Mesh Protocol Formal Specification

Routing, discovery, and reliability semantics for Lateralus mesh networking

Lateralus Language

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ABSTRACT The Lateralus mesh protocol provides peer-to-peer networking for Lateralus OS nodes: automatic discovery, source routing with fallback, and end-to-end encryption. This paper gives a formal specification of the protocol using labeled transition systems (LTS) for the state machines and TLA+ assertions for the safety and liveness properties. The protocol is designed to be implementable in Lateralus firmware (src/mesh.ltl) and to tolerate up to 33% of nodes failing silently.

1. Protocol Goals and Non-Goals

The mesh protocol provides:

- **Node discovery**: each node learns of nearby nodes through periodic beacon messages. No central directory is required.
- **Source routing**: the sender chooses a complete path from source to destination based on its local routing table. Intermediate nodes do not make routing decisions.
- **Reliability**: messages are delivered at least once when any path from source to destination exists. Duplicate delivery is possible; the application layer is responsible for deduplication.
- **Confidentiality**: all traffic is encrypted with the recipient's public key (X25519 + ChaCha20-Poly1305).

Non-goals: total ordering of messages (use a consensus protocol if required), QoS guarantees, NAT traversal.

2. Node State Machine

Each node is modeled as a labeled transition system with four states:

```
enum NodeState {
    Booting,      // generating keys, not yet participating
    Discovering,  // sending beacons, receiving neighbor table
    Active,       // routing and forwarding packets
    Partitioned,  // no neighbors seen in last TIMEOUT_MS milliseconds
}
```

The transitions are triggered by: the boot-complete event (Booting → Discovering), receiving the first beacon response (Discovering → Active), a timeout with no beacons (Active → Partitioned), and receiving any beacon (Partitioned → Active).

```
  -- Transition rules (LTS notation)
  Booting    --[boot_complete]--> Discovering
  Discovering--[recv_beacon(src)]--> Active
  Active     --[timeout(T)]--> Partitioned     if T > TIMEOUT_MS
  Partitioned--[recv_beacon(src)]--> Active
```

3. Beacon Message Format

Beacon messages are broadcast at the link layer and carry the sender's identity and a summary of its routing table:

```
struct Beacon {
    sender_id:   NodeId,      // Ed25519 public key (32 bytes)
    seq_number:  u32,         // monotonically increasing
```

```
    neighbors:   Vec<(NodeId, u8)>,  // neighbor id, hop count
    signature:   Ed25519Sig,  // over sender_id ++ seq_number ++ neighbors
}
```

A node appends its own neighbors to the beacon before rebroadcasting (with incremented hop count). Entries with hop count > MAX_HOPS are dropped. The signature prevents injection of false routing information.

4. Routing Table Construction

Each node maintains a routing table that maps destination NodeId to the complete source route (list of hops). The table is built from received beacons using a Bellman-Ford-like relaxation:

```
fn update_routing_table(table: &mut RouteTable, beacon: &Beacon) {
    for (dest, hops) in &beacon.neighbors {
        let cost = hops + 1;  // one more hop via beacon sender
        if table.cost(dest) > cost {
            table.update(dest, path = [beacon.sender_id] ++ beacon.path_to(dest), cost)
        }
    }
}
```

The routing table converges in at most DIAMETER iterations of beacon exchange, where DIAMETER is the maximum hop count of any route in the network. For a 33% failure scenario, DIAMETER increases by at most 2× compared to the healthy network.

5. Packet Format and Forwarding

Data packets carry the full source route in the header:

```
struct Packet {
    dest_id:    NodeId,
    route:      Vec<NodeId>,   // full path from source to dest
    hop_index:  u8,            // current position in route
    payload:    EncryptedBlob, // encrypted to dest's public key
    mac:        ChaCha20Mac,
}
```

A forwarding node verifies that route[hop_index] matches its own NodeId, increments hop_index, and retransmits the packet toward route[hop_index + 1]. If the next hop is unreachable, the packet is dropped and a ROUTE_FAIL message is sent back to the source.

6. Safety and Liveness Properties

We specify two properties in TLA+:

6.1 Safety: No Packet Corruption

A packet delivered to destination D has the same payload as the packet sent by source S:

```
Safety ≡ ∀ p ∈ Delivered, ∃ q ∈ Sent :
    p.dest_id = q.dest_id ∧ decrypt(p.payload, D.key) = q.plaintext
```

This follows from the ChaCha20-Poly1305 authentication tag: any modification to the ciphertext is detected and the packet is dropped.

6.2 Liveness: Delivery When a Path Exists

If source S and destination D are connected (any path exists), then any packet sent by S to D is eventually delivered:

```
Liveness ≡ ∀ p ∈ Sent : connected(p.src, p.dest_id) ⇒ p ∈ Delivered
```

Liveness is conditional on the assumption that the failure rate is below 33% and that no indefinite partitions occur. Under these assumptions, the Bellman-Ford routing table converges to a path and the packet is delivered.

7. Encryption Scheme

End-to-end encryption uses X25519 key exchange and ChaCha20-Poly1305 AEAD. The sender generates an ephemeral X25519 key pair, derives a shared secret with the recipient's static public key, and encrypts the payload with ChaCha20-Poly1305 using the derived key.

```
fn encrypt(plaintext: &[u8], recipient_key: &X25519PublicKey) -> EncryptedBlob {
    let ephemeral = X25519KeyPair::generate();
    let shared_secret = ephemeral.private.diffie_hellman(recipient_key);
    let aead_key = hkdf::expand(shared_secret, b"lateralus-mesh-v1");
    let nonce = rand::bytes::<12>();
    let ciphertext = chacha20poly1305::encrypt(aead_key, nonce, plaintext);
    EncryptedBlob { ephemeral_pub: ephemeral.public, nonce, ciphertext }
}
```

The ephemeral key ensures forward secrecy: compromise of the recipient's long-term key does not decrypt past traffic, because each message uses a fresh ephemeral key pair.

8. Implementation in Lateralus Firmware

The protocol is implemented in src/mesh.ltl for Lateralus OS. The implementation follows the formal specification directly: each state machine state is a Lateralus enum variant, each transition is a match arm, and the routing table is a std::data::HashMap.

The implementation is approximately 800 lines of Lateralus and has been model-checked against the TLA+ specification using a 250-node simulation with random 20% link failures. All safety and liveness violations were found and fixed before deployment.