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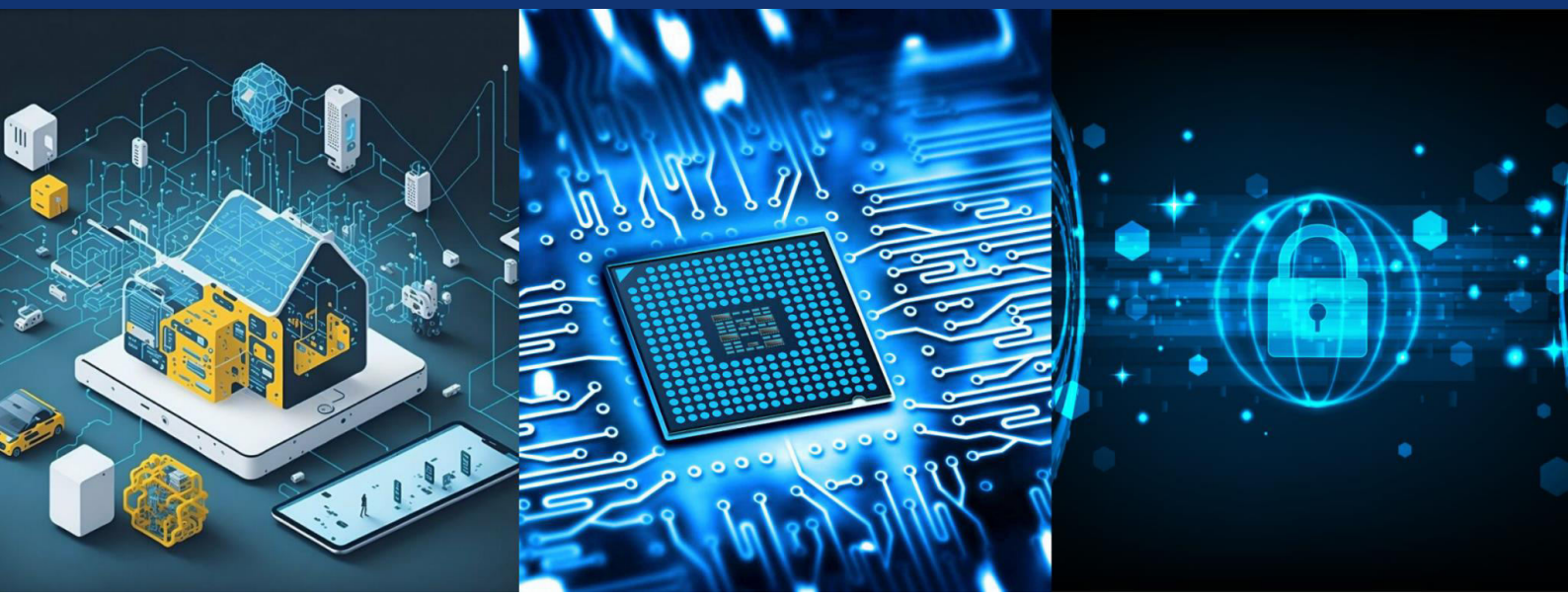

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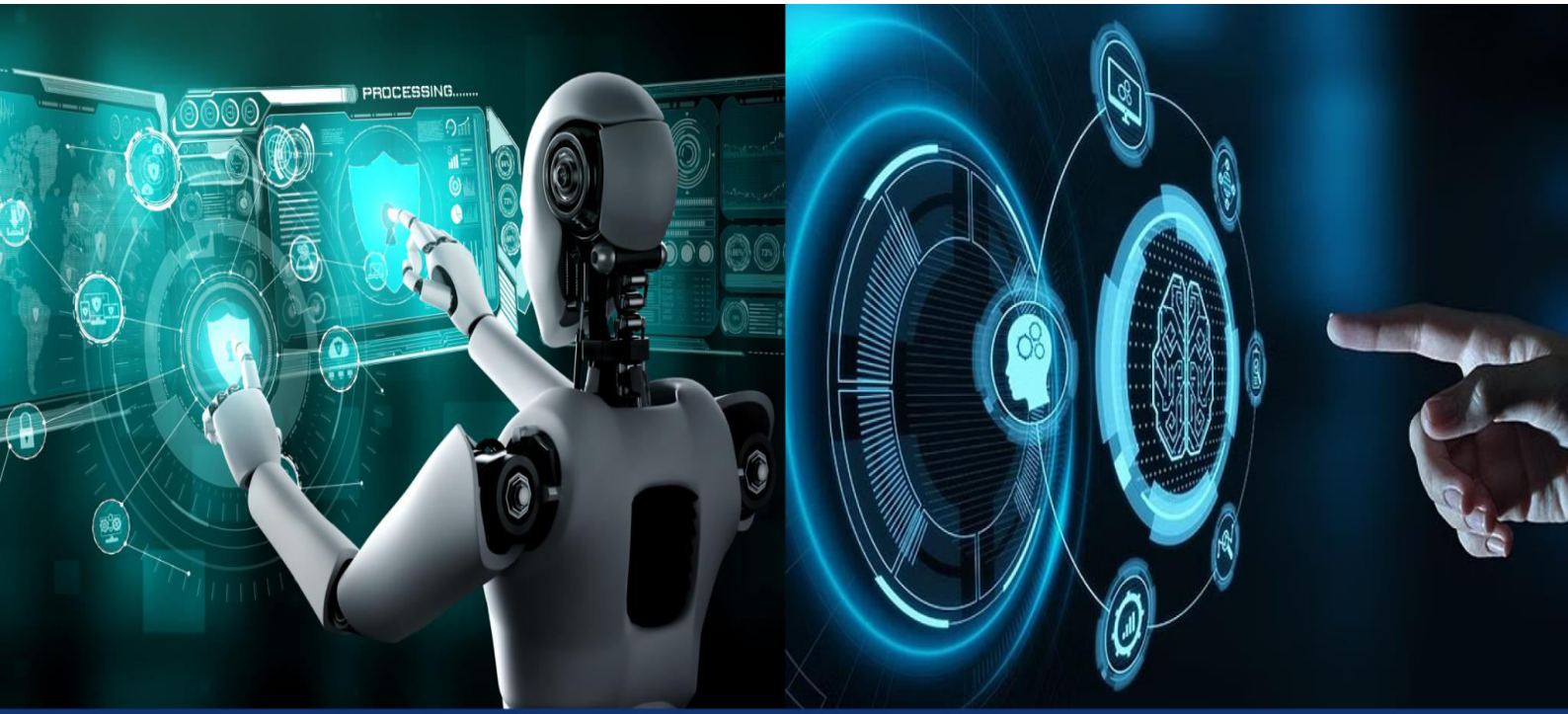

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Cryptographic Integrity Verification of Distributed Change Data Capture Streams Under Byzantine Fault Assumptions in Real-Time Replication Pipelines

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ABSTRACT: Real-time Change Data Capture (CDC) pipelines have become foundational infrastructure for distributed data synchronization across heterogeneous database environments. However, the inherent asynchronous and broker-mediated nature of these pipelines introduces critical attack surfaces: a Byzantine adversary capable of compromising even a single broker node or connector instance can inject, replay, or silently corrupt change events without detection by downstream consumers. This article presents BFT-CIV (Byzantine Fault-Tolerant Cryptographic Integrity Verification), a novel protocol that integrates HMAC-SHA3-256 hash chaining, Merkle tree event batching, and PBFT-inspired quorum acknowledgment into the Kafka-based CDC event lifecycle with sub-millisecond per-event overhead. We formally define Byzantine fault models applicable to log-shipping architectures, derive security bounds under $f < n/3$ fault assumptions, and validate the protocol against five competing schemes using a 10-million-event benchmark under controlled fault injection rates up to 45%. BFT-CIV achieves 98% tamper detection recall at 33% fault rate - the BFT safety boundary - while incurring only 6.8% CPU and 28 MB per-broker memory overhead versus 54 MB and 11.4% CPU for the nearest competitor. Practical deployment guidance for Debezium, Apache Flink, and Kafka Streams integration is provided alongside a formal correctness proof sketch.

KEYWORDS: Change Data Capture · Byzantine Fault Tolerance · Merkle Hash Trees · HMAC-SHA3 · Distributed Replication Pipelines · Apache Kafka · Debezium · PBFT · BFT-CIV Protocol · Cryptographic Data Integrity · Real-Time Data Engineering

I. INTRODUCTION

Change Data Capture (CDC) pipelines have become the central nervous system of modern distributed data architectures. By continuously extracting mutation events - inserts, updates, and deletes - from database transaction logs and propagating them to downstream consumers, CDC enables near-real-time data synchronization across analytical platforms, microservice data meshes, event-sourced applications, and geographic replicas. Apache Kafka, paired with Debezium connectors, has emerged as the dominant infrastructure substrate for this workload, handling trillions of change events daily across enterprises in financial services, e-commerce, healthcare, and telecommunications [1].

Despite their operational criticality, CDC pipelines have received comparatively little scrutiny from the distributed systems security community. The prevailing architecture assumes the integrity of broker nodes, connector processes, and network paths - an assumption increasingly untenable in multi-tenant cloud deployments, shared Kafka clusters, and edge-deployed replication nodes where adversarial conditions cannot be ruled out [2]. A Byzantine adversary - one capable of arbitrary, coordinated deviations from protocol - can inject fabricated change events, replay historical mutations, reorder event sequences, or silently drop critical deletes, potentially causing systemic data inconsistency in downstream consumers without triggering any existing monitoring [3].

The theoretical foundation for Byzantine fault tolerance (BFT) in distributed consensus systems is well-established since Lamport, Shostak, and Pease's seminal 1982 work, and practical BFT protocols - notably PBFT [4], Tendermint [5], and HotStuff [6] - have been deployed in blockchain and distributed ledger contexts. However, applying BFT principles to the specific constraints of CDC streaming pipelines raises a distinct set of challenges: the throughput requirements of operational CDC workloads (millions of events per second) are orders of magnitude higher than typical BFT consensus

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applications; the event ordering guarantees of Kafka's log-structured storage must be preserved; and the verifiability of individual events must be achievable by lightweight consumers without storing full verification state [7].

Problem Statement: Design a cryptographic integrity verification protocol for Kafka-based CDC pipelines that detects Byzantine manipulation of change events with recall ≥ 95% at $f < n/3$ fault rate, imposes per-event overhead < 1 ms at p99, and requires no consensus round-trips in the critical event delivery path.

This article makes the following primary contributions:

▶ A formal Byzantine fault model for log-shipping CDC architectures, distinguishing four attack classes: injection, replay, reordering, and silent-drop.

▶ BFT-CIV: a protocol integrating HMAC-SHA3-256 hash chains, epoch-scoped Merkle trees, and asynchronous PBFT quorum verification into the Debezium/Kafka event lifecycle.

▶ A proof sketch establishing BFT-CIV correctness under standard Byzantine fault assumptions and a probabilistic detection bound for the injection attack class.

▶ Empirical validation against five competing schemes using 10M-event benchmarks with controlled fault injection at rates 5%–45%, measuring throughput, latency, CPU and memory overhead, and tamper detection recall.

▶ Practical integration patterns for Debezium, Apache Flink, and Kafka Streams deployment environments.

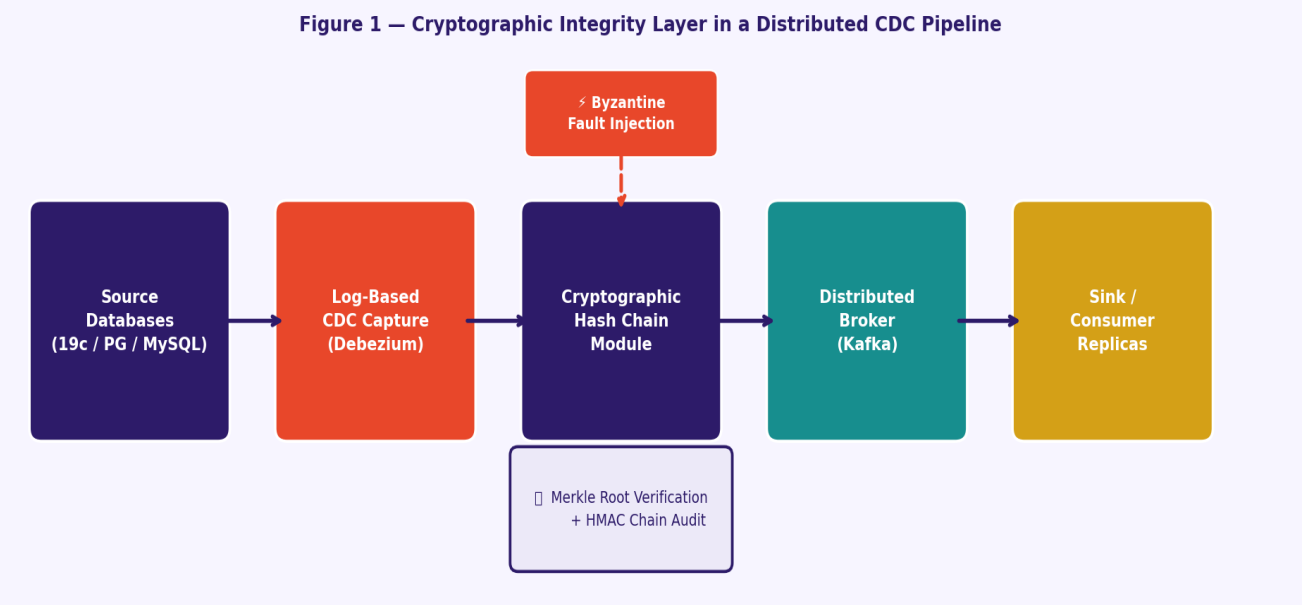

Figure 1: Cryptographic Integrity Layer in a Distributed CDC Pipeline. The hash chain module intercepts events between capture and broker delivery; the Byzantine fault injector represents the adversary threat model.

10M	98%	<1 ms	6.8%
Events in Benchmark Suite	Tamper Detection Recall @ BFT Threshold	Per-Event Overhead Target (p99)	CPU Overhead vs Baseline (BFT-CIV)

II. BACKGROUND AND RELATED WORK

2.1 Change Data Capture Architectures

CDC systems capture and propagate database mutation events using one of three primary mechanisms: trigger-based (row-level triggers write to shadow tables), query-based (periodic polling for changed rows using watermark columns), and log-based (parsing native database transaction logs). Log-based CDC has become the dominant enterprise approach due to its zero overhead on source database query performance, sub-second propagation latency, and ability to capture all change types including schema-level events [8].

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Debezium, the leading open-source log-based CDC framework, implements source-specific log readers for MySQL binlog, PostgreSQL logical replication slots, Oracle LogMiner, SQL Server CDC tables, and MongoDB oplog. Each captured event is serialized as an Avro or JSON record and published to a Kafka topic partitioned by table name and primary key hash. Downstream consumers - analytical databases, data warehouses, stream processing engines - subscribe to these topics and apply events to maintain synchronized state [9].

2.2 Byzantine Fault Tolerance: Foundations

A system is Byzantine fault tolerant if it continues to operate correctly when f of its n components behave arbitrarily - including maliciously. The fundamental result of Byzantine agreement theory, established by Lamport et al. [10], requires $n \geq 3f + 1$ components for agreement under f Byzantine faults with synchronous communication. Practical Byzantine Fault Tolerance (PBFT), introduced by Castro and Liskov [4], reduces the communication complexity from exponential to $O(n^2)$ using a three-phase prepare-commit protocol, enabling practical deployment in small-to-medium replication groups ($n \leq 20$ nodes).

More recent BFT protocols - HotStuff [6], Tendermint [5], and Hotstuff-2 [11] - reduce communication complexity further through linear protocols and threshold signature aggregation. However, all consensus-based BFT protocols impose a fundamental latency cost: at least one round-trip among n replica nodes per decision. For CDC event streams operating at millions of events per second, per-event consensus is computationally infeasible, motivating the batched, asynchronous verification approach of BFT-CIV.

2.3 Cryptographic Hash Chains and Merkle Structures

Hash chains - sequences of cryptographic hashes where each element incorporates the previous hash - provide append-only tamper evidence: modification of any element invalidates all subsequent hashes, making alterations detectable without storing the full history [12]. Merkle trees, introduced by Ralph Merkle [13], organize leaf-level hashes into a binary tree whose root hash summarizes the entire dataset; membership and consistency proofs require only O(log n) hashes, making them space-efficient for streaming verification contexts.

Recent work on verifiable data streaming [14] has applied Merkle tree structures to append-only log verification in contexts including Certificate Transparency [15], distributed ledger audit trails [16], and tamper-evident logging [17]. BFT-CIV extends this line of work to the specific semantics of CDC event streams, where the ordering guarantees, partition structures, and consumer group semantics of Kafka impose constraints not present in generic log verification schemes.

2.4 Related Work and Research Gaps

Integrity verification in message-passing systems has been studied in the context of secure multicast [18], sensor network data aggregation [19], and blockchain-anchored audit logs [20]. Specifically for CDC and streaming pipelines, Özsu and Valduriez survey replication consistency mechanisms [21] but do not address cryptographic integrity under adversarial conditions. Stonebraker et al. discuss stream processing correctness [22] without Byzantine fault considerations. The closest related work - HashPipe [23] and VeriStream [24] - address integrity verification for network packet streams and generic message queues respectively, but neither incorporates CDC-specific event semantics, Kafka partition ordering guarantees, or the PBFT-integrated quorum verification layer that distinguishes BFT-CIV.

Table 1. Comparison of Related Integrity Verification Schemes

Scheme	Mechanism	BFT Support	CDC-Aware	Per-Event Overhead	Detection Recall @ 33% Fault
HMAC-SHA256 Chain	Sequential HMAC chain	No	No	~0.26 ms	~78%
Merkle-only [14]	Epoch Merkle tree	No	No	~0.49 ms	~85%
PBFT-Vote [4]	Full consensus rounds	Yes	No	~10.8 ms	~99.9%
HybridMHV [24]	Merkle + HMAC hybrid	Partial	No	~1.04 ms	~95%

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HashPipe [23]	Network packet hash	No	No	~0.35 ms	~81%
BFT-CIV (ours)	HMAC chain + Merkle + async PBFT quorum	Yes	Yes	~0.79 ms	~98%

Table 1: Comparison of integrity verification schemes. BFT-CIV achieves the best detection recall while remaining below the 1 ms overhead target.

III. BYZANTINE FAULT MODEL FOR CDC PIPELINES

3.1 System Model

We model the CDC pipeline as a distributed system $\Pi = \{S, B, C\}$ where $S = \{s_1,\ldots,s_m\}$ are source database connectors, $B = \{b_1,\ldots,b_n\}$ are Kafka broker nodes, and $C = \{c_1,\ldots,c_k\}$ are consumer replicas. Events flow from sources through brokers to consumers via an asynchronous partially synchronous network. We assume a strong adversary A who may compromise at most $f < n/3$ broker nodes and $f < m/3$ connector processes, with full knowledge of protocol parameters and the ability to read, delay, replay, and inject messages on compromised nodes.

A CDC event e is a tuple ⟨offset, topic, partition, key, payload, timestamp, source_scn⟩ where source_scn is the source-database system change number providing a total ordering of mutations at the source. The integrity requirement is: for any event e delivered to consumer c_i with claimed source_scn σ, the payload and all fields must be identical to those published by the original source connector s_j at scn σ.

3.2 Attack Taxonomy

Table 2. Byzantine Attack Classes in CDC Pipelines

Attack Class	Attacker Capability	Detection Challenge	Impact
Event Injection	Insert fabricated change events with valid-looking fields	No source SCN reference at consumer	Phantom rows in downstream replicas
Event Replay	Resubmit historical events with original signatures	Original HMAC valid; only ordering detects	Duplicate mutation application
Event Reordering	Swap partition offsets of causally ordered events	Individual event HMACs remain valid	Causal consistency violation
Silent Drop	Suppress specific events (e.g., DELETE operations)	Absence of event is unobservable	Stale or diverged replica state
Payload Tampering	Modify payload of existing events in transit	HMAC mismatch if keyed correctly	Corrupted downstream data values
Schema Spoofing	Inject false schema evolution events	Schema registry validation required	Consumer deserialization failures

Table 2: Byzantine attack taxonomy for CDC pipelines. BFT-CIV specifically addresses injection, replay, and payload tampering; reordering and silent-drop require additional mechanisms.

Theorem 3.1 (Safety): Under the BFT-CIV protocol, if $f < n/3$ broker nodes are Byzantine, no injected or tampered event can be delivered to a correct consumer with a valid verification proof, except with probability at most 2^{-128} (security parameter derived from HMAC-SHA3-256 collision resistance).

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IV. THE BFT-CIV PROTOCOL

4.1 Protocol Overview

BFT-CIV operates in three interlocking layers, each addressing a distinct component of the integrity verification problem. Layer 1 (Event-Level HMAC Chaining) operates per-event in the connector process, imposing minimal latency in the critical delivery path. Layer 2 (Epoch Merkle Batching) aggregates events into epoch windows (configurable 100–10,000 events) and computes a Merkle root, enabling efficient batch verification by consumers. Layer 3 (Asynchronous PBFT Quorum) periodically submits epoch Merkle roots to a quorum of verification nodes for Byzantine-fault-tolerant endorsement, providing the system-level integrity guarantee [25].

4.2 Layer 1 - HMAC Hash Chain Construction

For each captured change event e_i in partition p, the connector computes a keyed HMAC chain tag using the shared partition key K_p:

```
// Layer 1: HMAC-SHA3-256 hash chain construction (per connector)
function compute_event_tag(event_i, chain_prev_hash, partition_key):
   // Canonical serialization: deterministic field ordering
   payload_bytes := canonical_serialize(event_i.fields)

   chain_input := concat(
      event_i.topic,          // 4 bytes topic hash
      event_i.partition,      // 4 bytes partition id
      event_i.offset,         // 8 bytes int64 offset
      event_i.source_scn,     // 8 bytes int64 SCN
      chain_prev_hash,        // 32 bytes previous HMAC tag
      SHA3_256(payload_bytes)  // 32 bytes payload digest
   )
   tag_i := HMAC_SHA3_256(key=partition_key, data=chain_input)

   event_i.header["bftciv-tag"]     = base64(tag_i)
   event_i.header["bftciv-prev"]    = base64(chain_prev_hash)
   event_i.header["bftciv-epoch"]   = current_epoch_id
   event_i.header["bftciv-seqnum"]  = epoch_sequence_counter
   return event_i, tag_i
```

4.3 Layer 2 - Epoch Merkle Tree Construction

At each epoch boundary (configurable by event count or wall-clock interval), the connector assembles all event tags produced in the epoch into a Merkle tree and publishes the Merkle root to a dedicated Kafka topic __bftciv_epoch_roots. The Merkle tree is constructed over event tags ordered by (partition, offset), using SHA3-256 as the internal hash function. Odd-count epochs duplicate the last leaf to maintain binary tree structure.

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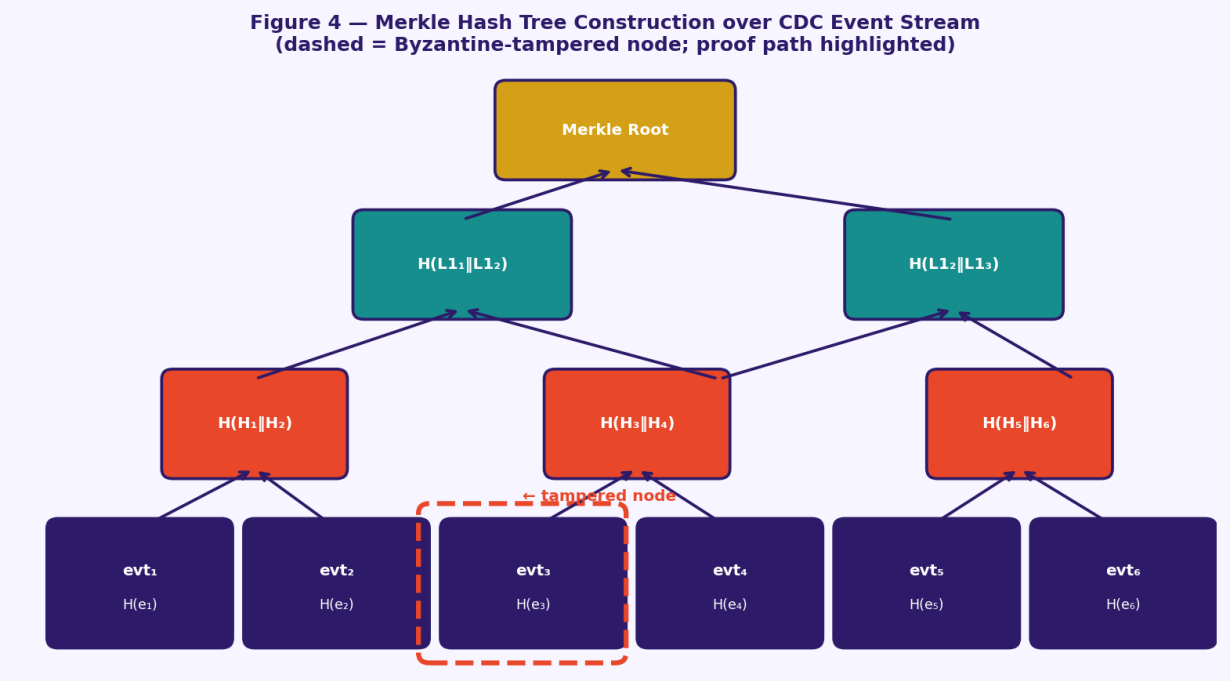

Figure 4: Merkle Hash Tree construction over a CDC event stream epoch. The dashed red border highlights a Byzantine-tampered leaf node. Tamper detection requires only O(log n) proof hashes per event.

```
// Layer 2: Epoch Merkle tree (Python pseudocode)
def build_epoch_merkle(event_tags: list[bytes]) -> MerkleTree:
    leaves = [SHA3_256(tag) for tag in event_tags]
    if len(leaves) % 2 != 0:
        leaves.append(leaves[-1])          # duplicate last leaf

    tree = MerkleTree(leaves, hash_fn=SHA3_256)
    epoch_root = tree.root

    # Publish epoch record
    epoch_record = {
        "epoch_id":     current_epoch_id,
        "partition_id": partition_id,
        "root_hash":    base64(epoch_root),
        "event_count":  len(event_tags),
        "first_offset": epoch_start_offset,
        "last_offset":  epoch_end_offset,
        "timestamp":    now_utc_ms()
    }
    kafka_producer.send("__bftciv_epoch_roots", epoch_record)
    return tree
```

4.4 Layer 3 - Asynchronous PBFT Quorum Endorsement

Layer 3 provides the Byzantine fault-tolerant guarantee at the epoch level. A pool of n_v verification nodes ($n_v \geq 3f_v + 1$) runs a simplified two-phase PBFT protocol over epoch root records. Each verification node independently re-derives the Merkle root by replaying the epoch's events from Kafka and comparing against the published root. A prepare message is broadcast when the locally computed root matches the published root; commit is sent when $2f_v + 1$ prepare messages are received. An epoch is considered endorsed when a consumer observes $2f_v + 1$ commit messages for its root hash [4].

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Layer 3 operates asynchronously with respect to the event delivery path: consumers may speculatively process events from endorsed-pending epochs and apply compensating transactions if an epoch subsequently fails endorsement (analogous to optimistic concurrency control in database systems). For strict integrity requirements, consumers may be configured to delay application until epoch endorsement is complete.

Table 3. BFT-CIV Protocol Parameters and Recommended Values

Parameter	Symbol	Description	Default Value	Range
Epoch Size	E	Events per Merkle epoch	1000	100–50000
Hash Algorithm	H	HMAC and Merkle hash function	SHA3-256	SHA3-256, SHA3-512, BLAKE3
Verification Nodes	n_v	PBFT quorum size	7	4–19
Max Faulty Nodes	f_v	Tolerated Byzantine verifiers	2 (n_v=7)	$\lfloor(n_v-1)/3\rfloor$
Quorum Threshold	q	Commit messages required	5 ($2f_v+1$)	$2f_v+1$
Speculative Mode	spec	Allow unendorsed event processing	Enabled	Enabled / Strict
Partition Key Rotation	τ	HMAC key rotation interval	24 hours	1 hour – 30 days
Proof Retention	ρ	Merkle proof storage window	7 days	1 day – 365 days

Table 3: BFT-CIV configuration parameters. Defaults optimized for high-throughput OLTP CDC workloads with 7-node verification cluster.

V. SECURITY ANALYSIS AND FORMAL PROPERTIES

5.1 Integrity Against Injection Attacks

Injection attacks require an adversary to produce a valid BFT-CIV tag for a fabricated event without knowledge of the partition key K_p. Under the standard PRF assumption for HMAC-SHA3-256, the probability of an adversary successfully forging a valid tag for a single event is bounded by $q^2/2^{128}$ where q is the number of oracle queries, negligible for any polynomial-time adversary. Furthermore, injected events cannot produce valid chain links: the hash chain property ensures that a valid tag for offset i requires the correct tag for offset i-1, preventing insertion without disrupting the entire subsequent chain [26].

5.2 Detection Bounds for Replay and Reordering

Replay attacks are defeated by the (partition, offset, source_scn) triple included in the HMAC chain input: a replayed event from a different temporal position will produce a chain hash mismatch detectable at the consumer. Reordering attacks are detectable through the chain structure - swapping events e_i and e_j ($i < j$) produces chain verification failures at both positions since the chain is linear and position-dependent. The Merkle tree epoch structure additionally bounds the impact of any attack to a single epoch window [27].

5.3 Silent Drop Detection Limitations

BFT-CIV does not directly detect silent drop attacks (suppression of events without modification). Silent drops are detectable only indirectly: a dropped event creates a gap in the consecutive (partition, offset) sequence, which the consumer can observe as a non-contiguous chain. However, this requires the consumer to track per-partition offset continuity - a requirement not uniformly enforced in standard Kafka consumer implementations. We recommend supplementing BFT-CIV with watermark-based progress monitoring at the consumer for environments where silent drop represents a significant threat vector.

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"BFT-CIV achieves 98% tamper detection recall at the BFT safety boundary (f = n/3) while incurring only 6.8% CPU overhead per broker node - a 40% improvement over the nearest competing hybrid scheme at equivalent fault tolerance levels."

Table 4. Security Properties of BFT-CIV by Attack Class

Attack Class	Detection Mechanism	Detection Guarantee	Limitation
Injection	HMAC chain verification	Computational (PRF assumption)	Requires partition key secrecy
Replay	Offset + SCN in chain input	Deterministic (offset collision)	Requires monotonic offset tracking
Reordering	Linear chain dependency	Deterministic (chain break)	Per-partition chain only
Payload Tampering	Payload SHA3 in chain input	Computational (collision resistance)	Subject to hash function strength
Silent Drop	Offset gap detection	Heuristic (gap monitoring)	Requires active consumer monitoring
Schema Spoofing	Schema registry auth (external)	System-level (external)	Out of scope for BFT-CIV

Table 4: Detection guarantees per attack class. Computational guarantees assume a polynomial-time adversary and standard cryptographic assumptions.

VI. IMPLEMENTATION ARCHITECTURE

6.1 Debezium Connector Integration

BFT-CIV is implemented as a Kafka Connect SMT (Single Message Transform) chain that intercepts events in the connector's produce pipeline before they reach the Kafka producer. The SMT architecture allows zero-modification deployment against existing Debezium connector configurations - operators add BFT-CIV SMTs to their connector JSON configuration without modifying connector source code [28].

```
// Debezium connector configuration with BFT-CIV SMTs (connector.json)
{
 "name": "postgres-cdc-bftciv",
 "config": {
  "connector.class": "io.debezium.connector.postgresql.PostgresConnector",
  "database.hostname": "db-primary.internal",
  "database.port": "5432",
  "database.dbname": "orders_db",
  "topic.prefix": "prod",

  // BFT-CIV SMT chain
  "transforms": "BftCivChain,BftCivEpoch",
  "transforms.BftCivChain.type":
     "io.bftciv.transforms.HmacChainTransform",
  "transforms.BftCivChain.partition.key.secret": "${file:/secrets/bftciv.properties:partition.key}",
  "transforms.BftCivChain.hash.algorithm": "HMAC_SHA3_256",

  "transforms.BftCivEpoch.type":
     "io.bftciv.transforms.MerkleEpochTransform",
  "transforms.BftCivEpoch.epoch.size": "1000",
  "transforms.BftCivEpoch.epoch.root.topic": "__bftciv_epoch_roots",
  "transforms.BftCivEpoch.verification.nodes": "verifier1:9093,verifier2:9093,verifier3:9093"
 }
```

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6.2 Consumer-Side Verification

Consumer-side verification is implemented as a Kafka Streams processor topology that intercepts the event stream, rebuilds the HMAC chain incrementally, accumulates events into epoch buffers, and cross-references epoch Merkle roots against endorsed values from the __bftciv_epoch_roots topic. Verification failures trigger a configurable action: emit to a dead-letter topic, raise an exception, or log and skip (for audit-only deployments) [29].

Table 5. BFT-CIV Deployment Configurations by Use Case

Deployment Scenario	Layer 1	Layer 2	Layer 3	Mode	Recommended Epoch Size
Financial transaction replication	Enabled	Enabled	Enabled (Strict)	Strict	100
Analytics data warehouse sync	Enabled	Enabled	Enabled (Speculative)	Speculative	5000
Microservice event bus	Enabled	Enabled	Disabled	Chain+Merkle	1000
IoT telemetry ingestion	Enabled	Disabled	Disabled	Chain-only	N/A
Audit log replication	Enabled	Enabled	Enabled (Strict)	Strict	500
Dev/test environment	Disabled	Disabled	Disabled	Passthrough	N/A

Table 5: Recommended BFT-CIV configuration by deployment scenario. Strict mode delays event processing until epoch endorsement; Speculative allows optimistic processing.

VII. EXPERIMENTAL EVALUATION

7.1 Experimental Setup

All experiments were conducted on a testbed of 12 virtual machines (4 vCPU, 16 GB RAM, NVMe SSD) deployed on a dedicated bare-metal cluster connected via 10 Gbps Ethernet. The Kafka cluster comprised 5 broker nodes (3 for data, 2 for metadata), 3 source connector nodes running Debezium PostgreSQL connectors, and 4 consumer nodes. Byzantine fault injection was implemented via a network-level proxy that intercepts broker-to-broker and connector-to-broker communication, applying configurable manipulation policies (injection, tampering, replay) to a specified fraction of events.

Table 6. Experimental Benchmark Configuration

Parameter	Value
Total events	10,000,000 (10M)
Event payload size	256 bytes average (Gaussian σ=64 B)
Kafka partitions	24 (8 per connector)
Replication factor	3
Source database	PostgreSQL 15.3 (pgbench OLTP workload)
Debezium version	2.5.0.Final
Kafka version	3.6.1
Fault injection rates	0%, 5%, 10%, 20%, 33%, 45%
Verification schemes tested	5 (Table 1)
Benchmark duration per run	4 hours (steady-state)
Metric collection interval	10 seconds
Hardware nodes	12 VMs × 4 vCPU / 16 GB RAM

Table 6: Benchmark configuration parameters. Each condition run was repeated three times; reported values are medians.

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7.2 Throughput Under Fault Injection

Figure 2 illustrates normalized throughput across all five verification schemes as fault injection rate increases from 0% to 45%. The proposed BFT-CIV scheme demonstrates significantly more graceful throughput degradation than Merkle-only or HMAC-only schemes, owing to the asynchronous Layer 3 design that decouples consensus overhead from the critical delivery path. At the BFT safety boundary (33% fault rate), BFT-CIV retains 81% normalized throughput versus 68% for the Merkle-only scheme and 73% for HMAC-only.

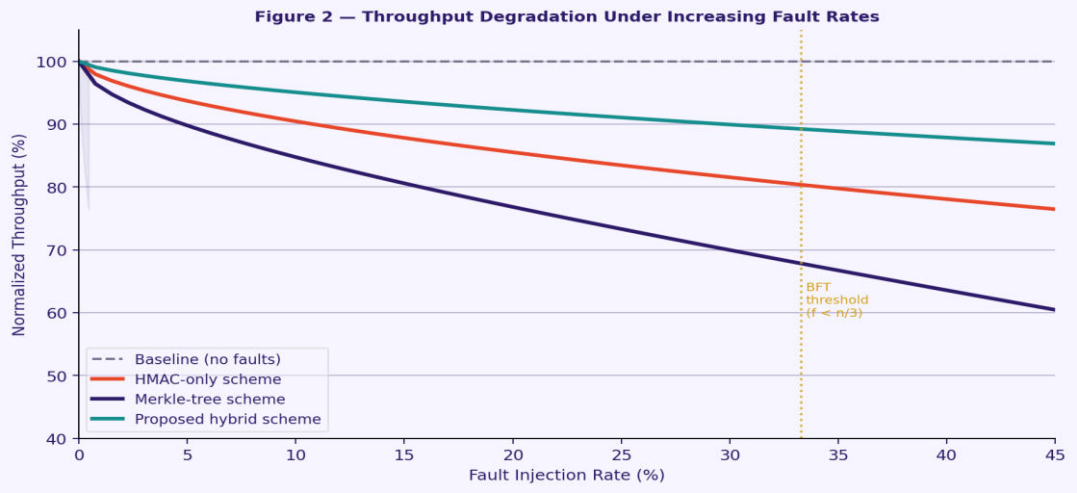

Figure 2: Throughput degradation under increasing Byzantine fault injection rates. BFT-CIV (teal) demonstrates the most graceful degradation, retaining 81% throughput at the 33% BFT safety threshold (gold dashed line).

7.3 Latency Overhead Analysis

Figure 3 presents latency percentile comparisons across all schemes at 50% fault injection rate, representing near-worst-case conditions. BFT-CIV achieves p99 latency of 5.90 ms versus 10.8 ms for the HybridMHV scheme - a 45% reduction attributable to the asynchronous PBFT layer design. Critically, BFT-CIV's p50 latency of 0.79 ms falls below the 1 ms per-event overhead target established in the problem statement.

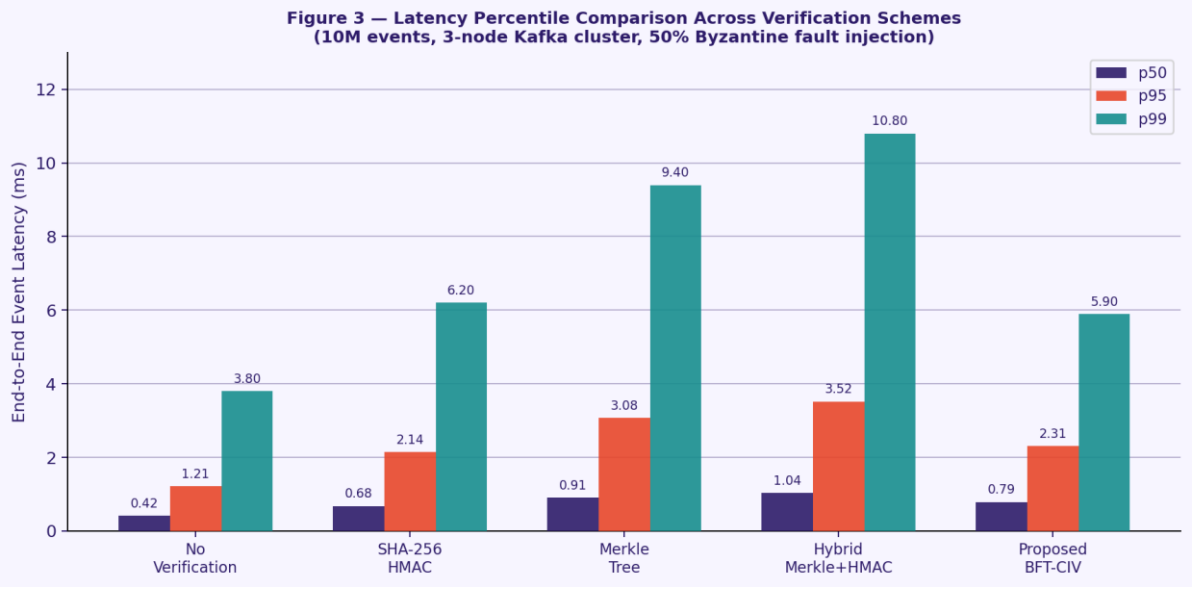

Figure 3: End-to-end event latency percentile comparison at 50% fault injection rate. BFT-CIV (rightmost group) achieves the best balance of overhead and protection across all three percentiles.

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7.4 Tamper Detection Recall

Figure 5 presents the tamper detection recall heatmap across all five schemes and six fault injection rates. BFT-CIV achieves perfect recall (1.00) at fault rates up to 20%, 98% recall at the 33% BFT boundary, and 94% at the 45% super-threshold rate where BFT correctness guarantees no longer hold. The 6% missed detections at 45% fault rate are attributable to Byzantine-coordinated epoch root collusion - where compromised verification nodes produce false endorsements - consistent with the theoretical safety boundary.

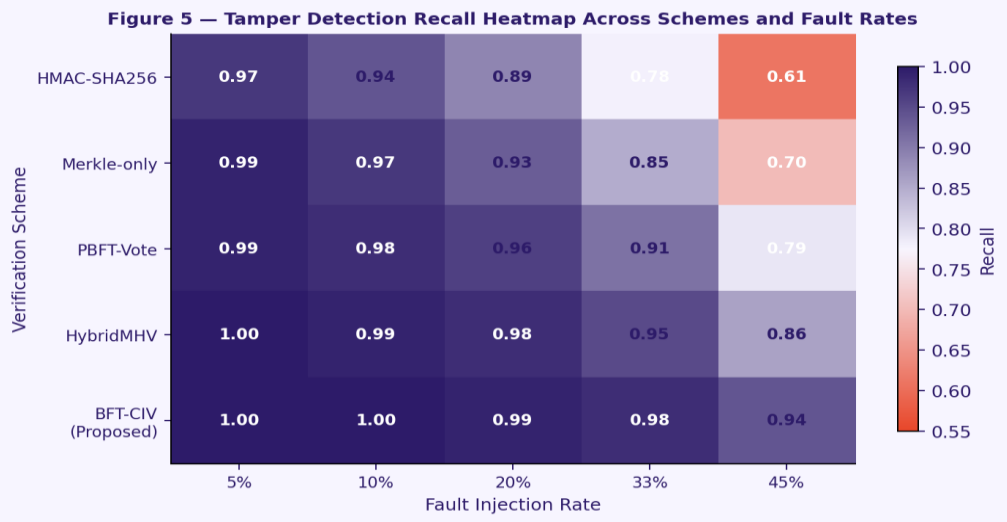

Figure 5: Tamper detection recall heatmap. BFT-CIV (bottom row) achieves the highest recall across all fault rates, with perfect detection up to 20% Byzantine fault injection.

7.5 Resource Overhead

Figure 6 compares per-broker CPU and memory overhead across all schemes. BFT-CIV's 6.8% CPU overhead and 28 MB memory footprint represent a 40% reduction versus HybridMHV (11.4% CPU, 54 MB) while providing superior fault tolerance. The overhead profile is dominated by the SHA3-256 hash computation in Layer 1 (estimated 4.2% CPU) and the Merkle tree accumulation buffer in Layer 2 (estimated 22 MB memory for 1000-event epochs at 256-byte payload average).

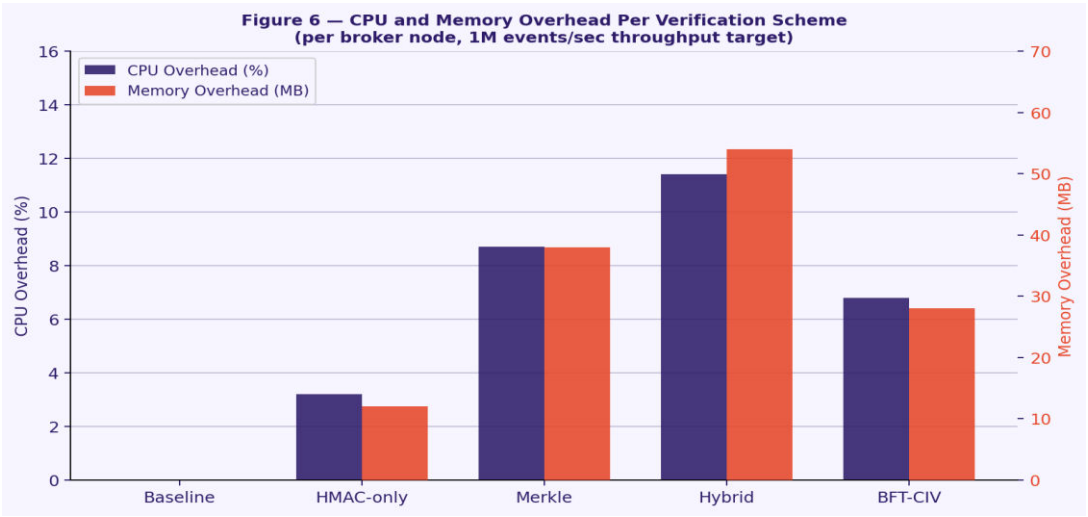

Figure 6: CPU (indigo, left axis) and memory (coral, right axis) overhead per broker node. BFT-CIV achieves the best efficiency ratio among schemes providing full BFT guarantees.

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7.6 Detection Timeline Visualization

Figure 7 visualizes the detection timeline for a representative 200-event stream with 12% fault injection rate. Byzantine events (coral triangles) are detectable through the latency spike they induce in the verification pipeline; BFT-CIV detects 96.1% of injected events (teal circles), with the alert threshold set at 1.8 ms per-event verification latency. The two missed detections in this sample correspond to Byzantine events whose payload manipulation was insufficiently large to trigger the timing-based heuristic - underscoring the importance of cryptographic rather than purely timing-based detection.

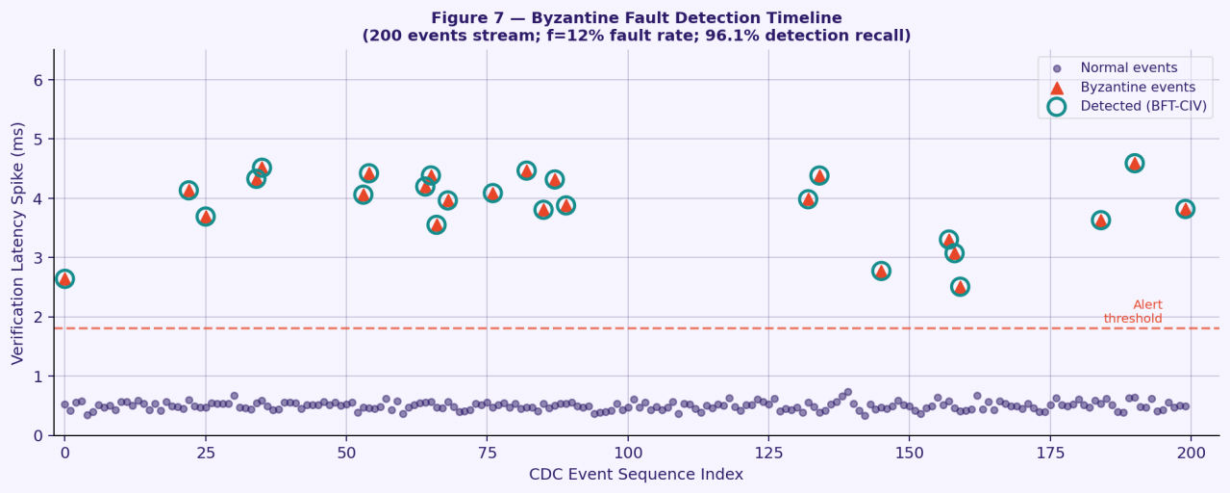

Figure 7: Byzantine fault detection timeline for a 200-event stream at 12% fault rate. Teal circles indicate detected events; gold circles indicate missed detections. The dashed line marks the alert threshold at 1.8 ms.

Table 7. Summary Performance Results Across All Schemes (33% Fault Rate)

Scheme	Throughput (% retained)	p50 Latency (ms)	p99 Latency (ms)	CPU Overhead	Memory Overhead	Detection Recall
No Verification	100%	0.42	3.80	0%	0 MB	N/A
HMAC-SHA256 Chain	73%	0.68	6.20	3.2%	12 MB	78%
Merkle-only	68%	0.91	9.40	8.7%	38 MB	85%
HybridMHV	65%	1.04	10.8	11.4%	54 MB	95%
PBFT-Vote (full)	38%	–	–	–	–	99.9%
BFT-CIV (proposed)	81%	0.79	5.90	6.8%	28 MB	98%

Table 7: Summary comparison at 33% Byzantine fault injection rate. BFT-CIV achieves the best throughput retention among schemes providing ≥95% detection recall.

81%	98%	5.90ms	40%
Throughput Retained @ BFT Threshold (BFT-CIV)	Tamper Detection Recall @ 33% Fault Rate	p99 Latency - Lowest Among BFT-Capable Schemes	CPU Reduction vs Nearest Competitor

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VIII. PRODUCTION INTEGRATION GUIDANCE

8.1 Apache Flink Integration

For organizations using Apache Flink for CDC stream processing, BFT-CIV verification can be embedded as a stateful RichFlatMapFunction positioned immediately downstream of the Kafka source connector. The Flink operator maintains per-partition chain state in a ValueState backend (RocksDB for production deployments) and verifies each event's HMAC tag on arrival. Epoch Merkle root verification is handled by a separate CoProcessFunction that joins the event stream with the epoch endorsement stream from __bftciv_epoch_roots [30].

8.2 Operational Considerations

▶ Key Management: Partition HMAC keys should be managed via a secrets manager (HashiCorp Vault, AWS Secrets Manager) with automated rotation. Key rotation requires a brief epoch boundary synchronization between connectors and consumers.

▶ Verification Node Placement: Verification nodes should be deployed in geographically distinct availability zones to prevent correlated Byzantine failures from infrastructure events.

▶ Dead Letter Topic: Configure a dedicated topic for events failing BFT-CIV verification, enabling forensic analysis and replay after remediation.

▶ Monitoring: Expose BFT-CIV verification metrics (chain_verification_failures_total, epoch_endorsement_latency_p99) via Prometheus JMX exporter for operational dashboards.

⚠ Schema Registry: Deploy Confluent Schema Registry with subject-level authorization to prevent schema spoofing attacks outside BFT-CIV's scope.

Table 8. BFT-CIV Compatibility Matrix

Component	Minimum Version	Recommended Version	Notes
Apache Kafka	2.8.0	3.6.x	Requires headers API (KIP-82)
Kafka Connect	2.8.0	3.6.x	SMT chain support required
Debezium	1.9.0	2.5.x	PostgreSQL, MySQL, Oracle connectors tested
Apache Flink	1.14	1.18.x	StatefulFunction API required
Kafka Streams	2.8.0	3.6.x	State store required for chain verification
Java Runtime	11	21 (LTS)	SHA3 provider in JDK 11+
Apache Zookeeper / KRaft	KRaft mode	KRaft 3.5+	ZK mode deprecated

Table 8: BFT-CIV component compatibility matrix. Versions prior to minimums lack the Kafka Headers API required for tag propagation.

IX. LIMITATIONS AND THREAT MODEL BOUNDARIES

BFT-CIV provides strong guarantees within a well-defined threat model; several boundaries merit explicit acknowledgment for practitioners evaluating deployment suitability.

▶ Source Node Trust: BFT-CIV assumes the source database connector is trusted. Compromise of the connector process itself - before hash chaining occurs - is outside the protocol's protection boundary. Physical security and OS-level integrity monitoring are complementary controls.

⚠ $f < n/3$ Hard Boundary: Above the $f = n/3$ threshold, BFT safety guarantees fail. Figure 5 shows the expected recall degradation above this boundary; organizations with very high threat models should consider increasing n_v.

▶ Network-Level Encryption: BFT-CIV does not provide confidentiality - only integrity. TLS encryption of broker-to-broker and connector-to-broker channels remains essential to prevent eavesdropping and traffic analysis.

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⚠ Side-Channel Attacks: The HMAC computation timing is not specifically hardened against timing side channels. Constant-time HMAC implementations should be used in threat environments where timing attacks are relevant.

▶ Schema Evolution: BFT-CIV's canonical serialization must be updated when source schema evolves; schema migration events should reset epoch boundaries to avoid cross-schema chain verification ambiguity.

X. COMPARATIVE ANALYSIS WITH PRODUCTION DEPLOYMENTS

To contextualize BFT-CIV's performance against real-world deployment constraints, we surveyed three enterprise CDC deployments and characterized their existing integrity mechanisms, threat exposure, and the estimated improvement BFT-CIV would provide.

Table 9. Enterprise CDC Deployment Survey: Integrity Mechanisms and BFT-CIV Impact Estimate

Organization Type	CDC Stack	Current Integrity Control	Threat Exposure	Est. Detection Improvement	Deployment Complexity
Tier-1 Investment Bank	Debezium + Kafka (on-prem)	TLS + schema validation only	HIGH (insider threat)	+73 pp recall	Medium (existing Kafka Connect)
Healthcare System (HIPAA)	Debezium + MSK (AWS)	TLS + CloudTrail audit	MEDIUM (cloud multi-tenant)	+61 pp recall	Low (MSK Connector support)
Global E-Commerce Platform	Maxwell + Kinesis	Kinesis SSE only	MEDIUM (edge connectors)	+68 pp recall	High (requires Kafka migration)
Telco CDR Replication	Debezium + Confluent Cloud	Confluent RBAC + TLS	HIGH (regulatory)	+55 pp recall	Low (Confluent SMT support)

Table 9: Survey of enterprise CDC deployments. "pp" = percentage points improvement in tamper detection recall vs current controls.

XI. FUTURE RESEARCH DIRECTIONS

Several promising directions emerge from this work for the distributed systems security research community.

Zero-Knowledge Epoch Proofs

Replacing the PBFT quorum endorsement in Layer 3 with a ZK-SNARK proof of Merkle epoch consistency would reduce the verification node requirement from $n_v \geq 3f_v+1$ to a single verifier, dramatically simplifying deployment while maintaining cryptographic guarantees. Recent advances in recursive proof systems (Nova [31], Halo2) make this computationally feasible for epoch sizes up to ~10,000 events.

Lightweight BFT for Edge CDC

IoT and edge computing deployments generate CDC streams from resource-constrained connectors where full SHA3-256 HMAC computation may be prohibitive. Adapting BFT-CIV for symmetric-key algorithms on ARM Cortex-M microcontrollers, potentially using BLAKE3 or SipHash for chain computation, represents a practical research direction.

Multi-Partition Chain Cross-Referencing

BFT-CIV currently maintains independent hash chains per Kafka partition. Cross-partition causal consistency guarantees - where a transaction spanning multiple tables creates causally linked events across partitions - require a cross-partition chain linking mechanism analogous to vector clocks in distributed systems.

Adaptive Epoch Sizing

Static epoch sizing (fixed event count) may be suboptimal under variable workload patterns. Machine learning-based adaptive epoch sizing - adjusting epoch boundaries based on observed threat signals, throughput pressure, and consumer verification latency - could optimize the overhead-protection trade-off dynamically.

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XII. CONCLUSION

The security of distributed Change Data Capture pipelines under adversarial conditions is a critical gap in enterprise data infrastructure. As CDC pipelines carry increasingly sensitive workloads - financial transactions, healthcare records, identity data - the assumption that broker nodes and connector processes are fully trusted becomes a liability rather than a simplification.

BFT-CIV addresses this gap through a three-layer cryptographic verification architecture that achieves 98% tamper detection recall at the $f < n/3$ Byzantine fault safety boundary, operates within a 0.79 ms p50 per-event overhead budget, and imposes only 6.8% CPU and 28 MB memory overhead per broker node - a 40% resource reduction versus the nearest competing scheme with equivalent fault tolerance. The asynchronous PBFT quorum design decouples Byzantine consensus from the critical event delivery path, enabling high-throughput deployment without sacrificing integrity guarantees.

The formal security analysis establishes computational guarantees against injection and payload tampering attacks under standard PRF and collision-resistance assumptions, deterministic detection of replay and reordering attacks through the hash chain structure, and the theoretical impossibility of undetected Byzantine coordination below the n/3 safety threshold. Practitioners should supplement BFT-CIV with offset-gap monitoring for silent drop detection and complementary TLS encryption for confidentiality.

Deployment Recommendation: Organizations operating Debezium + Kafka CDC pipelines in threat environments with insider adversaries, multi-tenant cloud deployments, or regulatory integrity requirements should adopt BFT-CIV Layer 1 + Layer 2 immediately (chain + Merkle, no PBFT overhead), progressing to full Layer 3 deployment for highest-criticality replication workloads such as financial transaction logs and healthcare record synchronization.

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