SECURE LIGHTWEIGHT AUTHENTICATION FOR INTERNET OF THINGS

M.Tech Thesis

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under the guidance of

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CERTIFICATE

This is to certify that M.Tech Thesis entitled **Secure Lightweight Authentication for Internet of Things** which is submitted by Harshit Tyagi, Roll No - 23/SWE/08, Department of Software Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of degree Master Of Technology (Software Engineering) is a record of the candidate work carried out by him under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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CANDIDATE'S DECLARATION

I Harshit Tyagi (23/SWE/08) hereby declare that the work which is being presented in the thesis entitled **Secure Lightweight Authentication for Internet of Things** in partial fulfilment of the requirements for the award of the degree of Master Of Technology submitted in the Department of Software Engineering, Delhi Technological University is a bonafide record of my own work carried out during the period from August 2023 to June 2025 under the supervision of Dr. Divyashikha Sethia.

The material contained in the thesis has not been submitted by me for the award of any other degree of this or any other institute.

Date: 20 May 2025

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Candidate's Signature

This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

The proliferation of Internet of Things (IoT) devices across various domains has introduced new challenges in ensuring secure and efficient communication over inherently insecure networks. Authentication protocols in such environments must balance robustness, lightweight execution, and resilience against evolving attack vectors. Given the limitations of conventional schemes in resource-constrained and high-risk settings, this thesis report presents two novel contributions designed to enhance authentication security in IoT ecosystems through cryptographic and architectural innovations.

As part of this effort, the first contribution targets security enhancement in Internet-of-Medical-Things (IoMT) scenarios. Robust schemes are particularly critical in such settings due to the transmitted data's sensitivity and resource-constrained device limitations. While Masud et al. proposed a protocol for securing data in IoMT networks, their approach remains vulnerable to offline password-guessing and privileged insider attacks, posing serious privacy and patient safety risks. To address these issues, this report proposes a novel protocol, *P-MASFEP* (security-enhanced PUF (Physically Unclonable Functions)-based Mutual Authentication & Session key establishment using Fuzzy Extractor & PKI (Public Key Infrastructure)). P-MASFEP integrates PUFs with fuzzy extractors to actively derive stable cryptographic keys from biometric input, mitigating password-guessing risks. It also employs PKI to distribute session keys securely and ensures protection against insider threats through mutual authentication.

The second contribution focuses on overcoming the inherent limitations of a traditional authentication framework, Kerberos. Its traditional design faces challenges in resource-constrained IoT environments, including computational inefficiencies, lack of clock synchronization, and limited scalability. In addition to these limitations, Kerberos remains vulnerable to several modern attacks such as password-guessing, Kerberoasting, Golden Ticket, and Silver Ticket attacks. Prapty et al.'s *KESIC*, adapts Kerberos for IoT by introducing optimizations. However, it relies on symmetric cryptography for authentication and key exchange. Additionally, it remains susceptible to password-based attacks, necessitating a more secure approach. This work proposes two novel protocols to address these issues: (1) *Kerberos with FIDO (Fast Identity Online) Integration (KFI)*, which integrates FIDO's passwordless authentication to eliminate password-derived vulnerabilities; and (2) *Kerberos with FIDO and Lightweight extension for IoT (KFLIT)*, which extends KFI by incorporating lightweight HMAC and XOR operations to reduce computational overhead, counter-based synchronization to eliminate dependency on real-time clocks, and an attestation mechanism to verify IoT device integrity before granting access.

Together, the proposed solutions address critical gaps in current authentication mechanisms for constrained environments. By tackling domain-specific (IoMT) and general-purpose (IoT) challenges, this report contributes to building a secure and scalable authentication foundation for next-generation connected systems.

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Chapter 1

Introduction

The Internet of Things (IoT) has transformed how devices interact and exchange data across domains such as healthcare, industrial automation, and smart cities. This paradigm shift enables seamless, real-time communication between heterogeneous devices, offering automation, efficiency, and enhanced decision-making capabilities. One of the most impactful verticals emerging from this revolution is the Internet of Medical Things (IoMT), which integrates IoT technology into medical systems to facilitate remote monitoring, diagnosis, and treatment [1, 2].

However, this hyperconnectivity brings forth substantial security and privacy concerns. IoT devices operate in resource-constrained environments with limited computational power, memory, and battery life. Furthermore, they are frequently exposed to open or semi-trusted networks, making them vulnerable to a wide range of attacks [3, 4]. In a sensitive domain such as IoMT, these vulnerabilities become particularly alarming as they can lead to unauthorized access to patient records, manipulation of medical data, and even disruption of critical services, potentially endangering patient lives [5–7].

In response, the research community has proposed several lightweight authentication protocols to mitigate these threats while maintaining efficiency in constrained environments. Many schemes leverage cryptographic primitives such as Physically Unclonable Functions (PUFs), biometric-based key generation, and optimized handshake procedures to ensure secure access with minimal overhead [8–10]. One notable contribution is Masud et al.'s Mutual Authentication and Secret Key (MASK) protocol [11], which combines hash functions, nonces, and XOR operations for mutual authentication in IoMT. While MASK achieves efficiency and resistance to many known attacks, it remains susceptible to offline password guessing and insider threats.

Simultaneously, efforts have been made to adapt well-established and robust protocols like Kerberos to meet the security demands of modern IoT environments. Initially designed for enterprise networks, Kerberos offers strong mutual authentication through a ticket-based mechanism [12, 13]. However, its reliance on synchronized timestamps, computationally intensive encryption, and password-based logins makes it unsuitable for IoT ecosystems, where real-time clocks and resource availability are limited [14]. To overcome these limitations, researchers have proposed enhancements such as integrating biometric credentials [15], adopting public key cryptography [16], and employing HMAC-based cryptography with counter synchronization [17]. While these modifications improve efficiency, many still inherit Kerberos' susceptibility to password-based attacks, including Kerberoasting, Silver Ticket, and Golden Ticket exploits [18–20].

Against this backdrop, the need for authentication schemes that are both lightweight and resilient against modern threats has become paramount. This thesis explores two such advanced protocols: one that enhances lightweight mutual authentication using fuzzy extractors and PKI for secure IoMT deployments and another that reimagines Kerberos with FIDO-based passwordless authentication and IoT-focused optimizations. Together, these solutions aim to contribute toward building secure, scalable, and practical authentication mechanisms for the evolving landscape of interconnected devices.

1.1 Background

Several authentication protocols have been proposed to address the security concerns in IoT environments. Alladi et al. [9] proposed a low-power Healthcare Authentication protocol using resource-constrained IoT devices (HARCI). The protocol leverages PUFs to generate secure session keys for two-way authentication and ensures end-to-end security between network devices using distinct session keys. Ashraf et al. [8] highlighted the importance of secure remote user authentication to protect sensitive data in healthcare. Their protocol emphasizes lightweight cryptographic techniques to reduce computational overhead and transmission costs while maintaining authorized access. Gaba et al. [10] proposed a Lightweight Key Exchange (LKE) protocol for the fast-evolving Industrial Internet of Things (IIoT) using certificate renewal to ensure robust security. Gope et al. [21] designed a physically secure key establishment scheme for Industrial Wireless Sensor Networks (IWSNs), aiming to enhance the reliability and trustworthiness of network communications. Shao et al. [22] developed a secure PUF-based authentication protocol tailored for Wireless Medical Sensor Networks (WMSNs) to safeguard patient data. Masud et al. [11] introduced the Mutual Authentication and Secret Key (MASK) protocol, which utilizes lightweight cryptographic primitives such as one-way hash functions, nonces, PUFs, and bitwise XOR operations to provide secure communication in IoT-based healthcare.

To adapt widely used and well-established protocols such as Kerberos to the demands of IoT environments and modern security challenges, researchers have proposed various enhancements to reduce its computational and synchronization overhead. Downard [16] extended Kerberos using public-key cryptography (PKC), replacing password-based authentication with digital signatures to improve scalability. Han et al. [15] enhanced Kerberos for mobile computing by embedding watermarks derived from session keys into fingerprint images, linking user biometrics with device credentials. Tbatou et al. [23] tackled password-guessing vulnerabilities by integrating Diffie-Hellman key exchange with dynamic salt generation, providing stronger resistance against brute-force attacks. Kadhim et al. [24] introduced a scheme combining biometric data with dynamic virtual passwords, enhancing login security while minimizing public-key computation. In a step towards IoT-specific adaptation, Prapty et al. [17] proposed KESIC, which replaces traditional encryption with HMAC operations and introduces counter-based synchronization in place of timestamp dependency—optimizing Kerberos for resource-constrained IoT environments.

1.2 Problem Statement

With IoT's expansion, particularly in critical sectors like healthcare, ensuring secure yet lightweight authentication has become a significant challenge. Protocols such as MASK [11] have made notable strides using lightweight primitives like hash functions, PUFs, and XOR operations to enable secure communication in IoMT environments. While MASK defends against several common threats, including replay, MITM, and cloning attacks, it remains vulnerable to offline password-guessing and privileged insider threats—two highly critical attack vectors in medical systems [25, 26]. Furthermore, MASK suffers from session continuity issues due to identity update mechanisms, potentially causing legitimate authentication attempts to fail. These shortcomings highlight the need for more secure, context-aware authentication mechanisms for IoMT deployments.

In parallel, Kerberos remains a well-established protocol for authenticating users over traditional networks [12]. However, it was not designed for IoT ecosystems, where devices operate under severe resource constraints and lack reliable time synchronization. Kerberos's reliance on password-based authentication makes it susceptible to advanced attack techniques like Kerberoasting [18], Silver Ticket, and Golden Ticket attacks [19,20]. Additionally, its computationally intensive encryption and dependence on synchronized timestamps make it ill-suited for constrained IoT devices. These limitations call for a fundamental rethinking of Kerberos' architecture to adapt it for secure, scalable, and lightweight operation in modern distributed environments.

1.3 Proposed Solution

To address the security limitations of the MASK protocol [11] in IoMT environments, this report introduces *P-MASFEP* (security-enhanced PUF (Physical Unclonable Functions)-based Mutual Authentication & Session key establishment using Fuzzy Extractor & PKI(Public Key Infrastructure)). The fuzzy extractor [27] strengthens resistance against offline password-guessing attacks by deriving stable cryptographic keys from noisy biometric inputs. Once the user's authenticity is verified, the protocol establishes a session key that is securely shared using PKI [28], thereby preventing privileged insider attacks. Combining biometric resilience with asymmetric cryptography, P-MASFEP ensures strong mutual authentication and secure communication tailored to resource-constrained and high-risk medical IoT environments.

To overcome the limitations of traditional Kerberos in IoT ecosystems, this report further proposes *KFLIT* (Kerberos with FIDO and Lightweight extension for the Internet of Things). As a foundational step, *KFI* (Kerberos with FIDO Integration) is developed by replacing password-based authentication with FIDO's passkey mechanism, thus eliminating vulnerabilities such as Kerberoasting [18], Silver Ticket [19], and Golden Ticket attacks [20]. *KFLIT* extends KFI by optimizing the protocol for resource-constrained IoT environments. It replaces computationally heavy encryption with lightweight HMAC and XOR operations to reduce processing overhead and employs counter-based synchronization to eliminate the need for real-time clocks. An attestation mechanism is introduced in the initial authentication phase to verify IoT device integrity before access is granted.

These enhancements make KFLIT a secure, scalable, and efficient authentication framework suited for diverse IoT applications.

1.4 Contributions

This report aims to design and evaluate lightweight and secure authentication protocols suitable for IoT environments. The contributions are divided into two parts based on the proposed protocols: *P-MASFEP* for IoMT security and *KFLIT* for general IoT authentication. The contributions of the report are as follows:

1. P-MASFEP

1. Investigate existing authentication protocols in the context of IoMT, focusing on PUF-based schemes, lightweight key exchanges, and privacy-preserving remote authentication.

2. Analyze the MASK protocol [11], highlighting its susceptibility to offline password guessing, privileged insider threats, and identity update failure.

3. Proposal of P-MASFEP, a lightweight authentication protocol that combines PUFs, fuzzy extractors, and PKI to establish secure session keys and defend against insider and password-based attacks [27, 28].

4. Validate P-MASFEP through informal security analysis, comparative performance evaluation with MASK, and formal protocol verification using the Scyther tool [29, 30].

2. KFLIT

1. Examine the limitations of traditional Kerberos authentication in IoT, particularly its reliance on passwords, timestamp synchronization, and encryption-heavy operations [17, 18, 31].

2. Proposal for KFI and KFLIT, Kerberos-based protocols that eliminate password dependence using FIDO and incorporate lightweight HMAC and XOR operations for secure authentication in IoT [32].

3. Evaluate KFLIT through informal security analysis, comparison with KESIC [17], and formal verification using the Scyther tool [29, 30].

1.5 Thesis Layout

This thesis is organized into six chapters. Chapter 2 presents the technical background. Chapter 3 introduces the proposed P-MASFEP protocol. Chapter 4 discusses the KFLIT protocols. Chapter 5 provides the results. Finally, Chapter 6 concludes the thesis with key insights and outlines potential directions for future work.

Chapter 2

Technical Background

This chapter presents the foundational technologies and security principles underpinning the design of the proposed authentication protocols, P-MASFEP and KFLIT. Given the unique challenges in securing resource-constrained IoT environments, it is essential to understand the tools and mechanisms that enable secure, lightweight, and scalable authentication.

2.1 Physically Unclonable Functions (PUFs)

Physically Unclonable Functions (PUFs) are entities embedded in physical structures (e.g., integrated chips) that use a Challenge-Response Pair (CRP) mechanism to generate a unique response based on inherent physical attributes of the silicon [33]. These unpredictable physical variations arise during manufacturing, making each PUF instance unique and resistant to duplication. PUFs exhibit properties similar to one-way hash functions—when the same challenge is fed as input to a PUF, it consistently generates the same response, ensuring repeatability under stable environmental conditions. Moreover, if the same challenge is applied to different devices, the responses will differ due to the distinct physical characteristics of each chip. This uniqueness provides a strong defense against cloning and physical attacks, making PUFs an excellent lightweight security primitive for IoT and embedded devices [34].

PUF-based authentication involves two main phases: enrollment and authentication. During the enrollment phase, the device's PUF interacts with the server, which issues a sequence of challenges and records the corresponding responses. These CRPs are securely stored in a database. Later, during authentication, the server sends a random challenge to the device. The device computes a response using its internal PUF and returns it to the server. If the response matches the enrolled value, the device is considered genuine. If not, the authentication fails. This CRP-based model enables lightweight, hardware-rooted authentication without storing sensitive keys on the device.

PUFs offer inherent resistance to physical and invasive attacks since the response behavior is deeply tied to uncontrollable silicon-level properties. Additionally, PUFs are highly advantageous in resource-constrained IoT environments due to their minimal hardware overhead and ability to generate volatile, on-demand secrets without relying on secure memory [35,36]. These features have made PUFs increasingly popular in secure embedded system design and lightweight cryptographic protocols.

2.2 Fuzzy Extractor (FE)

The fuzzy extractor (FE) is a cryptographic technique designed to resist offline password-guessing attacks by extracting robust cryptographic keys from noisy and non-deterministic biometric data [27]. Biometric traits such as fingerprints, iris scans, or voice patterns are inherently variable due to environmental factors, sensor inaccuracies, or user conditions. Unlike passwords or tokens, these biometrics cannot be reproduced identically each time. Therefore, a mechanism is needed to consistently extract the same secret from similar but not identical inputs—this is where fuzzy extractors prove essential. Without compromising security, FE can derive stable cryptographic keys from inputs close to, but not the same as, the original. It allows legitimate users to be authenticated even when the biometric reading slightly varies, thus supporting real-world usability while resisting brute-force attempts.

The FE consists of two core algorithms: Key Generation ($FE.Gen$) and Key Reconstruction ($FE.Rec$). In the key generation phase, the algorithm takes an original biometric input (BIO_i) and generates a secure cryptographic key (K) along with public helper data (h_d). This helper data is designed to leak minimal information about BIO_i, preserving the secrecy of the key. In the reconstruction phase, even if a slightly noisy version of the original biometric (BIO_i') is provided, the algorithm uses the stored h_d to regenerate the same key K ensuring robustness and resilience to noise in biometric readings, making FE ideal for scenarios like secure device authentication in IoMT and IoT systems.

Fuzzy extractors are increasingly being used in combination with Physically Unclonable Functions (PUFs) and public-key cryptography to build lightweight authentication mechanisms that are resistant to password-related threats and side-channel attacks, particularly in healthcare and embedded environments [34, 36].

2.3 Public Key Infrastructure (PKI)

Public Key Infrastructure (PKI) ensures that data exchanged over untrusted networks, such as the Internet, remains secure and trustworthy. PKI provides a framework that enables encryption, digital signing, and identity verification through a combination of cryptographic elements and trust hierarchies. It uses components like digital certificates, certificate authorities (CAs), registration authorities (RAs), and key pairs to establish and verify the authenticity of communicating entities.

At the core of PKI lies the concept of asymmetric cryptography, which uses a public-private key pair. These keys are mathematically linked but computationally infeasible to derive one from the other [28,37]. The public key is openly shared and used for encryption or signature verification, while the private key is kept secret and used for decryption or signing. When users wish to send encrypted data, they retrieve the recipient's public key (typically embedded in a digital certificate issued by a trusted CA). This public key encrypts the data, resulting in a ciphertext that only the corresponding private key can decrypt. Since only the intended recipient possesses the private key, confidentiality is preserved. This same infrastructure also allows users to digitally sign messages, ensuring integrity and non-repudiation, which is critical in sensitive domains such as e-governance, healthcare, and secure device communication.

PKI is foundational in modern IoT and IoMT authentication schemes, especially those involving mutual authentication and secure session key establishment. By integrating PKI, systems can resist man-in-the-middle (MITM) attacks and privileged insider threats by confirming the legitimacy of every party involved in a transaction. Thus, PKI supports encryption and facilitates trusted identity binding in complex network environments, making it a cornerstone of secure communication architectures [28, 37].

2.4 Mutual Authentication and Key Establishment General Scheme

In a general IoMT-based services setting, a typical setup unfolds in two pivotal phases: user device and sensor node registration, mutual authentication, and session key establishment. Fig. 2.1 illustrates the general scheme.

In phase 1, the gateway initiates the registration process for both the user device and the sensor node. The user device retrieves its unique ID and prompts the user to enter a password. Upon receiving this information, the gateway registers the user's device and stores the password for future verification. The gateway sends a registration request to the sensor node, and the node responds with its unique ID. The gateway uses this ID to complete the node's registration.

In phase 2, the user is required to enter their password. The gateway verifies the user's identity by checking the accuracy of the password. After successful authentication, the user device sends its identity to the gateway. The gateway verifies the message to ensure the user's device is authentic. Similarly, the gateway sends its identity to the user device, which verifies the gateway's authenticity. Subsequently, the sensor node and server mutually authenticate each other. The gateway then generates a session key and safely distributes it to the user's device and the sensor node. This comprehensive structure ensures secure device registration, mutual authentication, and session key establishment, enabling safe communication.

2.5 Fast Identity Online (FIDO)

The Fast Identity Online (FIDO) authentication mechanism replaces traditional password-based authentication with a secure, public-key cryptography-based framework [32]. This passwordless approach enhances security and usability by mitigating risks such as phishing, credential theft, and replay attacks. The user device (UD) generates a unique public-private key pair during the registration phase. The private key ($FIDO\text{-}Priv_{UD}$) is securely stored in a hardware-based FIDO authenticator (e.g., USB token, biometric-enabled device), while the corresponding public key ($FIDO\text{-}Pub_{UD}$) is registered with the authenticator server (AS) and associated with the identity of UD.

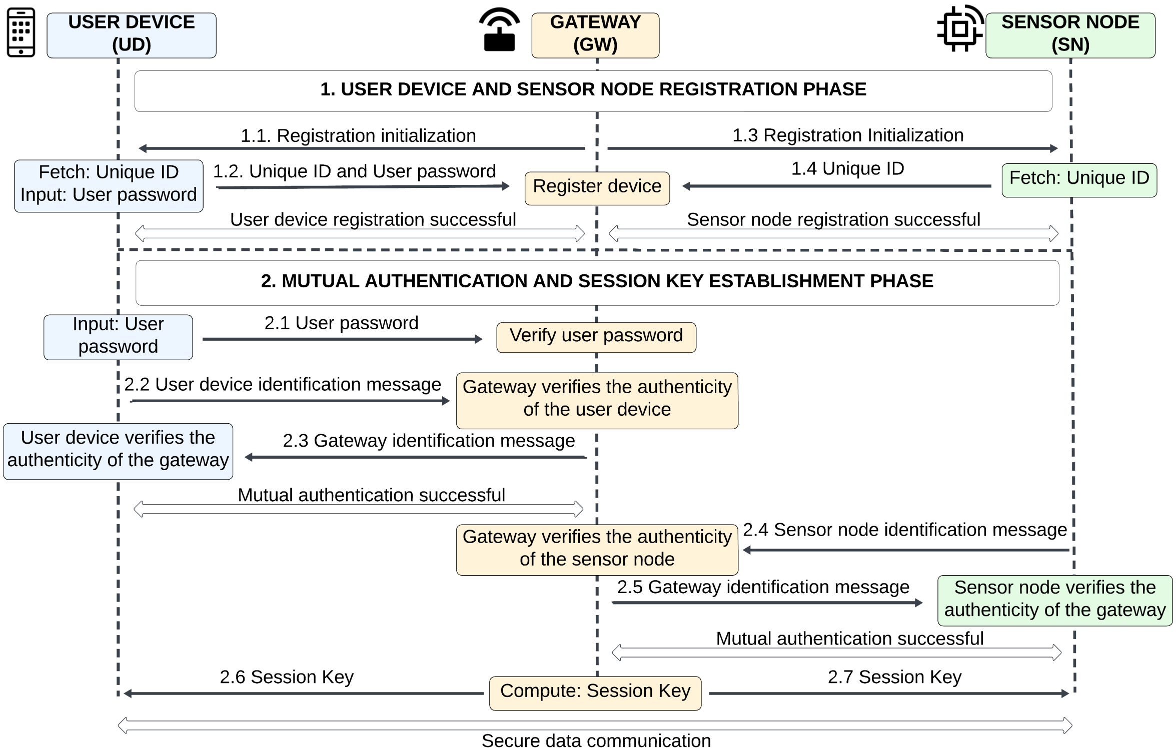

Figure 2.1: Mutual authentication and key establishment general scheme.

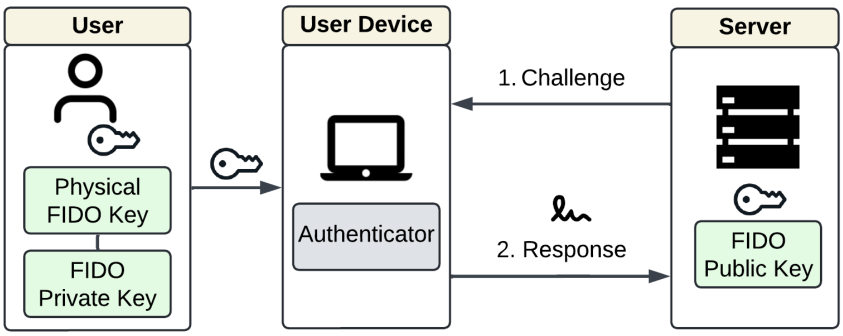

Figure 2.2: FIDO authentication process.

Fig. 2.2 illustrates the authentication process. AS issues a challenge to UD, which signs it using $FIDO\text{-}Priv_{UD}$ stored in the FIDO key. UD then sends the signed response back to AS, which verifies it using $FIDO\text{-}Pub_{UD}$. Successful verification authenticates UD securely and without transmitting any password.

1. ***Challenge:*** AS sends a cryptographic challenge ($Challenge_{AS,UD}$) to UD.

2. ***Response:*** The user inserts the physical FIDO key into UD, enabling the authenticator to compute a digital signature using $FIDO\text{-}Priv_{UD}$. UD sends the signed response back to AS, which verifies it using $FIDO\text{-}Pub_{UD}$. If the verification succeeds, AS authenticates UD.

This two-step authentication process—challenge issuance followed by signed response verification—ensures mutual trust without ever transmitting or storing user credentials. By replacing shared secrets with cryptographic key pairs, FIDO delivers a strong, phishing-resistant, scalable authentication framework. It is particularly well-suited for modern security architectures in distributed and resource-constrained environments such as IoT and enterprise systems [32].

2.6 Kerberos Authentication Protocol

Kerberos is a symmetric-key-based network authentication protocol designed to securely verify user identities over insecure networks [12]. It employs a trusted Key Distribution Center (KDC), composed of the Authenticator Server (AS) and Ticket Granting Server (TGS), to facilitate mutual authentication between a User Device (UD) and a Target Device (TD). The protocol ensures secure access by issuing time-limited encrypted tickets and never transmitting plaintext passwords across the network.

During the pre-registration phase, UD securely registers with KDC by sharing ID_{UD} and password. KDC derives a long-term symmetric key $K_{UD,AS}$ from the password, typically using a one-way cryptographic hash function. This key is securely stored and used later for authenticating UD without exposing the password over the network. However, this design is susceptible to offline password-guessing attacks. If an attacker captures an encrypted message protected by $K_{UD,AS}$, they can attempt to brute-force it offline. Fig. 2.3 illustrates the process. The notation used is summarised in Table 4.2. The Kerberos authentication process consists of the following steps:

1. ***Pre-Registration Phase:*** UD registers with KDC over a secure channel by submitting its identity (ID_{UD}) and password. KDC derives the long-term symmetric key ($K_{UD,AS}$ = Hash(Password)), which is securely stored and later used for authentication [38].

2. ***Authentication Request:*** To initiate authentication, UD sends an authentication request ($Req_{UD,AS} = ID_{UD} \parallel ID_{TGS} \parallel TS_{UD,AS}$) to AS. AS retrieves $K_{UD,AS}$ and generates a TGT and a session key ($k_{UD,TGS}$), then computes the ticket, $TGT = E_{K_{TGS,AS}}[k_{UD,TGS} \parallel ID_{UD} \parallel AD_{UD} \parallel ID_{TGS} \parallel L_2 \parallel TS_{AS,UD}]$ and $Res_{AS,UD} = E_{K_{UD,AS}}[TGT \parallel k_{UD,TGS}]$, which is sent to UD [39].

3. ***TGT Issuance:*** Upon receiving $Res_{AS,UD}$, UD decrypts it using $K_{UD,AS}$ to obtain $k_{UD,TGS}$ and TGT. TGT remains encrypted under $K_{TGS,AS}$, ensuring that UD cannot read or alter its contents [40].

4. ***Service Ticket Request:*** UD generates $A_{UD,TGS} = E_{k_{UD,TGS}}[ID_{UD} \parallel AD_{UD} \parallel TS_{UD,TGS}]$ and sends $Req_{UD,TGS} = ID_{TD} \parallel TGT \parallel A_{UD,TGS}$ to TGS, which decrypts and validates the TGT using $K_{TGS,AS}$ and the authenticator using $k_{UD,TGS}$ [40].

5. ***Service Ticket Issuance:*** TGS generates a session key ($k_{UD,TD}$) and constructs the service ticket ($T_{TD} = E_{K_{TD,TGS}}[k_{UD,TD} \parallel ID_{UD} \parallel AD_{UD} \parallel ID_{TD} \parallel TS_{TGS,UD} \parallel L_4]$) and response ($Res_{TGS,UD} = E_{k_{UD,TGS}}[T_{TD} \parallel k_{UD,TD}]$), which is sent to UD.

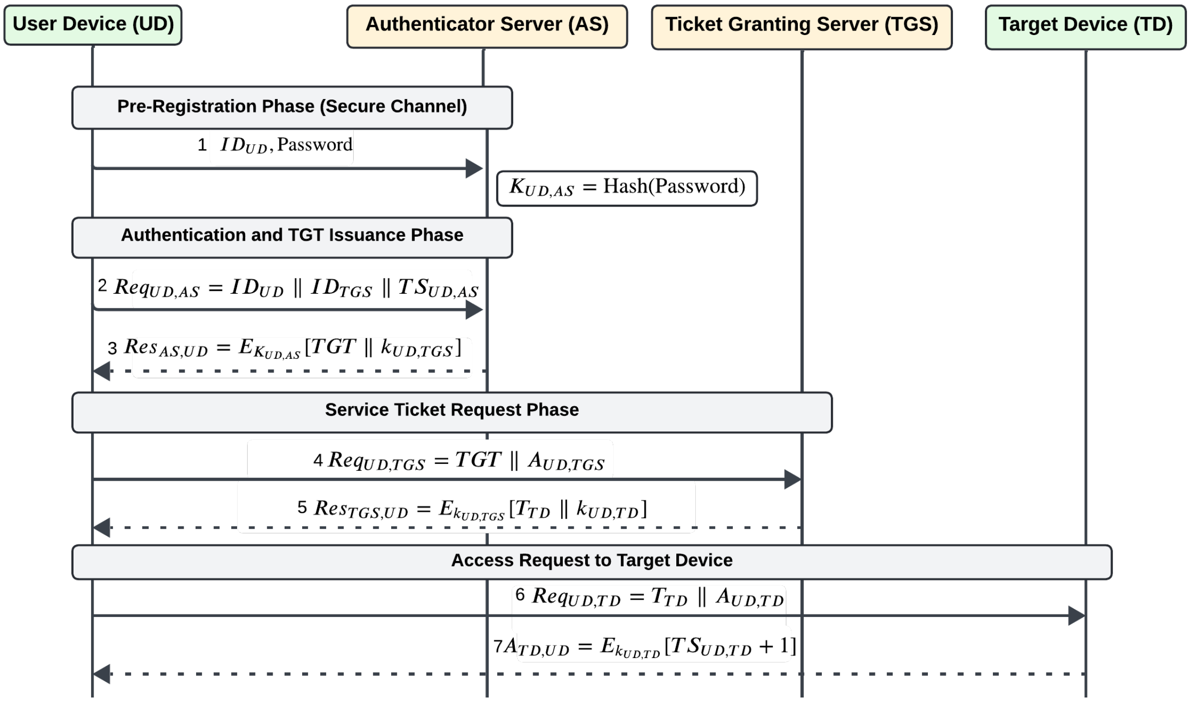

Figure 2.3: Kerberos steps.

6. ***Access Request to Target Device:*** UD decrypts $Res_{TGS,UD}$ to retrieve $k_{UD,TD}$ and T_{TD}, and constructs an authenticator ($A_{UD,TD} = E_{k_{UD,TD}}[TS_{UD,TD}]$). It then sends $Req_{UD,TD} = T_{TD} \parallel A_{UD,TD}$ to TD.

7. ***Target Device Validation and Access Granting:*** TD decrypts T_{TD} using $K_{TD,TGS}$ and verifies $A_{UD,TD}$ using $k_{UD,TD}$. Upon successful verification, it responds with $A_{TD,UD} = E_{k_{UD,TD}}[TS_{UD,TD} + 1]$ to confirm mutual authentication and grants UD access [40].

In summary, Kerberos provides a secure and efficient authentication protocol by leveraging symmetric key cryptography and time-bound tickets to enforce mutual trust and protect against credential theft. However, its dependence on password-derived keys exposes it to offline password-guessing attacks, particularly if long-term keys are compromised. Moreover, the reliance on synchronized timestamps and computationally intensive encryption operations can hinder its applicability in resource-constrained IoT environments. These limitations motivate the need for enhanced variants of Kerberos, such as the proposed KFI and KFLIT protocols, which strengthen authentication security while maintaining lightweight and scalable performance.

2.7 Scyther Protocol Verification Tool

Scyther is a protocol verification tool used to analyze and verify the security of cryptographic protocols. Cas Cremers [30] created it and used formal techniques, namely symbolic model checking, to evaluate a protocol's correctness and resilience against various security attributes. Using a high-level protocol description language, Scyther enables researchers and developers to define the protocol's behaviour, including its participants, messages sent, and security assumptions. Using automated analysis techniques, Scyther investigates every scenario to find potential security flaws, such as cryptographic flaws, protocol weaknesses, or vulnerabilities to particular attacks, such as impersonation, replay, or MITM attacks [29]. Scyther ensures that cryptographic protocols comply with security requirements and standards by thoroughly examining the protocol's behaviour and comparing it to predetermined security properties. This process yields essential insights into the reliability and efficacy of the protocols in actual deployment scenarios.

2.8 IoT vulnerabilities

1. ***Limited Processing Capabilities and Hardware Restrictions:*** IoT devices have limited processing capacity since manufacturers design them for specific purposes. There is little space left for adding strong security and data protection measures because of this restriction.

2. ***Heterogeneous Transmission Technology:*** Various communication methods are used by IoT devices to connect with the network. This variability makes creating uniform standards and safety precautions for every encounter difficult.

3. ***Gap in User Security Awareness:*** Many consumers are unaware of safeguarding their medical devices. Consumers can expose their devices to potential dangers without their knowledge.

4. ***Weak Physical Security:*** Many components of the IoT-based devices are physically accessible. This lack of physical security makes it more likely that items will be tampered with or that unauthorized individuals will gain access.

2.9 IoT Security Requirements

1. ***Confidentiality:*** One of the most important security goals is maintaining confidentiality since it creates guidelines and standards for limiting who can access what data. Sensitive medical data is better protected when only authorized parties can access important user data.

2. ***Integrity:*** Integrity is the preservation of the accuracy and dependability of data. Retaining data correctness and reliability requires maintaining integrity. Ensuring that instructions sent to the IoT devices or the data these devices receive remain authentic and unchanged.

3. ***Availability:*** It ensures that IoT functionalities are always available to authorized users and linked devices, regardless of when or where they choose to access them.

2.10 IoT Security Threats

1. ***Privileged insider attacks:*** In IoT systems, users with elevated access—such as administrators, service providers, or system integrators—may intentionally or

unintentionally misuse their privileges. Such actions can compromise system integrity, leak sensitive information, or turn off services. Mitigating these threats requires strict access control, role-based authentication, and continuous monitoring mechanisms.

2. ***Offline password guessing attacks:*** Offline attacks occur when an adversary captures encrypted authentication data and attempts to guess passwords without interacting with the target system in real-time. In IoT, where devices may store credentials locally, this can lead to unauthorized access, data leaks, or manipulation of device behaviour. Strong password policies, key derivation functions, and encryption help defend against such threats.

3. ***Replay attacks:*** A replay attack captures legitimate data transmissions and retransmits them to deceive the recipient into accepting duplicated messages. In IoT, this can result in repeated commands, unauthorized access, or data manipulation. Secure timestamping, nonces, and challenge-response mechanisms are essential to prevent these attacks.

4. ***Denial-of-Service (DoS) attacks:*** IoT devices are particularly vulnerable to DoS attacks, where high traffic or requests overwhelm device or network resources, causing service unavailability. Traffic rate limiting, anomaly detection, and robust network design are critical countermeasures [41].

5. ***Man-in-the-Middle (MITM) attacks:*** In MITM attacks, an adversary intercepts communication between two IoT entities, potentially modifying or injecting data to manipulate operations. Secure communication protocols, end-to-end encryption, and digital signatures are necessary defences.

6. ***Impersonation attacks:*** Attackers may spoof the identity of legitimate devices or users to gain unauthorized access to IoT systems. Mitigation strategies include strong mutual authentication, device attestation, and anomaly detection techniques.

7. ***Physical attacks:*** IoT devices are often deployed in uncontrolled or public environments, making them susceptible to tampering, side-channel attacks, or hardware-level exploitation. Adversaries may extract sensitive data or disrupt operations through direct physical access. Tamper-evident enclosures, secure boot mechanisms, and regular firmware updates are essential for protecting physical-layer security.

Chapter 3

Proposed P-MASFEP Protocol

This chapter presents P-MASFEP (PUF-based Mutual Authentication and Session key establishment using Fuzzy Extractor and PKI), a secure and lightweight authentication protocol for IoMT environments. The proposed protocol addresses critical vulnerabilities in existing schemes, including offline password guessing and privileged insider attacks. The chapter introduces the motivation behind developing P-MASFEP, outlines related work, and defines the system and adversary models. It then details the complete design of the protocol, including the registration phase and the mutual authentication with the session key establishment process.

3.1 Motivation

IoMT has recently seen tremendous growth and success. IoMT integrates the healthcare industry with the IoT ecosystem, which enables medical data creation, collection, transmission, and analysis by connecting different healthcare systems and sensors using various technologies such as Wi-Fi, Bluetooth, and cellular networks [1,2]. The patient's medical sensors collect and monitor physiological parameters, wirelessly transmitting the data to the physician's devices. Hence, the doctor can conduct a more thorough patient health assessment based on this data [42].

Although IoMT offers convenient healthcare services to patients, it is imperative to acknowledge that this technological advancement has introduced specific challenges, particularly in the security realm [3]. These encompass a spectrum of concerns, ranging from replay attacks, man-in-the-middle (MITM) attacks, impersonation, privileged insider threats, offline password guessing, and denial of service (DoS) to physical hijacking [4]. Among all possible threats, offline password guessing is the most common vulnerability in many IoMT-based networks for several reasons [25]. The availability of advanced tools, computational resources, and inadequate password regulations allows attackers to repeatedly try passwords without alerts or network shutdown [6]. Unauthorized access can result in several adverse events, including data theft, medical record tampering, and compromising patient privacy and safety [5]. Additionally, attackers may use password-guessed IoMT devices to launch DoS attacks, flooding networks or services with traffic and causing disruptions, resource exhaustion, or service interruptions [5].

Within the IoMT network, insiders like helper staff and administrators have authorized access to medical equipment. Since patients' health records are valuable and already have a foothold in the system, they are attractive candidates for conducting privileged insider attacks to steal patients' medical data [26]. This health data makes purchasing medications, obtaining medical attention, or submitting false medical claims possible. The integrity, confidentiality, and accessibility of patients' medical records and services are jeopardised by these security breaches [7]. Therefore, protecting the security and integrity of IoMT is paramount to prevent such malicious activities and ensure patient safety.

3.2 Objective

Masud et al. [11] suggested a lightweight Mutual Authentication and Secret Key establishment (MASK) protocol for protecting sensitive data in IoMT networks. MASK leverages lightweight cryptographic primitives to confirm the authenticity of the nodes before generating a session key. The scheme prevents many security threats like replay, MITM, cloning, and side-channel attacks.

However, MASK is vulnerable to offline password-guessing and privileged insider attacks, which can cause severe problems by granting unauthorized access to the patient's medical records and threatening life and privacy. The approach also has a device update difficulty. Due to this, even if the user is legitimate, the following protocol run will not be allowed to be executed.

To address the security vulnerabilities in the MASK [11] scheme, this thesis introduces P-MASFEP: security-enhanced PUF-based Mutual Authentication and Session key establishment using Fuzzy Extractor and PKI. The scheme leverages the fuzzy extractor [27], a cryptographic technique that generates secure cryptographic keys from biometrics to resist offline password-guessing attacks. Following lightweight mutual authentication, the session key is generated and securely transmitted to the authenticated physician using public-key cryptography [28], effectively preventing privileged insider attacks.

3.3 Related Work

Alladi et al. [9] proposed a A uthentication protocol using Resource-constrained Internet of Things devices (HARCI) to target healthcare networks that contain devices that are limited in their resources. The protocol uses PUFs to generate secure session keys for two-way authentication between patient devices, patient sensor nodes, and the healthcare cloud server. HARCI provides end-to-end authentication, using distinct session keys at each stage of the authentication process and using the various responses provided by PUFs as challenge inputs. Because the Internet of Things devices typically have limited memory capacity, battery life, and computational power, the protocol addresses the necessity for energy-efficient security solutions in these devices. The scheme is insecure against DoS attacks and faces scalability, resource constraints, security analysis, interoperability, and user privacy limitations.

Ashraf et al. [8] stated that IoT-based intelligent healthcare systems must incorporate secure remote user authentication, which makes it necessary to protect sensitive patient data and improve safe healthcare services in the Internet of Things era. Privacy and security must be appropriately maintained when adopting Internet of Things devices for remote patient monitoring. To lower the costs of calculation and transmission, the Lightweight Privacy-Preserving Remote User Authentication and Key Agreement Protocol solve these problems. For authorized users, such as clinical personnel and medical professionals, the protocol enhances security and allows them to access patient information securely. The protocol could benefit from extensive testing to assess its resilience against advanced cyber threats and attacks. The scheme cannot resist impersonation, privileged insider, cloning and side-channel attacks. Furthermore, exploring the integration of advanced encryption techniques could enhance the security and privacy aspects of the protocol, addressing potential vulnerabilities and ensuring robust protection of sensitive healthcare data.

Gaba et al. [10] introduced a Lightweight Key Exchange (LKE) based on certificate renewal for the rapidly increasing field of the Industrial Internet of Things (IIoT). Faster data accessibility, problem detection, performance analysis, and manager remote machine control are all made possible by Industry 4.0. Despite its advantages, it is risky since the Internet of Things nodes use unprotected wireless networks. The unprotected wireless channel provided many more opportunities for the illegal nodes to obtain information and take over the industrial machinery. Legitimate IoT nodes can exchange keys on a lightweight platform with LKE, which also forbids illegitimate usage. LKE uses lightweight Elliptic Curve Qu-Vanstone (ECQV) based implicit certificates to generate keys and establish confidence between entities. The scheme is not secure against cloning and side-channel attacks. Further investigation is required into the protocol's scalability for large-scale industrial networks, exploring potential vulnerabilities under different attack scenarios and evaluating the protocol's performance in real-world industrial environments.

Gope et al. [21] developed a physically safe, lightweight, anonymous mutual authentication system designed explicitly for Industrial Wireless Sensor Networks (IWSN). IWSNs are a new class of generic wireless sensor networks (WSNs) with limitations on coverage, energy consumption, security, and connectivity. However, security and privacy are two significant concerns because IWSN nodes are Internet-connected and situated in unattended environments with little human intervention. A user's ability to obtain real-time information from the chosen sensor nodes is essential for IWSN. This task requires a protocol for user authentication. The protocol utilizes PUFs and lightweight cryptographic primitives to provide private and secure user authentication in IWSNs. The protocol can increase the reliability and credibility of IWSNs by enhancing their efficiency, security, and privacy in real-time data access. The suggested protocol uses lightweight cryptographic primitives such as bitwise exclusive (XOR) operations, PUF, and one-way cryptographic hash functions. The scheme cannot withstand DoS and privileged insider attacks. According to a security and performance study, the proposed scheme is effective and safe for sensing devices in IWSN that have limited resources. The protocol's resilience to advanced attacks and scalability to accommodate growing sensor nodes must be investigated. Furthermore, the impact of hardware constraints and energy efficiency on the protocol's practical implementation in resource-constrained sensor nodes remains a significant research gap that requires attention.

Shao et al. [22] introduced a unique PUF-based anonymous authentication technique to protect patient data in wireless medical sensor networks (WMSNs). The protocol generates safe session keys while mutually authenticating doctors, sensors, and gateway nodes using cryptographic hash functions, fuzzy extractors, PUFs, and XOR operations. The technique regularly collects data from medical sensors and transports it via gateways to a monitoring centre, enabling real-time patient monitoring. The protocol may benefit from additional analysis and enhancements to address potential vulnerabilities related to insider attacks, desynchronization attacks, and sensor impersonation. Future research could focus on optimizing the communication and computation costs of the scheme to ensure efficient operation in resource-constrained WMSNs while maintaining a high level of security and privacy protection for sensitive medical data.

Masud et al. [11] proposed a lightweight and reliable Mutual Authentication and Secret Key (MASK) setup protocol for protecting sensitive health data in IoMT networks. Since the IoT nodes communicate critical data across the insecure wireless medium between virtual medical facilities, security is a significant concern in IoMT. This paper presents a lightweight, physically secure mutual authentication and secret key establishment protocol that employs PUF. PUF prevents side-channel, cloning, and manipulation attacks on sensor nodes deployed in unsupervised and hostile environments. Its design protects it from side-channel assaults, physical device loss, and security threats. It also ensures resource efficiency. The protocol uses lightweight encryption primitives such as bitwise XOR operations, nonces, PUFs, and one-way hash functions. The method thoroughly examines the adversary model, demonstrating the efficacy and efficiency of the MASK protocol in safeguarding IoMT networks. The scheme prevents many security threats, such as replay, MITM, cloning and side-channel attacks. However, MASK [11] is susceptible to offline password-guessing and privileged insider attacks, which can cause severe problems by granting unauthorized access to the patient's medical information and threatening life and privacy. The approach also has a device update difficulty. After each successful protocol run, the user's device will update the temporary identity. The device calculates the value used to verify the user's legitimacy using the expired identity. Therefore, even if the user is legitimate, the following protocol run will not be allowed to be executed.

Table 3.1: Comparison of authentication schemes for IoMT.

Scheme	**Objective**	**Key Features**
HARCI [9]	Secure healthcare authentication protocol for resource-constrained IoT devices	Three-layered architecture, utilizes PUFs for secure session key generation, separate session keys for each authentication phase
Ashraf et al. [8]	Ensure secure remote user authentication and key exchange in IoT-based healthcare systems	Symmetric session key exchange, lightweight solution, reduces computation and transmission costs, enhances security and privacy for remote patient monitoring
LKE [10]	Provides mutual authentication and secret key establishment for IIoT devices	Lightweight protocol, stresses certificate renewal, ensures message integrity, defends against attacks, preserves data privacy
Gope et al. [21]	Secures user authentication in IWSNs	Lightweight cryptographic primitives, utilizes PUFs for physical security, enhances security, privacy, and efficiency in IWSNs
Shao et al. [22]	Protects patient data in WSNs	Utilizes PUFs, cryptographic hash functions, fuzzy extractors, XOR operations, enables real-time patient monitoring
MASK [11]	Secures health information transfer in IoMT	Lightweight cryptography, one-way hash functions, nonces, PUFs, bit-wise XOR operations, prevents physical device loss, resilient against security threats, detailed system model and performance analysis

3.4 Limitations of the MASK Scheme

The MASK [11] scheme follows the general scheme discussed in Section 2.4. It prevents many security threats like replay, impersonation, cloning, and side-channel attacks. However, an adversary can effectively execute privileged insider and offline password-guessing attacks, which can expose sensitive information. Furthermore, MASK experiences a device update issue when logging in for the next session. The details are as follows.

3.4.1 Two Implementation Issues

In the MASK scheme, the user's device must provide the gateway with the sensor node's pseudo-identity to perform mutual authentication and secret session key establishment. However, during registration, the user's device does not record the sensor node's identity or take input from the user. As a result, it is impossible to complete the following steps. Furthermore, the user's device will update the temporary identity in the first protocol run. The user must input a password to prove its legitimacy in the second run. The user's device calculates the value used to verify the user's legitimacy using the expired identity. Therefore, the device will not permit the execution of the following protocol run, even if the user is authentic and enters the correct password. Thus, the protocol's implementation had flaws. Refer to the general scheme discussed in Section 2.4.

3.4.2 Offline Password Guessing Attack

In the MASK scheme, verifying a guessed password's accuracy is possible using data extracted from the user's device. Refer to Step 2.1 of the General Scheme discussed in Section 2.4. The attacker computes a value based on the guessed password and compares it with a value derived from the actual password and device data without triggering alerts or shutting down the network. If the values match, the attacker has successfully guessed the password, which makes the MASK scheme vulnerable to offline password-guessing attacks. In contrast, the proposed P-MASFEP scheme enhances security by using a fuzzy extractor to generate stable cryptographic keys from the user's biometrics, verifying the user's legitimacy. This process is detailed in Step 1 of the mutual authentication and session key establishment phase in Section 3.7.

3.4.3 Privileged Insider Attack

In the MASK scheme, a privileged insider with access to the gateway's resources could misuse their authority to compute the session key. During the mutual authentication and session key establishment phase, the insider could combine a unique user identifier with a constant extracted from the gateway's resources to calculate a specific value. The insider could eventually derive the session key using this value and another identifier linked to the user. In contrast, the proposed P-MASFEP scheme ensures that the sensor node generates the session key after mutual authentication. The sensor node then securely transmits the session key to the authenticated device using PKI, preventing privileged insiders from accessing the session key. This process is detailed in Steps 9 and 13 of the mutual authentication and session key establishment phase in Section 3.7.

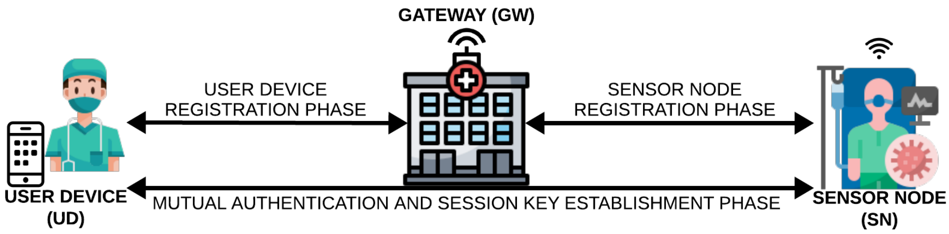

Figure 3.1: System model of P-MASFEP.

3.5 System Model

The User Device (UD), Gateway (GW), and Sensor Node (SN) comprise the system model depicted in Fig. 3.1.

1. ***User Device:*** The user connects to the sensor node to access real-time patient medical data, enabling quick patient care decisions.
2. ***Gateway:*** The gateway relays the patient's medical data, connecting the trusted user device and sensor node.
3. ***Sensor Node:*** The sensor nodes gather and transmit the patient's medical data to the user device via the gateway.

3.6 Adversary Model

The Dolev–Yao (DY) model [43] assumes an adversary with unlimited computational power and full access to all messages transmitted over the network. The adversary can eavesdrop, modify, delete, and insert messages on the public channel. In addition, the Canetti-Krawczyk (CK) adversary model [44] is employed to evaluate protocols with active adversaries who can manipulate messages and interact with honest participants. In this model, an attacker can also exploit power analysis attacks [45] to access the gateway's ephemeral parameters. The DY and CK adversary models account for many potential attacks. Further details are provided below.

- Ephemeral parameters of the gateway can be obtained by a privileged insider who can act as an adversary.
- The sensor node is vulnerable to physical assaults.
- An adversary can carry out several attacks, including impersonation, offline password guessing, privileged insider, replay, DoS, and MITM.

Table 3.2: Notations for P-MASFEP.

Notation	Definition
UD	User Device
GW	Gateway
SN	Sensor Node
P_{UD}, P_{SN}	P: Physically Unclonable Function, UD: User Device, SN: Sensor Node
C_{E}^{N}, R_{E}^{N}	C: Challenge, R: Response, E: Entity, N: Number
N_{UD}, N_{GW}, N_{SN}	N: Nonce, UD: User Device, GW: Gateway, SN: Sensor Node
TID_{UD}, TID_{SN}	TID: Temporary Identity, UD: User Device, SN: Sensor Node
D_{LN}	Unique License Number of the Doctor Issued by the Medical Council
D_{ID}	Unique Identity of the Doctor Issued by the Hospital
SN_{IEI}	International Equipment Identity of the Sensor Node
SK	Session Key
$A \equiv^{?} B$	Is A identical to B
$\oplus$, $\Vert$	Bit-wise XOR and Concatenation Operator
BIO_{i}	Biometrics of the i^{th} User
$FE.Gen(.)$	Fuzzy Extractor Generation Function
$FE.Rec(.)$	Fuzzy Extractor Reconstruction Function
K	Key
h_d	Helper Data
CPW_{i}	Computed Password of the i^{th} User
$PubK_{\text{UD}}$, $PubK_{\text{SN}}$	PubK: Public Key, UD: User Device, SN: Sensor Node
$PvtK_{\text{UD}}$, $PvtK_{\text{SN}}$	PvtK: Private Key, UD: User Device, SN: Sensor Node
$h(.)$	Cryptographic Hash Function
$E(.)$	Cryptographic Encryption Function
$D(.)$	Cryptographic Decryption Function

3.7 Proposed P-MASFEP Scheme Framework

The proposed P-MASFEP scheme extends the MASK [11] scheme, which follows the general scheme discussed in Section 2.4. P-MASFEP focuses on enhancing registration, mutual authentication, and session key establishment to address privileged insider and offline password-guessing attacks. Table 3.2 presents the notations utilized to explain the proposed scheme. The following assumptions are taken into account when creating the scheme:

1. UD and SN registration phase is completed using a secure channel.
2. UD, GW, and SN compute the same cryptographic functions to secure data by converting it into ciphertext. It makes it computationally challenging to reverse, ensuring the data's confidentiality, integrity, and authenticity.
3. UD, GW, and SN compute the same hash function. Properties include pre-image resistance (given a hash value, it should be computationally infeasible to find the original input), second pre-image resistance (given an input, it should be computationally infeasible to find another input with the same hash), and collision resistance (it should be computationally infeasible to find two different inputs with the same hash) [46].
4. GW is a reliable entity with sufficient processing power and storage.
5. UD and SN have enough processing power and storage to handle cryptographic functions.

3.7.1 User Device and Sensor Node Registration Phase

The following subsections present the stepwise explanation of the registration phase between the user device (UD), sensor node (SN), and gateway (GW).

User Device Registration Phase

Fig. 3.2 illustrates how the User Device (UD) registers with the Gateway (GW), establishing the initial trust and enabling subsequent authenticated interactions with the Sensor Node (SN). The registration leverages Physically Unclonable Functions (PUFs), user-specific identifiers, and biometric-enhanced credential generation for robust identity binding.

Step 1–2: The Gateway (GW) initiates the registration by generating a random PUF challenge and a set of synchronization challenges:

$$C_{UD}^{0}, C_{UD}^{SYN} \leftarrow \text{Random}() \tag{3.1}$$

GW constructs a registration message containing both challenges and sends it to UD:

$$Msg_{GW\to UD} = \{C_{UD}^{0}, C_{UD}^{SYN}\} \tag{3.2}$$

These challenges are stimuli to extract a device-unique response from UD's embedded PUF circuit.

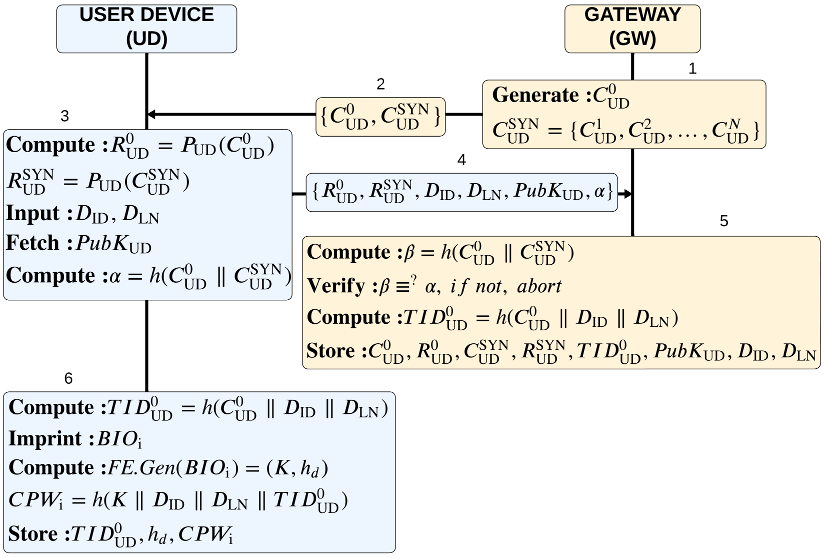

Figure 3.2: User device registration phase.

Step 3–4: Upon receiving the challenge set, UD computes two response tokens using its onboard PUF:

$$R^0_{UD} = PUF(C^0_{UD}) \tag{3.3}$$

$$R^{SYN}_{UD} = PUF(C^{SYN}_{UD}) \tag{3.4}$$

The user then inputs their unique identifiers: device ID (D_{ID}) and location/network ID (D_{LN}). UD also fetches its public key ($PubK_{UD}$) and computes a challenge digest:

$$\alpha = h(C^0_{UD} \parallel C^{SYN}_{UD}) \tag{3.5}$$

This digest enables GW to validate the integrity and pairing of the challenge-response pairs. UD then sends its registration request:

$$Msg_{UD \to GW} = \{R^0_{UD}, R^{SYN}_{UD}, D_{ID}, D_{LN}, PubK_{UD}, \alpha\} \tag{3.6}$$

Step 5: Upon receiving the message, GW performs the following operations:

→ It recomputes $\beta = h(C^0_{UD} \parallel C^{SYN}_{UD})$ and verifies whether $\beta \equiv \alpha$, confirming that the challenge and response pairings received from UD are valid.

→ If verification succeeds, GW binds the identity of UD by computing a unique temporary identifier:

$$TID^0_{UD} = h(C^0_{UD} \parallel D_{ID} \parallel D_{LN}) \tag{3.7}$$

→ Finally, GW securely stores: $\{C^0_{UD}, R^0_{UD}, C^{SYN}_{UD}, R^{SYN}_{UD}, TID^0_{UD}, PubK_{UD}, D_{ID}, D_{LN}\}$

Step 6: In parallel, UD computes the same temporary identity locally:

$$TID^0_{UD} = h(C^0_{UD} \parallel D_{ID} \parallel D_{LN}) \tag{3.8}$$

UD then performs biometric enrollment. It captures the biometric imprint BIO_i and applies a fuzzy extractor to derive:

$$(K, h_d) = FE.Gen(BIO_i) \tag{3.9}$$

This pair (K, h_d) enables reproducible key generation in future authentications. Next, UD derives the credential:

$$CPW_i = h(K \parallel D_{ID} \parallel D_{LN} \parallel TID^0_{UD}) \tag{3.10}$$

It securely stores TID^0_{UD}, h_d, and CPW_i for future use during mutual authentication.

This registration phase establishes a strong device identity at GW and securely binds it to user-specific and hardware-specific secrets on UD. The combination of PUF, biometrics, and cryptographic hashing enhances resistance against cloning, impersonation, and offline attacks.

Sensor Node Registration Phase

This phase enables the Sensor Node (SN) to securely register with the Gateway (GW) using PUF-based authentication and unique node identity parameters. It establishes a trusted identity for SN in the system, allowing it to participate in future authenticated communication with user devices (UD). Fig. 3.3 depicts the detailed registration steps.

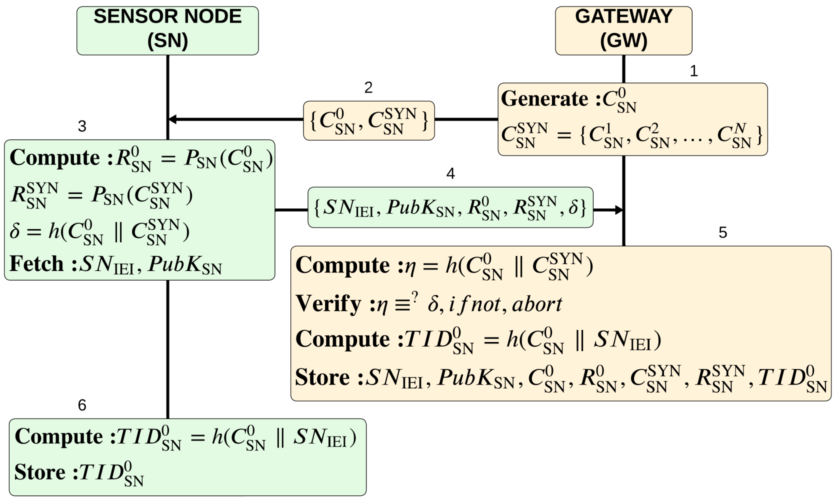

Figure 3.3: Sensor node registration phase.

Step 1–2: The Gateway (GW) begins SN registration by generating a unique challenge for the PUF along with a synchronization challenge set:

$$C^0_{SN},\ C^{SYN}_{SN} \leftarrow \text{Random}() \tag{3.11}$$

It transmits the challenge bundle to SN:

$$Msg_{GW \to SN} = \{C^0_{SN}, C^{SYN}_{SN}\} \tag{3.12}$$

These challenges are designed to extract device-specific fingerprints from the SN using its physical PUF circuit.

Step 3–4: Upon receiving the challenges, SN computes the corresponding responses:

$$R^0_{SN} = PUF(C^0_{SN}) \tag{3.13}$$
$$R^{SYN}_{SN} = PUF(C^{SYN}_{SN}) \tag{3.14}$$
$$\delta = h(C^0_{SN} \parallel C^{SYN}_{SN}) \tag{3.15}$$

It then prepares a registration message containing:

→ SN_{IEI}: The Sensor Node's Identity and Environment Information (e.g., hardware or deployment profile).

→ $PubK_{SN}$: SN's public key for future encrypted communication.

→ The PUF responses and challenge digest δ for integrity verification.

SN sends this message to GW:

$$Msg_{SN \to GW} = \{SN_{IEI}, PubK_{SN}, R_{SN}^0, R_{SN}^{SYN}, \delta\} \tag{3.16}$$

Step 5: GW verifies SN's response by recalculating the challenge digest:

$$\eta = h(C_{SN}^0 \parallel C_{SN}^{SYN}) \tag{3.17}$$

It compares η with the received δ. If they match, GW proceeds to bind SN's identity to the challenge by computing:

$$TID_{SN}^0 = h(C_{SN}^0 \parallel SN_{IEI}) \tag{3.18}$$

This temporary identifier ensures unique and traceable registration of the SN in the system. GW stores the complete record: $\{SN_{IEI}, PubK_{SN}, C_{SN}^0, R_{SN}^0, C_{SN}^{SYN}, R_{SN}^{SYN}, TID_{SN}^0\}$ for future reference.

Step 6: SN independently computes the same temporary identifier for local storage and future use:

$$TID_{SN}^0 = h(C_{SN}^0 \parallel SN_{IEI}) \tag{3.19}$$

This identifier binds the SN's physical identity (via PUF) and its environmental tag (SN_{IEI}), ensuring that only the legitimate node can later authenticate itself.

This registration process securely links the physical and digital identity of the sensor node, making it resilient to cloning and impersonation attacks. By storing both the PUF responses and key metadata, GW can verify the authenticity of SN later during mutual authentication.

3.7.2 Mutual Authentication and Session Key Establishment Phase

This phase ensures secure mutual authentication between the user device (UD) and sensor node (SN) through the gateway (GW), and establishes a session key for encrypted communication. The process combines biometric-based credential verification, PUF-based device authentication, and public key encryption for confidentiality. Fig. 3.4 presents the overall message flow.

Step 1–2: The user must first prove the identity by entering D_{ID}, D_{LN} and imprint BIO_i. P-MASFEP makes it harder for an attacker to guess the password by using biometric information BIO_i to calculate:

$$K^* = \text{FE.Rec}(BIO_i, h_d) \tag{3.20}$$

$$CPW_i^* = h(K^* \parallel D_{ID} \parallel D_{LN} \parallel TID_{UD}^0) \tag{3.21}$$

If $CPW_i^* \equiv CPW_i$, UD generates a nonce N_{UD}^1 and computes:

$$N_{UD}^{1*} = N_{UD}^1 \oplus D_{ID} \tag{3.22}$$

$$TID_{UD}^{0*} = TID_{UD}^0 \oplus D_{LN} \tag{3.23}$$

UD composes a message containing $\{N_{UD}^{1*}, TID_{UD}^{0*}\}$ and transmits it to GW.

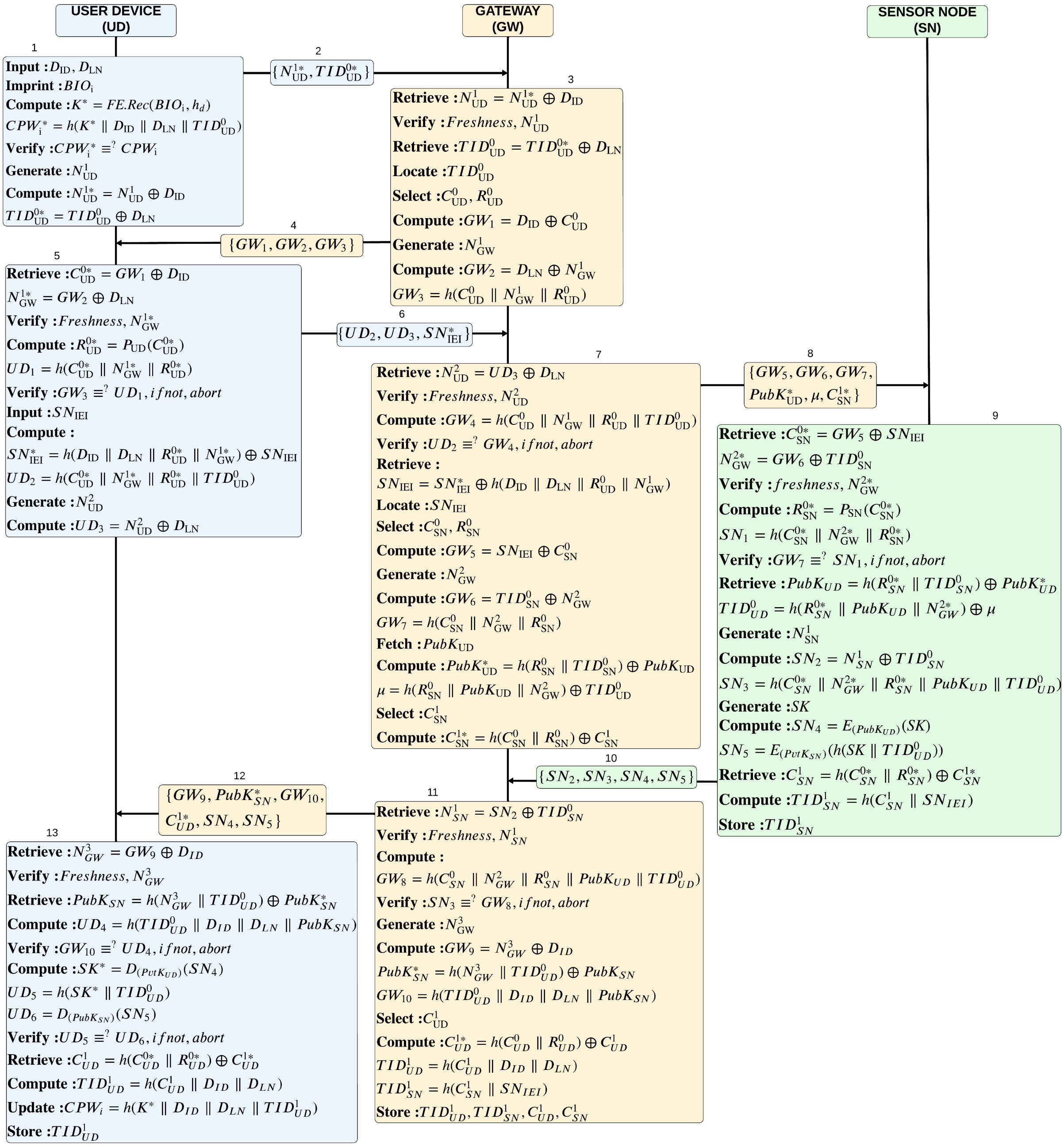

Figure 3.4: Mutual authentication and session key establishment phase.

Step 3–4: GW extracts the real nonce, $N_{UD}^1 = N_{UD}^{1*} \oplus D_{ID}$. Next, GW checks whether the nonce is fresh; if not, it aborts. GW derives the temporary identity, $TID_{UD}^0 = TID_{UD}^{0*} \oplus D_{LN}$ and matches with the database. If found, the authenticity of UD is proven; if not, it is a bogus request. Then GW selects the corresponding CRP, (C_{UD}^0, R_{UD}^0) and encloses the real C_{UD}^0 in:

$$GW_1 = D_{ID} \oplus C_{UD}^0 \tag{3.24}$$

$$GW_2 = D_{LN} \oplus N_{GW}^1 \tag{3.25}$$

$$GW_3 = h(C_{UD}^0 \parallel N_{GW}^1 \parallel R_{UD}^0) \tag{3.26}$$

GW sends $\{GW_1, GW_2, GW_3\}$ to UD.

Step 5–6: UD computes:

$$C_{UD}^{0*} = GW_1 \oplus D_{ID} \tag{3.27}$$

$$N_{GW}^{1*} = GW_2 \oplus D_{LN} \tag{3.28}$$

$$R_{UD}^{0*} = P_{UD}(C_{UD}^{0*}) \tag{3.29}$$

$$UD_1 = h(C_{UD}^{0*} \parallel N_{GW}^{1*} \parallel R_{UD}^{0*}) \tag{3.30}$$

If $UD_1 \equiv GW_3$, GW is authenticated. UD creates a pseudo-identity for SN and computes:

$$SN_{IEI}^* = h(D_{ID} \parallel D_{LN} \parallel R_{UD}^{0*} \parallel N_{GW}^{1*}) \oplus SN_{IEI} \tag{3.31}$$

$$UD_2 = h(C_{UD}^{0*} \parallel N_{GW}^{1*} \parallel R_{UD}^{0*} \parallel TID_{UD}^0) \tag{3.32}$$

$$UD_3 = N_{UD}^2 \oplus D_{LN} \tag{3.33}$$

UD sends $\{UD_2, UD_3, SN_{IEI}^*\}$ to GW.

Step 7–8: GW retrieves $N_{UD}^2 = UD_3 \oplus D_{LN}$ and computes:

$$GW_4 = h(C_{UD}^0 \parallel N_{GW}^1 \parallel R_{UD}^0 \parallel TID_{UD}^0) \tag{3.34}$$

$$SN_{IEI} = SN_{IEI}^* \oplus h(D_{ID} \parallel D_{LN} \parallel R_{UD}^0 \parallel N_{GW}^1) \tag{3.35}$$

Verifies $UD_2 \equiv GW_4$. GW selects CRP (C_{SN}^0, R_{SN}^0) and nonce N_{GW}^2 and computes:

$$GW_5 = SN_{IEI} \oplus C_{SN}^0 \tag{3.36}$$

$$GW_6 = TID_{SN}^0 \oplus N_{GW}^2 \tag{3.37}$$

$$GW_7 = h(C_{SN}^0 \parallel N_{GW}^2 \parallel R_{SN}^0) \tag{3.38}$$

$$PubK_{UD}^* = h(R_{SN}^0 \parallel TID_{SN}^0) \oplus PubK_{UD} \tag{3.39}$$

$$\mu = h(R_{SN}^0 \parallel PubK_{UD} \parallel N_{GW}^2) \oplus TID_{UD}^0 \tag{3.40}$$

$$C_{SN}^{1*} = h(C_{SN}^0 \parallel R_{SN}^0) \oplus C_{SN}^1 \tag{3.41}$$

GW sends $\{GW_5, GW_6, GW_7, PubK_{UD}^*, \mu, C_{SN}^{1*}\}$ to SN.

Step 9–10: SN computes:

$$C_{SN}^{0*} = GW_5 \oplus SN_{IEI} \tag{3.42}$$

$$N_{GW}^{2*} = GW_6 \oplus TID_{SN}^0 \tag{3.43}$$

$$R_{SN}^{0*} = P_{SN}(C_{SN}^{0*}) \tag{3.44}$$

$$SN_1 = h(C_{SN}^{0*} \parallel N_{GW}^{2*} \parallel R_{SN}^{0*}) \tag{3.45}$$

Verifies $SN_1 \equiv GW_7$. Then retrieves and computes:

$$PubK_{UD} = h(R_{SN}^{0*} \parallel TID_{SN}^0) \oplus PubK_{UD}^* \quad (3.46)$$
$$TID_{UD}^0 = h(R_{SN}^{0*} \parallel PubK_{UD} \parallel N_{GW}^{2*}) \oplus \mu \quad (3.47)$$
$$SN_2 = N_{SN}^1 \oplus TID_{SN}^0 \quad (3.48)$$
$$SN_3 = h(C_{SN}^{0*} \parallel N_{GW}^{2*} \parallel R_{SN}^{0*} \parallel PubK_{UD} \parallel TID_{UD}^0) \quad (3.49)$$
$$SN_4 = E_{PubK_{UD}}(SK) \quad (3.50)$$
$$SN_5 = E_{PvtK_{SN}}(h(SK \parallel TID_{UD}^0)) \quad (3.51)$$
$$C_{SN}^1 = h(C_{SN}^{0*} \parallel R_{SN}^{0*}) \oplus C_{SN}^{1*} \quad (3.52)$$
$$TID_{SN}^1 = h(C_{SN}^1 \parallel SN_{IEI}) \quad (3.53)$$

SN sends $\{SN_2, SN_3, SN_4, SN_5\}$ to GW.

Step 11–12: GW authenticates SN:

$$N_{SN}^1 = SN_2 \oplus TID_{SN}^0 \quad (3.54)$$
$$GW_8 = h(C_{SN}^0 \parallel N_{GW}^2 \parallel R_{SN}^0 \parallel PubK_{UD} \parallel TID_{UD}^0) \quad (3.55)$$

Verifies $SN_3 \equiv GW_8$. Then generates nonce N_{GW}^3 and computes:

$$GW_9 = N_{GW}^3 \oplus D_{ID} \quad (3.56)$$
$$PubK_{SN}^* = h(N_{GW}^3 \parallel TID_{UD}^0) \oplus PubK_{SN} \quad (3.57)$$
$$GW_{10} = h(TID_{UD}^0 \parallel D_{ID} \parallel D_{LN} \parallel PubK_{SN}) \quad (3.58)$$
$$C_{UD}^{1*} = h(C_{UD}^0 \parallel R_{UD}^0) \oplus C_{UD}^1 \quad (3.59)$$
$$TID_{UD}^1 = h(C_{UD}^1 \parallel D_{ID} \parallel D_{LN}) \quad (3.60)$$

GW sends $\{GW_9, PubK_{SN}^*, GW_{10}, C_{UD}^{1*}, SN_4, SN_5\}$ to UD.

Step 13: UD reconstructs session credentials:

$$N_{GW}^3 = GW_9 \oplus D_{ID} \quad (3.61)$$
$$PubK_{SN} = h(N_{GW}^3 \parallel TID_{UD}^0) \oplus PubK_{SN}^* \quad (3.62)$$
$$UD_4 = h(TID_{UD}^0 \parallel D_{ID} \parallel D_{LN} \parallel PubK_{SN}) \quad (3.63)$$
$$SK^* = D_{PvtK_{UD}}(SN_4) \quad (3.64)$$
$$UD_5 = h(SK^* \parallel TID_{UD}^0) \quad (3.65)$$
$$UD_6 = D_{PubK_{SN}}(SN_5) \quad (3.66)$$

If $UD_5 \equiv UD_6$, authentication is complete. UD then updates:

$$C_{UD}^1 = h(C_{UD}^{0*} \parallel R_{UD}^{0*}) \oplus C_{UD}^{1*} \quad (3.67)$$
$$TID_{UD}^1 = h(C_{UD}^1 \parallel D_{ID} \parallel D_{LN}) \quad (3.68)$$
$$CPW_i = h(K^* \parallel D_{ID} \parallel D_{LN} \parallel TID_{UD}^1) \quad (3.69)$$

Chapter 4

Proposed KFLIT Protocol

This chapter presents *KFLIT* protocol, an enhanced authentication framework designed to address the limitations of traditional Kerberos in password security and IoT applicability. *KFLIT* builds upon a foundational protocol, *KFI*, by eliminating password dependencies through FIDO's passwordless mechanism. It further extends *KFI* to suit resource-constrained IoT environments by incorporating lightweight cryptographic operations, counter-based synchronization, and device attestation. This chapter introduces the motivation for developing *KFLIT*, discusses related Kerberos-based schemes, identifies prevailing research gaps, and outlines the system and adversary models. The final sections detail the *KFI* and *KFLIT* protocols step by step.

4.1 Motivation

Kerberos is a widely adopted authentication protocol originally designed for traditional enterprise networks [12,14]. It provides mutual authentication using a ticket-based framework grounded in symmetric key cryptography. Despite its success in centralized and well-resourced environments, Kerberos faces growing limitations in modern security contexts.

A primary concern is Kerberos' reliance on user-chosen passwords, which exposes it to password-centric threats such as offline password guessing, Kerberoasting, Silver Ticket, and Golden Ticket attacks [18–20]. These attacks have been exploited in real-world intrusions, including APT20 [47] and FIN7 [48], highlighting critical weaknesses in Kerberos' password-dependent architecture.

Furthermore, Kerberos is not well-suited for IoT environments. Devices in IoT networks typically have constrained resources — limited processing power, memory, and energy — and often operate without stable real-time clocks. Kerberos' dependence on synchronized timestamps, frequent ticket exchanges, and encryption-heavy operations creates significant overhead that exceeds the capabilities of most IoT nodes [17, 49]. Although efforts like KESIC [17] have attempted to adapt Kerberos by introducing lightweight primitives such as HMAC and counter-based synchronization, they retain several inherent limitations. These include continued reliance on password-based logins, lack of built-in device integrity verification, and challenges in scaling across diverse and heterogeneous IoT environments.

These limitations underline the urgent need for an authentication protocol that retains Kerberos' strengths in mutual authentication while overcoming its unsuitability for passwordless and resource-constrained systems.

4.2 Objective

Although Kerberos avoids password transmission, it still depends on the secrecy and strength of user-chosen passwords. Weak passwords can be exploited through offline dictionary or brute-force attacks, leading to several advanced threats such as Kerberoasting [18], Golden Ticket attacks [20], and Silver Ticket attacks [19]. Furthermore, adapting Kerberos for IoT environments introduces new challenges due to device constraints and protocol design. Based on these observations, the following research gaps are identified:

1. ***Vulnerability to password-based attacks:*** Using password-derived keys in Kerberos makes it susceptible to brute-force, dictionary, and ticket forgery attacks.

2. ***Limitations in IoT environments:*** Traditional Kerberos requires clock synchronization and performs heavyweight cryptographic operations, making it inefficient for resource-constrained IoT devices.

To overcome these challenges, this thesis proposes two enhancements. The first, *KFI* (Kerberos with FIDO Integration), eliminates password-based login by incorporating FIDO's asymmetric passkey authentication, thereby addressing Kerberos' vulnerability to password-derived attacks. The second, *KFLIT* (Kerberos with FIDO and Lightweight Extension for IoT), extends KFI to make it compatible with IoT environments. KFLIT replaces encryption-heavy operations with lightweight primitives such as HMAC and XOR, employs counter-based synchronization to remove timestamp dependency, and integrates device attestation to verify the integrity of participating IoT devices before granting access. Together, these enhancements provide a secure, scalable, and resource-efficient authentication solution tailored for the evolving landscape of IoT.

4.3 Related Work

Several works in the literature have explored adaptations of the Kerberos protocol to enhance authentication in diverse environments. These include schemes integrating public-key, biometric, or blockchain-based mechanisms. Table 4.1 summarizes existing Kerberos-based approaches' key authentication mechanisms, features, and limitations.

Neuman et al. [12] introduced Kerberos as a secure authentication service designed for open network systems. It relies on symmetric cryptography and a trusted third party to establish secure authentication between clients and servers. The protocol mitigates the exposure of sensitive information by using encrypted tickets. However, Kerberos remains vulnerable to password-based attacks because it relies on user-chosen passwords. Additionally, the requirement for synchronized clocks and the computational overhead of encryption operations present challenges in resource-constrained environments.

Downnard [16] introduced public-key cryptography enhancements to the Kerberos protocol, addressing its reliance on password-based authentication and enhancing security and scalability. One of the key modifications is PKINIT (Public-Key-Based Initial Authentication), which replaces password-based authentication with public-key cryptography in the initial login. In PKINIT, the Kerberos server authenticates users through digital signatures and encrypts the TGT and session key with the user device's public key, safeguarding credentials against interception. Additionally, PKCROSS (Public-Key-Based Cross-Realm Authentication) enables secure cross-realm authentication by using public-key cryptography for KDC-to-KDC communication, removing the need for pre-shared symmetric keys across realms and thus streamlining multi-realm configurations. Another modification, PKDA (Public-Key-Based Distributed Authentication), extends the protocol by enabling direct client-to-server authentication using public-key signatures, which reduces the load on the centralized KDC, minimizes network bottlenecks, and enhances privacy. These enhancements mitigate Kerberos' susceptibility to password-related attacks, strengthen inter-realm security, and enable more flexible, distributed authentication across networks.

Tbatou et al. [23] proposed a mutual Kerberos authentication protocol for distributed systems, enhancing the security of the traditional Kerberos V5 by integrating the Diffie-Hellman key exchange and a dynamic salt generator for robust key management. The protocol operates in three phases: registration, communication, and renewal. In the registration phase, the client and KDC use Diffie-Hellman to securely generate initial authentication parameters with dynamic salts, ensuring unique session keys per User. The communication phase further enhances security with functions named S2KexS and DKexS, which use password-derived keys and dynamic salts for per-session encryption, making it more resilient against dictionary and brute-force attacks. Finally, the renewal phase allows for the periodic updating of client authentication parameters, enhancing security by preventing long-term exposure of sensitive data. This approach improves Kerberos' robustness against password-related attacks while ensuring a secure channel for distributed systems.

Han et al. [15] proposed a biometric-Kerberos authentication protocol explicitly designed for secure mobile computing services. The protocol combines traditional Kerberos authentication with biometric data to enhance security, especially for mobile devices in m-commerce applications. The scheme combines fingerprint biometrics captured through a smartphone camera with a watermark generated from the device's unique serial number. The watermark is embedded into the fingerprint image at the acquisition time, linking the biometric data to the specific device. The watermark embedding key is derived from the Kerberos session key, and only the trusted KDC can remove the watermark. This approach enables forensic traceability, ensuring that only a legitimate device and user can authenticate, as the watermark needs to be removed for a successful biometric match. By integrating this watermark with the biometric data, the protocol provides a cost-effective, high-security solution suitable for mobile environments with higher security risks due to device portability and the potential for interception on wireless networks.

Chen et al. [50] proposed DKSM, a decentralized protocol extending Kerberos for secure service management in IoT environments. DKSM innovatively combines blockchain technology and Ciphertext-Policy Attribute-Based Encryption (CP-ABE) to address Kerberos' limitations, such as single-point failure and replay attacks. The protocol decentralizes key distribution using smart contracts for transparent and immutable interactions. DKSM enhances privacy with fine-grained access control and robust nonce-based time synchronization. Experimental results on Ethereum and FISCO platforms validate their cost-efficiency and scalability. By integrating blockchain's traceability with Kerberos' authentication framework, DKSM provides a resilient and adaptable solution for distributed IoT ecosystems.

Gaikwad et al. [49] introduced a smart home automation system leveraging IoT and a robust three-level Kerberos authentication mechanism to enhance security. The proposed system integrates GSM/GPRS modules, RF communication, and microcontroller-based hardware for reliable and low-cost automation. Kerberos authentication is employed to mitigate security vulnerabilities, with three layers ensuring password protection, ticket-based authentication, and session management. The study demonstrates a seamless and secure process for monitoring and controlling household appliances, highlighting the system's scalability and resilience. The proposed solution addresses IoT-specific challenges like real-time communication and device integration while ensuring confidentiality and integrity in distributed environments.

Prapty et al. proposed *KESIC* [17], a lightweight Kerberos-based protocol for IoT environments. While *KESIC* introduces HMAC-based ticket generation and counter-based synchronization to reduce computational and memory overhead, it still relies on symmetric cryptography for authentication and key exchange. This dependency increases computational complexity and resource consumption, making it less suitable for highly constrained IoT devices. Moreover, *KESIC* retains Kerberos' password-based authentication, leaving it vulnerable to brute-force and dictionary attacks.

Table 4.1: Comparison of Kerberos-based authentication schemes.

Scheme	Authentication Mechanism	Key Features	Limitations
Neuman et al. [12]	Password-based authentication	Symmetric cryptography; Ticket-based authentication; Avoids password transmission over network	Vulnerable to brute-force and dictionary attacks; Requires clock synchronization; Computationally heavy
Downnard [16]	Public-key authentication	Eliminates password dependency; Supports cross-realm authentication	High computational overhead; Unsuitable for IoT
Tbatou et al. [23]	Password-based with Diffie-Hellman key exchange	Secure session keys; Periodic authentication updates	Increased complexity; Frequent key updates reduce efficiency
Han et al. [15]	Biometric authentication	Fingerprint-based authentication with watermarking	Requires biometric hardware; Vulnerable to biometric spoofing
Chen et al. [50]	Blockchain-based authentication	Decentralized key management with CP-ABE encryption	High reliance on blockchain; Latency in large-scale networks
Gaikwad et al. [49]	Ticket-based authentication	Three-layer authentication; Real-time monitoring	Struggles with scalability in dynamic IoT environments
KESIC [17]	Password-based authentication	Lightweight Kerberos adaptation; Counter-based synchronization	Vulnerable to password attacks; Still relies on symmetric cryptography, increasing computational overhead

Table 4.2: Notations for KFLIT.

Notation	Definition
	Entities and Components
UD	User Device
KDC	Key Distribution Center
AS	Authenticator Server
TGS	Ticket Granting Server
TD	Target Device
ITS	IoT Server
IN	IoT Node
	Keys and Cryptographic Operations
$K_{x,y}$	Long-term shared key between x and y
$k_{x,y}$	Short-term (session) key between x and y
$FIDO\text{-}Pub_{UD}$	User Device's FIDO Public Key
$FIDO\text{-}Priv_{UD}$	User Device's FIDO Private Key
$E_K[\cdot]$	Symmetric Encryption using key K
$D_K[\cdot]$	Symmetric Decryption using key K
$HMAC(K, M)$	HMAC operation with key K and message M
	Authentication and Ticketing
ID_x	Identity of Entity x
AD_{UD}	Network Address of the User Device
$TS_{x,y}$	Timestamp sent from x to y
L_n	Ticket Expiration Timestamp
T_x	Ticket for Entity x
TGT	Ticket Granting Ticket
$Req_{x,y}$	Request sent from x to y
$Res_{x,y}$	Response sent from x to y
$A_{x,y}$	Authenticator sent from x to y
$Challenge$	Challenge
$Attest$	Attestation phase operation
$Serv$	Service request

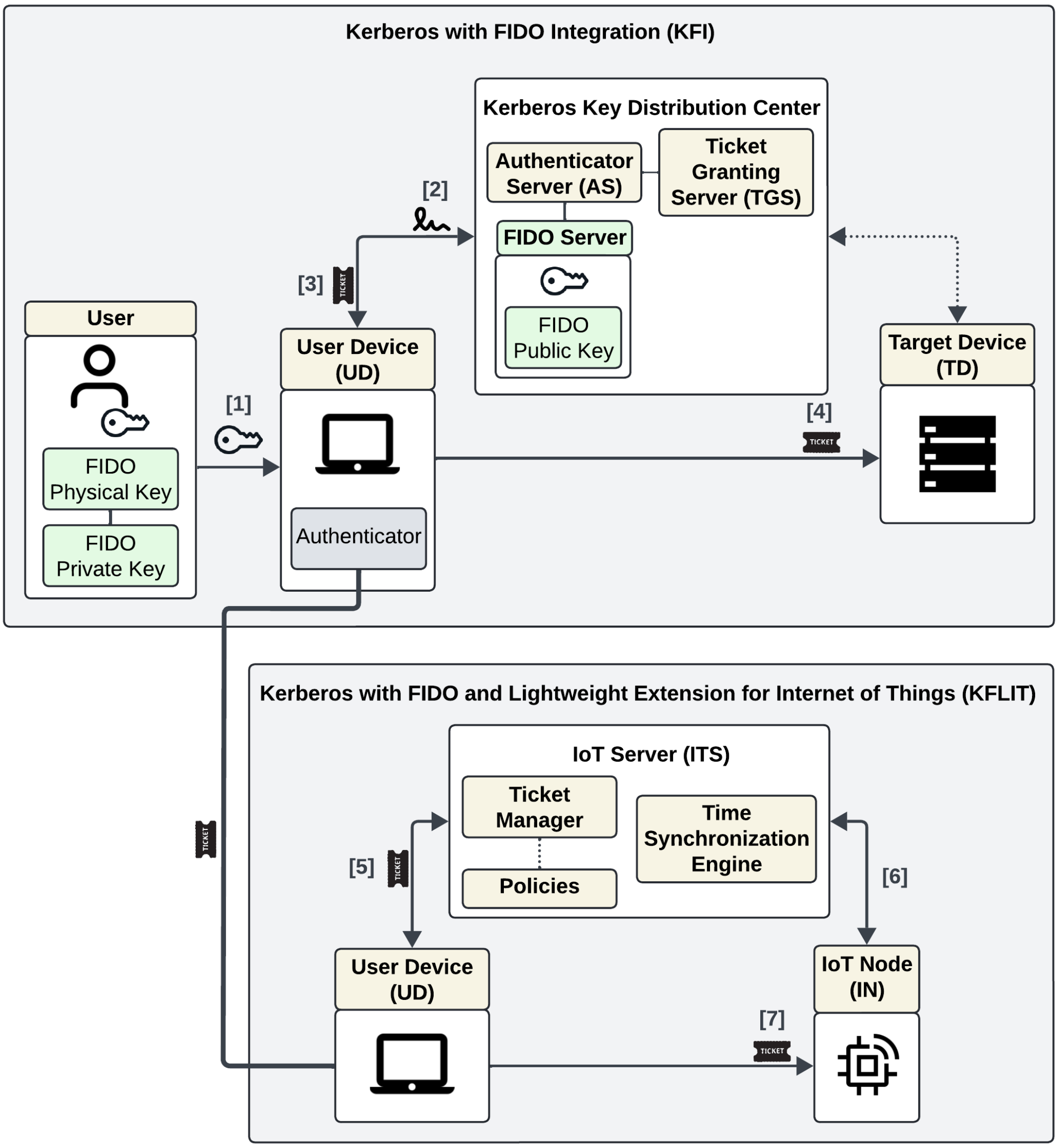

Figure 4.1: KFI and KFLIT system model.

4.4 System Model

This thesis proposes two novel protocols designed to overcome the limitations of traditional Kerberos while extending its applicability to address modern authentication challenges. Fig. 4.1 illustrates the overall architecture, which depicts both protocols: *KFI* and *KFLIT*.

1. ***Kerberos with FIDO Integration (KFI):*** *KFI* eliminates password-based vulnerabilities in traditional Kerberos by integrating FIDO's passkey mechanism. This integration replaces static passwords with a secure, passwordless authentication framework based on public-key cryptography. The entities involved are:

   (a) ***User:*** Possesses a physical FIDO key that securely stores the FIDO private key ($FIDO\text{-}Priv_{UD}$) used for authentication. The user interacts with the user device (UD) by inserting the FIDO key and completing the authentication challenge.

(b) ***User Device*** (UD)***:*** Initiates the authentication process to access a protected target device (TD). It is equipped with a FIDO authenticator that signs challenges using the private key stored in the physical FIDO key. UD communicates with the Kerberos key distribution center (KDC) to request and obtain tickets.

(c) ***Kerberos Key Distribution Center*** (KDC)***:*** A trusted authentication entity comprising two components:

→ *Authenticator Server (AS):* Verifies the FIDO-signed challenge during initial authentication and issues a ticket-granting ticket (TGT).

→ *Ticket Granting Server (TGS):* Receives TGT and issues service-specific tickets to allow access to TD.

(d) ***Target Device*** (TD)***:*** Represents the resource or application that UD intends to access securely. TD validates the service ticket and mutual authenticator before granting access.

2. ***Kerberos with FIDO and Lightweight Extension for Internet of Things (KFLIT):*** *KFLIT* extends *KFI* to address constraints specific to IoT environments. It replaces traditional encryption with lightweight HMAC and XOR operations to reduce computational overhead, uses counter-based synchronization to eliminate dependency on real-time clocks, and includes an attestation mechanism to verify device integrity. *KFLIT* introduces an additional server, the IoT server (ITS), to enable secure interaction between the user device (UD) and the IoT node (IN). The entities involved in *KFLIT* are:

(a) ***User Device*** (UD)***:*** Reuses the ticket obtained via the *KFI* protocol to initiate communication with ITS. UD is the requesting device in IoT environments, and it must be proven authentic before accessing IN.

(b) ***IoT Server*** (ITS)***:*** Serves as the security coordinator in IoT environments. It validates the ticket issued by KDC, issues access tickets for IN, and ensures integrity through device attestation. ITS comprises:

→ *Ticket Manager:* Handles issuing and verifying IoT-specific service tickets.

→ *Policies Module:* Enforces predefined access control rules for secure UD-IN communication.

→ *Time Synchronization Engine:* Maintains synchronization with IN using counters, thereby avoiding reliance on real-time clocks.

(c) ***IoT Node*** (IN)***:*** A lightweight endpoint representing an IoT device that UD wants to access. IN collaborates with ITS for attestation, allowing ITS to verify that the node has not been compromised before granting access.

In the *KFI* protocol, the process starts with the user [1] inserting the FIDO physical key into UD, which performs passwordless authentication with *AS* [2] using the FIDO private-public key pair. Upon successful verification, *AS* generates TGT and interacts with TGS [3] to issue a service ticket. UD then uses this ticket to securely access TD [4]. In the *KFLIT* protocol, UD communicates with ITS [5] using the ticket acquired from the *KFI* phase. ITS performs ticket validation, synchronizes with IN [6] using counter-based methods, and verifies device integrity through attestation. Upon successful verification, UD receives permission to interact with IN [7], completing a lightweight, secure authentication tailored for IoT environments.

Together, *KFI* and *KFLIT* provide a unified and secure authentication framework. While *KFI* enhances traditional Kerberos by integrating FIDO-based passwordless authentication, *KFLIT* further optimizes it for scalable and resource-efficient authentication in IoT ecosystems.

4.5 Adversary Model

The adversary model is defined under the following assumptions:

1. The adversary can launch remote attacks targeting IN to compromise its software and manipulate its behaviour. However, the adversary cannot compromise the hardware integrity or access securely stored credentials within IN.
2. The adversary cannot compromise the software, data, or cryptographic keys residing within the trusted servers, including AS, TGS, and ITS. These servers are assumed to be fully secure and trusted.
3. The adversary can compromise UD through various means, including impersonation (to bypass TD/IN access policies), eavesdropping (to intercept session keys or authentication data), tampering (to alter message content and disrupt protocol flow), and replay attacks (to reuse intercepted messages for unauthorized access).
4. The adversary cannot access the FIDO private keys stored within UD or on the external FIDO security keys. These keys remain protected within secure hardware modules and are inaccessible to external adversaries.

4.6 Proposed Protocol Framework

The proposed framework comprises two protocols designed to overcome the limitations of traditional Kerberos and adapt them to modern authentication challenges: *KFI* and *KFLIT*. Table 4.2 presents the notations utilized to explain the proposed scheme.

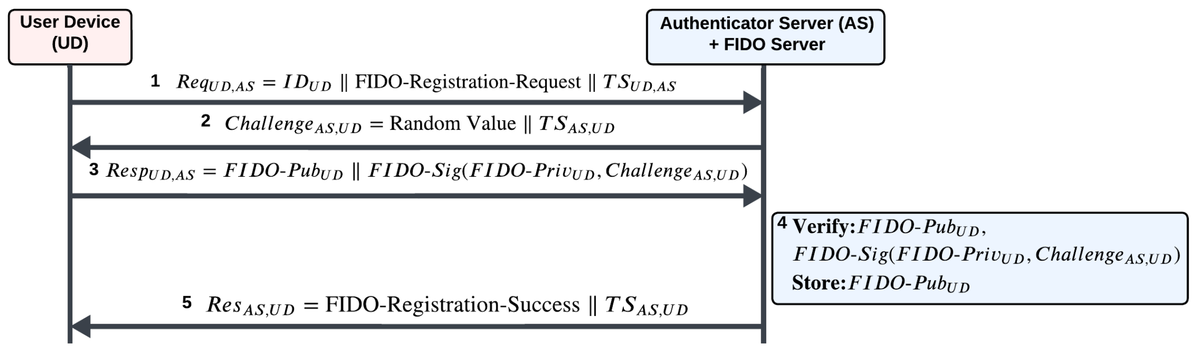

Figure 4.2: KFI: FIDO registration phase.

4.6.1 KFI: Kerberos with FIDO Integration

KFI integrates FIDO's passwordless authentication mechanism into its framework, aligning with the industry's shift toward passwordless authentication. Its main phases include registration, authentication, and ticket-granting, each detailed below.

4.6.1.1 FIDO Registration Phase

Step 1: UD initiates the FIDO registration by sending the registration request:

$$Req_{UD,AS} = ID_{UD} \parallel \text{FIDO-Registration-Request} \parallel TS_{UD,AS} \tag{4.1}$$

Step 2: AS responds by generating a random challenge and timestamp:

$$Challenge_{AS,UD} = \text{Random Value} \parallel TS_{AS,UD} \tag{4.2}$$

Step 3: UD signs the challenge using its FIDO private key and sends the following response:

$$Resp_{UD,AS} = FIDO\text{-}Pub_{UD} \parallel FIDO\text{-}Sig(FIDO\text{-}Priv_{UD}, Challenge_{AS,UD}) \tag{4.3}$$

Step 4: AS verifies the received signature using the public key and, upon successful verification, stores the key:

$$\text{Verify: } (FIDO\text{-}Pub_{UD}, FIDO\text{-}Sig(FIDO\text{-}Priv_{UD}, Challenge_{AS,UD}))$$

$$\text{Store: } FIDO\text{-}Pub_{UD}$$

Step 5: AS sends a registration success confirmation:

$$Res_{AS,UD} = \text{FIDO-Registration-Success} \parallel TS_{AS,UD} \tag{4.4}$$

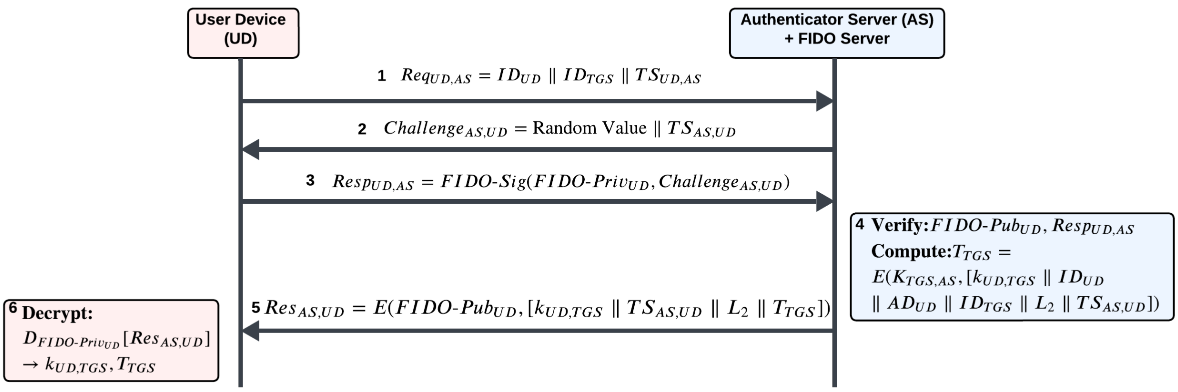

Figure 4.3: KFI: Initial authentication with AS.

4.6.1.2 Initial Authentication with AS

Step 1: UD initiates the authentication by computing the request $Req_{UD,AS}$ (Eq. 4.5), which contains its identity, the identity of the TGS, and a timestamp:

$$Req_{UD,AS} = ID_{UD} \parallel ID_{TGS} \parallel TS_{UD,AS} \tag{4.5}$$

Step 2: AS responds with a challenge $Challenge_{AS,UD}$ (Eq. 4.6) that includes a random value and timestamp:

$$Challenge_{AS,UD} = \text{Random Value} \parallel TS_{AS,UD} \tag{4.6}$$

Step 3: UD computes the response $Resp_{UD,AS}$ by signing the received challenge using its FIDO private key:

$$Resp_{UD,AS} = FIDO\text{-}Sig(FIDO\text{-}Priv_{UD}, Challenge_{AS,UD}) \quad (4.7)$$

Step 4: AS verifies the FIDO signature and generates the TGS ticket (Eq. 4.8). It then encrypts the response using UD's FIDO public key (Eq. 4.9):

$$T_{TGS} = E_{K_{TGS,AS}}[k_{UD,TGS} \parallel ID_{UD} \parallel AD_{UD} \parallel ID_{TGS} \parallel L_2 \parallel TS_{AS,UD}] \quad (4.8)$$

Step 5: AS sends $Res_{AS,UD}$ to UD.

$$Res_{AS,UD} = E_{FIDO\text{-}Pub_{UD}}[k_{UD,TGS} \parallel TS_{AS,UD} \parallel L_2 \parallel T_{TGS}] \quad (4.9)$$

Step 6: UD decrypts the response and extracts $k_{UD,TGS}$ and T_{TGS}.

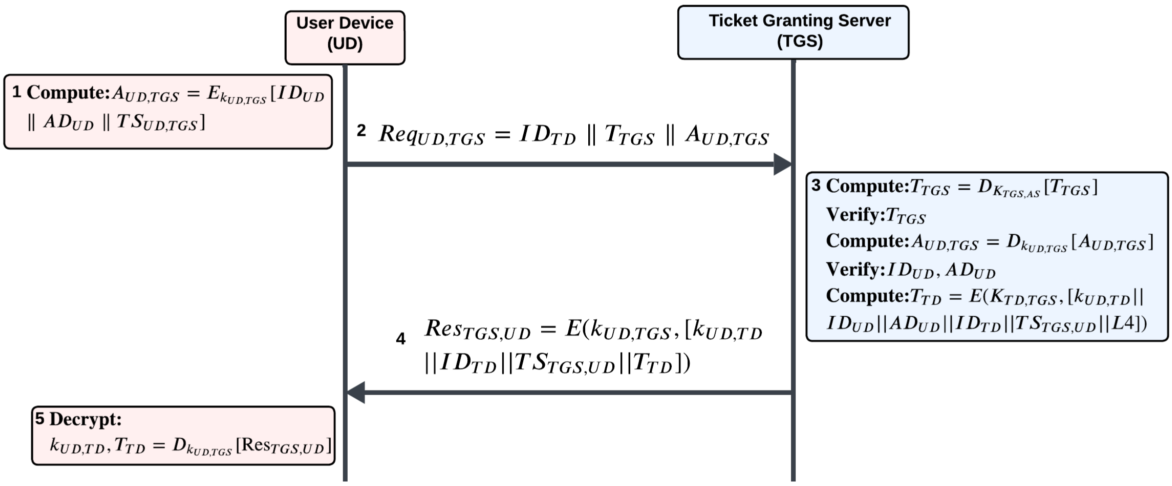

Figure 4.4: KFI: TGS interaction phase.

4.6.1.3 TGS Interaction Phase

Step 1: UD computes the authenticator $A_{UD,TGS}$ using its session key shared with the TGS and constructs the request:

$$A_{UD,TGS} = E_{k_{UD,TGS}}[ID_{UD} \parallel AD_{UD} \parallel TS_{UD,TGS}] \quad (4.10)$$

Step 2: UD sends $Req_{UD,TGS}$ to TGS.

$$Req_{UD,TGS} = ID_{TD} \parallel T_{TGS} \parallel A_{UD,TGS} \quad (4.11)$$

Step 3: TGS performs the following operations:

→ Decrypts T_{TGS} using $K_{TGS,AS}$

→ Verifies the contents of T_{TGS}

→ Decrypts $A_{UD,TGS}$ using $k_{UD,TGS}$

→ Verifies the identity and address of UD

→ Computes the ticket T_{TD} and response $Res_{TGS,UD}$

$$T_{TD} = E_{K_{TD,TGS}}[k_{UD,TD} \parallel ID_{UD} \parallel AD_{UD} \parallel ID_{TD} \parallel TS_{TGS,UD} \parallel L_4] \tag{4.12}$$

Step 4: TGS sends $Res_{TGS,UD}$ to UD.

$$Res_{TGS,UD} = E_{k_{UD,TGS}}[k_{UD,TD} \parallel ID_{TD} \parallel TS_{TGS,UD} \parallel T_{TD}] \tag{4.13}$$

Step 5: UD decrypts $Res_{TGS,UD}$ using $k_{UD,TGS}$ and retrieves:

$$k_{UD,TD}, T_{TD} = D_{k_{UD,TGS}}[Res_{TGS,UD}]$$

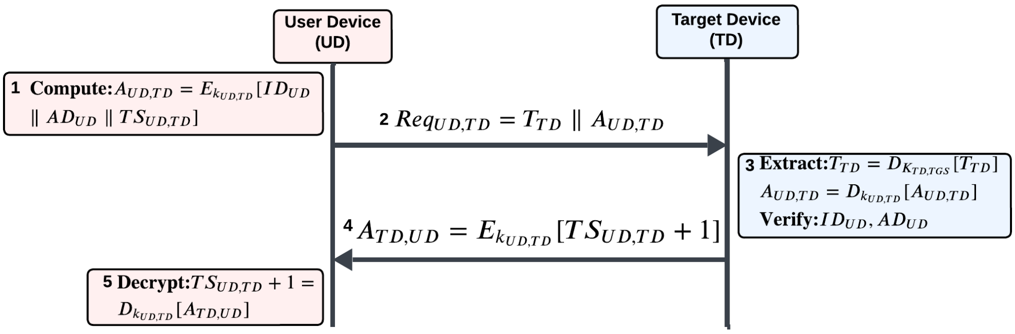

Figure 4.5: KFI: Accessing the service.

4.6.1.4 Accessing the Service

Step 1: UD computes the authenticator $A_{UD,TD}$ using its session key shared with the target device and constructs the request:

$$A_{UD,TD} = E_{k_{UD,TD}}[ID_{UD} \parallel AD_{UD} \parallel TS_{UD,TD}] \tag{4.14}$$

Step 2: UD sends $Req_{UD,TD}$ to TD.

$$Req_{UD,TD} = T_{TD} \parallel A_{UD,TD} \tag{4.15}$$

Step 3: TD performs the following actions:

→ Decrypts T_{TD} using $K_{TD,TGS}$

→ Decrypts $A_{UD,TD}$ using $k_{UD,TD}$

→ Verifies ID_{UD} and AD_{UD}

Step 4: TD computes the response and sends it back to UD.

$$A_{TD,UD} = E_{k_{UD,TD}}[TS_{UD,TD} + 1] \tag{4.16}$$

Step 5: UD decrypts the received message using $k_{UD,TD}$ and verifies it to ensure the freshness and authenticity of the session.

$$TS_{UD,TD} + 1 = D_{k_{UD,TD}}[A_{TD,UD}]$$

4.6.2 KFLIT: Kerberos with FIDO and Lightweight Extension for Internet of Things

KFLIT extends the fourth phase of *KFI*, leveraging its robust passwordless authentication mechanism as a foundational component. By adapting Kerberos for IoT, *KFLIT* addresses challenges in resource-constrained and clockless devices. Enhancing the lightweight model of KESIC [17], *KFLIT* eliminates encryption operations, replacing them with computationally efficient HMAC and XOR mechanisms. It has an attestation phase to verify device integrity before granting access, ensuring trust in authentication. This design optimizes Kerberos for IoT-specific requirements, providing a scalable, efficient, and secure authentication framework while integrating the security strengths of *KFI*.

4.6.2.1 Attestation and Time Synchronization Phase

The Attestation and Time Synchronization Phase ensures the integrity of IN and synchronizes its counter with ITS. The steps involved are as follows:

Step 1: IN increments its counter and computes:

$$A_{IN,ITS} = HMAC(K_{ITS,IN}, [ID_{IN} \parallel CO_{\text{sync}}]) \tag{4.17}$$

Step 2: IN sends the attestation request to ITS:

$$Req_{IN,ITS} = ID_{IN} \parallel CO_{\text{sync}} \parallel A_{IN,ITS} \tag{4.18}$$

Step 3: ITS verifies the counter value, and HMAC then generates a challenge and computes:

$$A^{\text{attest}}_{ITS,IN} = HMAC(K_{IN,ITS}, [ID_{ITS} \parallel \text{Challenge}]) \tag{4.19}$$

Step 4: ITS sends the attestation challenge to IN:

$$Req^{\text{attest}}_{ITS,IN} = ID_{ITS} \parallel \text{Challenge} \parallel A^{\text{attest}}_{ITS,IN} \tag{4.20}$$

Step 5: IN verifies the received attestation HMAC and computes:

$$k_{\text{attest},IN,ITS} = HMAC(K_{IN,ITS}, [\text{Challenge}]) \tag{4.21}$$

$$\text{Attst}_{\text{HMAC}} = HMAC(k_{\text{attest},IN,ITS}, [\text{Memory}]) \tag{4.22}$$

Step 6: IN sends the attestation response:

$$\text{Attst}_{\text{Response},IN,ITS} = \text{Attst}_{\text{HMAC}} \tag{4.23}$$

Step 7: ITS verifies the attestation response and computes the following:

$$A_{ITS,IN} = HMAC(K_{ITS,IN}, [ID_{ITS} \parallel CO_{\text{sync}} \parallel TS_{ITS,IN}]) \tag{4.24}$$

Step 8: ITS sends the time synchronization response to IN:

$$Res_{ITS,IN} = ID_{ITS} \parallel CO_{\text{sync}} \parallel TS_{ITS,IN} \parallel A_{ITS,IN} \tag{4.25}$$

Step 9: IN verifies the authenticity of the response and updates its local time reference.

$$\text{Verify: } A_{ITS,IN} = HMAC(K_{ITS,IN}, [ID_{ITS} \parallel CO_{\text{sync}} \parallel TS_{ITS,IN}])$$

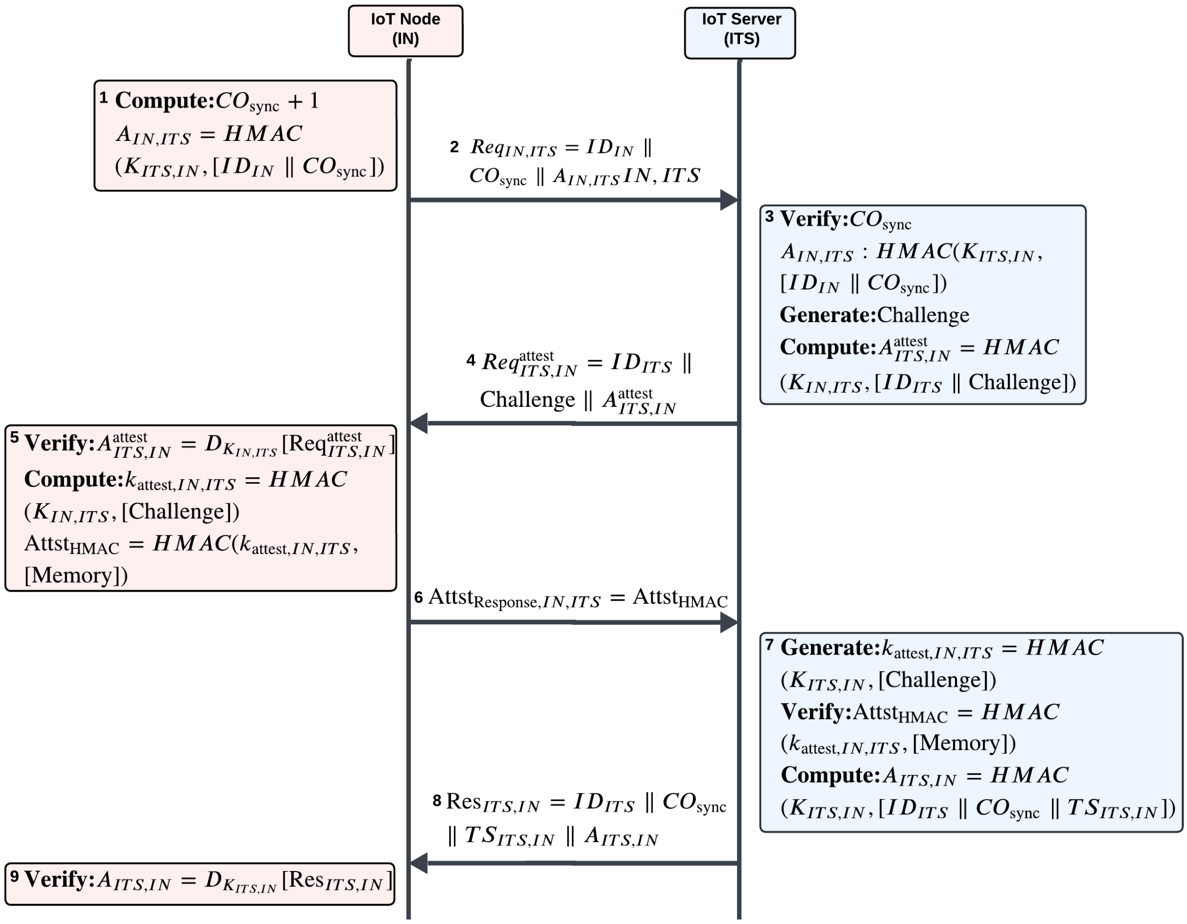

Figure 4.6: KFLIT: Attestation and time synchronization phase.

4.6.2.2 Ticket Issuing Phase

The Ticket Issuing Phase enables ITS to securely issue tickets for IN by interacting with UD. This phase relies on TGT for ITS, T_{ITS}, issued through the *KFI* protocol. By leveraging T_{ITS}, ITS ensures that only authorized UDs can request tickets for accessing IoT Nodes. The steps involved are as follows:

Step 1: UD computes the HMAC-based authenticator:

$$A_{UD,ITS} = HMAC(k_{UD,ITS}, [ID_{UD} \parallel AD_{UD} \parallel TS_{UD,ITS}]) \tag{4.26}$$

Step 2: UD sends the request to ITS:

$$Req_{UD,ITS} = ID_{IN} \parallel T_{ITS} \parallel A_{UD,ITS} \parallel TS_{UD,ITS} \tag{4.27}$$

Step 3: ITS decrypts and verifies the received ticket and computes:

$$T_{IN} = HMAC(K_{IN,ITS}, [ID_{UD} \parallel AD_{UD} \parallel L_6 \parallel ID_{IN} \parallel TS_{ITS,UD}]) \tag{4.28}$$

$$Mask = [ID_{IN} \parallel k_{UD,IN} \parallel TS_{ITS,UD} \parallel L_6 \parallel T_{IN}] \oplus k_{UD,ITS} \tag{4.29}$$

Step 4: ITS responds with an obfuscated payload and authentication code:

$$Res_{ITS,UD} = [Mask \parallel HMAC(k_{UD,ITS}, Mask)] \oplus k_{UD,ITS} \tag{4.30}$$

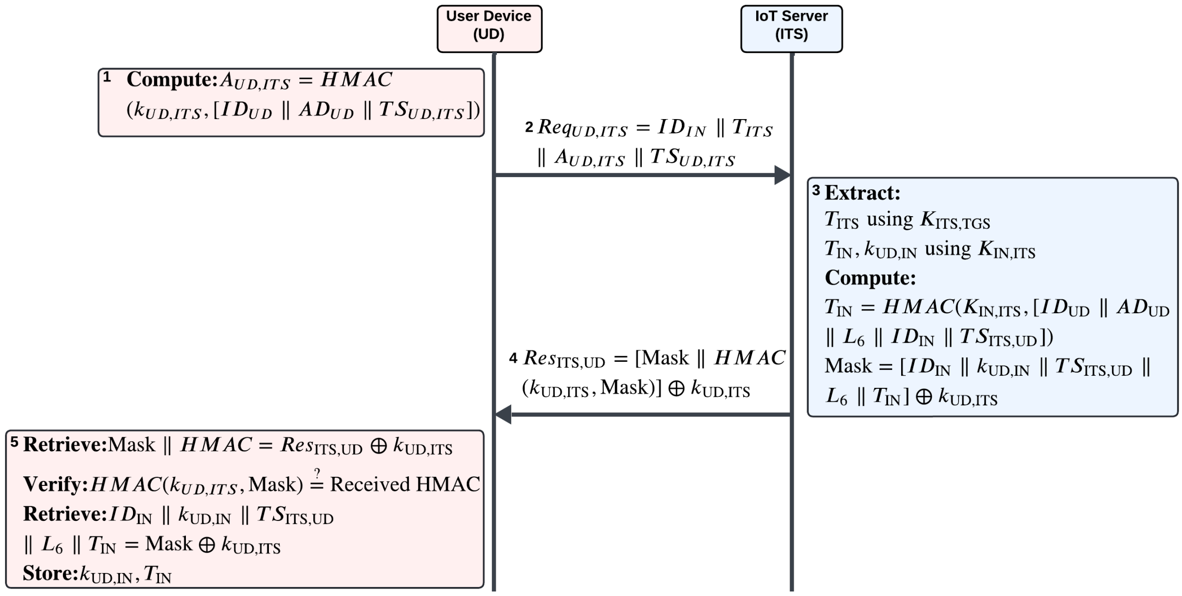

Figure 4.7: KFLIT: Ticket issuing phase.

Step 5: UD retrieves and verifies the response:

$$\text{Retrieve: } Mask \parallel HMAC = Res_{ITS,UD} \oplus k_{UD,ITS} \tag{4.31}$$

$$\text{Verify: } HMAC(k_{UD,ITS}, Mask) \stackrel{?}{=} \text{Received HMAC} \tag{4.32}$$

$$\text{Retrieve: } ID_{IN} \parallel k_{UD,IN} \parallel TS_{ITS,UD} \parallel L_6 \parallel T_{IN} = Mask \oplus k_{UD,ITS} \tag{4.33}$$

$$\text{Store: } k_{UD,IN}, T_{IN} \tag{4.34}$$

This secure mechanism ensures UD receives credentials to access IN while maintaining confidentiality and integrity through HMAC and XOR-based masking.

4.6.2.3 Service Phase

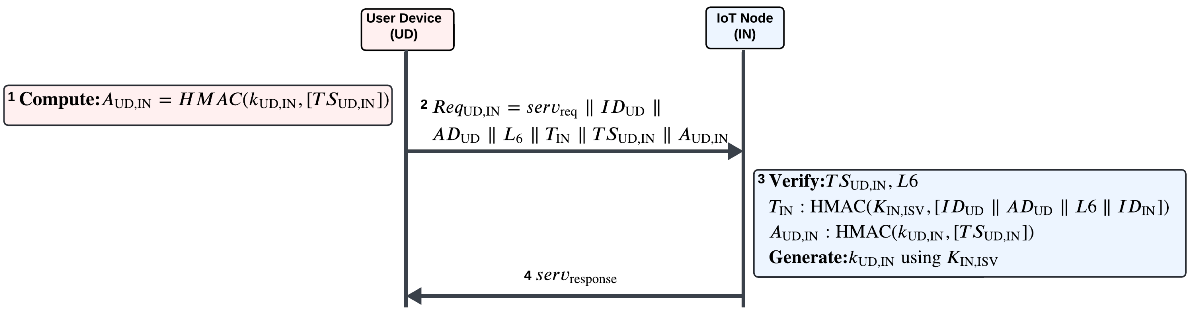

Figure 4.8: KFLIT: Service phase.

The Service Phase ensures secure communication between UD and IN for accessing requested services. The steps involved are as follows:

Step 1: UD computes the authenticator to initiate the service request:

$$A_{UD,IN} = HMAC(k_{UD,IN}, [TS_{UD,IN}]) \tag{4.35}$$

Step 2: UD sends the service request to IN:

$$Req_{UD,IN} = serv_{req} \parallel ID_{UD} \parallel AD_{UD} \parallel L_6 \parallel T_{IN} \parallel TS_{UD,IN} \parallel A_{UD,IN} \tag{4.36}$$

Step 3: IN verifies the received timestamp and level value, then validates:

$$T_{IN} = HMAC(K_{IN,ISV}, [ID_{UD} \parallel AD_{UD} \parallel L_6 \parallel ID_{IN}]) \tag{4.37}$$

$$A_{UD,IN} = HMAC(k_{UD,IN}, [TS_{UD,IN}]) \tag{4.38}$$

If the verifications are successful, IN generates $k_{UD,IN}$ using $K_{IN,ISV}$ if not already derived.

Step 4: IN responds with $serv_{response}$, completing the service access phase.

Chapter 5

Results

This chapter presents the comprehensive evaluation of the proposed authentication protocols—P-MASFEP and KFLIT—designed to enhance the security and efficiency of IoT environments. The review encompasses qualitative and quantitative analyses, including informal security assessments, computation and communication cost comparisons, and formal Scyther tool verification. P-MASFEP is tailored for IoMT applications, addressing threats such as offline password guessing and privileged insider attacks. At the same time, KFLIT builds upon Kerberos and FIDO principles to provide lightweight, scalable authentication for general IoT ecosystems. The results demonstrate that both protocols balance security robustness and performance efficiency, making them suitable for deployment in resource-constrained and security-critical IoT domains.

5.1 Security and Performance Evaluation of P-MASFEP

5.1.1 Informal Security Analysis

The informal security analysis demonstrates that the P-MASFEP fulfils the security prerequisites of IoMT-based healthcare services.

1. ***Resistant to privileged insider attacks:*** SN is responsible for generating the session key SK and compute $SN_4 = E_{(PubK_{UD})}(SK)$. SN_4 is shared with UD via GW. Even if a privileged insider at GW manages to steal TID^0_{UD}, $PubK_{\text{UD}}$, D_{ID}, and D_{LN}, they cannot retrieve SK without the private key of UD, $PvtK_{\text{UD}}$, which is only known to UD. Therefore, the P-MASFEP protocol is secure against privileged insider attacks.

2. ***Resistant to offline password guessing attacks:*** The proposed P-MASFEP scheme strengthens defence against offline password guessing by employing a fuzzy extractor with biometric information BIO_{i} to compute $FE.Gen(BIO_{\text{i}}) = (K, h_d)$ and $CPW_{\text{i}} = h(K \| D_{\text{ID}} \| D_{\text{LN}} \| TID^0_{\text{UD}})$. Since the user's biometrics are not stored for authentication, an attacker cannot guess the password. Additionally, CPW_{i} is dependent on TID_{UD}, which updates with each session. Therefore, the P-MASFEP scheme enhances defence against offline password-guessing attacks.

3. ***Resilient against replay attacks:*** Suppose an adversary captures the message $\{GW_1, GW_2, GW_3\}$ and later attempts to relay it to UD. Upon receiving the message $\{GW_1, GW_2, GW_3\}$, UD verifies the freshness of the nonce N^{1*}_{GW}. UD terminates the session since the relayed message contains an outdated nonce. This

procedure is applied to all messages, ensuring that P-MASFEP is secure against replay attacks.

4. ***Secure against DOS attacks:*** The hash and cryptographic encryption using asymmetric keys restrict the adversary's ability to obtain the session key, making it extremely difficult for an adversary to decipher the message. The entities verify the integrity of each received message. Therefore, a DoS attack is impractical in P-MASFEP.

5. ***Resistant to MITM attacks:*** Imagine that the message $\{UD_2,\ UD_3\ \ SN^{*}_{\mathrm{IEI}}\}$ was intercepted by an adversary. Any try to perform MITM will be unsuccessful since the messages $UD_2 = h(C^{0*}_{\mathrm{UD}} \| N^{1*}_{\mathrm{GW}} \| R^{0*}_{\mathrm{UD}} \| TID^{0}_{\mathrm{UD}})$, $UD_3 = N^{2}_{\mathrm{UD}} \oplus D_{\mathrm{LN}}$ and $SN^{*}_{\mathrm{IEI}} = h(D_{\mathrm{ID}} \| D_{\mathrm{LN}} \| R^{0*}_{\mathrm{UD}} \| N^{1*}_{\mathrm{GW}}) \oplus SN_{\mathrm{IEI}}$ are computed through bitwise XOR and cryptographic hash function. The collision-resistant property of hash functions [35] makes it harder for the adversary to retrieve or predict the values. Hence, P-MASFEP is secure against MITM attacks.

6. ***Resistant to impersonation attacks:*** Suppose an adversary intercepts the message $\{GW_5,\ GW_6,\ GW_7,\ PubK^{*}_{\mathrm{UD}}\}$. Due to the collision-resistant property of hash functions [35], it is computationally infeasible for the attacker to retrieve $PubK_{\mathrm{UD}}$ or TID^{0}_{UD}. Additionally, each device is equipped with a distinct PUF, making it impossible for the attacker to replicate its identity.

7. ***Protection against physical attacks:*** If an adversary physically tampers with SN to clone or extract data from its chip, PUFs in UD and SN act as safeguards. Any interference with PUF would damage the unique properties of UD, rendering it useless since PUF output depends on inherent physical variations in the integrated circuit [33]. Thus, P-MASFEP is protected from cloning and side-channel attacks.

8. ***Exhibits message freshness and integrity:*** The P-MASFEP scheme sends the messages as a message digest and checks the freshness of the shared messages over the channel using nonces. These techniques ensure that the received message remains unaltered during transmission, thereby verifying the integrity of the data.

9. ***Mutual authentication:*** UD, GW, and SN perform mutual authentication and verify the genuineness before establishing a session key to secure further communication. The effective execution of this protocol is contingent upon the legitimacy of every entity involved in the authentication process.

10. ***Ensures data privacy:*** Suppose an adversary captures the message $\{GW_9,\ PubK^{*}_{\mathrm{SN}},\ GW_{10},\ C^{1*}_{\mathrm{UD}},\ SN_4,\ SN_5\}$ in an attempt to extract sensitive information. In this message, N^{3}_{GW} and D_{ID} are enclosed as $GW_9 = N^{3}_{\mathrm{GW}} \oplus D_{\mathrm{ID}}$. The actual values of D_{ID} and N^{3}_{GW} are never transmitted over the communication channel. As a result, the adversary is unable to retrieve this information. Moreover, other parameters are computed using bitwise XOR and cryptographic hash operations, ensuring the privacy of the message's contents.

11. ***Session key security:*** The real SK is never disclosed over the public channel; instead, it is encrypted as $SN_4 = E_{(PubK_{UD})}(SK)$, which ensures secrecy over the public channel. As a result, an adversary cannot retrieve SK. Thus, the P-MASFEP scheme ensures session key security.

Table 5.1: Computation cost calculations of P-MASFEP & related schemes.

Scheme	**Computation Cost**
Alladi et al. [9]	$8C_{\text{HMAC}} + 16C_{\text{F}}$
Gope et al. [21]	$22C_{\text{H}} + 3C_{\text{HMAC}}$
Shao et al. [22]	$37C_{\text{H}}$
MASK [11]	$23C_{\text{H}} + 4C_{\text{F}}$
P-MASFEP	$28C_{\text{H}} + 2C_{\text{AED}} + C_{\text{FE}}$

C_{H}: Computation of Hash Function, C_{HMAC}: Computation of Hash Message Authentication Code, C_{F}: Computation of Cryptographic Function, C_{AED}: Computation of Asymmetric Key Encryption/Decryption, C_{FE}: Computation of Fuzzy Extractor.

12. ***User device and sensor node identity anonymity and untraceability:*** Suppose an adversary intercepts the message $\{N_{\text{UD}}^{1*}, TID_{\text{UD}}^{0*}\}$ in an attempt to extract real D_{LN} and D_{ID}. The adversary cannot retrieve this information, as D_{LN} and D_{ID} are never used during the session key establishment phase. Additionally, GW generates new temporary identities, TID_{UD} and TID_{SN}, for future communication and converts these temporary identities into pseudo-identities during mutual authentication and key establishment. Moreover, the scheme updates the temporary identities each session, preventing an adversary from tracking UD or SN.

5.1.2 Comparative Analysis

This section compares P-MASFEP to evaluate the scheme's functionality, communication, and computation costs against those of other relevant schemes.

Computation Cost Comparison

The computational overhead encompasses all cryptographic operations to establish mutual authentication and session keys. Multiprecision Integer and Rational Arithmetic Library (MIRACL) [51] is an open-source library designed to facilitate the testing of cryptographic protocols. It provides a robust platform for performing complex arithmetic operations on large integers and rational numbers, essential in various cryptographic applications, such as public key cryptography. This paper uses the methodology outlined by Yu et al. [36] based on MIRACL to derive the computation costs. The following assumptions are taken into account while calculating the computation costs of various schemes: C_{H}: Computation of Hash Function $\approx$ 0.309 ms (for example, Secure Hash Algorithm (SHA-256) [52]), C_{HMAC}: Computation of Hash Message Authentication Code (HMAC) $\approx$ 0.618 ms (HMAC takes approximately twice the time of a standalone hash operation [53]), C_{F}: Computation of Cryptographic Function $\approx$ 0.012 ms (for example, Advanced Encryption Standard (AES) [54]), C_{AED}: Computation of Asymmetric Key Encryption/Decryption $\approx$ 0.522 ms (for example, Rivest Shamir Adelman (RSA) [55]) and C_{FE}: Computation of Fuzzy Extractor $\approx$ 2.848 ms. It is worth noting that the total computational cost of the proposed P-MASFEP scheme is 10.690 ms, which is slightly more than MASK's [11] 7.155 ms. Table 5.1 outlines each protocol's detailed computation cost calculations, highlighting the operations involved in the cost estimation.

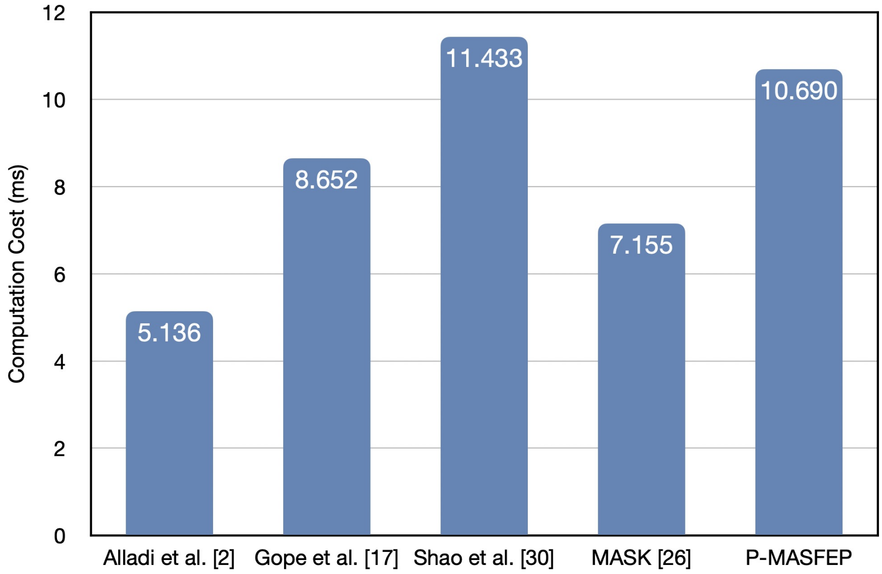

Figure 5.1: Computation cost comparison of P-MASFEP.

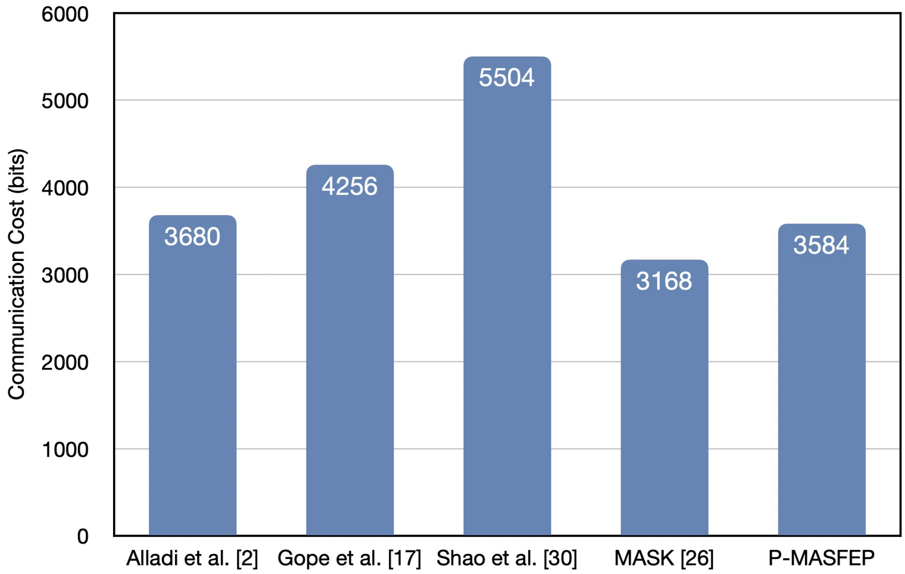

Figure 5.2: Communication cost comparison of P-MASFEP.

Fig. 5.1 visually compares the total computational costs of P-MASFEP and other schemes. Although P-MASFEP incurs a slightly higher computational overhead, its robust security guarantees justify this trade-off, which is critical for IoMT applications. Compared to different schemes, P-MASFEP achieves a favourable balance between computational efficiency and security, making it a practical solution for resource-constrained IoMT devices.

Communication Cost Comparison

The communication overhead is the amount of information the participants send or receive to complete the authentication process. The following assumptions are taken into account while calculating the communication costs of various schemes: the hash is 160 bits, random nonces, and the identities are 128 bits, the cryptographic encryption/decryption block is 256 bits, PUF is 128 bits, and the timestamp is 32 bits according to Banerjee et al. [34]. Fig. 5.2 visually represents the communication cost comparison for various schemes. The MASK [11] scheme has a communication cost of 3168 bits, whereas the proposed P-MASFEP scheme has a communication cost of 3584 bits, indicating a marginal increase in overhead. Although MASK [11] incurs a lower communication cost, it is insecure as it is vulnerable to offline password guessing and privileged insider attacks. In contrast, the slight increase in P-MASFEP's communication cost is justified by its enhanced security guarantees, making it a robust choice for IoMT systems.

5.1.3 Formal Verification Using Scyther

Scyther [29] is a widely used automated protocol verification tool. Scyther can verify and characterize protocols, producing a finite representation of all potential behaviour. It validates multiple security properties using the Security Protocol Description Language (SPDL) script. The script describes protocols as a collection of roles containing events and different claims to reflect desired security features like secrecy, non-injunctive synchronization (Nisynch), aliveness of roles (Aliveness), non-injunctive agreement (Niagree) and weak agreement of roles (Weakagree) [30]. The script verifies seventeen secret claim events to confirm the scheme's confidentiality, security, and legitimacy. Additionally, Niagree, Alive, Nisynch, and Weakagree authentication claims are evaluated for each of the three roles to ensure the overall security of the proposed P-MASFEP scheme. According to the Scyther simulation, P-MASFEP satisfies all security and authentication standards. The script is available in Annexure I. Fig. 5.3 shows the simulation output used to evaluate P-MASFEP.

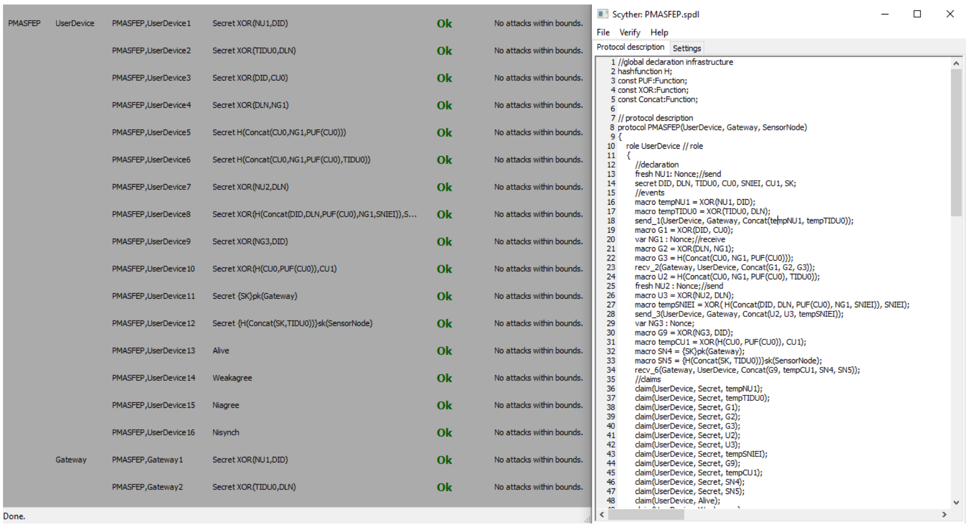

Figure 5.3: Result obtained from Scyther for the P-MASFEP scheme.

Table 5.2: Security comparison of KESIC & KFLIT.

Attack Type	**KESIC [17]**	**KFLIT (Proposed)**
Password-Guessing and Dictionary Attacks	×	✓
Kerberoasting	×	✓
Golden Ticket Attacks	×	✓
Silver Ticket Attacks	×	✓
Replay Attacks	✓	✓
Man-in-the-Middle (MitM) Attacks	✓	✓

✓: Attack Mitigated   ×: Attack Not Mitigated

5.2 Security and Performance Evaluation of KFLIT

5.2.1 Informal Security Analysis

To assess the resilience of the proposed protocols against modern attack vectors, Table 5.2 presents a comparative analysis of *KFLIT* and *KESIC* [17]. It highlights the key security improvements introduced in *KFLIT*, demonstrating its effectiveness in mitigating a broader range of attacks, including those not addressed by existing schemes like *KESIC*.

1. ***Password-Guessing and Dictionary Attacks:*** Using public-private key cryptography, *KFI* eliminates static passwords, rendering brute-force and dictionary attacks infeasible. *KFLIT* inherits this passwordless foundation, ensuring secure authentication specifically adapted for resource-constrained IoT environments.

2. ***Kerberoasting:*** Kerberoasting attacks [18] exploit weak encryption in Kerberos tickets to extract service account credentials for offline brute-force attacks. *KFI*

mitigates this threat by eliminating password-derived keys and using FIDO's asymmetric authentication mechanism, making it impractical for attackers to extract usable credentials from tickets.

3. ***Golden Ticket Attacks:*** Golden Ticket attack [19] involves forging TGTs to obtain unrestricted access. *KFI* ensures that TGTs cannot be forged without access to the FIDO private key, which remains securely stored on the user's physical key and is never transmitted. *KFLIT* carries forward this security to IoT environments, preserving integrity even across lightweight nodes.

4. ***Silver Ticket Attacks:*** Silver Ticket attacks [20] aim to impersonate users at the service level by forging service-specific tickets. In *KFI*, FIDO's challenge-response process ensures client authenticity, thwarting impersonation attempts. *KFLIT* strengthens this by using HMAC-bound session tickets, preventing ticket forgery and reuse, and maintaining secure communication with IoT nodes.

5. ***Replay Attacks:*** Replay attacks involve reusing captured authentication messages to gain unauthorized access. *KFI* neutralizes this threat by generating unique FIDO-signed challenge responses per session, ensuring message freshness. *KFLIT* complements this mechanism with counter-based synchronization, removing the reliance on real-time clocks while effectively detecting and blocking replayed messages.

6. ***Man-in-the-Middle (MitM) Attacks:*** MitM attacks aim to intercept and manipulate communication between parties. *KFI* prevents such attacks by enforcing message integrity through FIDO. *KFLIT* enhances this with HMAC-secured communication between UD, ITS, and IN, ensuring tamper-proof data transmission across enterprise and IoT settings.

5.2.2 Comparative Analysis

This section compares *KFLIT* with *KESIC* [17] to evaluate its communication and computation costs. The comparison highlights the improvements in efficiency and security introduced by *KFLIT* while extending the lightweight principles of *KESIC*.

Computation Cost Comparison

The computational overhead includes all cryptographic operations required for mutual authentication. To evaluate the operations, the Multiprecision Integer and Rational Arithmetic Library (MIRACL) [51] is used. It relies on following computational cost assumptions [36]: C_{HMAC}: 0.618 ms, $C_{\text{Encryption/Decryption}}$: 0.572 ms, and C_{XOR}: 0.003 ms. *KFLIT* achieves enhanced security at a lower computational cost than *KESIC*.

Communication Cost Comparison

Communication costs are calculated based on assumptions of data block sizes for IDs (8 bytes), synchronization counters and challenges (32 bytes), symmetric encryption blocks (256 bytes), XOR operations (12 bytes), HMAC blocks (64 bytes), and timestamps (4 bytes) [34]. Table 5.4 demonstrates that while *KFLIT* increases the number of messages, its communication cost is lower due to the efficient use of lightweight operations. In contrast, *KFI* incurs a higher communication cost owing to its additional FIDO-based

Table 5.3: Computation cost comparison of KFLIT.

Scheme	With Attestation (ms)	Without Attestation (ms)
Kerberos [12]	7.822	-
KFI (Proposed)	7.214	-
KESIC [17]	10.670	6.614
KFLIT (Proposed)	9.960	5.412

Table 5.4: Communication cost comparison of KFLIT.

Scheme	Number of Messages	Communication Cost (Bytes)
Kerberos [12]	7	672
KFI (Proposed)	12	814
KESIC [17]	6	696
KFLIT (Proposed)	8	584

exchanges. Still, this overhead is justified by its ability to mitigate advanced attacks such as Kerberoasting, Golden Ticket, and Silver Ticket, which are not effectively addressed in existing schemes like *KESIC*.

5.2.3 Formal Verification Using Scyther

Scyther verifies and characterizes protocols, producing a finite representation of all potential behaviours. It validates multiple security properties using the Security Protocol Description Language (SPDL) script. The script describes protocols as a collection of roles containing events and claims to reflect desired security properties such as secrecy, non-injective synchronization (Nisynch), aliveness of roles (Alive), non-injective agreement (Niagree), and weak agreement of roles (Weakagree) [30]. For the proposed protocols, Scyther confirms that *KFI* and *KFLIT* satisfy all evaluated security and authentication properties, ensuring their robustness against potential threats. Table 5.5 summarizes the verified security attributes for the protocols. The script is available in Annexure II.

Table 5.5: Verified security attributes of KFI & KFLIT.

KFI					
Security Attributes	Secrecy	Nisynch	Aliveness	Niagree	Weakagree
User Device	✓	✓	✓	✓	✓
Authenticator Server	✓	✓	✓	✓	✓
Ticket Granting Server	✓	✓	✓	✓	✓
Target Device	✓	✓	✓	✓	✓
KFLIT					
Security Attributes	Secrecy	Nisynch	Aliveness	Niagree	Weakagree
User Device	✓	✓	✓	✓	✓
IoT Server	✓	✓	✓	✓	✓
IoT Node	✓	✓	✓	✓	✓

✓: Verified.

Chapter 6

Conclusion and Future Work

Secure, efficient, and scalable authentication mechanisms are essential for the evolving landscape of IoT. The two novel protocols, P-MASFEP and KFLIT, address distinct but complementary challenges in IoT authentication through innovative cryptographic and architectural enhancements. P-MASFEP focuses on IoMT, where security vulnerabilities such as offline password-guessing and privileged insider attacks pose significant risks to patient data confidentiality and system integrity. By integrating PUFs, FE, and PKI, P-MASFEP ensures secure mutual authentication and session key establishment. KFLIT extends the capabilities of traditional Kerberos by incorporating FIDO's passwordless authentication model and tailoring the protocol for IoT ecosystems. The foundational scheme, KFI, addresses password-derived threats such as Kerberoasting, Golden Ticket, and Silver Ticket attacks by replacing password-based login with FIDO's cryptographic passkeys. Building on KFI, KFLIT introduces lightweight cryptographic operations (HMAC and XOR), counter-based synchronization instead of timestamping, and attestation mechanisms to verify IoT device integrity. These enhancements significantly reduce computational complexity while maintaining Kerberos' robust ticket-based framework, making KFLIT well-suited for secure and efficient authentication in large-scale and heterogeneous IoT deployments. Future work will explore the practical deployment of both protocols in real-world environments. For P-MASFEP, this includes addressing deployment challenges across various healthcare infrastructures. For KFI and KFLIT, future directions include performance benchmarking in high-traffic networks, enhancing support for cross-domain authentication in distributed IoT environments, and ensuring interoperability across heterogeneous infrastructures.

Annexure I

Scyther Script for P-MASFEP

```
//global declaration infrastructure
hashfunction H;
const PUF:Function;
const XOR:Function;
const Concat:Function;
// protocol description
protocol PMASFEP(UserDevice, Gateway, SensorNode)
{
    role UserDevice // role
    {
        //declaration
        fresh NU1: Nonce;//send
        secret DID, DLN, TIDU0, CU0, SNIEI, CU1, SK;
        //events
        macro tempNU1 = XOR(NU1, DID);
        macro tempTIDU0 = XOR(TIDU0, DLN);
        send_1(UserDevice, Gateway, Concat(tempNU1, tempTIDU0));
        macro G1 = XOR(DID, CU0);
        var NG1 : Nonce;//receive
        macro G2 = XOR(DLN, NG1);
        macro G3 = H(Concat(CU0, NG1, PUF(CU0)));
        recv_2(Gateway, UserDevice, Concat(G1, G2, G3));
        macro U2 = H(Concat(CU0, NG1, PUF(CU0), TIDU0));
        fresh NU2 : Nonce;//send
        macro U3 = XOR(NU2, DLN);
        macro tempSNIEI = XOR( H(Concat(DID, DLN, PUF(CU0), NG1, SNIEI)), SNIEI);
        send_3(UserDevice, Gateway, Concat(U2, U3, tempSNIEI));
        var NG3 : Nonce;
        macro G9 = XOR(NG3, DID);
        macro tempCU1 = XOR(H(CU0, PUF(CU0)), CU1);
        macro SN4 = {SK}pk(Gateway);
        macro SN5 = {H(Concat(SK, TIDU0))}sk(SensorNode);
        recv_6(Gateway, UserDevice, Concat(G9, tempCU1, SN4, SN5));
        //claims
        claim(UserDevice, Secret, tempNU1);
        claim(UserDevice, Secret, tempTIDU0);
        claim(UserDevice, Secret, G1);
        claim(UserDevice, Secret, G2);
        claim(UserDevice, Secret, G3);
        claim(UserDevice, Secret, U2);
        claim(UserDevice, Secret, U3);
        claim(UserDevice, Secret, tempSNIEI);
        claim(UserDevice, Secret, G9);
        claim(UserDevice, Secret, tempCU1);
```

```
    claim(UserDevice, Secret, SN4);
    claim(UserDevice, Secret, SN5);
    claim(UserDevice, Alive);
    claim(UserDevice, Weakagree);
    claim(UserDevice, Niagree);
    claim(UserDevice, Nisynch);
}
role Gateway // role
{
    //declaration
    var NU1: Nonce;//receive
    secret DID, DLN, TIDU0, CU0, SNIEI, CSN0, TIDSN0, CSN1, SK, CU1;
    //events
    macro tempNU1 = XOR(NU1, DID);
    macro tempTIDU0 = XOR(TIDU0, DLN);
    recv_1(UserDevice, Gateway, Concat(tempNU1, tempTIDU0));
    macro G1 = XOR(DID, CU0);
    fresh NG1 : Nonce;//send
    macro G2 = XOR(DLN, NG1);
    macro G3 = H(Concat(CU0, NG1, PUF(CU0)));
    send_2(Gateway, UserDevice, Concat(G1, G2, G3));
    macro U2 = H(Concat(CU0, NG1, PUF(CU0), TIDU0));
    var NU2 : Nonce;//send
    macro U3 = XOR(NU2, DLN);
    macro tempSNIEI = XOR( H(Concat(DID, DLN, PUF(CU0), NG1, SNIEI)), SNIEI);
    recv_3(UserDevice, Gateway, Concat(U2, U3, tempSNIEI));
    macro G5 = XOR(SNIEI, CSN0);
    fresh NG2 : Nonce;// send
    macro G6 = XOR(TIDSN0, NG2);
    macro G7 = H(Concat(CSN0, NG2, PUF(CSN0)));
    macro tempCSN1 = XOR(H(Concat(CSN0, PUF(CSN0))), CSN1);
    send_4(Gateway, SensorNode, Concat(G5, G6, G7, tempCSN1));
    var NSN1 : Nonce; //receive
    macro SN2 = XOR(NSN1, TIDSN0);
    macro SN4 = {SK}pk(Gateway);
    macro SN5 = {H(Concat(SK, TIDU0))}sk(SensorNode);
    recv_5(SensorNode, Gateway, Concat(SN2, SN4, SN5));
    fresh NG3 : Nonce;
    macro G9 = XOR(NG3, DID);
    macro tempCU1 = XOR(H(CU0, PUF(CU0)), CU1);
    send_6(Gateway, UserDevice, Concat(G9, tempCU1, SN4, SN5));
    //claims
    claim(Gateway, Secret, tempNU1);
    claim(Gateway, Secret, tempTIDU0);
    claim(Gateway, Secret, G1);
    claim(Gateway, Secret, G2);
    claim(Gateway, Secret, G3);
    claim(Gateway, Secret, U2);
```

```
        claim(Gateway, Secret, U3);
        claim(Gateway, Secret, tempSNIEI);
        claim(Gateway, Secret, G5);
        claim(Gateway, Secret, G6);
        claim(Gateway, Secret, G7);
        claim(Gateway, Secret, tempCSN1);
        claim(Gateway, Secret, SN2);
        claim(Gateway, Secret, SN4);
        claim(Gateway, Secret, SN5);
        claim(Gateway, Secret, G9);
        claim(Gateway, Secret, tempCU1);
        claim(Gateway, Alive);
        claim(Gateway, Weakagree);
        claim(Gateway, Niagree);
        claim(Gateway, Nisynch);
    }
    role SensorNode //role
    {
        //declaration
        secret CSN0, SNIEI, TIDSN0, TIDU0, CSN1, SK;
        //events
        macro G5 = XOR(SNIEI, CSN0);
        fresh NG2 : Nonce;// send
        macro G6 = XOR(TIDSN0, NG2);
        macro G7 = H(Concat(CSN0, NG2, PUF(CSN0)));
        macro tempCSN1 = XOR(H(Concat(CSN0, PUF(CSN0))), CSN1);
        recv_4(Gateway, SensorNode, Concat(G5, G6, G7, tempCSN1));
        fresh NSN1 : Nonce;
        macro SN2 = XOR(NSN1, TIDSN0);
        macro SN4 = {SK}pk(Gateway);
        macro SN5 = {H(Concat(SK, TIDU0))}sk(SensorNode);
        send_5(SensorNode, Gateway, Concat(SN2, SN4, SN5));
        //claims
        claim(SensorNode, Secret, G5);
        claim(SensorNode, Secret, G6);
        claim(SensorNode, Secret, G7);
        claim(SensorNode, Secret, tempCSN1);
        claim(SensorNode, Secret, SN2);
        claim(SensorNode, Secret, SN4);
        claim(SensorNode, Secret, SN5);
        claim(SensorNode, Alive);
        claim(SensorNode, Weakagree);
        claim(SensorNode, Niagree);
        claim(SensorNode, Nisynch);
    }
}
```

Annexure II

Scyther Script for KFLIT

```
// Global Declarations
hash function H;          // Cryptographic Hash Function
const XOR:Function;      // XOR Function
const Concat:Function;   // Concatenation Operator
const FIDO:Function;     // FIDO-Related Operations
const TS:Function;       // Timestamp Function
const Ticket:Function;   // Kerberos Ticket Representation
protocol KFI(UD, AS, TGS, TD)
{
    role UD
    {
        fresh NU1: Nonce; // Nonce for FIDO Authentication
        secret ID_UD, FIDO_PrivUD, k_ud_tgs, k_ud_td;
        // Step 1: FIDO Registration
        send_1(UD, AS, Concat(ID_UD, "FIDO-Registration", TS(UD -> AS)));
        // Step 2: FIDO Authentication (Challenge-Response)
        recv_2(AS, UD, Concat("Challenge(AS -> UD)"));
        send_3(UD, AS, Concat(FIDO("Pub(UD)"), FIDO("Sig(FIDO_PrivUD,
        Challenge)")));
        // Step 3: Receive TGT from AS
        recv_4(AS, UD, Concat(Ticket(TGS), k_ud_tgs));
        // Step 4: Send TGT to TGS for Service Ticket
        send_5(UD, TGS, Concat(ID(TD), Ticket(TGS), HMAC(k_ud_tgs, [ID(UD),
        TS(UD -> TGS)])));
        // Step 5: Receive Service Ticket
        recv_6(TGS, UD, Concat(Ticket(TD), k_ud_td));
        // Step 6: Access Target Device
        send_7(UD, TD, Concat(Ticket(TD), HMAC(k_ud_td, [ID(UD), TS(UD -> TD)])));
        recv_8(TD, UD, HMAC(k_ud_td, [ID(TD), TS(TD -> UD)]));
        // Claims for UD
        claim(UD, Secret, FIDO_PrivUD);
        claim(UD, Secret, k_ud_tgs);
        claim(UD, Secret, k_ud_td);
        claim(UD, Secret, Ticket(TGS));
        claim(UD, Secret, Ticket(TD));
        claim(UD, Alive);
        claim(UD, Weakagree);
        claim(UD, Niagree);
        claim(UD, Nisynch);
    }
    role AS
    {
        secret ID_AS, k_as_tgs;
        var FIDO_PubUD: PublicKey;
```

```
        // Step 1: Handle FIDO Registration Request
        recv_1(UD, AS, Concat(ID(UD), "FIDO-Registration", TS(UD -> AS)));
        send_2(AS, UD, Concat("Challenge(AS -> UD)"));
        // Step 2: Verify FIDO Response and Issue TGT
        recv_3(UD, AS, Concat(FIDO_Pub(UD), FIDO_Sig));
        send_4(AS, UD, Concat(Ticket(TGS), k_ud_tgs));
        // Claims for AS
        claim(AS, Secret, Ticket(TGS));
        claim(AS, Secret, k_as_tgs);
        claim(AS, Alive);
        claim(AS, Weakagree);
    }
    role TGS
    {
        secret ID_TGS, k_tgs_td;
        var Ticket(TGS): Ticket;
        var k_ud_tgs: SessionKey;
        // Step 1: Handle Request for Target Device Ticket
        recv_5(UD, TGS, Concat(ID(TD), Ticket(TGS), HMAC(k_ud_tgs, [ID(UD),
        TS(UD -> TGS)])));
        send_6(TGS, UD, Concat(Ticket(TD), k_ud_td));
        // Claims for TGS
        claim(TGS, Secret, Ticket(TGS));
        claim(TGS, Secret, k_ud_td);
        claim(TGS, Alive);
        claim(TGS, Weakagree);
    }
    role TD
    {
        secret ID_TD, k_td_tgs, k_ud_td;
        var Ticket(TD): Ticket;
        // Step 1: Handle Service Request
        recv_7(UD, TD, Concat(Ticket(TD), HMAC(k_ud_td, [ID(UD), TS(UD -> TD)])));
        send_8(TD, UD, HMAC(k_ud_td, [ID(TD), TS(TD -> UD)]));
        // Claims for TD
        claim(TD, Secret, Ticket(TD));
        claim(TD, Secret, k_ud_td);
        claim(TD, Alive);
        claim(TD, Weakagree);
    }
}
protocol KFLIT(UD, ITS, IN)
{
    role UD
    {
        fresh NU1: Nonce;
        secret ID_UD, k_ud_its, k_ud_in, T(ITS), T(IN);
        // Phase 1: Attestation and Counter Synchronization
```

```
    send_1(UD, ITS, Concat(ID(UD), T(ITS), HMAC(k_ud_its, [ID(UD),
    TS(UD -> ITS)])));
    recv_2(ITS, UD, Concat(HMAC(k_ud_its, [ID(ITS), TS(ITS -> UD)])));
    // Phase 2: IoT Ticket Request
    send_3(UD, ITS, Concat(ID(IN), T(ITS), HMAC(k_ud_its, [ID(UD),
    TS(UD -> ITS)])));
    recv_4(ITS, UD, Concat(T(IN), k_ud_in));
    // Phase 3: Service Access
    send_5(UD, IN, Concat(T(IN), HMAC(k_ud_in, [ID(UD), TS(UD -> IN)])));
    recv_6(IN, UD, HMAC(k_ud_in, [ID(IN), TS(IN -> UD)]));
    // Claims for UD
    claim(UD, Secret, k_ud_its);
    claim(UD, Secret, k_ud_in);
    claim(UD, Secret, T(ITS));
    claim(UD, Secret, T(IN));
    claim(UD, Alive);
    claim(UD, Weakagree);
    claim(UD, Niagree);
    claim(UD, Nisynch);
}
role ITS
{
    secret ID_ITS, k_its_in;
    var T(ITS): Ticket;
    var k_ud_its: SessionKey;
    // Phase 1: Handle Attestation
    recv_1(UD, ITS, Concat(ID(UD), T(ITS), HMAC(k_ud_its, [ID(UD), TS(UD
    -> ITS)])));
    send_2(ITS, UD, Concat(HMAC(k_ud_its, [ID(ITS), TS(ITS
    -> UD)])));
    // Phase 2: Issue IoT Ticket
    recv_3(UD, ITS, Concat(ID(IN), T(ITS), HMAC(k_ud_its, [ID(UD),
    TS(UD -> ITS)])));
    send_4(ITS, UD, Concat(T(IN), k_ud_in));
    // Claims for ITS
    claim(ITS, Secret, k_ud_its);
    claim(ITS, Secret, k_ud_in);
    claim(ITS, Secret, T(ITS));
    claim(ITS, Alive);
    claim(ITS, Weakagree);
}
role IN
{
    secret ID_IN, k_in_its, k_ud_in;
    var T(IN): Ticket;
    // Phase 3: Handle Service Request
    recv_5(UD, IN, Concat(T(IN), HMAC(k_ud_in, [ID(UD), TS(UD -> IN)])));
    send_6(IN, UD, HMAC(k_ud_in, [ID(IN), TS(IN -> UD)]));
```

```
        // Claims for IN
        claim(IN, Secret, T(IN));
        claim(IN, Secret, k_ud_in);
        claim(IN, Alive);
        claim(IN, Weakagree);
    }
}
```

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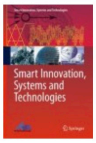

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CSCT 2024: Notification of your paper ID 728: Acceptance

Microsoft CMT <email@msr-cmt.org> Fri, 15 Nov at 00:01
Reply to: CSCT SCRS <csct.scril@gmail.com>
To: Harshit Tyagi <harshittyagi_23swe08@dtu.ac.in>

Dear Harshit Tyagi,

Thank you for submitting your research article to the CSCT 2024 - (3rd Congress on Smart Computing Technologies) to be organized by National Institute of Technology, Sikkim, India during December 14-15, 2024.

We are pleased to inform you that based on reviewers' comments, your paper titled "P-MASFEP: security-enhanced PUF-based Mutual Authentication & Session key establishment using Fuzzy Extractor & PKI" has been accepted for presentation during CSCT 2024, and publication in the proceedings to be published in Scopus-indexed Springer Book Series "Smart Innovation, Systems and Technologies" subject to the condition that you submit a revised version as per the comments, available at Authors CMT account. It is also required that you prepare a response to each comment from the reviewer and upload it as a separate file along with the revised paper.

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Feel free to write to the "General Chairs, CSCT 2024" at csct.scril@gmail.com, should you have any questions or concerns. Please remember to always include your Paper ID- 728, whenever inquiring about your paper. For regular updates on CSCT 2024, please join the SCRS Telegram channel https://t.me/+78ZOewUxF_AwNzhl

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Dear Harshit Tyagi,

Greetings!

Congratulations on the acceptance of your Paper titled "P-MASFEP: security-enhanced PUF-based Mutual Authentication & Session key establishment using Fuzzy Extractor & PKI” for presentation in 3rd Congress on Smart Computing Technologies (CSCT 2024) to be held on December 14-15, 2024 at National Institute of Technology, Sikkim, India and publication in the proceedings to be published in SCOPUS Indexed Springer Book Series Smart Innovation, Systems and Technologies.

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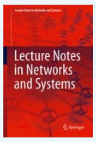

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Dear Harshit Tyagi,

Thank you for submitting your manuscript to 5th International Conference on Intelligent Vision and Computing (ICIVC 2025) to be held on June 13-14, 2025 at ICFAI University, Dehradun, India in Hybrid Mode. Proceedings of ICIVC 2025 will be published in the SCOPUS Indexed Springer Book Series Lecture Notes in Networks and Systems .

We are pleased to inform you that based on reviewers' comments, your paper titled "KFLIT: Kerberos with FIDO and Lightweight extension for Internet of Things" has been accepted for presentation during ICIVC 2025, and publication in the proceedings to be published in Scopus-indexed Springer Book Series "Lecture Notes in Networks and Systems" subject to the condition that you submit a revised version as per the comments, available at Authors CMT account. It is also required that you prepare a response to each comment from the reviewer and upload it as a separate file along with the revised paper.

The similarity index in the final paper must be less than 20%. Please note that the high plagiarism and any kind of multiple submissions of this paper to other conferences or journals will lead to rejection at any stage. Please note that the publisher, i.e. Springer Nature may ask for any other changes during the production which are supposed to be implemented. The publisher has the final right to exclude the paper from the proceedings if they found it unsuitable for publication.

Please carry out the steps to submit the camera-ready paper and online registration (Under "Regular Author" Category) as per the instructions available at

https://scrs.in/conference/icivc2025/page/Camera_Ready_Paper_Submission

In order to register in the SCRS member category (subsidized registration fees), you can first become a member at https://www.scrs.in/register and then register for the conference OR you may register as a Regular Author Category.

Please note that the Last date for submission of the camera-ready paper, payment of the registration fee, and online registration is May 30, 2025

Feel free to write to the "General Chairs, ICIVC 2025" at icivc.scrs@gmail.com, should you have any questions or concerns. Please remember to always include your Paper ID- 674, whenever inquiring about your paper.

With Regards
ICIVC 2025 (https://www.scrs.in/conference/icivc2025)
Join us on Telegram: https://t.me/+78ZOewUxF_AwNzhl

23/SWE/08 HARSHIT TYAGI <harshittyagi_23swe08@dtu.ac.in>

ICIVC 2025 (Paper ID - 674) : Registration Pending for Scopus-indexed Springer Book Series "LNNS"

1 message

Microsoft CMT <noreply@msr-cmt.org> Wed, May 21, 2025 at 9:19 PM
To: Harshit Tyagi <harshittyagi_23swe08@dtu.ac.in>

Dear Harshit Tyagi,

Greetings!

As per the record, you have not registered your Paper titled "KFLIT: Kerberos with FIDO and Lightweight extension for Internet of Things" for 5th International Conference on Intelligent Vision and Computing (ICIVC 2025). As the last date of registration is 30 May 2025, you are requested to carry out the steps to submit the camera-ready paper and online registration as per the instructions available at

https://scrs.in/conference/icivc2025/page/Camera_Ready_Paper_Submission

Feel free to write to the "General Chairs, ICIVC 2025" at icivc.scrs@gmail.com, should you have any questions or concerns. Please remember to always include your Paper ID-674, whenever inquiring about your paper.

Looking forward to meeting you during the conference.

With Regards
Team ICIVC 2025

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Harshit Tyagi
1/4563, STREET NUMBER 3, MANDOLI ROAD, RAMNAGAR, SHAHDARA
harshittyagi_23swe08@dtu.ac.in
For Paper ID: 674
Paper Title: KFLIT: Kerberos with FIDO and Lightweight extension for Internet of Things

DESCRIPTION	
Event Name	5th International Conference on Intelligent Vision and Computing (ICIVC2025) https://scrs.in/conference/icivc2025
Event Dates	13 Jun 2025 - 14 Jun 2025
Category of Registration	Regular Author
Registration Fee	INR 10000
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5th International Conference on Intelligent Vision and Computing (ICIVC 2025)

Organized by

The ICFAI University, Dehradun

Certificate of Presentation

This certificate is awarded to

Harshit Tyagi

who has presented the paper titled **"KFLIT: Kerberos with FIDO and Lightweight extension for Internet of Things"** authored by **Harshit Tyagi, Divyashikha Sethia** in the 5th International Conference on Intelligent Vision and Computing (ICIVC 2025) held at **The ICFAI University, Dehradun** during **June 13 – 14, 2025.**

Puneet Kumar Gupta
General Chair

Springer

Apu Kumar Saha
General Chair

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DECLARATION

I hereby certify that the work which is presented in the Major Project-II entitled **Secure Lightweight Authentication for Internet of Things** in fulfillment of the requirement for the award of the Degree of Master of Technology in Software Engineering and submitted to the Department of Software Engineering, Delhi Technological University, Delhi is an authentic record of my own, carried out during a period from January to May 2025 under the supervision of **Dr. Divyashikha Sethia**.

The mater presented in this report has not been submitted by me for the award of any other degree of this or any other Institute/University. The work has been published/accepted/communicated in SCI/SCI expanded/SSCI/Scopus indexed journal OR peer reviewed Scopus indexed conference with the following details.

Title of the Paper: **P-MASFEP: security-enhanced PUF-based Mutual Authentication & Session key establishment using Fuzzy Extractor & PKI**
Author names (in sequence): Harshit Tyagi, Dr. Divyashikha Sethia
Name of Conference/Journal: 3rd Congress on Smart Computing Technologies (CSCT2024)
Conference dates with venue: 14-15th December 2024, Sikkim, India
Status of paper (Accepted/Published/Communicated): Accepted
Date of paper communication: October 10, 2024
Date of paper acceptance: November 25, 2024
Date of paper publication: July 18, 2025

Harshit Tyagi
Roll No. 23/SWE/08

Student Roll No., Name and Signature

SUPERVISOR CERTIFICATE

To the best of my knowledge, the above work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere. I further certify that the publication and indexing information given by the students is correct.

May 21 2025

Date: 20 May 2025 **Dr. Divyashikha Sethia**

Place: New Delhi **Supervisor Name and Signature**

DECLARATION

I hereby certify that the work which is presented in the Major Project-II entitled **Secure Lightweight Authentication for Internet of Things** in fulfillment of the requirement for the award of the Degree of Master of Technology in Software Engineering and submitted to the Department of Software Engineering, Delhi Technological University, Delhi is an authentic record of my own, carried out during a period from January to May 2025 under the supervision of **Dr. Divyashikha Sethia**.

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Author names (in sequence): Harshit Tyagi, Dr. Divyashikha Sethia
Name of Conference/Journal: 5th International Conference on Intelligent Vision and Computing (ICIVC2025)
Conference dates with venue: 13-14th June 2025, Dehradun, Uttarakhand, India
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Date of paper communication: April 05, 2025
Date of paper acceptance: May 15, 2025
Date of paper publication: N/A

Tyagi

Harshit Tyagi
Roll No. 23/SWE/08

Student Roll No., Name and Signature

SUPERVISOR CERTIFICATE

To the best of my knowledge, the above work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere. I further certify that the publication and indexing information given by the students is correct.

Divya. May 21 2025

Date: 20 May 2025 **Dr. Divyashikha Sethia**

Place: New Delhi **Supervisor Name and Signature**