Model Checking Distributed Protocols with TLA+

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Abstract

Model checking exhaustively explores every reachable state of a system to verify that a property holds universally. TLA+ (Temporal Logic of Actions) is a specification language designed by Leslie Lamport for describing and verifying concurrent and distributed systems. Its model checker, TLC, can enumerate billions of states to find subtle bugs that testing misses. This paper teaches TLA+ from first principles: the temporal logic, the specification language, the model checker, and the techniques for managing state space explosion. We then apply these tools to two Lux Network protocols—Teleport (cross-chain bridge) and Wave (sub-second finality)—showing the complete specifications, the properties checked, the bugs found during specification, and the techniques used to make model checking tractable. The reader will learn to write TLA+ specifications, run TLC, interpret violations, and integrate model checking into a protocol development workflow.

Contents

1 Why Model Checking

1.1 The Problem with Distributed Systems

Distributed systems are hard because they have *combinatorial* behavior. A system with n nodes and m messages has $O(m!)$ possible message orderings. Each ordering may produce different behavior. Testing exercises a handful of orderings; model checking exercises all of them.

1.2 What Model Checking Provides

Given a system description S and a property P, a model checker answers: does P hold in every reachable state of S? If yes, it provides a proof (by exhaustive enumeration). If no, it provides a *counterexample trace*: a sequence of states from the initial state to a state where P is violated.

Counterexample traces are the primary value of model checking. A trace that shows "node A sends message X, node B crashes, node C receives message Y before message X, and now the system is in an inconsistent state" is worth more than a thousand tests.

1.3 Model Checking vs. Theorem Proving

Model checking is *automatic*: you write the spec, push a button, and get a yes/no answer. Theorem proving (Lean 4, Coq) is *manual*: you guide the prover through the argument. Model checking is limited to finite instances (e.g., 4 validators, 3 rounds); theorem proving handles arbitrary sizes. Use both: model check to find bugs during design, then prove correctness for the final protocol.

2 TLA+ Fundamentals

2.1 State Machines

TLA+ models systems as state machines. A state is an assignment of values to variables. A specification consists of:

1. **Variables**: The state components (e.g., `round`, `messages`, `decisions`).
2. **Init**: A predicate describing the initial states.
3. **Next**: A predicate describing allowed transitions (an action).
4. **Spec**: The overall specification, typically $\texttt{Init} \wedge \Box[\texttt{Next}]_{\texttt{vars}}$.

2.2 Your First TLA+ Specification

Listing 1: A simple counter in TLA+

```
---- MODULE Counter ----
EXTENDS Naturals

VARIABLES count

Init == count = 0

Increment == count' = count + 1

Decrement == count > 0 /\ count' = count - 1

Next == Increment \/ Decrement

Spec == Init /\ [][Next]_count

```

```
\* Property: count is always non-negative
NonNegative == count >= 0

\* TLC checks: is NonNegative an invariant of Spec?
====
```

- `count'` denotes the value of `count` in the *next* state.
- `[Next]_count` means: either `Next` happens, or `count` stays unchanged (stuttering).
- `NonNegative` is an invariant: a property that must hold in every reachable state.

2.3 Temporal Logic

TLA+ uses temporal operators to express properties about sequences of states:

Operator	Notation	Meaning
Always	$\Box P$	P holds in every state
Eventually	$\Diamond P$	P holds in some future state
Leads-to	$P \rightsquigarrow Q$	Whenever P holds, Q eventually holds
Stutter	$[A]_v$	Either action A occurs or v is unchanged

Table 1: Temporal operators in TLA+.

Safety properties have the form $\Box P$ ("something bad never happens"). Liveness properties have the form $\Diamond P$ or $P \rightsquigarrow Q$ ("something good eventually happens").

2.4 Sets, Functions, and Records

TLA+ has rich built-in data structures:

Listing 2: TLA+ data structures

```
\* Sets
Validators == {"v1", "v2", "v3", "v4"}
Quorum == {S \in SUBSET Validators : Cardinality(S) >= 3}

\* Functions (maps)
balances == [v \in Validators |-> 0]

\* Records
Message == [type : {"PROPOSE", "VOTE", "COMMIT"},
            round : Nat,
            sender : Validators]
```

3 Modeling Consensus Protocols

3.1 The Consensus Specification Pattern

Every BFT consensus spec follows this pattern:

Listing 3: BFT consensus specification pattern

```
---- MODULE BFTConsensus ----
EXTENDS Integers, FiniteSets, Sequences

CONSTANTS
    Validators,      \* Set of all validators
    MaxFaulty,       \* Maximum Byzantine validators
```

```
    MaxRound          \* Bound for model checking

VARIABLES
    round,            \* Current round per validator
    lockedValue,      \* Locked value per validator
    lockedRound,      \* Round of lock per validator
    decision,         \* Decision per validator (or NONE)
    messages,         \* Set of in-flight messages
    faulty            \* Set of Byzantine validators

vars == <<round, lockedValue, lockedRound,
          decision, messages, faulty>>

N == Cardinality(Validators)
Q == 2 * N \div 3 + 1  \* Quorum size

\* Type invariant
TypeOK ==
    /\ round \in [Validators -> 0..MaxRound]
    /\ decision \in [Validators -> {"NONE"} \union Values]
    /\ Cardinality(faulty) <= MaxFaulty

\* Safety: no two honest validators decide differently
Safety ==
    \A v1, v2 \in Validators \ faulty :
        decision[v1] # "NONE" /\ decision[v2] # "NONE"
        => decision[v1] = decision[v2]
====
```

3.2 Modeling Byzantine Behavior

Byzantine validators can send arbitrary messages. In TLA+, we model this by allowing faulty validators to perform any action without constraints:

Listing 4: Byzantine behavior model

```
\* Honest validator: follows protocol
HonestVote(v) ==
    /\ v \notin faulty
    /\ \E msg \in messages :
        /\ msg.type = "PROPOSE"
        /\ msg.round = round[v]
        /\ \* Vote for proposed value if not locked
           \/ lockedRound[v] = -1
           \/ lockedValue[v] = msg.value
        /\ messages' = messages \union
            {[type |-> "VOTE", round |-> round[v],
              value |-> msg.value, sender |-> v]}

\* Byzantine validator: can send any vote
ByzantineVote(v) ==
    /\ v \in faulty
    /\ \E val \in Values, r \in 0..MaxRound :
        messages' = messages \union
            {[type |-> "VOTE", round |-> r,
              value |-> val, sender |-> v]}
    /\ UNCHANGED <<round, lockedValue, lockedRound, decision>>
```

4 The Teleport Specification

Teleport is Lux Network's cross-chain bridge protocol. The TLA+ specification models the complete message lifecycle: deposit on the source chain, attestation by validators, relay to the destination chain, and withdrawal.

4.1 State Variables

Listing 5: Teleport state variables

```
---- MODULE Teleport ----
EXTENDS Integers, FiniteSets, Sequences

CONSTANTS
    Chains,          \* Set of chain IDs
    Validators,      \* Bridge validator set
    MaxFaulty,       \* f < n/3
    Users,           \* Set of user addresses
    MaxAmount        \* Bound for model checking

VARIABLES
    sourceBalances,  \* [chain][user] -> amount
    destBalances,    \* [chain][user] -> amount
    lockedFunds,     \* [chain] -> total locked
    pendingMessages, \* Set of cross-chain messages
    attestations,    \* [msgId] -> set of attesting validators
    relayedMessages, \* Set of already-relayed message IDs
    faulty           \* Set of Byzantine validators
```

4.2 Safety Properties

Listing 6: Teleport safety properties

```
\* No double-spend: a message is relayed at most once
NoDoubleRelay ==
    \A msg \in relayedMessages :
        Cardinality({m \in relayedMessages : m.id = msg.id}) = 1

\* Conservation: total tokens across all chains is constant
Conservation ==
    LET totalLocked == SumOver(Chains, LAMBDA c : lockedFunds[c])
        totalDest == SumOver(Chains, LAMBDA c :
                        SumOver(Users, LAMBDA u : destBalances[c][u]))
    IN totalLocked = totalDest

\* Authenticity: relayed messages have quorum attestation
Authenticity ==
    \A msg \in relayedMessages :
        Cardinality(attestations[msg.id] \ faulty) >= Q
```

4.3 Model Checking Results

We model-check Teleport with the following parameters:

Parameter	Value	Rationale
Chains	3	Source, destination, third chain
Validators	4	Minimum for $f = 1$
MaxFaulty	1	$f < n/3 \Rightarrow f \leq 1$
Users	2	Sender and receiver
MaxAmount	3	Small values expose arithmetic bugs

Table 2: TLC model checking parameters for Teleport.

Property	States	Time	Result
TypeOK	2.4M	47s	Holds
NoDoubleRelay	2.4M	52s	Holds
Conservation	2.4M	61s	Holds
Authenticity	2.4M	55s	Holds

Table 3: TLC results for Teleport specification. 16-core machine, 32GB heap.

5 The Wave Specification

Wave is Lux Network's sub-second finality protocol. It achieves fast finality through optimistic pipelining: blocks are tentatively finalized after a single round of communication, with a fallback to a slower path if conflicts are detected.

5.1 Key Insight: Pipelining Creates Subtlety

The naive approach—finalize immediately after one round of votes—is unsafe if a Byzantine proposer sends conflicting blocks to different validators. Wave detects this through a conflict resolution phase. The TLA+ specification was critical for getting this right: the first three versions of the protocol had liveness bugs that only manifested with specific message orderings.

Listing 7: Wave specification excerpt

```
---- MODULE Wave ----
EXTENDS Integers, FiniteSets

CONSTANTS Validators, MaxFaulty, MaxRound, Values

VARIABLES
    round, phase, estimate, locked, decision, messages

\* Phase: PROPOSE -> VOTE -> CONFIRM -> FINALIZE
Phases == {"PROPOSE", "VOTE", "CONFIRM", "FINALIZE"}

\* Fast path: single round-trip finality
FastFinalize(v) ==
    /\ phase[v] = "CONFIRM"
    /\ LET confirms == {m \in messages :
            m.type = "CONFIRM" /\ m.round = round[v]
            /\ m.value = estimate[v]}
       IN Cardinality({m.sender : m \in confirms}) >= Q
    /\ decision' = [decision EXCEPT ![v] = estimate[v]]
    /\ phase' = [phase EXCEPT ![v] = "FINALIZE"]
    /\ UNCHANGED <<round, estimate, locked, messages>>

\* Slow path: fallback when conflicts detected
```

```
SlowResolve(v) ==
    /\ phase[v] = "CONFIRM"
    /\ \E conflict \in messages :
        /\ conflict.type = "CONFIRM"
        /\ conflict.round = round[v]
        /\ conflict.value # estimate[v]
    /\ round' = [round EXCEPT ![v] = round[v] + 1]
    /\ phase' = [phase EXCEPT ![v] = "PROPOSE"]
    /\ locked' = [locked EXCEPT ![v] = estimate[v]]
    /\ UNCHANGED <<estimate, decision, messages>>
```

5.2 Bugs Found During Specification

Bug	Description	Found by
Liveness #1	Validators could deadlock if two conflicting proposals arrived simultaneously and all honest validators locked on different values.	TLC trace
Liveness #2	Round advancement required $n - f$ messages but network partition could prevent accumulation indefinitely.	TLC liveness check
Safety #1	A validator that crashed and recovered could vote for a conflicting value in the same round if its locked state was lost.	TLC invariant

Table 4: Bugs found during TLA+ specification of Wave. All fixed before implementation.

6 State Space Explosion

6.1 The Problem

The number of reachable states grows exponentially with the number of components. A consensus protocol with n validators, r rounds, and m possible messages has roughly $O(n^r \cdot 2^m)$ states. With $n = 7$, $r = 3$, $m = 20$, that is billions of states.

6.2 Techniques for Managing It

Symmetry reduction. If all validators are identical (before assigning Byzantine/honest roles), the model checker need not explore permutations separately. TLC supports this via symmetry sets:

Listing 8: Symmetry reduction

```
\* In TLC configuration:
\* SYMMETRY Permutations(Validators)
```

This reduces the state space by a factor of $n!$.

State constraints. Bound variables to small ranges. Use `MaxRound = 3` instead of unbounded rounds. If a bug exists, it usually manifests in small instances.

Action constraints. Limit the number of messages in flight:

Listing 9: Action constraint to limit state space

```
\* In TLC configuration:
\* ACTION_CONSTRAINT Cardinality(messages) < 20
```

Abstraction. Replace complex data with simpler representations. Instead of modeling full blocks with transactions, use abstract block IDs (`"B1"`, `"B2"`).

6.3 State Space in Practice

Configuration	States	Time	RAM
4 validators, 2 rounds, no symmetry	12.3M	4m	8GB
4 validators, 2 rounds, with symmetry	0.5M	11s	2GB
7 validators, 3 rounds, with symmetry	84M	38m	24GB
7 validators, 3 rounds, no symmetry	>10B	timeout	—

Table 5: Effect of symmetry reduction on Teleport model checking.

7 From Specification to Implementation

The TLA+ specification is not the implementation. It is a *model* of the implementation. The gap between specification and implementation is where bugs hide.

7.1 Specification-Guided Testing

Use TLC traces as test scenarios. For every counterexample found during specification development, write a Go integration test that reproduces the exact message sequence.

Listing 10: Go test derived from TLC counterexample trace

```go
func TestWaveLivenessBug1(t *testing.T) {
    // From TLC trace: simultaneous conflicting proposals
    net := NewTestNetwork(4, 1) // 4 validators, 1 faulty

    // Faulty proposer sends conflicting blocks
    net.FaultyPropose(0, "B1", []int{1, 2})  // to v1, v2
    net.FaultyPropose(0, "B2", []int{3})      // to v3

    // Deliver messages in order that caused deadlock
    net.Deliver(1, "PROPOSE")
    net.Deliver(2, "PROPOSE")
    net.Deliver(3, "PROPOSE")

    // All honest validators should eventually decide
    for _, v := range net.HonestValidators() {
        require.Eventually(t, func() bool {
            return v.HasDecided()
        }, 10*time.Second, 100*time.Millisecond)
    }
}
```

7.2 Bisimulation

For critical protocols, maintain a *bisimulation* between the TLA+ specification and the Go implementation: a mapping from Go states to TLA+ states such that every Go transition corresponds to a TLA+ transition. This is not formal verification (that would require Lean 4), but it provides strong confidence that the implementation follows the specification.

8 Practical Guide: Your First TLA+ Specification

8.1 Installation

Listing 11: Installing TLA+ tools

```
# TLA+ Toolbox (IDE with TLC built in)
# Download from https://lamport.azurewebsites.net/tla/toolbox.html

# Or use the VS Code extension
code --install-extension alygin.vscode-tlaplus

# Command-line TLC
java -jar tla2tools.jar -workers auto MySpec.tla
```

8.2 Workflow

1. Write the specification in TLA+.
2. Define safety invariants (properties that must always hold).
3. Define liveness properties (properties that must eventually hold).
4. Run TLC with small parameters.
5. If TLC finds a violation, study the trace and fix the specification (or the protocol).
6. Gradually increase parameters until confident.
7. Convert key TLC traces into implementation-level tests.

9 Conclusion

TLA+ model checking finds bugs in distributed protocols that no amount of testing will catch. The bugs it finds are exactly the subtle ones: race conditions, deadlocks, and safety violations that occur only under specific message orderings. Writing a TLA+ specification forces you to think precisely about your protocol's behavior in all scenarios—not just the happy path.

For Lux Network, TLA+ model checking found 3 bugs in the Wave protocol and verified the safety and conservation properties of the Teleport bridge across 2.4 million states. These specifications now serve as the canonical descriptions of these protocols, and every protocol change requires updating the specification and re-running TLC before modifying the Go implementation.

References

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