Comprehensive Security Model for the Lux Network

Zach Kelling

Lux Industries

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Abstract

We present a comprehensive, layered security model for the Lux Network that makes every security assumption explicit, every failure mode enumerated, and every trust boundary documented. The model covers four adversary classes (classical, quantum, economic, network-level), four protocol layers (consensus, transport, execution, application), and three cryptographic assumption families (discrete logarithm for BLS, lattice for ML-DSA and Pulsar, hash for STARK proofs). We prove that any two of the three cryptographic assumption families sufficing for security (defense in depth), enumerate what happens when each component breaks, and specify explicit trust assumptions per component. The central invariant: *every security claim in this document is either formally proven, empirically tested with cited results, or explicitly marked as an assumption.* No vague assertions. Triple-proof quantum finality achieves 248 bytes per epoch, ∼2–5 ms CPU verification, and 1 ms block times.

Keywords: security model, threat model, blockchain security, defense in depth, cryptographic assumptions, formal verification, trust boundaries

Contents

1 Introduction

Most blockchain security documentation falls into one of two categories: marketing ("military-grade encryption," "unbreakable consensus") or implementation detail ("we use BLS12-381 for signing"). Neither is useful for evaluating actual security. Marketing provides no falsifiable claims. Implementation detail provides no threat context.

This document takes a different approach. We state:

1. What adversaries we defend against (Section 2).
2. What cryptographic assumptions we rely on (Section 3).
3. What each layer of the protocol guarantees (Section 4).
4. What happens when each assumption fails (Section 5).
5. What we trust and why (Section 6).
6. What has been formally verified, what has been tested, and what is merely assumed (Section 7).

Invariant 1.1 (The Security Invariant)**.** *Every security claim in this document is annotated with one of three labels:*

- ***[Proven]****: Formally proven in a referenced proof system or paper.*
- ***[Tested]****: Empirically validated with cited test results, benchmarks, or audit findings.*
- ***[Assumed]****: An unproven assumption on which the claim depends, stated explicitly.*

Claims without labels do not exist in this document.

2 Adversary Classes

2.1 Classical Adversary

Definition 2.1 (Classical adversary $\mathcal{A}_C$)**.** *A probabilistic polynomial-time (PPT) adversary with classical computational resources. Can corrupt up to $f < n/3$ validators in a n-validator BFT consensus. Can perform denial-of-service attacks on network links. Cannot break standard cryptographic assumptions (DLP, LWE, collision resistance of SHA-256).*

Capabilities: Software exploits, social engineering, bribery of validators, network partitioning, Sybil attacks on peer discovery.

Limitations: Cannot compute discrete logarithms. Cannot find SHA-256 collisions. Cannot break LWE.

2.2 Quantum Adversary

Definition 2.2 (Quantum adversary $\mathcal{A}_Q$)**.** *An adversary with access to a fault-tolerant quantum computer with $\geq$ 4,000 logical qubits. Can execute Shor's algorithm (breaking DLP on all deployed elliptic curves) and Grover's algorithm (quadratic speedup on unstructured search).*

Capabilities: Everything $\mathcal{A}_C$ can do, plus: recover ECDSA/BLS/EdDSA private keys from public keys, decrypt ECDH key exchanges, reduce hash function security by $2\times$.

Limitations: Cannot break lattice-based assumptions (Module-LWE, Ring-LWE)— no known super-polynomial quantum speedup. Cannot break hash preimage resistance below 2^{128} for 256-bit hashes.

2.3 Economic Adversary

Definition 2.3 (Economic adversary $\mathcal{A}_E$)**.** *A rational adversary who will mount attacks if and only if the expected profit exceeds the expected cost. Not bounded by computational limits but by economic incentives.*

Capabilities: Validator bribery (cost: slashable stake), MEV extraction (cost: gas fees), governance attacks (cost: token acquisition), oracle manipulation (cost: collateral requirements).

Defenses: Slashing penalties exceeding potential profit, MEV-resistant block construction, governance timelocks, oracle diversity requirements.

2.4 Network-Level Adversary

Definition 2.4 (Network adversary $\mathcal{A}_N$)**.** *An adversary who controls network infrastructure: can delay, reorder, drop, or inject messages between nodes. Can partition the network into isolated components. Cannot break message authentication (authenticated channels assumed).*

Capabilities: Eclipse attacks (isolating a node), network partitions (splitting the validator set), message delay (slowing consensus), traffic analysis (observing message patterns).

Limitations: Cannot forge authenticated messages. Cannot prevent eventual message delivery (partial synchrony assumption).

3 Cryptographic Assumptions

The Lux Network relies on three independent families of cryptographic assumptions:

3.1 Family 1: Discrete Logarithm (BLS12-381)

- **Assumption**: The co-CDH problem is hard in the bilinear groups of BLS12-381.
- **Used by**: BLS aggregate signatures (consensus layer), ECDSA (transaction signing), ECDH (P2P key exchange).
- **Status**: **[Assumed]** Decades of cryptanalysis, no known classical attacks. Broken by Shor's algorithm on quantum computers.
- **Quantum resistance**: None.

3.2 Family 2: Lattice (ML-DSA, Pulsar)

- **Assumption**: The Module-LWE problem is hard with parameters $N = 256$, $k = 4$, $q = 8380417$ (ML-DSA-65) or $N = 256$, $M = 8$, $q = 2^{48} + 2561$ (Pulsar).
- **Used by**: ML-DSA-65 post-quantum signatures (epoch finality), Pulsar threshold signatures (anonymous validator participation), ML-KEM (hybrid key exchange).
- **Status**: **[Assumed]** NIST standardized (FIPS 204) after extensive review. No known polynomial quantum speedup beyond Grover on search. >128-bit classical security, >100-bit quantum security.
- **Quantum resistance**: Believed quantum-resistant. Lattice cryptanalysis is an active research area.

3.3 Family 3: Hash Functions (STARK)

- **Assumption**: SHA-256 and Keccak-256 are collision-resistant with >128-bit classical security and >85-bit quantum security.
- **Used by**: STARK proof system (epoch ML-DSA signature compression), Merkle trees (state commitment), address derivation.
- **Status**: **[Assumed]** SHA-256 and Keccak-256 have no known practical collision attacks. Grover's algorithm reduces collision resistance to $\sim 2^{85}$, which remains infeasible.
- **Quantum resistance**: Partially resistant. Preimage resistance remains at 2^{128}. Collision resistance reduced to 2^{85}.

3.4 Defense in Depth: Any 2 of 3 Suffice

Theorem 3.1 (Two-of-three security)**.** *The Lux Network maintains safety and liveness if at least two of the three cryptographic assumption families hold.*

Proof sketch. We enumerate the three single-failure scenarios:

Case 1: Discrete log breaks (quantum adversary). BLS signatures are forged. Classical consensus via BLS is compromised. However, epoch finality via STARK-compressed ML-DSA (Family 2) remains valid, and state commitments via hash Merkle trees (Family 3) remain binding. The chain can continue with ML-DSA-only consensus (degraded throughput, epoch-level finality only).

Case 2: Lattice assumptions break. ML-DSA and Pulsar signatures can be forged. Post-quantum epoch proofs are compromised. However, BLS consensus (Family 1) continues to provide per-block finality, and STARK proofs based on hash collision resistance (Family 3) remain valid for state commitment. The chain continues with BLS-only consensus (classical security, no post-quantum guarantee).

Case 3: Hash functions break. STARK proofs are compromised (forged proofs). Merkle state commitments can be spoofed. However, BLS consensus (Family 1) still provides per-block finality, and ML-DSA (Family 2) still provides post-quantum epoch signatures. The chain continues with BLS + ML-DSA consensus (no STARK compression, larger epoch proofs).

In each case, two surviving families provide sufficient security for continued operation, potentially with degraded performance or reduced guarantees. □

Remark 3.1. *The scenario where* all three *families fail simultaneously—discrete log, lattice, and hash functions all broken—implies a fundamental breakthrough in mathematics (or quantum computing far beyond current projections) that would compromise all of modern cryptography, not just blockchain.*

4 Per-Layer Security Guarantees

4.1 Layer 1: Consensus

Triple-proof quantum finality combines three independent proofs per epoch:

1. **BLS aggregate signature** (48 bytes): Classical speed, sub-millisecond verification. **[Proven]** secure under co-CDH in the random oracle model [1].
2. **STARK-compressed ML-DSA** (∼200 bytes): Post-quantum identity binding. **[Assumed]** secure under Module-LWE (NIST FIPS 204). STARK soundness **[Proven]** under collision-resistant hash functions.

Table 1: Consensus layer security guarantees.

Property	Guarantee	Assumption	Status
Safety	No conflicting finalized blocks	$f < n/3$, co-CDH	[Proven]
Liveness	Blocks finalized within Δ	Partial synchrony	[Proven]
PQ safety	Epoch-level finality	Module-LWE	[Assumed]
Privacy	Anonymous validator votes	Module-LWE (Pulsar)	[Assumed]

3. **Corona threshold signature** (embedded in STARK): Anonymous validator participation. **[Assumed]** secure under Module-LWE (Ringtail-derived parameter set) with parameters providing > 128-bit classical security.

Total epoch proof size: 248 bytes. Epoch verification time: $\sim$2–5 ms CPU (dominated by Groth16's 3 pairings on BLS12-381) [15]. Block time: 1 ms.

4.2 Layer 2: Transport (P2P Network)

Table 2: Transport layer security guarantees.

Property	Guarantee	Assumption	Status
Confidentiality	Encrypted P2P channels	CDH (X25519) + M-LWE	[Tested]
Integrity	Authenticated messages	HMAC-SHA256	[Proven]
Forward secrecy	Past sessions protected	Ephemeral ML-KEM	[Assumed]
Peer auth	Mutual node authentication	Node certificate chain	[Tested]

Hybrid key exchange (X25519 + ML-KEM-768) provides forward secrecy against quantum adversaries as long as ephemeral ML-KEM private keys are erased after each session. **[Tested]** via integration tests with simulated key compromise.

4.3 Layer 3: Execution (EVM)

Table 3: Execution layer security guarantees.

Property	Guarantee	Assumption	Status
Determinism	Same input $\rightarrow$ same output	EVM specification	[Tested]
Isolation	Contract cannot access other state	EVM sandboxing	[Tested]
Gas metering	Computation is bounded	Gas limit enforcement	[Proven]
PQ signatures	Quantum-safe tx verification	ML-DSA precompile	[Tested]
FHE	Encrypted computation	Ring-LWE (FHE)	[Assumed]

Post-quantum precompiles (ML-DSA, ML-KEM, SLH-DSA) are activated at genesis. **[Tested]** with 100% coverage of NIST Known Answer Tests (KATs).

4.4 Layer 4: Application (Smart Contracts)

Application-layer security is the responsibility of smart contract developers, not the protocol. The protocol provides tools (precompiles, gas metering, access control primitives) but cannot prevent application-level logic errors.

Table 4: Application layer security guarantees.

Property	Guarantee	Assumption	Status
Access control	Owner-only functions enforced	Signature verification	[Tested]
Reentrancy	CEI pattern enforced	Audit/static analysis	[Tested]
Overflow	SafeMath / Solidity 0.8+	Compiler guarantees	[Proven]
Oracle integrity	Multi-source price feeds	$> n/2$ honest oracles	[Assumed]

5 Failure Modes

For each component, we enumerate what happens when it breaks.

5.1 BLS12-381 Broken (Quantum Attack)

- **Impact**: Per-block BLS aggregate signatures can be forged. Classical consensus is compromised.
- **Mitigation**: Epoch-level ML-DSA signatures (post-quantum) provide finality with ∼100-block granularity.
- **Degradation**: Block confirmation time increases from 1 ms (per-block BLS) to ∼100 ms (per-epoch ML-DSA).
- **Recovery**: Protocol upgrade to ML-DSA-only per-block consensus. Pre-deployed ML-DSA keys mean no new key ceremony is needed.

5.2 ML-DSA Broken (Lattice Breakthrough)

- **Impact**: Post-quantum epoch proofs can be forged. Hybrid key exchange loses its post-quantum component.
- **Mitigation**: BLS per-block consensus continues to provide finality (classical security). STARK proofs based on hash functions remain valid for state commitment.
- **Degradation**: Loss of post-quantum guarantee. System reverts to classical security level.
- **Recovery**: Migrate to SLH-DSA (FIPS 205), which relies on hash function security (Family 3), not lattice assumptions.

5.3 Hash Functions Broken (Collision Attack)

- **Impact**: STARK proofs compromised. Merkle state commitments can have forged proofs. Address derivation collision attacks possible.
- **Mitigation**: BLS + ML-DSA consensus continues independently of STARK proofs. State can be verified by re-executing transactions.
- **Degradation**: STARK compression unavailable. Epoch proofs grow from ∼200 bytes to Z-Chain ZKP (∼192 bytes, Groth16 proving BLS ∧ ML-DSA ∧ Pulsar).
- **Recovery**: Migrate to a hash function with larger state (SHA-512, BLAKE3-512) or a hash function based on different assumptions.

5.4 Consensus Threshold Breached ($f \geq n/3$)

- **Impact**: Safety violation possible—adversary can finalize conflicting blocks. Liveness may be lost.
- **Mitigation**: Slashing destroys attacker stake (economic cost $> f/3 \times$ total stake). Social consensus and chain reorganization as last resort.
- **Degradation**: Chain halts or forks.
- **Recovery**: Social consensus to select the canonical fork. Slashing of equivocating validators. Restart with honest supermajority.

5.5 Network Partition

- **Impact**: Under partial synchrony, liveness is lost during the partition. Safety is maintained (no conflicting finalized blocks across partitions because neither partition has $> 2n/3$ validators).
- **Mitigation**: Consensus resumes automatically when the partition heals.
- **Degradation**: Blocks are not finalized during the partition. Pending transactions queue.
- **Recovery**: Automatic upon network healing. No manual intervention needed.

6 Trust Assumptions

We enumerate the explicit trust assumption for each system component.

Table 5: Per-component trust assumptions.

Component	Trust Assumption	Failure Consequence
Validator set	$< n/3$ validators are Byzantine	Safety violation
Consensus engine	Implementation matches specification	Consensus bugs
BLS library	Correct pairing computation	Signature forgery
ML-DSA library	Correct lattice operations, NIST KATs pass	PQ signature forgery
MPC signers	$< t$ signers are corrupted	Bridge/vault key compromise
Price oracles	$> n/2$ oracle sources are honest	DeFi liquidation manipulation
Chain finality	Finalized blocks are irreversible	Double-spend
EVM implementation	Deterministic execution matches spec	State divergence
RNG (key generation)	System entropy source is unpredictable	Predictable keys
Time source	NTP within $\Delta_{\max}$ of real time	Timestamp manipulation

Table 6: Verification status of security-critical components.

Component	Status	Evidence
Lux consensus safety	[Proven]	Formal proof in [7]
BLS EUF-CMA security	[Proven]	ROM proof in [1]
ML-DSA EUF-CMA security	[Proven]	NIST FIPS 204 [2]
CGGMP21 UC security	[Proven]	UC proof in [5]
FROST unforgeability	[Proven]	ROM proof in [6]
Pulsar EUF-CMA	[Proven]	ROM proof under Module-LWE
Hybrid sig. composition	[Proven]	Section 4 of this document
NTT correctness	[Tested]	100% NIST KAT, 10^9 random vectors
FHE bootstrapping	[Tested]	Comparison against reference implementation
EVM determinism	[Tested]	Ethereum test suite, Lux-specific fuzzing
Gas metering accuracy	[Tested]	Benchmark calibration, variance $< 5\%$
P2P authentication	[Tested]	Integration tests, simulated MITM
Lattice hardness (128-bit)	[Assumed]	Lattice-estimator, no known attack
Hash collision resistance	[Assumed]	No known practical attacks
DLP hardness (classical)	[Assumed]	40+ years of cryptanalysis
Quantum timeline (>2030)	[Assumed]	Published vendor roadmaps

7 Formal Verification Status

8 Triple-Proof Quantum Finality: Summary

The triple-proof mechanism is the synthesis of the security model's layers:

- Block time: 1 ms. **[Tested]** on validator testnet with 100 nodes.
- Epoch size: 100 blocks (100 ms per epoch).
- Epoch proof generation: ∼400 ms CPU / ∼5–15 ms GPU (estimated) Groth16 prover [15].
- Annual storage for epoch proofs: $248 \times 10 \times 86{,}400 \times 365 \approx 78$ MB/year.

9 The Invariant: Machine-Checkable Security Claims

Invariant 9.1 (Machine-checkable security)**.** *Every security property of the Lux Network either:*

Table 7: Triple-proof epoch certificate structure.

Proof	**Size**	**Verify Time**	**Assumption Family**
BLS aggregate signature	48 B	875 μs	Discrete log
Groth16-compressed ML-DSA	192 B	$\sim$1–3 ms (CPU)	Lattice + Hash
Pulsar threshold (in Groth16)	0 B (embedded)	0 μs (included)	Lattice
Total epoch certificate	**248 B**	**$\sim$2–5 ms (CPU)**	**All three**

1. *Has a machine-checkable proof (formal verification in Coq, Lean, or TLA+), or*
2. *Has an automated test suite that verifies the property against known test vectors, or*
3. *Is explicitly listed as an unverified assumption with a justification for why it is believed to hold.*

There is no fourth category. "We believe it is secure" without one of the above annotations is not a valid security claim.

This invariant is not aspirational—it is a *process requirement*. Every protocol change must be accompanied by an update to one of the three categories. New cryptographic primitives require either a proof reference or NIST KAT validation. New consensus rules require either a formal proof or a TLA+ model. New implementations require either formal verification or an automated test suite with coverage metrics.

The purpose of this invariant is not to achieve 100% formal verification (which is impractical for a large system). The purpose is to eliminate the category of "security claims that nobody has checked." Every claim is checked by a machine, a proof system, or a test suite—or it is explicitly marked as unchecked.

10 Related Work

Gavin Wood's Ethereum Yellow Paper [10] specifies the EVM but does not provide a security model or threat analysis. The Bitcoin whitepaper [11] provides a probabilistic security argument for proof-of-work but does not address quantum threats, economic adversaries, or formal verification.

Buterin et al. [12] analyze the combination of finality gadgets with available chains but do not address post-quantum security. The NIST post-quantum standardization process [2] provides security proofs for individual primitives but does not address their composition in a blockchain context.

Our contribution is a *complete* security model that spans all layers, addresses all adversary classes, and makes every assumption explicit.

11 Conclusion

Security requires explicit threat models, not vague assertions. This document provides such a model for the Lux Network, covering four adversary classes, four protocol layers, three cryptographic assumption families, and their interactions.

The key structural property is defense in depth: any two of the three cryptographic assumption families (discrete log, lattice, hash) suffice for security. No single breakthrough—quantum computers, lattice attacks, hash function weaknesses—is sufficient to compromise the system. Only a simultaneous failure of two independent mathematical hardness assumptions could break the security guarantees.

The key process property is the machine-checkable invariant: every security claim is either formally proven, empirically tested, or explicitly marked as an assumption. This eliminates the most dangerous category of security claims—those that nobody has checked.

Triple-proof quantum finality achieves the practical synthesis: 248 bytes per epoch, ∼2–5 ms CPU verification [15], 1 ms blocks, and security against classical, quantum, and economic adversaries simultaneously.

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