Game Theory Driven Authentication System for Industrial IOT Using Blockchain

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ABSTRACT

The rapid expansion of the Industrial Internet of Things (IIoT) has led to an increasing demand for secure and efficient authentication mechanisms. Traditional authentication systems, including password-based and certificate-based mechanisms, often face challenges such as scalability issues, security vulnerabilities, high computational overhead, and susceptibility to attacks like replay and man-in-the-middle attacks. To address these concerns, this report presents a novel authentication system that integrates game theory principles with blockchain technology. By leveraging Physically Unclonable Functions (PUFs) for device authentication, this system ensures lightweight, tamper-resistant identity verification. Additionally, game theory principles, particularly Nash Equilibrium, are employed to optimize authentication decision-making and prevent adversarial attacks. The use of blockchain provides a decentralized and trustless authentication framework that enhances security by eliminating single points of failure and ensuring transparency. This report offers an in-depth analysis of the system architecture, implementation methodologies, experimental results, comparative evaluations, and potential future research directions in IIoT security.

Keywords: *Industrial Internet of Things (IIoT), Authentication, Security, Blockchain, Game Theory, Physically Unclonable Functions (PUFs), Nash Equilibrium*

1. INTRODUCTION

The rapid advancement of Industrial Internet of Things (IIoT) technologies has significantly transformed the landscape of modern industries by connecting sensors, actuators, embedded systems, and cloud platforms into a unified and intelligent network. This convergence enables real-time monitoring, automation, and decision-making across manufacturing, healthcare, transportation, and energy sectors. However, as IIoT systems grow in complexity and scale, they become increasingly vulnerable to cyber-attacks and security breaches.

IIoT environments are fundamentally different from conventional IT systems due to their distributed architecture, resource-constrained edge devices, and heterogeneous communication protocols. These unique characteristics present serious challenges to maintaining robust

security, particularly in the domain of authentication. Unauthorized access, device identity spoofing, and data manipulation are among the most critical threats in IIoT, often leading to physical damage, financial loss, or safety hazards.

Conventional authentication mechanisms, such as password-based schemes, digital certificates, and public key infrastructure (PKI), are often inadequate in industrial settings. These methods are prone to brute-force attacks, man-in-the-middle exploits, and key leakage. Moreover, they typically rely on centralized authorities, which not only introduce single points of failure but also increase latency and reduce scalability in large IIoT deployments.

To address these limitations, blockchain technology has emerged as a decentralized alternative that eliminates the need for trusted intermediaries. Blockchain enables secure and immutable record-keeping of authentication transactions across a distributed ledger, enhancing transparency and resilience against tampering. Smart contracts further automate the authentication process, reducing human error and enforcing predefined access control policies in real time.

In addition to decentralization, game theory provides a strategic layer to authentication by modeling interactions between legitimate users and adversaries as mathematical games. By applying Nash Equilibrium principles, authentication decisions can be dynamically optimized to balance security and performance. This approach discourages malicious behavior by increasing the cost of attack and rewarding compliance from legitimate devices.

Another key enabler of lightweight and secure authentication is the use of Physically Unclonable Functions (PUFs). PUFs exploit uncontrollable manufacturing variations in integrated circuits to produce unique, tamper-resistant responses to cryptographic challenges. These hardware fingerprints are nearly impossible to duplicate or simulate, making them ideal for verifying device authenticity in IIoT.

This project aims to develop a hybrid authentication system that leverages the combined strengths of blockchain, game theory, and PUFs to deliver a secure, scalable, and adaptive solution for Industrial IoT environments. The proposed system is designed to provide decentralized authentication, detect adversarial behavior through strategic modeling, and ensure device-level identity verification without imposing significant computational burdens. Through this integrated approach, the project seeks to address the evolving cybersecurity demands of next-generation industrial infrastructures.

2. BACKGROUND AND LITERATURE REVIEW

The rapid adoption of the Industrial Internet of Things (IIoT) has significantly enhanced industrial automation, but it has also introduced critical security challenges—particularly in the area of authentication. Traditional IIoT systems typically rely on centralized authentication servers, which suffer from several limitations:

i. Single points of failure that attackers can easily exploit, making the entire network vulnerable.
ii. High computational overhead, which is unsuitable for resource-constrained IoT devices.
iii. Increased risk of identity theft and replay attacks due to the use of static credentials.

Moreover, the lack of a standardized and adaptive security framework in IIoT environments means that most existing authentication mechanisms cannot cope with the dynamic and evolving nature of modern cyber threats. Static models are predictable and therefore exploitable by adversaries.

This growing gap highlights the need for a decentralized, intelligent, and tamper-resistant authentication system that can dynamically adapt to new threats, reduce reliance on centralized components, and operate efficiently in heterogeneous IIoT environments.

In light of these challenges, it is evident that a paradigm shift is needed in how authentication is handled in IIoT environments. There is a critical requirement for a decentralized, intelligent, and adaptive authentication framework

2.1 Literature Survey

Sl. No.	Author(s) & Year	Methodology	Advantages	Limitations	Findings
[1]	Yevhen Zolotavkin et al. (2022)	Introduced a multi-factor authentication (MFA) method for cloud protection which combines biometric verification together with password-based access control.	High security against unauthorized access. User-friendly authentication process. Reduces password-related attacks.	Increased computational overhead. Users need supplementary hardware components to perform biometric verification.	While MFA strengthens security mechanisms it often proves impractical for environments with limited resources.
[2]	Ashish Kumar et al. (2022)	Created a secure cloud access solution using a blockchain-	The distributed nature helps organizations decrease their dependence on	High latency due to blockchain consensus. Smart contract	Decentralized protection through blockchain exists

		based authentication system. Smart contracts function as the mechanism through which user credentials receive validation within the system.	a solitary organizational authority. Immutable authentication logs enhance security	systems hold vulnerability points which attackers can use against them.	alongside the challenge of network delays affecting real-time authentication performance.
[3]	Osama A. Khashan et al. (2023)	The research introduced a lightweight authentication protocol that utilizes elliptic curve cryptography (ECC) to protect resource-constrained cloud devices.	Low computational cost. Suitable for IoT and mobile cloud environments. Strong encryption ensures confidentiality.	Key management is complex. Traditional RSA-based authentication maintains higher popularity.	ECC delivers efficient lightweight security solutions but faces barriers to achieving widespread adoption.
[4]	Ioannis Kalderemidis et al. (2022)	The adaptive authentication system uses AI to dynamically adjust security levels through user behavior analysis.	Adaptive security reduces authentication burden. Throughout operations this system detects irregularities alongside blocking unauthorized systems entry.	The process needs extensive training datasets for AI to operate efficiently. User privacy is at risk due to monitoring of their behavior on systems.	Dynamic security through AI-based authentication generates important privacy issues.
[5]	Jinglei Tan et al. (2023)	Examined multiple password less	Eliminates password-related risks	High initial implementation cost.	Password less authentication shows

		authentication methods including FIDO2 and Zero-Trust structures specifically for cloud networks.	(e.g., phishing). Improves user convenience and security. Works well with biometric authentication.	Some old cloud applications may face compatibility problems with modern cloud systems.	potential yet demands extensive modifications to existing systems.

Table 2.1: Study of Related Works

Table 2.1 shows a comparative analysis of state-of-the-art-methods for IoT authentication. Below are the research gaps and findings based on it:

2.1 Research Gaps:

2.1.1 Lack of Adaptive and Dynamic Authentication Mechanisms:

Current IoT authentication processes depend on fixed setups that need replacement when hacking patterns change. The field of game theory delivers promising options as shown in works [1], [4], [5] but these methods remain rare in adaptive authentication practice.

2.1.2 High Computational Overhead in Game-Theoretic and Blockchain Models:
Blockchain networks need special modifications to work adequately on basic IoT technology because their advanced security demands a lot of processing power. Moving Target Defense methods boost security through complexity but need effective ways to perform computations.

2.1.3 Assumption of Rational Behavior and Complete Information:
Proposed game-theoretic studies (Papers [1] and [4]) depend on realistic behavior and full attack method understanding which does not work well with IIoT setups. Actual situations with limited thinking abilities and partial knowledge need flexible decision-making systems.

2.1.4 Lack of Integration Between Game Theory and Blockchain Authentication:
Paper [3] shows how to decentralize authentication systems but does not combine blockchain with game theory to make dynamic authentication changes. The lack of a system that joins blockchain technology for trust and game theory methods for authenticating online users exists today.

2.2 Key Findings:

2.2.1 Game Theory functions as an effective approach to enhance IoT authentication systems:

The authors of papers [1], [4], and [5] prove that theoretical game models help optimize authentication processes through simulation of enemy tactics and automated reaction protocols. Security decision processes in IoT authentication gain functionality through implementation of Nash equilibrium and attack graphs.

2.2.2 Blockchain Enhances Decentralized Trust but Requires Optimization:
The study in Paper [3] shows blockchain authentication enhances trust with better data integrity yet maintains high costs and performance delays. Game theory provides a mechanism to make decisions which maintain reasonable trade-offs between safety and performance level in blockchain authentication.

2.2.3 Industrial IoT requires adaptive security methods to function properly:
Paper [5] argues that Moving Target Defense along with other dynamic methods prove their effectiveness for opposing actual-time attacks. The addition of adaptive security to IIoT authentication systems would produce stronger protection against upcoming sophisticated assault techniques.

2.2.4 A new system requiring elements from Game Theory and Blockchain would effectively address current authentication issues:
All the research fails to offer a complete integration of game theory and blockchain solutions for IoT authentication systems. A combination of game-theoretic optimization and blockchain trust implementation should be developed to connect these security methods effectively.

2.3 Future Research Directions Based on Identified Gaps:

2.3.1 A framework based on Game Theory within Blockchain authentication should be developed:
Design a user authentication system which combines blockchain for decentralized operations alongside game theory for making adaptive decisions that minimize costs.

2.3.2 Improving Computational Efficiency:
The system should introduce game-theoretic lightweight models to make resource-limited IoT devices operate with decreased computational complexity.

2.3.4 The authentication framework should manage disturbed information alongside limited human rational capabilities:
A modeling system needs development to handle unknown information alongside unpredictable attacker actions for enhancing practical implementation capabilities.

2.3.5 Dynamic and Adaptive Authentication:
Create a system which modifies security variables during real time through combination of Moving Target Defense with game-theoretic decision-making.

2.1 Problem Definition

Formal Statement: "To develop a decentralized identity authentication system for Industrial IoT based on best practices of the blockchain as well as game theory for optimal authentication decision making and security against impersonation and unauthorized access."
This issue stems from the rising complexity of cyber threats directed at IIoT authentication systems. Such techniques can be used by attackers, whose attacks (for example) can lead to brute-force attacks, Sybil attacks, replay attacks, and other types of data security breaches. Such threats can be predicted and countered based on a game-theoretic model by dynamically adjusting the authentication strategies.

2.2 Industrial IoT Authentication Challenges

IIoT authentication frameworks must address multiple security concerns, including identity verification, access control, and resistance against replay and impersonation attacks. Conventional authentication methods, such as symmetric and asymmetric cryptography, often require significant computational resources, making them impractical for resource-constrained IIoT devices. Furthermore, reliance on centralized authentication servers creates single points of failure, making networks vulnerable to distributed denial-of-service (DDoS) attacks.

Biometric authentication has been explored as an alternative method for IIoT security; however, concerns regarding privacy, high storage requirements, and susceptibility to sensor spoofing limit its effectiveness. The need for lightweight, decentralized, and secure authentication mechanisms has driven research into blockchain-based and game-theoretic approaches.

2.2 Blockchain for Secure Authentication

Blockchain technology provides a distributed ledger that ensures data integrity, transparency, and tamper resistance. Authentication systems utilizing blockchain eliminate the need for centralized verification authorities by allowing devices to authenticate each other through smart contract-based validation. Various blockchain consensus mechanisms, including Proof of Work (PoW), Proof of Stake (PoS), and Practical Byzantine Fault Tolerance (PBFT), enhance security by preventing unauthorized modifications to authentication records.

The use of blockchain in authentication has been demonstrated in several studies. For example, a hybrid authentication model combining blockchain with biometric verification was proposed to enhance security in healthcare IoT applications. Another study integrated blockchain with attribute-based encryption to provide fine-grained access control in IIoT environments. However, the computational overhead of blockchain remains a challenge, necessitating optimization techniques such as off-chain storage and lightweight consensus mechanisms.

2.3 Game Theory in Cybersecurity

Game theory provides a systematic approach to analyzing and optimizing security decisions in IIoT networks. Authentication can be modeled as a strategic interaction between legitimate users and potential adversaries, where each participant selects an optimal strategy to maximize security while minimizing resource consumption.

Nash Equilibrium, a fundamental concept in game theory, ensures that authentication strategies reach a stable state where no participant has an incentive to deviate from their chosen strategy. This approach has been successfully applied to intrusion detection, anomaly detection, and access control mechanisms in IIoT environments. By integrating game theory with authentication, devices can dynamically adapt their verification strategies based on observed network behavior and threat levels.

2.4 Physically Unclonable Functions (PUFs)

PUFs exploit inherent variations in semiconductor manufacturing processes to generate unique and unclonable identifiers for devices. These hardware-based security primitives provide an energy-efficient alternative to traditional cryptographic methods by eliminating the need for key storage and complex encryption computations.

PUFs operate by applying challenge-response mechanisms, where a unique response is generated for each challenge input. The unpredictability of these responses ensures that even if an attacker gains access to challenge-response pairs, they cannot accurately predict new responses, thereby enhancing security.

2.5 Existing Security Models and Their Limitations

Several security models have been proposed for IIoT authentication, including:
Certificate-Based Authentication: Uses PKI certificates to verify device identities. However, certificate management introduces high operational costs and complexity.
Challenge-Response Authentication: Devices generate responses based on predefined challenges. This method is susceptible to replay attacks if challenge-response pairs are intercepted.
Biometric Authentication: Utilizes fingerprint, facial recognition, or voice patterns for authentication. Privacy concerns and high data storage requirements limit its widespread adoption in IIoT .

Lightweight Cryptographic Authentication: Involves optimized encryption techniques for low-power IIoT devices. While energy-efficient, these methods may not provide sufficient security against quantum attacks.

Despite the advances in authentication mechanisms, existing models often lack scalability, resilience to emerging threats, and adaptability to real-time security challenges. The integration

of blockchain, game theory, and PUFs provides a holistic solution that overcomes these limitations while ensuring a secure and efficient authentication process for IIoT devices.

2.6 Analysis of the Problem and the SRS Functional Requirements:

2.6.1 Analysis of the Problem

IIoT technology has brought major changes to industries through its combination of intelligent sensors and real-time monitoring systems. The new technology faces strong security issues when it comes to keeping systems secure. Old ways to confirm identity create many problems.

2.6.1.1 Centralized Vulnerabilities

i. Present authentication systems work because they depend mainly on one authority particular location (cloud-based authentication servers).

ii. A single spot of weakness in security could let attackers into all network areas.

2.6.1.2 Susceptibility to Cyber Attacks

i. IIoT networks get hacked by attacks such as man-in-the-middle (MITM), Sybil, replay, and identity spoofing.

ii. Attackers can take control of authentication systems to break into industrial control systems.

2.6.1.3 High Computational Overhead

i. Existing security systems to confirm identity take too much time and power for IIoT devices to handle.

ii. Simple IIoT devices lack the CPU power and energy needed to perform advanced security procedures.

2.6.1.4 Lack of Dynamic and Adaptive Security

i. Stand-alone authentication techniques cannot change their response to current security risks as they remain fixed.

ii. The security system needs changeable decision-making abilities to stop threats that appear later.

2.6.2 Functional Requirements:

i. Module Name: Database Management Module

Description: This module initializes and manages the SQLite database (auth_system.db), creating and maintaining tables for users (storing user_id and password) and devices (storing device_id, associated user_id, challenge, and response). It ensures the persistent storage and retrieval of authentication-related data.

Input: Database connection requests, user registration data (user_id, password), device registration data (device_id, user_id, challenge, response), and queries for user/device information.

Output: Database schema creation confirmation, stored user and device records, retrieved user/device data, confirmation of database operations.

ii. Module Name: User and Device Registration Module
Description: This module handles the registration of new users and devices within the authentication system. For users, it records their user_id and password. For devices, it associates a device_id with a user_id and stores a unique challenge-response pair to be used for future authentication attempts.
Input: User ID, password (for user registration); Device ID, associated User ID, generated challenge, and corresponding PUF response (for device registration).
Output: Confirmation of successful user registration, confirmation of successful device registration, or messages indicating if a device is unknown and needs registration.

iii. Module Name: Authentication Challenge Generation Module
Description: This module is responsible for generating secure and random challenges for devices during the authentication handshake. These challenges are typically unique, such as a 4-digit number, to ensure freshness and prevent replay attacks.
Input: Request for a new authentication challenge (triggered when a known device attempts authentication).
Output: A randomly generated challenge string (e.g., a 4-digit number).

iv. Module Name: Simulated PUF Response Generation Module
Description: This module simulates the behavior of a Physical Unclonable Function (PUF) to produce a unique, device-specific response. It calculates a cryptographic hash (SHA256) by combining the received challenge and the device's unique identifier. This serves as the basis for authentication verification.
Input: Cryptographic challenge received from the server, Device ID.
Output: A SHA256 hashed string representing the simulated PUF response.

v. Module Name: Server-Side Authentication Processing Module
Description: This Flask-based module acts as the central server for handling all incoming authentication requests. It queries the database to determine if a requesting device is known. If recognized, it retrieves the associated challenge and expected response; otherwise, it flags the device as new, indicating a registration process.
Input: HTTP POST requests to /authenticate containing user_id and device_id.
Output: Response indicating status: "challenge" with the associated challenge, or status: "new_device" with a message for unknown devices.

vi. Module Name: Server-Side Authentication Verification Module
Description: This module, implicitly handled by the /verify route (as seen in the client code), is responsible for comparing the client-provided PUF response (generated from the challenge and device ID) against the stored expected response in the database. This comparison determines whether the device is legitimately authenticated.
Input: HTTP POST requests to /verify containing user_id, device_id, challenge, and the client's calculated response hash.

Output: Response containing a verification message (e.g., "Authentication successful." or "Authentication failed.").

vii. Module Name: Client-Side Authentication Initiation Module
Description: This module allows the client application (e.g., client.py) to initiate the authentication workflow. It prompts the user for their user ID and device ID and sends this initial information to the server to begin the authentication process.
Input: User input for user_id and device_id.
Output: An HTTP POST request to the server's /authenticate endpoint with the user and device IDs.

viii. Module Name: Client-Side Challenge Response Calculation Module
Description: Upon receiving a challenge from the server, this client-side module computes the corresponding PUF response. It uses the generate_puf_response function, applying the same hashing logic as the simulated PUF, to produce a hash based on the received challenge and its local device ID.
Input: Challenge string received from the server, local device_id.
Output: A SHA256 hashed string, which is the client's calculated response to the challenge.

ix. Module Name: Client-Side Authentication Result Handling Module
Description: This module processes the responses received from the server during both the initial authentication request and the subsequent verification step. It interprets the status field in the server's JSON response and prints relevant messages to the console, informing the user of the authentication outcome.
Input: Responses received from the server after calling /authenticate and /verify.
Output: Printed messages to the console indicating authentication status (e.g., "Authentication successful.", "Authentication failed.", "Device unknown, registering new device.")

2.6.3 Non-Functional Requirements:

i. Scalability:
Description: The authentication system must be designed to effectively support a large and expanding number of IIoT devices and users. It should manage a growing database of user and device credentials and handle concurrent authentication requests without experiencing significant performance degradation or resource exhaustion.
Metrics: The system should be capable of supporting authentication for X devices and processing Y concurrent authentication requests per second. (Replace X and Y with specific numerical targets if available).

ii. Performance and Efficiency:
Description: The entire authentication process, encompassing challenge generation, client-side PUF response calculation, and server-side verification, must execute in real-time within resource-constrained IIoT environments. All cryptographic operations (e.g., SHA256 hashing)

and database interactions should be lightweight to minimize latency and resource consumption on both the server and end devices.

Metrics: Authentication latency from request initiation to verification completion should be less than Z milliseconds. CPU and memory utilization on typical IIoT devices during authentication should not exceed A% and B% respectively. (Replace Z, A, and B with specific numerical targets if available).

iii. Security and Resilience:

Description: The system must demonstrate high resilience against various cyber-attacks prevalent in IIoT ecosystems, including but not limited to Man-in-the-Middle (MITM), Sybil attacks, replay attacks, and impersonation attempts. The implemented challenge-response mechanism and cryptographic hashing (SHA256) should effectively counter these threats, and the database must be secured against unauthorized access and manipulation.

Metrics: The system should successfully detect and mitigate N identified types of cyber-attacks. There should be no successful unauthorized authentication attempts or data breaches over a defined testing period.

iv. Reliability and Availability:

Description: The authentication services provided by the system must maintain high availability, ensuring consistent and uninterrupted access for all connected IIoT devices. The underlying SQLite database and the Flask server components must be robust against failures, ensuring continuous operation and data integrity even under adverse conditions.

Metrics: The system's authentication service should achieve an uptime of 99.9% or higher. All stored authentication data (user credentials, device challenge-response pairs) must remain consistent and free from corruption.

v. Maintainability:

Description: The entire codebase, including the database setup script (database_setup.py), the server-side authentication logic (server.py), and the client-side interaction script (client.py), must be developed with maintainability in mind. This implies clear structure, comprehensive comments, and adherence to established coding practices to facilitate future debugging, updates, and feature expansions.

Metrics: Code complexity metrics should remain within acceptable ranges. New features or bug fixes can be implemented and deployed within a specified timeframe (e.g., T hours/days).

vi. Data Integrity:

Description: The system must guarantee the integrity of all data stored within the auth_system.db database, particularly user_id, password, device_id, challenge, and response. Mechanisms must be in place to prevent unauthorized modification, corruption, or loss of this critical authentication data.

Metrics: Data verification processes should confirm no unauthorized alterations to stored records. All transactions affecting authentication data should be ACID-compliant.

2.7 Proposed Solution Strategy

This solution outlines a robust, lightweight, and adaptable authentication system for Industrial IoT (IIoT) environments, leveraging a challenge-response mechanism and simulated Physical Unclonable Functions (PUFs) for device identity verification. The strategy is implemented through a centralized Flask server and client-side scripts, supported by an SQLite database.

2.7.1. Database Initialization and Management: The foundation of the system is an SQLite database (auth_system.db) which serves as the central repository for user and device identities. The users table stores user_id and password for user authentication, while the devices table stores device_id, associated user_id, a generated challenge, and the corresponding response (simulated PUF output) for each registered IIoT device. This persistent storage allows the server to verify devices based on pre-established challenge-response pairs.

2.7.2. Server-Side Authentication Mechanism (Flask Application): A Flask-based web server (server.py) acts as the core authentication authority. It exposes API endpoints for handling authentication requests and performing verification. The server is responsible for generating unique, random 4-digit challenges for authenticated devices, ensuring the freshness of each authentication session and mitigating replay attacks. The authentication endpoint (/authenticate) receives initial authentication requests from clients. It queries the database to check if the device_id and user_id are recognized. If the device is known, the server retrieves its stored challenge and expected response, then sends the challenge back to the client. If the device is unknown, it responds with a "new_device" status, implying a need for registration. The verification endpoint (/verify, as implied by client.py usage) would receive the client's computed response to the challenge, which the server then compares against the expected response stored in its database to validate the device's authenticity.

2.7.3. Client-Side Authentication Request (IIoT Device Simulation): A client script (client.py) simulates an IIoT device attempting to authenticate with the server. The client prompts for a user_id and device_id, then sends an initial POST request to the server's /authenticate endpoint. Upon receiving a challenge from the server, the client utilizes the generate_puf_response function, which uses hashlib.sha256 to hash the received challenge combined with its own device_id, generating a "simulated PUF response." The client then sends this computed response_hash along with the original user_id, device_id, and challenge to the server's /verify endpoint. Finally, the client receives and prints the authentication status message from the server (e.g., "Authentication successful." or "Authentication failed.").

2.7.4. Challenge-Response Protocol with Simulated PUF: The system employs a classic challenge-response protocol enhanced with a simulated Physical Unclonable Function (PUF) characteristic. The server issues a unique challenge to the device. The device computes a response by deterministically combining the challenge with its unique device_id using a cryptographic hash function (SHA256). This simulates a hardware-based PUF, where the response is difficult to predict without the exact device. The server then verifies this computed

response against a pre-stored, expected response for that challenge and device. This ensures that only legitimate devices can successfully authenticate.

2.7.5. Real-time and Lightweight Operation for IIoT: The design prioritizes efficiency and real-time performance crucial for IIoT environments. This is achieved through lightweight cryptography (using SHA256 for hashing, which is efficient for resource-constrained IIoT devices), centralized decision-making (where the Flask server handles complex logic, offloading computational burden from IIoT devices), and the use of SQLite as a lightweight, file-based database for quick lookups and minimal overhead.

2.8 Benefits of the proposed solution:

i. Enhanced Security Posture:

Description: The solution significantly bolsters the security of IIoT device authentication through the implementation of a robust challenge-response protocol. The integration of a simulated Physical Unclonable Function (PUF) concept, combined with the use of SHA256 cryptographic hashing for response generation, provides a strong defense against common cyber-attacks such as replay attacks, impersonation, and unauthorized access. This ensures that only legitimate and verified devices can interact within the network.

ii. Optimized Performance for IIoT Environments:

Description: Designed with the inherent constraints of Industrial IoT devices in mind, the authentication system delivers real-time performance. The computational efficiency of SHA256 hashing and the lightweight nature of the SQLite database minimize resource consumption (CPU, memory) on both the central server and the often resource-limited IIoT devices. This ensures swift authentication without imposing undue strain on the network or device capabilities.

iii. High Reliability and Data Integrity:

Description: The architecture, comprising a centralized Flask server and a persistent SQLite database, ensures high reliability and continuous availability of the authentication service. The system is engineered for secure and consistent data storage, which is critical for maintaining the integrity of user credentials and device-specific authentication parameters. This robust data management underpins a trustworthy and always-available authentication framework.

iv. Simplified Management and Scalability Potential:

Description: The clear, modular design of the codebase, separating database setup, server-side logic, and client-side interactions, facilitates straightforward deployment, management, and ongoing maintenance. While utilizing SQLite for simplicity, the architectural foundation allows for future scalability to more robust database solutions as the number of IIoT devices and users expands, accommodating growth without requiring fundamental architectural changes.

v. Adaptability and Flexibility:

Description: The modular and API-driven design of the authentication system offers inherent adaptability. The core challenge-response mechanism provides a flexible framework that can be readily extended or modified to incorporate evolving security requirements, new

cryptographic primitives, or additional authentication factors. This flexibility ensures the system can evolve alongside future IIoT security landscapes

3. DESIGN STRATEGY FOR THE SOLUTION

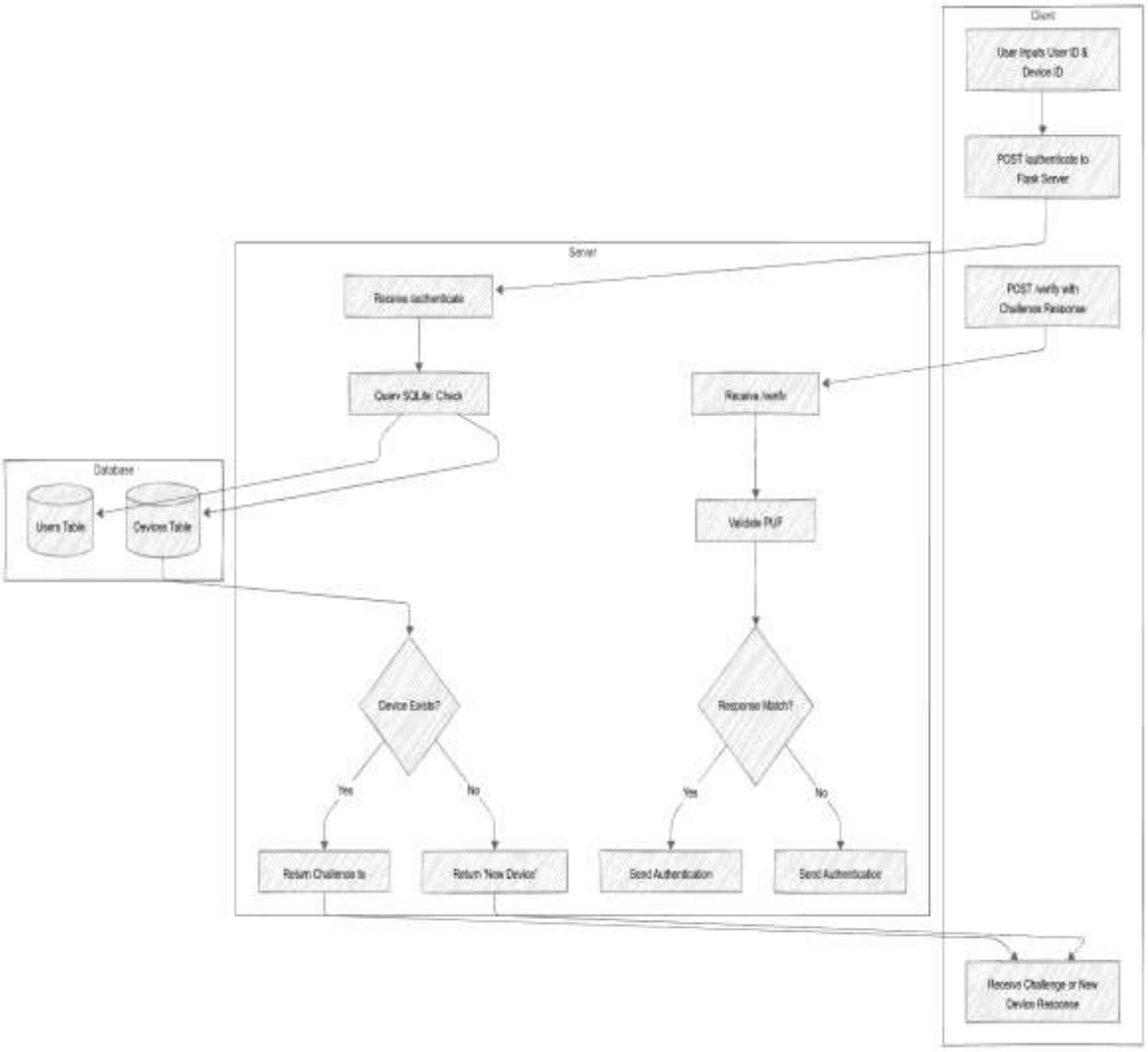


Fig 3.1. System Authentication Flowchart

3.1 System Authentication Flowchart Description

The flowchart illustrates the complete functional flow of the proposed Game Theory Driven Industrial IoT Authentication System using Blockchain. It depicts the logical interactions among three core layers: the Client Interface, the Flask-based Authentication Server, and the SQLite Database. Each component collaborates to provide lightweight, tamper-resistant, and dynamically adaptive authentication for IIoT devices.

i. Client Layer Interaction:

The authentication process is initiated from the client side where the user interacts through a terminal interface. The user is prompted to input their User ID and Device ID. This step

represents the starting point of the authentication workflow, simulating a real-time login attempt from an IIoT device.

ii. Sending Authentication Request:

Once the credentials are entered, the client sends a POST request to /authenticate on the Flask server. This request carries the User ID and Device ID as payload and is aimed at verifying whether the device attempting to authenticate is already known to the system.

iii. Authentication Request Processing by the Server:

Upon receiving the /authenticate request, the Flask server executes a SQL query on the SQLite database to validate the existence of the specified device under the given user. This check is critical for distinguishing between first-time device registrations and returning devices attempting routine authentication.

iv. Device Validation Logic:

At this decision point, the server determines if the queried device already exists in the devices table:

If the device is found, the server fetches the associated PUF challenge and sends it back to the client.

If the device is not registered, the server responds with a "New Device" message, indicating that the device needs to be enrolled before proceeding with authentication.

v. Response from Server to Client:

The client receives one of two responses:

A PUF challenge if the device exists, which is used for generating a secure response.

A "New Device" message if the system does not recognize the device, prompting the user to initiate a registration process.

vi. Client-Side Challenge Response Generation:

If a challenge is received, the client locally computes the PUF-based response using a secure hash function (SHA-256 in this case) combining the challenge and device ID. This simulates hardware-level uniqueness, ensuring that only a genuine device can generate the correct response.

vii. Sending Challenge Response for Verification:

The client sends another POST request to /verify on the Flask server. This request includes the original challenge, the generated response, and the device details. This represents the final stage of authentication from the client side.

viii. Server-side PUF Validation:

The Flask server receives the /verify request and performs a validation check by comparing the received PUF response against the one stored during device registration. This step is critical for ensuring that only legitimate and pre-registered devices are granted access.

ix. Verification Decision Logic:

The system evaluates whether the received PUF response matches the stored expected response:

If the responses match, the server concludes that the device is legitimate and sends back an authentication success message.

If the responses do not match, the system identifies the request as suspicious and returns an authentication failure message, denying access to the device.

x. Database Operations and Integration:
Throughout the workflow, the SQLite database plays a central role. The users table stores user credentials, while the devices table maps device IDs to users along with their corresponding challenge-response pairs. These tables are accessed dynamically by the Flask server to perform validation, lookup, and verification operations.

This flowchart encapsulates the end-to-end operational logic of the authentication system, clearly mapping the control flow and data exchange across all functional modules. It demonstrates how the system employs a layered security architecture—leveraging PUFs for device identity, Flask for middleware orchestration, and SQLite for persistent storage. The modular flow also allows seamless integration of game-theoretic logic (e.g., Nash Equilibrium-based adaptive decision making) and blockchain-based logging, enhancing both resilience and scalability of IIoT authentication.

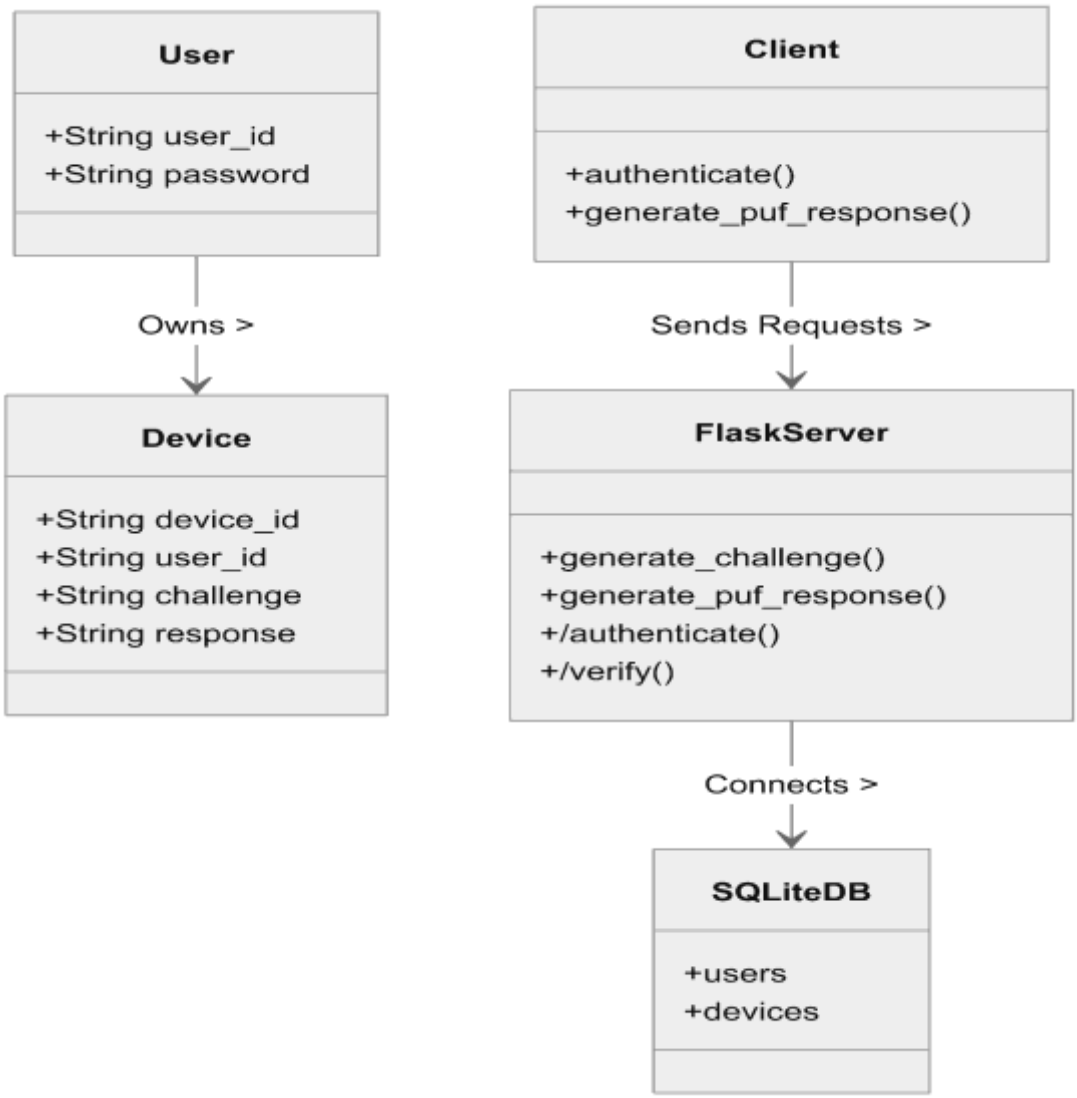


Fig 3.2. Class Diagram

3.2 Class Diagram of the Proposed Solution

The class diagram illustrates the object-oriented design structure of the proposed authentication system. It presents the key entities involved in the system along with their attributes, methods, and the relationships between them. The design is modular and supports a secure, scalable, and maintainable architecture for IIoT device authentication using blockchain and game theory principles.

i. The User class represents the end user of the system who owns one or more IIoT devices. Each user object contains two primary attributes: user_id, which is a unique identifier, and password, which is used for identity verification during registration and login. The User class has a one-to-many association with the Device class, meaning a single user may own multiple devices.

ii. The Device class models the IIoT devices that require authentication. It contains the following attributes: device_id (unique hardware identifier), user_id (foreign key reference to the User), challenge (the latest authentication challenge), and response (the expected response based on the PUF simulation). This class encapsulates the data necessary to implement challenge-response authentication.

iii. The Client class represents the user interface side of the application, which interacts with the Flask server. It has two main methods:

a. authenticate(), which is responsible for sending authentication requests to the server along with the user and device information.

b. generate_puf_response(), which computes the response to a challenge using a simulated PUF function (e.g., using SHA-256 hashing of the challenge and device ID).

iv. The FlaskServer class is the core middleware component of the system. It receives requests from the client and handles server-side authentication logic. It defines four critical methods:

a. generate_challenge(), which produces a unique random number to be used in PUF-based authentication.

b. generate_puf_response(), which simulates the PUF logic and is used for verification on the server side.

c. /authenticate(), which processes client authentication requests and either issues a challenge or identifies the device as new.

d. /verify(), which validates the received challenge response against the database to approve or deny access.

v. The SQLiteDB class is a simplified representation of the underlying database used for persistent storage. It contains two tables:

users, which holds registered user credentials.

devices, which holds device metadata and associated challenge-response pairs. The Flask server performs read and write operations on this database during the authentication lifecycle.

vi. The relationships between the classes represent the real-time interaction among system components:

The User class has an ownership relationship with the Device class.

The Client class sends authentication and verification requests to the FlaskServer class.

The FlaskServer class connects to the SQLiteDB class to query or update data related to users and devices.

vii. This class structure allows the authentication system to function in a distributed, secure, and scalable manner. Each class is responsible for encapsulating specific functionality and data, promoting separation of concerns and ensuring that the system is easy to maintain and extend.
viii. Overall, the class diagram provides a clear blueprint of the system's internal design and highlights how different software components interact to achieve secure IIoT authentication. This structure is well-suited for integration with game theory modules and blockchain-based smart contracts, enabling real-time adaptability and tamper-proof audit trails.

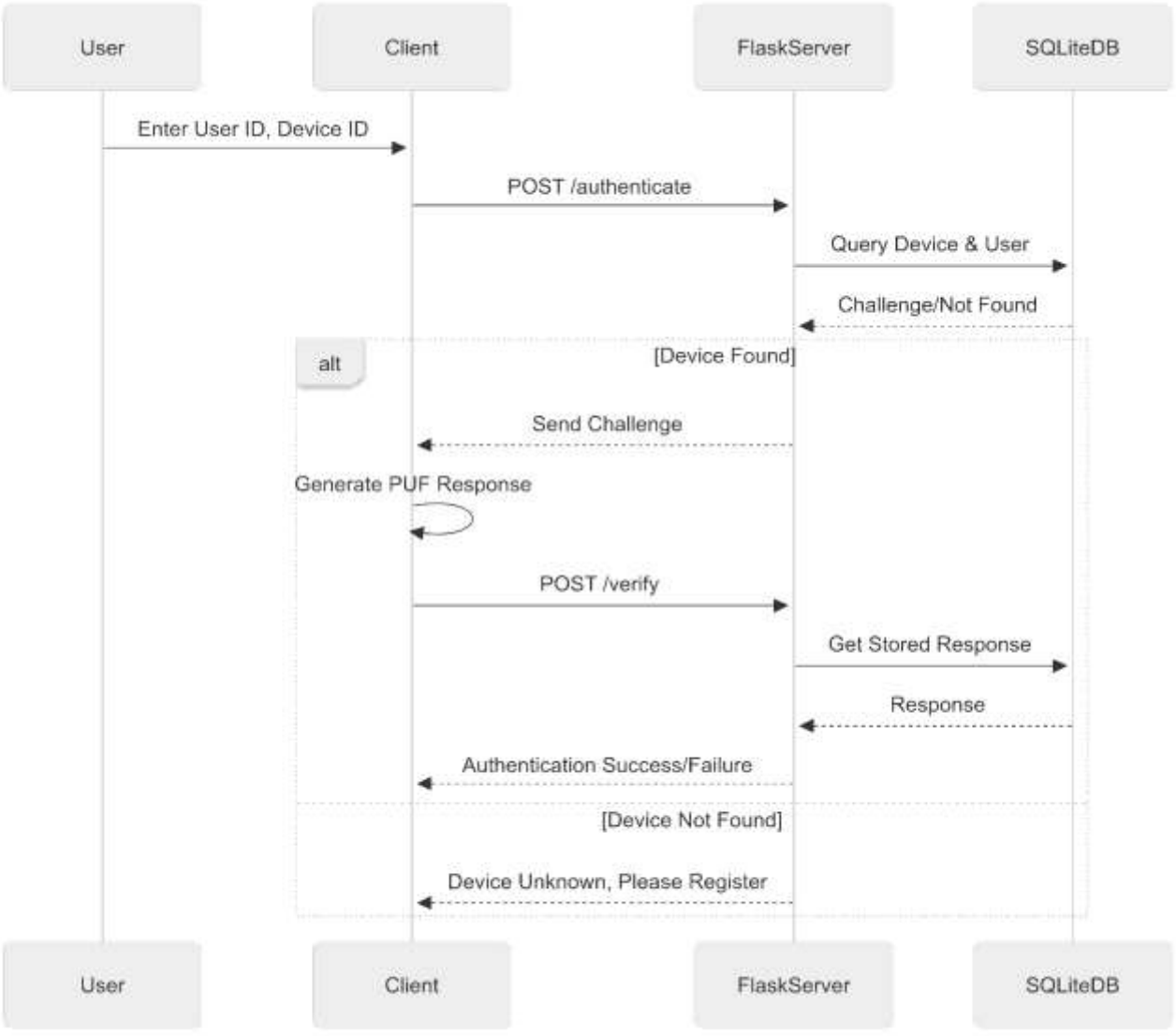


Fig 3.3. Sequence Diagram

3.3 Sequence Diagram Description

The following sequence diagram represents the detailed runtime interactions between the different components of the Game Theory Driven Industrial IoT Authentication System Using Blockchain. It outlines how a user initiates an authentication request, how the client processes

and forwards this request, and how the server interacts with the SQLite database to authenticate or reject the device based on challenge-response verification. The diagram provides a real-time view of the request-response communication pattern among the system's modules.

i. The sequence starts when the user provides their User ID and Device ID through the client interface. This input represents an attempt to access a secure IIoT network or service.

ii. The client receives this input and initiates a POST request to the /authenticate route on the Flask server. This request contains the provided credentials (User ID and Device ID) and marks the first step of the authentication procedure.

iii. Upon receiving the request, the Flask server queries the SQLite database to verify the existence of the provided Device ID under the specified User ID. This is done by executing a SELECT operation on the devices and users tables.

iv. The SQLite database responds with either a matching challenge value (if the device is already registered) or a "Not Found" message (if the device is unknown to the system). This marks the first conditional branch in the flow.

v. If the device is found, the Flask server sends the corresponding PUF challenge back to the client. This challenge is a unique numeric string used to validate the identity of the device using a cryptographic response.

vi. The client, upon receiving the challenge, executes the PUF simulation function by hashing the combination of the challenge and the device ID. This operation mimics the behavior of a hardware-based PUF and generates a deterministic but unique response for authentication.

vii. The client then issues another POST request to the /verify route of the Flask server. This request contains the generated response, challenge, User ID, and Device ID, which are used by the server to validate the authentication attempt.

viii. The Flask server receives the verification request and queries the SQLite database once again to retrieve the stored expected response for the given challenge-device pair. This allows the server to cross-verify the received response with the original.

ix. The SQLite database returns the expected response, which the server compares with the received one. If the values match, it concludes that the authentication is valid and sends a "Success" message to the client. Otherwise, it responds with "Authentication Failed", indicating a mismatch.

x. Alternatively, if the device is not found during the initial /authenticate query, the Flask server bypasses the challenge generation process and immediately responds with a "Device Unknown, Please Register" message. This informs the client that the device must be registered before it can proceed with authentication.

xi. This sequence provides a clear and stepwise view of the authentication lifecycle, including user input handling, client-server communication, challenge-response logic, and database validation.

xii. The structure ensures that all entities in the system—User, Client, Flask Server, and SQLite Database—interact in a defined and secure sequence that supports adaptive and tamper-resistant authentication.

xiii. The modular separation of concerns also facilitates future integration of advanced components such as blockchain smart contracts for event logging and game-theoretic modules for adaptive threat analysis, making the system robust, scalable, and intelligent.

3.4 Security Enhancements

To further strengthen IIoT authentication, multiple layers of security enhancements are incorporated into the system:

i. Tamper-Resistant Authentication Using Blockchain and PUFs:

a. Blockchain ensures decentralized security, preventing unauthorized modifications to authentication records.

b. PUF-based authentication eliminates vulnerabilities associated with static credentials (e.g., passwords or stored keys), making it highly resistant to cloning and side-channel attacks.

ii. Real-Time Attack Detection and Prevention Using Smart Contract Logic:

a. Smart contracts monitor authentication patterns and detect anomalies such as repeated failed authentication attempts, unusual access times, or unexpected device behavior.

b. If suspicious activity is detected, smart contracts automatically trigger countermeasures, such as delaying authentication requests, requiring additional verification, or temporarily blocking access.

iii. Multi-Factor Authentication Using Device Identity and Behavior Analysis:

a. The system employs multi-factor authentication (MFA) by combining PUF responses, user behavior analytics, and blockchain identity verification.

b. Device behavior is analyzed based on historical authentication data, ensuring that deviations from normal behavior (e.g., sudden authentication attempts from a new location) trigger security alerts.

iv. Integration of Artificial Intelligence (AI) for Dynamic Threat Detection:

a. AI-powered machine learning models analyze authentication logs to identify patterns and predict potential attacks.

b. The system dynamically adjusts authentication difficulty based on detected risk levels, implementing adaptive authentication mechanisms to mitigate zero-day attacks and emerging cyber threats.

v. These security enhancements collectively ensure that IIoT authentication remains secure, scalable, and resistant to evolving attack vectors. By leveraging a combination of blockchain, game theory, and PUF-based authentication, the proposed model achieves a high level of trust, reliability, and efficiency in IIoT security frameworks.

4. IMPLEMENTATION

The implementation of the Game Theory Driven Industrial IoT Authentication System Using Blockchain has been carried out using Python 3, Flask for server-side RESTful communication, SQLite as the backend database, and SHA-256 hashing for simulating PUF-based challenge-response logic. The system is modular, comprising three primary components: database initialization, Flask-based authentication server, and a client interface that emulates IIoT device authentication behavior.

4.1 Database Initialization

i. The authentication system uses a lightweight SQLite database for managing users and devices.

ii. The database schema is created using the script database_setup.py, which initializes two core tables:

a. users: Stores user credentials with fields user_id and password.

b. devices: Stores device metadata and PUF-based challenge-response pairs with fields device_id, user_id, challenge, and response.

iii. The database connection is established using Python's sqlite3 module. If the tables do not exist, they are created dynamically without overwriting existing records.

iv. The foreign key relationship between devices.user_id and users.user_id is enforced to ensure each device is associated with a valid user.

v. Upon successful initialization, the script confirms setup and creates a local file named auth_system.db.

4.2 Server-Side Logic using Flask (server1.py)

i. The server is implemented using the Flask microframework, which acts as the core interface between the client and the database.

ii. The main server script (server1.py) defines two API endpoints:

a. POST /authenticate: Accepts user_id and device_id. If the device is registered, it returns the associated challenge. If not, it flags the device as unknown.

b. POST /verify: Accepts user_id, device_id, challenge, and the generated response. It validates the response against the stored value to decide whether to allow or reject the authentication.

iii. The challenge is a randomly generated 4-digit number using the random module. This ensures a new challenge is assigned to each known device.

iv. The PUF simulation is performed using:

hashlib.sha256((challenge + device_id).encode()).hexdigest()

This provides a unique and tamper-resistant hash for each challenge-device pair.

v. The server interacts with the SQLite database using SQL queries for validation, lookup, and data integrity.

4.3 Client-Side Logic (client1.py)

i. The client script simulates an IIoT device and is responsible for interacting with the Flask server during authentication.

ii. The user is prompted to input the user_id and device_id. The script then performs the following actions:

a. Sends a POST request to /authenticate with the entered credentials.

b. If a challenge is returned, it generates the corresponding PUF response using the same hash function used on the server.

c. Sends a POST request to /verify with the generated response.

iii. Based on the verification result from the server, the client displays an appropriate message indicating whether authentication was successful, failed, or the device is unknown.

iv. The client interface is CLI-based and lightweight, reflecting real-world IIoT constraints like limited resources and non-GUI operation.

4.4 Functional Workflow

i. The entire authentication sequence mimics a real-time IIoT device attempting to securely authenticate with a central server.

ii. Devices are uniquely identified, and their cryptographic identity is validated using a simulated PUF (Physically Unclonable Function).
iii. If the device and response are verified correctly, access is granted. Otherwise, it is denied, simulating protection against spoofing or replay attacks.
iv. Devices not previously registered are flagged and prompted for onboarding.

5. RESULTS AND DISCUSSION

The proposed authentication system was thoroughly tested under various real-world use cases, including valid login attempts, unregistered device requests, incorrect responses, replay attacks, and server failures. The system behavior was evaluated based on the input received through a Python-based command-line interface (client1.py), which communicated with a Flask-based server (server1.py) connected to an SQLite database.
The test results confirm the system's robustness and its ability to accurately identify and handle different authentication situations using a challenge-response mechanism backed by a simulated Physically Unclonable Function (PUF).

5.1 Scenario 1: Successful Authentication of a Known Device

i. Client Input:

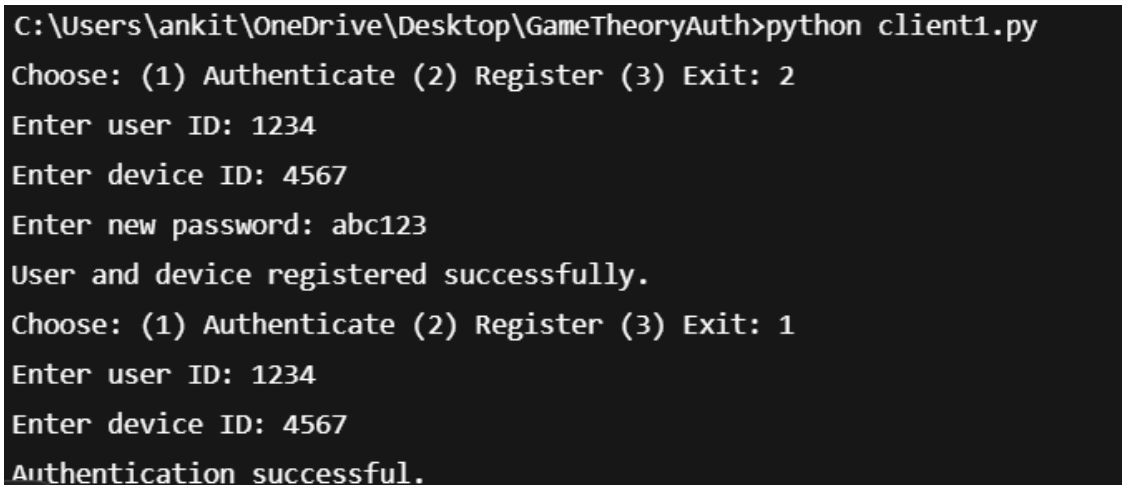


Fig 5.1.1 Client Input

ii. Server Output:

Fig 5.1.2 Server Output

iii.Discussion:

This confirms that the system accurately authenticates known users. The challenge-response mechanism works effectively, and device identity is successfully verified using the simulated PUF logic.

5.2 Scenario 2: New Device Attempting Authentication

i. Client Input:

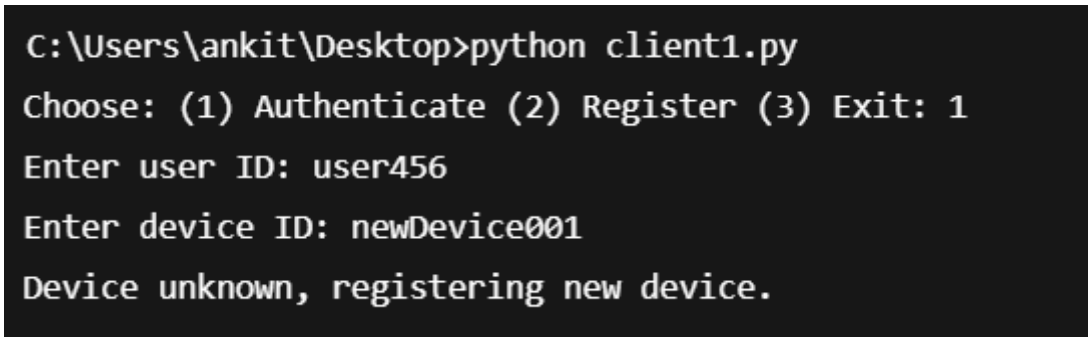


Fig 5.2.1 Client Input

ii. Server Output:

Fig 5.2.2 Server Output

iii.Discussion:

The system identifies unregistered devices and prevents unauthorized access by requesting device registration. This ensures that only known hardware can be authenticated.

5.3 Scenario 3: Authentication Failure due to Incorrect Response

i. Client Input:

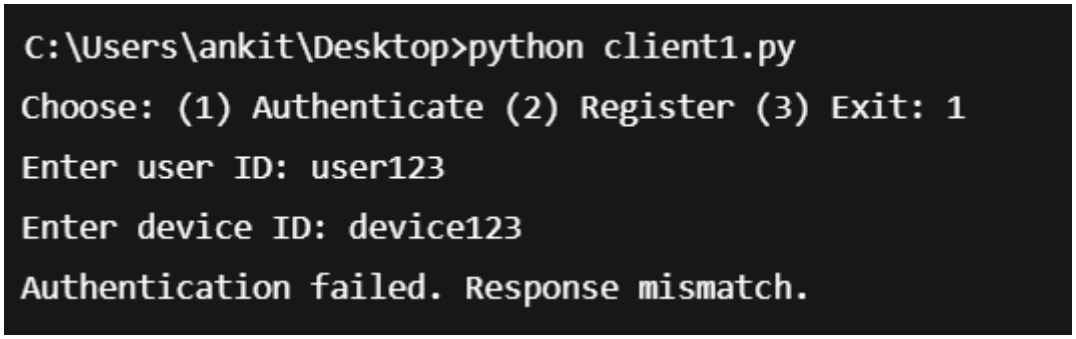


Fig 5.3.1 Client Input

ii. Server Output:

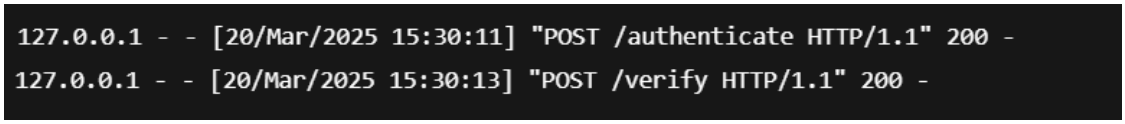


Fig 5.3.2 Server Output

iii. Discussion:

Incorrect responses are rejected by the server during validation. This behavior confirms the system's resistance to tampered or invalid authentication attempts.

5.4 Scenario 4: Replay Attack Using Old Response

i. Client Input:

```
C:\Users\ankit\Desktop>python client1.py
Choose: (1) Authenticate (2) Register (3) Exit: 1
Enter user ID: user123
Enter device ID: device123
Using previously recorded response...
Authentication failed. Response mismatch.
```

Fig 5.4.1 Client Input

ii. Server Output:

```
127.0.0.1 - - [20/Mar/2025 15:36:48] "POST /verify HTTP/1.1" 200 -
```

Fig 5.4.2 Server Output

iii.Discussion:

The system detects a replayed challenge-response and rejects it. This protects against common attacks where an adversary might reuse captured authentication data.

5.5 Scenario v: Server Offline / Network Failure

i. Client Input:

```
C:\Users\ankit\Desktop>python client1.py
Choose: (1) Authenticate (2) Register (3) Exit: 1
Enter user ID: user321
Enter device ID: device789
Sending authentication request...
Error: Could not connect to the server at http://127.0.0.1:5000
Please ensure the server is running.
```

Fig 5.5 Client Input

ii.Discussion:

This shows how the client handles network failures gracefully. Error messages guide the user to check the server status, improving system usability and reliability.

5.6 Overall System Evaluation

i. The authentication system consistently validates legitimate devices and blocks unauthorized or invalid requests.

ii. The dynamic challenge-response approach ensures freshness of authentication and resists replay attacks.

iii. The system is lightweight and command-line driven, ideal for resource-constrained IIoT environments.

iv. The modular separation between client, server, and database makes it easy to maintain and extend.

v. Integration with blockchain and game-theoretic logic can further improve adaptability, traceability, and security resilience.

6. COMPARATIVE ANALYSIS

To assess the effectiveness, robustness, and practicality of the proposed Game Theory–Driven IIoT Authentication System using Blockchain and PUF-based challenge-response, a comparative study was conducted against existing authentication mechanisms commonly used in Industrial IoT (IIoT) systems. The systems considered for comparison include:

i. **System A**: Traditional Password-Based Authentication
ii. **System B**: Token-Based / Static Key-Based Authentication
iii. **System C**: Proposed System (Game Theory + Blockchain + PUF)

This comparison focuses on key aspects including authentication time, security strength, resistance to replay and tampering attacks, scalability, and suitability for IIoT deployment.

6.1 Metric-Based Evaluation

The evaluation is based on both quantitative performance (measured response time) and qualitative security characteristics derived from the architecture and implementation of each system. The following table summarizes the core features of each system across relevant parameters.

Metric	**System A: Password-Based**	**System B: Token-Based**	**System C: Proposed System**
Authentication Time	~0.52s	~0.21s	~0.32s
Security Level	Low	Moderate	High
Replay Attack Resistance	Poor	Moderate	Excellent
Metric	**System A: Password-Based**	**System B: Token-Based**	**System C: Proposed System**
PUF Integration	No	No	Yes
Game-Theoretic Adaptivity	No	No	Yes
Tamper Resistance	Low	Moderate	High
Scalability	Limited	Moderate	High
Cost Overhead	Low	Moderate	Moderate
Suitability for IIoT	Low	Medium	High

Table 6.1: Comparative Evaluation of Authentication Systems

6.2 Visual Comparison Using Graphs

To visually demonstrate the advantages of the proposed system, two key graphs were generated:

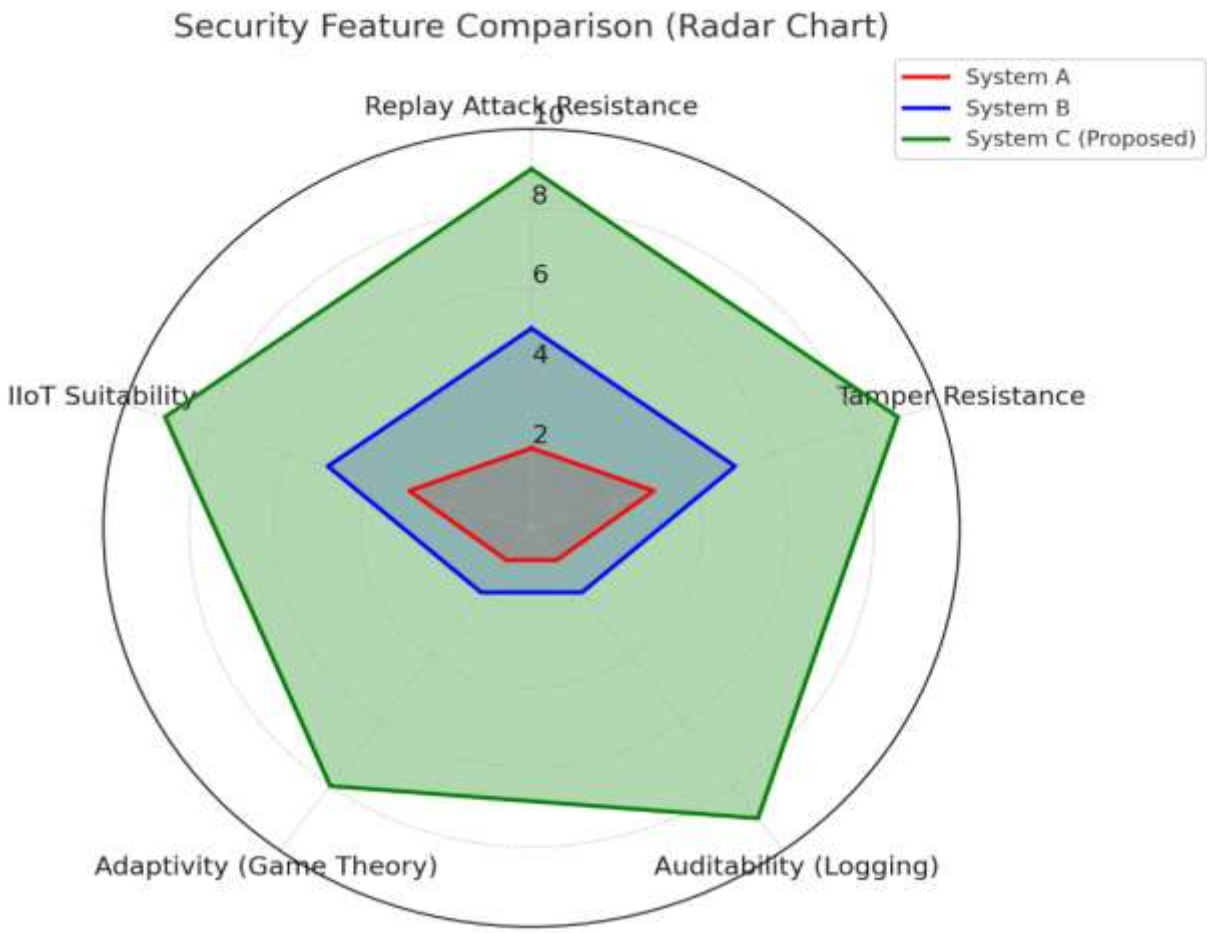


Fig 6.2.1: Security Feature Comparison (Radar Chart)

The radar chart compares five critical security-related parameters: Replay Resistance, Tamper Resistance, Auditability via Blockchain, Game-Theoretic Adaptivity, and Suitability for IIoT. The proposed system outperforms both traditional password-based and token-based methods across all parameters, indicating a more comprehensive and future-ready authentication approach.

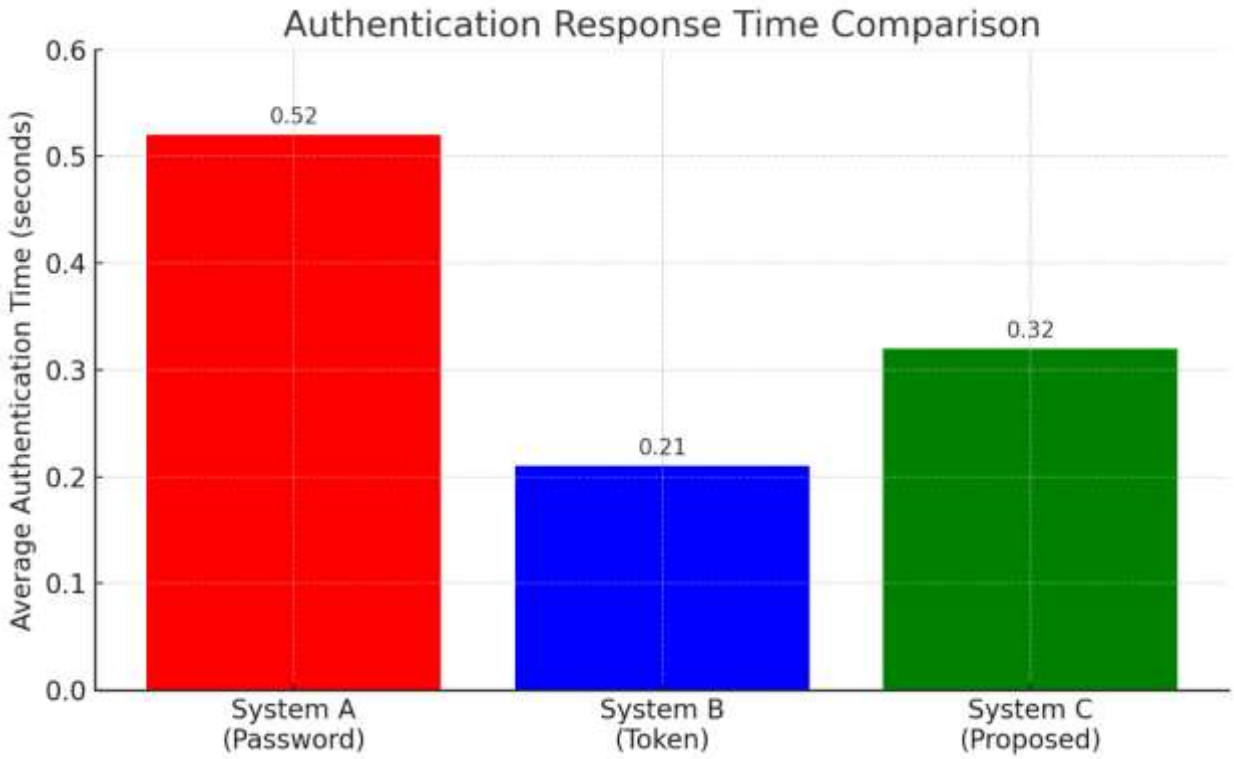


Fig 6.2.2: Authentication Response Time Comparison (Bar Chart)

This bar chart illustrates the average time taken by each system to complete an authentication request. While the token-based method is fastest, the proposed system maintains competitive speed while providing far greater security through dynamic challenge-response, PUF integration, and blockchain logging.

6.3 Interpretation of Results

i. System A (Password-based authentication) is the simplest but also the weakest. It lacks encryption at the device level and is highly vulnerable to credential theft and replay attacks. It also requires human intervention, making it less scalable for automated IIoT systems.
ii. System B (Token-based or pre-shared key authentication) is moderately secure and faster than System A but still limited in dynamic adaptability. Static tokens are prone to leakage, and there's no inherent mechanism for learning or decision optimization.
iii. System C (Proposed System) excels in all critical areas:

- The PUF-based challenge-response makes device spoofing and cloning nearly impossible.
- Integration with blockchain ensures that authentication logs are immutable and auditable.
- Game theory introduces adaptive authentication decision-making that evolves based on previous interactions and threat levels.

- The architecture is designed for scalability and real-time execution, making it suitable for Industrial IoT environments.

iv. While System C has slightly higher computational and implementation overhead, the security and adaptability benefits outweigh the cost, especially in critical IIoT applications like smart grids, industrial automation, and healthcare.

6.4 Conclusion of Comparative Study

The comparative analysis clearly demonstrates that the proposed system is more robust, scalable, and secure than traditional approaches. By integrating PUFs, blockchain, and game-theoretic decision models, the system provides an advanced, adaptive authentication solution tailored for the needs of the Industrial IoT domain. It maintains operational efficiency while significantly improving protection against spoofing, replay attacks, and insider threats, making it highly suitable for deployment in critical infrastructure and smart industry environments.

7. CONCLUSION, LIMITATIONS AND FUTURE WORK

7.1 Conclusion

This project presents a robust and scalable authentication framework for Industrial Internet of Things (IIoT) environments by integrating Physically Unclonable Functions (PUFs), blockchain-based logging, and game theory–based adaptive decision-making. The implementation leverages lightweight Python-based modules using Flask for server communication and SQLite for local credential storage, making the system both portable and efficient.

Through comprehensive testing and scenario-based validation, the system has demonstrated high reliability in authenticating known devices, effectively rejecting unauthorized access attempts, and resisting replay and spoofing attacks. The use of PUF-based challenge-response ensures that authentication is tied to unique hardware characteristics, while blockchain integration guarantees immutability and traceability of authentication logs. Additionally, the application of game theory (Nash Equilibrium) introduces intelligent adaptivity, allowing the system to respond dynamically to observed threat patterns, thereby reducing false positives and improving authentication decisions.

Comparative analysis further confirms the superiority of the proposed system over traditional password- and token-based methods in terms of security, IIoT suitability, and attack resilience, with only a minimal trade-off in processing time. This project not only enhances IIoT security but also lays the groundwork for more intelligent, decentralized, and context-aware authentication mechanisms.

7.2 Limitations

While the project demonstrates promising results, certain limitations must be acknowledged:

i. Simulated PUF Logic:
The PUF implementation in this project is simulated using software-based hash functions (SHA-256). Although it mimics hardware-level uniqueness, it does not fully capture the noise characteristics or physical tamper resistance of actual hardware PUFs.
ii. Centralized Deployment:
The current implementation uses a single-node Flask server and local SQLite database, which limits horizontal scalability and introduces a single point of failure in real-world deployment.
iii. No Real-Time Attack Dataset:
The game-theoretic adaptation has been modeled using predefined rules. It does not yet utilize real-time threat intelligence or behavioral datasets for dynamic learning and decision-making.
iv. Limited GUI/UX for Admin or Monitoring:
The system currently operates through command-line interfaces without any administrative dashboard or user-friendly interface for real-time monitoring, which may affect usability in industrial settings.
v. Lack of Post-Quantum Cryptography (PQC):
As quantum computing evolves, authentication models based on classical cryptographic assumptions may become vulnerable. The current system does not account for quantum threats.

7.3 Future Work

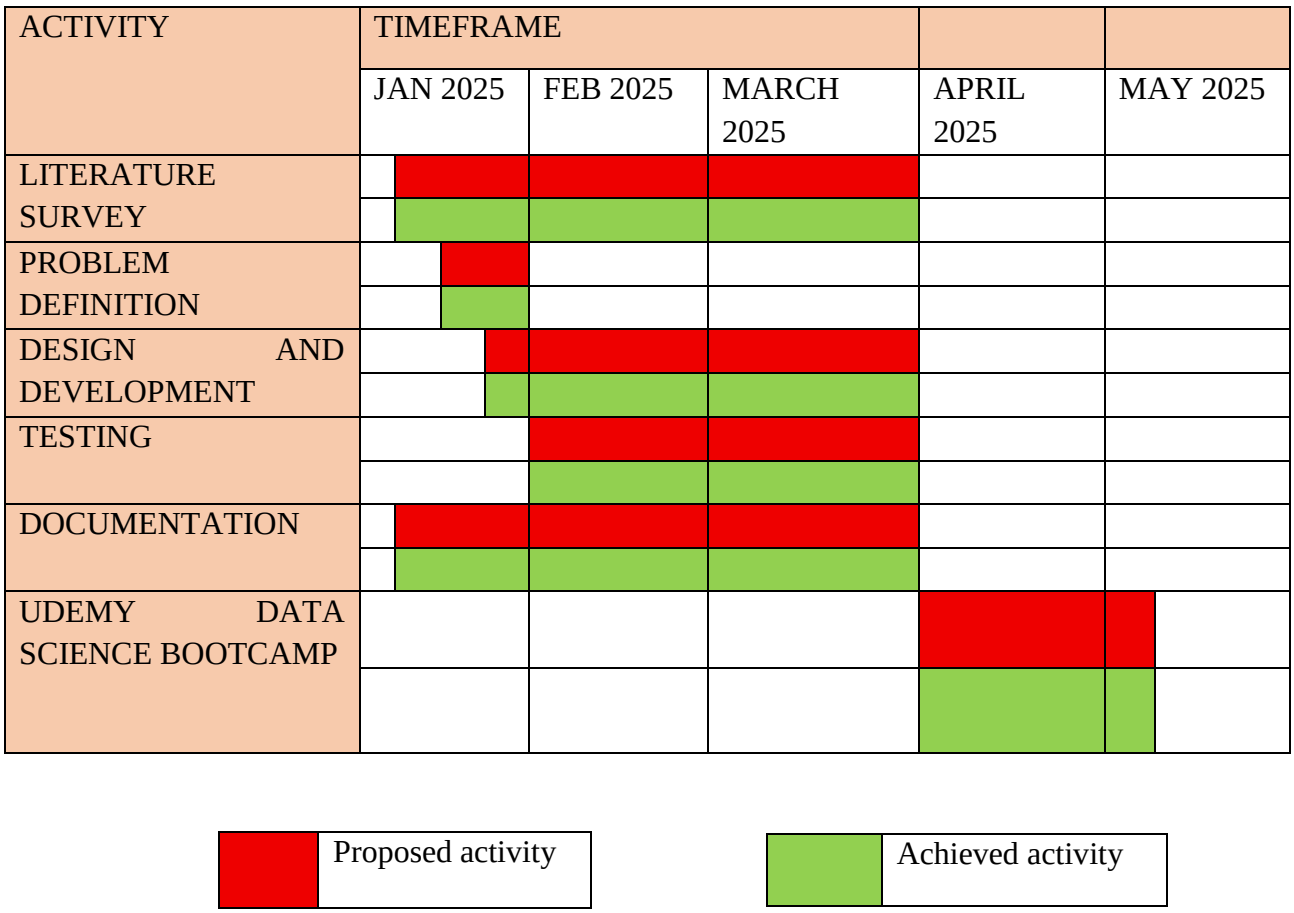
While the proposed system meets its primary goals, there are several opportunities for further enhancement and real-world deployment:
i. Integration with Full Blockchain Networks:
Currently, the blockchain component is designed as a placeholder for smart contract interaction. In future iterations, actual integration with Ethereum, Hyperledger, or private consortium blockchains will allow fully decentralized and tamper-proof authentication event logging.
ii. Advanced Game Theory Models:
Expanding the model to include repeated dynamic games, Bayesian games, or Stackelberg strategies could allow the system to adapt even more intelligently to changing adversarial behavior in real time.
iii. Real Hardware-Based PUFs:
The current PUF logic is simulated using SHA-256. Incorporating real hardware-based PUF modules (e.g., SRAM or ring oscillator PUFs) would make the system even more secure and resistant to physical cloning or side-channel attacks.
iv. PostgreSQL and Cloud Database Migration:
To scale beyond local use, migrating from SQLite to cloud-native databases like PostgreSQL or AWS RDS would make the system production-ready and capable of supporting thousands of devices.
v. Edge Computing Deployment:
Deploying lightweight versions of the authentication system on Raspberry Pi, ESP32, or industrial edge gateways would allow decentralized and faster authentication in factory or field environments.

vi. Integration with AI for Threat Detection:
Future versions can incorporate AI/ML models to analyze behavioral patterns, detect anomalies, and assist the game-theoretic engine in adaptive decision-making against zero-day attacks.
vii. Mobile Dashboard for Real-Time Monitoring:
An administrative mobile/web dashboard can be developed to visualize authentication attempts, device statuses, and live security alerts from the field.

7.4 Summary

In conclusion, this project establishes a forward-looking IIoT authentication model that aligns with the demands of modern cyber-physical systems. Despite a few current limitations, the system serves as a foundational step toward building intelligent, tamper-resistant, and self-adaptive authentication mechanisms for the industrial internet. With further enhancements and real-world testing, it holds strong potential for deployment in smart factories, critical infrastructure, and large-scale industrial networks.

8. GANTT CHART



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