

1 AC-BlockDFL: Audit-driven Committee BlockDFL for Secure Federated Learning

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3 ANONYMOUS AUTHOR(S)

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5 Blockchain-based Federated Learning (BCFL) faces a critical scalability-security trade-off. While committee-based architectures
6 significantly reduce communication overhead, they introduce a fundamental vulnerability: the *Progressive Committee Capture Attack*
7 (PCCA). In PCCA, rational adversaries exploit the stake-election-reward feedback loop to gradually capture committee control through
8 strategic starvation and stake accumulation. We propose *AC-BlockDFL*, a defense framework that decouples system security from
9 committee honesty through optimistic execution and asynchronous auditing. By internalizing the externalities of malicious behavior
10 via a game-theoretic slashing protocol, AC-BlockDFL ensures that attacks yield negative expected utility. Our evaluation over 2,000
11 rounds demonstrates that AC-BlockDFL suppresses malicious stake ratios from $1.3\times$ to $0.37\times$, reducing unavailability rates from 22.3%
12 to below 1% while maintaining $O(C^2)$ communication complexity.

13

14 CCS Concepts: • Security and privacy → Distributed systems security; • Computing methodologies → Artificial intelligence.

15

16 Additional Key Words and Phrases: Federated Learning, Blockchain, Committee Consensus, Game Theory, Incentive Compatibility

17

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21

22 1 Introduction

23

24 Blockchain-based Federated Learning (BCFL) has emerged as a promising paradigm for collaborative machine learning
25 in environments where mutual trust among participants cannot be assumed. Real-world deployments in Low Earth
26 Orbit (LEO) satellite networks [8, 24, 32], vehicular networks (V2X) [16, 25], and Industrial IoT [17, 27] demonstrate
27 compelling use cases where decentralized coordination is essential. In LEO constellations, for instance, ground station
28 contact windows last merely five minutes with downlink bandwidth limited to approximately 8 Mbps [32], rendering
29 centralized aggregation architectures impractical. BCFL addresses these constraints by establishing decentralized trust
30 infrastructure across heterogeneous satellite operators, reducing model convergence time by up to thirty hours [8].

31

32 However, BCFL systems face a fundamental scalability bottleneck when approaching large-scale deployment. The
33 predominant use of Practical Byzantine Fault Tolerance (PBFT) [4] and its variants introduces $O(N^2)$ message complexity,
34 causing consensus latency to dominate training time as participant counts grow. Empirical measurements from
35 FLCoin [28] reveal that at 100 nodes, single-round consensus generates over 20,000 message exchanges with latency
36 exceeding 25 seconds—comparable to or exceeding the model training duration itself. Storage requirements compound
37 this challenge: Bitcoin full nodes require approximately 200 GB while Ethereum exceeds 465 GB, fundamentally
38 incompatible with edge devices possessing only KB-to-MB scale memory [1].

39

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53 *The Committee Mechanism.* To address these scalability constraints, recent work has converged on *committee-based*
54 architectures that delegate verification responsibility to a smaller subset of validators. Selection mechanisms include hash-
55 ring sampling [26], stake-weighted election [15, 28], and Verifiable Random Function (VRF) based sortition [12, 29, 31].
56 These approaches yield substantial efficiency gains: FLCoin [28] reports 90% communication overhead reduction and
57 5.7× training speedup through sliding-window election, while BFLC [15] achieves sub-three-second consensus latency.
58 Effectively, committee mechanisms reduce communication complexity from $O(N^2)$ to $O(C^2)$ or even $O(C)$, where
59 $C \ll N$ is the committee size.
60

62 *The Blind Spot.* Despite these advances, existing BCFL literature harbors a critical yet overlooked vulnerability:
63 the implicit assumption that committee members remain honest or that the proportion of malicious nodes stays
64 static throughout system operation. Current defenses focus predominantly on data-plane attacks—Byzantine-robust
65 aggregation rules such as Krum, Trimmed Mean, and Median [3, 34] assume an honest majority among aggregating
66 nodes. However, these mechanisms provide no protection when the committee itself becomes compromised. As
67 FedBlock [20] observes, when any participant may become a validator, systems cannot rely solely on honest majority
68 assumptions but must actively detect and isolate malicious verifiers—a capability conspicuously absent from current
69 BCFL architectures.
70

73 *The PCCA Threat.* We identify and formalize a novel attack vector: the *Progressive Committee Capture Attack* (PCCA).
74 Unlike direct Byzantine attacks, PCCA adversaries employ *strategic starvation*—upon gaining committee control,
75 attackers prioritize processing their own model updates while systematically denying service to honest participants.
76 This manipulation of the reward distribution mechanism enables attackers to “legitimately” accumulate stake over
77 successive rounds, progressively cementing their dominance until decentralized governance collapses entirely. Crucially,
78 once the honest majority assumption fails in any given round, existing systems lack mechanisms to identify or penalize
79 malicious actors, allowing attackers to maintain their advantage indefinitely.
80

83 *Contributions.* This paper presents *Audit-driven Committee BlockDFL* (AC-BlockDFL), a defense framework that
84 decouples system security from collective committee honesty through optimistic execution with asynchronous auditing.
85 Our contributions are threefold:
86

- 88 (1) **Attack Formalization.** We provide the first formal definition of the Progressive Committee Capture Attack
89 (PCCA) and a rational adversary model that captures strategic, incentive-driven behavior. Through systematic
90 simulation, we quantify PCCA’s destructive impact on long-term incentive compatibility.
- 92 (2) **AC-BlockDFL Architecture.** We propose a novel defense architecture combining optimistic execution with
93 asynchronous auditing. A distributed challenger network performs post-hoc verification of committee decisions,
94 enabling detection and penalization of fraudulent aggregation results even when the committee is fully
95 compromised.
- 97 (3) **Game-Theoretic Guarantees.** We design an internal slashing protocol grounded in game-theoretic analysis,
98 ensuring that auditing costs remain strictly below potential gains from malicious behavior. We prove that
99 honest participation constitutes the unique Nash equilibrium under repeated play [6]. Extensive simulations
100 over 2,000 rounds demonstrate that AC-BlockDFL maintains model accuracy above 98.6% under 30% adversarial
101 collusion, reduces communication overhead by 44.4% at equivalent security levels, and suppresses minimum
102 unavailability rate from 20% to below 5%.

105 2 Background

106 This section establishes the theoretical foundations and technical background necessary for understanding the security
 107 challenges in committee-based blockchain federated learning. We first discuss the fundamental trust dilemma in
 108 federated learning, then introduce the principles of Byzantine fault tolerance, and finally establish the baseline system
 109 model for committee-based architectures.

112 2.1 Federated Learning and the Trust Dilemma

114 Federated learning (FL) represents a paradigm shift in distributed machine learning, encapsulating the principle of
 115 “bringing the model to the data” rather than aggregating data centrally [18]. While FL significantly enhances data
 116 privacy by locally constraining raw data, its standard architecture relies on a fundamental assumption: participants
 117 must trust a central aggregation server to honestly execute aggregation and uniformly distribute results.

119 In the absence of verifiable consistency, the central server constitutes a single point of failure and a primary
 120 vulnerability. A malicious or compromised server could perform selective aggregation, intentionally excluding specific
 121 updates, or directly tamper with the global model to inject backdoors [2, 10]. Furthermore, while FL avoids direct data
 122 transmission, a malicious aggregator can still infer sensitive information from client updates [11, 36]. This trust dilemma
 123 severely restricts the deployment of FL in high-value, cross-organizational scenarios where participating entities may
 124 be independent or competitive, necessitating a decentralized trust infrastructure [13, 17].

127 2.2 Byzantine Fault Tolerance Fundamentals

129 Blockchain technology, characterized by immutability, transparency, and decentralization, serves as an ideal infrastruc-
 130 ture to resolve the FL trust dilemma. However, the security of blockchain fundamentally relies on consensus protocols
 131 designed to tolerate malicious behavior, rooted in the Byzantine Generals Problem [14].

133 The mathematical constraint of Byzantine Fault Tolerance (BFT) dictates that a system of N nodes can tolerate
 134 at most f malicious nodes, requiring $N \geq 3f + 1$. This one-third threshold originates from the *quorum intersection*
 135 *principle*: to ensure sufficient honest endorsements, any decision needs $2f + 1$ confirmations. The intersection of any
 136 two $2f + 1$ sets guarantees the inclusion of at least $f + 1$ nodes, meaning at least one honest node witnesses both
 137 decisions, preventing contradictory states.

139 Practical Byzantine Fault Tolerance (PBFT) [4] reduces the communication complexity of BFT consensus to $O(N^2)$
 140 through a three-phase commit protocol (Pre-prepare, Prepare, Commit). While efficient for small networks, the quadratic
 141 communication cost becomes a severe bottleneck for large-scale FL systems requiring frequent iterations involving
 142 hundreds of participants.

145 2.3 Committee-based BCFL Architecture

147 To reconcile the efficiency demands of federated learning with the security requirements of blockchain, the *committee-*
 148 *based architecture* has emerged as the prevailing design paradigm. By delegating consensus responsibilities to a smaller,
 149 representative subset of nodes (the committee), these systems reduce communication complexity from $O(N^2)$ to
 150 $O(C^2 + N)$ where the committee size $C \ll N$ [15, 20, 28].

152 *Baseline System Model: BlockDFL..* We adopt BlockDFL [26] as our baseline system model, representing the state-of-
 153 the-art in peer-to-peer BCFL. BlockDFL implements role separation, partitioning participants into three distinct roles
 154 per training round:

- 157 (1) **Update Providers:** Execute local model training on private data and submit bounded updates.
 158 (2) **Aggregators:** Collect updates, perform filtering, and compute the aggregated global proposal.
 159 (3) **Validators:** Form the committee to evaluate competing proposals via Krum scoring [3] and execute PBFT
 160 consensus to select the final model.
 161

162
 163 *The Stake-Election-Reward Cycle.* Role assignment in BlockDFL relies on *stake-weighted deterministic random selection*,
 164 using the previous block’s hash as an unpredictable entropy source mapping onto a stake-weighted hash ring. This
 165 creates a critical economic incentive structure designed to solve the free-rider problem:
 166

- 167 • **Stake:** Determines election probability; participants with higher stake bounds are proportionally more likely to
 168 be selected as Aggregators or Validators.
 169
- 170 • **Reward:** Distributed exclusively to contributors of the accepted proposal (the winning Aggregator, included
 171 Update Providers, and Validators who voted for it).
 172

173 This mechanism instantiates a *positive feedback loop*: receiving rewards increases absolute stake, which enhances future
 174 election probability and aggregation weight, thereby amplifying the likelihood of subsequent rewards. While intended
 175 to cultivate long-term honest contributions, this very dynamic introduces vulnerabilities to strategic persistence.
 176

177 3 Related Work

178 The convergence of federated learning and blockchain technology has precipitated diverse architectural innovations
 179 to address decentralized coordination, privacy, and security [21]. Early systems like DeepChain [31] and Biscotti [29]
 180 focused on preserving privacy during aggregation using cryptographic commitments and differential privacy. However,
 181 scaling BFT consensus to accommodating hundreds of FL clients remained a persistent challenge due to its $O(N^2)$
 182 communication overhead [16, 27].
 183

184 3.1 Evolution of Committee Architectures

185 To mitigate consensus bottlenecks, recent literature has pivoted toward committee-based designs inspired by Algorand’s
 186 sortition [12]. By randomly selecting a constant-size committee to perform consensus, systems effectively decouple
 187 performance from total network size. FLCoin [28] utilized a sliding-window mechanism based on contribution history
 188 to form dynamic committees, achieving up to 90% reduction in communication overhead. Similarly, BFLC [15] adopted
 189 a reputation-based election scheme, prioritizing nodes with high historical quality scores. Recent works such as
 190 FedBlock [20] and RapidChain [35] further explore sharding and adaptive committee selection to optimize efficiency.
 191

192 While optimization successes are evident, these election mechanisms inherently couple system security to committee
 193 composition. If an adversary captures a supermajority (e.g., $> 2/3$) of the committee seats, traditional data-layer defenses
 194 like Krum [3] or Trimmed Mean [34] are entirely bypassed because the compromised committee itself executes these
 195 algorithms.
 196

197 3.2 Limitations of Existing Verification Methods

198 Addressing Byzantine behavior in decentralized aggregation currently relies on three primary verification paradigms:
 199

200 201 *Cryptographic Verification (zkML).* Zero-Knowledge Machine Learning (zkML) provides the strongest security
 202 guarantees by compiling learning computations into arithmetic circuits, allowing verification without re-execution [5],
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[37], [30]. However, zkML faces prohibitive computational bottlenecks [33]. Compiling simple architectures like ResNet-18 generates millions of polynomial constraints, and generating proofs takes minutes. More critically, zkML currently cannot support complex, non-linear Byzantine-robust aggregation algorithms like Krum, which require $O(N^2 \cdot d)$ pairwise distance calculations that cause circuit explosions [9].

Optimistic Execution (opML)... Optimistic Machine Learning (opML) defaults to accepting computations but allows a challenge window during which "AnyTrust" challengers can submit fraud proofs via interactive bisection protocols [7], [23]. While efficient, mainstream opML architectures natively resolving disputes on-chain require challenge periods extending up to a week (e.g., Optimism [22]). These latencies fundamentally conflict with the high-frequency iterative nature of federated learning, rendering opML broadly inapplicable for per-round FL aggregation.

Committee Consensus and Static Blindspots. Committee-based verification remains the most pragmatic solution but is underpinned by static probabilistic assumptions: current security analyses calculate committee capture probability by assuming a fixed adversarial population distribution [15, 28]. This static view completely overlooks the behavior of *rational, strategic adversaries* [6, 19]. As indicated by our analysis of the stake-election-reward cycle, systems like BlockDFL [26] and FedBlock [20] contain positive feedback loops. Strategic attackers can exploit this by behaving honestly ("lurking") to accumulate stake and reputation until they acquire sufficient influence to capture the committee ("starving" honest participants) [6].

3.3 Our Contribution

Our work directly addresses the systemic blindspot in static committee security. We define and analyze the Progressive Committee Capture Attack (PCCA), demonstrating how rational adversaries bypass conventional defenses. In contrast to existing static committee systems, AC-BlockDFL breaks the stake feedback loop through optimistic execution coupled with an asynchronous, stake-slashing auditing layer, securing the system economically while preserving the efficiency benefits of committee architectures.

4 AC-BlockDFL System Design

Traditional Byzantine fault-tolerant (BFT) consensus mechanisms provide robust security guarantees but their $O(N^2)$ communication complexity inherently conflicts with the highly iterative nature of federated learning. As analyzed in Section 5.1, existing committee-based approaches mitigate this overhead but introduce severe structural vulnerabilities: small committees are susceptible to progressive stake accumulation, and their reliance on honest-majority assumptions fails to deter rational, strategic attackers.

To break this deadlock, we introduce Audit-driven Committee BlockDFL (AC-BlockDFL). This framework builds upon the baseline BlockDFL model but fundamentally shifts the paradigm from "threshold security" to "economic security" through asynchronous auditing and internal slashing protocols.

4.1 Design Philosophy

The core design philosophy of AC-BlockDFL stems from re-evaluating the relationship between a blockchain's state finality and the iterative training characteristics of federated learning. Financial transaction systems demand immediate, irrevocable correctness for every transaction because any error could lead to permanent asset loss; this forces traditional blockchains to achieve network-wide consensus *before* any state change. However, federated learning operates through

261 multiple rounds of iterative refinement. A single round's deviation can be naturally corrected by subsequent training
 262 rounds.
 263

264 This observation creates the design space to decouple synchronous execution from correctness verification. AC-
 265 BlockDFL adopts an *optimistic execution* philosophy: it allows the system to immediately commit model updates once the
 266 small committee reaches consensus, while rigorous correctness verification is deferred to a non-blocking, asynchronous
 267 background audit. Security is maintained not by preventing malicious behavior upfront, but by ensuring that any
 268 attempt to manipulate committee consensus faces an economic penalty that exponentially exceeds any potential gain,
 269 thereby eliminating the economic incentive for attacks in a game-theoretic setting.
 270

272 4.2 System Architecture and Workflow

273 AC-BlockDFL preserves the foundational training workflow of BlockDFL—including the localized training by Update
 274 Providers, proposal generation by Aggregators, and Krum-based [3] scoring via PBFT by Validators. However, it
 275 introduces three critical architectural extensions:
 276

- 277 (1) **The Challenger Role:** A fourth participant role subject to open-access principles. Any network node willing
 278 to stake the required deposit can act as a Challenger for a given round. This ensures supervisory power
 279 remains highly decentralized. Challengers continuously monitor on-chain records, independently re-execute
 280 the deterministic Krum algorithm, and compare their results against the committee's committed global update.
 281
- 282 (2) **Off-chain Storage Integration:** To prevent ledger bloat, AC-BlockDFL offloads the heavy model gradients to
 283 the InterPlanetary File System (IPFS), recording only Content Identifiers (CIDs) and metadata on-chain. This
 284 reduces on-chain storage complexity from $O(\text{ModelSize})$ to $O(\text{HashSize})$. To ensure data availability during
 285 audits, nodes pin the relevant IPFS data for the duration of a defined Challenge Window.
 286
- 287 (3) **Execute-then-Audit Paradigm:** Unlike BlockDFL where committee decisions are final without recourse,
 288 AC-BlockDFL commits the model immediately but simultaneously opens an asynchronous audit window. This
 289 retains high liveness while preserving the ability to trigger a network-wide arbitration if anomalies are detected,
 290 effectively democratizing oversight to the entire network.
 291

292
 293 *Instant Update Protocol.* Algorithm 1 formalizes the protocol's "happy path." During Phase 1, role assignment is
 294 deterministically computed by all nodes based on stake-weighted randomness derived from the previous block hash.
 295 In Phase 2, aggregators upload aggregated proposals to IPFS and submit the resulting CIDs on-chain. In Phase 3, the
 296 Validator committee retrieves these proposals, executes Krum scoring, and votes via PBFT. The winning model w_{r+1}
 297 is committed *immediately* upon achieving $> 2/3$ committee agreement. Finally, Phase 4 initiates the asynchronous
 298 challenge window.
 299

303 4.3 Asynchronous Audit and Challenge Mechanism

304 The asynchronous audit mechanism entirely decouples synchronous verification from execution. By shifting the strict
 305 correctness validation into a non-blocking background process, the system achieves maximum throughput without
 306 sacrificing long-term security.
 307

308
 309 *Challenge Trigger Logic.* Algorithm 2 details the challenge execution flow. The trigger logic relies heavily on the
 310 profound decoupling of determinism and data transparency. Because Krum is strictly deterministic, a challenger locally
 311

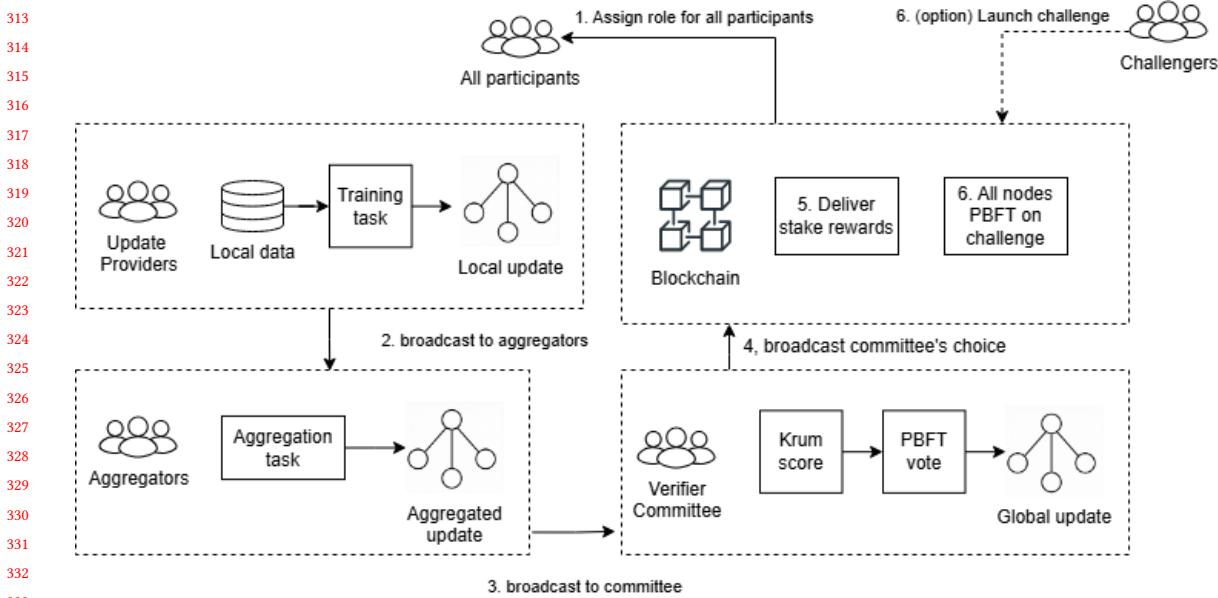


Fig. 1. AC-BlockDFL System Architecture and Workflow. The committee performs optimistic execution while the Challenger network performs asynchronous auditing.

Algorithm 1 AC-BlockDFL Execution Protocol (Instant Update)

Require: Round r , Total Stake Weighted Nodes \mathcal{N}

Ensure: Updated Global Model w_{r+1}

- 1: **Phase 1 – Role Assignment:** Select $\mathcal{V}, \mathcal{A}, \mathcal{U} \subset \mathcal{N}$ via stake-weighted randomness.
 - 2: **Phase 2 – Training & Off-chain Storage:** Each $u \in \mathcal{U}$ trains on local data; $a \in \mathcal{A}$ aggregates into proposal p_a .
 - 3: Upload p_a to IPFS → obtain CID $_a$; submit CID $_a$ on-chain.
 - 4: **Phase 3 – On-chain Consensus & Instant Update:** \mathcal{V} retrieves $\{p_a\}$ via CIDs, verifies data availability, and runs Krum.
 - 5: Vote via PBFT. **Commit** w_{r+1} immediately upon majority.
 - 6: Record winning CID* and voter identities on-chain. Dispense round rewards.
 - 7: **Phase 4 – Audit Window Opens:** Asynchronous challenge period begins. Nodes pin IPFS data.
-

executing the algorithm on identical IPFS inputs will inevitably produce the objectively correct output. Any deviation by the committee is thus easily recognizable.

When a challenger detects a discrepancy, they submit a challenge transaction enclosed with a deposit $D_{challenge}$. This deposit serves two critical purposes: (1) it acts as a defensive barrier against Denial-of-Service attacks, preventing malicious actors from spamming invalid challenges and exhausting network resources; and (2) it guarantees compensation for the computational and data-transfer overhead incurred by the entire network during the arbitration process, thereby solving the classic decentralized oversight motivation gap. Once triggered, the entire network downloads the proposals and executes Krum. If $> 2/3$ confirm the misbehavior, colluding committee members suffer complete stake slashing.

Algorithm 2 Asynchronous Challenge Mechanism

Require: Challenger ch , on-chain CID references, IPFS store
Ensure: Punishment for malicious committee actions

- 1: ch retrieves proposal CIDs from chain, downloads $\{p_a\}$ from IPFS.
- 2: ch re-executes Krum on $\{p_a\}$.
- 3: **if** outcome mismatches committed w_{r+1} **then**
- 4: ch posts challenge transaction with deposit $D_{\text{challenge}}$.
- 5: **Arbitration Triggered:** All consensus nodes verify independently.
- 6: **if** malicious consensus confirmed by $> 2/3$ of network **then**
- 7: **Slash** full stake of colluding validators \mathcal{V}_{mal} .
- 8: Reward Challenger ch ; distribute remainder to honest participants.
- 9: // Note: Model w_{r+1} is NOT reverted.
- 10: **else**
- 11: Forfeit ch 's deposit $D_{\text{challenge}}$.

Endogenous Dynamic Staking Model. A decentralized system's core parameters must derive from verifiable internal metrics rather than external oracles, which introduce vulnerabilities (e.g., price manipulation or latency). AC-BlockDFL anchors its penalty pricing exclusively to internal economic activity.

Under the rational game theory assumption, the maximum immediate gain from committee capture is bounded by the round reward R_{round} . To build an impenetrable economic deterrent, the slashing penalty D_{slash} must dynamically shadow R_{round} :

$$D_{\text{slash}} = \lambda \times R_{\text{round}}, \quad \lambda \gg 1 \quad (1)$$

By setting $\lambda \approx 100$, a single slashing event perfectly wipes out the equivalent of 100 rounds of honest participation.

Similarly, the challenge deposit $D_{\text{challenge}}$ must simultaneously satisfy economic sustainability and accessibility. If a challenge fails, the forfeited deposit must cover the marginal computational cost ϵ of the N_{arb} nodes participating in arbitration (i.e., $D_{\text{challenge}} \geq N_{\text{arb}} \cdot \epsilon$). Practically, $D_{\text{challenge}}$ can be defined as $\alpha \times R_{\text{round}}$. Since R_{round} scales with network economic scale, the costs dynamically adjust to all market conditions.

State Finality and No-Rollback Policy. When arbitration confirms malicious consensus, AC-BlockDFL executes economic slashing but deliberately *does not* revert the committed model update. Reverting historical states fundamentally contradicts the blockchain principle of immutability and finality, leaving the system highly vulnerable to Long-Range Attacks. In a federated learning context, arbitration latency means that by the time an early round is deemed malicious, tens or hundreds of subsequent blocks may have been appended.

Furthermore, rolling back the global state demands extreme coordination complexity, requiring all distributed nodes to simultaneously revert to a historical snapshot and discard immense amounts of valid computational work. AC-BlockDFL instead embraces a “Forward Correction” strategy: the severe economic penalty liquidates the attacker’s future governance influence, cutting off the attack vector permanently. The minor mathematical deviation introduced by a single anomalous epoch is naturally digested and rectified by the iterative self-healing property of subsequent honest training rounds.

417 4.4 Efficiency and Overhead Analysis

418 By shifting the security paradigm from threshold-based to economic-based, AC-BlockDFL successfully decouples the
 419 stringent relationship between security guarantees and committee size, yielding substantial efficiency dividends across
 420 communication and storage.

421 *Communication Complexity.* In standard BlockDFL deployments, suppressing the attack probability p_{risk} near zero
 422 obligates the system to maintain a large committee. For instance, in a 100-node network with a 30% adversarial fraction,
 423 maintaining $p_{\text{risk}} < 0.01$ mathematically dictates $C \geq 9$. The resulting PBFT communication complexity acts as a rigid,
 424 preventative premium $O(81)$ exacted uniformly across every single round, regardless of whether the network is under
 425 attack.

426 AC-BlockDFL neutralizes this overhead by ensuring that even if the committee is compromised, attackers cannot
 427 profit. Consequently, the mechanism satisfies foundational security constraints with a smaller committee size $C = 7$,
 428 dropping the baseline communication complexity to $O(49)$ —a nearly 40% reduction. The heavy network-wide PBFT
 429 arbitration cost $O(N^2)$ is strictly conditional. In equilibrium, because the penalty mechanism eliminates the exploit
 430 incentive, the objective probability of an attack p approaches 0. The expected communication complexity seamlessly
 431 converges to standard committee levels:

$$432 E[\text{Comm}] = (1 - p) \cdot O(C^2) + p \cdot (O(C^2) + O(N^2)) = O(C^2) + p \cdot O(N^2) \quad (2)$$

433 This establishes a highly efficient “pay-as-you-go” security model rather than a perpetual static penalty.

434 *Storage Overhead.* Recording pristine neural network gradients on an immutable ledger guarantees exponential
 435 bloat. While IPFS cleanly mitigates on-chain storage, AC-BlockDFL uniquely incorporates a strict lifecycle management
 436 and pinning strategy. During the challenge window, validator nodes are mathematically obligated to pin the IPFS
 437 chunks, ensuring data availability for prospective challengers. However, the moment the challenge Time-To-Live (TTL)
 438 window expires uninterrupted, nodes safely unpin the historical epoch’s parameters. This ephemeral storage footprint
 439 ensures the system scales gracefully, slashing permanent on-chain storage mapping from $O(\text{ModelSize})$ completely
 440 down to $O(\text{HashSize})$, preserving systemic decentralization without burdening node operators with unsustainable disk
 441 requirements.

452 5 Threat Model and Security Analysis

453 The security of AC-BlockDFL rests on mitigating sophisticated, economically-driven vulnerabilities while maintaining
 454 committee-scale efficiency. In this section, we formalize the adversary model, define the Progressive Committee Capture
 455 Attack (PCCA), and establish the dual-layer security guarantees and game-theoretic incentive compatibility of our
 456 framework.

457 5.1 Threat Model and Adversary Capabilities

458 Unlike traditional Byzantine fault tolerance research that assumes purely destructive behavior, our threat model
 459 considers a *Rational Adversary* whose primary objective is long-term economic utility maximization and governance
 460 control. This aligns with realistic blockchain incentive structures.

461 *Capabilities.* The adversary controls a fraction of the network nodes, denoted by f , where typically $f \leq 0.3$. These
 462 malicious nodes are not isolated; they can collude, coordinate voting strategies, and share information. Crucially, the

adversary is highly strategic: malicious nodes can perfectly emulate honest behavior to build reputation and accumulate resources during early stages, instantly switching to malicious actions when an advantageous opportunity arises. Furthermore, the adversary has full visibility into the public blockchain state, including stake distributions and historical committee components.

Limitations. The adversary is constrained by standard cryptographic assumptions (e.g., unforgeable digital signatures, collision-resistant hash functions) and cannot tamper with immutable historical records on the blockchain. Furthermore, the adversary cannot command an absolute network majority (e.g., > 50%) due to the prohibitively high capital costs. Finally, their actions are governed by economic rationality; they will not execute attacks where the expected financial penalty strictly outweighs the potential gains.

5.2 Progressive Committee Capture Attack (PCCA)

Current BlockDFL defenses overwhelmingly focus on data-plane attacks (e.g., data poisoning), relying on robust aggregation algorithms like Krum [3] or Trimmed Mean [34]. However, these algorithms implicitly assume that the validators executing them are honest. We formalize the *Progressive Committee Capture Attack (PCCA)*, a consensus-plane vulnerability that exploits the positive feedback loop of stake-based committee selections: “Stake → Election → Reward → Stake”. By subverting the committee, PCCA enables attackers to entirely bypass data-plane defenses. The attack unfolds in two distinct phases:

Phase 1: Lurking (Shadow Mode). Because committee selection relies on stake-weighted random sampling, gaining a majority requires significant capital or chance. In this phase, the adversary strictly adheres to protocol rules—submitting high-quality model updates and verifying proposals honestly. This patience allows the adversary to accumulate baseline stake and evade anomaly detection. The adversary waits for a serendipitous election window where malicious nodes coincidentally obtain a supermajority (e.g., > 2/3) of the seats in a single committee.

Phase 2: Occupying (Capture Mode). Upon securing a committee supermajority, the adversary drops the honest facade. The specific execution depends on the alignment of the current round’s aggregator:

- **Strategic Starvation:** If the aggregator is honest, the malicious committee executes a denial-of-service by systematically voting against valid, high-quality proposals. Consequently, honest aggregators and data providers are denied their block rewards. This starvation stunts the stake growth of honest participants, mathematically guaranteeing that the adversary captures a disproportionately larger share of the systemic inflation. Over successive rounds, this inflates the adversary’s probability of being selected for future committees.
- **Full Stack Poisoning:** If the aggregator is also controlled by the adversary, they achieve “full-stack control.” The malicious aggregator deliberately accepts poisoned model updates (e.g., backdoor triggers or flipped labels), and the malicious committee force-approves the proposal. This directly degrades the global model’s accuracy while monopolizing the round’s rewards.

Through PCCA, the adversary’s relative stake advantage over honest nodes dynamically shifts, converging to a steady-state advantage $\lim_{t \rightarrow \infty} \frac{S_{mal}(t)}{S_{hon}(t)} = \alpha \cdot \frac{S_{mal}(0)}{S_{hon}(0)}$ (where $\alpha > 1$ represents the reward control factor). This locks the system into a permanent governance imbalance, transforming a decentralized network into an oligarchy.

521 **5.3 Security Guarantees**

522 Our security model comprises two layers with distinct trust assumptions designed specifically to break the PCCA
 523 feedback loop: a *detection layer* requiring only a single honest challenger, and an *arbitration layer* leveraging standard
 524 Byzantine fault tolerance.

525 *Detection Layer: 1-of-N Honest Assumption.* The detection layer operates under an exceptionally weak assumption:
 526 among all N network participants, at least one honest node is willing to act as a challenger. This is substantially weaker
 527 than the $2/3$ honest majority required by traditional BFT systems, as it requires only the *existence* of a single honest
 528 participant rather than coordinated action by a majority. The feasibility of this assumption stems from blockchain's
 529 transparency—all proposal CIDs are recorded on-chain with corresponding data publicly accessible via IPFS, enabling
 530 any node to independently verify committee decisions.

531 **THEOREM 5.1 (DETECTION COMPLETENESS).** *Let V_r denote the verification committee for round r , $\text{Krum}(\{p_a\})$ be
 532 the deterministic correct result of executing Krum over all aggregation proposals, and w_{r+1} be the global update actually
 533 committed by the committee. If $w_{r+1} \neq \text{Krum}(\{p_a\})$ and there exists at least one honest node c^* among all N participants
 534 willing to act as challenger, then this deviation is necessarily detected.*

535 **PROOF.** The proof relies on Krum's determinism and the public verifiability of on-chain data. Given identical inputs
 536 $\{p_a\}$, any executor obtains the unique output $\text{Krum}(\{p_a\})$ regardless of identity or location. Since all proposal CIDs are
 537 recorded on-chain during committee consensus and corresponding data is accessible via IPFS, the honest challenger c^*
 538 can: (1) retrieve the identical input set $\{p_a\}$ from IPFS, (2) independently execute Krum locally to obtain $\text{Krum}(\{p_a\})$,
 539 and (3) compare against the committed w_{r+1} . Any discrepancy constitutes verifiable proof of deviation, enabling c^* to
 540 submit a valid challenge transaction. Since verification depends solely on publicly accessible on-chain CIDs, IPFS data,
 541 and deterministic computation, the committee cannot evade detection through information hiding or ambiguity. \square

542 *Arbitration Layer: Global 2/3 Honest Assumption.* When a challenge is initiated, adjudication authority transfers from
 543 the committee to the entire network under standard BFT assumptions: honest nodes must exceed $2/3$ of total nodes, i.e.,
 544 $N_{\text{total}} > 3f$ where f is the number of Byzantine nodes. During arbitration, all validators download relevant proposals
 545 via IPFS, re-execute Krum, and vote on challenge validity through PBFT consensus.

546 **THEOREM 5.2 (PUNISHMENT CERTAINTY).** *Let N_{total} be the total network nodes with Byzantine count f satisfying
 547 $N_{\text{total}} > 3f$. If a challenger successfully detects committee misbehavior per Theorem 5.1 and submits a valid challenge
 548 transaction, then the misbehavior is necessarily confirmed during arbitration, and all colluding committee members suffer
 549 complete stake slashing.*

550 **PROOF.** Upon challenge submission, the smart contract retrieves all proposal CIDs for the disputed round and
 551 triggers network-wide re-verification. By Krum's determinism, all honest validators compute identical correct results
 552 $\text{Krum}(\{p_a\})$ and can determine whether w_{r+1} deviates. Under $N_{\text{total}} > 3f$, at least $N_{\text{total}} - f > 2N_{\text{total}}/3$ honest nodes
 553 participate in arbitration voting. These honest nodes, based on identical deterministic computation, unanimously vote
 554 to confirm the deviation. Since PBFT requires $> 2/3$ agreement and honest nodes exceed this threshold, arbitration
 555 consensus necessarily succeeds. The smart contract then automatically executes predefined slashing logic, confiscating
 556 the full stake of all committee members who endorsed the deviant result. This execution is guaranteed by smart contract
 557 determinism and immune to external interference. \square

573 Theorems 5.1 and 5.2 jointly establish the complete security logic: the former ensures misbehavior is *necessarily discovered*, the latter ensures discovered misbehavior is *necessarily punished*. This dual certainty forms the logical foundation for economic security.
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577 5.4 Cost of Attack

578 We now formalize the capital threshold an attacker must surpass to execute a profitable attack while evading punishment.
579 Two distinct barriers must be overcome: (1) probabilistically winning $> 2/3$ committee seats via random election, and
580 (2) deterministically controlling $\geq 1/3$ of network voting power to block arbitration.
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583 **THEOREM 5.3 (ATTACK COST LOWER BOUND).** *In AC-BLOCKDFL, an attacker seeking to execute a malicious committee decision while completely evading economic punishment must control stake capital satisfying:*

$$\text{Cost}_{\text{total}} \geq \frac{1}{3} N \cdot \bar{s} \quad (3)$$

584 where N is the total network size and \bar{s} is the average stake per node. Even with this capital, the attacker must still
585 probabilistically obtain $> 2/3$ committee seats through random election.
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587 **PROOF.** Achieving “successful attack without punishment” requires overcoming two security layers. At the committee level, the attacker must obtain $> 2/3$ validator seats in the target round’s random election—a probabilistic event determined by stake proportion that cannot be made certain. At the network level, per Theorem 5.2, once a challenge is initiated and verified, all malicious stakes are fully slashed. To evade punishment, the attacker must control $\geq [N/3]$ of network voting power to break arbitration liveness by preventing PBFT consensus. This deterministic capital threshold scales linearly with network size as $O(N)$. Since punishment evasion is a logical prerequisite for profitable attack, the total attack cost lower bound is $\frac{1}{3}N \cdot \bar{s}$. \square
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592 This theorem reveals a fundamental security amplification: AC-BLOCKDFL’s asynchronous audit mechanism elevates the economic barrier from committee-scale $O(C)$ to network-scale $O(N)$. In traditional BlockDFL without post-hoc accountability, attack cost depends solely on controlling a small committee. AC-BLOCKDFL forces attackers to first solve the problem of countering a $2/3$ honest network majority before mounting any concrete attack. Given typical deployments where $N \gg C$ (e.g., $N = 100$, $C = 7$ in our experiments), this layered defense provides substantial robustness.
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610 5.5 Game-Theoretic Analysis

611 We employ game-theoretic analysis to demonstrate that honest behavior constitutes the unique Nash equilibrium for all rational participants under AC-BLOCKDFL’s economic mechanism.
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615 *Attacker Payoff Model.* For a rational attacker, the decision problem can be modeled as expected payoff computation in a single-shot game. Let G_{attack} denote the maximum single-round gain from controlling the committee, and L_{slash} the stake loss from full slashing. The expected payoff is:
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$$E[\text{Payoff}] = P_{\text{success}} \cdot G_{\text{attack}} - P_{\text{caught}} \cdot L_{\text{slash}} \quad (4)$$

620 where P_{success} is the probability of controlling the committee in a given round, and P_{caught} is the probability of detection and punishment. Note that P_{success} measures election outcomes while P_{caught} measures detection probability—distinct
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Table 1. Attacker payoff matrix under AC-BLOCKDFL

Strategy	Gain	Loss (if detected)
Honest behavior	R_{round} (proportional)	0
Attack (success)	≤ 7.0 units	500 units

events at different layers. The attacker can only mount an attack when winning the election; once attacked, Theorems 5.1–5.2 ensure $P_{\text{caught}} \rightarrow 1$ under our dual-layer assumptions. Thus:

$$E[\text{Payoff}] = P_{\text{success}} \cdot (G_{\text{attack}} - L_{\text{slash}}) \quad (5)$$

Incentive Compatibility Condition. The sufficient condition for incentive compatibility emerges clearly: whenever $L_{\text{slash}} > G_{\text{attack}}$, expected payoff is strictly negative regardless of P_{success} . Under our endogenous staking model, $L_{\text{slash}} = \lambda \times R_{\text{round}}$ while G_{attack} is upper-bounded by $C \times R_{\text{round}}$ (monopolizing all validation rewards). Since $\lambda \gg C$ by design, this condition holds stably independent of token market fluctuations.

Numerical Analysis. Using our experimental parameters: committee size $C = 7$, per-validator reward 1.0 units, initial stake 100 units. Maximum single-round gain $G_{\text{attack}} \leq 7.0$ units. Upon detection, at least 5 colluding members each lose their full 100-unit stake, yielding $L_{\text{slash}} = 500$ units—approximately 71× the potential gain.

This extreme risk-reward asymmetry ensures negative expected payoff even under optimistic attacker assumptions. For $E[\text{Payoff}] < 0$, we require $P_{\text{caught}} > G_{\text{attack}}/L_{\text{slash}} \approx 1.4\%$. Our security theorems guarantee $P_{\text{caught}} \rightarrow 1$, far exceeding this minimal threshold.

Nash Equilibrium. Honest behavior constitutes the unique Nash equilibrium: no rational player can improve their payoff by unilaterally deviating to attack. The slashing mechanism breaks the positive feedback loop enabling gradual committee capture attacks [6]—instead of accumulating stake through manipulation, attackers suffer substantial stake reduction, permanently eliminating their governance influence. This equilibrium remains stable across all token market conditions due to the endogenous stake pricing design.

6 Evaluation

We evaluate AC-BlockDFL through systematic experiments designed to validate its defense effectiveness against Progressive Committee Capture Attacks (PCCA). Rather than treating model accuracy as the primary metric, our evaluation focuses on whether the economic security mechanism effectively deters rational adversaries and maintains long-term governance stability. This perspective shift reflects our core design philosophy: when the defense objective transitions from “preventing attacks” to “ensuring attacks are unprofitable,” the evaluation metrics should correspondingly shift from model quality to the adversary’s economic decision space.

Our experiments adopt a worst-case analysis methodology, assuming adversaries attack whenever possible regardless of economic rationality. This design enables a critical inference: if the mechanism ensures every attack is detected and penalized under worst-case conditions, rational adversaries will preemptively conclude that expected returns are negative and abstain from attacking, allowing the system to naturally converge toward stable equilibrium.

Table 2. Experimental Parameters

Parameter	Value
Training rounds	$R = 300$ (baseline) / $R = 2000$ (long-term)
Validator pool size	$N = 100$
Committee size	$C = 7$
Malicious nodes	$M = 30$ (initial stake ratio 30%)
Per-round rewards	Validator: 1.0, Aggregator: 1.0, Provider: 0.05
Slashing rule	Full stake confiscation upon successful challenge

6.1 Experimental Setup

We use the MNIST dataset with a standard CNN (two convolutional layers, two fully connected layers) as our federated learning testbed. Training data is distributed IID across clients—a deliberate choice since our defense operates at the consensus layer rather than the data layer. Committee composition and voting outcomes determine attack success, which are logically independent of underlying data distribution characteristics.

Table 2 summarizes the experimental configuration. The 30% initial malicious stake ratio represents a severe threat scenario approaching the theoretical tolerance limit of most Byzantine fault-tolerant systems. Under hypergeometric distribution analysis (Section 6.2), malicious nodes have approximately 2.4% probability of capturing ≥ 5 of 7 committee seats in any single round. While seemingly modest, this probability accumulates over hundreds to thousands of training rounds, providing ample attack opportunities for rigorous defense validation.

6.2 Committee Security Analysis

The probability of k malicious nodes being selected in a committee of size C from a pool N with M malicious nodes follows the hypergeometric distribution:

$$P(X = k) = \frac{\binom{M}{k} \binom{N-M}{C-k}}{\binom{N}{C}} \quad (6)$$

With $N = 100$, $M = 30$, $C = 7$, the probability of an adversarial takeover ($k \geq 5$) is $\sim 2.41\%$.

6.3 Long-term Governance Equilibrium

The critical question our evaluation addresses is whether short-term penalty effectiveness translates into long-term governance stability where attacks naturally cease. The 2000-round simulation provides definitive evidence.

Figure 2 reveals fundamentally divergent governance trajectories. In BlockDFL, the malicious stake ratio stabilizes around 1.3 after initial fluctuations and persists throughout the experiment. This seemingly modest advantage masks a profound governance crisis: the 1.3× ratio translates to significantly elevated committee election probabilities, sustaining continuous attack capability across 2000 rounds. Without accountability mechanisms, adversaries reinforce their stake advantage through each successful capture, confirming the positive feedback loop predicted in Section 5.2.

AC-BlockDFL exhibits a starkly different pattern. The malicious stake ratio undergoes five distinct step-wise decreases at rounds 15, 136, 695, 815, and 1332, declining from the initial 1.0 to a final 0.37. This terminal value indicates that malicious nodes retain barely one-third the average stake of honest participants—a 1.3/0.37 ≈ 3.5× difference from BlockDFL representing fundamental governance reversal rather than incremental improvement.

Table 3 provides direct causal evidence for the stake trajectories. BlockDFL records 107 committee capture events (averaging one per 19 rounds), none receiving economic sanction. AC-BlockDFL records only 5 attacks, all successfully

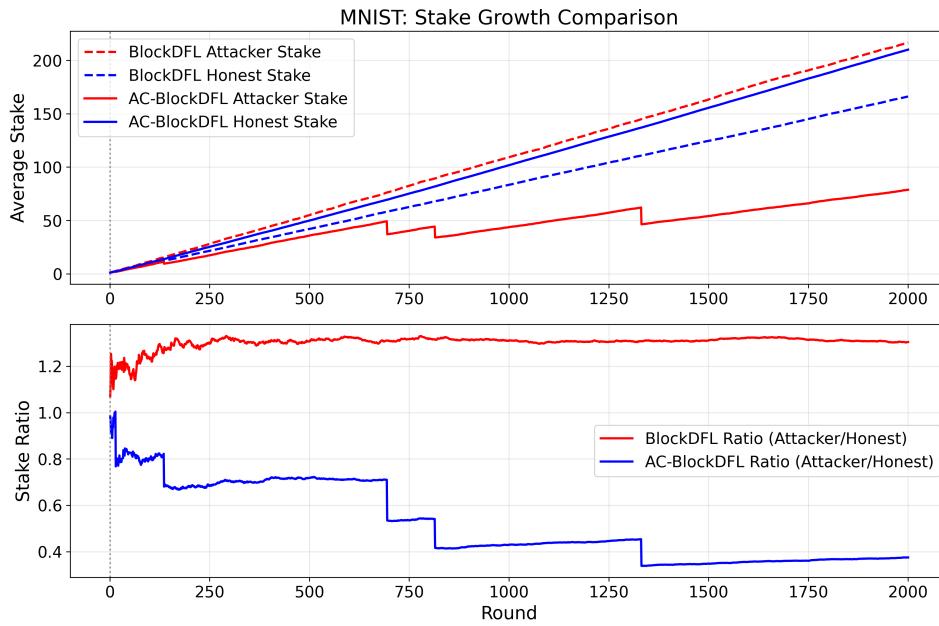


Fig. 2. Stake dynamics over 2000 rounds. BlockDFL exhibits persistent governance imbalance with malicious stake ratio stabilizing at 1.3 \times , while AC-BlockDFL achieves progressive purification through five slashing events, reducing malicious stake to 0.37 \times of honest nodes.

Table 3. Attack Event Statistics (2000-round Simulation)

Metric	BlockDFL	AC-BlockDFL
Total attacks	107	5
Strategic starvation	18	2
Full-stack poisoning	89	3
Detected & slashed	0	5 (100%)
Final stake ratio	1.30	0.37

detected and penalized—a >20 \times reduction stemming from two reinforcing mechanisms: slashing directly depletes the malicious stake base, reducing subsequent committee election probability; simultaneously, diminished stake ratios raise the difficulty of achieving $\geq 5/7$ committee control even when selected.

The increasing intervals between slashing events provide key evidence of convergence toward equilibrium. Specifically: 121 rounds between events 1–2, 559 rounds between 2–3, 120 rounds between 3–4, 517 rounds between 4–5, and 668 rounds of silence following the fifth event through experiment termination. This pattern is not statistical noise but a mathematical consequence of stake depletion: as malicious stake fraction decreases from 30% toward 20%, the single-round probability of achieving committee control drops from ~2.4% to <0.5%, directly manifesting as attack window rarefaction. The 668-round silent period following the final slashing confirms the system has converged to a state where attacks become structurally improbable.

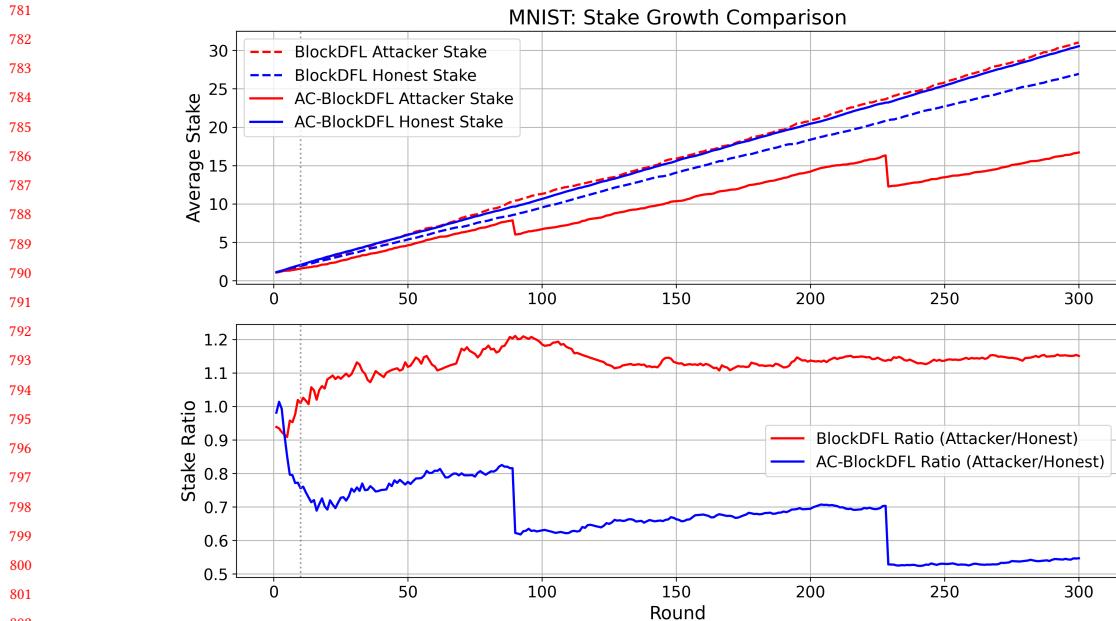


Fig. 3. Stake evolution comparison (300-round baseline). AC-BlockDFL demonstrates immediate stake ratio drops upon each slashing event, while BlockDFL shows continuous malicious stake accumulation.

6.4 Immediate Mechanism Response

The 300-round baseline experiment provides a controlled window for examining the immediate impact of individual slashing events on governance structure.

Figure 3 shows the early-stage stake trajectories. In BlockDFL, 10 committee capture events occur over 300 rounds (4 strategic starvation, 6 full-stack poisoning), all unpunished, enabling the malicious stake ratio to climb steadily from 1.0 toward 1.15. AC-BlockDFL records only 2 attacks at rounds 90 and 229, both detected and slashed with 100% accuracy.

The first slashing event illustrates the mechanism’s precision. By round 90, malicious nodes had accumulated a 1.25 stake ratio through honest participation, translating to elevated committee selection probability. When 5 malicious nodes achieved committee control and executed full-stack poisoning, a challenger detected the deviation by locally re-executing Krum aggregation and submitted a challenge transaction. Upon arbitration confirmation, the smart contract automatically confiscated the full stakes of all 5 colluding members. The economic impact was immediate and severe: the malicious stake ratio plummeted from 1.25 to 0.62—a single event reversing the adversary’s 25% lead into a 38% deficit.

This magnitude of impact warrants careful interpretation. The slashed nodes lost not merely the current round’s potential gains (bounded by ~7.0 reward units) but their entire accumulated stake from 89 rounds of honest participation. More critically, stake-zeroed nodes are effectively excluded from future high-reward role elections, constituting “permanent governance exclusion” that degrades long-term attack capability beyond the immediate economic penalty.

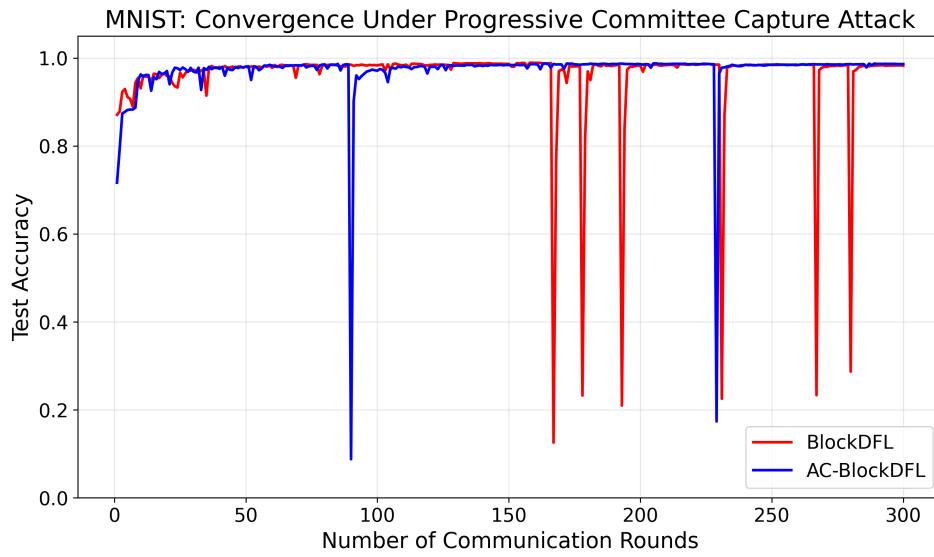


Fig. 4. Model accuracy convergence comparison. AC-BlockDFL exhibits smoother training dynamics with fewer disruption-recovery cycles.

The second slashing at round 229 reduced the stake ratio from 0.70 to 0.52. The 139-round interval between attacks (versus BlockDFL’s average of 30 rounds) directly reflects the first slashing’s suppressive effect on attack opportunity windows.

6.5 Service Quality Under Security Guarantees

A critical concern is whether security guarantees impose unacceptable performance costs. We evaluate both system availability and model convergence quality.

System Availability. We define minimum unavailability rate as the fraction of rounds where model performance is significantly degraded due to full-stack poisoning attacks. Each attack requires approximately 5–25 rounds for federated learning’s self-healing mechanism to restore accuracy. Using the conservative 5-round estimate, BlockDFL’s 89 full-stack attacks yield a minimum unavailability rate of $89 \times 5/2000 = 22.3\%$. AC-BlockDFL achieves $3 \times 5/2000 = 0.75\%$ —a >96% improvement attributable entirely to attack frequency suppression rather than enhanced per-attack resilience.

Model Convergence. Figure 4 compares accuracy trajectories over 300 rounds. BlockDFL exhibits pronounced sawtooth patterns corresponding to its 6 full-stack poisoning events, with each attack causing sharp accuracy drops followed by multi-round recovery periods. AC-BlockDFL’s curve is notably smoother, experiencing only 2 disruptions. Despite one severe attack at round 90 dropping accuracy to 9.5% (near random-guess baseline for MNIST’s 10-class task), the system recovered within ~20 rounds. Final accuracies are comparable (98.26% vs. 98.63%), confirming that the “no-rollback” design philosophy (Section 4.3) is practically sound: federated learning’s iterative nature provides inherent self-healing capability, obviating the coordination overhead of state rollback mechanisms.

Table 4. Communication Complexity Comparison

Scheme	Complexity	Overhead (MB/round)
Full BFT	$O(N^2)$	25.4
BlockDFL	$O(C^2)$	4.2
AC-BlockDFL	$O(pN^2 + C^2)$	4.3

Communication Efficiency. As analyzed in Section 6.5 and summarized in Table 4, AC-BlockDFL achieves $O(C^2)$ communication complexity under equilibrium conditions where the challenge trigger probability $p \rightarrow 0$. Compared to approaches requiring equivalent security guarantees through full replication, this represents approximately 40% reduction in per-round communication overhead while maintaining the same Byzantine tolerance threshold.

6.6 Summary

Our evaluation validates AC-BlockDFL’s defense effectiveness through three complementary lenses. At the micro level, each malicious committee decision triggers immediate detection and slashing with 100% accuracy. At the macro level, five slashing events progressively reduce the malicious stake ratio from 1.0 to 0.37, with increasing inter-event intervals and a terminal 668-round silent period confirming convergence to attack-free equilibrium. Service quality analysis demonstrates that these security guarantees impose minimal performance cost: unavailability rate drops from 22.3% to 0.75%, while model convergence remains uncompromised. These results complete the inference chain: worst-case testing proves all attacks are detected; rational adversaries therefore anticipate penalties and abstain; the system operates at designed efficiency under the resulting equilibrium.

7 Conclusion

This paper identifies and formalizes the Progressive Committee Capture Attack (PCCA), demonstrating how rational adversaries can systematically compromise committee-based blockchain federated learning systems through strategic stake accumulation. Our long-horizon simulations confirm that conventional committee architectures exhibit stake ossification and governance capture under sustained attack.

To address this threat, we propose AC-BlockDFL, an audit-driven committee architecture that decouples security guarantees from committee size. The key insight underlying our design is a paradigm shift from *threshold security*—which seeks to minimize the probability of committee compromise—to *economic security*—which ensures that even successful compromise yields negative expected utility for rational adversaries. Through asynchronous auditing and the internal slashing protocol, AC-BlockDFL achieves progressive purification of malicious participants while maintaining the efficiency benefits of small committees.

Our experimental results validate three principal contributions: (1) formal threat modeling of PCCA with empirical verification of its feasibility; (2) demonstration that slashing mechanisms effectively break the positive feedback loop of malicious stake accumulation, internalizing the externalities of adversarial behavior; and (3) evidence that shifting from preventive to reactive security breaks the tight coupling between security guarantees and communication overhead, enabling practical deployment in resource-constrained edge computing scenarios.

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