this type (capped at 255)
    min_cost: u16,      // cheapest provider (log₂-encoded µNXS/byte, same as
CompactPathCost)
    avg_cost: u16,      // average cost across providers
    min_hops: u8,       // nearest provider (hop count)
    max_hops: u8,       // farthest provider (hop count)
}
// 8 bytes per capability type; typical Ring 1 summary: 5–6 types × 8 = 40–48 bytes
```

A Ring 1 gossip message contains one `CapabilitySummary` per capability type present in the 2-3 hop neighborhood. Nodes that appear in multiple capability types are counted in each.

Ring 2 — Trust Neighborhood

```
Scope: Nodes reachable through the trust graph (friends of friends)
Update frequency: Periodic, via trust-weighted gossip
Detail level: Neighborhood capability summary
Example: "Your neighborhood has 5 gateways, 20 storage nodes"
```

The trust graph provides a natural scope for aggregated capability information. Trusted peers share more detailed information than strangers — this is both efficient (trust = proximity in most cases) and privacy-preserving.

Ring 3 — Beyond Neighborhood

```
Scope: Nodes beyond the trust graph
Update frequency: On demand (query-based)
Detail level: Coarse hints via Reticulum announces
Example: "A node with GPU compute exists at cost ~X, 8 hops away"
```

Beyond-neighborhood discovery is intentionally coarse and query-driven. The details are resolved when a node actually needs to use a remote capability.

Bandwidth Efficiency

The ring structure ensures that the most detailed (and most bandwidth-expensive) capability information is only exchanged between direct neighbors, where communication is free. As discovery scope increases, detail decreases proportionally:

```
Ring 0: ~200 bytes per neighbor per round (full capabilities)
Ring 1: ~50 bytes per summary per round (aggregated)
Ring 2: proportional to trust neighborhood size (periodic)
Ring 3: 0 bytes proactive (query-only)
```

On constrained links (< 10 kbps), Rings 2-3 are pull-only — no proactive gossip, only responses to explicit requests. This fits within Tier 3 of the bandwidth budget.

Discovery Process

When a node needs a capability it doesn't have locally:

1. **Check Ring 0**: Can any direct neighbor provide this?
2. **Check Ring 1**: Are there known providers 2-3 hops away?
3. **Check Ring 2**: Does the trust neighborhood have this capability?

4. **Query Ring 3**: Send a capability query beyond the neighborhood

Most requests resolve at Ring 0 or Ring 1. The further out a query goes, the higher the latency and cost — which naturally incentivizes local provision of common capabilities.

Mobile Handoff

When a mobile node (phone, laptop, vehicle) moves between areas, its Ring 0 neighbors change. Old relay agreements and payment channels become unreachable. The handoff protocol re-establishes connectivity in the new location.

Presence Beacons

NEXUS nodes periodically broadcast a lightweight presence beacon on all their interfaces:

```
PresenceBeacon {
    node_id: [u8; 16],       // destination hash
    capabilities: u16,        // bitfield (see below)
    cost_tier: u8,            // 0=free/trusted, 1=cheap, 2=moderate, 3=expensive
    load: u8,                 // current utilization (0-255)
}
// 20 bytes — broadcast every 10 seconds

Capability bitfield assignments:
  Bit 0:  relay (L1+ — will forward packets)
  Bit 1:  gateway (internet uplink available)
  Bit 2:  storage (NXS-Store provider)
  Bit 3:  compute_byte (NXS-Byte interpreter)
  Bit 4:  compute_wasm (WASM runtime — Light or Full)
  Bit 5:  pubsub (NXS-Pub hub)
  Bit 6:  dht (NXS-DHT participant)
  Bit 7:  naming (NXS-Name resolver)
  Bits 8-15: reserved (must be 0; future: inference, bridge, etc.)
```

Beacons are transport-agnostic — they go out over whatever interfaces the node has (LoRa, WiFi, BLE, etc.). A mobile node passively receives beacons to discover local NEXUS nodes before initiating any connection. This is the decentralized equivalent of a cellular tower scan.

Handoff Sequence

When a mobile node detects new beacons (new area) or loses contact with its current relay:

```
Handoff:
  1. Select best relay from received beacons (lowest cost × load)
  2. Connect and establish link-layer encryption
```

```
  3. Open payment channel (both sign initial state)
  4. Resume communication through new relay
```

On high-bandwidth links (WiFi, BLE), this completes in under 500ms. On LoRa, a few seconds.

Credit-Based Fast Start

For latency-sensitive handoffs (e.g., active voice call), a credit mechanism allows immediate relay before the payment channel is fully established:

```
CreditGrant {
    grantor: NodeID,              // relay
    grantee: NodeID,              // mobile node
    credit_limit_bytes: u32,      // relay allowance before channel required
    valid_for_ms: u16,            // credit window (default: 30 seconds)
    condition: enum {
        VisibleBalance(min_nxs),  // grantee has balance on CRDT ledger
        TrustGraph,               // grantee is in grantor's trust graph
        Unconditional,            // free initial credit (attract users)
    },
}
```

The relay checks the mobile node's balance on the CRDT ledger (already available via gossip) and extends temporary credit. Packets flow immediately while the channel opens in the background.

Staleness tolerance: The relay's CRDT view may be stale (especially after a partition). The credit grant is bounded by `credit_limit_bytes` and `valid_for_ms`, limiting risk to at most one credit window of unpaid traffic. Relays rate-limit fast start grants to **one active grant per unknown node** — a node that exhausts its credit without opening a channel cannot receive another grant for 10 minutes. For `VisibleBalance` grants, the relay requires a balance of at least `2 × credit_limit_bytes × cost_per_byte` to absorb staleness.

If the mobile node has no visible balance and no trust relationship, it must complete the channel open first.

Roaming Cache

Mobile nodes cache relay information for areas they've visited:

```
RoamingEntry {
    area_fingerprint: [u8; 16],  // Blake3 hash of sorted beacon node_ids
    relays: [{
        node_id: NodeID,
        capabilities: u16,
        last_cost_tier: u8,
        last_seen: Timestamp,
        channel: Option<ChannelState>,  // preserved from last visit
```

```
    }],
    ttl: Duration,                // expire after 30 days of non-visit
}
```

When a mobile node enters a previously visited area, it recognizes the beacon fingerprint and reconnects to a cached relay. If a preserved `ChannelState` exists and the relay is still alive, the old channel resumes with zero handoff latency — no new negotiation needed.

Fingerprint tolerance: The area fingerprint is approximate — node churn between visits is expected. The mobile node matches if at least 60% of current beacon node_ids appear in the cached fingerprint's sorted set. This is computed as `|intersection| / |cached_set| ≥ 0.6`. If below threshold, the area is treated as new (full discovery). Beacon node_ids are sorted by numeric value of the destination hash.

Graceful Departure

No explicit teardown:

- Old agreements expire naturally via `valid_until`
- Old payment channels remain valid and settle lazily (next contact, or via gossip)
- The mobile node's trust graph travels with it — if trusted peers exist in the new area, relay is free immediately

Capability Agreements

When a requester finds a suitable provider through discovery, they form a bilateral agreement. Agreements are between two parties only — no network-wide registration required.

Cost Structure

Agreements use a discriminated cost model that adapts to different capability types:

```
CostStructure: enum {
    PerByte {
        cost_per_byte: u64,         // µNXS per byte transferred
    },
    PerInvocation {
        cost_per_call: u64,         // µNXS per function invocation
        max_input_bytes: u32,       // cost covers up to this input size
    },
    PerDuration {
        cost_per_epoch: u64,        // µNXS per epoch of service
    },
    PerCycle {
        cost_per_million_cycles: u64, // µNXS per million compute cycles
        max_cycles: u64,             // hard limit
    },
}
```

Capability	Typical CostStructure
Relay / Bandwidth	`PerByte`
Storage	`PerDuration`
Compute (contract)	`PerCycle`
Compute (function)	`PerInvocation`
Internet gateway	`PerByte` or `PerDuration`

Agreement Structure

```
CapabilityAgreement {
    provider: NodeID,
    consumer: NodeID,
    capability: CapabilityType,     // compute, storage, relay, proxy
    payment_channel: ChannelID,     // existing bilateral channel
    cost: CostStructure,
```

```
    valid_until: Timestamp,

    proof_method: enum {
        DeliveryReceipt,            // for relay
        ChallengeResponse,          // for storage (random read challenges)
        ResultHash,                 // for compute (hash of output)
        Heartbeat,                  // for ongoing services
    },

    signatures: (Sig_Provider, Sig_Consumer),
}
```

Key Properties

Bilateral

Agreements are strictly between two parties. This means:

- No central registry of agreements
- No third party needs to be involved or informed
- Agreements can be formed and dissolved without network-wide coordination
- Privacy is preserved — only the two parties know the terms

Payment-Linked

Every agreement references an existing payment channel between the two parties. Payment flows automatically as the service is delivered.

Time-Bounded

Agreements have an expiration (`valid_until`). This prevents stale agreements from persisting when nodes move or go offline. Parties can renew by forming a new agreement.

Proof-Verified

Each agreement specifies how the consumer verifies that the provider is actually delivering. See Verification for details on each proof method.

Agreement Types

Capability	Typical Duration	Proof Method	Example
Relay/Bandwidth	Per-packet or ongoing	Delivery Receipt	"Route my packets for the next hour"

Storage	Hours to months	Challenge-Response	"Store this 10 MB file for 30 days"
Compute	Per-invocation	Result Hash	"Run Whisper on this audio file"
Internet Gateway	Ongoing	Heartbeat	"Proxy my traffic to the internet"

Negotiation

Negotiation is **single-round** (take-it-or-leave-it) and strictly local — no auction, no bidding, no global price discovery:

```
Negotiation protocol:
  1. Consumer sends CapabilityRequest to provider
  2. Provider responds with CapabilityOffer (or Reject)
  3. Consumer accepts (signs) or walks away
  4. If accepted: both signatures form the CapabilityAgreement
  5. Service begins; payment flows through the channel

CapabilityRequest {
    consumer: NodeID,
    capability: CapabilityType,       // compute, storage, relay, proxy
    desired_cost: CostStructure,      // max cost consumer will accept
    desired_duration: u32,            // seconds
    payment_channel: ChannelID,       // existing channel with this provider
    proof_preference: ProofMethod,    // DeliveryReceipt, ChallengeResponse, etc.
    nonce: u64,                       // replay prevention
}
// Signed by consumer

CapabilityOffer {
    request_nonce: u64,               // matches the request
    provider: NodeID,
    actual_cost: CostStructure,       // provider's terms (≤ desired_cost, or reject)
    valid_until: Timestamp,           // agreement expiration
    proof_method: ProofMethod,        // may differ from preference
    constraints: Option<Vec<u8>>,     // provider-specific (e.g., max object size)
}
// Signed by provider
```

Timeout: If the provider doesn't respond within 30 seconds (or 3 gossip rounds on constrained links), the request is considered rejected. The consumer may retry with a different provider.

No counter-offers: The provider either meets or undercuts the consumer's desired cost, or rejects. This keeps negotiation to a single round-trip — critical for LoRa where each message takes seconds. If the consumer wants to negotiate, they send a new request with adjusted terms.

Prices are set by providers based on their own cost structure. Within trust neighborhoods, trusted peers often offer discounted or free services.

Verification

The capability marketplace requires that consumers can verify providers are actually delivering the agreed service. NEXUS uses different verification methods depending on the type of capability.

Relay / Bandwidth Verification

Method: Cryptographic delivery receipts

The destination node signs a receipt proving the packet arrived. The relay chain can prove it delivered. This creates an unforgeable chain of evidence:

```
Packet sent by Alice → relayed by Bob → relayed by Carol → received by Dave

Dave signs: Receipt(packet_hash, timestamp)
Carol proves: "I forwarded to Dave, here's Dave's receipt"
Bob proves: "I forwarded to Carol, here's the chain"
```

A relay node can only earn routing fees by actually delivering packets to their destination.

Storage Verification

Method: Merkle-proof challenge-response (see NXS-Store for full details)

The consumer challenges a random chunk and the provider returns a Blake3 hash plus a Merkle proof:

```
Challenge-Response Protocol:
1. At storage time, consumer builds a Merkle tree over 4 KB chunks
   and stores only the merkle_root locally
2. Periodically, consumer sends:
   Challenge(data_hash, random_chunk_index, nonce)
3. Provider responds:
   Proof(Blake3(chunk_data || nonce), merkle_siblings)
4. Consumer recomputes merkle root from proof — if it matches, data is verified
```

This is:

- **Lightweight**: Runs on ESP32 in under 10ms — no GPU, no heavy crypto
- **Nonce-protected**: The random nonce prevents pre-computation of responses
- **Merkle-verified**: Consumer only stores the root hash, not the full data
- **Bandwidth-efficient**: ~320 bytes per proof (for a 1 MB file)

- **Partition-safe**: Works between any two directly connected nodes, no chain needed

Three consecutive failed challenges trigger repair — the consumer reconstructs the lost shard from erasure-coded replicas and stores it on a replacement node.

Compute Verification

Compute verification uses three tiers, scaled to the stakes involved:

Tier 1: Reputation Trust (Cheapest)

Accept the result. The provider has no incentive to lie — getting caught destroys their reputation and all future income.

Use for: Low-stakes operations where the cost of a wrong answer is low.

Tier 2: Optimistic Verification (Moderate)

Accept the result but randomly re-execute 1-in-N requests on a different node. Divergent results flag the provider for investigation.

```
Optimistic Verification:
1. Send compute request to Provider A
2. Accept result immediately
3. With probability 1/N, also send same request to Provider B
4. Compare results
5. If divergent: flag Provider A, reduce reputation
```

Use for: Medium-stakes operations. The random audit probability can be tuned — higher for newer/less-trusted providers, lower for established ones.

Tier 3: Redundant Execution (Expensive)

Send the same request to K independent nodes. The majority result wins.

```
Redundant Execution:
1. Send compute request to K nodes (e.g., K=3)
2. Collect results
3. Majority wins (2 of 3 agree)
4. Dissenting node is flagged
```

Use for: High-stakes operations where the result affects payments or irreversible state changes.

Verification Cost Tradeoffs

Tier	Cost	Latency	Trust Required	Use Case
Reputation	1x	1x	High	Cheap, frequent ops
Optimistic	~1.1x	1x	Moderate	Default for most compute
Redundant	Kx	~1x (parallel)	Minimal	Payment-affecting compute

Heartbeat Verification

For ongoing services (internet gateway, persistent connections), a simple heartbeat mechanism verifies continued availability:

```
Heartbeat Protocol:
1. Consumer sends periodic ping (every N seconds)
2. Provider responds with signed pong
3. If M consecutive heartbeats are missed: agreement terminated
4. Payment stops when heartbeats stop
```

This is suitable for services where the consumer can directly observe whether the service is working (e.g., "I can reach the internet through this gateway").

NXS-Store: Content-Addressed Storage

NXS-Store is the storage layer of NEXUS. Every piece of data is addressed by its content hash — if you know the hash, you can retrieve the data from anywhere in the network. Storage is maintained through bilateral agreements, verified through lightweight challenge-response proofs, and protected against data loss through erasure coding.

Data Objects

```
DataObject {
    hash: Blake3Hash,               // content hash = address
    content_type: enum { Immutable, Mutable, Ephemeral },
    owner: Option<NodeID>,          // for mutable objects
    created: Timestamp,
    ttl: Option<Duration>,          // for ephemeral objects
    size: u32,
    priority: enum { Critical, Normal, Lazy },
    min_bandwidth: u32,             // don't attempt transfer below this bps

    // Merkle tree root over 4 KB chunks (for verification)
    merkle_root: Blake3Hash,

    payload: enum {
        Inline(Vec<u8>),            // small objects (under 4 KB)
        Chunked([ChunkHash]),       // large objects (4 KB chunks)
    },
}
```

Content Types

Immutable

Once created, the content never changes. The hash is the permanent address. Used for: messages, posts, media files, contract code.

Mutable

The owner can publish updated versions, signed with their key. The highest sequence number wins. Any node can verify the signature. Used for: profiles, status updates, configuration.

Versioning rules:

- Sequence numbers must be **strictly monotonic** — each update must have a higher sequence number than the previous one
- Updates are only valid when signed by the owner's Ed25519 key
- **Fork detection**: If two updates with the same sequence number but different content are observed (both validly signed), this is treated as evidence of key compromise or device cloning. Nodes that detect a fork should flag the object's owner identity as potentially compromised and refuse further updates until the conflict is resolved via a KeyCompromiseAdvisory

Ephemeral

Data with a time-to-live (TTL). Automatically garbage-collected after expiration. Used for: presence information, temporary caches, session data.

Storage Agreements

Storage on NEXUS is maintained through **bilateral agreements** between data owners and storage nodes. This is how data stays alive on the network.

```
StorageAgreement {
    data_hash: Blake3Hash,          // what's being stored
    data_size: u32,                 // bytes
    provider: NodeID,               // who stores it
    consumer: NodeID,               // who pays for it
    payment_channel: ChannelID,     // bilateral channel
    cost_per_epoch: u64,            // NXS per epoch
    duration_epochs: u32,           // how long
    challenge_interval: u32,        // how often to verify (in gossip rounds)
    erasure_role: Option<ShardInfo>,// if part of an erasure-coded set
    signatures: (Sig_Provider, Sig_Consumer),
}
```

Payment Model

Storage is **pay-per-duration** — like rent, not like purchase. The data owner pays the storage node a recurring fee via their bilateral payment channel.

Duration	Billing	Use Case
Short-term (hours)	Per-epoch micro-payments	Temporary caches, session data
Medium-term (weeks)	Prepaid for N epochs	Messages, posts, media
Long-term (months+)	Recurring per-epoch	Persistent data, profiles, hosted content

When payment stops, the storage node garbage-collects the data after a grace period (1 epoch). The data owner is responsible for maintaining payment — there is no "permanent storage"

guarantee.

Free Storage Between Trusted Peers

Just like relay traffic, storage between trusted peers is **free**:

```
Storage decision:
  if data owner is trusted:
    store for free (no agreement needed, no payment)
  else:
    require a StorageAgreement with payment
```

A trust neighborhood where members store each other's data operates with zero economic overhead — no tokens, no agreements, no challenges. This is how a community mesh handles local content naturally.

Proof of Storage

How does a data owner know a storage node actually has their data? Through **lightweight challenge-response proofs** that run on any hardware, including ESP32.

Challenge-Response Protocol

```
Proof of Storage:
  1. Data owner builds a Merkle tree over 4 KB chunks at storage time
     (stores only the merkle_root — not the full tree)

  2. Periodically, owner sends:
     Challenge {
         data_hash: Blake3Hash,
         chunk_index: u32,          // random chunk to verify
         nonce: [u8; 16],           // prevents pre-computation
     }

  3. Storage node responds:
     Proof {
         chunk_hash: Blake3(chunk_data || nonce),
         merkle_proof: [sibling hashes from chunk to root],
     }

  4. Owner verifies:
     a. Recompute merkle root from chunk_hash + merkle_proof
     b. Compare against stored merkle_root
     c. If match: storage verified
     d. If mismatch: node is lying or lost the data
```

Why This Works on Constrained Devices

Operation	Compute Cost	RAM Required
Generate challenge	16 random bytes	Negligible
Compute chunk hash (storage node)	1 Blake3 hash of 4 KB	4 KB
Verify Merkle proof (owner)	~10 Blake3 hashes (for 1 MB file)	~320 bytes

An ESP32 can verify a storage proof in under 10ms. No GPU needed, no heavy cryptography, no sealing. This is intentionally simpler than Filecoin's Proof of Replication — we trade the ability to detect deduplicated storage for something that actually runs on mesh hardware.

Challenge Frequency

Data Priority	Challenge Interval
Critical	Every gossip round (60 seconds)
Normal	Every 10 gossip rounds (~10 minutes)
Lazy	Every 100 gossip rounds (~100 minutes)

Challenges are staggered across stored objects so a storage node never faces a burst of challenges at once.

What If a Challenge Fails?

```
Challenge failure handling:
  1. First failure: retry after 1 gossip round (could be transient)
  2. Second consecutive failure: flag the storage node
  3. Third consecutive failure: consider data lost on this node
     → trigger repair (see Erasure Coding below)
     → reduce node's storage reputation
     → terminate the StorageAgreement
```

Erasure Coding

Full replication is wasteful. Storing 3 complete copies of a file costs 3x the storage. **Erasure coding** achieves the same durability with far less overhead.

Reed-Solomon Coding

NEXUS uses Reed-Solomon erasure coding to split data into **k data shards + m parity shards**, where any k of (k + m) shards can reconstruct the original:

```
Erasure coding example (4, 2):
  Original file: 1 MB
  → Split into 4 data shards (256 KB each)
  → Generate 2 parity shards (256 KB each)
  → 6 shards total, stored on 6 different nodes
  → Any 4 of 6 shards can reconstruct the original
  → Total storage: 1.5 MB (1.5x overhead)

Compare with 3x replication:
  → 3 full copies = 3 MB (3x overhead)
  → Tolerates 2 node failures (same as erasure coding)
  → But uses 2x more storage
```

Default Erasure Parameters

Data Size	Scheme	Shards	Overhead	Tolerates
Under 4 KB	No erasure (inline)	1	1x	Replication only
4 KB – 1 MB	(2, 1)	3 shards	1.5x	1 node loss
1 MB – 100 MB	(4, 2)	6 shards	1.5x	2 node losses
Over 100 MB	(8, 4)	12 shards	1.5x	4 node losses

The data owner chooses the scheme based on durability requirements and willingness to pay. Higher redundancy = more shards = more storage agreements = higher cost.

Shard Distribution

Shards are distributed across nodes in **different trust neighborhoods** to maximize independence:

```
Shard placement strategy:
  1. Prefer nodes in different trust neighborhoods
  2. Prefer nodes with different transport types (LoRa, WiFi, cellular)
  3. Prefer nodes with proven uptime (high storage reputation)
  4. Never place two shards of the same object on the same node
```

This ensures that a single neighborhood going offline (power outage, network split) doesn't lose more shards than the erasure code can tolerate.

Repair

When a storage node fails challenges or goes offline, the data owner must **repair** — reconstruct the lost shard and store it on a new node.

```
Repair flow:
  1. Detect: storage node fails 3 consecutive challenges
  2. Assess: how many shards are still healthy?
     - If ≥ k shards remain: reconstruction is possible
     - If fewer than k: data is lost (this is why shard distribution matters)
  3. Reconstruct: download k healthy shards, regenerate the lost shard
  4. Re-store: form a new StorageAgreement with a different node
  5. Upload the reconstructed shard
```

Automated Repair

For users who can't be online to monitor their data, repair can be delegated:

```
RepairAgent {
    data_hash: Blake3Hash,
    shard_map: Map<ShardIndex, NodeID>,
    merkle_root: Blake3Hash,
    authorized_spender: NodeID,     // can spend from owner's channel
    max_repair_cost: u64,           // budget cap
}
```

A RepairAgent is an NXS-Compute contract that periodically challenges storage nodes on behalf of the data owner. If a shard is lost, it handles reconstruction and re-storage automatically, spending from the owner's pre-authorized budget.

Bandwidth Adaptation

The `min_bandwidth` field controls how data propagates across links of different speeds:

```
Example:
  A 500 KB image declares min_bandwidth: 10000 (10 kbps)

  LoRa node (1 kbps):
    → Propagates hash and metadata only
    → Never attempts to transfer the full image

  WiFi node (100 Mbps):
    → Transfers normally
```

This is a property of the data object that the storage and routing layers respect. Applications set `min_bandwidth` based on the nature of the data, and the network handles the rest.

Garbage Collection

Storage nodes manage their disk space through a priority-based garbage collection system:

```
Garbage collection priority (lowest priority deleted first):
  1. Expired TTL + no active agreement → immediate deletion
  2. Unpaid (agreement expired, no renewal) → delete after 1 epoch grace
  3. Cached content (no agreement, just opportunistic) → LRU eviction
  4. Low-priority paid data → delete only under extreme space pressure
  5. Normal paid data → never delete while agreement is active
  6. Critical paid data → never delete while agreement is active
  7. Trusted peer data → never delete while trust relationship exists
```

A storage node never deletes data that has an active, paid agreement. Data whose agreement expires is kept for a 1-epoch grace period (to allow renewal), then garbage-collected.

Chunking

Large objects are split into 4 KB chunks, each independently addressed by hash:

```
Large file (1 MB):
  → Split into 256 chunks of 4 KB each
  → Each chunk has its own Blake3 hash
  → Merkle tree built over all chunk hashes
  → The DataObject stores the chunk hash list and merkle_root
  → Chunks can be retrieved from different nodes in parallel
  → Missing chunks can be re-requested individually
```

Chunking enables:

- Parallel downloads from multiple peers
- Efficient deduplication (identical chunks across objects are stored once)
- Resumable transfers on unreliable links
- Fine-grained storage proofs (challenge any individual chunk)
- Erasure coding at the chunk level for large objects

Comparison with Other Storage Protocols

Aspect	Filecoin	Arweave	NEXUS (NXS-Store)
Payment	Per-deal, on-chain	One-time endowment	Per-duration, bilateral channels
Proof	PoRep + PoSt (GPU-heavy, minutes to seal)	SPoRA (mining-integrated)	Challenge-response (milliseconds, runs on ESP32)
Durability	Slashing for failures (requires blockchain)	Incentivized mining of historical data	Erasure coding + repair agents

Permanent storage	No (deals expire)	Yes (pay once)	No (pay per duration, data owner's responsibility)
Blockchain	Required (proof submission on-chain)	Required (block weave)	Not needed (bilateral agreements)
Minimum hardware	GPU for sealing	Standard PC	ESP32 for verification, Pi for storage
Partition tolerance	No (needs chain access)	No (needs chain access)	Yes (bilateral proofs work offline)
Free tier	No	No	Yes (trusted peer storage)

NEXUS deliberately chooses lightweight proofs over heavy cryptographic guarantees. The tradeoff: a storage node could store the same data once and claim to store it twice (unlike Filecoin's Proof of Replication). This is acceptable because:

1. The economic incentive is weak — the node earns the same fee either way
2. The data owner doesn't care *how* the node stores the data, only that it can return it on demand
3. Erasure coding across multiple nodes provides real redundancy regardless

NXS-DHT: Distributed Hash Table

NXS-DHT maps keys to the nodes that store the corresponding data. It uses proximity-weighted gossip rather than Kademlia-style strict XOR routing, because link quality varies wildly on a mesh network.

Distance Metrics: Routing vs. DHT

NEXUS uses two different distance metrics for different purposes:

- **Ring distance** (routing layer): `min(|a − b|, 2^128 − |a − b|)` over the destination hash space. Used for greedy forwarding to route packets toward their destination. This is the Kleinberg small-world model.
- **XOR distance** (DHT layer): `a ⊕ b` over DHT key space. Used for determining storage responsibility — which nodes are "closest" to a given key and should store its data.

Both operate over 128-bit spaces derived from the same hash functions, but they serve different roles. Routing cares about navigating to a destination efficiently; the DHT cares about partitioning key-space responsibility among nodes.

Why Not Kademlia?

Traditional Kademlia routes lookups based on XOR distance between node IDs and key hashes, assuming roughly uniform latency between any two nodes. On a NEXUS mesh:

- A node 1 XOR-hop away might be 10 LoRa hops away
- A node 10 XOR-hops away might be a direct WiFi neighbor
- Link quality varies by orders of magnitude

NXS-DHT uses **proximity-weighted gossip** that considers both XOR distance and actual network cost when deciding where to route lookups. XOR distance determines the **target** (which nodes should store a key); network cost determines the **path** (how to reach those nodes efficiently).

Routing Algorithm

Lookup Scoring Function

Each DHT lookup hop selects the next node by minimizing:

```
dht_score(candidate, key) = w_xor × norm_xor_distance(candidate.id, key)
                          + (1 − w_xor) × norm_network_cost(candidate)
```

Where:

- `norm_xor_distance` = `xor(candidate.id, key) / max_xor_in_candidate_set`, normalized to [0, 1]
- `norm_network_cost` = `cumulative_cost_to(candidate) / max_cost_in_candidate_set`, normalized to [0, 1]
- `w_xor = 0.7` (default — favor key-space closeness, but avoid expensive paths)

This produces the same iterative-closest-node behavior as Kademlia but routes around expensive links rather than blindly following XOR distance.

Replication Factor

Each key is stored on the **k=3 closest nodes** in XOR distance that are reachable within a cost budget:

```
Storage responsibility:
  1. Sort all known nodes by xor(node.id, key)
  2. Walk the sorted list; skip nodes whose network cost exceeds 10× the cheapest
  3. First k=3 reachable nodes are the storage set
```

The cost filter prevents a node on the far side of a LoRa link from being assigned storage responsibility for a key it can barely reach. The XOR ordering ensures deterministic agreement on who stores what.

Rebalancing

- **Node join**: A new node announces itself. Existing nodes whose stored keys are now closer (in XOR) to the new node push those keys via gossip. The new node pulls full data for keys it's now responsible for.
- **Node departure**: Detected via missed heartbeats (3 consecutive gossip rounds with no response). Remaining storage-set members detect the gap and re-replicate to the next-closest node, restoring k=3.

Lookup Process

```
DHT Lookup:
  1. Query direct neighbors for the key
  2. Each responds with either the data or a referral to a closer node
     (selected by dht_score — balancing XOR closeness and network cost)
```

```
  3. Follow referrals iteratively until data is found or all k closest nodes queried
  4. Cache result locally with TTL
  5. Parallel lookups: query α=3 nodes concurrently, use first valid response
```

Bandwidth per Lookup

Component	Size
Query	~64 bytes
Response (referral)	~48 bytes (node_id + cost hint)
Response (data found)	~128 bytes + data size
Typical lookup (3-5 hops on LoRa)	2-3 seconds

Publication Process

```
DHT Publication:
  1. Store the object locally
  2. Gossip key + metadata (not full data) to neighbors
  3. Nodes close to the key's hash (k=3 storage set) pull the full data
  4. Neighborhood-scoped objects gossip within the trust neighborhood only
```

Publication gossips only metadata — the full data is pulled on demand. This prevents large objects from flooding the gossip channel.

Metadata Format

```
DHTMetadata {
    key: [u8; 32],           // Blake3 content hash (32 bytes)
    size: u32,               // object size in bytes (4 bytes)
    content_type: u8,        // 0=Immutable, 1=Mutable, 2=Ephemeral (1 byte)
    owner: [u8; 16],         // publisher's destination hash (16 bytes)
    ttl_remaining: u32,      // seconds until expiry (4 bytes)
    lamport_ts: u64,         // publisher's Lamport timestamp (8 bytes, for mutable
ordering)
    signature: [u8; 64],     // Ed25519 signature over (key || size || content_type ||
lamport_ts) (64 bytes)
}
// Total: 129 bytes per metadata entry
// Signature prevents metadata forgery; content hash prevents data forgery
```

For **mutable objects**, `lamport_ts` determines freshness — the highest timestamp with a valid signature wins. For **immutable objects**, `lamport_ts` is the publication time and the content hash is sufficient for verification.

Cache invalidation: Mutable objects are invalidated by receiving a metadata entry with a higher `lamport_ts` for the same `owner` and logical key. There is no push-invalidation mechanism — caches rely on TTL expiry and periodic re-query of the storage set for freshness-critical data.

Cache TTL

Cache lifetime follows a two-level policy:

- **Publisher TTL**: Set by the data owner. Maximum lifetime for the cached copy. Range: 60 seconds to 30 days.
- **Local cap**: `min(publisher_ttl, 24 hours)`. Prevents stale caches from persisting when publishers update their data.
- **Access refresh**: Accessing a cached item resets its local TTL to `min(remaining_publisher_ttl, 24 hours)`. Frequently accessed items stay cached; idle items expire.
- **Eviction**: When local cache exceeds its storage budget, least-recently-used entries are evicted first regardless of remaining TTL.

Neighborhood-Scoped DHT

Objects can be scoped to a trust neighborhood, meaning:

- Their metadata only gossips between trusted peers and their neighbors
- Only nodes within the trust neighborhood can discover them
- Storage nodes within the neighborhood are preferred
- Cross-neighborhood lookups require explicit queries (Ring 3 discovery)

This is useful for community content that doesn't need global visibility. Scoping emerges naturally from the trust graph — there is no explicit "zone" to configure.

Caching

Lookup results are cached locally with a TTL (time-to-live). This means:

- Frequently accessed data is served from local cache
- The DHT is queried only when the cache expires
- Popular content naturally distributes across many caches
- Cache TTL is set by the data publisher

Light Client Verification

Mobile nodes and other constrained devices delegate DHT lookups to a nearby relay rather than participating in the DHT directly. This creates a trust problem: how does the light client know the relay's response is honest?

Three verification tiers handle this, scaled by data type:

Tier 1 — Content-Addressed Lookups (Zero Overhead)

Most DHT objects are stored by content hash. Verification is automatic:

```
Light client lookup by hash:
  1. Request key K from relay
  2. Relay returns data D
  3. Verify: Blake3(D) == K
  4. Match → data is authentic (relay honesty irrelevant)
  5. Mismatch → discard, flag relay, retry via different node
```

No extra bandwidth, no extra queries. The hash the client already knows is the proof.

Tier 2 — Signed Object Lookups (Signature Check)

For mutable data (NXS-Name records, capability advertisements, profile updates), objects carry the owner's Ed25519 signature:

```
Light client lookup for mutable object:
  1. Request mutable key from relay
  2. Relay returns: { data, owner_pubkey, signature, lamport_timestamp }
  3. Verify: Ed25519_verify(owner_pubkey, data || timestamp, signature)
  4. Valid → data is authentic (relay cannot forge owner's signature)
  5. Invalid → discard, flag relay
```

A malicious relay can return **stale but validly signed** data. It cannot forge new data. Staleness is handled by Tier 3.

Tier 3 — Multi-Source Queries (Anti-Censorship, Anti-Staleness)

For lookups where censorship or staleness matters, the client queries multiple independent nodes:

```
Multi-source lookup (quorum_size N):
  1. Send lookup to N independent nodes (relay + N-1 others from Ring 0/1)
  2. Collect responses with timeout
  3. Content-addressed: any valid response is sufficient
  4. Mutable: highest lamport_timestamp with valid signature wins
  5. "Not found" accepted only if unanimous across all N
  6. Divergent results: flag dissenting node(s), trust majority
```

Default quorum sizes:

Lookup Type	Default N	Notes
Content-addressed	1	Hash verification is sufficient
Name resolution	2	First resolution of unknown name uses N=3
Mutable object	2	N=3 if freshness is critical
Service discovery	1	N=2 if results seem incomplete

Trusted Relay Shortcut

If the client's relay is in its trust graph, single-source queries (N=1) are sufficient for all tiers. Multi-source queries are only needed for untrusted relays. A trusted relay has economic skin in the game — trust means absorbing the trusted node's debts, making dishonesty self-punishing.

Overhead

Scenario	Extra Queries	Extra Bandwidth
Content-addressed, any relay	0	0
Mutable, trusted relay	0	0
Mutable, untrusted relay	+1	~192 bytes
Name resolution	+1	~192 bytes

NXS-Pub: Publish/Subscribe

NXS-Pub provides a publish/subscribe system for real-time notifications across the mesh. It supports multiple subscription types and delivery modes, allowing applications to choose the right tradeoff between immediacy and bandwidth.

Subscriptions

```
Subscription {
    subscriber: NodeID,
    topic: enum {
        Key(hash),              // specific key changed
        Prefix(hash_prefix),    // any key with prefix changed
        Node(NodeID),           // any publication by this node
        Neighborhood(label),    // any publication in this community label
    },
    delivery: enum {
        Push,                   // immediate, full payload
        Digest,                 // batched summaries, periodic
        PullHint,               // hash-only notification
    },
}
```

Subscription Topics

Topic Type	Use Case
Key	Watch a specific data object for changes (e.g., a friend's profile)
Prefix	Watch a category of keys (e.g., all posts in a forum)
Node	Follow all publications from a specific user
Neighborhood	Watch all activity from nodes with a given community label

Delivery Modes

Push

Full payload delivered immediately when published. Best for high-bandwidth links where real-time updates matter.

Use on: WiFi, Ethernet, Cellular

Digest

Batched summaries delivered periodically. Reduces bandwidth by aggregating multiple updates into a single digest.

Use on: Moderate bandwidth links, or when real-time isn't critical

PullHint

Only the hash of new content is delivered. The subscriber decides whether and when to pull the full data.

Use on: LoRa and other constrained links where bandwidth is precious

Application-Driven Delivery Selection

Delivery mode selection is the **application's responsibility**, informed by link quality. The protocol provides tools; the application decides:

```
// Application code (pseudocode)
let link = query_link_quality(publisher_node);

if link.bandwidth_bps > 1_000_000 {
    subscribe(topic, Push);       // WiFi: get everything immediately
} else if link.bandwidth_bps > 10_000 {
    subscribe(topic, Digest);     // moderate: batched summaries
} else {
    subscribe(topic, PullHint);   // LoRa: just tell me what's new
}
```

The pub/sub system doesn't make this decision — the application does, based on `query_link_quality()` from the capability layer.

Bandwidth Characteristics

Delivery Mode	Per-notification overhead	Suitable for
Push	Full object size	WiFi, Ethernet
Digest	~50 bytes per item (hash + summary)	Moderate links
PullHint	~32 bytes (hash only)	LoRa, constrained links

NXS-Compute: Contract Execution

NXS-Compute provides a restricted execution environment for data validation, state transitions, and access control. It supports two execution tiers: NXS-Byte (a minimal bytecode for constrained devices) and WASM (for capable nodes).

NXS-Byte: Minimal Bytecode

```
NXS-Contract {
    hash: Blake3Hash,
    code: Vec<u8>,              // NXS-Byte bytecode
    max_memory: u32,
    max_cycles: u64,
    max_state_size: u32,
    state_key: Hash,            // current state in NXS-Store
    functions: [FunctionSignature],
}
```

NXS-Byte is a minimal bytecode with a ~50 KB interpreter, designed to run on constrained devices like the ESP32. It supports:

Capability	Description
Cryptographic primitives	Hash, sign, verify
CRDT operations	Merge, compare
CBOR/JSON manipulation	Structured data processing
Bounded control flow	Loops with hard cycle limits

NXS-Byte explicitly **does not** support:

- I/O operations
- Network access
- Filesystem access
- Unbounded computation

All execution is **pure deterministic computation**. Given the same inputs, any node running the same contract produces the same output. This is what makes verification possible.

Opcode Set (47 Opcodes)

Category	Opcodes	Cycle Cost	Description
Stack (6)	PUSH, POP, DUP, SWAP, OVER, ROT	1	Stack manipulation
Arithmetic (9)	ADD, SUB, MUL, DIV, MOD, NEG, ABS, MIN, MAX	1–3	64-bit integer, overflow traps
Bitwise (6)	AND, OR, XOR, NOT, SHL, SHR	1	Bitwise operations
Comparison (6)	EQ, NEQ, LT, GT, LTE, GTE	1	Pushes 0 or 1
Control (7)	JMP, JZ, JNZ, CALL, RET, HALT, ABORT	2–5	Bounded control flow
Crypto (3)	HASH, VERIFY_SIG, VERIFY_VRF	500–2000	Blake3, Ed25519, ECVRF
System (10)	BALANCE, SENDER, SELF, EPOCH, TRANSFER, LOG, LOAD, STORE, MSIZE, EMIT	2–50	State access and side effects

Cycle cost model: The base unit is 1 cycle ≈ 1 µs on ESP32 (the reference platform). Faster hardware executes more cycles per wall-clock second but charges the same cycle cost per opcode. Gas price in µNXS/cycle is set by each compute provider in their capability advertisement.

Specification approach: The reference interpreter (in Rust) serves as the authoritative specification. A comprehensive test vector suite ensures cross-platform conformance. Formal specification (Yellow Paper-style) is deferred until the opcode set stabilizes through real-world usage.

WASM: Full Execution

Gateway nodes and more capable hardware can offer full WASM (WebAssembly) execution as an additional compute capability. A contract declares its WASM requirement tier:

```
Contract execution path:
  1. Contract specifies: wasm_tier: None
     → Can run on any node with NXS-Byte interpreter (~50 KB)

  2. Contract specifies: wasm_tier: Light
     → Requires Community-tier or above (Pi Zero 2W+)
     → 16 MB memory limit, 10^8 fuel limit, 5 second wall-clock

  3. Contract specifies: wasm_tier: Full
     → Requires Gateway-tier or above (Pi 4/5+)
     → 256 MB memory limit, 10^10 fuel limit, 30 second wall-clock
     → Delegated via capability marketplace if local node can't execute
```

WASM Sandbox

The WASM execution environment uses **Wasmtime** (Bytecode Alliance, Rust-native) as the reference runtime. Wasmtime provides AOT compilation on Gateway+ nodes, fuel-based execution metering that maps to NXS-Byte cycle accounting, and configurable memory limits per contract.

```
WasmSandbox {
    runtime: Wasmtime,
    max_memory: u32,              // from contract's max_memory field
    max_fuel: u64,                // from contract's max_cycles (1 fuel ≈ 1 NXS-Byte cycle)
    max_wall_time_ms: u32,        // 5,000 (Light) or 30,000 (Full)
}
```

Host imports: WASM contracts call back into the NEXUS system through a restricted host API mirroring the NXS-Byte System opcodes:

Host Function	NXS-Byte Equivalent	Fuel Cost
`nexus_balance(node_id) → u64`	BALANCE	10
`nexus_sender() → [u8; 16]`	SENDER	2
`nexus_self() → [u8; 16]`	SELF	2
`nexus_epoch() → u64`	EPOCH	5
`nexus_transfer(to, amount) → bool`	TRANSFER	50
`nexus_log(data)`	LOG	10
`nexus_store_load(key) → Vec<u8>`	LOAD	3
`nexus_store_save(key, value)`	STORE	3
`nexus_hash(data) → [u8; 32]`	HASH	500
`nexus_verify_sig(pubkey, msg, sig) → bool`	VERIFY_SIG	1000

No other host imports are available. WASM contracts cannot access the filesystem, network, clock, or random number generator — all execution remains pure and deterministic.

Light WASM (Community Tier)

Community-tier devices (Pi Zero 2W, 512 MB RAM) support a restricted WASM profile: 16 MB max memory, 10^8 max fuel, 5-second wall-clock limit, interpreted via Cranelift baseline (no AOT). Contracts exceeding Light WASM limits are automatically delegated to a more capable node via compute delegation.

Compute Delegation

If a node can't execute a contract locally, it delegates to a capable neighbor via the capability marketplace:

```
Delegation flow:
  1. Node receives request to execute contract
  2. Node checks: can I run this locally?
  3. If no: query nearby capabilities for compute
  4. Find a provider, form agreement, send execution request
  5. Receive result, verify (per agreement's proof method)
  6. Return result to requester
```

This is transparent to the original requester — they don't need to know whether their contract ran locally or was delegated.

Heavy Compute as Capabilities

ML inference, transcription, translation, text-to-speech, and any other heavy computation are **not protocol primitives**. They are compute capabilities offered by nodes that have the hardware:

```
A GPU node advertises:
  offered_functions: [
    { function_id: hash("whisper-small"), cost: 50 μNXS/minute },
    { function_id: hash("piper-tts"), cost: 30 μNXS/minute },
  ]
```

A consumer requests execution of that function through the standard compute delegation path. The protocol is **agnostic to what the function does** — it only cares about discovery, negotiation, execution, verification, and payment.

Contract Use Cases

Application	Contract Purpose
Naming	Community-label-scoped name resolution (`maryam@tehran-mesh` → NodeID)
Forums	Append-only log management, moderation rules
Marketplace	Listing validation, escrow logic
Wiki	CRDT merge rules for collaborative documents
Group messaging	Symmetric key rotation, member management
Access control	Permission checks for mutable data objects

Resource Limits

Every contract declares its resource bounds upfront:

- **max_memory**: Maximum memory allocation
- **max_cycles**: Maximum CPU cycles before forced termination
- **max_state_size**: Maximum persistent state

These limits are enforced by the runtime. A contract that exceeds its declared limits is terminated immediately. This prevents denial-of-service through runaway computation.

Private Compute (Optional)

By default, compute delegation has **no input privacy** — the compute node sees your input and produces a result. This is fine for most workloads (contract execution, public data processing, non-sensitive queries). But for sensitive data — medical records, private messages, financial analysis — you need the compute node to process data it cannot read.

Private compute is **opt-in per agreement**. The consumer chooses a privacy tier based on sensitivity and willingness to pay:

```
CapabilityAgreement {
    ...
    privacy: enum {
        None,                   // default — compute node sees input/output
        SplitInference,         // model partitioned, node sees only middle layers
        SecretShared,           // input split across multiple nodes
        TEE,                    // hardware-attested secure enclave
    },
}
```

Tier 0: No Privacy (Default)

The compute node receives plaintext input, executes, and returns the result. Verification is via result hash or redundant execution. This is the cheapest and fastest option.

Use for: Public data, non-sensitive queries, contract execution, anything where the input isn't secret.

Tier 1: Split Inference

For ML/AI workloads. The neural network is partitioned across nodes so no single node sees both the raw input and the final output:

```
Split inference flow:
  1. Consumer runs first 1–3 layers locally (transforms raw input)
```

```
  2. Intermediate activations are sent to Inference node
     (optionally with calibrated DP noise for formal privacy guarantees)
  3. Inference node runs the heavy middle layers
  4. Intermediate result sent back to consumer
  5. Consumer runs final 1–2 layers locally (produces final output)

What the Inference node sees:
  ✗ Raw input (transformed by early layers)
  ✗ Final output (produced by consumer's final layers)
  ✓ Intermediate activations (a compressed, transformed representation)
```

Overhead: ~1.2–2x latency vs plaintext. Bandwidth for activation transfer at cut points. Consumer needs enough compute for a few neural network layers (Gateway tier or above).

Privacy strength: Moderate. Adding differential privacy noise to activations at cut points provides formal (ε, δ)-privacy guarantees at the cost of some accuracy (2–15% depending on privacy budget).

Use for: AI inference on personal data — voice transcription, document analysis, image processing — where the compute node shouldn't see the raw content.

Tier 2: Secret-Shared Computation

Input data is split using Shamir's Secret Sharing into N shares, each sent to a different compute node. No individual node can reconstruct the input.

```
Secret-shared compute flow:
  1. Consumer splits input into 3 shares (2-of-3 threshold)
  2. Each share sent to a different compute node
  3. Each node computes on its share independently
     - Additions and scalar multiplications: free (local computation)
     - Multiplications between secrets: one communication round between nodes
  4. Consumer collects result shares and reconstructs the output

What each compute node sees:
  ✗ Original input (only a random-looking share)
  ✗ Other nodes' shares
  ✗ Final output
  ✓ Its own share (information-theoretically meaningless alone)
```

Overhead: 3x bandwidth (3 shares), 3x compute cost (3 nodes). Linear operations are nearly free; non-linear operations require inter-node communication.

Trust assumption: At most 1 of 3 nodes may be malicious (honest majority). The consumer selects 3 nodes from different trust neighborhoods to minimize collusion risk.

Best for: Linear/affine workloads — aggregation, statistics, linear classifiers, search queries. For neural networks with many non-linear layers, combine with Tier 1: secret-share the input, run the

first layers as MPC on shares, then switch to split inference for the deep non-linear layers.

Use for: Medical data analysis, private search, financial computation — anything where the input must remain hidden from all compute providers.

Tier 3: TEE (Hardware-Attested)

Compute runs inside a Trusted Execution Environment (AMD SEV-SNP, NVIDIA H100 Confidential Computing, or ARM CCA). The hardware enforces that even the node operator cannot read the data being processed.

```
TEE compute flow:
  1. Consumer discovers a node advertising TEE capability
  2. Consumer requests and verifies a remote attestation report
     (proves specific code is running inside a genuine TEE)
  3. Consumer sends encrypted input (encrypted to the TEE's ephemeral key)
  4. TEE decrypts, processes, encrypts output for consumer
  5. Consumer decrypts result

What the node operator sees:
  ✗ Input (encrypted for the TEE)
  ✗ Output (encrypted for the consumer)
  ✗ Intermediate state (protected by hardware)
  ✓ That a computation happened, its duration, and data sizes
```

Overhead: Under 5% compute overhead. Near-zero bandwidth overhead. Requires server-grade hardware (AMD EPYC, NVIDIA H100).

Trust assumption: You trust the hardware vendor (AMD, Intel, NVIDIA) to have correctly implemented the TEE. You do NOT trust the node operator.

Limitation: Only available on Inference-tier nodes with server hardware. Not available on ESP32, Raspberry Pi, or consumer hardware.

Use for: Highest-sensitivity workloads — end-to-end encrypted AI inference, confidential data processing — where you're willing to trust the hardware vendor but not the node operator.

Choosing a Privacy Tier

Tier	Overhead	Privacy	Hardware Required	Cost
None	1x	None	Any	Cheapest
Split Inference	1.2–2x	Moderate (DP-configurable)	Consumer: Gateway+. Provider: any.	Low premium

Secret Shared	3x+	Strong (information-theoretic)	3 compute nodes	3x compute cost
TEE	~1x	Strong (hardware-attested)	Provider: server-grade with TEE	Slight premium

The default is **no privacy**. Most compute delegation doesn't need it — you're running a public contract on public data, or the result hash verification is sufficient. Private compute is for when the **input itself** is sensitive.

Combining Tiers

Tiers can be combined for defense in depth:

- **Split + Secret Shared**: Secret-share the input, run first layers as MPC across 3 nodes, then split inference for deep layers. Maximum software-based privacy.
- **Split + TEE**: Run the heavy middle layers inside a TEE. The TEE never sees raw input (early layers run locally), and you get hardware attestation for the critical computation.

The consumer specifies the desired combination in the capability agreement. The marketplace handles discovery of nodes that support the requested privacy tier.

Messaging

End-to-end encrypted, store-and-forward messaging built on the NEXUS service primitives.

Architecture

Messaging composes multiple service layers:

Component	Built On
Message storage & persistence	NXS-Store
Delivery notifications	NXS-Pub
Transport encryption	Link-layer encryption (Reticulum-derived)
End-to-end encryption	E2E encryption

How It Works

1. **Compose**: Alice writes a message to Bob
2. **Encrypt**: Message encrypted end-to-end for Bob's public key
3. **Store**: Encrypted message stored as an immutable DataObject in NXS-Store
4. **Notify**: NXS-Pub sends a notification to Bob (or his relay nodes)
5. **Deliver**: If Bob is online, he retrieves immediately. If offline, relay nodes cache the message for later delivery.
6. **Pay**: Relay and storage fees paid automatically via payment channels

Offline Delivery

Relay nodes cache messages for offline recipients. When Bob comes back online:

1. His nearest relay nodes inform him of pending messages
2. He retrieves and decrypts them
3. The relay nodes are paid for the storage duration

This is store-and-forward messaging — similar to email, but encrypted and decentralized.

Group Messaging

Group messages use shared symmetric keys managed by an NXS-Compute contract:

```
GroupState {
    group_id: Blake3Hash,
    members: Set<NodeID>,
    current_key: ChaCha20Key,        // current group symmetric key
    key_epoch: u64,                   // increments on every rotation
    admin: NodeID,                    // creator; can add/remove members
    co_admins: Vec<CoAdminCertificate>,  // up to 3 delegated co-admins
    admin_sequence: u64,             // monotonic counter for admin operations
}

CoAdminCertificate {
    co_admin: NodeID,
    permissions: enum { Full, MembersOnly, RotationOnly },
    granted_by: NodeID,              // must be the group creator
    signature: Ed25519Signature,     // creator's signature over (group_id, co_admin,
permissions)
}
```

Key Management

- **Creation**: The group creator generates the first symmetric key and encrypts it individually for each member's public key (standard E2E envelope per member)
- **Rotation**: When a member joins or leaves, the admin (or any authorized co-admin) generates a new key and distributes it to all current members. The key epoch increments. Old keys are retained locally so members can decrypt historical messages
- **No forward secrecy for groups**: A new member receives only the current key — they cannot decrypt messages sent before they joined. A removed member retains old keys for messages they already received but cannot decrypt new messages (new key was never sent to them)
- **Maximum group size**: Practical limit of ~100 members, constrained by key distribution bandwidth (each rotation sends one E2E-encrypted key envelope per member, ~100 bytes each)

Co-Admin Delegation

The group creator can delegate admin authority to up to 3 co-admins via signed `CoAdminCertificate` records. This solves the single-admin availability problem without requiring threshold cryptography.

- **Any co-admin can independently**: add/remove members, rotate the group key, and (if granted `Full` permission) promote/demote other co-admins
- **Conflict resolution**: All admin operations carry a monotonically increasing `admin_sequence` number. If two co-admins issue conflicting operations (e.g., simultaneous key rotations), members accept the operation with the highest sequence number. Ties are broken by lowest admin public key hash

- **No threshold crypto**: Co-admin delegation uses only Ed25519 signatures — no multi-round key generation protocols, no new cryptographic primitives. Each delegation certificate is ~128 bytes
- **Graceful degradation**: If all admins go offline, the group continues functioning with its current key. No key rotation or membership changes occur until at least one admin returns

Bandwidth on LoRa

A 1 KB text message over LoRa takes approximately 10 seconds to transmit — comparable to SMS delivery times. This is viable for text-based communication in constrained environments.

Attachments are DataObjects with `min_bandwidth` set appropriately. A photo attachment might declare `min_bandwidth: 10000` (10 kbps), meaning it will transfer when the recipient has a WiFi link available but won't be attempted over LoRa.

Social

A decentralized social network built on NEXUS primitives. No central servers, no algorithmic recommendations — just chronological feeds assembled locally from followed users.

Architecture

Each user has:

- **Profile**: A mutable DataObject containing display name, bio, avatar hash, etc.
- **Feed**: An append-only log of posts, where each post is an immutable DataObject
- **Followers**: Subscribers are tracked via NXS-Pub subscriptions

Feed Assembly

Feed aggregation is entirely local. Each device:

1. Maintains a list of followed users (NodeIDs)
2. Subscribes to each followed user via NXS-Pub
3. Receives notifications when followed users publish new posts
4. Assembles the timeline locally in chronological order

There is no algorithmic recommendation. No engagement optimization. Just a reverse-chronological feed of content from people you follow.

Media Tiering

Media adapts to available bandwidth using `min_bandwidth` on DataObjects:

Content Type	Size	min_bandwidth	Available On
Text post	~200 bytes	0 (any link)	Everywhere
Blurhash thumbnail	~64 bytes	0	Everywhere, including LoRa
Compressed image	~50 KB	10,000 (10 kbps)	WiFi and above
Full resolution image	~500 KB	100,000 (100 kbps)	WiFi and above
Video	>1 MB	1,000,000 (1 Mbps)	High-bandwidth links only

The application decides which tier to request based on current link quality:

```
let link = query_link_quality(author_node);

if link.bandwidth_bps < 1000 {
    // LoRa: text + blurhash only
    fetch(post.text);
    fetch(post.blurhash_thumbnail);
} else if link.bandwidth_bps < 100_000 {
    // Moderate: add compressed images
    fetch(post.compressed_image);
} else {
    // High bandwidth: full resolution
    fetch(post.full_image);
}
```

Privacy

- Posts can be public (replicated broadly) or neighborhood-scoped (visible only within a trust neighborhood)
- No central server has a copy of anyone's social graph
- Following is a local operation — only you and the person you follow need to know
- Unfollowing is purely local — just stop subscribing

Voice

Voice communication in NEXUS ranges from push-to-talk over LoRa to full-duplex calls over WiFi, adapting to available bandwidth.

Codec Selection by Link Quality

Link Type	Codec	Bitrate	Mode
LoRa (10+ kbps)	Codec2	700-3,200 bps	Push-to-talk
WiFi / Cellular	Opus	6-510 kbps	Full-duplex

Codec2 on LoRa

Codec2 is an open-source voice codec designed for very low bitrates. At 700 bps, it produces intelligible speech — not high-fidelity, but functional for communication. At 3,200 bps, quality is similar to AM radio.

A 10 kbps LoRa link has enough bandwidth for Codec2 push-to-talk with room for protocol overhead.

Opus on WiFi

On higher-bandwidth links, Opus provides near-CD-quality voice with full-duplex operation (both parties can talk simultaneously).

Encryption

Voice streams are **end-to-end encrypted** using the standard E2E encryption mechanism — each session generates an ephemeral X25519 keypair, and the symmetric session key is derived from a Diffie-Hellman exchange with the remote party's public key. Relay nodes carry encrypted voice packets they cannot decrypt.

Bandwidth Bridging

When participants are on different link types, the application can use compute delegation to bridge:

```
Scenario: Alice is on LoRa, Bob is on WiFi
```

```
Option 1: Codec conversion
  Alice sends Codec2 audio over LoRa to a bridge node
  Bridge node transcodes Codec2 → Opus
  Bridge node sends Opus audio to Bob over WiFi

Option 2: Speech-to-text bridging
  Alice sends Codec2 audio over LoRa
  A nearby compute node runs STT (Whisper) on the audio
  Text is sent to Bob over WiFi
  Bob's device optionally runs TTS to play it as audio
```

This is an **application-level decision** using standard compute delegation. The protocol has no concept of "voice" — it routes bytes. The application decides how to adapt between bandwidth tiers.

Push-to-Talk Protocol

On half-duplex links (LoRa), push-to-talk works as:

1. Sender presses talk button
2. Audio captured, encoded with Codec2
3. Encoded frames sent as a stream of small packets
4. Receiver buffers and plays back
5. Sender releases button, receiver can now respond

The protocol handles this as ordinary data packets — there is no special voice channel.

Naming (NXS-Name)

NXS-Name provides human-readable names scoped to community labels. There is no global namespace — names resolve locally based on proximity and trust.

Community-Scoped Names

Names follow the format `name@community-label`:

```
maryam@tehran-mesh
alice@portland-mesh
relay-7@backbone-west
```

Resolution works by proximity:

1. Parse the community label from the name (`portland-mesh`)
2. Search nearby nodes with that `community_label` set
3. Within that cluster, resolve the name via local naming records
4. Use the returned NodeID for routing

Why No Global Namespace?

A global namespace requires global consensus on name ownership. Global consensus contradicts NEXUS's partition tolerance requirement. If two partitioned networks both register the name "alice," there is no partition-safe way to resolve the conflict.

Community-scoped names solve this:

- Names are locally consistent within their trust neighborhood
- Different communities can have different "alice" users — they are `alice@portland-mesh` and `alice@tehran-mesh`
- No global coordination needed
- Community labels are self-assigned, not centrally managed

Name Registration

Names are registered locally by announcing a name binding:

```
NameBinding {
    name: String,               // "alice"
    community_label: String,    // "portland-mesh"
    node_id: NodeID,
    signature: Ed25519Signature,
}
```

Name bindings propagate via gossip within the trust neighborhood. Conflicts (two nodes claiming the same name in the same community label) are resolved by precedence:

1. **Trust-weighted** (highest priority) — if one claimant is in your trust graph and the other is not, the trusted claimant wins regardless of timing. Between two trusted claimants, the one with the shorter trust distance wins.
2. **First-seen** (tiebreaker) — if both claimants have equal trust status (both trusted at the same distance, or both untrusted), the first binding your node received wins.
3. **Local petnames** (ultimate fallback) — if you need guaranteed resolution regardless of conflicts, assign a local petname (see below). Petnames override all network name resolution.

Cross-Community Resolution

To resolve a name in a different community:

1. Query propagates toward nodes with the target community label
2. Nearest matching cluster responds with the name binding
3. Result is cached locally with a TTL

Because community labels are not unique, resolution finds the **nearest** cluster with that label. This is usually what you want — `alice@portland-mesh` resolves to the Portland cluster nearest to you.

Local Petnames

As a fallback and privacy feature, each user can assign **petnames** — local nicknames for NodeIDs on their own device:

```
User's petname mapping (local only, never shared):
  "Mom"    → 0x3a7f ... b2c1
  "Work"   → 0x8e2d ... f4a9
  "Doctor" → 0x1b5c ... d3e7
```

Petnames are:

- Completely private (stored only on the user's device)

- Not resolvable by anyone else
- Useful when community names aren't available or desired
- The most censorship-resistant naming possible — no one can take your petnames from you

Community Applications

Community applications — forums, marketplaces, and wikis — are built on NXS-Compute contracts managing CRDT state. All degrade gracefully to text-only on constrained links.

Forums

Forums are append-only logs managed by moderation contracts:

- **Posts** are immutable DataObjects, appended to a topic log
- **Moderation** is handled by an NXS-Compute contract that enforces community rules
- **Threading** is local — each client assembles thread views from the flat log
- **Propagation** uses neighborhood-scoped gossip for local forums, or wider replication for public forums

Moderation Model

The moderation contract defines:

- Who can post (trusted peers, vouched users, anyone)
- Content rules (enforced at the contract level)
- Moderator keys (who can remove content)
- Appeal mechanisms

Since moderation is a contract, different forums can have different moderation policies. There is no platform-wide content policy.

Marketplace

Marketplace listings are DataObjects with neighborhood-scoped propagation:

- **Listings** are mutable DataObjects (sellers can update price, availability)
- **Search** is local — each node indexes listings it has received
- **Transactions** happen off-protocol (physical exchange, external payment) or through NXS escrow contracts
- **Reputation** feeds back into the node's general reputation score

Escrow

For NXS-denominated transactions, an escrow contract can hold payment:

1. Buyer deposits NXS into escrow contract
2. Seller delivers goods/services
3. Buyer confirms delivery
4. Contract releases payment to seller
5. Disputes resolved by community moderators (trusted peers with moderator keys)

Wiki

Wikis are CRDT-merged collaborative documents:

- **Pages** are mutable DataObjects using CRDT merge rules
- **Concurrent edits** merge automatically without conflicts (using operational transforms or CRDT text types)
- **History** is preserved as a chain of immutable snapshots
- **Permissions** managed by an NXS-Compute contract (who can edit, who can view)

Bandwidth Degradation

All community applications degrade to text-only on constrained links:

Application	Full Experience	LoRa Experience
Forums	Rich text, images, threads	Text posts, flat view
Marketplace	Photos, maps, categories	Text listings
Wiki	Formatted text, images, tables	Plain text

The application layer handles this adaptation using `query_link_quality()` — the protocol doesn't need to know about the application's content format.

Hosting on NEXUS

Traditional web hosting requires a server, a domain name, a certificate, and ongoing payment to a hosting provider. On NEXUS, hosting is just storing DataObjects and letting the network serve them. No server. No DNS. No certificate authority.

Hosting a Website

A "website" on NEXUS is a collection of DataObjects — HTML, CSS, JavaScript, images — stored in NXS-Store and addressed by content hash or human-readable NXS-Name.

Static Site

```
Site structure:
  root = DataObject {
      hash: Blake3("index.html contents"),
      content_type: Immutable,
      payload: Inline("<html>...links to sub-objects...</html>"),
      replication: Network(5),    // 5 copies across the network
  }

  Sub-objects:
    style.css  → DataObject { hash: ..., replication: Network(5) }
    logo.png   → DataObject { hash: ..., replication: Network(3) }
    about.html → DataObject { hash: ..., replication: Network(5) }
```

A visitor retrieves the root DataObject by name (`mysite@portland-mesh`) or by hash. The root object links to sub-objects by their content hashes. The visitor's node fetches each sub-object from the nearest replica in the mesh.

How Visitors Access Your Site

```
Access flow:
  1. Visitor queries NXS-Name: "mysite@portland-mesh"
  2. Name resolves to root DataObject hash
  3. Visitor's node fetches root from nearest NXS-Store replica
  4. Root contains hashes of sub-objects (CSS, images, etc.)
  5. Visitor's node fetches sub-objects (in parallel, from different replicas)
  6. Local browser or app renders the content
```

Content-addressed storage means:

- **No single server** — content is served from whichever node has a copy

- **No downtime** — as long as any replica is reachable, the site is available
- **No tampering** — content hash guarantees integrity
- **Global CDN by default** — popular content gets cached everywhere automatically

Updating Your Site

For static content, publish new DataObjects and update the NXS-Name binding to point to the new root hash. Old content remains available at its hash (immutable), but the name now resolves to the new version.

For dynamic content (blog, profile, etc.), use **mutable DataObjects**:

```
Blog post feed:
  feed = DataObject {
      content_type: Mutable,
      owner: your_node_id,
      payload: Inline([post_hash_1, post_hash_2, ...]),
      // Owner can update the post list by publishing a new version
      // Each individual post is immutable — only the feed index changes
  }
```

Hosting a Social Feed

A social feed is an append-only log of posts, served via NXS-Pub:

```
Your feed:
  1. Profile: Mutable DataObject (name, bio, avatar hash)
  2. Posts: Immutable DataObjects (each post is permanent)
  3. Feed index: Mutable DataObject listing post hashes in order
  4. Subscriber notifications via NXS-Pub
```

Publishing a Post

```
Publishing flow:
  1. Create an immutable DataObject for the post content
  2. Store it in NXS-Store with replication
  3. Update your feed index (mutable) to include the new post hash
  4. NXS-Pub notifies all subscribers of the update
```

Following Someone

```
Following flow:
  1. Subscribe to their feed via NXS-Pub (topic: Node(their_node_id))
  2. Choose delivery mode based on your link quality:
```

```
      - WiFi: Push (full content immediately)
      - Moderate: Digest (batched summaries)
      - LoRa: PullHint (hash-only, pull content when convenient)
   3. Your device assembles your timeline locally from all followed feeds
```

No server assembles your feed. No algorithm decides what you see. Your device pulls from the people you follow, in chronological order.

Cost of Hosting

What	Cost	Notes
Store a 10 KB page	~50 µNXS/month	With 5 replicas
Store a 1 MB image	~5,000 µNXS/month	With 3 replicas
NXS-Name registration	Free	First-seen-wins within your community label
Bandwidth when someone views your page	Paid by the viewer	You don't pay for serving — viewers pay relay costs

The key economic difference from traditional hosting: **you pay for storage, not for traffic.** The viewer pays the relay cost to reach your content. Popular content is cheaper to host because it gets widely cached.

Comparison with Traditional Hosting

Aspect	Traditional Web	NEXUS Hosting
Server	Required (or hosting provider)	None — content lives in the mesh
Domain name	Rent from registrar ($10-50/year)	NXS-Name (free, self-registered)
SSL certificate	Required (free via Let's Encrypt, or paid)	Not needed — all links encrypted, content verified by hash
Uptime	Depends on your server/provider	Depends on replica count — more replicas = higher availability
Bandwidth costs	You pay for traffic spikes	Viewers pay their own relay costs
Censorship resistance	Server can be seized, domain can be seized	No single point to seize — content is replicated across the mesh
Offline access	Not possible	Cached content available even when original author is offline

Hosting a Community Forum

A forum is a more complex application, but the primitives are the same:

```
Forum structure:
  Forum config: Mutable DataObject (rules, moderator keys)
  Topic list: Mutable DataObject (list of topic hashes)
  Each topic: Mutable DataObject (list of post hashes)
  Each post: Immutable DataObject (content + author signature)
  Moderation: NXS-Compute contract enforcing community rules
```

New posts are published as DataObjects, appended to the topic log, and propagated via neighborhood-scoped NXS-Pub to all subscribers. Moderation rules are enforced by an NXS-Compute contract — see Community Apps for details.

Running a Service

Beyond static hosting, you can run persistent services on the network:

- **API endpoint**: An NXS-Compute contract that responds to requests
- **Bot/automation**: A node running custom logic, discoverable via the capability marketplace
- **Proxy service**: Bridge NEXUS to the traditional web (serve NEXUS content via HTTP, or fetch web content for mesh users)

Services are advertised as capabilities and discovered through the marketplace. Consumers find your service, form agreements, and pay via payment channels — all handled by the protocol.

Hardware Reference Designs

NEXUS is designed to run on hardware ranging from $30 solar-powered relays to GPU workstations. Every device participates at whatever level its hardware allows.

Device Tiers Overview

Tier	Hardware	Cost	Power	Primary Role
Minimal	ESP32 + LoRa SX1276	~$30	0.5W (solar)	Relay only
Community	Pi Zero 2 W + LoRa HAT + WiFi	~$100	3W	LoRa/WiFi bridge, basic compute
Gateway	Pi 4/5 + LoRa + cellular modem + SSD	~$300	10W	Internet uplink, storage, compute
Backbone	Mini PC + directional WiFi + fiber	~$500+	25W+	High-bandwidth backbone
Inference	x86 + GPU + Ethernet	~$500+	100W+	Heavy compute, ML inference

Minimal Relay Node

Target: Lowest-cost, always-on mesh relay

```
Components:
  - ESP32-S3 microcontroller
  - LoRa SX1276/SX1262 radio module
  - Small solar panel (2W) + LiPo battery
  - Weatherproof enclosure

Capabilities:
  - Packet relay only
  - NXS-Byte interpreter (~50 KB)
  - No storage beyond routing tables
  - 24/7 operation on solar power

Software:
  - NEXUS firmware (Rust, no_std)
  - Transport: LoRa only
  - Runs: routing, payment channels, gossip
  - Cannot run: WASM, storage, heavy compute
```

Earns from: Routing fees (1-5 μNXS per packet relayed)

Range: 2-15 km line-of-sight with LoRa

Community Bridge Node

Target: Bridge between LoRa mesh and local WiFi network

```
Components:
  - Raspberry Pi Zero 2 W
  - LoRa HAT (SX1262)
  - Built-in WiFi
  - SD card (32 GB)
  - USB power supply (5V/2A)

Capabilities:
  - LoRa ↔ WiFi bridging
  - Basic NXS-Compute (NXS-Byte + light WASM)
  - Local storage (~16 GB usable)
  - NXS-DHT participation
  - Message caching for offline nodes

Software:
  - NEXUS daemon (Rust, Linux)
  - Dual transport: LoRa + WiFi
  - Full protocol stack
```

Earns from: Bridging fees, compute delegation, storage

Gateway Node

Target: Internet uplink for the mesh

```
Components:
  - Raspberry Pi 4/5 (4 GB+ RAM)
  - LoRa HAT
  - 4G/LTE cellular modem (or Ethernet)
  - SSD (256 GB+)
  - Powered supply (12V)

Capabilities:
  - Internet gateway (HTTP proxy, DNS relay)
  - Full NXS-Store storage node
  - NXS-DHT backbone participation
  - Full WASM compute
  - Epoch consensus participation

Software:
```

```
  - Full NEXUS stack
  - Triple transport: LoRa + WiFi + Cellular/Ethernet
  - Gateway proxy services
```

Earns from: Internet gateway fees, storage fees, compute fees, routing

Backbone Node

Target: High-bandwidth infrastructure linking mesh segments

```
Components:
  - Mini PC (Intel NUC or equivalent)
  - Directional WiFi antenna (point-to-point)
  - Fiber connection (where available)
  - SSD (1 TB+)
  - UPS/battery backup

Capabilities:
  - High-throughput routing (100+ Mbps)
  - Large-scale storage
  - Full compute services
  - Neighborhood discovery services
  - Epoch consensus coordination

Software:
  - Full NEXUS stack, optimized for throughput
  - Transport: Directional WiFi + Fiber + Ethernet
```

Earns from: Bulk routing fees, backbone transit, storage

Inference Node

Target: Heavy compute (ML inference, transcription, TTS)

```
Components:
  - x86 PC or server
  - GPU (NVIDIA RTX series or equivalent)
  - Ethernet connection
  - SSD (512 GB+)
  - Standard power supply

Capabilities:
  - ML model inference (Whisper, LLaMA, Stable Diffusion, etc.)
  - Speech-to-text, text-to-speech
  - Translation services
  - Any GPU-accelerated computation

Software:
```

```
  - Full NEXUS stack
  - WASM runtime + native GPU compute
  - Model serving framework
  - Advertises offered_functions with pricing
```

Earns from: Compute fees for ML inference and heavy processing

Device Capabilities by Tier

Each hardware tier has different capabilities, which determine what the node can do on the network and how it earns NXS.

Capability Matrix

Capability	Minimal	Community	Gateway	Backbone	Inference
Packet relay	Yes	Yes	Yes	Yes	Yes
LoRa transport	Yes	Yes	Yes	Optional	No
WiFi transport	No	Yes	Yes	Yes (directional)	Optional
Cellular transport	No	No	Yes	No	No
Ethernet/Fiber	No	No	Optional	Yes	Yes
NXS-Byte contracts	Yes	Yes	Yes	Yes	Yes
WASM contracts	No	Light	Full	Full	Full
NXS-Store storage	No	~16 GB	~256 GB	~1 TB	~512 GB
NXS-DHT participation	Minimal	Yes	Backbone	Backbone	Yes
Epoch consensus	No	No	Yes	Yes	Yes
Internet gateway	No	No	Yes	Optional	Optional
ML inference	No	No	No	No	Yes
Gossip participation	Full	Full	Full	Full	Full
Payment channels	Yes	Yes	Yes	Yes	Yes

Power and Deployment

Tier	Power Draw	Power Source	Typical Deployment
Minimal	0.5W	Solar + LiPo	Outdoor, pole/tree-mounted
Community	3W	USB wall adapter	Indoor, near window for LoRa
Gateway	10W	12V supply	Indoor, weatherproof enclosure
Backbone	25W+	Mains + UPS	Indoor, rack-mounted or desktop
Inference	100W+	Mains	Indoor, rack or desktop

Earning Potential

What each tier naturally earns from:

Minimal (ESP32 + LoRa)

- Packet relay fees only
- Low per-packet revenue but high volume and zero operating cost (solar)
- Value: extends mesh range, maintains connectivity

Community (Pi Zero + LoRa + WiFi)

- Bridging fees (LoRa ↔ WiFi translation)
- Basic compute delegation
- Small-scale storage
- Value: connects LoRa mesh to local WiFi network

Gateway (Pi 4/5 + Cellular)

- Internet gateway fees (highest per-byte revenue)
- Storage fees
- Compute fees
- Epoch consensus participation
- Value: connects mesh to the wider internet

Backbone (Mini PC + Directional WiFi)

- High-volume transit routing
- Large-scale storage
- Full compute services
- Value: high-bandwidth links between mesh segments

Inference (GPU Workstation)

- ML inference fees (highest per-invocation revenue)
- Heavy compute services
- Value: provides advanced capabilities to the entire mesh

Delegation Patterns

Since nodes delegate what they can't do locally, natural delegation chains form:

```
Minimal relay
  → delegates everything except routing to →
Community bridge
  → delegates bulk storage and internet to →
Gateway node
  → delegates heavy compute to →
Inference node
```

Each delegation is a bilateral capability agreement with payment flowing through channels.

Implementation Roadmap

The NEXUS implementation is organized into four phases, progressing from core networking fundamentals to a full ecosystem. Each phase has concrete milestones with acceptance criteria.

Phase 1: Foundation

Focus: Core networking and basic economics — the minimum to run a mesh with cost-aware routing and micropayments.

Milestone 1.1: Transport + Identity

- Implement `NodeIdentity` (Ed25519 keypair generation, destination hash derivation, X25519 conversion)
- Link-layer encryption (X25519 ECDH + ChaCha20-Poly1305, counter-based nonces, key rotation)
- Packet framing (Reticulum-compatible: header, addresses, context, data)
- Interface abstraction (LoRa, WiFi, serial — at least 2 transports working)
- Announce generation and forwarding with Ed25519 signature verification

Acceptance: Two nodes on different transports (e.g., LoRa + WiFi) can establish an encrypted link, exchange announces, and forward packets to each other. Packet contents are encrypted and unauthenticated nodes are rejected.

Milestone 1.2: Routing + Gossip

- `CompactPathCost` (6-byte encoding/decoding, log-scale math, relay update logic)
- Routing table (`RoutingEntry` with cost, latency, bandwidth, hop count, reliability)
- Greedy forwarding with `PathPolicy` scoring (Cheapest, Fastest, Balanced)
- Gossip protocol (60-second rounds, bloom filter state summaries, delta exchange)
- Bandwidth budget enforcement (4-tier allocation, constrained-link adaptation)
- Announce propagation rules (event-driven + 30-min refresh, hop limit, expiry, link failure detection)

Acceptance: A 5-node mesh (mixed LoRa + WiFi) converges routing tables within 3 gossip rounds. Packets are forwarded via cost-optimal paths. Removing a node causes re-routing within 3 minutes. Gossip overhead stays within 10% budget on all links.

Milestone 1.3: Congestion Control

- CSMA/CA on half-duplex links (listen-before-talk with exponential backoff)
- Per-neighbor token bucket (fair share, payment-weighted priority)
- 4-level priority queuing (P0 real-time through P3 bulk, starvation prevention)
- Backpressure signaling (4-byte CongestionSignal)
- Dynamic cost response (quadratic formula, propagated via gossip)

Acceptance: Under synthetic load, P0 packets (voice) maintain latency below 500ms while P3 (bulk) is throttled. Congestion on one link causes traffic to reroute via cost increase. No link exceeds its bandwidth budget.

Milestone 1.4: Payment Channels

- VRF lottery implementation (ECVRF-ED25519-SHA512-TAI per RFC 9381)
- Adaptive difficulty (local per-link, formula: `win_prob = target_updates / observed_packets`)
- `ChannelState` (200 bytes, dual-signed, sequence-numbered)
- Channel lifecycle (open, update on win, settle, dispute with 2,880-round window, abandon after 4 epochs)
- `SettlementRecord` generation and dual-signature

Acceptance: Two nodes relay 1,000 packets. The relay wins the VRF lottery approximately `1000 × win_probability` times (within 2σ). Channel updates occur only on wins. Settlement produces a valid dual-signed record. Dispute resolution correctly rejects old states.

Milestone 1.5: CRDT Ledger

- `AccountState` (GCounter for earned/spent, GSet for settlements)
- GCounter merge (pointwise max per-node entries)
- Settlement flow (validation: 2 sig checks + Blake3 hash + GSet dedup, gossip forward)
- Balance derivation (`earned − spent`, reject negative)
- Gossip integration (settlements propagate via Tier 2 bandwidth budget)

Acceptance: Three nodes settle channels pairwise. All balances converge correctly across the mesh within O(log N) gossip rounds. Duplicate settlements are rejected. A forged settlement (bad signature) is silently dropped by all nodes.

Milestone 1.6: Hardware Targets

- ESP32 + LoRa firmware (relay only: transport, routing, gossip, payment channels, CRDT ledger)
- Raspberry Pi software (bridge: all ESP32 capabilities + multi-interface bridging + basic CLI)
- CLI tools: `nexus-keygen`, `nexus-node` (start/stop), `nexus-status` (routing table, channels, balances), `nexus-peer` (add/remove trusted peers)

Acceptance: An ESP32 node relays packets and earns VRF lottery wins. A Raspberry Pi bridges LoRa to WiFi. CLI tools show correct routing table, channel states, and balances. ESP32 firmware fits in flash and runs within 520 KB RAM.

Phase 1 Deliverable

A working mesh network with cost-aware routing, encrypted links, stochastic micropayments, and a convergent CRDT ledger — running on real hardware (ESP32 + Raspberry Pi) with CLI management tools.

Phase 2: Economics

Focus: Real-world deployment, economic mechanisms, and the minimum viable marketplace.

Milestone 2.1: Trust Neighborhoods

- `TrustConfig` implementation (trusted peers, cost overrides, community labels)
- Free relay logic (sender trusted AND destination trusted → no lottery)
- Transitive credit (direct: full, friend-of-friend: 10%, 3+ hops: none)
- Credit rate limiting per trust distance

Acceptance: Trusted peers relay traffic for free with zero economic overhead. A friend-of-friend gets exactly 10% of the direct credit line. An untrusted node gets no transitive credit.

Milestone 2.2: Epoch Compaction

- Epoch trigger logic (3-trigger: settlement count, GSet size, small-partition adaptive)
- Epoch proposer selection (eligibility rules, conflict resolution)
- Bloom filter construction (k=13 Blake3-derived, 0.01% FPR)
- Epoch lifecycle (Propose → Acknowledge at 67% → Activate → Verify → Finalize)
- Settlement proof submission during grace period
- Merkle-tree snapshot (full on backbone, sparse on constrained)
- `BalanceProof` generation and verification (~640 bytes for 1M nodes)
- `RelayWinSummary` aggregation and spot-check verification

Acceptance: A 20-node test network triggers epochs correctly under all three conditions. Bloom filter FPR is within 2× of theoretical 0.01%. Late-arriving settlements are recovered during the grace period. ESP32 nodes operate with sparse snapshots under 5 KB.

Milestone 2.3: Capability Discovery

- `NodeCapabilities` advertisement structure (connectivity, compute, storage, availability)
- `PresenceBeacon` (20 bytes, broadcast every 10 seconds)
- Discovery rings (Ring 0 full, Ring 1 summarized, Ring 2 periodic, Ring 3 query-only)
- Mobile handoff (beacon scan → relay selection → link establishment → channel open)
- Credit-based fast start (`CreditGrant` with staleness tolerance and rate limiting)
- Roaming cache (area fingerprint with 60% overlap tolerance, 30-day TTL)

Acceptance: A mobile node (laptop) moves between two WiFi areas and hands off to a new relay within 500ms. Credit-based fast start allows immediate traffic while the channel opens. Returning to the first area reuses the cached channel with zero handoff latency.

Milestone 2.4: Reputation

- `PeerReputation` scoring (relay, storage, compute scores 0-10000)
- Score update formulas (success: diminishing gains, failure: 10% penalty)
- Trust-weighted referrals (1-hop, capped at 50%, weighted at 30% × trust, 500-round expiry)
- Reputation integration with credit line sizing and capability selection

Acceptance: A node that successfully relays 100 packets has a relay score above 5000. A node that fails 3 out of 10 agreements has a score below 3000. Referral scores are capped at 5000 and overwritten by first-hand experience.

Milestone 2.5: Test Networks

- Deploy 3-5 physical test networks (urban, rural, indoor, mixed)
- Each network: 10-50 nodes across at least 2 transport types
- Instrument for: routing convergence time, payment overhead, epoch timing, gossip bandwidth
- Run for at least 4 weeks per network
- Document: failure modes, parameter tuning, real-world performance vs. spec predictions

Acceptance: Test networks operate continuously for 4 weeks. Routing converges within spec. Payment overhead stays within 0.5% on LoRa. At least one epoch completes successfully per network. Published test report with metrics.

Phase 2 Deliverable

Test networks with functioning trust-based economics, epoch compaction, capability discovery, mobile handoff, and reputation scoring — validated on real hardware over multiple weeks.

Phase 3: Services

Focus: Service primitives and first applications.

Milestone 3.1: NXS-Store

- `DataObject` types (Immutable, Mutable, Ephemeral)
- Storage agreements (bilateral, pay-per-duration)
- Proof of storage (Blake3 Merkle challenge-response)
- Erasure coding (Reed-Solomon, default schemes by size)
- Repair protocol (detect failure → assess → reconstruct → re-store)
- Garbage collection (7-tier priority)

Milestone 3.2: NXS-DHT

- DHT routing (XOR distance + cost weighting, α=0.7)
- k=3 replication with cost-bounded storage set
- Lookup and publication protocols
- Cache management (publisher TTL, 24-hour local cap, LRU eviction)
- Light client verification (3-tier: content-hash, signature, multi-source)

Milestone 3.3: NXS-Pub

- Subscription types (Key, Prefix, Node, Neighborhood)
- Delivery modes (Push, Digest, PullHint)
- Bandwidth-adaptive mode selection

Milestone 3.4: NXS-Compute (NXS-Byte)

- 47-opcode interpreter implementation in Rust
- Cycle cost enforcement (ESP32-calibrated)
- Resource limit enforcement (max_memory, max_cycles, max_state_size)
- Compute delegation via capability marketplace
- Reference test vector suite for cross-platform conformance

Milestone 3.5: Applications

- Messaging (E2E encrypted, store-and-forward, group messaging with co-admin delegation)
- Social (profiles, feeds, followers, media tiering)
- NXS-Name (community-label-scoped naming, conflict resolution, petnames)

Phase 3 Deliverable

Usable messaging and social applications running on the mesh, with decentralized storage, DHT-based content discovery, and contract execution on constrained devices.

Phase 4: Ecosystem

Focus: Advanced capabilities and ecosystem growth.

Milestone 4.1: Advanced Compute

- WASM execution environment for gateway/backbone nodes
- Private compute tiers (Split Inference, Secret Sharing, TEE)
- Heavy compute capabilities (ML inference, transcription, TTS)

Milestone 4.2: Rich Applications

- Voice (Codec2 on LoRa, Opus on WiFi, bandwidth bridging)
- Forums (append-only logs, moderation contracts)
- Marketplace (listings, escrow contracts)
- Wiki (CRDT-merged collaborative documents)

Milestone 4.3: Interoperability

- Third-party protocol bridges (SSB, Matrix, Briar) — standalone gateway services with identity attestation
- Onion routing implementation (`PathPolicy.ONION_ROUTE`, per-packet layered encryption)

Milestone 4.4: Ecosystem Growth

- Hardware partnerships and reference design refinement
- Developer SDK and documentation
- Community-driven capability development

Phase 4 Deliverable

A full-featured decentralized platform with rich applications, privacy-enhanced routing, and interoperability with existing protocols.

Implementation Language

The primary implementation language is **Rust**, chosen for:

- Memory safety without garbage collection (critical for embedded targets)
- `no_std` support for ESP32 firmware
- Strong ecosystem for cryptography and networking
- Single codebase from microcontroller to server

Test Network Strategy

Real physical test networks, not simulations:

- Simulation cannot capture the realities of LoRa propagation, WiFi interference, and real-world device failure modes
- Each test network should represent a different deployment scenario (urban, rural, indoor, mixed)
- Test networks validate both the protocol and the economic model

Phase 1 Implementability Assessment

Phase 1 is **fully implementable** with the current specification. All protocol-level gaps have been resolved:

Component	Spec Status	Key References
Identity + Encryption	Complete	Security
Packet format + CompactPathCost	Complete (wire format specified)	Network Protocol
Routing + Announce propagation	Complete (scoring, announce rules, expiry, failure detection)	Network Protocol
Gossip protocol	Complete (bloom filter, bandwidth budget, 4-tier)	Network Protocol
Congestion control	Complete (3-layer, priority levels, backpressure)	Network Protocol
VRF lottery + Payment channels	Complete (RFC 9381, difficulty formula, channel lifecycle)	Payment Channels
CRDT ledger + Settlement	Complete (validation rules, GCounter merge, GSet dedup)	CRDT Ledger
Hardware targets	Complete (ESP32 + Pi reference designs)	Reference Designs

Design Decisions Log

This page documents the key architectural decisions made during NEXUS protocol design, including alternatives considered and the rationale for each choice.

Network Stack: Reticulum as Initial Transport

Chosen	Use Reticulum Network Stack as the initial transport implementation; treat it as a swappable layer
Alternatives	Clean-room implementation from day one, libp2p, custom protocol
Rationale	Reticulum already solves transport abstraction, cryptographic identity, mandatory encryption, sender anonymity (no source address), and announce-based routing — all proven on LoRa at 5 bps. NEXUS extends it with CompactPathCost annotations and economic primitives rather than reinventing a tested foundation. The transport layer is an implementation detail: NEXUS defines the interface it needs and can switch to a clean-room implementation in the future without affecting any layer above.

Routing: Kleinberg Small-World with Cost Weighting

Chosen	Greedy forwarding on a Kleinberg small-world graph with cost-weighted scoring
Alternatives	Pure Reticulum announce model, Kademlia, BGP-style routing, Freenet-style location swapping
Rationale	The physical mesh naturally forms a small-world graph: short-range radio links serve as lattice edges, backbone/gateway links serve as Kleinberg long-range contacts. Greedy forwarding achieves $O(\log^2 N)$ expected hops — a formal scalability guarantee. Cost weighting trades path length for economic efficiency. Unlike Freenet, no location swapping is needed because destination hashes are self-assigned and Reticulum announcements build the navigable topology.

Payment: Stochastic Relay Rewards

Chosen	Probabilistic micropayments via VRF-based lottery (channel update only on wins)
Alternatives	Per-packet accounting, per-minute batched accounting, subscription-based, random-nonce lottery
Rationale	Per-packet and batched payment require frequent channel state updates, consuming ~2-4% bandwidth on LoRa links. Stochastic rewards achieve the same expected income but trigger updates only on lottery wins — reducing economic overhead by ~10x. Adaptive difficulty ensures fairness across traffic levels. The law of large numbers guarantees convergence for active relays. **The lottery uses a VRF (ECVRF-ED25519-SHA512-TAI, RFC 9381)** rather than a random nonce to prevent relay nodes from grinding nonces to win every packet. The VRF produces exactly one verifiable output per (relay key, packet) pair, reusing the existing Ed25519 keypair.

Settlement: CRDT Ledger

Chosen	CRDT ledger (GCounters + GSet)
Alternatives	Blockchain, federated sidechain
Rationale	Partition tolerance is non-negotiable. CRDTs converge without consensus. A blockchain requires global ordering, which is impossible when network partitions are expected operating conditions. **Tradeoff**: double-spend prevention is probabilistic, not perfect. Mitigated by channel deposits, credit limits, reputation staking, and blacklisting — making cheating economically irrational for micropayments.

Communities: Emergent Trust Neighborhoods

Chosen	Trust graph with emergent neighborhoods (no explicit zones)
Alternatives	Explicit zones with admin keys and admission policies (v0.8 design)
Rationale	Explicit zones require someone to create and manage them — centralized thinking in decentralized clothing. They impose UX burden and artificially fragment communities. Trust neighborhoods emerge naturally from who you trust: free communication between trusted peers, paid between strangers. No

	admin, no governance, no admission policies. Communities form the same way they form in real life — through relationships, not administrative acts. The trust graph provides Sybil resistance economically (vouching peers absorb debts).

Compaction: Epoch Checkpoints with Bloom Filters

Chosen	Epoch checkpoints with bloom filters
Alternatives	Per-settlement garbage collection, TTL-based expiry
Rationale	The settlement GSet grows without bound. Bloom filters at 0.01% FPR compress 1M settlement hashes from ~~32 MB to ~2.4 MB. A settlement verification window during the grace period recovers any settlements lost to false positives. Epochs are triggered by settlement count (~~10,000 batches), not wall-clock time, for partition tolerance.

Compute Contracts: NXS-Byte

Chosen	NXS-Byte (minimal bytecode, ~50 KB interpreter)
Alternatives	Full WASM everywhere
Rationale	ESP32 microcontrollers can't run a WASM runtime. NXS-Byte provides basic contract execution on even the most constrained devices. WASM is offered as an optional capability on nodes with sufficient resources.

Encryption: Ed25519 + X25519

Chosen	Ed25519 for identity/signing, X25519 for key exchange (Reticulum-compatible)
Alternatives	RSA, symmetric-only
Rationale	Ed25519 has 32-byte public keys (compact for radio), fast signing/verification, and is widely proven. X25519 provides efficient Diffie-Hellman key exchange. Compatible with Reticulum's crypto model. RSA keys are too large for constrained links.

Source Privacy: No Source Address (Default)

Chosen	No source address in packet headers (inherited from Reticulum) as the default; opt-in onion routing for high-threat environments
Alternatives	Mandatory onion routing for all traffic
Rationale	Onion routing adds 21% payload overhead on LoRa — unacceptable as a default for all traffic. Omitting the source address is free and effective against casual observation. Per-packet layered encryption is available opt-in via `PathPolicy.ONION_ROUTE` for users who need stronger traffic analysis resistance.

Naming: Neighborhood-Scoped, No Global Namespace

Chosen	Community-label-scoped names (e.g., `alice@portland-mesh`)
Alternatives	Global names via consensus
Rationale	Global consensus contradicts partition tolerance. Community labels are self-assigned and informational — no authority, no uniqueness enforcement. Multiple disjoint clusters can share a label; resolution is proximity-based. Local petnames provide a fallback.

Cost Annotations: Compact Path Cost (No Per-Relay Signatures)

Chosen	6-byte constant-size `CompactPathCost` (running totals updated by each relay, no per-relay signatures)
Alternatives	Per-relay signed CostAnnotation (~84 bytes per hop), aggregate signatures, signature-free with Merkle proof
Rationale	Per-relay signatures make announces grow linearly with path length — 84 bytes × N hops. On a 1 kbps LoRa link with 3% routing budget, this limits convergence to ~1 announce per 22+ seconds. CompactPathCost uses 6 bytes total regardless of path length: log-encoded cumulative cost, worst-case latency, bottleneck bandwidth, and hop count. Per-relay signatures are unnecessary because routing decisions are local (you trust your link-authenticated neighbor), trust is transitive at each hop, and the market enforces honesty (overpriced relays get routed around, underpriced relays lose money). The announce itself remains signed by the destination node.

Congestion Control: Three-Layer Design

Chosen	Link-level CSMA/CA + per-neighbor token bucket + 4-level priority queuing + economic cost response
Alternatives	Pure CSMA/CA only, rigid TDMA, end-to-end TCP-style congestion control
Rationale	A single mechanism is insufficient across the bandwidth range (500 bps to 10 Gbps). CSMA/CA handles collision avoidance on half-duplex radio. Token buckets enforce fair sharing across neighbors. Priority queuing ensures real-time traffic (voice) isn't starved by bulk transfers. Economic cost response (quadratic cost increase under congestion) signals scarcity through the existing cost routing mechanism, causing natural traffic rerouting without new protocol extensions. End-to-end congestion control (TCP-style) is wrong for a mesh — the bottleneck is typically a single constrained link, and hop-by-hop control responds faster. Rigid TDMA wastes bandwidth when some slots are unused.

Transport Layer: Swappable Implementation

Chosen	Define transport as an interface with requirements; use Reticulum as the current implementation
Alternatives	Hard dependency on Reticulum, clean-room from day one
Rationale	Reticulum provides a proven transport layer tested at 5 bps on LoRa, saving significant implementation effort. But coupling NEXUS to Reticulum's codebase or community roadmap creates fragility. Instead, NEXUS defines the transport interface it needs (transport-agnostic links, announce-based routing, mandatory encryption, sender anonymity) and uses Reticulum as the current implementation. NEXUS extensions are carried as opaque payload in the announce DATA field — a clean separation. Three participation levels (L0 transport-only, L1 NEXUS relay, L2 full NEXUS) ensure interoperability with the underlying transport. This allows a future clean-room implementation without affecting any layer above transport.

Storage: Pay-Per-Duration with Erasure Coding

Chosen	Bilateral storage agreements, pay-per-duration, Reed-Solomon erasure coding, lightweight challenge-response proofs
Alternatives	Filecoin-style PoRep/PoSt with on-chain proofs; Arweave-style one-time-payment permanent storage; simple full replication
Rationale	Filecoin's Proof of Replication requires GPU-level computation (minutes to seal a sector) — impossible on ESP32 or Raspberry Pi. Arweave's permanent storage requires a blockchain endowment model and assumes perpetually declining storage costs. Both require global consensus. NEXUS uses simple Blake3 challenge-response proofs (verifiable in under 10ms on ESP32) and bilateral agreements settled via payment channels. Erasure coding (Reed-Solomon) provides the same durability as 3x replication at 1.5x storage overhead. The tradeoff: we can't prove a node stores data *uniquely* (no PoRep), but we can prove it stores data *at all* — and the data owner doesn't care how the node organizes its disk.

Mobile Handoff: Presence Beacons + Credit-Based Fast Start

Chosen	Transport-agnostic presence beacons, credit-based fast start, roaming cache with channel preservation
Alternatives	Pre-negotiated handoff (cellular-style), pure re-discovery from scratch, always-connected overlay
Rationale	Cellular handoff requires a central controller — incompatible with decentralized mesh. Pure re-discovery works but is slow for latency-sensitive sessions. Presence beacons (20 bytes, broadcast every 10 seconds on any interface) let mobile nodes passively discover local relays before connecting. Credit-based fast start allows immediate relay if the mobile node has visible CRDT balance, while the payment channel opens in the background. The roaming cache preserves channels for previously visited areas, enabling zero-latency reconnection on return. No explicit teardown needed — old agreements expire via `valid_until`.

Light Client Trust: Content Verification + Multi-Source Queries

Chosen	Three-tier verification: content-hash check (Tier 1), owner-signature check (Tier 2), multi-source queries (Tier 3)
Alter	Merkle proofs over DHT state, SPV-style state root verification, full DHT replication on clients

natives	
Rationale	Merkle proofs require a global state root, which contradicts partition tolerance (no consensus). SPV-style verification has the same problem. Full DHT replication is too bandwidth-heavy for phones. Instead, content addressing (Tier 1) gives zero-overhead verification for the most common case — `Blake3(data) == key` proves authenticity regardless of relay honesty. Signed objects (Tier 2) prevent forgery of mutable data. Multi-source queries (Tier 3, N=2-3 independent nodes) detect censorship and staleness. Trusted relays skip to single-source for all tiers. Overhead is minimal: at most one extra 192-byte query for critical lookups via untrusted relays.

Epoch Triggers: Adaptive Multi-Criteria

Chosen	Three-trigger system: settlement count ≥ 10,000 (large mesh), GSet size ≥ 500 KB (memory pressure), or partition-proportional threshold with gossip-round floor (small partitions)
Alternatives	Fixed 10,000-settlement-only trigger, wall-clock timer, per-node independent compaction
Rationale	A 20-node village on LoRa with low traffic might take months to reach 10,000 settlements. ESP32 nodes (520 KB usable RAM) would exhaust memory first. The adaptive trigger fires at max(200, active_set × 10) settlements with a 1,000-gossip-round floor (~17 hours), keeping GSet under ~6.4 KB for small partitions. The 500 KB GSet size trigger is a safety net regardless of partition size. Proposer eligibility adapts too — only 3 direct links needed (not 10) in small partitions. Wall-clock timers were rejected because they require clock synchronization. Per-node compaction was rejected because it fragments global state.

Ledger Scaling: Merkle-Tree Snapshots with Sparse Views

Chosen	Merkle-tree account snapshot; full tree on backbone nodes, sparse view + Merkle root on constrained devices, on-demand balance proofs (~640 bytes)
Alternatives	Flat snapshot everywhere, sharded epochs, neighborhood-only ledgers
Rationale	At 1M nodes the flat snapshot is ~~32 MB — unworkable on ESP32 or phones. Sharded epochs fragment the ledger and complicate cross-shard verification. Neighborhood-only ledgers lose global balance consistency. A Merkle tree over the sorted account snapshot gives the best of both: backbone nodes store the full tree (32 MB, feasible on SSD), constrained devices store only their own balance + channel~~

	~~partners + trust neighbors~~ (1.6 KB for 50 accounts) plus the Merkle root. Any balance can be verified on demand with a ~640-byte proof (20 tree levels × 32 bytes). No global state transfer needed.

Transforms/Inference: Compute Capability, Not Protocol Primitive

Chosen	STT/TTS/inference as compute capabilities in the marketplace
Alternatives	Dedicated transform layer (considered in v0.5 draft)
Rationale	Speech-to-text, translation, and other transforms are just compute. Making them protocol primitives over-engineers the foundation. The capability marketplace already handles discovery, negotiation, execution, verification, and payment for arbitrary compute functions.

Group Admin: Delegated Co-Admin (No Threshold Signatures)

Chosen	Delegated co-admin model: group creator signs delegation certificates for up to 3 co-admins; any co-admin can independently rotate keys and manage members
Alternatives	Threshold signatures (e.g., 2-of-3 Schnorr multisig), single admin only, leaderless consensus
Rationale	Threshold signatures (Schnorr multisig, FROST) require multi-round key generation and signing protocols that are too expensive for ESP32 and too complex for LoRa latency. Leaderless consensus contradicts the "no global coordination" principle. Instead, the group creator signs `CoAdminCertificate` records (admin public key + permissions + sequence number, ~128 bytes each) that authorize up to 3 co-admins. Any co-admin can independently add/remove members, rotate the group symmetric key, and promote/demote other co-admins (if authorized). Operations are sequence-numbered; conflicts are resolved by highest sequence number, ties broken by lowest admin public key hash. Overhead is one Ed25519 signature per admin action — no new cryptographic primitives needed. If all admins go offline, the group continues functioning with its current key; no key rotation or membership changes occur until at least one admin returns.

Reputation: Bounded Trust-Weighted Referrals

Chosen	First-hand scores primary; 1-hop trust-weighted referrals as advisory bootstrap for unknown peers, capped and decaying
Alternatives	Pure first-hand only (no referrals), full gossip-based reputation, global reputation aggregation
Rationale	Pure first-hand scoring means new nodes have zero information about any peer until direct interaction — leading to poor initial routing and credit decisions. Full reputation gossip enables manipulation: a colluding cluster can flood the network with inflated scores. Global aggregation requires consensus. The chosen design: trusted peers (direct trust edges) can share their first-hand scores as referrals. Referrals are weighted by the querier's trust in the referrer (trust_score / max_score × 0.3) and capped at 50% of max reputation — a referral alone cannot make a peer fully trusted. Only 1-hop referrals are accepted (no transitive gossip), limiting the manipulation surface to corruption of direct trusted peers, which already breaks the trust model. Referral scores are advisory: they initialize a peer's reputation but are overwritten by first-hand experience after the first few direct interactions. Referrals expire after 500 gossip rounds (~8 hours) without refresh. This helps new nodes bootstrap while keeping the attack surface minimal.

Onion Routing: Per-Packet Layered Encryption (Opt-In)

Chosen	Per-packet layered encryption via `PathPolicy.ONION_ROUTE`, stateless relays, 3 hops default, optional cover traffic
Alternatives	Circuit-based onion routing (Tor-style), mix networks, no onion routing (status quo)
Rationale	Circuit-based onion routing requires multi-round-trip circuit establishment — on a 1 kbps LoRa link with 2-second round trips, building a 3-hop circuit takes ~~12 seconds before any data flows. Mix networks add latency by design (batching and reordering), which is unacceptable for interactive messaging. Per-packet layered encryption has zero setup: the sender wraps the message in N encryption layers (default N=3), each layer containing the next-hop destination hash and the inner ciphertext. Each relay decrypts one layer, reads the next hop, and forwards. No circuit state on relays — each packet is independently routable. Overhead: 32 bytes per hop (16-byte nonce + 16-byte Poly1305 tag), so 3 hops = 96 bytes, leaving 369 of 465 usable bytes on LoRa~~ (21% overhead). Relay selection: sender picks from known relays, requiring at least one relay outside the sender's trust neighborhood. Optional constant-rate cover traffic (1

	dummy packet/minute, off by default) provides additional resistance to timing analysis on high-threat links. Onion routing is opt-in and not recommended for real-time voice (latency and payload overhead). The existing no-source-address design remains the default privacy layer for most traffic.

NXS-Byte: 47 Opcodes with Reference Interpreter

Chosen	47 opcodes in 7 categories, reference interpreter in Rust, cycle costs calibrated to ESP32
Alternatives	Formal specification (Yellow Paper-style), minimal 20-opcode set, EVM-compatible opcode set
Rationale	A formal specification (Ethereum Yellow Paper style) would freeze the design prematurely — the opcode set needs real-world usage feedback before committing to a formal spec. An EVM-compatible set imports unnecessary complexity (256-bit words, gas semantics) that doesn't fit constrained devices. A minimal 20-opcode set omits crypto and system operations needed for the core use cases. The chosen 47 opcodes cover 7 categories: **Stack** (6): PUSH, POP, DUP, SWAP, OVER, ROT. **Arithmetic** (9): ADD, SUB, MUL, DIV, MOD, NEG, ABS, MIN, MAX — all 64-bit integer, overflow traps. **Bitwise** (6): AND, OR, XOR, NOT, SHL, SHR. **Comparison** (6): EQ, NEQ, LT, GT, LTE, GTE. **Control** (7): JMP, JZ, JNZ, CALL, RET, HALT, ABORT. **Crypto** (3): HASH (Blake3), VERIFY_SIG (Ed25519), VERIFY_VRF. **System** (10): BALANCE, SENDER, SELF, EPOCH, TRANSFER, LOG, LOAD, STORE, MSIZE, EMIT. Cycle costs are tiered: stack/arithmetic/bitwise/comparison (1–3 cycles), control (2–5), memory (2–3), crypto (500–2000), system (10–50). ESP32 is the reference platform (~1 µs per base cycle). Faster hardware executes more cycles per second but charges the same cycle cost — gas price in µNXS/cycle is set by each compute provider. A comprehensive test vector suite ensures cross-platform conformance. Formal specification is a post-stabilization goal.

Emission Schedule: Epoch-Counted Discrete Halving

Chosen	Initial reward of 10^12 µNXS per epoch, discrete halving every 100,000 epochs, tail emission floor at 0.1% of circulating supply annualized
Altern	Continuous exponential decay, wall-clock halving (every 2 calendar years), fixed perpetual emission

atives	
Rationale	Wall-clock halving requires clock synchronization, which contradicts partition tolerance — partitioned nodes would disagree on the current halving period. Continuous decay is mathematically elegant but harder to reason about and implement correctly on integer-only constrained devices. Fixed perpetual emission provides no scarcity signal. Discrete halving every 100,000 epochs is epoch-counted (partition-safe), easy to compute (bit-shift), and predictable. At an estimated ~1 epoch per 10 minutes (varies with network activity since epochs are settlement-triggered), 100,000 epochs ≈ 1.9 years — close to the original 2-year target. Initial reward of 10^12 μNXS/epoch yields ~1.5% of the supply ceiling minted in the first halving period, providing strong bootstrap incentive. Tail emission activates when the halved reward drops below `0.001 × circulating_supply / estimated_epochs_per_year` (trailing 1,000-epoch moving average of epoch frequency). This ensures perpetual relay incentive while keeping inflation negligible. Partition minting interaction: each partition mints `(local_active_relays / estimated_global_relays) × epoch_reward`; on merge, GCounter max-merge preserves individual balances, and overminting is bounded by the existing partition_scale_factor tolerance (max 1.5×).

Protocol Bridges: Standalone Gateway Services

Chosen	Bridges as standalone gateway services advertising in the capability marketplace; one-way identity attestation; bridge operator bears NEXUS-side costs
Alternatives	Bridges as NXS-Compute contracts, bridge as protocol-level primitive, no bridge design (defer entirely)
Rationale	NXS-Compute contracts are sandboxed with no I/O or network access — bridges require persistent connections to external protocols (SSB replication, Matrix homeserver federation, Briar Tor transport). A protocol-level primitive over-engineers the foundation for what is fundamentally a gateway service. Bridges run as standalone processes that advertise their bridging capability in the marketplace like any other service. **Identity mapping**: Users create signed bridge attestations linking their NEXUS Ed25519 key to their external identity. The bridge stores these attestations and handles translation. No global identity registry — the bridge is the only entity that knows the mapping. External users see messages as coming from the bridge identity in the external protocol. **Payment model**: NEXUS-to-external traffic — the NEXUS sender pays the bridge operator via a standard marketplace agreement. External-to-NEXUS traffic — the bridge operator pays NEXUS relay costs and recoups via the external protocol's economics (or operates as a public good). This keeps the NEXUS economic model clean: the bridge is just another service consumer/provider. Bridge operators can support multiple protocols simultaneously and set their own pricing.

WASM Sandbox: Wasmtime with Tiered Profiles

Chosen	Wasmtime (Bytecode Alliance) as WASM runtime; two tiers: Light (Community, 16 MB / 10^8 fuel / 5s) and Full (Gateway+, 256 MB / 10^10 fuel / 30s); 10 host imports mirroring NXS-Byte System opcodes
Alternatives	Wasmer, custom interpreter, single WASM profile for all devices
Rationale	Wasmtime is Rust-native (matches the reference implementation language), provides fuel-based metering that maps directly to NXS-Byte cycle accounting, and supports AOT compilation on Gateway+ nodes. Wasmer has a broader language ecosystem but less tight Rust integration. A custom interpreter would duplicate Wasmtime's battle-tested sandboxing. A single WASM profile either excludes Community-tier devices (too high limits) or handicaps Gateway nodes (too low limits). Two tiers match the natural hardware split: Pi Zero 2W (512 MB RAM, interpreted Cranelift) vs. Pi 4/5+ (4-8 GB, AOT). Host imports are restricted to 10 functions mirroring NXS-Byte System opcodes — no filesystem, network, clock, or RNG access. WASM execution remains pure and deterministic, enabling the same verification methods as NXS-Byte. Contracts exceeding Light limits are automatically delegated to a more capable node via compute delegation.

Presence Beacon: 8-Bit Capability Bitfield

Chosen	8 assigned capability bits in 16-bit field; bits 8-15 reserved for future use
Alternatives	Variable-length capability list, TLV-encoded capabilities, separate beacon per capability
Rationale	The beacon must fit in 20 bytes total and broadcast every 10 seconds on LoRa — every byte matters. A 16-bit bitfield encodes up to 16 boolean capabilities in 2 bytes, zero parsing overhead. The 8 assigned bits cover all current service types: relay (L1+), gateway, storage, compute-byte, compute-wasm, pubsub, DHT, and naming. Bits 8-15 are reserved (must be zero) for future services like inference, bridge, etc. Variable-length lists or TLV encoding would bloat the beacon and complicate parsing on ESP32. Separate beacons per capability would multiply broadcast bandwidth.

Ring 1 Discovery: CapabilitySummary Format

Chosen	8-byte `CapabilitySummary` per capability type: type (u8), count (u8), min/avg cost (u16 each, $\log_2$-encoded), min/max hops (u8 each)
Alternatives	Full capability advertisements forwarded, Bloom filter of providers, free-text summaries
Rationale	Ring 1 gossips summaries every few minutes — bandwidth must stay under ~50 bytes per round. At 8 bytes per type and typically 5-6 types present in a 2-3 hop neighborhood, the total is 40-48 bytes — within budget even on LoRa. Forwarding full capability advertisements would scale linearly with provider count. Bloom filters compress provider identity but lose cost/distance information needed for routing decisions. The $\log_2$-encoded cost fields match `CompactPathCost` encoding, keeping the representation consistent across the protocol. Count is capped at 255 (u8) — sufficient since Ring 1 covers only 2-3 hops.

DHT Metadata: 129-Byte Signed Entries

Chosen	129-byte `DHTMetadata`: 32-byte Blake3 key, u32 size, u8 content_type (Immutable/Mutable/Ephemeral), 16-byte owner, u32 TTL, u64 Lamport timestamp, 64-byte Ed25519 signature
Alternatives	Minimal key-only gossip (no metadata), full object gossip, variable-length metadata with optional fields
Rationale	DHT publication gossips metadata to let storage-set nodes decide whether to pull full data. Key-only gossip forces blind pulls — wasting bandwidth on unwanted or expired data. Full object gossip floods the gossip channel with arbitrarily large payloads. The 129-byte fixed format includes everything a storage node needs to decide: content hash (for deduplication), size (for storage budgeting), content type (for cache policy), owner (for mutable-object freshness ordering), TTL (for garbage collection), and Lamport timestamp (for mutable conflict resolution). The Ed25519 signature prevents metadata forgery — a node cannot falsely advertise objects it doesn't own. Content hash prevents data forgery on pull. For mutable objects, highest Lamport timestamp with valid signature wins; for immutable objects, the content hash is the sole arbiter. Cache invalidation is TTL-based with no push-invalidation — keeping the protocol simple and partition-tolerant.

Negotiation Protocol: Single-Round Take-It-or-Leave-It

Chosen	Single round-trip negotiation: consumer sends `CapabilityRequest` (with desired cost, duration, proof preference, nonce); provider responds with `CapabilityOffer` (actual terms) or reject; consumer accepts or walks away. 30-second timeout. No counter-offers.
Alternatives	Multi-round bidding/auction, Dutch auction, sealed-bid auction, negotiation-free fixed pricing
Rationale	Multi-round negotiation is untenable on LoRa where each message takes seconds — a 3-round negotiation would take 30+ seconds before service begins. Auctions require multiple participants to discover each other simultaneously, which contradicts the bilateral, privacy-preserving nature of agreements. Fixed pricing (no negotiation) removes the consumer's ability to express budget constraints. The single-round protocol: the consumer states their maximum acceptable cost; the provider either meets it, undercuts it, or rejects. One round-trip, then service begins. The nonce in `CapabilityRequest` prevents replay attacks; the `request_nonce` echo in `CapabilityOffer` binds offer to request. Both messages are signed — the two signatures together form the `CapabilityAgreement`. If the consumer wants different terms, they send a new request with adjusted parameters — no counter-offer complexity. This keeps capability negotiation under 2 seconds on WiFi and under 10 seconds on LoRa.

Formal Verification: Priority-Ordered TLA+ Targets

Chosen	TLA+ for concurrent protocol properties; 4-tier priority: (1) CRDT merge, (2) payment channels, (3) epoch checkpoints, (4) full composition deferred
Alternatives	Coq/Lean theorem proving, no formal verification (testing only), verify everything before v1.0
Rationale	Coq/Lean have a steep learning curve that limits contributor access. Pure testing cannot prove absence of bugs in concurrent distributed protocols. Verifying everything delays launch indefinitely. TLA+ is battle-tested for distributed systems (used by Amazon for AWS services, by Microsoft for Azure) and has a practical learning curve. **Priority 1 — CRDT merge convergence** (must verify before v1.0): Prove commutativity, associativity, and idempotency of GCounter max-merge and GSet union. If merge diverges, the entire ledger is broken. **Priority 2 — Payment channel state machine** (must verify before v1.0): Prove no balance can go negative, dispute resolution always terminates within the challenge window, and channel states form a total order by sequence number. Direct financial impact if buggy. **Priority 3 — Epoch checkpoint correctness** (should verify): Prove no confirmed settlement is permanently lost after

	finalization, bloom filter false positive recovery covers all edge cases during the grace period. Property-based testing (QuickCheck-style) initially, formal TLA+ proof if resources allow. **Priority 4 — Full protocol composition** (defer to post-v1.0): Interaction between subsystems (e.g., channel dispute during epoch transition) is tracked as a long-term research goal. Individual component proofs provide sufficient confidence for launch.

Open Questions

All design questions — both architectural and implementation-level — have been resolved. This page tracks the resolution history.

Resolved in Implementation Spec (Phase 1-2)

#	Question	Resolution	Location
1	WASM Sandbox Specification	Wasmtime runtime; Light (16 MB, 10^8 fuel, 5s) and Full (256 MB, 10^10 fuel, 30s) tiers; 10 host imports mirroring NXS-Byte System opcodes	NXS-Compute
2	Presence Beacon Capability Bitfield	8 assigned bits (relay, gateway, storage, compute-byte, compute-wasm, pubsub, dht, naming); bits 8-15 reserved	Discovery
3	Ring 1 Capability Aggregation Format	`CapabilitySummary` struct: 8 bytes per type (type, count, min/avg cost, min/max hops)	Discovery
4	DHT Metadata Format	`DHTMetadata` struct: 129 bytes (key, size, content_type, owner, ttl, lamport_ts, Ed25519 signature)	NXS-DHT
5	Negotiation Protocol Wire Format	Single-round take-it-or-leave-it; 30-second timeout; `CapabilityRequest` + `CapabilityOffer` with nonce replay prevention	Agreements

Resolved in v1.0 Spec Review

#	Question	Resolution	Design Decision
1	Multi-admin group messaging	Delegated co-admin model (up to 3 co-admins, no threshold signatures)	Design Decisions
2	Reputation gossip vs. first-hand only	Bounded 1-hop trust-weighted referrals, capped at 50%, advisory only	Design Decisions
3	Onion routing for high-threat environments	Per-packet layered encryption, opt-in via PathPolicy, 3 hops default, 21% overhead on LoRa	Design Decisions
4	NXS-Byte full opcode specification	47 opcodes in 7 categories, reference interpreter in Rust, ESP32-calibrated cycle costs	Design Decisions
5	Bootstrap emission schedule parameters	10^12 µNXS/epoch initial, discrete halving every 100K epochs, 0.1% tail floor	Design Decisions

6	Protocol bridge design (SSB, Matrix, Briar)	Standalone gateway services, identity attestation, bridge operator pays NEXUS costs	Design Decisions
7	Formal verification targets	TLA+ priority-ordered: CRDT merge, payment channels, epoch checkpoints; composition deferred	Design Decisions

Resolved in v1.0 Spec Hardening

Protocol-level gaps identified during comprehensive spec review, all resolved inline in the relevant spec pages:

Gap	Resolution	Location
Announce propagation frequency	Event-driven + 30-min periodic refresh, 128-hop limit, 3-round link failure detection	Network Protocol
ChaCha20 nonce handling	64-bit counter per session key, zero-padded to 96 bits	Security
Session key rotation timing	Local monotonic clock, either side can initiate	Security
KeyCompromiseAdvisory replay	Added monotonic `sequence` field	Security
Difficulty target formula	Local per-link computation, `win_prob = target_updates / observed_packets`	Payment Channels
Settlement validation	Every node validates (2 sig checks + hash + GSet lookup), invalid dropped silently	CRDT Ledger
Active set definition	Nodes appearing as party in at least 1 settlement in last 2 epochs	CRDT Ledger
Bloom filter construction	k=13 Blake3-derived hash functions, 19.2 bits/element at 0.01% FPR	CRDT Ledger
Relay compensation tracking	RelayWinSummary with spot-check proofs, challengeable during grace period	CRDT Ledger
Roaming cache fingerprint stability	60% overlap threshold for area recognition	Discovery
Credit-based fast start staleness	Rate-limited grants, 2× balance requirement for staleness tolerance	Discovery
Trust relationship revocation	Asymmetric, revocable at any time, downgrades stored data priority	Trust Neighborhoods

import DownloadButton from '@site/src/components/DownloadButton';

NEXUS Protocol Specification v1.0

This page is the normative reference for the NEXUS protocol. Individual documentation pages provide detailed explanations; this page summarizes the protocol constants, wire formats, and layer dependencies in one place.

Status

Version	1.0
Status	Design complete, pre-implementation
Normative sections	Layers 0–5 (transport through services)
Informative sections	Layer 6 (applications), hardware reference, roadmap

Protocol Constants

Constant	Value	Defined In
Gossip interval	60 seconds	Network Protocol
Protocol overhead budget	≤10% of link bandwidth	Bandwidth Budget
CompactPathCost size	6 bytes (constant)	Network Protocol
NexusExtension magic byte	`0x4E` ('N')	Network Protocol
Destination hash size	16 bytes (128-bit)	Network Protocol
Smallest NXS unit	1 μNXS	NXS Token
Supply ceiling	2^64 μNXS (asymptotic)	NXS Token
Default relay lottery probability	1/100	Stochastic Rewards
Payment channel state size	200 bytes	Payment Channels
Dispute challenge window	2,880 gossip rounds (~48h)	Payment Channels
Channel abandonment threshold	4 epochs	Payment Channels
Epoch trigger: settlement count	≥10,000 batches	CRDT Ledger
Epoch trigger: GSet memory	≥500 KB	CRDT Ledger
Epoch acknowledgment threshold	67% of active set	CRDT Ledger

Epoch verification window	4 epochs after activation	CRDT Ledger
Bloom filter FPR (epoch)	0.01%	CRDT Ledger
DHT replication factor	k=3	NXS-DHT
DHT XOR weight (w_xor)	0.7	NXS-DHT
Storage chunk size	4 KB	NXS-Store
Presence beacon size	20 bytes	Discovery
Presence beacon interval	10 seconds	Discovery
Transitive credit limit	10% per hop, max 2 hops	Trust & Neighborhoods

Cryptographic Primitives

Purpose	Algorithm	Output / Key Size
Identity / Signing	Ed25519	256-bit (32-byte public key)
Key Exchange	X25519 (Curve25519 DH)	256-bit
Identity Hashing	Blake2b	256-bit → 128-bit truncated
Content Hashing	Blake3	256-bit
Symmetric Encryption	ChaCha20-Poly1305	256-bit key, 96-bit nonce
Relay Lottery (VRF)	ECVRF-ED25519-SHA512-TAI (RFC 9381)	80-byte proof
Erasure Coding	Reed-Solomon	Configurable k,m

Layer Dependency Graph

```
Layer 6: Applications
  ├── Messaging, Social, Voice, Naming, Forums, Hosting
  └── depends on ↓

Layer 5: Service Primitives
  ├── NXS-Store, NXS-DHT, NXS-Pub, NXS-Compute
  └── depends on ↓

Layer 4: Capability Marketplace
  ├── Discovery, Agreements, Verification
  └── depends on ↓

Layer 3: Economic Protocol
  ├── NXS Token, Stochastic Rewards, CRDT Ledger, Trust Neighborhoods
  └── depends on ↓

Layer 2: Security
```

```
  ├── Link encryption, E2E encryption, Authentication, Key management
  └── depends on ↓

Layer 1: Network Protocol
  ├── Identity, Addressing, Routing, Gossip, Congestion Control
  └── depends on ↓

Layer 0: Physical Transport
  └── LoRa, WiFi, Cellular, Ethernet, BLE, Fiber, Serial
```

Each layer depends **only** on the layer directly below it. Applications never touch transport details. Payment never touches routing internals.

Wire Format Summary

Packet Format (Reticulum-derived)

```
[HEADER 2B] [DEST_HASH 16B] [CONTEXT 1B] [DATA 0–465B]
Max packet size: 484 bytes
Source address: NOT PRESENT (structural sender anonymity)
```

NEXUS Announce Extension

```
[MAGIC 1B: 0x4E] [VERSION 1B] [CompactPathCost 6B] [TLV extensions ... ]
Minimum: 8 bytes. Carried in announce DATA field.
```

CompactPathCost

```
[cumulative_cost 2B] [worst_latency_ms 2B] [bottleneck_bps 1B] [hop_count 1B]
Total: 6 bytes (constant regardless of path length)
```

Payment Channel State

```
[channel_id 16B] [party_a 16B] [party_b 16B] [balance_a 8B]
[balance_b 8B] [sequence 8B] [sig_a 64B] [sig_b 64B]
Total: 200 bytes
```

Specification Sections

Spec Section	Documentation Page
0. Design Philosophy	Introduction

1. Layer 0: Physical Transport	Physical Transport
2. Layer 1: Network Protocol	Network Protocol
3. Layer 2: Security	Security
4. Layer 3: Economic Protocol	NXS Token, Stochastic Relay Rewards, CRDT Ledger, Trust & Neighborhoods, Real-World Economics
5. Layer 4: Capability Marketplace	Overview, Discovery, Agreements, Verification
6. Layer 5: Service Primitives	NXS-Store, NXS-DHT, NXS-Pub, NXS-Compute
7. Layer 6: Applications	Messaging, Social, Voice, Naming, Community Apps, Hosting
8. Hardware Reference	Reference Designs, Device Tiers
9. Implementation Roadmap	Roadmap
10. Design Decisions	Design Decisions
11. Open Questions	Open Questions

Version History

Version	Status	Description
v0.1-v0.5	Superseded	Early design iterations
v0.8	Superseded	Introduced explicit community zones (later replaced by trust neighborhoods)
v1.0	**Current**	Consolidated specification — Reticulum foundation, stochastic relay rewards, emergent trust neighborhoods

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This specification consolidates design work from v0.1 through v1.0. The foundation — Reticulum-based transport, cryptographic identity, Kleinberg small-world routing, stochastic relay rewards, CRDT settlement, epoch compaction, emergent trust neighborhoods, and the capability marketplace — is the protocol. Everything above it — storage, compute, pub/sub, naming, and applications — are services built on that foundation.