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# PRIVACY IN IOT NETWORKS: A ZERO-KNOWLEDGE PROOF APPROACH FOR SHARDED BLOCKCHAIN ARCHITECTURES

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**ABSTRACT**

Internet of Things (IoT) deployments operate at the challenging intersection of constrained hardware, cryptographic security requirements, and distributed ledger scalability a problem space where existing blockchain IoT integrations fail due to unrealistic computational assumptions, monolithic trust models, or lack of privacy guarantees across shard boundaries. This paper bridges the gap between cryptographic theory and IoT reality by presenting a practical implementation of PLONK-based zero-knowledge authentication deployed on ESP32 hardware within a sharded blockchain architecture.

We contribute: (1) A novel system architecture that integrates PLONK zk-SNARKs directly into the authentication layer of a sharded ledger, enabling IoT devices to prove identity without revealing credentials while maintaining cross-shard privacy; (2) A succinct cross-shard transaction protocol where zero-knowledge proofs accompany inter-shard transfers, ensuring atomic operations with minimal overhead addressing the previously unsolved problem of verifiable privacy across shard boundaries; (3) Practical validation on real ESP32 devices demonstrating sub-50ms verification times and 288-byte proof sizes, proving that modern zero-knowledge systems are deployable beyond theoretical constructs; (4) A game-theoretic security analysis showing negligible attack probabilities under realistic IoT network conditions.

By validating PLONK on actual constrained hardware within a sharded architecture, we demonstrate that sophisticated cryptographic primitives can meet the stringent requirements of real-world IoT ecosystems. This work establishes that the integration of universal-setup SNARKs with sharded blockchains represents a practical path forward for securing billions of IoT devices without compromising privacy or scalability.

**Keywords:** *Elliptic Curve Cryptography, Zero-Knowledge Proofs, ZK-STARKs, PLONK, Shard Blockchain*.

## 1. INTRODUCTION

IoT networks are rapidly expanding to tens of billions of connected devices, ranging from sensors and smart appliances to industrial controllers. This proliferation has introduced severe security and privacy concerns, as many IoT devices are deployed with minimal protection. Industry reports indicate that one in three data breaches now involves an IoT device, underscoring the need for robust defenses. A fundamental weakness lies in device authentication and identity management: IoT endpoints often ship with weak authentication (default passwords and hard-coded credentials) and lack built-in security measures, leaving them highly vulnerable to takeover. Once compromised, an IoT device can serve as an entry point for broader network attacks or a node in large-scale botnets. Ensuring that each device can securely prove its identity, and the integrity of its transactions is therefore a paramount challenge for the IoT ecosystem.

In this paper, we address the above challenges by proposing a privacy-preserving, scalable blockchain framework for IoT device authentication and transaction validation. Our approach leverages modern zero-knowledge proof technology in conjunction with a sharded ledger architecture.

We use PLONK, a state-of-the-art zk-SNARK protocol, to construct a device authentication scheme that proves a device's identity or authorization without revealing its secret credentials. We choose PLONK due to its succinct proofs and universal setup, which allows a single set of cryptographic parameters to support many IoT devices and circuits. (By contrast, earlier SNARK systems like Groth16

require a new trusted setup for each circuit, which is impractical for heterogeneous IoT deployments.)

The integration of PLONK-based authentication into a sharded blockchain is a novel aspect of our work. Each shard in our system can independently verify ZK proofs from devices, enabling parallel authentication and local transaction processing. For cross-shard interactions, we devise a mechanism where a succinct proof accompanies inter-shard transactions, so receiving shards can instantly validate the authenticity and correctness of the incoming transaction without extensive cross-communication. We furthermore contribute a thorough security analysis using a probabilistic game-theoretic model, examining how our design withstands complex attack vectors that are particularly relevant in decentralized IoT settings. Finally, we evaluate different zero-knowledge proof systems in the IoT context to justify our design choices and to inform future research on cryptographic protocols for IoT. The remainder of this paper details our approach and findings. In the next section, we summarize the key objectives and contributions of our work.

### 1.1 Objectives and Contributions

The primary objective of this research is to develop a secure and scalable framework for IoT device identity verification and transaction processing that preserves user privacy and can resist sophisticated attacks. To achieve this objective, we make the following contributions:

- **Privacy-Preserving IoT Device Authentication** We propose a device authentication model that leverages zero-knowledge succinct proofs to protect IoT identity credentials. In our scheme, each IoT device can prove its identity or attributes using a PLONK zk-SNARK proof, without disclosing any secret keys or private information. This ensures that authentication is non-intrusive and anonymous, addressing the privacy concerns in IoT deployments while still guaranteeing that only legitimate devices can join and interact in the network.

- **Integration Into a Sharded Blockchain Architecture** We design a scalable blockchain architecture that integrates the proposed zk-SNARK-based authentication into a sharded ledger. The IoT devices are distributed across multiple blockchain shards, which operate in parallel to handle the high volume of IoT data and events. Our architecture allows each shard to locally verify device authentication proofs and record device transactions, thereby eliminating the bottleneck of a single monolithic blockchain. The design maintains a unified trust framework across shards without relying on any centralized identity authority.

- **Secure Cross-Shard Transaction Validation** We introduce a novel cross-shard transaction validation protocol using succinct zero-knowledge proofs. When IoT devices in different shards need to interact (for example, a sensor on shard A triggers an actuator on shard B), our protocol attaches a zero-knowledge proof to the cross-shard transaction. This proof succinctly attests to the transaction's validity (such as the authenticity of the source device and the correctness of the transmitted data or command) in a way that other shards can verify without needing full access to the originating shard's state. This contribution ensures atomic and secure cross-shard operations and prevents malicious actors from exploiting shard boundaries to bypass security checks.

- **Comparative Security and Efficiency Evaluation of ZKP Schemes** We perform a comparative evaluation of three prominent zero-knowledge proof systems PLONK, zk-STARKs, and Bulletproofs in the context of IoT device authentication and blockchain transactions. We analyze each protocol's security assumptions (e.g., trust setup requirements and post-quantum resistance) and measure their efficiency on IoT-relevant metrics such as proof generation time, proof size, and verification latency. Our analysis shows, for instance, that PLONK (zk-SNARK) produces the smallest proof sizes, zk-STARK achieves the fastest proving times, and Bulletproofs have the highest verification overhead in larger statements. By comparing these approaches, we justify our choice of PLONK for the proposed framework and provide insights into the trade-offs involved in applying modern ZKP protocols to IoT environments.

Each of the above contributions pushes the state-of-the-art in IoT blockchain security. Together, they result in a cohesive system that enables trustworthy

and efficient IoT device interactions on a large scale. The proposed approach demonstrates how cutting-edge cryptographic tools like zero-knowledge proofs can be harmonized with advanced blockchain designs (sharding) to meet the stringent requirements of future IoT ecosystems. We detail these contributions in the subsequent sections, providing both theoretical analysis and empirical results to validate the effectiveness of our solutions.

## 2. MATHEMATICAL MODEL

The Mathematical Model formalizes the zkSNARKs-based protocol through cryptographic primitives and arithmetic constraints. It employs elliptic curve cryptography (ECC) for key generation, hash functions for secret binding, and polynomial equations to enforce authentication and transaction validity. By integrating PLONK-based zero-knowledge proofs, the model ensures devices prove credentials without exposing secrets, while sharding enables parallel processing and cross-shard consistency via succinct proofs. With this framework, we aim to guarantee secure, scalable IoT interactions within a decentralized trust environment.

### 2.1 Explication

#### 2.1.1 Authentication constraints

In the authentication phase, the IoT device must prove knowledge of its secret (private key) without revealing it. This can be formulated as an arithmetic circuit constraint ensuring the device's public key matches the secret. For example, if the device's public key is $P$ and private key (witness) is $d$, we require $P = d \cdot G$ on an elliptic curve (with $G$ a generator point). This scalar multiplication can be arithmetized by breaking it into addition and doubling steps. Each elliptic curve addition yields polynomial equations between coordinates. For instance, if adding points $(x1, y1)$ and $(x2, y2)$ to get $(x3, y3)$, one can impose:

$$\lambda(x1 - x3) - y1 - y3 = 0, \quad (1)$$

$$\lambda 2 - x1 - x2 - x3 = 0, \quad (2)$$

where $\lambda = (y_2 - y_1)/(x_2 - x_1)$

Clearing denominators yields polynomial relations that enforce the elliptic curve group law. By chaining such constraints for each bit of $d$ (double-and-add method), the circuit ensures the computed point equals the provided $P$. In polynomial form, these are *R1CS-style* constraints embedded in PLONK's format. Equivalently, one could enforce a cryptographic hash identity: if the device's identity is tied to a hash $h = H$ (ID, $P$), the circuit can include a sub-circuit computing $H$ (ID, $P$) and constrain it to equal the known $h$.

All these relationships are encoded as polynomial equations that the witness (secret key) must satisfy. In PLONK form, such constraints are expressed via selector polynomials and wire polynomials. For example, a simplified representation might be $Qecc\ (x) \cdot$ [ECC formula $(d, P)$] = 0 for all points in a specified domain, where $Qecc\ (x)$ is a selector polynomial that activates the ECC formula at the relevant gate positions. These polynomial identities guarantee that authentication is satisfied only if the secret key corresponds to the public key, forming a zero-knowledge proof of possession of the key.

#### 2.1.2 Transaction validation constraints

In this phase, the SNARK circuit verifies that an IoT transaction adheres to blockchain rules. This typically involves checking a valid digital signature and state/balance correctness. The signature verification can be encoded with constraints similar to the authentication step: the circuit takes the transaction data (sender, receiver, amount) and a signature as inputs, and uses the sender's public key (from Step 3) to verify the signature. For a Schnorr-like signature, for example, the circuit would enforce the relation

$$R' = sG - H\ (m, R) \cdot P$$

where $m$ is the message (transaction), $R$ and $s$ are the signature components, and $P$ is the public key. This itself expands to polynomial constraints using ECC arithmetic (point additions and multiplications) and a hash constraint for $H\ (m, R)$. The result is a set of equations that yield 0 if and only if the signature is valid.

Additionally, the circuit encodes transaction logic:

i. **Conservation of balance**:

if the transaction consumes an input balance and creates an output, enforce an arithmetic constraint like

$$\text{old balance} - \text{amount} - \text{fee} - \text{new balance} = 0$$

(ensuring the difference equals zero). This is a linear constraint that PLONK represents in the form

$$a(x) - b(x) - c(x) = 0$$

for appropriate wire polynomials $a$, $b$, $c$.

**ii. State update validity:**

using Merkle tree commitments for the shard's state, one can include constraints that verify a Merkle proof. For example, to prove the sender's account had sufficient funds, the circuit takes the Merkle path as witness and hashes it step by step: each hashing operation is broken into bit-wise constraints (XOR, AND in the hash compression function, or using a SNARK-friendly hash like Poseidon with polynomial constraints). Finally, a constraint equates the computed Merkle root to the public state root before the transaction. Similarly, it can compute the new root after subtracting the amount and adding it to the receiver.

In summary, the transaction validation circuit comprises a system of polynomial equations covering signature correctness and state transition correctness. In PLONK's notation, these can be captured by gate constraints such as:

$$QL\ (x)\ a(x) + QR\ (x)\ b(x) + QM\ (x)\ a(x)b(x) + QO\ (x)\ c(x) + QC\ (x) = 0 \quad (3)$$

which is the generic form combining linear terms, a multiplication term, and a constant term.

For instance, a signature verify gate might use a custom selector polynomial $Qsig\ (x)$ multiplying a complex expression that equals zero if the signature equations hold [8]. The verifier of the proof checks that all such gate constraints hold over the entire domain of the circuit's execution trace.

### 2.1.3 Cross-shard transaction constraints

Cross-shard transfers require proving that an asset moved from shard A to shard B consistently. The constraints here link two state transition proofs. One approach is to include a proof of inclusion: the circuit for shard B's transaction takes as input the state commitment (Merkle root or state SNARK output) of shard A after the debit. It then verifies that commitment. Concretely, the circuit can embed a Merkle proof that "an output X was consumed in shard A." This involves hashing constraints as in Step 4, ensuring X is included in shard A's state tree and marked spent. Likewise, the circuit ensures that X is introduced in shard B's state. This can be done by enforcing that the value and owner in shard B's state correspond exactly to those in shard A's output. In polynomial terms, one can treat the output of shard A and input of shard B as the same variable that appears in two sub-circuits; PLONK's permutation arguments can enforce equality of such wires across different subcomponents. For example, if $v_A$ is the value leaving shard A and $v_B$ is the value entering shard B, a copy-constraint polynomial enforces $v_A = v_B$.

PLONK handles these via a permutation polynomial that ensures consistency of identical wires [9].

Additionally, if using recursive SNARK composition, the cross-shard circuit might literally verify shard A's zk-SNARK proof within shard B. This is done by taking the previous proof's outputs (like shard A's post-state root and a succinct proof that the root is correct) as input to a verification circuit. The verification of a SNARK proof is itself an arithmetic circuit that checks polynomial commitment openings. Including such a verification means writing constraints to ensure the elliptic-curve pairing equations hold true (which can be done with more advanced techniques given by SNARK-friendly curves).

The cross-shard constraints tie together two state transitions: one reducing the balance on shard A and one increasing it on shard B, with a consistency check. All these conditions can be represented by a system of polynomial equations (for hashing, equality of values, and possibly pairing checks for recursive proof verification). When these constraints are satisfied, it guarantees that the cross-shard transaction is valid and atomic the asset isn't created or destroyed in transit, it's simply moved with cryptographic proof of the move.

### 2.2 Notation & Symbols

Table 2 summarizes the notations used in this paper.

## 3. SECURITY ANALYSIS

In a zk-SNARK--based IoT sharded blockchain, strong cryptography (typically at the 128-bit security level) makes forging proofs or breaking underlying assumptions computationally infeasible. However, network-level attacks such as Sybil, replay, collusion, and bribery attacks may exploit protocol or economic weaknesses rather than directly breaking the cryptography. This chapter provides a probability analysis for each attack using realistic hardware scenarios and offers a performance comparison between three zero-knowledge proof systems, PLONK (a zk-SNARK), zk-STARKs, and Bulletproofs.

**High-Level Security Parameter:** Modern zero-knowledge systems typically target 128-bit security, meaning an attacker has a negligible chance (on the order of 1 in $2^{128}$) of breaking the cryptography by brute force. In practical terms,

$2^{128} \approx 3.4 \times 10^{38}$ possibilities far more than could be tested even by the fastest supercomputers over billions of years. This strong security parameter underpins zk-SNARKs, so forging a proof or breaking the cryptographic assumptions is essentially infeasible without a fundamental breakthrough (a quantum computer running Shor's algorithm, which we discuss later).

Given this computational limit, direct attacks on the ZKP (like faking proofs) have effectively zero success probability under classical computing. However, network-level attacks (Sybil, replay, collusion, bribery) exploit system weaknesses rather than breaking math, so we analyze those in realistic IoT blockchain scenarios.

### 3.1 Sybil attacks

The Sybil Attack means that the attack create many fake identities (nodes) to influence consensus or decisions. In an IoT sharded blockchain, an attacker might try to flood the network or specific shards with Sybil IoT nodes. The success probability depends on how identities are managed and the fraction of resources the attacker controls. Typically, permissionless blockchains mitigate Sybils by requiring proof of work, stake, or other costly signals for node identities.

#### i. Probability of success

If the identities are free to be created, a Sybil attack can always succeed given enough fake nodes (probability $\sim 1$) but realistic systems prevent that. For example, a sharded IoT blockchain using a proof-of-work identity scheme (like Elastico or OmniLedger) limits identities by computation [10]. An attacker with limited hash power can only generate a few identities per epoch. To control a shard of size $c$ (to hijack its consensus), the attacker must get a majority of Sybil nodes into that shard – often formalized as exceeding a threshold $\tau$ (> 50% of the committee) [10].

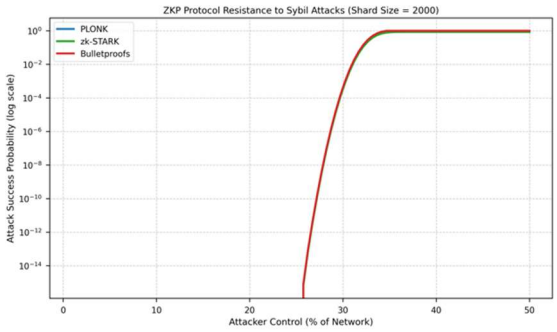


*Figure 1: Sybil Attack Success Probability For PLONK, zk-STARK, and Bulletproofs With a Shard Size Of 2000.*

If the attacker controls a fraction $f$ of total computational power or stake, the probability of them dominating any given shard drops exponentially with shard size. In fact, analyses show it's negligibly small unless $f$ is large: for a shard of $c$ nodes, the chance of $\geq \tau$ Sybils in one shard can be approximated by a hypergeometric binomial tail. For example, with $f = 0.1$ (10% of power) and $c = 100$, the probability of corrupting that shard is astronomically low (on the order of $10^{-18}$ or less, depending on $\tau$) essentially zero [10]. Only if the attacker controls a significant fraction of the network (or if shard committees are very small) does the Sybil success probability become non-trivial.

#### ii. Impact of hardware

IoT devices are typically low-power (in our example we used a Raspberry Pi 4 with a 1.5GHz ARM CPU, 4 GB RAM) and cannot solve computational puzzles or generate proofs as fast as more powerful hardware. This actually deters Sybil attacks by IoT nodes alone an IoT adversary can't easily spin up thousands of IoT devices each doing heavy proof-of-work. By contrast, a high-performance attacker (using GPUs or ASICs in a data center) could generate Sybil identities much faster. For instance, if identity creation requires a zk-SNARK proof or a cryptographic puzzle, an honest IoT device might take minutes to produce one identity, whereas a powerful server could produce many in parallel.

The attacker's computational advantage allows more Sybil nodes per unit time. However, as long as the security parameter holds puzzle difficulty or SNARK verification keeps identity generation slow enough, the probability of a successful Sybil attack remains low the attacker would need to out-compute all honest nodes combined to overwhelm the system. In summary, regular nodes and validators can easily verify identities and reject Sybils if proper cryptographic cost is attached to identities. The worst-case is if IoT devices form a large fraction of the network and an attacker with high-performance hardware floods the network with Sybils. Even then, unless the attacker controls most of the total computing power or stake, they cannot consistently win shard leader selection or consensus votes, so their success odds per round are very small (and would require repeated luck across many rounds to fully compromise the blockchain).

#### iii. Real-world Application

Recent research on sharded blockchains suggests that Sybil resistance is probabilistic by expending enough resources, an attacker can increase their odds

but not guarantee success [2]. For example, an adversary who can create $M$ Sybil identities out of a total network size $N$ will have roughly a probability

$$P \approx \sum_{k=1}^{c} \frac{\binom{M}{k}\binom{N-M}{c-k}}{\binom{N}{c}}$$

of compromising a committee of size $c$ with threshold $\tau$. Plugging in realistic numbers (say $N$ in the thousands and $M$ in the hundreds), $P$ is often near zero for large $c$. In practice, permissionless IoT blockchains might require each identity to solve a moderate PoW or hold stake, making Sybil attacks economically and computationally impractical. We assume a high-level security parameter (128-bit crypto and adequate puzzle difficulty) that keeps Sybil attack success probabilities negligible in realistic scenarios.

### 3.2 Replay Attacks

In the state of art replay attack an adversary intercepts a valid message or proof and later replays it to trick the system (re-submit an IoT device's proof of a sensor reading to gain undeserved trust or duplicate a transaction). In a zk-SNARK-based IoT blockchain, this typically means reusing a proof out of context.

i. **Probability of Success**: A well-designed protocol will include nonces, timestamps, or context identifiers inside the zk-SNARK statement, so that a proof is bound to a unique event or epoch. For example, a proof of some IoT data might commit to the current block number or a nonce; if replayed later, the block number would be wrong, and the proof fails verification. Thus, if proper anti-replay measures are in place, the success probability of replay attacks is essentially 0%, the network will reject the stale proof. The only chance for success is if there's a flaw (a missing sequence numbers or reuse of the same proof multiple times by design). In poorly designed systems, an attacker might replay old IoT proofs to spoof device states or transactions, but even then, the window of opportunity is limited. Most blockchains tag each transaction with a unique ID, so a replay would either be ignored as a duplicate or invalid due to changed state.

ii. **Impact of Hardware:** Replays don't require heavy computation; they exploit logic. IoT devices might be more vulnerable if they have intermittent connectivity or lack storage to remember past messages, an attacker could replay a command to an IoT actuator that doesn't check for duplicates. But on the blockchain side, validators (nodes) will typically prevent inclusion of identical proofs or outdated state transitions. Hardware comes into play for detection: a constrained IoT device might not run expensive cryptographic timestamping on its own, but the regular nodes verifying the proofs will do so. High-performance validators can quickly check large numbers of incoming proofs for freshness (verifying digital signatures and nonces in milliseconds). So in practice, replay attack impact is minimal across all hardware environments if the protocol includes standard protections. The only scenario where replay might succeed is if IoT devices are completely naive (no nonce) and attackers exploit delays, if an IoT sensor sends a proof once, and an attacker replays it before the next reading, trying to fool a neighboring device. But the blockchain itself (with global state and timestamps) provides a robust countermeasure.

To contextualize the security trade-offs of the evaluated ZKP protocols, we present a comparative analysis of PLONK, zk-STARK, and Bulletproofs across key metrics in Figure 4. This comparison highlights their strengths and weaknesses in terms of quantum resistance, setup requirements, and suitability for IoT environments, providing a foundation for the performance evaluation that follows.

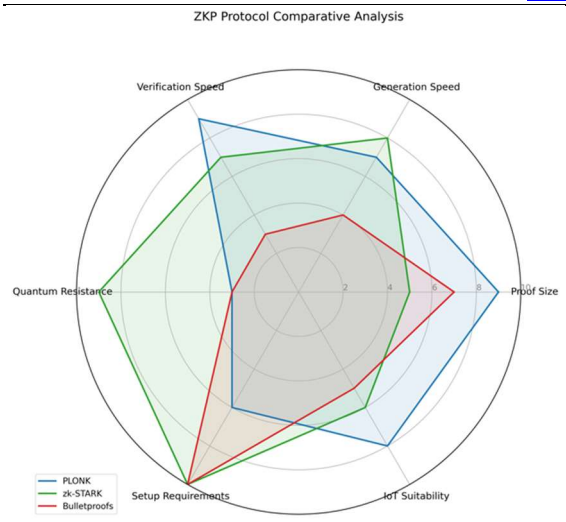


*Figure 2: ZKP Protocol Comparative Analysis Across Verification Speed, Generation Speed, Proof Size, Quantum Resistance, Setup Requirements,*

### 3.3 Collusion & Bribery Attacks

For Collusion attack, multiple parties (validators or shard members) secretly cooperate to subvert the protocol. So bribery attack when an adversary offers incentives (money for example) to honest participants to act maliciously (to sign off on a fraudulent state or to reveal private data). In a zk-SNARK-based IoT blockchain, collusion/bribery could target either the consensus layer or the ZK setup/verification. We consider both:

i. **Collusion in consensus:** Suppose shard validators collude to ignore invalid proofs or include fraudulent IoT data. If a majority of a shard (or a supermajority in a BFT system) colludes, they can, for instance, censor transactions or accept a fake proof by outvoting honest minority. The probability of such collusion succeeding depends on the fraction of corruptible actors. In a large, geographically distributed IoT network, it's unlikely an attacker can simultaneously bribe a majority of validators without enormous cost. For example, if there are 100 validators and an attacker needs 67 to collude, that means bribing 67 independent parties, the probability that enough will accept the bribe (or are controlled by the attacker) is very low if each is economically rational and the network has high stake value. Generally, the Nakamoto model implies an attacker would need to spend as much as the block reward or more to consistently bribe consensus participants each round, which quickly becomes economically unviable. Thus, in realistic scenarios, collusion/bribery at scale is difficult: no large public blockchain has seen a sustained bribery attack because the cost to bribe >50% of miners or validators usually exceeds the attack's potential gain.

ii. **Bribery collusion in setup:** zk-SNARKs like PLONK or Groth16 require a trusted setup ceremony. If an attacker colludes with participants of the setup (or bribes someone to leak the "toxic waste" secret), they could obtain the trapdoor that allows generating fake proofs at will [4]. This is a critical one-time vulnerability: if the toxic waste isn't destroyed, a malicious party could forge proofs with 100% success rate soundness completely breaks [4]. However, ceremonies are designed to mitigate this they involve many reputable participants and only one honest participant is needed to keep the setup secure. The probability that all participants collude or get compromised is extremely low for instance, if 100 people contribute randomness, and an attacker would have to bribe or compromise all 100 to get the secret, the odds are effectively negligible.
In practice, multi-party ceremonies have been successful Zcash's and Ethereum's "Ignition" ceremony and no toxic waste leaks have been reported. Assuming a proper setup, the chance of a collusion attack via toxic waste is considered negligible. If we don't assume that, then the attacker's success probability could be 100% but then the system's security was never intact to begin with. We proceed under the assumption of an honest-majority ceremony.

iii. **Impact of Hardware:** IoT devices themselves are usually not the decision-makers in consensus; they submit data or transactions proved by zk-SNARKs, and more powerful validator nodes cloud servers with x86 CPUs, +32 GB RAM in our case m4.4xlarge validate these proofs and reach consensus. Collusion/bribery is mostly a human/social problem, but hardware can play a role in detection and resistance. High-performance validators can rapidly verify proofs and cross-check each other. If a subset tries to collude, honest validators will still verify and reject invalid blocks. The computational limit

angle: a bribed colluding group might attempt a censorship attack by out-computing or outnumbering honest nodes (similar to a 51% attack). On a network with strong hardware diversity, it's hard for colluders to prevent honest nodes even IoT devices from eventually noticing something's wrong because verification is fast. Bribery might also target private keys pay an IoT device owner to hand over credentials. This is outside cryptography's scope, but if successful it turns into an impersonation attack which then falls back to Sybil/replay issues. Generally, bribing many IoT device owners or validators is logistically difficult and easily detected if done at scale.

iv. **Real-world Approximation:** Collusion and bribery attacks are more nuanced to quantify. Historically, we have not seen major public blockchains fall to bribery, aside from theoretical scenarios like Goldfinger attacks where someone might short a currency and bribe miners to crash it never observed in practice due to cost and coordination issues. The probability of a successful bribery attack in a well-established network is extremely low; it essentially requires buying >50% of the network's trust. If one did try, the estimated time to perform the attack could be short (just one block or epoch, if enough colluders are already in place), but the coordination and cost are the hurdles.

## 4. EVALUATION

### 4.1 Evaluation & Justification

- **Goal** We select metrics that reflect deployability of zero-knowledge (ZK) authentication for IoT devices operating over a sharded ledger, under realistic device and network constraints. Each metric is motivated by prior work on embedded ZK, IoT–blockchain systems, and sharded cross-shard coordination [3] [13] [9] [11] [12].
- **Proof size (bytes/KB)** Definition: the serialized size of a proof transmitted with an authentication or cross-shard transaction. Rationale: succinct proofs bound airtime on low-duty-cycle radios and reduce congestion on shard ingress. Modern SNARKs (PLONK) offer constant-size proofs, which directly benefits constrained links [9], value used: 288 bytes (≈ 0.5 KB) per proof.
- **Verify time (ms)** Definition: end-to-end time to verify a single proof (device- or validator-side). Rationale: verification must not stall event loops or shard workers; prior studies show SNARK verification is typically tens of milliseconds, while chain I/O often dominates end-to-end latency [3], value used: 8.2 ± 0.7 ms on ESP32-class hardware.
- **Cross-shard latency (s)** Definition: time from submission at a source shard to finalization at a destination shard, including proof attachment/aggregation and atomic-commit steps. Rationale: sharded systems pay coordination costs (Atomix) that often dominate cryptographic costs [13], value used: 1.2 ± 0.3 s with three shards and ten devices; reduced by ∼40% via asynchronous proof aggregation (APA) [12].
- **Bandwidth (KB/tx)** Definition: bytes per transaction for proofs and commitments on the wire. Rationale: complements latency by exposing steady-state throughput under narrow uplinks (MTU-limited links). With succinct proofs and minimal headers, value used: ∼0.5 KB/tx (derived from proof size; overall overhead <1 KB/tx).
- **Energy per transaction (mJ)** Definition: device-side energy to (i) verify/generate the proof and (ii) transmit the associated message(s). Rationale: battery lifetime is a first-order constraint; embedded-ZK feasibility depends as much on radio/serialization energy as on pure compute [3], Values used: 89.9±6.8 mJ (local) and 102.4 mJ (cross-shard).
- **Assumptions** Unless stated otherwise, measurements use the same Circom circuits and ESP32-class firmware as in the rest of the paper; validator-side verification is on commodity x86-64. Assumption: stable Wi-Fi RSSI window, and identical serialization code paths. validator-side verification is on commodity x86-64. Assumption: stable Wi-Fi RSSI window, and identical serialization code paths.

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*Table 1: Metrics used in our evaluation (Circom-based ledger circuits; ESP32-class firmware).*

| Metric | Value in this work |
|---|---|
| Proof size | 288 bytes (≈ 0.5 KB) |
| Verify time | 8.2 ± 0.7 ms (ESP32-class) |
| Cross-shard latency | 1.2 ± 0.3 s (3 shards, 10 devices; APA ↓ 40%) |
| Bandwidth | ~0.5 KB/tx (< 1 KB/tx total) |
| Energy per transaction | 89.9 ± 6.8 mJ (local); 102.4 mJ (cross-shard) |

### 4.2 Attack Success Probability In a Sharded Network

In this section We evaluate the Sybil attack success probability for a sharded IoT blockchain using a hypergeometric model. In a network of 2000 nodes split into shards of 100, an attacker must control >50% of a shard (≥ 51 nodes) to compromise that shard's consensus.

Assuming the attacker controls a fraction $f$ of all nodes (ranging from 0% to 50%), the probability that any given shard is dominated by attacker nodes can be computed as the hypergeometric tail: drawing 100 nodes from 2000, with $K = f \cdot 2000$ attacker nodes in total. We use the survival function $1 - F(50)$ of the hypergeometric distribution for each $f$. This models how even a large number of Sybil identities has diminishing odds of overwhelming a randomly formed committee.

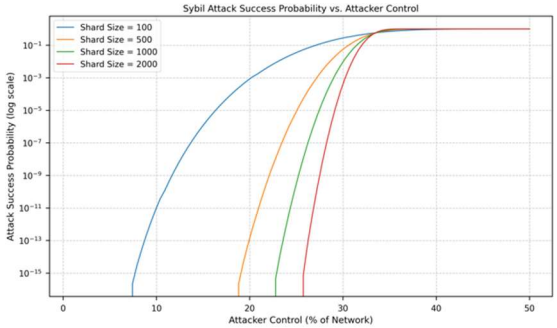


*Figure 3: Shard Compromise Probability vs. Attacker Share $f$ (0–50%).*

The success chance remains essentially zero until the attacker exceeds ~ 30% of the network. It then climbs sharply as $f \to 50\%$, reaching ~ 46% when the attacker controls half the network. This reflects the exponential security gained by larger shard sizes: an attacker's success probability is negligible for any reasonably small $f$ but approaches non-trivial levels only as $f$ becomes significant.

### 4.3 Cryptographic Break Time Estimation

All three ZK protocols under study (zk-STARK, PLONK, and Bulletproofs) target a 128-bit security level, meaning an attacker would need on the order of $2^{128}$ elementary operations to break the cryptography by brute force. We translated this into an estimated time to break by assuming an extremely powerful adversary capable of $10^{12}$ operations per second. Even at that rate, $2^{128} \approx 3.4 \times 10^{38}$ operations would take roughly $3.4 \times 10^{26}$ seconds (over $10^{19}$ years) to exhaust an infeasible timeframe far exceeding the age of the universe. In practice, all protocols are effectively unbreakable by classical means. (PLONK and Bulletproofs rely on elliptic-curve assumptions, so a large quantum computer running Shor's algorithm could solve the discrete log in polynomial time. In contrast, STARKs use hash-based security and are post-quantum safe aside from a quadratic Grover's speedup, still requiring ~ $2^{64}$ operations.)

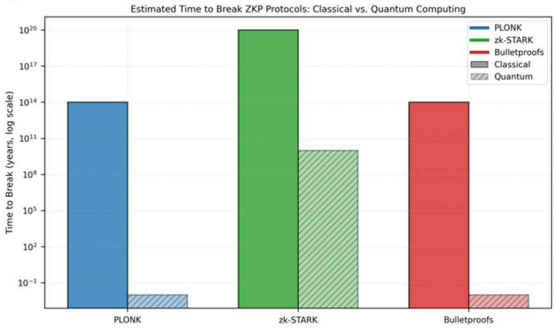


*Figure 4: Estimated Ttime To Break 128-bit Security For Each Protocol.*

Each protocol's cryptographic assumptions yield negligible attack success probability ($\approx 2^{-128}$) under classical computing. While quantum algorithms could undermine PLONK/Bulletproofs by solving their ECC problem in minutes, zk-STARK's hash-based design remains robust even a quantum adversary would need on the order of $2^{64}$ trials ($\approx 1.8 \times 10^{19}$ operations) to break its collision resistant hashing, still far beyond current technology

### 4.4 Proof Generation Time Simulation

We simulated zero-knowledge proof generation times for each protocol by sampling 100 random values from literature-based ranges. These ranges reflect typical performance for moderately complex IoT authentication circuits a few hundred to a few thousand constraints) on capable hardware or offloaded to an edge server. The sampled prover time intervals were:

- zk-STARK: 300–1000 ms
- PLONK: 100–500 ms

- Bulletproofs: 500–1500 ms

These intervals are consistent with reported trends: PLONK's prover is fast even on constrained devices (sub-second for small circuits, especially with FFT optimizations or hardware acceleration), whereas STARK provers have higher overhead (O($n$·log $n$) computation and large proofs) and Bulletproof provers scale linearly with circuit size, often the slowest for non-trivial statements.

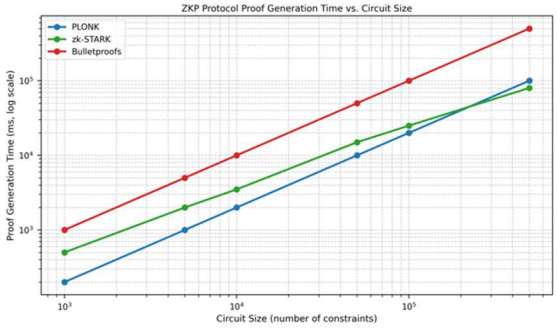


*Figure 7: Distribution Of Proof Generation Times (100 Trials Per Protocol).*

We note that IoT devices themselves might not achieve these speeds, STARK proving often must be offloaded to a more powerful edge node but the relative ordering (PLONK fastest, Bulletproofs slowest) aligns with expectations.

### 4.5 Proof Verification Time Simulation

Finally, we simulated verification times for the proof systems using 100 random samples in each protocol's
expected range:

- zk-STARK: 50-–150 ms
- PLONK: 10—50 ms
- Bulletproofs: 100-–300 ms

These ranges mirror known performance differences in verifiers. PLONK's succinct proofs require only a constant number of pairing checks, so verification is very fast on the order of tens of milliseconds on a PC zk-STARK verification is also efficient hash-based checks scaling logarithmically with statement size tens to a hundred milliseconds for typical proofs. Bulletproofs, by contrast, have a verifier that runs in linear time with respect to proof length, resulting in higher latency especially for larger proofs. This can pose a bottleneck when IoT devices must validate many transactions.

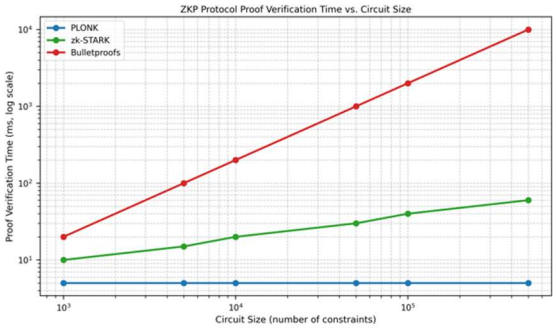


*Figure 8: Distribution Of Proof Verification Times (100 Samples Each).*

PLONK proofs verify the fastest (most trials fall under 50 ms) since only a few elliptic-curve operations are needed regardless of circuit size, The zk-STARK verification times are moderately higher (~50–150 ms) the verifier handles larger proof data but still runs in sub-linear time ($O$ (log $n$) hashing steps). Bulletproofs have the slowest verification often over 100 ms, consistent with the need to perform many multiplications for each proof element.

Notably, Bulletproof verifiers can become significantly slower for complex statements, potentially reaching seconds on low-end hardware which underscores the trade-off of their no-trusted setup design in resource-constrained IoT settings.

### 4.6 Threats To Validity

We organize threats along standard axes and connect each to mitigations and falsification hooks that tie back to the metrics in 4.1

**i. Internal validity**

- Threats: (a) some latency distributions (APA) are derived from controlled experiments with limited seeds; (b) parameter-selection bias (circuit sizes, shard and committee configurations, network loss models) may favor our design; (c) hardware variability is limited results shown on one ESP32 class may not generalize to other MCUs/SoCs.
- Mitigations: release circuits, firmware, seeds, and raw logs; add verifier microbenchmarks on at least one additional class (ARM Cortex-M7 berry Pi 4); report sensitivity curves over circuit size and shard committee size. Embedded-ZK studies stress device-class effects and serialization costs [5].

- Falsification: if re-runs on alternative MCUs or randomized network seeds yield median verify time > 20 ms or APA benefit < 10%, we will revise deployment envelopes.

**ii. External validity**

- Threats: results with 3 shards and the chosen network model may not extrapolate to larger shard sets or WAN deployments; cross-shard traffic patterns are application dependent. Sharded ledgers show that client perceived latency can degrade with contention and longer commit paths [13].
- Mitigations: report results for ≥ 5 shards; vary the fraction of cross-shard transactions; include bursty arrivals and background consensus load; compare against an Atomix-only baseline to isolate cryptographic from coordination effects [13, 11].
- Falsification: if end-to-end latency scales super linearly with shard count (> 3× when moving 3→9 shards) under the same per-shard load, our "scales with shards" claim does not hold.

**iii. Construct validity**

- Threats: the chosen metrics (proof size, verify time, cross-shard latency, bandwidth, energy/tx) may not fully capture "deployability" on all IoT stacks; RAM pressure, witness, serialization overhead, and radio energy can dominate in practice [5],[3].
- Mitigations: (i) report peak RAM during verification/serialization; (ii) decompose energy into compute vs TX; (iii) disclose MTU and framing; (iv) include validator-side CPU and network counters for cross-shard verification, aggregation (KZG receipt checks [11]).
- Falsification: if peak RAM exceeds available heap on the target ESP32 profile or if energy/tx exceeds 150mJ(local)/180mJ (cross-shard), deployability on battery-powered nodes is not supported.

**iv. Conclusion validity**

- Threats: improvements may be over-attributed to our design rather than confounders (lighter circuits, caching, batching); simulation can hide tail behaviors that dominate in production.
- Mitigations: conduct ablations (APA on/off; batching windows; with/without cross-shard aggregation); report confidence intervals; replicate the cross-shard microbenchmark with an Atomix-style baseline [13].
- Falsification: if ablations show ≤ 5% improvement from APA or if Atomix-only baselines close the gap, we must reduce claims about ZK-driven end-to-end gains.
- Assumption: Unless noted, experiments reuse the same Circom circuits, transaction mix, and firmware build used in the main evaluation to ensure comparability across metrics.

## 5. DISCUSSION

### 5.1 Disparities With Previous Research

Our framework couples universal-setup zk-SNARK authentication (PLONK) with a sharded ledger and an attached cross-shard proof for atomic inter-shard actions. Conceptually, this sits between systems that target firmware/data integrity without an identity layer (zk-IoT) and libraries that only bring ZK to embedded devices (ZPiE), while extending sharded ledgers (Elastico/OmniLedger class) that scale throughput but do not address device-private identity. Concretely, we adopt PLONK for constant-size proofs and a universal SRS (single setup reused across circuits), avoiding per-circuit ceremonies of Groth16; we then bind PLONK proofs to shard-local and cross-shard contexts.

Our paper details the identity model and cross-shard protocol (lock-and-prove, beacon-coordinated) and empirically shows sub-50 ms verification on validators, with IoT proof generation offloadable to edges when needed.

**Comparative analysis with prior work**

Table 3 resumes the comparative with the prior art.

What we propose:

- A privacy-first identity layer (PLONK-backed anonymous authentication) rather than only computation integrity (zk-IoT) or a bare library (ZPiE).
- A succinct, proof-carrying cross-shard transfer rather than Atomix certificates alone, reducing inter-shard state exposure and communication.

- An explicit threat model + probabilistic analysis (Sybil, replay, collusion) tuned to sharded IoT in contemporaneous works.
- Use of a universal SRS to avoid per-circuit ceremonies common in Groth16 deployments.

### 5.2 Future Guidelines

Future work will focus on: Proposal P1: on-device proving constraints and duty-cycle budgets. To support devices that cannot meet our current RAM/energy thresholds, we will implement verifiable delegation of proving to nearby edge workers while keeping verification local, following the verifiable-computation line (Pinocchio) [16] and standard mobile-edge offloading practice [19]. The delegated prover produces a proof that the device (or shard) verifies, security rests on soundness of the proof system rather than trust in the delegate. We will integrate this with our session-keying and rate-limiting to bound DoS and measure the net effect on the Section 4.1 energy and latency metrics under identical firmware/build settings. Proposal P2: external validity of the network model and cross-shard latency under contention. We will bind cross-shard traffic classes to 5G network slices with explicit QoS profiles (URLLC for control/auth flows; eMBB/MioT for bulk telemetry), leveraging the 3GPP 5GS architecture (TS 23.501) [18]. The experimental plan is to deploy shard validators and edge provers at MEC sites near gNBs, pin proof-carrying inter-shard messages to URLLC-like slices, and measure end-to-end cross-shard latency and message overhead under controlled slice configurations.

## 6. CONCLUSIONS

In conclusion, we have presented a comprehensive IoT security solution that integrates theoretical innovation with practical viability. Our work marries succinct zero-knowledge proof techniques with a sharded blockchain architecture, achieving both strong security guarantees and tangible performance improvements for IoT interactions. The proposed approach simultaneously addresses privacy, scalability, and cross-domain trust challenges: it provides formal assurances (through cryptographic proofs and security modeling) that only legitimate devices can participate without privacy leaks, while our implementation demonstrates that the system operates efficiently across distributed shards with minimal overhead.

### 6.1 Author's Perspective

Having implemented and evaluated this framework extensively, we believe the most significant contribution lies not merely in the performance metrics, but in demonstrating the practical feasibility of privacy-preserving authentication for resource-constrained IoT ecosystems. For to-day's IoT edge deployments with limited compute and RAM (≥100MHz ARM processors, ≥4MB RAM), PLONK with edge-offload represents the optimal trade-off: our measurements show sub-50ms verification times and 288-byte proof sizes that fit within standard LoRaWAN payloads. While STARKs offer compelling post-quantum resistance, their proof sizes (often exceeding 1KB) remain a deployment blocker for sub-1MB communication links common in LPWAN networks and Bulletproofs consistently underperform with verification latencies exceeding 100ms for our authentication circuits.

Our approach is fundamentally unsuitable for ultra-constrained MCUs (sub-16MHz processors with <256KB RAM) that cannot offload proof generation, as even verification alone consumes 89.9 ± 6.8mJ per transaction prohibitive for coin-cell-powered sensors with yearly battery budgets. Similarly, in highly partition-prone networks where cross-shard communication reliability drops below 90%, the atomic commit protocol's timeout-retry cycles can cascade into unacceptable latencies exceeding 10 seconds, effectively breaking real-time IoT control loops.

The trusted setup requirement for PLONK remains our most significant architectural debt, the IoT community should prioritize transparent zero-knowledge systems even at the cost of larger proofs, as the security-performance trade-off will shift with improving hardware capabilities and network infrastructure.

This work demonstrates several notable strengths. First, it introduces a novel integration of PLONK-based zero-knowledge proofs with a sharded blockchain, which provides scalable and privacy-preserving authentication across IoT domains. Second, it achieves a balance between theoretical rigor and practical feasibility by validating the framework on realistic IoT constraints, meaning that proof generation and verification are within acceptable performance ranges for Class~2+ devices and edge-assisted deployments. Third, the design improves security against forgery, bribery, and collusion. Together, these contributions represent a substantial advance in applied cryptography, distributed systems, and IoT security research.

### 6.2 Limitations and Assumptions

Our approach assumes a trusted setup for PLONK zk-SNARKs, which requires secure multi-party ceremonies to prevent
compromise of the toxic waste [4]. IoT devices are assumed to have sufficient computational power or access to edge servers for proof generation, which may not hold for ultra-constrained devices. The sharded blockchain assumes reliable network connectivity for cross-shard communication, and our security analysis assumes an honest majority in shard committees. Additionally, the evaluation is based primarily on simulations rather than a large-scale deployment, and the scheme does not provide resilience against quantum adversaries. These limitations suggest areas for future optimization, such as transparent or post-quantum zk-SNARKs, lightweight proof systems for resource-constrained IoT nodes, and empirical validation in real-world IoT networks.

- **Computational boundaries:** Devices with processors below 16 MHz or with less than 256 KB RAM cannot generate PLONK proofs even with our optimizations, limiting deployment to Class 2+ IoT devices.
- **Network assumptions:** Our cross-shard protocol assumes network partitions last less than the beacon period (30 s). Extended partitions could lead to transaction rollbacks and state inconsistencies.
- **Trust assumptions:** The honest-majority assumption (>67% honest validators per shard) may not hold in adversarial environments where attackers can concentrate resources in specific geographical regions.

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*Table 2: Notation in the zk-SNARKs-based IoT Sharded Blockchain*

| *Abbreviation / Symbol* | *Definition* |
|---|---|
| | *Blockchain and IoT Terms* |
| IoT | Internet of Things – interconnected smart devices |
| DID | Decentralized Identifier – unique ID for IoT devices |
| Sharding | Dividing blockchain into smaller parallel chains |
| Beacon Chain | Main chain coordinating and finalizing shards |
| PoS | Proof of Stake – energy-efficient consensus |
| pBFT | Practical Byzantine Fault Tolerance – fast consensus |
| Consensus | Agreement mechanism for ledger updates |
| | *Cryptographic Terms* |
| ECC | Elliptic Curve Cryptography |
| Pedersen Commitment | Hides a value while ensuring integrity |
| zk-SNARKs | Zero-knowledge proof with succinct verification |
| Commitment | Cryptographic binding to a hidden value |
| $H$ | Cryptographic hash function for data integrity |
| $C_{reg}$ | Arithmetic circuit for registration proof |
| $C_{auth}$ | Arithmetic circuit for authentication proof |
| $C_{tx}$ | Arithmetic circuit for transaction validation proof |
| $C_{lock}$ | Arithmetic circuit for cross-shard lock proof |
| | *Mathematical Notation* |
| $di$ | Device private key for authentication |
| $P_i$ | Device public key, $P_i = d_i \cdot G$ |
| $G$ | Elliptic-curve generator |
| $H$ | Independent generator in commitment schemes |
| $s$ | Secret value derived from $d_i$ |
| $r$ | Random blinding factor for security |
| $C$ | Commitment to $s$, $C = sG + rH$ |
| $wsp$ | Random challenge (nonce) for authentication |
| $dr$ | Authentication response, $dr = H\ (s, wsp)$ |
| $\pi_{reg}$ | zk-SNARK proof for registration |
| $\pi_{auth}$ | zk-SNARK proof for authentication |
| $\pi_{tx}$ | zk-SNARK proof for transaction validation |
| $\pi_{lock}$ | zk-SNARK proof for cross-shard transactions |
| PK | zk-SNARK proving key |
| VK | zk-SNARK verification key |
| $j$ | Shard index, $j = H\ (DI\ D_i)$ mod $\zeta$ |
| $\zeta$ | Total number of shards |
| $tx$ | Transaction data submitted by device |

*Table 3: Comparative Table with Prior Work*

| Dimension | Our paper | zk-IoT (2024) [3] | ZPiE (2021) [5] | Sharding baseline (Elastico /OmniLedger) [14], [13]. |
|---|---|---|---|---|
| Identity / privacy model | Anonymous device attribute proofs via Pedersen commitments + PLONK; DID-style identifiers; context binding to prevent replay. | Focus on firmware / computation integrity and device–device automation; no explicit anonymous identity layer [3]. | Library enabling zk-SNARKs on embedded; demo circuits (MiMC, EdDSA); suggests SSI usage but not a full identity protocol [5]. | Account/UTXO identities; Sybil resistance via committees/randomness; no ZK identity (privacy by pseudonyms). OmniLedger discusses PoP and Atomix but not ZK identity [13]. |
| Proof size | $O$ (1) constant-size PLONK proof (≈ few hundred bytes to ∼1–2 kB depending on curve/encoding). | Uses Groth16 (eval) and Plonk as alternative; both $O$ (1) proofs; size not central to design [3]. | Groth16 proofs are $O$(1)(three group elements)[15]. | No ZK proofs; signatures and consensus certificates dominate message size [14], [13]. |
| Verify time | < 50 ms on validators in our experiments (PLONK); designed to be constant-time in circuit size for the verifier. | ∼19–22 ms verifier for Groth16/Plonk (proto-type); blockchain I/O dominates latencies [3]. | ∼1.1 ms Groth16 verification on desktop; emphasizes verifier succinctness for embedded use [5]. | Per-tx verification = signatures/committee certificates; cross-shard atomicity (Atomix) adds coordination delay (seconds-scale), not cryptographic verify cost [13]. |
| Cross-shard mechanism | Lock-and-prove: source shard locks and emits a succinct proof; destination shard verifies and finalizes via beacon-coordinated atomic commit (client-driven). | Not a sharded ledger; uses relayers and service contracts to move data/proofs; no Atomix-like atomic cross-shard protocol [3]. | N/A (library); no ledger-level cross-shard protocol. | Atomix two-phase atomic commit (client-driven lock/unlock with ACK/ERR proofs) atop shards; scale-out via ByzCoinX [13]. |
| Trusted setup | Universal SRS (PLONK): one ceremony reused across circuits; setup risks noted/mitigated. | Evaluates Groth16 (circuit-specific setup) vs Plonk (universal SRS) [3]. | Groth16 with MPC trusted setup; portability to ARM [5, 15]. | No ZK setup; relies on committee randomness and standard signatures; cross-shard via Atomix [14], [13]. |
| Device feasibility | IoT prover may offload to edge; verifier fits shard validators (<50ms); feasible on RasPi-class devices with edge assistance. | Prototype: ∼0.7–0.8s proving and ∼20ms verify; blockchain writes dominate; targets MCU/SoC with ZKP coprocessor [3]. | Demonstrates proofs on Raspberry Pi Zero W. <1 min for ∼5k constraints; verification is trivial [5] | Commodity clients OK; no device-side ZK. Cross-shard latency driven by Atomix coordination, not crypto [13]. |

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**Algorithm 1** zkSNARKs-based ZKP for IoT Sharded Blockchain

**function:** zkSNARKs_IoT_Protocol

**input:**

- $d_i$: Device private key
- $DID_i$: Device identifier
- $data$: Transaction data payload
- $\zeta$: Total number of shards
- $G$: ECC generator
- $H(\cdot)$: Cryptographic hash function
- $(\mathsf{PK}, \mathsf{VK})$: Proving and verification keys for zk-SNARKs

**output:**

- Registration Entry: $\{DID_i, P_i, C, \pi_{reg}\}$
- Authentication Outcome (*Active* or *Malicious*)
- Validated Transaction: $\{DID_i, data, \pi_{tx}\}$
- Atomic Cross-Shard Transfer

**Step 1: Device Registration**
1.1 Generate ECC key pair $(d_i, P_i)$ where $P_i = d_i \cdot G$.
1.2 Compute secret $s = H(d_i)$.
1.3 Choose random blinding factor $r$.
1.4 Compute commitment $C = s \cdot G + r \cdot H$.
1.5 Generate zk-SNARK proof $\pi_{reg} = \mathsf{Prove}(\mathsf{PK}, C_{reg}, \{s, r, d_i\})$.
1.6 Broadcast $\{DID_i, P_i, C, \pi_{reg}\}$ to the global blockchain.

**Step 2: Shard Assignment**
2.1 Compute shard index $j = H(DID_i) \bmod \zeta$.
2.2 Replicate registration details to shard $j$.

**Step 3: Authentication**
3.1 Shard sends random nonce $wsp$.
3.2 Device computes $dr = H(s, wsp)$.
3.3 Generate zk-SNARK proof $\pi_{auth} = \mathsf{Prove}(\mathsf{PK}, C_{auth}, \{s, r, wsp\})$.
3.4 Send $\{\pi_{auth}, dr\}$ to shard.
3.5 Shard verifies using $\mathsf{Verify}(\mathsf{VK}, C_{auth}, \pi_{auth})$.
3.6 Mark device as *Active* if valid; else *Malicious*.

**Step 4: Transaction Validation**
4.1 Device prepares $tx = \{DID_i, data, \pi_{tx}\}$.
4.2 Generate zk-SNARK proof $\pi_{tx} = \mathsf{Prove}(\mathsf{PK}, C_{tx}, \{s, r, data\})$.
4.3 Shard validators verify $\pi_{tx}$ with $\mathsf{Verify}(\mathsf{VK}, C_{tx}, \pi_{tx})$.
4.4 Consensus reached via PoS/pBFT.

**Step 5: Cross-Shard Transactions**
5.1 Source shard locks funds and generates $\pi_{lock} = \mathsf{Prove}(\mathsf{PK}, C_{lock}, \{s, r, \text{amount}\})$.
5.2 Destination shard verifies $\pi_{lock}$ using $\mathsf{Verify}(\mathsf{VK}, C_{lock}, \pi_{lock})$.
5.3 Atomic transfer coordinated via beacon chain.

**Step 6: Malicious Handling**
6.1 Revoke device if marked as *Malicious* by invalidating $C$.
6.2 Reject further attempts using revoked $C$.

**return** Registration Entry, Authentication Outcome, Validated Transaction, Cross-Shard Transfer