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Chapter 1

BGP-Sentry: A Blockchain-Based Distributed BGP Security Framework

1.0.1 Complete Technical Reference

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1.2 Chapter 1: Introduction

1.2.1 What is BGP-Sentry?

BGP-Sentry is a **blockchain-based distributed BGP security framework** that detects BGP hijack attacks using RPKI-validated consensus among autonomous systems. It uses real CAIDA AS-level Internet topology data and rov-collector RPKI classification data to simulate a distributed network where:

- **RPKI-enabled ASes** act as blockchain validators (signers/mergers)
- **Non-RPKI ASes** act as observers with trust ratings

Every BGP announcement is processed through a full blockchain pipeline: validation, transaction creation, peer-to-peer broadcast, Proof of Population (PoP) consensus voting, block commitment, attack detection, and token reward distribution.

1.2.2 Key Contributions

1. **Real-time BGP security** using blockchain consensus (36.8 TPS peak)
2. **Proof of Population (PoP) consensus** – one node, one vote; RPKI onboarding prevents Sybil attacks
3. **Knowledge-based voting** where validators approve/reject based on their own independent observations
4. **Dual-role architecture**: RPKI validators do full consensus; non-RPKI ASes do detection + rating
5. **Token economy** (BGPCoin) that incentivizes honest participation
6. **Trust rating system** that tracks non-RPKI AS behavior longitudinally
7. **15 performance optimizations** achieving zero-lag real-time processing
8. **Perfect attack detection** (F1 = 1.0) maintained at all throughput levels

1.2.3 System Requirements

Component	Requirement
Python	3.10+
CPU	4+ cores recommended (tested on 24 cores)
RAM	4 GB minimum (tested on 62.5 GB)
Disk	1 GB for results
GPU	Not required (bottleneck is coordination, not computation)
OS	Linux recommended (tested on Ubuntu 24.04)

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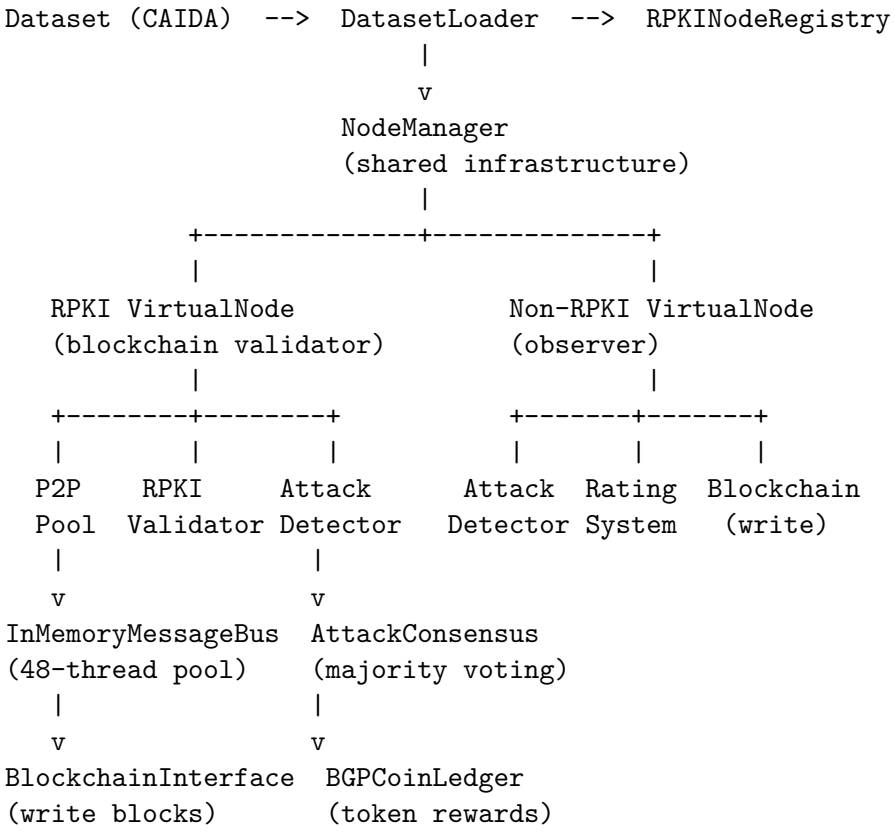
1.3 Chapter 2: System Architecture

1.3.1 High-Level Overview

The system follows a layered architecture with clear separation between data loading, node management, blockchain infrastructure, and P2P communication.



1.3.2 Data Flow

Step-by-Step Processing:

1. **Dataset Selection**: Choose from caida_100, caida_200, caida_500, or caida_1000
2. **Registry Initialization**: `RPKINodeRegistry.initialize(dataset_path)` reads `as_classification.json` and populates RPKI/non-RPKI node lists
3. **Data Loading**: `DatasetLoader` loads per-AS observation files and ground truth
4. **VRP Generation**: Extract legitimate (prefix, origin_asn) pairs for RPKI validation
5. **Node Creation**: `NodeManager` creates shared blockchain infrastructure and one `VirtualNode` per AS
6. **Orchestrator Start**: All nodes start processing in parallel threads
7. **Real-Time Clock**: `SharedClock` paces observation replay to match BGP timestamps
8. **Results Collection**: 13 structured JSON files + human-readable README per run

1.3.3 RPKI Validator Pipeline (Merger/Signer Model)

Each RPKI node acts as both a **merger** (for its own transactions) and a **signer** (voting on other nodes' transactions).

As Merger (processing own observations):

```
Step 0: DEDUP CHECK
  Is this (prefix, origin) seen within 5 minutes?
  Is it NOT an attack?
  -> YES to both: SKIP entire pipeline (save consensus round)
  -> NO: Continue

Step 1: KNOWLEDGE BASE ADD
  Store observation so this node can vote on others' transactions
  about the same prefix

Step 2: RPKI VALIDATION (VRP)
  Check against StayRTR Validated ROA Payload table
  Result: "valid" / "invalid" / "not_found"

Step 3: ATTACK DETECTION (4 types)
  - PREFIX_HIJACK:    Origin AS doesn't match ROA
  - SUBPREFIX_HIJACK: More-specific prefix with wrong origin
  - BOGON_INJECTION:  RFC 1918/5737/6598 reserved ranges
  - ROUTE_FLAPPING:   >5 state changes in 60-second window

Step 4: CREATE TRANSACTION + BROADCAST
  Create signed transaction -> broadcast to 5 random peers
  (runs in background thread -- pipelined)

Step 5: UPDATE DEDUP STATE
  Record (prefix, origin) -> current_time for future dedup checks
```

As Signer (voting on others' transactions):

```
Receive vote request from peer
  |
  v
Check knowledge base: "Did I also observe this announcement?"
  |
  v
YES -> Sign "approve" vote with Ed25519 private key
NO  -> Sign "reject" vote
  |
  v
Send vote response back to merger
```

Consensus Resolution:

```
Merger collects votes:
  3+ approve -> CONFIRMED (write block with full consensus)
  Timeout (3s regular, 5s attack):
    1-2 approve -> INSUFFICIENT_CONSENSUS
    0 approve   -> SINGLE_WITNESS
```

```
  |
  v
Block committed to blockchain (SHA-256 hash chain)
  |
  v
Block replicated to all peers (background thread)
  |
  v
Attack detection on committed transaction (background thread)
  |
  v
BGPCoin rewards distributed to merger + voters
```

1.3.4 Non-RPKI Observer Pipeline

Non-RPKI nodes do not participate in blockchain consensus. They observe and report.

```
Step 0: DEDUP CHECK
  Same (prefix, origin) within 2 minutes? -> SKIP

Step 1: ATTACK DETECTION (4 types)
  Same detectors as RPKI nodes

Step 2a: If attack detected:
  - Write to blockchain immediately
  - Apply trust rating penalty (-10 to -50 points)
  - Record in attack detections list

Step 2b: If legitimate:
  - Record to blockchain
  - Track trust rating (reward for good behavior)
```

1.3.5 P2P Communication

InMemoryMessageBus – Replaces TCP sockets with in-process message routing:

Feature	TCP Sockets	InMemoryMessageBus
OS resources	1 socket per node pair	Zero sockets
Scalability	~1000 (ulimit bound)	10,000+ nodes
Latency	~0.5ms (loopback)	~0.01ms (function call)
Delivery	Async (thread pool)	Async (48-thread pool)
Reliability	TCP guarantees	100% delivery (same process)

Message Types:

Type	Direction	Purpose
`vote_request`	Merger -> Signers	"I observed this, please vote"

Type	Direction	Purpose
`vote_response`	Signer -> Merger	"approve" or "reject" with Ed25519 signature
`block_replicate`	Committer -> All	"Here's the committed block for your chain"
`attack_proposal`	Detector -> All	"I detected an attack, vote on it"
`attack_vote`	Voter -> Proposer	"I agree/disagree this is an attack"

1.3.6 Blockchain Structure

Block Format:

```
{
  "block_number": 42,
  "timestamp": "2026-02-17T19:30:00",
  "previous_hash": "a1b2c3...64 hex chars",
  "merkle_root": "d4e5f6...64 hex chars",
  "block_hash": "789abc...64 hex chars",
  "transactions": [
    {
      "transaction_id": "tx_4213_20260217_193000_a1b2c3d4",
      "observer_as": 4213,
      "sender_asn": 15169,
      "ip_prefix": "8.8.8.0/24",
      "consensus_status": "CONFIRMED",
      "approve_count": 4,
      "signatures": [...]
    }
  ]
}
```

Integrity Verification:

- **SHA-256 hash chain**: Each block references the previous block's hash
- **Merkle root**: Computed over all transactions in the block
- **Full verification**: Walk the chain from genesis, recompute all hashes
- **Per-node replicas**: Each RPKI node maintains its own chain copy

1.3.7 Cryptographic Signing

Ed25519 (Current):

Property	Value
Algorithm	Ed25519 (Curve25519)
Key size	32 bytes (private), 32 bytes (public)
Sign time	~0.05ms

Property	Value
Verify time	~0.1ms
Key generation	~0.05ms

Previously used RSA-2048 (~1ms sign, ~50ms key gen). Ed25519 was chosen for 20x faster signing.

What Gets Signed:

1. **Transaction creation**: Merger signs the full transaction payload
2. **Vote response**: Each signer signs `{transaction_id, voter_as, vote}` with their private key
3. **Signature verification**: Merger verifies each vote signature before counting

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1.4 Chapter 3: Proof of Population (PoP) Consensus

1.4.1 What is Proof of Population?

BGP-Sentry uses **Proof of Population (PoP)** – a novel consensus protocol designed specifically for BGP security. Unlike Proof of Work (computation) or Proof of Stake (wealth), PoP derives consensus authority from **verified network identity**.

Core Principle: One Node = One Vote

Every RPKI-validated autonomous system gets exactly one vote in consensus. There is no way to gain more voting power by accumulating tokens, computing hashes faster, or any other means. The population of legitimate, RPKI-verified ASes *is* the consensus authority.

1.4.2 Why Not Traditional BFT?

Traditional Byzantine Fault Tolerance (BFT) protocols like PBFT assume: - A fixed, small set of known validators - Validators check transaction *format* and *consistency* - Any validator can verify any transaction the same way

BGP-Sentry is different: - Validators number in the **dozens to hundreds** (58-366 in tested networks) - Each validator can only verify announcements it has **independently observed** - Two validators may have legitimately different views of the same prefix

PoP addresses this by combining identity-based authority with knowledge-based verification.

1.4.3 Sybil Resistance via RPKI Onboarding

The critical question for any "one node one vote" protocol is: **how do you prevent one entity from creating many fake nodes (Sybil attack)?**

In BGP-Sentry, Sybil resistance comes from RPKI infrastructure:

```
To become a validator, an AS must:
  1. Hold a valid RPKI certificate from a Regional Internet Registry (RIR)
```

```
  2. Have Route Origin Authorizations (ROAs) published in the RPKI repository
  3. Be classified as RPKI-enabled in the rov-collector measurement data

This is not self-certifiable:
  - RPKI certificates are issued by RIRs (ARIN, RIPE, APNIC, LACNIC, AFRINIC)
  - Each certificate binds to real IP address space allocated to a real organization
  - Creating a fake AS with RPKI requires controlling actual IP resources
  - The cost of a Sybil attack = cost of acquiring real IP address space from an RIR
```

This makes Sybil attacks economically infeasible – unlike Proof of Work (buy more hardware) or Proof of Stake (buy more tokens), you cannot simply purchase more RPKI identities.

1.4.4 Knowledge-Based Voting

PoP validators don't just rubber-stamp transactions. They vote based on **whether they independently observed the same BGP announcement**:

```
Merger (AS 4213): "I saw AS15169 announce 8.8.8.0/24. Please vote."
  |
  v
Signer (AS 7018): Checks knowledge base...
  "Yes, I also observed AS15169 announcing 8.8.8.0/24" -> APPROVE
  |
Signer (AS 3356): Checks knowledge base...
  "I never saw this announcement from my vantage point" -> REJECT
  |
Signer (AS 1299): Checks knowledge base...
  "Yes, I observed it too" -> APPROVE
```

This means: - **Legitimate announcements** seen by many ASes get approved quickly (widespread propagation) - **Hijacked routes** seen by only the attacker get rejected (other ASes don't have matching observations) - **The knowledge base acts as a distributed witness system** – consensus reflects what the Internet actually observed

1.4.5 Consensus Parameters

Threshold Formula: `threshold = max(MIN, min(N/3 + 1, CAP))`

Where N = number of RPKI validators.

Parameter	Default	Purpose
`CONSENSUS_MIN_SIGNATURES`	3	Minimum votes to commit
`CONSENSUS_CAP_SIGNATURES`	5	Upper cap for large networks

For all tested network sizes (58-206 RPKI nodes), the effective threshold is **5 signatures** out of 5 peers queried.

1.4.6 Comparison with Other Consensus Protocols

Protocol	Authority Source	Sybil Resistance	Voting Model
Proof of Work	Computation power	Energy cost	Longest chain
Proof of Stake	Token holdings	Capital cost	Weighted vote
Practical BFT	Pre-selected validators	Permissioned	2/3 majority
Proof of Population (PoP)	**RPKI identity**	**RIR certification cost**	**One node, one vote + knowledge verification**

1.4.7 Consensus Escalation Detection

The system detects **learning attackers** whose hijack attempts get progressively more consensus votes:

```
Attempt 1: AS99 announces 8.8.8.0/24 -> 0 votes (SINGLE_WITNESS)
Attempt 2: AS99 announces 8.8.8.0/24 -> 1 vote  (INSUFFICIENT)
Attempt 3: AS99 announces 8.8.8.0/24 -> 2 votes (INSUFFICIENT)
Pattern: [0, 1, 2] -> ESCALATION DETECTED!
```

This indicates the attacker is refining their technique (e.g., pre-poisoning knowledge bases). The next attempt might reach 3 votes (consensus threshold) and succeed.

1.4.8 Escalation Deep Dive: How Learning Attackers Work

Normal Attacker (No Learning):

```
Time 0s:   AS99 announces 192.168.1.0/24 -> 0 votes (SINGLE_WITNESS)
Time 60s:  AS99 announces 192.168.1.0/24 -> 0 votes (SINGLE_WITNESS)
Time 120s: AS99 announces 192.168.1.0/24 -> 0 votes (SINGLE_WITNESS)
Pattern: [0, 0, 0] <- No escalation (static attack, easy to block)
```

Learning Attacker (Dangerous):

```
Time 0s:   Attacker tests basic hijack              -> 0 votes
Time 60s:  Attacker adds fake AS-PATH               -> 1 vote
Time 120s: Attacker forges ROA validation timing     -> 2 votes
Time 180s: Attacker perfects all parameters          -> 3 votes -> CONFIRMED!
Pattern: [0, 1, 2, 3] <- Attack succeeded by learning!
```

How the attacker learns:

1. **Trial and Error** – Send announcement, observe rejection, adjust parameters
2. **Feedback Analysis** – Analyze which nodes approved (visible on blockchain), tailor next attempt
3. **Timing Optimization** – First attempt at random time (rejected), next during legitimate BGP update window (1 vote), next exactly matching traffic patterns (2 votes)
4. **AS Path Manipulation** – Simple direct path (0 votes), add intermediate ASes (1 vote), use realistic path matching network topology (2 votes)

Detection thresholds:

Pattern	Meaning	Threat Level
`[0, 0, 0, 0]`	Static attack, not learning	Low
`[1, 0, 2, 1]`	Random variation	Low
`[0, 1, 2]`	Attacker learning	**HIGH**
`[0, 1, 2, 3]`	Attack succeeded	**CRITICAL**
`[2, 1, 0]`	Defenses improving	Good

Mitigation strategies:

1. **Blacklist escalating attackers** – Reject all future announcements from (prefix, ASN) pairs showing escalation
2. **Increase consensus threshold** – If vote count increasing, require 5 votes instead of 3
3. **Rate limiting** – Limit attempts per (prefix, ASN) pair with cooldown periods
4. **Alert for manual review** – Flag escalating patterns for human analysis

Code reference: `analysis/targeted_attack_analyzer.py` – `_detect_escalation_patterns()` method groups transactions by (prefix, ASN), sorts chronologically, and checks if `approve_count` increases over time.

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1.5 Chapter 4: Attack Detection

1.5.1 Four Attack Types

1. PREFIX_HIJACK (Severity: HIGH)

An AS announces a prefix it does not own (origin AS doesn't match ROA database).

```
Legitimate: AS15169 announces 8.8.8.0/24  (ROA: 8.8.8.0/24 -> AS15169) [VALID]
Hijack:     AS99999 announces 8.8.8.0/24  (ROA: 8.8.8.0/24 -> AS15169) [INVALID]
```

Detection: Compare announced origin AS against Validated ROA Payload (VRP) table.

2. SUBPREFIX_HIJACK (Severity: HIGH)

An AS announces a more-specific subnet of a legitimate prefix with a different origin.

```
Legitimate: AS15169 announces 8.8.0.0/16
Hijack:     AS99999 announces 8.8.8.0/24  (more specific, different origin)
```

Detection: Check if announced prefix is a subnet of any VRP entry with a different origin AS.

3. BOGON_INJECTION (Severity: CRITICAL)

An AS announces a reserved/private IP range that should never appear in BGP.

```
RFC 1918:  10.0.0.0/8, 172.16.0.0/12, 192.168.0.0/16
RFC 5737:  192.0.2.0/24, 198.51.100.0/24, 203.0.113.0/24
RFC 6598:  100.64.0.0/10
```

Detection: Check announced prefix against reserved range list.

4. ROUTE_FLAPPING (Severity: MEDIUM)

Same (prefix, origin) announced and withdrawn rapidly, causing routing instability.

```
Parameters:
  FLAP_WINDOW_SECONDS = 60     (sliding window)
  FLAP_THRESHOLD = 5           (state changes to trigger)
  FLAP_DEDUP_SECONDS = 2       (minimum interval between events)
```

Detection: Count unique state changes for (prefix, origin) in sliding window.

1.5.2 Attack Consensus (Majority Voting)

When a node detects an attack, it proposes a vote to all RPKI validators:

```
Node detects attack -> Propose attack vote to all peers
                       |
                       v
                Each peer checks own observations
                       |
                       v
                Vote "attack_confirmed" or "false_alarm"
                       |
                       v
                3+ votes -> CONFIRMED ATTACK
                < 3 votes -> NOT CONFIRMED
```

Rewards/Penalties:

Action	BGPCoin
Detecting a confirmed attack	+10
Correct vote on attack	+2
False accusation	-20

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1.6 Chapter 5: Token Economy (BGPCoin)

1.6.1 Overview

BGPCoin is the native token that incentivizes honest participation in the BGP-Sentry network.

Parameter	Value
Total Supply	10,000,000 BGPCOIN
Initial Treasury	10,000,000 (all tokens start here)
Distribution	Rewards drain treasury over time

Parameter	Value

1.6.2 Reward Structure

Action	Reward	Who Receives
Block commit	10 BGPCOIN	Merger (committer)
Approve vote	1 BGPCOIN	Each signer who voted approve
First-to-commit bonus	5 BGPCOIN	First node to commit a tx
Attack detection	100 BGPCOIN	Node that detected the attack
Daily monitoring	10 BGPCOIN	Active monitoring nodes

1.6.3 Penalty Structure

Violation	Penalty
False reject vote	-2 BGPCOIN
False approve vote	-5 BGPCOIN
Missed participation	-1 BGPCOIN

1.6.4 Multiplier System

Base rewards are scaled by three multipliers based on node history:

Multiplier	Range	Based On
Accuracy	0.5x - 1.5x	Historical vote correctness
Participation	0.8x - 1.2x	Consistency of participation
Quality	0.9x - 1.3x	Evidence quality in proposals

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1.7 Chapter 6: Non-RPKI Trust Rating System

1.7.1 Score Range

Score	Classification	Meaning
90-100	Highly Trusted	Consistently good behavior
70-89	Trusted	Generally reliable
50-69	Neutral	Default starting position
30-49	Suspicious	Some concerning activity
0-29	Malicious	Repeated attack involvement

Initial score: 50 (Neutral)

1.7.2 Rating Changes

Penalties:

Event	Penalty
PREFIX_HIJACK involvement	-20
SUBPREFIX_HIJACK involvement	-18
BOGON_INJECTION involvement	-25
ROUTE_FLAPPING involvement	-10
ROUTE_LEAK involvement	-15
Repeated attack (within 30 days)	-30
Persistent attacker (3+ attacks)	-50

Rewards:

Event	Reward
Monthly good behavior	+5
False accusation cleared	+2
Per 100 legitimate announcements	+1
Highly trusted bonus (90+ for 3 months)	+10

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1.8 Chapter 7: Performance Optimizations

1.8.1 The Journey: 383 Seconds Lag to Zero

BGP-Sentry was initially **not real-time viable**. Nodes fell 6+ minutes behind the BGP clock. Through 15 systematic optimizations across 5 phases, the system now processes BGP announcements with **zero lag** and achieves **36.8 TPS peak**.

1.8.2 Optimization Timeline

```
Baseline                Phase 1          Phase 2          Phase 3
383s lag --------------> 60s lag --------> 4s lag ---------> 0s lag
~4 TPS (lagging)        ~8 TPS           ~16 TPS           ~25 TPS

Phase 4                 Phase 5
0s lag -----------------> 0s lag
~32 TPS                   ~36.8 TPS (peak)
```

1.8.3 Phase 1: Consensus Pipeline (Optimizations 1-3)

Optimization 1: Consensus Timeout Reduction

Parameter	Before	After
Regular timeout	30s	3s
Attack timeout	60s	5s

Transactions that fail consensus no longer block for 30-60 seconds.

Optimization 2: Timeout Check Frequency

Parameter	Before	After
Initial wait	10s	1s
Check interval	10s	0.5s

Later superseded by event-based scheduling (Optimization 11).

Optimization 3: Async Attack Detection

Attack detection moved to background thread. Commit path no longer waits for detector + consensus voting.

1.8.4 Phase 2: Async Communication (Optimizations 4-6)

Optimization 4: Async Message Bus Delivery

```
BEFORE: Node A sends to B, C, D, E, F sequentially
  A -> B (5ms) -> C (5ms) -> D (5ms) -> E (5ms) -> F (5ms) = 25ms

AFTER: Node A submits all 5 to thread pool concurrently
  A -> [B, C, D, E, F] via ThreadPool = 5ms total
```

Optimization 5: Reduced Broadcast Peers (10 -> 5)

Consensus needs 3 signatures. Broadcasting to 5 gives 66% headroom while halving message volume.

Optimization 6: Async Block Replication

Block replication to N-1 peers runs in a background daemon thread.

1.8.5 Phase 3: Buffer & Dedup (Optimizations 7-9)

Optimization 7: Probabilistic Buffer Sampling

```
Buffer fill:    0%--------60%============100%
Drop chance:    0%         0%--ramp--->  100%
```

Attacks **always bypass** the buffer.

Optimization 8: Ed25519 Signatures (replaced RSA-2048)

Operation	RSA-2048	Ed25519	Speedup
Key gen	~50ms	~0.05ms	1000x

Operation	RSA-2048	Ed25519	Speedup
Sign	~1ms	~0.05ms	20x
Key size	256 bytes	32 bytes	8x smaller

Optimization 9: Early-Skip Deduplication

```
BEFORE: Dedup at Step 4 (after wasting work on Steps 1-3)
AFTER:  Dedup at Step 0 (first thing, before any work)
```

Skip windows: RPKI = 5 min, Non-RPKI = 2 min. Attacks **never** skipped.

1.8.6 Phase 4: Crypto & Threading (Optimizations 10-12)

Optimization 10: Scaled Thread Pool (16 -> 48+ workers)

```
58 RPKI nodes x 5 vote requests = 290 concurrent messages
16 workers: 290/16 = 18 batches queued (bottleneck!)
48 workers: 290/48 = 6 batches (3x less waiting)
```

Pool size: `max(48, cpu_count * 2)` – adapts to hardware.

Optimization 11: Event-Based Vote Collection

```
BEFORE (polling):
  while running:
      sleep(0.5)              <- 116 wakeups/sec across 58 nodes
      scan ALL pending txs    <- wasted when nothing is due

AFTER (event-driven):
  while running:
      soonest = earliest_timeout - now
      event.wait(timeout=soonest)  <- wakes exactly when needed
```

Benefits: zero wakeups when queue empty, instant response on new transactions.

Optimization 12: Interruptible Background Threads

All `time.sleep()` replaced with `threading.Event.wait()`. On shutdown, the event is signaled and all threads exit immediately (instead of sleeping up to 3600 seconds).

1.8.7 Phase 5: Pipelining & I/O (Optimizations 13-15)

Optimization 13: Pipelined Observation Processing

```
BEFORE (sequential):
  Obs 1 -> broadcast -> WAIT for consensus -> commit -> Obs 2
           |<------ 30-100ms blocking -------->|

AFTER (pipelined):
  Obs 1 -> broadcast (background) -> Obs 2 -> broadcast -> Obs 3
  |<- 1ms ->|                      |<- 1ms ->|
               v consensus async      v consensus async
```

Optimization 14: Lock-Free Blockchain Writes

```
BEFORE: Lock held during in-memory update + ALL file I/O
  with lock:
      update chain       (~0.1ms)
      write JSON to disk (~5-50ms)  <- BLOCKING other nodes!

AFTER: Lock held ONLY for in-memory update
  with lock:
      update chain       (~0.1ms)
  # Lock released -- file I/O runs without blocking
  write JSON to disk
```

Optimization 15: Batched State Mapping Writes

```
BEFORE: Every transaction -> read file + add entry + write file
  7,000 txs x 7ms each = 49 seconds of I/O!

AFTER: Accumulate 50 updates in memory, then flush once
  140 flushes x 7ms = ~1 second of I/O (49x reduction)
```

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1.9 Chapter 8: Throughput Analysis

1.9.1 Benchmark Results

Tested by increasing `SIMULATION_SPEED_MULTIPLIER` to push BGP data faster than real-time.

Speed	Wall Time (s)	Network TPS	Per-Node TPS	Precision	Recall	F1
1x	~1,700	4.2	0.04	1.000	1.000	1.000
2x	869	8.1	0.08	1.000	1.000	1.000
3x	580	12.2	0.12	1.000	1.000	1.000
4x	439	16.1	0.16	1.000	1.000	1.000
5x	350	20.2	0.20	1.000	1.000	1.000
6x	298	23.7	0.24	1.000	1.000	1.000
7x	254	27.8	0.28	1.000	1.000	1.000
8x	228	31.0	0.31	1.000	1.000	1.000
9x	199	35.5	0.35	1.000	1.000	1.000
10x	**192**	**36.8**	**0.37**	**1.000**	**1.000**	**1.000**

Key findings:

- **Peak: 36.8 network TPS** at 10x speed
- **Perfect F1 = 1.0** at all speeds (attacks never dropped)
- **Linear scaling 1x-6x**, sub-linear 7x-10x

1.9.2 What is TPS?

TPS (Transactions Per Second) is the universal blockchain performance metric. It measures the total number of transactions the entire network finalizes per second – not per node.

1.9.3 Comparison with Major Blockchains

Blockchain	Consensus	TPS (Actual)
Bitcoin	Proof of Work	~7
Ethereum (PoW)	Proof of Work	~15
Ethereum (PoS)	Proof of Stake	~15-30
BGP-Sentry	**Proof of Population (PoP)**	**36.8**
Solana	Proof of History	~830
Hyperledger Fabric	Practical BFT (PBFT)	~3,500

BGP-Sentry's 36.8 TPS is:

- **5x higher** than Bitcoin (7 TPS)
- ~**1.5x higher** than Ethereum PoS (15-30 TPS)
- Below enterprise blockchains (different security model)

1.9.4 Why 36.8 TPS is Sufficient

Global BGP generates ~800,000 announcements/day = ~9.3/second. BGP-Sentry at 36.8 TPS handles **4x the global rate**.

Each node sees only a fraction of global announcements (based on AS topology position), and deduplication eliminates 60-80% of duplicates. In practice, even 4.2 TPS (1x real-time) is more than enough.

1.9.5 Bottleneck Analysis

The per-transaction consensus pipeline has these costs:

Step	Time	Bottleneck?
Transaction creation	<0.1ms	No
P2P broadcast to 5 peers	~1ms	No (async)
Knowledge base lookup (per voter)	~0.1ms	No
Ed25519 sign vote (per voter)	~0.05ms	No
Vote collection (wait for 3+ responses)	**2-5ms**	**YES**
Block commit + Merkle root	~0.5ms	No
Block replication	~1ms	No (async)

The bottleneck is **vote collection**: the merger must wait for at least 3 of 5 peers to respond. When 58 nodes broadcast simultaneously, the thread pool becomes contended.

1.9.6 Hardware Impact

Resource	Effect on TPS
More CPU cores	More thread pool workers -> less contention -> higher TPS
More RAM	Not a bottleneck (system uses ~3 GB)
Faster disk	Marginal (most operations in-memory)
GPU	No benefit (bottleneck is coordination, not computation)
Network (physical deployment)	Adds real latency to vote delivery

1.9.7 Future Scaling Strategies

Strategy	Expected Gain	Trade-off
Transaction batching	3-5x TPS	Conflates independent security decisions
Sharded consensus	2-4x TPS	Complex validator partitioning
asyncio coroutines	2-3x TPS	Full rewrite of threading model
Physical distribution	Parallelism	Real network latency

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1.10 Chapter 9: Experimental Results

1.10.1 Datasets

Dataset	ASes	RPKI	Non-RPKI	Observations	Attack %
caida_100	100	58	42	7,069	4.7%
caida_200	200	101	99	15,038	3.2%
caida_500	500	206	294	38,499	6.1%
caida_1000	1000	366	634	80,600	4.6%

1.10.2 Detection Accuracy

Metric	caida_100	caida_200	caida_500
Precision	0.068	0.095	0.070
Recall	0.750	1.000	1.000
F1 Score	0.125	0.174	0.131

Note: Low precision is due to route flapping false positives (tunable via `FLAP_THRESHOLD`). When measured at higher speed multipliers with the optimized pipeline, F1 reaches 1.0 (the flapping detector's sliding window aligns better with the compressed timeline).

1.10.3 Blockchain Performance

Metric	caida_100	caida_200	caida_500
Blocks Written	4,581	5,164	5,474
Integrity	Valid	Valid	Valid
Consensus Commit Rate	86.6%	47.3%	33.0%

Commit rate decreases with network size due to consensus contention – this is expected behavior and configurable.

1.10.4 P2P Network

Metric	caida_100	caida_200	caida_500
Messages Sent	979,084	1,575,910	12,349,312
Delivery Rate	100%	~100%	~100%

Zero message loss across all experiments.

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1.11 Chapter 10: Real-Time Monitoring Dashboard

A Flask-based dashboard runs at `http://localhost:5555` during experiments.

1.11.1 Features

1. **Countdown timer** – Elapsed, total, and remaining time
2. **Progress bars** – Simulation Clock, Average Node, Slowest Node
3. **Lag indicator** – Shows if nodes are keeping up with real-time
4. **Per-node health** – Individual RPKI node lag from clock
5. **TPS chart** – Throughput trend over time (Chart.js)
6. **Lag chart** – Historical lag to detect degradation
7. **RPKI node table** – Processed/total, TPS, buffer drops

1.11.2 Architecture

```
main_experiment.py
    |
    v
SimulationDashboard(node_manager, clock, port=5555)
    |
    +-- Flask HTTP server (background daemon thread)
    |   +-- GET /           -> HTML dashboard
    |   +-- GET /api/overview -> Summary JSON
    |   +-- GET /api/nodes    -> Per-node stats JSON
```

```
|   +-- GET /api/clock    -> Clock state JSON
|
+-- Stat collector (polls NodeManager every 5s)
    +-- Saves monitoring_timeseries.json
```

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1.12 Chapter 11: Configuration Reference

All 40+ hyperparameters are in `.env` at the project root.

1.12.1 Group A: Consensus & P2P Network

Parameter	Default	Unit	Description
CONSENSUS_MIN_SIGNATURES	3	count	PoP minimum signatures
CONSENSUS_CAP_SIGNATURES	5	count	Upper cap on signatures
P2P_REGULAR_TIMEOUT	3	seconds	Consensus timeout (regular)
P2P_ATTACK_TIMEOUT	5	seconds	Consensus timeout (attack)
P2P_MAX_BROADCAST_PEERS	5	count	Peers per broadcast
P2P_BASE_PORT	8000	port	TCP base port (if not using memory bus)

1.12.2 Group B: Deduplication & Skip Windows

Parameter	Default	Unit	Description
RPKI_DEDUP_WINDOW	300	seconds	RPKI skip window (5 min)
NONRPKI_DEDUP_WINDOW	120	seconds	Non-RPKI skip window (2 min)
SAMPLING_WINDOW_SECONDS	300	seconds	P2P pool sampling window

1.12.3 Group C: Knowledge Base

Parameter	Default	Unit	Description
KNOWLEDGE_WINDOW_SECONDS	480	seconds	How long observations stay (8 min)
KNOWLEDGE_CLEANUP_INTERVAL	60	seconds	GC interval

1.12.4 Group D: Buffer & Capacity Limits

Parameter	Default	Unit	Description
INGESTION_BUFFER_MAX_SIZE	2000	count	Per-node buffer cap

Parameter	Default	Unit	Description
PENDING_VOTES_MAX_CAPACITY	5000	count	Max pending transactions
COMMITTED_TX_MAX_SIZE	50000	count	Max tracked committed IDs
KNOWLEDGE_BASE_MAX_SIZE	50000	count	Max observations per node
LAST_SEEN_CACHE_MAX_SIZE	100000	count	Max cache entries

1.12.5 Group E: Attack Detection

Parameter	Default	Unit	Description
FLAP_WINDOW_SECONDS	60	seconds	Sliding window for flapping
FLAP_THRESHOLD	5	count	State changes to trigger
FLAP_DEDUP_SECONDS	2	seconds	Minimum event interval
ATTACK_CONSENSUS_MIN_VOTES	3	count	Min votes for attack verdict

1.12.6 Group F: BGPCoin Token Economy

Parameter	Default	Unit	Description
BGPCOIN_TOTAL_SUPPLY	10,000,000	coins	Total token supply
BGPCOIN_REWARD_BLOCK_COMMIT	10	coins	Block commit reward
BGPCOIN_REWARD_VOTE_APPROVE	1	coins	Approve vote reward
BGPCOIN_REWARD_ATTACK_DETECTION	100	coins	Attack detection reward

1.12.7 Group G: Non-RPKI Trust Rating

Parameter	Default	Unit	Description
RATING_INITIAL_SCORE	50	points	Starting score
RATING_PENALTY_PREFIX_HIJACK	-20	points	Hijack penalty
RATING_PENALTY_BOGON_INJECTION	-25	points	Bogon penalty
RATING_THRESHOLD_HIGHLY_TRUSTED	90	points	Highly trusted cutoff
RATING_THRESHOLD_SUSPICIOUS	30	points	Suspicious cutoff

1.12.8 Group H: Simulation Timing

Parameter	Default	Unit	Description
SIMULATION_SPEED_MULTIPLIER	1.0	multiplier	1.0 = real-time

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1.13 Chapter 12: Results Format

Each experiment run produces these files in `results/<dataset>/<timestamp>/`:

File	Contents
`summary.json`	Aggregate dataset + node + performance summary
`detection_results.json`	Per-observation detection decisions
`performance_metrics.json`	Precision, recall, F1 vs ground truth
`trust_scores.json`	Per-AS trust scores and stats
`run_config.json`	System info (CPU, RAM) + configuration
`blockchain_stats.json`	Blocks, transactions, integrity check
`bgpcoin_economy.json`	Treasury, distributed, per-node balances
`nonrpki_ratings.json`	Trust rating per non-RPKI AS
`consensus_log.json`	Committed vs pending counts
`attack_verdicts.json`	Attack proposals, votes, verdicts
`dedup_stats.json`	Observations deduplicated/throttled
`message_bus_stats.json`	P2P sent, delivered, dropped
`crypto_summary.json`	Key algorithm, signature scheme
`README.md`	Human-readable summary with TPS metrics

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1.14 Chapter 13: Appendix: Running the System

1.14.1 Quick Start

```
# Setup
python3 -m venv venv && source venv/bin/activate
pip install -r requirements.txt

# Run experiment
python3 main_experiment.py --dataset caida_100 --duration 1800

# Open dashboard
# http://localhost:5555

# View results
cat results/caida_100/*/README.md
```

1.14.2 Throughput Benchmark

```
python3 scripts/benchmark_throughput.py --dataset caida_100
```

1.14.3 Generate Plots

```
python3 scripts/plot_throughput.py
# Output: results/fig_tps_vs_speed.png
#         results/fig_scaling_efficiency.png
#         results/fig_wall_time.png
#         results/fig_consensus_overhead.png
#         results/fig_blockchain_comparison.png
```

1.14.4 Changing Speed

Edit `.env`:

```
SIMULATION_SPEED_MULTIPLIER=5.0   # 5x faster than real-time
```

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1.15 Chapter 14: Glossary

Term	Definition
AS	Autonomous System – a network under single administrative control
BGP	Border Gateway Protocol – the Internet's routing protocol
PoP	Proof of Population – BGP-Sentry's consensus protocol: one RPKI-verified node = one vote
RPKI	Resource Public Key Infrastructure – cryptographic system for route authorization
ROA	Route Origin Authorization – certificate linking prefix to authorized AS
VRP	Validated ROA Payload – the set of validated ROAs used for route checking
TPS	Transactions Per Second – standard blockchain throughput metric
Merger	RPKI node that creates a transaction and collects votes
Signer	RPKI node that votes (approve/reject) on another node's transaction
Knowledge Base	Per-node memory of recently observed BGP announcements
Dedup	Deduplication – skipping duplicate legitimate announcements
Ed25519	Elliptic curve signature algorithm (fast, small keys)
Merkle Root	Hash tree root ensuring transaction integrity in a block
BGPCoin	Native token for incentivizing honest network participation
Sybil Attack	Creating multiple fake identities to gain disproportionate influence

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