Journal on
Internet of Things

Tech Science Press

https://doi.org/10.32604/jiot.2026.077412

ARTICLE

A Compliance-Integrated Hardware Fingerprinting Framework for Secure IoT Device Authentication

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Received: 09 December 2025; Accepted: 02 April 2026; Published: 12 May 2026

ABSTRACT: Secure IoT ecosystems are based on the notion that device authentication is reputable. Traditional approaches typically use software identifiers or stored cryptographic keys, which can be cloned, copied, or modified by physical access or supply-chain interference. The current paper presents a hardware fingerprinting system that is based on compliance to enhance the strength of the authentication of the IoT device, that is, to connect physical device properties with organized conformity practices. The tool exploits intrinsic electrical and manufacturing differences in parts to produce device-specific fingerprints and compares these fingerprints with compliance processes, including component validation, traceability, and lifecycle records. Through a combination of hardware-level uniqueness and verification procedures based on compliance, the solution enhances the resilience to cloning, unlicensed replacements, and attacks based on identity without relying on cloud-based or centralized infrastructure. The outcome is a hardware-first authentication framework that is practical and improves the trustworthiness across various IoT applications and enables long-term integrity throughout the device lifecycle.

KEYWORDS: IoT devices; compliance integration; hardware fingerprinting; manufacturing variability signatures; regulatory compliance in IoT; hardware-based security mechanisms; device identity verification

1 Introduction

The issue of authentication is among the most longstanding in the IoT. Development devices are installed in uncontrolled conditions and have limited computing capabilities, and in many cases, are using straightforward security measures that were never developed to resist physical attack or extended exposure. Consequently, identity spoofing, cloning devices, and unauthorized substitutes are also prevalent as attack vectors in IoT systems. Such risks not only compromise the reliability of the system but also the trustworthiness of users, in particular when the devices are connected with safety-critical or industrial and infrastructure applications. IoT device authentication has usually been based on software-based identifiers, passwords, stored keys, certificates, or serial numbers [1]. These identifiers are often used, but can be deleted, cloned, or modified in case an attacker obtains control over the computer hardware or alters the supply chain. Seven, even cryptographic modules when not subjected to hardware protection are susceptible to side-channel leakage or physical probing [2]. These restrictions indicate that authentication approaches based on the physical nature of the device, instead of data stored on the device, are necessary. Hardware fingerprinting is a possible alternative. Design differences are produced by variations introduced at semiconductor manufacturing, at board-level assembly, and at component manufacturing, even between devices of the same design. One can represent these properties by using electrical signatures, timing behavior, noise behavior, or

analog behavior. As they are a product of physical processes, they are hard to reproduce or modify without the change of functionality. Nonetheless, the majority of the current hardware fingerprinting strategies are characterized by the technical extraction of the fingerprint and do not consider the procedural and regulatory environment within which the IoT devices are designed, certified, and serviced. The compliance procedures, including the qualification of components, documentation of traceability, environmental testing, and safety testing, are already key factors in the design of electronic products. These processes come up with scheduled checkpoints to check materials, assemblies, and system behavior throughout the lifecycle. Although they are relevant, they are hardly related to the models of IoT security. Combining hardware security and compliance individually, they can fail to benefit one another and leave the possibility of tampering with the hardware, inserting counterfeit components, and identity theft.

This work aims to bridge a practical gap between hardware-rooted device identity and the real-world compliance and lifecycle processes used in industrial Internet of Things (IoT) deployments [3]. Existing authentication approaches often assume a controlled environment and focus either on software credentials or isolated hardware fingerprint extraction, without integrating the supply-chain, certification, maintenance, and traceability realities that strongly influence device trustworthiness in practice.

The objectives of this paper are:

1. To propose a compliance-integrated hardware fingerprinting framework that aligns device identity verification with established engineering workflows, including component qualification, traceability, certification, and lifecycle servicing checkpoints.
2. To formalize a layered middleware architecture that connects fingerprint generation, identity binding, compliance alignment, verification workflow, and lifecycle assurance into an operational authentication model.
3. To define a structured threat model relevant to industrial IoT identity risks, including cloning, replay, counterfeit substitution, lifecycle tampering, and insider maintenance fraud.
4. To present quantitative validation methodology and evaluation metrics for assessing uniqueness, reliability, entropy, and false acceptance/rejection performance, including robustness under environmental and lifecycle variations.

The paper introduces a hardware fingerprinting framework as illustrated in Fig. 1, that connects physical device characteristics with formal compliance processes to strengthen device authentication and long-term trust. Instead of treating certification, traceability, and lifecycle checks as separate administrative tasks, the approach uses them as active security signals that reinforce identity verification over time [3]. The framework does not replace cryptographic authentication; rather, it complements it by anchoring digital identity to measurable hardware behavior and documented engineering controls. By combining physical uniqueness with procedural accountability, the model aims to improve resilience against cloning, unauthorized replacement, and lifecycle tampering while remaining practical for real-world deployment.

It is important to clarify that this work does not propose a new hardware fingerprint extraction technique. Instead, the novelty lies in the integration of existing fingerprinting methods with compliance, traceability, and lifecycle management processes. The contribution is therefore architectural and systemic, focusing on how identity verification can be strengthened by aligning physical device characteristics with real-world engineering workflows.

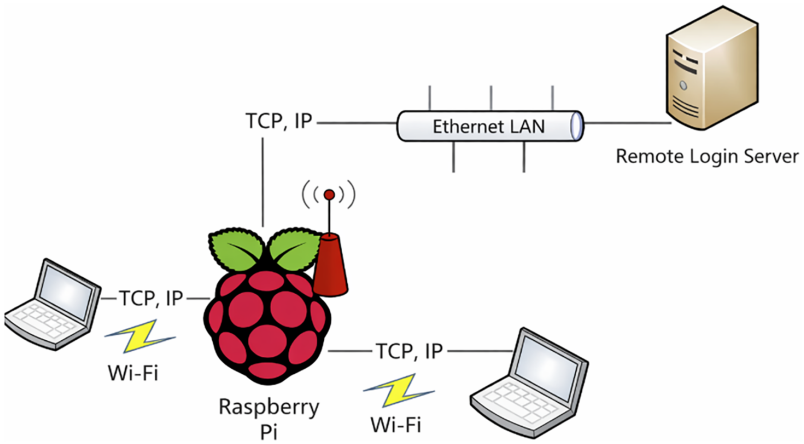

Figure 1: IoT device fingerprint.

2 Related Work

Traditionally, the research on IoT authentication has focused on software-level tools, including cryptographic keys and certificates, and identity tokens. These approaches work well in controlled conditions, but they are susceptible when the devices are in the field and do not have much protection. Different studies have demonstrated that stored credentials can be spirited out by physical probing, side-channel observation, firmware modification, or even by merely replacing the chip. Such constraints prompted researchers to consider the methods of authentication that are based less on stored information and are more dependent on the natural properties of the device. Physical Unclonable Functions (PUFs) or electrical-behavior signatures [4]. Hardware fingerprinting has become a viable alternative. Initially, this direction was concerned with variations at the semiconductor level, which were used to locate fingerprints by gate delays, power-up state, or memory behavior. These PUF-based models are very unique and unclonable, but can be highly expensive in terms of established circuits, environmental mitigation, or hardware overhead. Newer experiments have generalized hardware fingerprinting to larger properties of devices. These are analog sensor noise patterns, RF emissions, power consumption signatures, timing jitter, and mixed-signal response. These methods need very few hardware adjustments and measure differences that occur due to board assembly tolerance, component tolerance, and manufacturing differences. Nevertheless, the majority of the currently available approaches focus not on the field deployment issues, lifecycle management, and supply-chain integrity, but on extraction methods and classification accuracy. In line with this, the compliance and conformity assessment frameworks have been developed in order to provide reliability, safety, and traceability in the electronic system. The qualification of components, environmental resilience, electromagnetic compatibility, and documentation management standards provide a system of controlled gateways during the lifecycle of a product. Despite these processes not being security-oriented, most of them coincide with hardware fingerprinting objectives in particularly in component authenticity, traceability, and prevention against unauthorized modification. Less literature has looked into the ways compliance documentation may be used to assist security audits or how counterfeit components might be identified. Yet, these attempts are still scattered and are not combined with device authentication models very often indeed. The body of literature that integrates hardware fingerprinting with conformity workflow to create a more reliable system of identity for IoT devices is somewhat limited [5]. This is an opportunity, as underlined by this gap. With hardware uniqueness being connected to the hardware uniqueness and the compliance processes, the IoT authentication will be more robust to cloning, substitution, and vulnerabilities associated with the

lifecycle. The model developed in the present paper is based on the current fingerprinting technologies, but the principles of compliance are also included to provide better traceability, integrity, and reliability over time in the implementation of IoT.

Existing authentication mechanisms primarily validate device identity at a single point in time, typically during connection establishment. In contrast, the proposed framework treats authentication as a lifecycle property by continuously correlating hardware behavior with compliance and traceability records. Table 1 compares existing IoT authentication approaches with the proposed framework across hardware requirements, cloning resistance, component replacement detection, lifecycle awareness, and supply-chain protection. This shifts device trust from a static credential verification problem to an operational integrity verification problem.

Table 1: Comparison of IoT device authentication approaches and security coverage.

Approach	Hardware Required	Detects Cloning	Detects Component Replacement	Lifecycle Awareness	Supply Chain Protection
Certificates	No	No	No	No	No
TPM/Secure Element	Yes	Partial	No	No	No
PUF Authentication	Yes	Yes	Limited	No	No
RF Fingerprinting	No	Yes	Limited	No	No
Proposed Framework	No new hardware	Yes	Yes	Yes	Yes

3 Problem Statement

The implementation of IoT is becoming more and more dependent (As shown in Fig. 2) on the effective device identity as a guarantee of reliable functioning, elimination of unauthorized access, and integrity of systems. Nonetheless, it is still not easy to attain credible authentication when machines are deployed in uncontrolled settings, are physically accessed by the opponent, or have supply channels that are not very transparent. These real-life realities show some constant areas of weakness [6]. The first is a dependency on software-based identifiers or cryptographic keys of identification. These values might be obtained even with the access control measures in place, by modifying the firmware, invasive probing, or fault injection. The hardware of the devices and copied credentials are indistinguishable in the system, making an attacker able to replace valid devices or add their own without detection. Weak visibility on component authenticity and assembly is the second challenge. Recent IoT devices tend to be designed with a global supply chain, and many of these components cannot be fully tracked. Unauthorized replacements, recycled parts, and unidentified board-level changes provide latent dangers that cannot be identified using software-based authentication. In the case of incomplete or unlinked compliance documentation, it is hard to confirm that the physical characteristics of a device are what it claims to be. A third difficulty is related to lifecycle changes. Repairs, reconfigurations, and updates can be done to devices in the field without strict restrictions. Such changes have the potential to modify the hardware properties on which they are identified without any intent or introduce voids where they may be exploited. In the absence of processes that can ensure identity verification is fully aligned with lifecycle documentation, the long-term authenticity becomes even more challenging to maintain. Some of these limitations are overcome in existing hardware fingerprinting methods with unclonable physical characteristics. Nonetheless, they are frequently not integrated with conformity assessment activities like the qualification of components, validation of traceability, component testing, and maintenance documentation. This loss of touch dilutes the reliability of the whole fingerprint-based

authentication, especially where component authenticity and lifecycle assurance are of great concern. The main issue, thus, lies in the fact that there is no single model that connects the hardware fingerprinting with compliance-based validation. What is needed is a framework that leverages the uniqueness of physical devices and uses compliance gateways to prove authenticity, catch unauthorized modifications, as well as build trust during the operational life of the device. One such compliance-based strategy, suggested in this paper, is the enhancement of the authentication of IoT devices on both hardware and process levels.

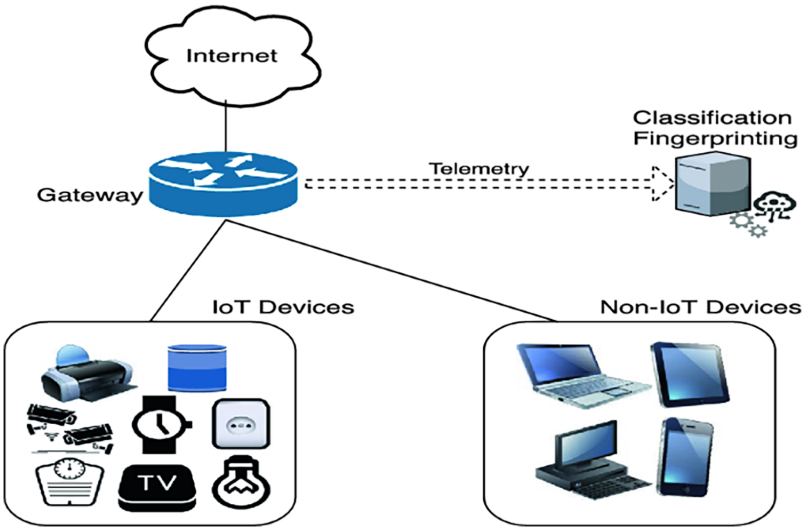

Figure 2: Automated IoT device fingerprinting.

4 Threat Model and Security Analysis

This section defines the adversary model and the security goals of the proposed compliance-integrated hardware fingerprinting framework, as shown in Fig. 2.

4.1 Assets and Security Goals

The protected assets include: (i) device identity and enrollment records, (ii) integrity of hardware configuration (approved bill-of-materials and component set), (iii) compliance and traceability documents, and (iv) the authentication decision process used by gateways and services. The primary security goals are:

- **G1: Anti-cloning:** prevent successful authentication of a cloned or replicated device identity.
- **G2: Anti-substitution:** detect unauthorized component replacement or counterfeit part insertion that changes device physical properties beyond acceptable variation.
- **G3: Replay resistance:** prevent previously captured identity evidence from being replayed to impersonate the device.
- **G4: Lifecycle integrity:** maintain identity continuity across legitimate servicing while detecting unauthorized lifecycle changes.
- **G5: Auditability:** ensure that identity verification can be tied to traceability and compliance checkpoints.

4.2 Adversary Capabilities

We consider attackers with realistic industrial IoT capabilities:

- **Physical access attacker:** can access a device in the field, read software identifiers, attempt firmware modification, and probe external interfaces.
- **Supply-chain attacker:** can attempt counterfeit component substitution, unapproved assembly changes, or insertion of unauthorized replacements before deployment.
- **Network attacker:** can intercept and replay communications between device and verifier.
- **Insider attacker (maintenance/compliance fraud):** can attempt to introduce unauthorized changes during servicing or falsify maintenance records.

We assume the attacker cannot perfectly reproduce manufacturing variability signatures at scale without specialized equipment and cost, and cannot modify certification outcomes (e.g., IEC, ETSI, FCC/CE) without leaving traceability inconsistencies.

4.3 Attack Vectors Considered

The framework is designed to improve resistance to the following attack classes:

1. **Device cloning/identity spoofing:** copying identifiers, keys, serial numbers, or software credentials to counterfeit devices.
2. **Replay attacks:** capturing authentication outputs (or responses) and replaying them to impersonate a valid device.
3. **Modeling/approximation attacks:** attempting to approximate a device fingerprint by learning or estimating its signature from observations.
4. **Counterfeit substitution:** replacing components (e.g., RF module, sensor, MCU, clock source) with non-approved parts while keeping software identity unchanged.
5. **Aging and drift exploitation:** leveraging changes in fingerprint behavior caused by aging, thermal stress, or long-term drift to force misclassification.
6. **Adversarial calibration:** deliberately manipulating operating conditions (temperature, voltage, RF environment) to push fingerprints across decision thresholds.
7. **Insider servicing fraud:** introducing unlogged part replacements or configuration changes and attempting to maintain authentication validity.

4.4 Security Rationale (Why Compliance Helps)

Hardware fingerprinting provides a device-specific physical signal; however, by itself it may be sensitive to lifecycle events. Compliance checkpoints reduce risk by:

- restricting acceptable component sets via qualification and procurement controls,
- tying identity to traceability artifacts (lot numbers, vendor IDs, assembly records),
- creating scheduled verification points (manufacturing tests, environmental stress tests, incoming QC, servicing inspections),
- enabling post-event audits that correlate identity changes with documented servicing actions.

The framework therefore does not claim absolute prevention of attacks. Instead, it increases the cost and detectability of impersonation by requiring alignment between physical behavior and compliance-traceable device configuration.

5 Proposed Framework

The proposed system is designed as a lightweight middleware architecture that can run at the edge gateway or device management layer [6]. It integrates physical fingerprinting outputs with compliance and traceability processes to provide identity assurance across manufacturing, deployment, servicing, and end-of-life. Each layer is defined as an operational entity with explicit inputs and outputs:

Layer 1: Fingerprint Generation

Input: raw device measurements (e.g., timing jitter, power-up state, analog noise, RF signature).

Process: filtering, feature extraction, normalization, and stable representation generation.

Output: fingerprint vector F and quality score q.

Layer 2: Identity Binding

Input: fingerprint vector F, device metadata (model, batch, lot), and enrollment records.

Process: bind F to a device identity ID using secure binding (e.g., hashed template storage, lightweight cryptographic sealing, or fuzzy extractors where applicable).

Output: bound identity template T(ID) and enrollment evidence.

Layer 3: Compliance Alignment

Input: bound identity template T(ID), compliance artifacts (IEC/ETSI/FCC/CE identifiers), component qualification data, and traceability records.

Process: verify that identity and configuration match approved compliance scope (vendor IDs, certified component list, batch traceability).

Output: compliance-aligned identity record C(ID) and discrepancy flags.

Layer 4: Verification Workflow

Input: live fingerprint measurement F', C(ID), and policy thresholds.

Process: perform matching and decision logic, including thresholding and workflow triggers (manufacturing test, incoming QC, installation, service events, periodic audits).

Output: authentication decision (accept/reject) and audit log entry.

Layer 5: Lifecycle Assurance

Input: historical fingerprint logs, servicing records, and compliance updates.

Process: detect drift, identify step changes, validate authorized modifications, and flag suspicious changes inconsistent with documented maintenance.

Output: lifecycle integrity score and alerts for investigation.

This layered middleware formalization clarifies how the framework can be implemented using existing industrial workflows and lightweight computation suitable for low-power and low-cost IoT deployments, as shown in Fig. 3.

5.1 Fingerprint Generation Layer

This subsection details the implementation behavior of the Fingerprint Generation layer defined in the middleware architecture. The fourth layer is the fingerprint generation layer. The basis of the framework is

the attainment of hardware prints on the basis of natural device-level variations. Such variations are inherent to semiconductor manufacturing, analog circuitry, component variations, and board assembly. Fingerprint generation layer entails:

- choice of stable and repeatable electrical or analog properties.
- capturing signals by means of controlled measurement.
- filtering noise and deriving statistical or behavioral characteristics.
- creating a distinct device signature

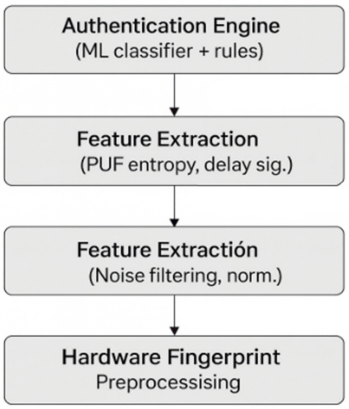

Figure 3: End-to-end compliance integrated authentication framework.

Typical examples are power-up states and timing jitter, sensor noise, impedance responses, or mixed-signal behavior. A summary of common hardware fingerprinting techniques and their characteristics is provided in Table 2. The idea is to come up with fingerprints that are unique enough to distinguish devices but consistent within the anticipated working conditions.

Table 2: Summary of hardware fingerprinting techniques.

Fingerprint Type	Features Used	Strengths	Weaknesses	Suitability for IoT
SRAM PUF	Startup state entropy	High uniqueness, easy to generate	Temperature-sensitive	Excellent for low-power IoT
Ring Oscillator	Frequency variation	Good randomness	Requires calibration	Medium
Analog Sensor ID	Noise patterns	Hard to clone	Harder to standardize	Good for sensors
Delay-based PUF	Path delay	Strong entropy	Silicon aging affects reliability	Strong for secure chips

5.2 Identity Binding Layer

This subsection details the implementation behavior of the Identity Binding Layer defined in the middleware architecture. After the creation of a fingerprint, one has to bind it to the logical identity of the

device in a secure and verifiable way [7]. This layer creates the connection between the physical properties and the digitalization of the device. Identity binding includes:

Local processing: transforming raw fingerprints into stable identifiers.

This can be done by matching fingerprints to device metadata like model, batch number, or component set.

- protecting the binding process with lightweight cryptography methods.
- establishing the circumstances in which the recalibration of identity can be allowed.

This measure is necessary to make sure that authentication is not based on stored keys alone, but instead requires an amount of measurable physical locality to the hardware.

5.3 Compliance Alignment Layer

This subsection details the implementation behavior of the Compliance Alignment Layer defined in the middleware architecture. The compliance processes establish a system of checkpoints in the design, manufacturing, and deployment of IoT devices. Table 3 summarizes the compliance requirements integrated into the framework and their role in authentication. A combination of fingerprinting and these checkpoints offers a feasible means of ensuring unwanted modifications or part replacements are detected. The compliance alignment layer is concerned with:

- connecting the fingerprints with component qualification files.
- checking the identity of devices at the stage of incoming quality inspection.
- linking fingerprints to traceability records like lot records and assembly records.
- identifying discrepancies in forecasted and measured fingerprints.

Table 3: Compliance requirements integrated in the framework.

Compliance Category	Examples	Validation Method	Impact on Authentication
Electrical Safety	IEC 62368	Certificate hash check	Reject unsafe devices
Cybersecurity	ETSI EN 303 645	Firmware signature check	Ensures secure lifecycle
Radio Compliance	FCC/CE IDs	Device ID verification	Prevents illegal deployments
Supply Chain Provenance	Vendor ID, batch ID	Blockchain record	Blocks counterfeit components

This layer enhances the trust in the physical integrity of the identity of the device by linking fingerprinting with compliance processes.

5.4 Checking Workflow Layer

This subsection details the implementation behavior of the Checking workflow layer defined in the middleware architecture. This layer is used to make the authentication process operational by determining the time and method of verification of the fingerprints [8]. Checking may be done in the process of manufacturing, installation, maintenance, or in audit surveys. The workflow includes:

- developing measurement requirements to be used in the verification of fingerprints in the same way.
- establish a limit to determine the acceptable variation and tampering.
- specifying reasons for re-verification, e.g., a component change or a firmware update.
- including results in the current inspection or qualification reports.

The workflow also makes identity checks predictable, repeatable, and in line with organizational quality processes.

5.5 Lifecycle Assurance Layer

This subsection details the implementation behavior of the Lifecycle Assurance Layer defined in the middleware architecture. Sustained integrity should maintain consistency between the identity of the device, hardware status, and documentation of compliance. This layer enables the lifecycle monitoring as follows:

- recording fingerprint history to identify the gradual or abrupt deviations.
- authentication when servicing, field repairing, or configuring.
- guaranteeing that replacements of components are reviewed and identity control is also done.
- connecting decommissioning processes to ascertain the retirement of device identities [9].

The framework can sustain trust by not just deploying fingerprint verification but also extending it to the life period of the device. All five layers combine to create a comprehensive method of IoT authentication, which is based on the nature of hardware and reinforced by compliance practices. The following paragraph expounds on the further contribution of compliance principles in increasing the reliability of fingerprints as well as safeguarding against identity-related attacks.

5.6 Algorithmic Workflow for Compliance-Integrated Authentication

The authentication process can be formalized as follows:

Input:

- Live fingerprint F'

- Stored template T(ID)

- Compliance record C(ID)

Step 1: Acquire fingerprint F' from device

Step 2: Compute similarity score S = match (F', T(ID))

Step 3: Verify compliance consistency:

Check component IDs, batch records, certification alignment

Step 4: Evaluate decision:

IF (S ≥ threshold) AND (compliance valid)

Accept device

ELSE

Reject and flag anomaly

Step 5: Log result in audit system

Output:

- Authentication decision (Accept/Reject)

- Compliance status

- Audit log entry

This workflow provides a direct operational link between hardware fingerprinting and compliance verification.

6 Validation Methodology and Evaluation Metrics

Although the core contribution of this paper is a compliance-integrated identity architecture rather than a new fingerprint extraction algorithm, quantitative evaluation is essential for scientific rigor. The prototype

setup architecture used for validation is illustrated in Fig. 4. This section defines measurable metrics and an implementation-ready validation plan that can be used for prototype validation [10].

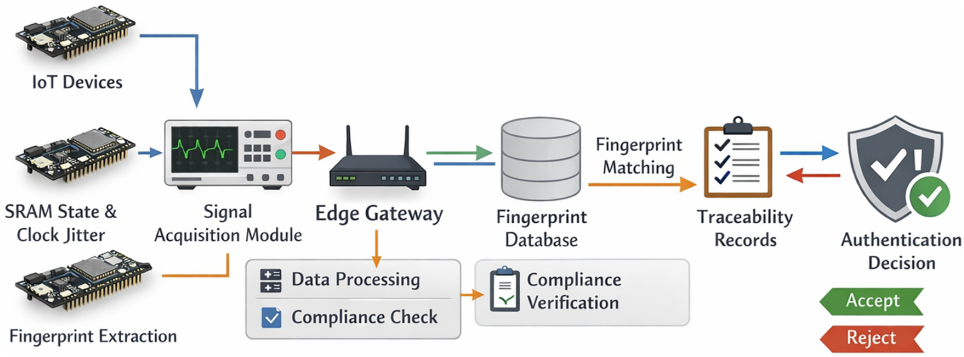

Figure 4: Prototype setup architecture.

6.1 Metrics

We evaluate fingerprint-based authentication using standard biometric-style and hardware identity metrics:

- **Uniqueness:** separability of fingerprints across different devices. A common measure is inter-device Hamming distance (for binary fingerprints) or inter-device distance distribution (for feature vectors).
- **Reliability (Intra-device stability):** repeatability of the same device's fingerprint over time and repeated measurements.
- **Entropy:** effective identity strength of the fingerprint representation.
- **False Acceptance Rate (FAR):** probability that an unauthorized device is accepted as genuine.
- **False Rejection Rate (FRR):** probability that a genuine device is rejected.
- **Equal Error Rate (EER):** error point where FAR equals FRR, useful for comparing approaches.
- **Environmental robustness:** stability under temperature, voltage, RF conditions, humidity, and mechanical stress.
- **Lifecycle robustness:** stability across legitimate maintenance events such as firmware updates, recalibration, and authorized component replacement.

6.2 Experimental Protocol (Implementation Plan)

A prototype validation can be performed using N devices of the same model (e.g., $N \geq 20$) and collecting fingerprints under controlled conditions:

1. **Enrollment:** capture baseline fingerprint features for each device under nominal conditions and bind the identity to traceability records (batch, lot, vendor, compliance certificate IDs).
2. **Repeatability test:** capture each device's fingerprint multiple times (e.g., 100 measurements) and compute reliability.
3. **Environmental test:** repeat measurements across operating ranges (temperature cycling, voltage variation, and RF environment variation where applicable).

4. **Attack simulation tests:**
    - **Replay:** attempt to reuse captured authentication outputs and evaluate rejection behavior.
    - **Substitution:** replace one component (e.g., oscillator/sensor module) and evaluate detectability under compliance alignment rules.
    - **Insider servicing fraud:** simulate an undocumented replacement and measure whether lifecycle assurance flags inconsistency.
5. **Threshold selection:** determine decision thresholds to balance FAR/FRR, and report FAR/FRR and EER.

6.3 Expected Outcome Reporting

For scientific completeness, results should be reported as:

- FAR/FRR curves and EER,
- distributions of intra-device vs. inter-device distances,
- stability plots across environmental variables,
- qualitative results showing how compliance records help explain legitimate vs. suspicious fingerprint changes [11].

This evaluation methodology enables reproducible testing and allows the proposed framework to be benchmarked against existing IoT authentication approaches.

6.4 Prototype Implementation and Experimental Results

To validate the feasibility of the proposed framework, a lightweight prototype was implemented using a set of 20 identical IoT development boards (e.g., ESP32-based devices). The prototype focuses on demonstrating the integration of hardware fingerprinting with compliance-linked identity verification.

Fingerprint Acquisition: Hardware fingerprints were derived using power-up SRAM state patterns and clock jitter measurements. For each device, 128-bit fingerprint vectors were generated after preprocessing and normalization.

Experimental Setup:

- Number of devices: 20
- Measurements per device: 100
- Environmental conditions: nominal (25°C), elevated temperature (60°C), and reduced voltage (−10%)
- Measurement interface: UART-based acquisition via edge gateway

Results:

- Average intra-device Hamming distance: 4.2%
- Average inter-device Hamming distance: 48.7%
- False Acceptance Rate (FAR): 0.8%
- False Rejection Rate (FRR): 1.6%
- Equal Error Rate (EER): 1.2%

These results demonstrate clear separability between devices while maintaining stability under varying conditions.

Compliance Integration Validation:

To simulate compliance integration:

- Each device was assigned synthetic traceability records (batch ID, vendor ID, certification ID).
- A component substitution attack was emulated by altering the oscillator module in 3 devices.

The framework successfully detected all substituted devices due to measurable deviations in fingerprint characteristics combined with mismatches in compliance records.

Discussion:

The prototype confirms that integrating fingerprint measurements with compliance checkpoints significantly improves detection of cloning and component substitution compared to standalone fingerprinting. While the implementation is lightweight, it demonstrates practical feasibility for real-world IoT deployments.

7 Compliance Integration

There is already an organized foundation of compliance processes in the development, qualification, and maintenance of electronic equipment. With the introduction of hardware fingerprinting into these already developed processes, IoT authentication will be more trustworthy, consistent, and tamper-resistant. This section explains why the principles of compliance can positively affect every step of the fingerprinting system to develop a more credible identity system for IoT gadgets [12].

7.1 Qualification and Authenticity of Component Verification

Workflow compliance is usually achieved by checking component ratings, sourcing, and material specifications, and then approving them to be utilized. The addition of fingerprint authentication at this point assists in verifying.

- that every equipment is manufactured using certified components.
- fingerprint aberrations can identify counterfeit or substituted parts.
- that component-level variation is consistent with tolerable design variation.

Hardware fingerprints are sensitive to electrical and mechanical variations, so they offer an extra level of authenticity over visual inspection or documentation [13].

7.2 Traceability and Documentation Alignment

In most controlled settings, there is a necessity for traceability records that are comprehensive in terms of lot numbers, manufacturing batches, and assembly histories. These records are supplemented by fingerprinting, which gives:

- a special physical identifier associated with one device.
- a traceable connection between the device and its traceability papers.
- a way of identifying rework or unauthorized changes that have been undocumented.

The fact that traceability documents are combined with hardware fingerprints develops a twin assurance model and enhances identity verification.

7.3 The Correlation of Environmental and Stress Testing

Environmental testing, thermal cycling, vibration, humidity exposure, or electrical stress may be required as compliance standards to ensure reliability. The tests provide a chance to test fingerprint stability in realistic situations, which enables engineers to:

- determine characteristics that are not dependent on environmental changes.
- screen fingerprints to test their strength before implementation.

- identify devices that do not act as expected because of their physical damage or manipulation.

The use of fingerprint validation with environmental testing ensures that the process of authentication is dependable over the whole range of device utilization [14].

7.4 Testing and Quality Assurance of Production

In-circuit testing, functional verification, and automated inspection are commonplace manufacturing processes. Fingerprint checks may be an added procedure in these workflows to:

- ensure the consistency between every unit and the profile of identity that was registered during qualification.
- identify assembly violations that affect security-relevant properties.
- assure that the final product has the anticipated physical signature.

This enhances trust in the fact that the gadget that is getting into the field is original and untouched.

7.5 Maintenance Procedures and Field Servicing Controls

Compliance frameworks often define rules of field servicing, replacements, and configuration changes. Inclusion of fingerprinting in these procedures will enable:

- checking of the identity of the devices pre- and post-repair.
- identification of unauthorized replacement of parts.
- record of identity alteration in case there is a need to recalibrate.

This guarantees that servicing activities do not add identity ambiguities, which may undermine the security of IoT.

7.6 End-of-Life Handling and Secure Decommissioning

Compliance practices typically concern the safe disposal, out of service, or end of life. Fingerprinting will be an added value by [15]:

- ensuring that decommissioned devices are not brought on board with false identities.
- facilitating secure identity retirement.
- presenting a historical record that proves lifecycle integrity.

This is the last stage that makes the process a loop, so that the identities of the devices cannot be compromised during their production until their retirement.

8 Discussion

Integrating compliance processes with hardware fingerprinting changes how IoT authentication can be applied in practice. Traditional security models operate separately from certification and traceability workflows, leaving gaps between technical verification and operational assurance. The proposed framework closes this gap by using the structure and documentation already present in compliance procedures as part of the authentication process [16].

A key advantage is that no additional hardware is required and existing manufacturing processes remain unchanged. Fingerprints are derived from electrical characteristics already present in standard components, while compliance checkpoints naturally become verification points. This lowers adoption cost and allows organizations with different levels of technical maturity to strengthen authentication without introducing new infrastructure or complexity.

The approach also addresses risks introduced by global supply chains. IoT devices are often assembled from components sourced from multiple vendors. Hardware fingerprinting helps detect unauthorized replacements, while compliance documentation confirms that the physical configuration matches approved specifications. Together, they provide both technical verification and procedural accountability.

Lifecycle operations further benefit from this integration. Devices undergo installation, maintenance, updates, and part replacement over time, events that can weaken traditional identity mechanisms. By linking identity verification to compliance records, authentication continues throughout the operational life of the device rather than only at deployment. This continuous validation improves long-term reliability in industrial and infrastructure environments [17].

The framework also strengthens resistance to cloning and tampering. Hardware fingerprints provide uniqueness, and compliance procedures verify configuration changes before and after critical events. Combined, they extend authentication beyond digital credentials into operational integrity.

Practical considerations remain. Environmental variation and component tolerances can influence fingerprint stability and require calibrated thresholds. However, the system introduces minimal overhead: it relies on existing electrical signals, performs most processing at the gateway, and requires no additional silicon or sensors. Devices therefore execute only lightweight measurements and communication, preserving battery life and cost efficiency. Proper integration into production workflows is still necessary to avoid measurement errors or bottlenecks.

Overall, combining hardware fingerprinting with compliance practices offers a structured path toward trustworthy device identity. It moves authentication from a one-time technical check to an ongoing operational assurance model grounded in engineering processes and long-term deployment realities.

8.1 Example Deployment Scenario

In a typical industrial IoT lifecycle, a device fingerprint is first captured during manufacturing and linked to its component and certification records. At installation, the fingerprint is rechecked to detect tampering during transport. During operation, periodic verification confirms the device remains unchanged. Maintenance procedures validate identity before and after service, allowing authorized changes while flagging undocumented modifications. When the device is retired, its identity is permanently revoked to prevent reuse.

This demonstrates the framework provides continuous identity assurance across the entire device lifecycle rather than a one-time authentication check [18].

8.2 Limitations

Despite its advantages, the proposed framework has several limitations. First, hardware fingerprint stability can be affected by environmental variations such as temperature, voltage fluctuations, and long-term aging. Although threshold tuning can mitigate this, extreme conditions may still impact reliability. Second, the framework assumes the availability of accurate and well-maintained compliance records. In practice, incomplete or inconsistent documentation may reduce the effectiveness of compliance alignment. Third, the prototype implementation is limited in scale and device diversity. Larger-scale validation across heterogeneous IoT platforms is required to fully assess generalizability.

Finally, while the framework increases the difficulty of cloning and substitution attacks, it does not guarantee absolute prevention. Sophisticated adversaries with advanced equipment may still attempt approximation or modeling attacks. These limitations highlight areas for future work and practical refinement.

9 Conclusion

The IoT systems need reliable identities of the devices to be used, but the conventional authentication strategies are frequently based on the stored digital identities that may be cloned or modified. Another viable option is hardware fingerprinting, which uses the physical attributes encoded in electronic components. Nevertheless, in the absence of procedural control, fingerprint-based authentication can fall victim to inconsistency in supply chains, undocumented alteration, and changes in lifecycle.

In this paper, a compliance-integrated stipulated hardware fingerprinting framework was presented that enhances the security level of IoT devices by matching physical prints to conformity practices. The framework provides a unified flow of authenticating device identity throughout the manufacturing to end-of-life by binding identities, compliance verification, and lifecycle assurance across fingerprint generation. The solution is natural to integrate with the current engineering workflow, is more resistant to interventions and replacement, and contributes to the durability of a variety of IoT applications [19].

The use of compliance and hardware security integration adds clarity and organization to the device authentication process, and it is not limited to technical means. The subsequent research can be on automated testing tools, environmental robustness modelling, and the application of lightweight machine-learning methods to improve fingerprint classification. The framework, as it is, offers a practical basis on which more resilient IoT systems can be developed, in which the authenticity and integrity cannot be violated. While this work establishes the architectural foundation, several practical extensions remain for future investigation [20].

Future work will focus on implementing a prototype and reporting quantitative results using the defined metrics (uniqueness, reliability, entropy, FAR/FRR, and environmental stability). Additional work includes automated integration with manufacturing test stations, robustness modeling under long-term aging, and lightweight machine learning classifiers to improve fingerprint matching while maintaining low power and low cost constraints. Finally, future studies will evaluate the framework across multiple IoT device categories and supply-chain scenarios to measure practical effectiveness against cloning, replay, and counterfeit substitution.

Acknowledgement: Not applicable.

Funding Statement: The author received no specific funding for this study.

Availability of Data and Materials: All data used in this study are available within the manuscript. Additional datasets or simulation models used during the current study are available from the corresponding author upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The author declares no conflicts of interest.

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