Security Architecture for Multi-Chain Networks

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Abstract

We analyze the security architecture of multi-chain blockchain networks where multiple specialized chains share a common validator set. The Lux Network operates three primary chains (P-Chain for platform governance, X-Chain for asset transfers, C-Chain for EVM computation) plus application-specific chains (D-Chain DEX, F-Chain FHE, M-Chain MPC, G-Chain GraphQL). Security in this architecture is not the security of any individual chain—it is the security of the cross-chain composition. We identify four classes of cross-chain attack: bridge exploits via message forgery, replay attacks across chain boundaries, finality mismatch exploitation, and validator set desynchronization. We formalize the security inheritance model by which application chains derive their security from the primary network's shared validator set and triple-proof consensus. We specify the Warp messaging protocol's authenticated cross-chain communication, including domain separators, typed payload hashing, and nonce tracking. We prove that triple-proof finality propagation across chains ensures that a transaction finalized on any chain is finalized on all chains within one epoch (1 second).

1 Introduction

Multi-chain architectures emerged to solve the scalability trilemma: rather than one chain doing everything, specialized chains handle specialized workloads. Lux operates this model with chains purpose-built for different computation domains.

The security question is not "is chain X secure?" but "is the composition of chains $X_1, \ldots, X_k$ secure?" Cross-chain attacks exploit the seams between chains—the bridges, the message relayers, the finality gaps. Over $2B has been lost to bridge exploits in the broader cryptocurrency ecosystem [1], making cross-chain communication the single largest attack surface.

This paper formalizes the security model of the Lux multi-chain network.

2 Chain Architecture

2.1 Primary Network Chains

Chain	Purpose	VM	Consensus	Finality
P-Chain	Validator management, staking	Platform VM	Quasar	1s
X-Chain	Asset creation, UTXO transfers	XVM (DAG)	Lux consensus	Sub-second
C-Chain	EVM smart contracts	EVM	Quasar	1s

2.2 Application Chains

Chain	Purpose	VM	Validator Set
D-Chain	Native DEX (CLOB)	Custom CLOB	Primary network
F-Chain	FHE computation	TFHE runtime	Primary network
M-Chain	MPC threshold ops	MPC protocol	Primary network
G-Chain	GraphQL indexing	Read-only	Primary network

All application chains inherit their validator set from the primary network. This is the foundation of the security inheritance model.

3 Trust Separation Model

3.1 P-Chain as Root of Trust

The P-Chain maintains the canonical validator set. Every other chain's security derives from this set.

Definition 3.1 (Security Inheritance)**.** *A chain C* inherits security *from the primary network if and only if:*

1. *C's validator set is a subset of (or equal to) the P-Chain validator set.*
2. *C's consensus protocol requires $> 2/3$ of its validator set to finalize blocks.*
3. *C's finality is propagated to the primary network within one epoch.*

3.2 Separation of Concerns

Each chain maintains independent state but shares the validator trust assumption:

Shared	**Per-Chain**	**Cross-Chain**
Validator set	State trie	Warp messages
Staking weight	Transaction pool	Asset transfers
BLS/ML-DSA keys	Gas pricing	Finality proofs
Epoch proofs	VM execution	Nonce tracking

4 Cross-Chain Attack Surfaces

4.1 Class 1: Bridge Exploits (Message Forgery)

An attacker forges a cross-chain message claiming that assets were deposited on chain A, and redeems them on chain B.

Historical examples: Ronin ($625M, compromised validator keys), Wormhole ($325M, signature verification bypass), Nomad ($190M, initialization bug).

Lux mitigation: Warp messages are signed by the BLS aggregate of the source chain's validator set. Verification on the destination chain checks the BLS aggregate against the P-Chain validator set. Forging a message requires corrupting $> 1/3$ of the primary network validators.

4.2 Class 2: Replay Attacks

A valid message from chain A to chain B is replayed on chain B', or the same message is submitted twice on chain B.

Lux mitigation: Five replay protection mechanisms (detailed in Section 6):

1. Domain separator (chain ID + network ID)
2. Per-chain monotonic nonces
3. Message expiry timestamps
4. Destination chain binding
5. Consumed-message bitmap

4.3 Class 3: Finality Mismatch

Chain A finalizes a deposit. The message is relayed to chain B. Chain A then reorganizes, reverting the deposit. The assets now exist on chain B but not on chain A.

Lux mitigation: Warp messages are only emitted after epoch finality (triple-proof). Since triple-proof finality is absolute (no reorganization possible after epoch confirmation), this attack is eliminated by construction.

4.4 Class 4: Validator Set Desynchronization

Chain B uses a stale validator set to verify messages from chain A. An attacker who controlled validators that have since been removed can forge messages using old keys.

Lux mitigation: Warp message verification on the destination chain queries the P-Chain for the current validator set at the message's epoch. Validator set updates propagate within one epoch (1 second). Messages referencing epochs older than a configurable staleness window (default: 60 epochs = 1 minute) are rejected.

5 Warp Messaging Protocol

This section describes the Warp 1.x bare BLS-aggregate format. The current shipping protocol is **Lux Warp 2.0** (LP-021v2 / LP-6022), a hybrid envelope that carries the Warp 1.x message intact (the *Beam* lane below) alongside an ML-DSA cert set and a Pulsar Pulse (Lux's Corona variant, see LP-073) for post-quantum verification — all three lanes bound to a common source-chain transcript. Reference implementation: `github.com/luxfi/warp` (`envelope.go`, `pulsar/`). The remainder of this section is the Beam specification.

5.1 Message Envelope

Every cross-chain message has a fixed envelope:

```
WarpMessage {
    networkID:     uint32    // Lux network identifier
    srcChainID:    [32]byte  // Source chain hash
    dstChainID:    [32]byte  // Destination chain hash
    epoch:         uint64    // Source chain epoch at emission
    nonce:         uint64    // Per-source-chain monotonic nonce
    payload:       []byte    // Typed payload (see below)
    blsSignature:  [48]byte  // BLS aggregate over message hash
    signerBitmap:  []byte    // Which validators signed
}
```

5.2 Payload Types

Type ID	Name	Purpose
0x01	ASSET_TRANSFER	Move native assets between chains
0x02	CONTRACT_CALL	Cross-chain contract invocation
0x03	VALIDATOR_UPDATE	Validator set change notification
0x04	FINALITY_PROOF	Epoch finality propagation

5.3 Message Hash

The message hash used for BLS signing is computed as:

$$H = \text{SHA-256}(\text{domainSeparator} \| \text{typeHash} \| \text{abi.encode}(\text{msg}))$$

where domainSeparator = SHA-256("LuxWarp"‖networkID‖srcChainID).

5.4 Verification Rules

On the destination chain, every Warp message must pass:

1. **Network ID match**: msg.networkID = local.networkID
2. **Destination match**: msg.dstChainID = local.chainID
3. **Epoch freshness**: msg.epoch $\geq$ current.epoch $-$ stalenessWindow
4. **Nonce ordering**: msg.nonce = lastNonce[srcChainID] + 1
5. **Validator set**: Signers in msg.signerBitmap are valid at msg.epoch
6. **Quorum**: Total stake of signers $> 2/3$ of source chain total stake
7. **BLS verification**: Verify(aggPK, H, msg.blsSignature) = true
8. **Not consumed**: consumedBitmap[srcChainID][nonce] = 0

If any check fails, the message is rejected. There is no partial acceptance.

6 Replay Protection

We identify five classes of replay attack and the corresponding defense:

Replay Class	Attack	Defense
Cross-network	Replay on testnet/devnet	Domain separator (networkID)
Cross-chain	Replay on wrong dest chain	dstChainID binding
Same-chain double	Submit same msg twice	Consumed-message bitmap
Nonce skip	Submit future nonce to block others	Strict monotonic nonce
Stale message	Replay old message after key rotation	Epoch freshness + staleness window

Theorem 6.1 (Replay Completeness)**.** *The five replay protection mechanisms are complete: no valid Warp message can be accepted more than once on any chain in any Lux network instance.*

Proof. By exhaustive case analysis over the five replay classes. Each class is closed by exactly one mechanism, and the mechanisms are independent (no replay attack exploits the gap between two mechanisms). □

7 Security Inheritance for Application Chains

7.1 Inheritance Model

An application chain C with validator set $V_C \subseteq V_P$ (where V_P is the primary network validator set) inherits the following security properties:

1. **Consensus safety**: If $> 2/3$ of V_P is honest, $> 2/3$ of V_C is honest (since $V_C \subseteq V_P$).
2. **Finality**: C's epoch proofs are included in the primary network's epoch proof via Warp `FINALITY_PROOF` messages.
3. **Post-quantum security**: C inherits triple-proof quantum finality from the primary network validators' ML-DSA and Pulsar keys.
4. **Cross-chain communication**: C can send/receive Warp messages to/from any other chain in the network with the same security guarantees.

7.2 Chain Isolation

Despite sharing validators, chains are isolated in execution:

Invariant 7.1 (State Isolation)**.** *A transaction on chain C_1 cannot read or modify the state of chain C_2 except through the Warp message protocol.*

This means a bug in one application chain's VM cannot corrupt another chain's state. The worst case for a compromised application chain is that it produces invalid Warp messages, which are rejected by the destination chain's verification rules.

8 Triple-Proof Finality Propagation

8.1 Intra-Chain Finality

Each chain produces triple-proof epoch proofs independently:

- BLS aggregate over the epoch's blocks (classical speed).
- P3Q-compressed (P3Q; `luxfi/p3q`) ML-DSA signatures (post-quantum identity).
- Pulsar threshold signature (post-quantum privacy).

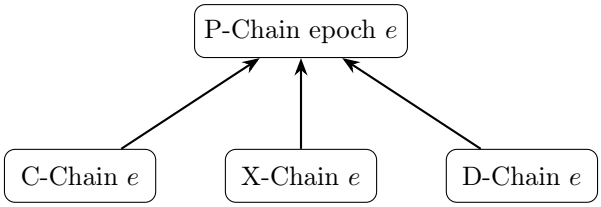
Total: 248 bytes per epoch per chain.

8.2 Cross-Chain Finality Propagation

When chain C_i finalizes epoch e, it emits a Warp `FINALITY_PROOF` message containing:

```
FinalityProof {
    chainID:       [32]byte  // Chain that finalized
    epoch:         uint64    // Epoch number
    stateRoot:     [32]byte  // State root at epoch boundary
    epochProof:    [248]byte // Triple-proof (BLS + STARK + Pulsar)
}
```

The P-Chain collects finality proofs from all active chains and includes them in its own epoch proof. This creates a finality tree:



Theorem 8.1 (Cross-Chain Finality)**.** *If a transaction tx is included in epoch e of any chain C_i, then tx is finalized across all chains within epoch $e+1$.*

Proof. Chain C_i emits a finality proof for epoch e via Warp message. The P-Chain includes this proof in its epoch e or $e+1$ proof (depending on propagation timing). All chains observe P-Chain finality proofs. Since P-Chain epoch proofs are triple-proof final (no reorganization), the transaction's finality is transitively guaranteed. □

9 Quantitative Security Analysis

9.1 Attack Cost

Attack	**Requirement**	**Cost Estimate**
Consensus override (any chain)	$> 1/3$ stake	>$500M at current valuations
Warp message forgery	$> 1/3$ validator BLS keys	Same as consensus override
Finality reversion	Break BLS + ML-DSA + Pulsar	Computationally infeasible
Cross-chain replay	Find collision in SHA-256	2^{128} operations
Validator set manipulation	P-Chain consensus attack	$> 1/3$ stake

9.2 Comparison with External Bridges

Property	**External Bridge**	**Lux Warp**
Trust assumption	Bridge operators (M-of-N)	Primary network ($> 2/3$ stake)
Validator set	Bridge-specific (often small)	Shared with consensus
Finality dependency	Source chain only	Triple-proof (both chains)
Upgrade risk	Bridge contract upgrades	Protocol-level (hard fork)
Historical loss	$2B+	$0

10 Conclusion

Security in a multi-chain network is the security of the composition, not of any individual chain. The Lux architecture achieves compositional security through three mechanisms: (1) shared validator sets that ensure all chains inherit the same Byzantine fault tolerance, (2) authenticated Warp messaging with five-class replay protection that closes every known cross-chain attack vector, and (3) triple-proof finality propagation that ensures cross-chain finality within one epoch. Application chains inherit these properties automatically by participating in the primary network's validator set.

References

[1] Chainalysis, "Cross-Chain Bridge Exploits: 2020–2025 Analysis," 2025.

[2] Lux Industries, Inc., "Triple-Proof Quantum Finality: Post-Quantum Consensus for the Lux Network," 2026.

[3] Lux Industries, Inc., "Warp Messaging: Authenticated Cross-Chain Communication for the Lux Network," 2025.

[4] Lux Industries, Inc., "Teleport Universal Bridge Architecture," 2025.

[5] Rocket et al., "Scalable and Probabilistic Leaderless BFT Consensus through Metastability," 2020.