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PUFTAP-IoT: PUF-Based Three-Factor Authentication Protocol in IoT Environment Focused on Sensing Devices

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Abstract: In IoT-based environments, smart services can be provided to users under various environments, such as smart homes, smart factories, smart cities, smart transportation, and healthcare, by utilizing sensing devices. Nevertheless, a series of security problems may arise because of the nature of the wireless channel in the Wireless Sensor Network (WSN) for utilizing IoT services. Authentication and key agreements are essential elements for providing secure services in WSNs. Accordingly, two-factor and three-factor-based authentication protocol research is being actively conducted. However, IoT service users can be vulnerable to ID/password pair guessing attacks by setting easy-to-remember identities and passwords. In addition, sensors and sensing devices deployed in IoT environments are vulnerable to capture attacks. To address this issue, in this paper, we analyze the protocols of Chunka et al., Amintoosi et al., and Hajian et al. and describe their security vulnerabilities. Moreover, this paper introduces PUF and honey list techniques with three-factor authentication to design protocols resistant to ID/password pair guessing, brute-force, and capture attacks. Accordingly, we introduce PUFTAP-IoT, which can provide secure services in the IoT environment. To prove the security of PUFTAP-IoT, we perform formal analyses through Burrows Abadi Needham (BAN) logic, Real-Or-Random (ROR) model, and scyther simulation tools. In addition, we demonstrate the efficiency of the protocol compared with other authentication protocols in terms of security, computational cost, and communication cost, showing that it can provide secure services in IoT environments.

Keywords: IoT; WSN; PUF; biometrics; honey list; authentication; BAN logic; ROR model; scyther

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1. Introduction

The rapid development of wireless networks and the Internet of Things (IoT) has created opportunities to communicate with things over the Internet. Wireless sensor networks (WSN), a combination of wireless networks and IoT sensors, are garnering increasing attention worldwide as an exciting new paradigm of IoT in various fields, such as smart home, smart city, smart transportation, and smart agriculture [1–3]. In this IoT-based environment, data are collected through various sensors and sensing devices, and users can access them through a gateway node. Through WSN, users can use convenient services in real-time through IoT devices in an IoT-based environment. For example, with their IoT devices, users can remotely operate the lights in their house or sprinklers in their garden.

However, because this convenient service is provided through a wireless network, it is vulnerable to illegal access by malicious attackers [4,5]. This can harm the convenience of IoT, such as invasions of user privacy and eavesdropping on privacy. Malicious attackers can also be insiders or outsiders seeking to breach network security and falsify data integrity. Moreover, problems of node and link failures (i.e., cascading failures) can occur due to the limitations of resources and energy of IoT equipment [6,7]. To this end, the development of lightweight protocols that provide secure communication between nodes and that can overcome resource and energy limitations is ongoing.

Key agreement and authentication protocols are an integral part of addressing security vulnerabilities in WSN and IoT environments and are being studied continuously. Two-factor-based authentication protocols consisting of passwords and smart cards have been proposed for secure communication in IoT-based environments [8–18]. However, these two-factor-based authentication protocols are also vulnerable to smart card theft and guessing attacks, among other attacks. In addition, some researchers have argued that, in two-factor authentication protocols, an attacker can guess an ID/password pair as users create easy-to-remember ID/password pair for convenience [19–21]. Therefore, the researchers argued that attackers can guess an ID/password pair within polynomial time. Accordingly, to respond to various attacks, including ID/password pair guessing attacks, three-factor-based authentication protocols have been proposed, involving user's biometric information [22–28].

Although the three-factor-based authentication protocol is more secure than the two-factor-based authentication protocol, some researchers have found that the three-factor authentication protocols proposed in WSN and IoT environments are also not secure against multiple attacks. Although three-factor-based authentication protocols can defend against ID/password pair guessing attacks, they are still vulnerable to attacks that can be performed with values obtained through device capture attacks. Additionally, the three-factor authentication protocol is still vulnerable to replay, impersonation, and session key disclosure attacks.

In this paper, we analyze the security of two-factor-based and three-factor-based authentication protocols to discover their vulnerabilities. Chunka et al.'s protocol [16] is vulnerable to known session-specific temporary information, ID/password pair guessing, and impersonation attacks. The protocol of Amintoosi et al. [18] is also vulnerable to ID/password pair guessing attacks, thus allowing impersonation attacks. The protocol of Hajian et al. [27] is vulnerable to device physical capture attacks, and through these attacks, device impersonation and session key disclosure attacks are possible.

This paper introduces the Physical Unclonable Function (PUF) [29], which can strengthen security against device capture attacks, and *honeylist* [30,31], which can prevent off-line guessing and brute-force attacks from solving the vulnerabilities of three-factor-based authentication protocols. With *honey_list*, the authentication protocol can be secure, even if two of three factors of the authentication protocol are leaked. In addition, we configure the authentication protocol with XOR and hash functions for real-time communication of sensing devices and prevention of system down.

Therefore, this study aims to solve the security vulnerabilities of the two-factor and three-factor-based WSN authentication protocols [16,18,27]. In addition, we propose PUFTAP-IoT, a secure protocol for IoT-based environments using the three factors that are safe against various attacks in the IoT environment.

We adopt two technologies for a secure protocol for sensing devices in the IoT environment. We also invoke *honey_list* technology to defend against online-guessing and brute-force attacks and consider PUF to be safe against takeover attacks of sensors and sensing devices. The contributions of this paper are as follows:

- We prove the vulnerabilities of protocols by Chunka et al. [16] and Amintoosi et al. [18], which are two-factor authentication protocols, and Hajian et al. [27], which is a three-factor authentication protocol.
- PUFTAP-IoT adopts PUF [29] and *honey_list* [30,31] technology to be safe against various attacks. In addition, to solve the resource problem of sensors and sensing devices, only XOR and hash functions excluding elliptic curve cryptography (ECC) functions are used to lighten the protocol.
- Informal (non-mathematical) analysis and formal analysis are performed to prove the security of the proposed PUFTAP-IoT. Formal analysis uses the widely adopted

Burrows Abadi Needham (BAN) logic [32] and Real-Or-Random (ROR) model [33]. We also use the scyther simulation tool [34] to show that PUFTAP-IoT is secure in networks over public channels.
- We compare PUFTAP-IoT with other authentication protocols in terms of computation cost, communication cost, and security to analyze its efficiency.

The remainder of this paper is organized as follows: Section 2 reviews two-factor and three-factor-based authentication protocols in IoT and WSN environments. Section 3 outlines the proposed system model, attacker model, PUF, fuzzy extraction, and honey list. We analyze the protocols of Zou et al., Amintoosi et al., and Hajian et al. to demonstrate security vulnerabilities. Section 5 describes PUFTAP-IoT, and the safety of PUFTAP-IoT is analyzed in Section 6. We also analyze the efficiency of the protocol in Section 7. Finally, Section 8 concludes the paper.

2. Related Works

Lamport [35] first proposed a password-based authentication protocol in 1981. Since then, many related studies on password-based, two-factor authentication protocols have been proposed in various network environments to protect users' privacy. In 2009, Das [8] proposed a two-factor authentication concept using a smart card with password in an IoT-based WSN environment. Das argued that the proposed scheme has a security advantage in that it uses only a hash function to reduce communication overhead and resist various attacks. However, He et al. [9] proved [8]'s authentication protocol is vulnerable to insider attacks along with impersonation attacks in 2010. In addition, He et al. presented an improved protocol as a countermeasure against these attacks. Unfortunately, it was found by Kumar and Lee [10] that He et al.'s protocol also does not guarantee mutual authentication and cannot generate a session key. Turkanović et al. proposed a new authentication and key agreement method in the WSN environment, focusing on heterogeneous IoT. The proposed scheme allows users to negotiate session keys securely with sensor nodes using the authentication protocol. However, Amin and Biswas [12] demonstrated that the protocol of Turkanović et al. is not secure against impersonation, identity guessing, and password guessing attacks. Moreover, they showed that their scheme has an inefficient authentication phase. Amin and Biswas proposed a protocol that compensated for these problems. However, Wu et al. [13] found that the protocol of Amin and Biswas are also vulnerable to sensor capture and guessing and spoofing attacks. Shuai et al. [14] suggested an authentication protocol for smart homes in 2019. In their protocol, they use Elliptic Curve Cryptography (ECC) for efficient and anonymous authentication. They demonstrate that their protocol is secure against a variety of attacks, including desynchronization and verification table stolen attacks. However, Zou et al. [15] proved Shuai et al.'s protocol is insecure against perfect forward secrecy, node capture attack, and impersonation attacks. Moreover, they proposed more secure user authentication schemes for smart homes. In 2021, Chunka et al. [16] point out the problems with the authentication protocol for WSN environment proposed by Kalra and Sood [17]. They pointed out that the protocol proposed by Kalra and Sood is vulnerable to sensor node capture attacks and cannot provide perfect forward secrecy. In 2022, Amintoosi et al. [18] proposed a two-authentication-based authentication and key agreement protocol to ensure the privacy and security of patients' health-related data. They claim that their protocol is safe from various attacks and is a lightweight protocol using only hash and XOR functions.

According to [19,20], people tend to choose ID/password pairs that are easy to remember. As a result, ID and password pairs are chosen from a small dictionary space. This allows an attacker to guess a user's ID and password in polynomial time [21]. Many researchers have proposed a secure three-factor authentication scheme to prevent simultaneous ID and password pair guessing attacks.

In 2016, Amin et al. [22] proposed a three-factor authentication protocol for WSN. They designed an anonymity-preserving authentication scheme for WSN and proved that their proposed protocol is secure against multiple attacks and is more efficient than other protocols. However, Jiang et al. [23] showed that the protocol of Amin et al. is insecure against replay attacks and does not provide complete forward secrecy. To solve this security flaw, Jiang et al. presented an authentication protocol based on the Rabin cryptosystem for WSN. However, Ostad-Sharif et al. [24] demonstrate that the Jiang et al. protocol also does not provide perfect forward secrecy. In 2019, Mo et al. [25] proposed a secure three-factor-based key agreement and user authentication protocol for WSN. They presented a protocol based on ECC. They demonstrated that their protocol is able to provide security against untraceability and user anonymity. However, Yu and Park [26] pointed out that the protocol of Mo et al. is not safe for impersonation, replay, and session key disclosure attacks. Unfortunately, Hajian et al. [27] proved that the protocol proposed by Ostad-Sharif et al. [24] and Yu et al. [26] is also vulnerable to some attacks. To prevent security problems, Hajian et al. proposed a lightweight authentication protocol for IoT environments. They argued that the proposed protocol can defend against multiple attacks. In 2022, Amintoosi et al. [18] pointed out the security vulnerabilities of the authentication protocol for e-health proposed by Aghili et al. [28]. They proposed a lightweight authentication protocol for smart healthcare services that solves the security vulnerabilities of Aghili et al.'s protocol.

However, we prove that some schemes [16,18,27] are vulnerable to security attacks. We found that Chunka et al. [16] protocol is vulnerable to known session-specific temporary information, ID/password pair guessing, and impersonation attacks. Additionally, we prove that Amintoosi et al.'s protocol [18] cannot withstand identity and password guessing attacks and smart card stolen attacks. Finally, Hajian et al.'s protocol [27] is vulnerable to device capture and session key disclosure attacks.

3. Preliminaries

This section introduces the PUFTAP-IoT system model and an adversary model for security analysis of authentication protocols. In addition, we briefly describe PUF, fuzzy extraction, and *honey_list*, which are the security technologies adopted in the proposed IoT-TFBAP.

3.1. The Proposed System Model

The system model of PUFTAP-IoT is shown in Figure 1. PUFTAP-IoT consists of following three entities:

- **User**: The user requests communication to the gateway to use the sensing device. Only registered users can use IoT services by requesting communication to the gateway.
- **Sensing device**: Sensing devices are smart devices deployed in various IoT environments. Examples in Figure 1 include smart agriculture, vehicles, smart doors, and smart watches. They collect data and provide it to users, and users can use the data to execute any commands they want. Sensing devices also have limited computational power.
- **Gateway**: All service users and sensing devices must be registered with the gateway. A gateway is a trusted entity that is responsible for the process and regulates authentication requests between users and sensing devices.

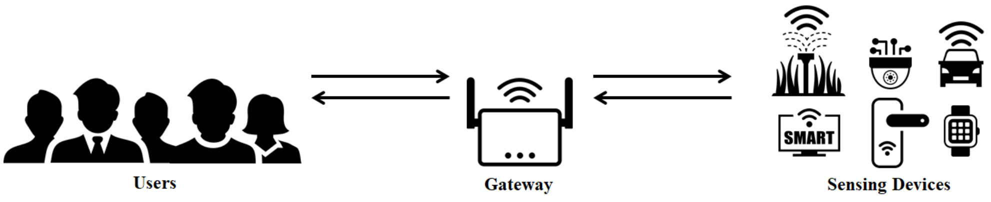


Figure 1. PUFTAP-IoT's system model.

Users must first register with the gateway when they want to communicate with a sensing device. The gateway stores relevant data from users and sensing devices, and controls communication between users and sensing devices. PUFTAP-IoT consists of a registration phase, login and authentication phase, and password and biometrics update phase. In the registration phase, users and sensing devices are registered with the gateway through secure channels. During the login and authentication phase, the user, gateway, and sensing device authenticate each other and generate a session key for communication. In the future, the user can safely communicate with the sensing device using this session key. In the password and biometrics update phase, users can update their passwords and biometrics if desired. To defend against malicious adversaries' ID/password guessing attacks and brute-force attacks, the gateway creates and stores *honey_list*. In addition, the sensing devices have built-in PUF technology to protect them from physical capture attacks.

3.2. The Adversary Model

We adopt the "Dolev-Yao (DY) adversary model" [36] to analyze the proposed protocols [15,18,27] and the IoT-TFBAP. The DY adversary model is a widely adopted model to analyze the security of wireless networks and assumes the following:

- The adversary can learn messages by intercepting messages delivered over insecure, public wireless channels. Through the learned message, the adversary can create a valid message and insert and modify it.
- The adversary can obtain stored values by stealing a valid user's smart card and sensing device [37].
- The adversary can guess the user's ID/password pair in polynomial time [21].
- The adversary can perform guessing, impersonation, known session-specific temporary information, and session key disclosure attacks using the acquired values.

3.3. Physical Unclonable Function

We adopt PUF technology to securely store secret parameters in the sensing device. PUF can be described as "the representation of the unique, non-replicable, instance-specific functionality of a physical entity" [29]. The randomness and uncertainty in integrated circuit fabrication is less likely to create duplicates, making PUFs increasingly visible in the security realm. PUF receives the challenge C and obtains its response R through the physical properties of C and the integrated chip (IC). Since both the accepted C and the generated R are strings of bits, PUF is expressed as $R = PUF(C)$ and can be considered as a one-way function. In an ideal situation, a one-to-one correspondence exists between a challenge–response pair and a PUF, where if a challenge is assigned to the same PUF multiple times, the generated response is the same, and when the same challenge is given to different PUFs, the response obtained is different. PUF also has the following characteristics:

- It is impossible to clone PUF to create the same device [38].
- Any attempt to change the device containing the PUF will change the PUF's behavior and destroy the PUF [39].
- In real-world manufacturing circuits, the difference between mapping input and output functions is fixed and unpredictable. In this respect, the hardware is equivalent to a one-way function [40].

However, due to environmental and circuit noise, PUFs always output varying responses with some margin of error in Cs. To solve this problem, PUF is being applied with fuzzy extractor technology [41].

3.4. Fuzzy Extraction

To solve the problem of noisy PUF, we introduce fuzzy extraction technology [41]. Moreover, we can use fuzzy extraction to solve the noise that can occur in the biometric input. The fuzzy extractor consists of the GEN function and the REP function.

The GEN function is for generating key information corresponding to the entered value. Entering the data D_i into the GEN function outputs the secret key data R_i, which is a uniform random string. The GEN function also outputs the string P_i, which helps to remove the noise and recover the key value.

The REP function restores the secret key R_i. Enter the data D_i and the helper string P_i into the REP function. At this time, D_i may generate noise. For this, P_i helps to output the correct R_i. To recover the same R_i, the metric space distance between D_i and $D_i^{'}$ must be within the specified tolerance.

3.5. Honey List

Assume that attackers attempt to obtain useful data by performing brute-force and online-guessing attacks. In this case, *honey_list* prevents the algorithm "Honey Encryption (HE)" [30,31] from attempting to obtain data by guessing the password. If an adversary attempts attacks with the wrong password, HE uses an algorithm to generate fake valid messages, "Honey words". [42] has more details on the honey word generation algorithm.

Various methods have been used to resist brute-force or online-guessing attacks using *honey_list* at the login and authentication phase. Out of all of them, PUFTAP-IoT calls *honey_list* by adopting the following method. If an attacker tries to login using the guessing password, the login proceeds as usual, but the gateway monitors the attacker's login source for intrusion detection. The gateway also kills the session "when the number of entries in honey_list exceeds a predefined threshold" and notifies the user to update their password.

4. Cryptanalysis of Authentication Protocols

This section shows the analysis of various authentication protocols using sensor or sensing devices in an IoT environment. A review of each protocol is omitted, and for convenience of explanation, S (sensor) of Chunka et al. and Amintoosi et al. and S (sensing device) of Hajian et al. are all denoted as SD (sensing device). The rest of the notation is the same as that of each authentication protocol. Table 1 shows the notations used in this paper.

Table 1. Notation.

Notations	Meanings
U_i	i-th user
SD_j	j-th sensing device
GW	Gateway node
SC	Smartcard
ID_i	Identity of U_i
SID_j	Identity of SD_j
PW_i	Password of U_i
HPW_i	The hidden password of i-th user
Bi	Biometrics of U_i
PUF	The Physical Unclonable Function
C_j, R_j	The challenge/response pair
GEN, REP	Generation and reproduction algorithm of fuzzy extractor
K_{gw}	Secret key of GW
R_x, N_x	Random nonces
T_x	Timestamps
$HID_i, PSID_j$	Pseudo-identity of U_i and SD_j
$THID_i$	Temporary user identity U_i
$Skey$	Session key
$\vert\vert$	Data concatenation operator
$\oplus$	Bitwise exclusive-or operator
$h(*)$	Collision-resistant one-way hash function

4.1. Cryptanalysis of Chunka et al.'s Protocol

We prove that Chunka et al.'s protocol [16] is not safe against known session-specific temporary information attacks and does not provide perfect forward secrecy.

4.1.1. Known Session-Specific Temporary Information Attacks

Suppose that the adversary Adv obtains a session-specific temporary information r_1. Then, Adv is able to compute the legitimate session key. The detailed steps are as follows:

Step 1: Adv computes $h(\alpha_i \oplus k) = r_1 \oplus MID_i$, since MID_i is public parameter. Then, Adv can obtain P_i, where P_i is obtained through an insecure channel.

Step 2: Adv computes $h(P_i||h(\alpha_i \oplus k)||r_1) = E_j \oplus h(r_1 \oplus r_2 \oplus r_3)$ via E_j, which is transmitted to the public channel.

Step 3: Finally, Adv can compute the legitimate session key $SK = h(r_1 \oplus r_2 \oplus r_3)||h(P_i||h(\alpha_i \oplus k)||r_1)$.

4.1.2. Off-Line Guessing Attacks

According to the adversary model in Section 3.2, the adversary Adv can guess the ID/PW pair in polynomial time. The detailed steps are as follows:

Step 1: Adv is able to obtain values $\{X_i, Z_i, Q_i, R_i, h(\cdot)\}$ stored on the smart card via smart card stolen attacks. Then, Adv picks ID_a/PW_a and computes $r_a = X_i \oplus h(ID_a||PW_a)$.

Step 2: Adv calculates $Z_{i_a} = h(ID_a||PW_a||r_a)$ and checks if $Z_{i_a} = Z_i$.

Step 3: If they are the same, Adv has successfully guessed the correct ID/password pair for the user. Otherwise, Adv repeats Steps 1 and 2.

4.1.3. Impersonation Attacks

After off-line guessing attacks, Adv can impersonate the valid user. The detailed steps are as follows.

Step 1: Through guessing attacks, Adv computes $h(ID_i||r)$. Then, Adv can compute $h(\alpha_i) = Q_i \oplus h(ID_i||r)$ and $h(\alpha_i \oplus k) = R_i \oplus h(ID_i||r)$ because R_i and Q_i are values stored in the smart card.

Step 2: Then, Adv generates a random nonce r_{1_a} and computes $Mid_a = h(\alpha_i \oplus k) \oplus r_a$, $N_a = h(h(\alpha_i \oplus k)||h(\alpha_i)||r_a)$.

Step 3: Finally, Adv sends the message $\{P_i, MID_i, N_i\}$. Thus, Adv can impersonate the legitimate user.

4.2. Cryptanalysis of Amintoosi et al.'s Protocol

This section shows that Amintoosi et al.'s protocol [18] is not secure to smart card stolen, off-line guessing, and impersonation attacks.

4.2.1. Off-line Guessing Attacks

The adversary Adv can obtain the sensitive information stored in the smart card. Then, Adv can guess the ID/password pair in polynomial time. The detailed steps are as follows:

Step 1: Adv can obtain values $\{b_i, A_i, B_i, a_i\}$ stored on the smart card. Then, Adv picks ID_a/PW_a and computes $p_a = h(ID_a||PW_a||a_i)$, $N_a = A_a \oplus p_a$, and $bID_a = h(b_i||ID_a)$.

Step 2: Adv calculates $M_a = h(b_i||ID_a||bID_a)$ and $B_a = h(M_a||ID_a||bID_a)$. Then, Adv checks if $B_a = B_i$.

Step 3: If they are the same, Adv has successfully guessed the correct ID/password pair for the user. Otherwise, Adv repeats Steps 1 and 2.

4.2.2. Impersonation Attacks

After guessing the legitimate user's ID/password pair, the Adv computes $\{M1_i, M2_i, T_1, b_i, M2_i\}$ can be masquerading. The detailed steps are as following.

Step 1: After off-line guessing attacks, Adv obtains valid values M_i and N_i. Then, Adv can compute $d_i = M1_i \oplus h(M_i||N_i||T_1)$ to obtain d_i, where $M1_i$ is transmitted to the public channel.

Step 2: Then, Adv also can compute $M2_i = h(M_i||N_i||d_i)$.

Step 3: Therefore, Adv can compute $M1_i, T_1, b_i$, and $M2_i$. This means that Adv can impersonate the valid user. So, we can say that Amintoosi et al.'s protocol is not secure against impersonation attacks.

4.3. Cryptanalysis of Hajian et al.'s Protocol

In this section, we show that Hajian et al.'s protocol [27] is vulnerable to device capture attacks, device impersonation attacks, and session key disclosure attacks.

4.3.1. Device Impersonation Attacks

The adversary Adv can obtain the $\{SID_j, x_j, f_j\}$ stored in SD through a device capture attack. After that, Adv can impersonate as a valid SD by generating a message using the obtained values. After the device capture attacks, the detailed steps of the Adv's device impersonation attack are as follows:

Step 1: Adv obtains the values $\{M_2, T_1\}$ via the message sent to the public channel. Then, Adv can obtain K_j through computing $K_j = h(x_j||f_j||T_1) \oplus M_2$.

Step 2: Adv can compute the legitimate $V_2 = h(SID_j||(x_j|| \oplus f_j)||K_j||T_1)$. Finally, Adv can compute the valid response message $\{M_2, V_2\}$. Thus, we can say that Adv can conduct device impersonation attacks.

4.3.2. Session Key Disclosure Attacks

After Adv conducts device impersonation attacks, Adv obtains x_j, f_j, and K_j. Adv can calculate the session key using these values. Therefore, an attacker can perform session key disclosure attacks, and the detailed steps are as follows:

Step 1: Adv can learn values M_1 and M_5 through the message sent over the open channel. Then, Adv can compute $M_5 \oplus h(T_1||f_j \oplus x_j) \oplus M_1 = (K_i^{'}||TID_i^{new})$.

Step 2: Then, Adv can obtain $K_i^{'}$ and TID_i^{new}.

Step 3: Therefore, Adv can compute the session key $SK_{ij} = h(K_i^{'} \oplus K_j||SID_j||TID_i^{new})$. Thus, we can say that Hajian et al.'s protocol is not secure against session key disclosure attacks.

5. The Proposed PUFTAP-IoT

In this section, we describe the proposed PUFTAP-IoT. In the proposed protocol, we adopt PUF technology to withstand device capture attacks. Additionally, we also apply the user's biometrics and *honey_list* to prevent online-guessing and brute-force attacks. Accordingly, our protocol is observed to be secure against various attacks. Finally, we propose a lightweight protocol using XOR and hash functions to consider the resource limitations of sensing devices and to prevent system down.

5.1. Registration Phase

In order for a service user to use IoT services through a sensing device in an IoT environment, first, he/she must register his/her information in the gateway. Moreover, the sensing device also registers its information in the gateway. The registration phase for service users and sensing devices is shown in Figure 2, and the detailed registration phase is described below.

ine	**Service User Registration Phase**
ine ine Service user (U_i)	Gateway (GW)
ine Inputs ID_i and PW_i and imprints B_i. Generates α and R_u.	
Computes $GEN(B_i) = (R_i, P_i)$, $HID_i = h(ID_i \| \| R_i)$, $HPW_i = h(ID_i \| \| PW_i \| \| R_u \| \| R_i)$.	Secret key: K_{gw} Checks the uniqueness of HID_i Generates a random nonce R_{gw}
$\xrightarrow{\langle HID_i,\, HPW_i \oplus \alpha \rangle}$ (via secure channel)	Computes $A_i = h(HID_i \| \| K_{gw} \| \| R_{gw})$, $B_i = A_i \oplus (HPW_i \oplus \alpha)$, $C_i = h(A_i \| \| HID_i)$. Generates temporary user identity $THID_i$. Stores $\{(HID_i, THID_i), R_{gw}, honey\_list = null\}$
Computes	$\xleftarrow{SC = \langle B_i, C_i, THID_i \rangle}$ (via secure channel)
$L_i = h(ID_i \| \| PW_i \| \| R_i) \oplus R_u$, $B_i' = B_i \oplus \alpha = A_i \oplus HPW_i$, $C_i' = h(C_i \| \| HPW_i)$. Store $\{L_i, B_i', C_i', THID_i\}$ into SC.	
ine ine	**Sensing Device Registration Phase**
ine ine Sensing Device (SD_j)	Gateway (GW)
ine Picks identity SID_j and challenge C_j. Generates random nonce R_{sd}.	
Computes $Req_j = SID_j \oplus h(R_{sd})$, $R_j = PUF(C_j)$. $GEN(R_j) = \langle SDR_j, SDP_j \rangle$ $HSID_j = h(SID_j \| \| SDR_j)$	Computes $SID_j = Req_j \oplus h(R_{sd})$. Generate random secret key RK_j. Computes $PSID_j = h(HSID_j \| \| RK_j)$, $SI_j = h(PSID_j \| \| h(K_{gw} \| \| RK_j))$.
$\xrightarrow{\langle Req_j, R_{sd}, HSID_j, C_j \rangle}$ (via secure channel)	Stores $\{(HSID_j, PSID_j), RK_j, C_j\}$
	$\xleftarrow{\langle PSID_j, SI_j \rangle}$ (via secure channel)
Stores $\{SID_j, PSID_j, SI_j, SDP_j\}$ ine	

Figure 2. Registration phase.

5.1.1. Service User Registration Phase

Service users create their own information through ID, password, and biometric information and register it with the gateway, and the gateway issues a smart card. Here are the detailed steps:

Step 1: The service user U_i inputs his/her identity ID, password PW_i, and imprints his/her biometrics B_i. Then, U_i generates α and R_u and computes $Gen(B_i) = (R_i, P_i)$, $HID_i = h(ID_i||R_i)$, and $HPW_i = h(ID_i||PW_i||R_u||R_i)$. U_i sends $\langle HID_i, HPW_i \oplus \alpha \rangle$ to the gateway GW through a secure channel.

Step 2: After receiving the registration request message, GW checks the uniqueness of HID_i. If it has the uniqueness, GW generates a random nonce R_{gw} and GW computes $A_i = h(HID_i||K_{gw}||R_{gw})$, $B_i = A_i \oplus (HPW_i \oplus \alpha)$, and $C_i = h(A_i||HID_i)$. Then, GW generates the temporary service user's identity $THID_i$ and stores $\{(HID_i, THID_i), R_{gw}, honey\_list = null\}$ in its secure database. GW issues the smart card $SC = \langle B_i, C_i, THID_i \rangle$ to U_i via a secure channel.

Step 3: U_i computes $L_i = h(ID_i||PW_i||R_i) \oplus R_u$, $B_i^{'} = B_i \oplus \alpha = A_i \oplus HPW_i$, and $C_i^{'} = h(C_i||HPW_i)$. Then, U_i deletes B_i and C_i in SC and stores L_i, $B_i^{'}$, and $C_i^{'}$ in SC.

5.1.2. Sensing Device Registration Phase

The sensing device SD_j utilizes the PUF function for registration and registers its own information with GW. The detailed registration steps are as follows:

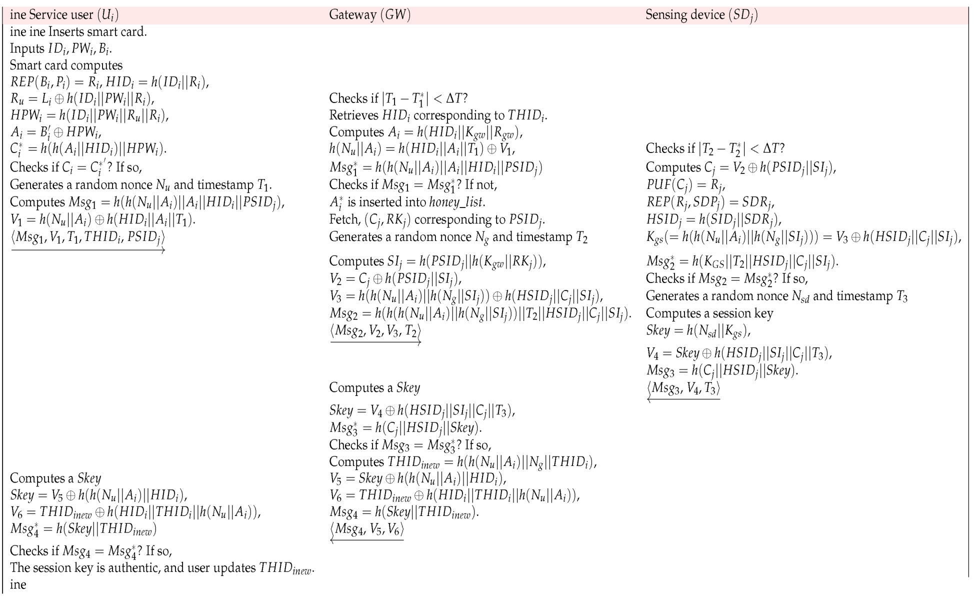
Step 1: SD_j picks its identity SID_j and PUF's challenge C_j. SD_j generates a random nonce R_{sd} and computes $Req_j = SID_j \oplus h(R_{sd})$, $R_j = PUF(C_j)$, $Gen(R_j) = \langle SDR_j, SDP_j \rangle$, and $HSID_j = h(SID_j||SDR_j)$. After that, SD_j transmits $\langle Req_j, R_{sd}, HSID_j, C_j \rangle$ to GW through a closed channel.

Step 2: GW computes $SID_j = Req_j \oplus h(R_{sd})$ and GW generates a random secret key RK_j. GW also computes $PSID_j = h(HSID_j||RK_j)$ and $SI_j = h(PSID_j||h(K_{gw}||RK_j)$. Finally, GW stores $\{(HSID_j, PSID_j), RK_j, C_j\}$ in its database and transmits $\langle PSID_j, SI_j\rangle$ to SD_j through a closed channels.

Step 3: After receiving the message, SD_j stores $\{SID_j, PSID_j, SI_j, SDP_j\}$.

5.2. Login and Authentication Phase

U_i sends an authentication request message to GW after login through his/her smart card and credential information. After confirming this, GW sends an authentication message to the corresponding SD_j, and each entity authenticates the response message. When authentication is completed, U_i, GW, and SD_j agree on a session key $Skey$, and secure communication can be guaranteed later through $Skey$. In addition, U_i and GW update $THID_i$ to $THID_{inew}$ when authentication and key agreement are successful. The detailed formula is as follows, and the entire steps are summarized in Figure 3:



ine Service user (U_i)	Gateway (GW)	Sensing device (SD_j)
ine ine Inserts smart card. Inputs ID_i, PW_i, B_i. Smart card computes $REP(B_i, P_i) = R_i$, $HID_i = h(ID_i\|\|R_i)$, $R_u = L_i \oplus h(ID_i\|\|PW_i\|\|R_i)$, $HPW_i = h(ID_i\|\|PW_i\|\|R_u\|\|R_i)$, $A_i = B_i^{'} \oplus HPW_i$, $C_i^* = h(h(A_i\|\|HID_i)\|\|HPW_i)$. Checks if $C_i = C_i^{*'}$? If so, Generates a random nonce N_u and timestamp T_1. Computes $Msg_1 = h(h(N_u\|\|A_i)\|\|A_i\|\|HID_i\|\|PSID_j)$, $V_1 = h(N_u\|\|A_i) \oplus h(HID_i\|\|A_i\|\|T_1)$. $\xrightarrow{\langle Msg_1, V_1, T_1, THID_i, PSID_j\rangle}$		
	Checks if $\|T_1 - T_1^*\| < \Delta T$? Retrieves HID_i corresponding to $THID_i$. Computes $A_i = h(HID_i\|\|K_{gw}\|\|R_{gw})$, $h(N_u\|\|A_i) = h(HID_i\|\|A_i\|\|T_1) \oplus V_1$, $Msg_1^* = h(h(N_u\|\|A_i)\|\|A_i\|\|HID_i\|\|PSID_j)$ Checks if $Msg_1 = Msg_1^*$? If not, A_i^* is inserted into *honey_list*. Fetch, (C_j, RK_j) corresponding to $PSID_j$. Generates a random nonce N_g and timestamp T_2 Computes $SI_j = h(PSID_j\|\|h(K_{gw}\|\|RK_j))$, $V_2 = C_j \oplus h(PSID_j\|\|SI_j)$, $V_3 = h(h(N_u\|\|A_i)\|\|h(N_g\|\|SI_j)) \oplus h(HSID_j\|\|C_j\|\|SI_j)$, $Msg_2 = h(h(h(N_u\|\|A_i)\|\|h(N_g\|\|SI_j))\|\|T_2\|\|HSID_j\|\|C_j\|\|SI_j)$. $\xrightarrow{\langle Msg_2, V_2, V_3, T_2\rangle}$	
		Checks if $\|T_2 - T_2^*\| < \Delta T$? Computes $C_j = V_2 \oplus h(PSID_j\|\|SI_j)$, $PUF(C_j) = R_j$, $REP(R_j, SDP_j) = SDR_j$, $HSID_j = h(SID_j\|\|SDR_j)$, $K_{gs}(= h(h(N_u\|\|A_i)\|\|h(N_g\|\|SI_j))) = V_3 \oplus h(HSID_j\|\|C_j\|\|SI_j)$, $Msg_2^* = h(K_{GS}\|\|T_2\|\|HSID_j\|\|C_j\|\|SI_j)$. Checks if $Msg_2 = Msg_2^*$? If so, Generates a random nonce N_{sd} and timestamp T_3 Computes a session key $Skey = h(N_{sd}\|\|K_{gs})$, $V_4 = Skey \oplus h(HSID_j\|\|SI_j\|\|C_j\|\|T_3)$, $Msg_3 = h(C_j\|\|HSID_j\|\|Skey)$. $\xleftarrow{\langle Msg_3, V_4, T_3\rangle}$
	Computes a *Skey* $Skey = V_4 \oplus h(HSID_j\|\|SI_j\|\|C_j\|\|T_3)$, $Msg_3^* = h(C_j\|\|HSID_j\|\|Skey)$. Checks if $Msg_3 = Msg_3^*$? If so, Computes $THID_{inew} = h(h(N_u\|\|A_i)\|\|N_g\|\|THID_i)$, $V_5 = Skey \oplus h(h(N_u\|\|A_i)\|\|HID_i)$, $V_6 = THID_{inew} \oplus h(HID_i\|\|THID_i\|\|h(N_u\|\|A_i))$, $Msg_4 = h(Skey\|\|THID_{inew})$. $\xleftarrow{\langle Msg_4, V_5, V_6\rangle}$	
Computes a *Skey* $Skey = V_5 \oplus h(h(N_u\|\|A_i)\|\|HID_i)$, $V_6 = THID_{inew} \oplus h(HID_i\|\|THID_i\|\|h(N_u\|\|A_i))$, $Msg_4^* = h(Skey\|\|THID_{inew})$ Checks if $Msg_4 = Msg_4^*$? If so, The session key is authentic, and user updates $THID_{inew}$. ine		

Figure 3. Login and authentication phase.

Step 1: The service user U_i inserts SC and inputs ID_i, PW_i, and B_i. Then, SC computes $Rep(B_i, P_i) = R_i$, $HID_i = h(ID_i||R_i)$, $R_u = L_i \oplus h(ID_i||PW_i||R_i)$, $HPW_i = h(ID_i||PW_i|| R_u|| R_i)$, $A_i = B_i^{'} \oplus HPW_i$, and $C_i^* = h(h(A_i||HID_i||HPW_i)$. SC checks $C_i = C_i^*$. If it is correct, SC generates a random nonce N_u and timestamp T_1. After that, SC computes $Msg_1 = h(h(N_u||A_i)||A_i||HID_i||PSID_j)$, $V_1 = h(N_u||A_i) \oplus h(HID_i||A_i||T_1)$. U_i sends the message $\langle Msg_1, V_1, T_1, THID_i, PSID_j\rangle$ through an open channel.

Step 2: When GW receives the request message, GW checks $|T_1 - T_1^*| < \Delta T$. GW retrieves HID_i corresponding to $THID_i$ and GW computes $A_i = h(HID_i||K_{gw}||R_{gw})$, $h(N_u||A_i) = h(HID_i||A_i||T_1) \oplus V_1$, $Msg_1^* = h(h(N_u||A_i)||A_i||HID_i||PSID_j)$. Then, GW checks if $Msg_2 = Msg_2^*$. If it is not same, GW inserts A_i^* into *honey_list*. Otherwise, GW retrieves (C_j, RK_j) corresponding to $PSID_j$. GW generates a random nonce N_g and timestamp T_2 and computes $SI_j = h(PSID_j||h(K_{gw}||RK_j))$, $V_2 = C_j \oplus h(PSID_j||SI_j)$, $V_3 = h(h(N_u||A_i)||h(N_g||SI_j)) \oplus h(HSID_j||C_j||SI_j)$, and $Msg_2 = h(h(h(N_u||A_i)||h(N_g||SI_j)) ||T_2|| HSID_j||C_j||SI_j)$. After computing, GW sends $\langle Msg_2, V_2, V_3, T_2)\rangle$ to SD_j via an open wireless channel.

Step 3: SD_j checks $|T_2 - T_2^*| < \Delta T$. Then, SD_j computes $C_j = V_2 \oplus h(PSID_j||SI_j)$, $PUF(C_j) = R_j$, $Rep(R_j, SDP_j) = SDR_j$, $HSID_j = h(SID_j||SDR_j)$, $K_{gs}(= h(h(N_u||A_i)|| h(N_g ||SI_j))) = V_3 \oplus h(HSID_j||C_j||SI_j)$, and$Msg_2^* = h(K_{GS}||T_2||HSID_j||C_j||SI_j)$. Then, SD_j checks $Msg_2 = Msg_2^*$. If it is the same, SD_j generates a random nonce N_{sd} and timestamp T_3 and SD_j computes a session key $Skey = h(N_{sd}||K_{gs})$. SD_j also computes $V_4 = Skey \oplus h(HSID_j||SI_j||C_j||T_3)$ and $Msg_3 = h(C_j||HSID_j||Skey)$. After that, SD_j sends the response message $\langle Msg_3, V_4, T_3 \rangle$ to GW.

Step 4: GW computes the session key $Skey = V_4 \oplus (HSID_j||SI_j||C_j||T_3)$, and computes $Msg_3^* = h(C_j||HSID_j||Skey)$. Then, GW checks if $Msg_3 = Msg_3^*$. If it verifies, GW computes $THID_{inew} = h(h(N_u||A_i)||N_g||THID_i)$, $V_5 = Skey \oplus h(h(N_u||A_i)||HID_i)$, $V_6 = THID_{inew} \oplus h(HID_i||THID_i||h(N_u||A_i))$, and $Msg_4 = h(Skey||THID_{inew})$. After computing, GW transmits $\langle Msg_4, V_5, V_6 \rangle$ to U_i through an insecure channel.

Step 5: After receiving the response message, U_i computes a session key $Skey = V_5 \oplus h(h(N_u||A_i)||HID_i)$. Additionally, U_i also computes $V_6 = THID_{inew} \oplus h(HID_i||THID_i|| h(N_u||A_i))$ and $Msg_4^* = h(Skey||THID_{inew})$. Then, U_i checks if $Msg_4 = Msg_4^*$. If it is correct, the session key is authentic, and U_i and GW update $THID_{inew}$.

5.3. Service User Password and Biometrics Update Phase

Assume that the service user U_i wants to use SC to change to a new password and biometrics. Specifically, this phase runs locally without any additional connections to GW, reducing computation and communication overhead. The following steps are the password and biometrics update process:

Step 1: The service user U_i inputs his/her identity ID and password PW_i and imprints his/her biometrics B_i. Then, SC computes $Rep(B_i, P_i) = R_i$, $HID_i = h(ID_i||R_i)$, $R_u = L_i \oplus h(ID_i||PW_i||R_i)$, $HPW_i = h(ID_i||PW_i||R_u|| R_i)$, $A_i = B_i' \oplus HPW_i, and C_i^* = h(h(A_i||HID_i||HPW_i)$. SC checks $C_i = C_i^*$. If it is valid, SC asks U_i to enter the new password and biometrics.

Step 2: U_i enters a new password PW_{inew} and new biometrics B_{inew}. SC proceeds to compute parameters $GEN(B_{inew}) = (R_{inew}, P_{inew})$, $HPW_{inew} = h(ID_i||PW_{inew}||R_u||R_{inew})$, $L_{inew} = h(ID_i||PW_{inew}||R_{inew}) \oplus R_u$, $B_{inew}' = B_i' \oplus HPW_i \oplus HPW_{inew}$, and $C_{inew}' = h(C_i'|| HPW_i)$. Then, SC replaces L_i, B_i', and C_i' with L_{inew}, B_{inew}', and C_{inew}'.

6. Security Analysis

In this section, we analyze the security of PUFTAP-IoT. We first show that the protocol is safe against various attacks through informal analysis. In addition, we prove that mutual authentication and session key agreement of the protocol can be safely achieved through the universally used BAN logic and ROR model. Finally, we demonstrate the security of PUFTAP-IoT on a wireless network using the scyther simulation tool.

6.1. Informal Security Analysis

Here, we perform an informal (non-mathematical) security analysis to show that PUFTAP-IoT is safe against various attacks and also provides various security features.

6.1.1. Offline and Online-Guessing Attacks

Assume that the adversary Adv obtains the U_i's SC and attempts an offline-guessing attack using parameters $\{L_i, B_i', C_i', THID_i\}$ in SC. However, since Adv is the value that R_i should be calculated as, the biometric of U_i, $R_u = L_i \oplus h(ID_i||PW_i||R_i)$ could not be calculated. Moreover, Adv tries an online-guessing attack for obtaining U_i's sensitive information. Unfortunately, the attacker does not know if the correct ID and password were guessed because of the *honey_list* stored on the gateway system. Moreover, PUFTAP-IoT is safe from online-guessing attacks because the session is terminated when the threshold of *honey_list* is exceeded. Therefore, PUFTAP-IoT is safe against offline- and online-guessing attacks.

6.1.2. Service User Anonymity

If Adv steals U_i's SC and obtains values stored in SC, Adv tries to obtain U_i's real identity, pseudo-identity or temporary identity. However, Adv cannot obtain the ID of U_i and HID_i because HID_i is masked by the hash function and R_i. Although $THID_i$ is transmitted through the public channel, $THID_{inew}$ is updated by GW when authentication and key agreement are successful. In addition, $THID_{inew}$ is masked with N_u and N_g, and these values change every session. Therefore, PUFTAP-IoT can safely guarantee the anonymity of service users.

6.1.3. Impersonation Attack

In order for Adv to disguise U_i, GW, and SD_j, Adv must be able to compute the messages sent to the public channel. Messages sent from PUFTAP-IoT to public channels change per session due to random values N_u, N_s, and N_{sd} and timestamps. In addition, $THID_i$ is also updated to $THID_{inew}$ when the authentication is successful, so Adv cannot calculate the correct message. Therefore, PUFTAP-IoT is resistant to impersonation attacks.

6.1.4. Sensing Device Physical Capture Attack

When Adv performs a physical capture attack on SD_j, Adv can obtain $\{SID_j, PSID_j, SI_j, SDP_j\}$ stored in SD_j. However, Adv cannot calculate the correct session key through these parameters. In order for Adv to calculate the session key, $K_{gs}(= h(h(N_u||A_i)||h(N_g ||SI_j))) = V_3 \oplus h(HSID_j||C_j||SI_j)$ must be calculated. However, since Adv cannot obtain R_j, Adv cannot compute SDR_j. Therefore, Adv is not able to compute $HSID_j = h(SID_j||SDR_j)$. This is because R_j is a value created by the PUF function, and the PUF is a function that is a physically unclonable circuit and cannot be duplicated. Therefore, PUFTAP-IoT is safe against sensing device physical capture attacks.

6.1.5. Replay and Man-in-the-Middle Attack

We assume that Adv obtains messages transmitted over a public channel and information of U_i's SC and SD_j. However, Adv cannot compute U_i's valid message as mentioned in Section 6.1.3. Additionally, Adv also cannot generate SD_j's valid messages according to Section 6.1.4. Additionally, every message changes with $N_u, N_g, andN_{sd}$ and timestamps every session. Therefore, we can say that PUFTAP-IoT is secure against replay and man-in-the-middle attacks.

6.1.6. Stolen Verifier Attack

Suppose Adv obtains the GW verification tables $\{HID_i, THID_i, R_{gw}, honey\_list = null\}$ and $\{HSID_j, PSID_j, RK_j, C_j\}$ to compute the session key $Skey$ or perform impersonation attacks. However, Adv cannot compute $A_i = h(HID_i||K_{gw}||R_{gw})$ and $SI_j = h(PSID_j||h(K_{gw}||RK_j)$ without GW's secret key K_{gw}. Furthermore, due to the nature of the PUF function, Adv cannot compute $R_j = PUF(C_j)$. Therefore, Adv cannot perform session key and impersonation attacks. Accordingly, we can say that PUFTAP-IoT is resistant to stolen verifier attacks.

6.1.7. Perfect Forward Secrecy

Assuming that GW's secret key K_{gw}, is leaked to Adv, Adv can try to calculate $Skey$ through K_{gw}. However, since A_i and SI_j are masked with K_{gw} as well as R_{gw} and RK_j which are secret keys generated for each entity, Adv cannot compute A_i and SI_j. Therefore, since Adv cannot calculate valid $Skey$, PUFTAP-IoT can guarantee perfect forward secrecy.

6.1.8. Session-Specific Random Number Leakage Attack

Assume that $N_u, N_g, andN_{sd}$, which are random nonces generated in the session, were leaked to Adv. With these values, Adv will try to compute $Skey$. However, Adv cannot compute the session key $Skey = h(N_{sd}||h(h(N_u||A_i)||h(N_g||SI_j)))$. To calculate a valid $Skey$, A_i and SI_j must be calculated, but as mentioned in the Sections above, A_i and SI_j cannot be calculated by Adv. Therefore, PUFTAP-IoT is safe against session-specific random number leakage attacks.

6.1.9. Session Key Disclosure Attack

Adv wants to compute the *Skey* for obtaining sensitive information. However, as discussed in Sections 6.1.6–6.1.8, *Adv* cannot compute the valid *Skey* because of the computationally infeasible problem. Thus, PUFTAP-IoT prevents session key disclosure attacks.

6.1.10. Mutual Authentication

In PUFTAP-IoT, all entities authenticate each other by verifying messages containing Msg_1, Msg_2, Msg_3, and Msg_4. Moreover, these messages are changed with random numbers and current timestamps. After all entities authenticate each other, they compute the same *Skey*. Thus, PUFTAP-IoT guarantees mutual authentication.

6.2. BAN Logic

For proving that PUFTAP-IoT is able to provide secure authentication, we conduct BAN logic [32]. The notations used in BAN logic are shown in Table 2, and the five rules used are as follows [43–45]:

1. **1.** Jurisdiction rule:

$$\frac{\chi \mid\equiv \omega \mid \Longrightarrow \varepsilon, \quad \chi \mid\equiv \omega \mid \equiv \varepsilon}{\chi \Big| \equiv \varepsilon}$$

2. **2.** Message meaning rule:

$$\frac{\chi \Big| \equiv \chi \overset{K}{\leftrightarrow} \omega, \quad \chi \lhd \{\varepsilon\}_K}{\chi \mid\equiv B \mid \sim \varepsilon}$$

3. **3.** Nonce verification rule:

$$\frac{\chi \mid\equiv \#(\varepsilon), \quad \chi \mid \equiv \omega \Big| \sim \varepsilon}{\chi \mid\equiv \omega \mid \equiv \varepsilon}$$

4. **4.** Belief rule:

$$\frac{\chi \Big| \equiv (\varepsilon, F)}{\chi \Big| \equiv \varepsilon}$$

5. **5.** Freshness rule:

$$\frac{\chi \Big| \equiv \#(\varepsilon)}{\chi \Big| \equiv \#(\varepsilon, F)}$$

Table 2. The basic notations of BAN logic.

Notations	Description
Skey	The session key in PUFTAP-IoT
$\#\varepsilon$	The statement S is **fresh**
$\chi \mid \equiv \varepsilon$	χ **believes** the statement ε
$\chi \lhd \varepsilon$	χ **sees** the statement ε
$\chi \mid \sim \varepsilon$	χ once **said** ε
$< \varepsilon >_F$	ε is **combined** with formula F
$\{\varepsilon\}_{Key}$	Encrypt ε with *Key*
$\chi \Rightarrow \varepsilon$	χ **controls** ε
$\chi \overset{Key}{\leftrightarrow} \omega$	χ and ω shard and use *Key* for communication

To implement BAN logic, we describe logical rules, goals, assumptions, and ideal forms, thereby proving that PUFTAP-IoT provides secure mutual authentication.

6.2.1. Goals

In order to prove that secure mutual authentication is achieved, the following goals must be achieved:

Goal 1: $U_i| \equiv (U_i \overset{Skey}{\longleftrightarrow} GW)$

Goal 2: $U_i| \equiv GW| \equiv (U_i \overset{Skey}{\longleftrightarrow} GW)$

Goal 3: $GW| \equiv (U_i \overset{Skey}{\longleftrightarrow} GW)$

Goal 4: $GW| \equiv U_i| \equiv (U_i \overset{Skey}{\longleftrightarrow} GW)$

Goal 5: $SD_j| \equiv (SD_j \overset{Skey}{\longleftrightarrow} GW)$

Goal 6: $SD_j| \equiv GW| \equiv (SD_j \overset{Skey}{\longleftrightarrow} GW)$

Goal 7: $GW| \equiv (SD_j \overset{Skey}{\longleftrightarrow} GW)$

Goal 8: $GW| \equiv SD_j| \equiv (SD_j \overset{Skey}{\longleftrightarrow} GW)$

6.2.2. Idealized Forms

The idealized forms are:

M_1**:** $U_i \rightarrow GW : \{h(N_u||A_i)\}_{HID_i}$
M_2**:** $GW \rightarrow SD_j : \{h(h(N_u||A_i)||h(N_g||SI_j))\}_{SI_j}$
M_3**:** $SD_j \rightarrow GW : \{h(N_{sd}||K_{gs})\}_{SI_j}$
M_4**:** $GW \rightarrow U_i : \{h(N_{sd}||K_{gs})\}_{HID_i}$

6.2.3. Assumptions

The following assumptions are generated for the initial state of PUFTAP-IoT to achieve the BAN logic proof:

A_1**:** $GW| \equiv U_i \overset{HID_i}{\longleftrightarrow} GW$
A_2**:** $GW| \equiv \#(N_u)$
A_3**:** $SD_j| \equiv GW \overset{SI_j}{\longleftrightarrow} SD_j$
A_4**:** $SD_j| \equiv \#(N_g)$
A_5**:** $GW| \equiv GW \overset{SI_j}{\longleftrightarrow} SD_j$
A_6**:** $GW| \equiv \#(N_{sd})$
A_7**:** $U_i| \equiv U_i \overset{HID_i}{\longleftrightarrow} GW$
A_8**:** $U_i| \equiv \#(N_g)$
A_9**:** $U_i| \equiv GW| \Rightarrow (U_i \overset{Skey}{\longleftrightarrow} GW)$
A_{10}**:** $GW| \equiv U_i| \Rightarrow (U_i \overset{Skey}{\longleftrightarrow} GW)$
A_{11}**:** $SD_j| \equiv GW| \Rightarrow (SD_j \overset{Skey}{\longleftrightarrow} GW)$
A_{12}**:** $GW| \equiv SD_j| \Rightarrow (SD_j \overset{Skey}{\longleftrightarrow} GW)$

6.2.4. Proof

The main proof using the rules and assumptions of BAN logic is:

Step 1: S_1 can be obtained from M_1.

$$S_1 : GW \triangleleft \{h(N_u||A_i)\}_{HID_i}$$

Step 2: S_2 can be obtained by applying the MMR with A_1.

$$S_2 : GW| \equiv U_i| \sim \{h(N_u||A_i)\}_{HID_i}$$

Step 3: S_3 can be gained from the FR with S_2 and A_2.

$$S_3 : GW| \equiv \#(h(N_u||A_i))$$

Step 4: S_4 can be acquired by applying the NVR with S_2 and S_3.

$$S_4 : GW| \equiv U_i| \equiv (h(N_u||A_i))$$

Step 5: S_5 can be obtained from M_2.

$$S_5 : SD_j \triangleleft \{h(h(N_u||A_i)||h(N_g||SI_j))\}_{SI_j}$$

Step 6: S_6 can be gained from MMR with S_5 and A_3.

$$S_6 : SD_j| \equiv GW| \sim \{h(h(N_u||A_i)||h(N_g||SI_j))\}_{SI_j}$$

Step 7: S_7 can be obtained by applying FR with S_6 and A_4.

$$S_7 : SD_j| \equiv \#(h(h(N_u||A_i)||h(N_g||SI_j)))$$

Step 8: S_8 can be obtained from NVR with S_6 and S_7.

$$S_8 : SD_j| \equiv GW| \equiv (h(h(N_u||A_i)||h(N_g||SI_j)))$$

Step 9: S_9 can be obtained from M_3.

$$S_9 : GW \triangleleft \{h(N_{sd}||K_{gs})\}_{SI_j}$$

Step 10: S_{10} can be gained from MMR with S_9 and A_5.

$$S_{10} : GW| \equiv SD_j| \sim \{h(N_{sd}||K_{gs})\}_{SI_j}$$

Step 11: S_{11} can be obtained by applying FR with S_{10} and A_6.

$$S_{11} : GW| \equiv \#(h(N_{sd}||K_{gs}))$$

Step 12: S_{12} can be obtained from NVR with S_{10} and S_{11}.

$$S_{12} : GW| \equiv SD_j| \equiv (h(N_{sd}||K_{gs}))$$

Step 13: S_{13} can be obtained from M_4.

$$S_{13} : U_i \triangleleft \{h(N_{sd}||K_{gs})\}_{HID_i}$$

Step 14: S_{14} can be obtained from MMR with S_{13} and A_7.

$$S_{14} : U_i| \equiv GW| \sim \{h(N_{sd}||K_{gs})\}_{HID_i}$$

Step 15: S_{15} can be obtained from FR with S_{14} and A_8, since $K_{gs} = h(h(N_u||A_i)||h(N_g||SI_j))$.

$$S_{15} : U_i| \equiv \#(h(N_{sd}||K_{gs}))$$

Step 16: S_{16} can be obtained from NVR with S_{14} and S_{15}.

$$S_{16} : U_i| \equiv GW| \equiv (h(N_{sd}||K_{gs}))$$

Step 17: S_{17} and S_{18} can be obtained from S_8 and S_{12} since $Skey = h(N_{sd}||K_{gs})$.

$$S_{17} : SD_j| \equiv GW| \equiv (SD_j \overset{Skey}{\longleftrightarrow} GW) \quad \textbf{(Goal 6)}$$

$$S_{18} : GW| \equiv SD_j| \equiv (SD_j \overset{Skey}{\longleftrightarrow} GW) \quad \textbf{(Goal 8)}$$

Step 18: S_{19} and S_{20} can be obtained by applying JR from S_{17}, S_{18}, A_{11}, and A_{12}.

$$S_{19} : SD_j| \equiv (SD_j \overset{Skey}{\longleftrightarrow} GW) \quad \textbf{(Goal 5)}$$

$$S_{20} : GW| \equiv (SD_j \overset{Skey}{\longleftrightarrow} GW) \quad \textbf{(Goal 7)}$$

Step 19: S_{21} and S_{22} can be obtained from S_4 and S_{16} since $Skey = h(N_{sd}||K_{gs})$.

$$S_{21} : U_i| \equiv GW| \equiv (U_i \overset{Skey}{\longleftrightarrow} GW) \quad \textbf{(Goal 2)}$$

$$S_{22} : GW| \equiv U_i| \equiv (U_i \overset{Skey}{\longleftrightarrow} GW) \quad \textbf{(Goal 4)}$$

Step 20: S_{23} and S_{24} can be obtained by applying JR from S_{21}, S_{22}, A_9, and A_{10}.

$$S_{23} : U_i| \equiv (U_i \overset{Skey}{\longleftrightarrow} GW) \quad \textbf{(Goal 1)}$$

$$S_{24} : GW| \equiv (U_i \overset{Skey}{\longleftrightarrow} GW) \quad \textbf{(Goal 3)}$$

Therefore, we prove that PUFTAP-IoT can satisfy all goals of BAN logic. Accordingly, it can be said that PUFTAP-IoT can guarantee secure mutual authentication.

6.3. ROR

We use the ROR model [33] to describe the semantic security of PUFTAP-IoT. We demonstrate that session key security can be guaranteed through the ROR model [46–48]. This section briefly describes the ROR model and presents a proof of the protocol's session key security in Theorem 1. PUFTAP-IoT in the ROR model has three participants $\mathcal{P}^t$, which are service user $\mathcal{P}^{t_1}_{U_i}$, gateway $mathcalP^{t_2}_{GW}$, and sensing device $\mathcal{P}^{t_3}_{S_j}$. Additionally, for each participant, tth represents an instance of the running participant. We assume that an attacker Adv can modify, remove, insert or learn messages sent during communication. In the ROR model, various queries are defined to simulate real-world attacks, $Execute$, $CorruptSC$, $Reveal$, $Send$, and $Test$ queries. A detailed description of the query follows:

- $Execute(\mathcal{P}^{t_1}_{U_i}, \mathcal{P}^{t_2}_{GW}, \mathcal{P}^{t_3}_{SD_j})$: Adv conducts $Execute$ query to obtain messages sent over insecure channels between U_i, GW, and SD_j.
- $CorruptSC(\mathcal{P}^{t_1}_{U_i})$: $CorruptSC$ indicates that Adv can obtain information stored in the smart card of U_i.

- $Reveal(\mathcal{P}^t)$: $Reveal(\mathcal{P}^t)$ is that Adv returns the session key $Skey$ between $\mathcal{P}^{t_1}_{U_i}$, $\mathcal{P}^{t_2}_{GW}$, and $\mathcal{P}^{t_3}_{SD_j}$. $Skey$ is safe if Adv reveals $Skey$ using the $Reveal(\mathcal{P}^t)$ query.
- $Send(\mathcal{P}^t, M)$: $Send$ query allows Adv to transmit the M message to $\mathcal{P}^t$ and receive a response.
- $Test(\mathcal{P}^t)$: A fair coin fc is tossed before the game starts, and the result is known only to Adv. Adv uses this result to determine $Test$ query. If Adv conducts this query and $Skey$ is fresh, $\mathcal{P}^t$ will return $Skey$ for fc = 1 or a random nonce for fc = 0. Otherwise, $\mathcal{P}^t$ returns a null ($\perp$).

After Adv conducts $Test$ query on participants, Adv has to separate resulting values. Adv checks the consistency of the random bit fc through the output of the $Test$ query. For Adv to win the game, the guessed bit fc' must equal fc. Additionally, the collision-resistant one-way hash function $h(\cdot)$ is accessible to all participants. Model $h(\cdot)$ is a random oracle $Hash$.

Security Proof

Theorem 1. *Adv can obtain information by breaking the session key security. Mark the advantage of Adv running in polynomial time as Adv_t. Then, we obtain:*

$$Adv_t \leq \frac{q_h^2}{|Hash|} + \frac{q_p^2}{|PUF|} + 2max\{C \cdot q_s^s, \frac{q_s}{2^{l_D}}\}$$

Here, q_h, q_p, and q_s are the number of Hash, PUF, and Send queries, respectively. $|Hash|$ and $|PUF|$ are the range space of the hash function $h(\cdot)$ and PUF function $PUF(\cdot)$, respectively. In addition, C and s denote Zipf's parameters, and l_D is the number of bits in the biometric B_i of U_i.

Proof. We run four sequence games GM_i to prove session key security, where $i \in [0, 4]$. $Succ_{Adv,i}$ represents the event that Adv wins GM_i by correctly guessing any bit fc. The advantage of Adv winning the game GM_i is denoted by $Pr[Succ_{Adv,GM_i}]$. Each game is described below.

- GM_0: Adv can execute a real attack on PUFTAP-IoT through this game. Adv selects fc at the beginning of GM_0. Then, according to this game, we obtain:

$$Adv_t = |2Pr[Succ_{Adv,GM_0}] - 1| \tag{1}$$

- GM_1: Adv conducts the $Execute(\mathcal{P}^{t_1}_{U_i}, \mathcal{P}^{t_2}_{GW}, \mathcal{P}^{t_3}_{SD_j})$ query through this game and eavesdrops transmitted messages $< Msg_1, V_1, T_1, THID_i, PSID_j >$, $< Msg_2, V_2, V_3, T_2 >$, $< Msg_3, V_4 >$, and $< Msg_4, V_5, V_6 >$. Adv then checks whether the derived $Skey$ is real to execute $Reveal$ and $Test$ queries. In PUFTAP-IoT, the session key consists of $Skey = h(N_{sd}||K_{gs})$. To derive $Skey$, Adv must know the ID and random numbers of U_i, GW, and SD_j. As a result, Adv never increases the probability of winning GM_1. Thus, GM_0 and GM_1 can be considered indistinguishable, and we obtain:

$$Pr[Succ_{Adv,GM_1}] = Pr[Succ_{Adv,GM_0}] \tag{2}$$

- GM_2: To obtain $Skey$, Adv conducts $Hash$ and $Send$ queries.Adv can modify exchanged messages to carry out active attacks. However, all exchanged messages are protected using the one-way hash function $h(\cdot)$ and consist of secret credentials and random numbers. Moreover, it is difficult for Adv to derive secret credentials and a random nonce because it is a computationally infeasible problem depending on the properties of $h(\cdot)$. So, using the birthday paradox, we obtain:

$$|Pr[Succ_{Adv,GM_2}] - Pr[Succ_{Adv,GM_1}]| \leq \frac{q_h^2}{2|Hash|} \tag{3}$$

- GM_3: It is similar to GM_2. Adv conducts $Send$ and PUF queries. As described in Section 3.3, $PUF(\cdot)$ has security properties. So, we can obtain the following result:

$$|Pr[Succ_{Adv,GM_3}] - Pr[Succ_{Adv,GM_2}]| \leq \frac{q_p^2}{2|PUF|} \tag{4}$$

- GM_4: In GM_4, Adv can try to obtain $Skey$ with the $CorruptSC$ query. By the $CorruptSC$ query, Adv can extract sensitive values $\{L_i, B_i', C_i', THID_i\}$ stored on the smart card of U_i. L_i, B_i', and C_i' are expressed as $L_i = h(ID_i||PW_i||R_i) \oplus R_u$, $B_i' = B_i \oplus \alpha = A_i \oplus HPW_i$, and $C_i' = h(C_i||HPW_i)$. Since Adv has no knowledge of identity ID_i and password PW_i, Adv must guess these parameters from the extracted values. However, it is computationally infeasible for Adv to guess ID, password, and B_i simultaneously. Thus, GM_3 and GM_4 are indistinguishable. By utilizing Zipf's law, we can obtain:

$$|Pr[Succ_{Adv,GM_4}] - Pr[Succ_{Adv,GM_3}]| \leq max\{C \cdot q_{send}^s, \frac{q_s}{2^{l_D}}\} \tag{5}$$

Now that all the games were run, Adv has to guess the bit to win the game. Thus, we can obtain following results:

$$Pr[Succ_{Adv,GM_4}] = \frac{1}{2} \tag{6}$$

From Equations (1) and (2), we obtain the result as follows:

$$\frac{1}{2}Adv_t = |Pr[Succ_{Adv,GM_0} - \frac{1}{2}]| = |Pr[Succ_{Adv,GM_1} - \frac{1}{2}]|. \tag{7}$$

With Equations (5) and (6), we derive the below equation:

$$\frac{1}{2}Adv_t = |Pr[Succ_{Adv,GM_1}] - Pr[Succ_{Adv,GM_4}]|. \tag{8}$$

Using the trigonometric inequality, we can obtain the results of Equations (4), (5), and (7).

$$\begin{aligned}
\frac{1}{2}Adv_t &= |Pr[Succ_{Adv,GM_1}] - Pr[Succ_{Adv,GM_4}]| \\
&\leq |Pr[Succ_{Adv,GM_1}] - Pr[Succ_{Adv,GM_3}]| \\
&\quad + |Pr[Succ_{Adv,GM_3}] - Pr[Succ_{Adv,GM_4}]| \\
&\leq |Pr[Succ_{Adv,GM_1}] - Pr[Succ_{Adv,GM_2}]| \\
&\quad + |Pr[Succ_{Adv,GM_2}] - Pr[Succ_{Adv,GM_3}]| \\
&\quad + |Pr[Succ_{Adv,GM_3}] - Pr[Succ_{Adv,GM_4}]| \\
&\leq \frac{q_h^2}{2|Hash|} + \frac{q_p^2}{2|PUF|} + max\{C \cdot q_{send}^s, \frac{q_s}{2^{l_D}}\}
\end{aligned} \tag{9}$$

Finally, multiply both sides of Equation (8) by 2 to obtain the desired result.

$$Adv_t \leq \frac{q_h^2}{|Hash|} + \frac{q_p^2}{|PUF|} + 2max\{C \cdot q_{send}^s, \frac{q_s}{2^{l_D}}\} \tag{10}$$

Therefore, we prove Theorem 1. □

6.4. Scyther Tool Simulation

In this section, we simulate IoT-PUFTAP using the scyther tool [34]. The scyther tool is a push-button tool to verify and analyze various security protocols. It supports unbounded model checking and multi-protocol analysis and provides a graphical user interface (GUI) to trace security vulnerabilities [49]. We validated the proposed protocol using the scyther tool according to the specifications below:

- Scyther tool checks security attack classes and possible protocol behaviors of the proposed protocol based on a pattern refinement algorithm.
- Scyther tool traces the most efficient and optimal security attacks through the "Find best attacks" setting.
- Scyther tool analyzes the security of the proposed protocol using claim events, including "Secret", "Alive", "Weakagree", "Niagree", and "Nisynch".
- To support multiple executions of protocols in the scyther tool, the "Maximum number of run" and "Maximum number of patterns per claim" parameters are set to 5 and 10, respectively.

To simulate IoT-PUFTAP, we write code in "Security Protocol Description Language (SPDL)". After that, the scyther tool simulates the "Secret", "Alive", "Weakagree", "Niagree", and "Nisynch" claim events under the DY model. Note that the claim event "Secret" means that the parameter can ensure confidentiality during the authentication phase. The claim event "Alive" denotes that the participants are alive and running the protocol in same session. "Weakagree" can be satisfied when participants actually communicate with a legal participant. "Niagree" can be guaranteed when participants agree on the exchanged parameters. "Nisynch" is the non-injective synchronization claim event, which means that messages are exchanged from legal participants in appropriate sequence. We conducted simulation on a Ubuntu 20.04.2 LTS virtual machine with an Intel Core i3-8100 3.60 GHz CPU and 16.0 GM of RAM.

6.4.1. Scyther Framework

Figure 4 shows the basic framework of the scyther tool. Firstly, we describe the proposed protocol into the scyther GUI according to the syntax of SPDL. Then, the scyther command-line tool performs the security validation using claim events. Finally, the command-line tool outputs the summary reports and trace class graphs. When the protocol satisfies each claim event, the result window displays the "OK" message and "No attacks" comment.

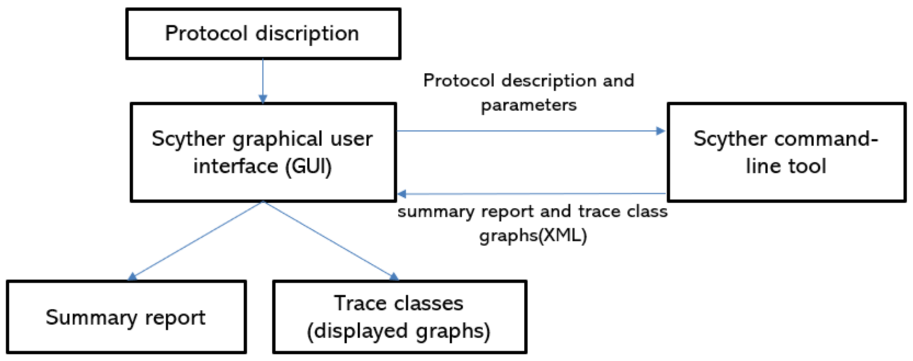
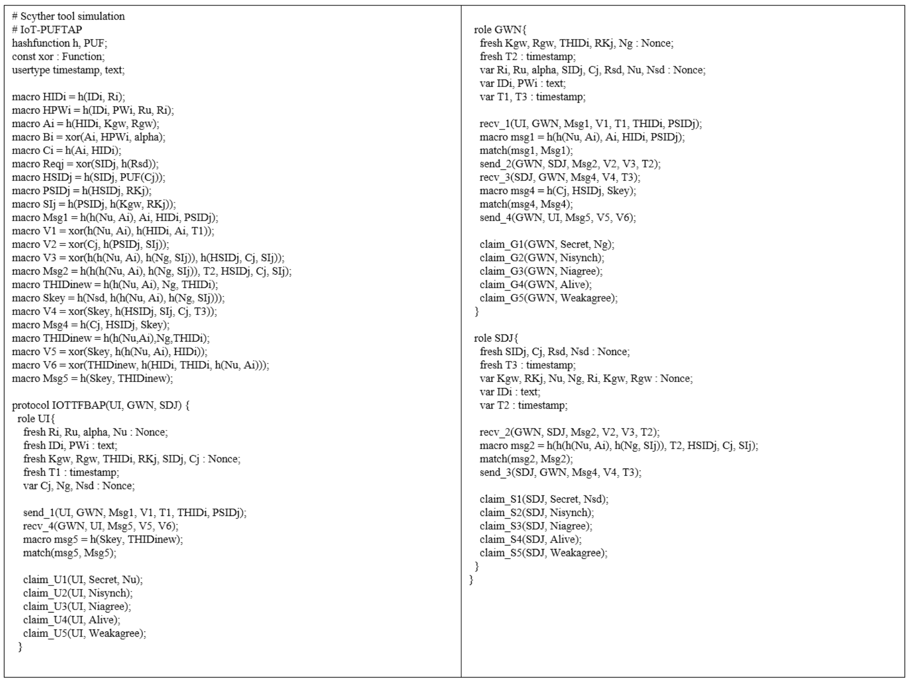

Protocol discription
Protocol description and parameters
Scyther graphical user interface (GUI)
Scyther command-line tool
summary report and trace class graphs(XML)
Summary report
Trace classes (displayed graphs)

Figure 4. Basic framework of the scyther tool.

6.4.2. SPDL Specification

Figure 5 shows the PUFTAP-IoT written in SPDL code. In PUFTAP-IoT, there are three roles : user UI, gateway GWN, and sensing device SDJ. The user UI sends an authentication request message $\{Msg_1, V_1, T_1, THID_i, PSID_j\}$ to the GWN using the $send_1$ function. Then, GWN receives the message using the $recv_1$ function and sends $\{Msg_2, V_2, V_3, T_2\}$ to the SDJ. The SDJ computes the session key $Skey$ and returns $\{Msg_3, V_4, T_3\}$. The GWN transmits $\{Msg_4, V_5, V_6\}$ to the UI.

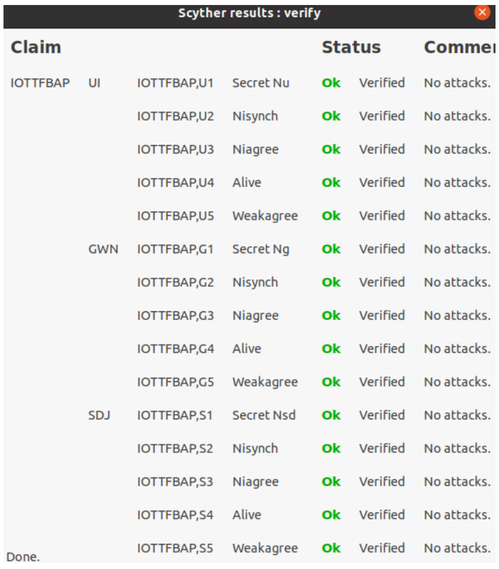


```
# Scyther tool simulation
# IoT-PUFTAP
hashfunction h, PUF;
const xor : Function;
usertype timestamp, text;

macro HIDi = h(IDi, Ri);
macro HPWi = h(IDi, PWi, Ru, Ri);
macro Ai = h(HIDi, Kgw, Rgw);
macro Bi = xor(Ai, HPWi, alpha);
macro Ci = h(Ai, HIDi);
macro Reqj = xor(SIDj, h(Rsd));
macro HSIDj = h(SIDj, PUF(Cj));
macro PSIDj = h(HSIDj, RKj);
macro SIj = h(PSIDj, h(Kgw, RKj));
macro Msg1 = h(h(Nu, Ai), Ai, HIDi, PSIDj);
macro V1 = xor(h(Nu, Ai), h(HIDi, Ai, T1));
macro V2 = xor(Cj, h(PSIDj, SIj));
macro V3 = xor(h(h(Nu, Ai), h(Ng, SIj)), h(HSIDj, Cj, SIj));
macro Msg2 = h(h(h(Nu, Ai), h(Ng, SIj)), T2, HSIDj, Cj, SIj);
macro THIDinew = h(h(Nu, Ai), Ng, THIDi);
macro Skey = h(Nsd, h(h(Nu, Ai), h(Ng, SIj)));
macro V4 = xor(Skey, h(HSIDj, SIj, Cj, T3));
macro Msg4 = h(Cj, HSIDj, Skey);
macro THIDinew = h(h(Nu,Ai),Ng,THIDi);
macro V5 = xor(Skey, h(h(Nu, Ai), HIDi));
macro V6 = xor(THIDinew, h(HIDi, THIDi, h(Nu, Ai)));
macro Msg5 = h(Skey, THIDinew);

protocol IOTTFBAP(UI, GWN, SDJ) {
 role UI{
  fresh Ri, Ru, alpha, Nu : Nonce;
  fresh IDi, PWi : text;
  fresh Kgw, Rgw, THIDi, RKj, SIDj, Cj : Nonce;
  fresh T1 : timestamp;
  var Cj, Ng, Nsd : Nonce;

  send_1(UI, GWN, Msg1, V1, T1, THIDi, PSIDj);
  recv_4(GWN, UI, Msg5, V5, V6);
  macro msg5 = h(Skey, THIDinew);
  match(msg5, Msg5);

  claim_U1(UI, Secret, Nu);
  claim_U2(UI, Nisynch);
  claim_U3(UI, Niagree);
  claim_U4(UI, Alive);
  claim_U5(UI, Weakagree);
 }

 role GWN{
  fresh Kgw, Rgw, THIDi, RKj, Ng : Nonce;
  fresh T2 : timestamp;
  var Ri, Ru, alpha, SIDj, Cj, Rsd, Nu, Nsd : Nonce;
  var IDi, PWi : text;
  var T1, T3 : timestamp;

  recv_1(UI, GWN, Msg1, V1, T1, THIDi, PSIDj);
  macro msg1 = h(h(Nu, Ai), Ai, HIDi, PSIDj);
  match(msg1, Msg1);
  send_2(GWN, SDJ, Msg2, V2, V3, T2);
  recv_3(SDJ, GWN, Msg4, V4, T3);
  macro msg4 = h(Cj, HSIDj, Skey);
  match(msg4, Msg4);
  send_4(GWN, UI, Msg5, V5, V6);

  claim_G1(GWN, Secret, Ng);
  claim_G2(GWN, Nisynch);
  claim_G3(GWN, Niagree);
  claim_G4(GWN, Alive);
  claim_G5(GWN, Weakagree);
 }

 role SDJ{
  fresh SIDj, Cj, Rsd, Nsd : Nonce;
  fresh T3 : timestamp;
  var Kgw, RKj, Nu, Ng, Ri, Kgw, Rgw : Nonce;
  var IDi : text;
  var T2 : timestamp;

  recv_2(GWN, SDJ, Msg2, V2, V3, T2);
  macro msg2 = h(h(h(Nu, Ai), h(Ng, SIj)), T2, HSIDj, Cj, SIj);
  match(msg2, Msg2);
  send_3(SDJ, GWN, Msg4, V4, T3);

  claim_S1(SDJ, Secret, Nsd);
  claim_S2(SDJ, Nisynch);
  claim_S3(SDJ, Niagree);
  claim_S4(SDJ, Alive);
  claim_S5(SDJ, Weakagree);
 }
}
```

Figure 5. PUFTAP-IoT written in SPDL code.

6.4.3. Simulation Result

Figure 6 indicates the simulation result of PUFTAP-IoT. The result shows that each role is not exposed to security attacks and ensures the "Secret", "Alive", "Weakagree", "Niagree", and "Nisynch" claim events. Therefore, we can demonstrate that PUFTAP-IoT can resist security vulnerabilities and ensure mutual authentication between each participant.



```
                          Scyther results : verify
Claim                                               Status           Commer
IOTTFBAP   UI    IOTTFBAP,U1   Secret Nu            Ok    Verified   No attacks.
                 IOTTFBAP,U2   Nisynch              Ok    Verified   No attacks.
                 IOTTFBAP,U3   Niagree              Ok    Verified   No attacks.
                 IOTTFBAP,U4   Alive                Ok    Verified   No attacks.
                 IOTTFBAP,U5   Weakagree            Ok    Verified   No attacks.
           GWN   IOTTFBAP,G1   Secret Ng            Ok    Verified   No attacks.
                 IOTTFBAP,G2   Nisynch              Ok    Verified   No attacks.
                 IOTTFBAP,G3   Niagree              Ok    Verified   No attacks.
                 IOTTFBAP,G4   Alive                Ok    Verified   No attacks.
                 IOTTFBAP,G5   Weakagree            Ok    Verified   No attacks.
           SDJ   IOTTFBAP,S1   Secret Nsd           Ok    Verified   No attacks.
                 IOTTFBAP,S2   Nisynch              Ok    Verified   No attacks.
                 IOTTFBAP,S3   Niagree              Ok    Verified   No attacks.
                 IOTTFBAP,S4   Alive                Ok    Verified   No attacks.
                 IOTTFBAP,S5   Weakagree            Ok    Verified   No attacks.
Done.
```

Figure 6. Scyther tool simulation result of PUFTAP-IoT.

7. Efficiency Analysis

In this section, we compare computation cost, communication cost, and security aspects with other relevant papers to prove the efficiency of PUFTAP-IoT.

7.1. Security and Functionality Features Comparison

In this section, we compare PUFTAP-IoT with the related existing protocols in terms of speculation, replay and man-in-the-middle, spoofing, guessing, known session-specific temporary information (KSSTI), device capture, device impersonation, and session key disclosure attacks and security features such as anonymity, forward secrecy, and secure mutual authentication. Table 3 indicates that the existing protocols do not meet all security requirements. On the other hand, PUFTAP-IoT meets all essential security requirements for communication in IoT environment.

Table 3. Security properties comparison.

Security Properties	PUFTAP-IoT	Chunka et al. [16]	Amintoosi et al. [18]	Hajian et al. [27]
Replay attack	o	o	o	o
Man-in-the-middle attack	o	o	o	o
Guessing attack	o	x	x	o
Impersonation attack	o	x	x	x
KSSTI attack	o	x	o	x
Smart card stolen attack	o	x	x	o
Device capture attack	o	o	o	x
Anonymity	o	x	x	o
Perfect forward secrecy	o	o	o	o
Using three factors	o	x	x	o
Using PUF	o	x	x	x
Using *honey_list*	o	x	x	x
Secure mutual authentication	o	x	x	x

x: insecure against an attack; o: secure against an attack.

7.2. Computation Cost Comparison

We cited [50,51] to compare and analyze computation cost with other authentication protocols. Accordingly, we hypothesized notations and times for cryptographic functions and functional functions as follows: T_h, T_{rg}, T_{puf}, and T_f as the execution time needed for hash function, random nonce generation, PUF function, and fuzzy extraction, where T_h, T_{rg}, T_{puf}, and T_f are 0.23 ms, 53.9 ms, 12ms, and 2.68 ms, respectively. Table 4 briefly shows the comparison results.

Table 4. Computation cost of login and authentication phase.

Protocol	User	Gateway/Sever	Sensing Device/Sensor	Total Cost
Chunka et al. [16]	$6T_h + 1T_{rg}$	$5T_h + 1T_{rg}$	$10T_h + 1T_{rg}$	$21T_h + 3T_{rg}$(166.53 ms)
Amintoosi et al. [18]	$8T_h + 1T_{rg}$	$10T_h + 1T_{rg}$	$10T_h + 1T_{rg}$	$23T_h + 3T_{rg}$(169.06 ms)
Hajian et al. [27]	$12T_h + 1T_{rg} + 1T_f$	$10T_h$	$5T_h + 1T_{rg}$	$27T_h + 2T_{rg} + 1T_f$(116.69 ms)
Ours	$11T_h + 1T_{rg} + 1T_f$	$16T_h + 1T_{rg}$	$7T_h + 1T_{rg} + 1T_{puf} + 1T_f$	$34T_h + 3T_{rg} + 1T_{puf} + 2T_f$(186.88 ms)

7.3. Communication Cost Comparison

In this section, we compare the cost of communication with other authentication protocols. We assume that each value according to [52]: SHA-1 hash digest, entities' identity, random nonce, and timestamp is 160, 160, 128, and 32 bits, respectively. Based on this assumption, the communication cost of PUFTAP-IoT is analyzed. Messages $\{Msg_1, V_1, T_1, THID_i, PSID_j\}$, $\{Msg_2, V_2, V_3, T_2\}$, $\{Msg_3, V_4, T_3\}$, and $\{Msg_4, V_5, V_6\}$ require (160 + 160 + 32 + 160 + 160 = 592), (160 + 160 + 160 + 32 = 512), (160 + 160 + 32 = 352), and (160 + 160 + 160 = 480) bits, respectively. Thus, the total communication cost requires $592 + 512 + 253 + 480 = 1837$ bits. Table 5 is the analysis of the communication cost consumption of different protocols.

Table 5. Communication cost of login and authentication phase.

Protocol	Total Communication Costs	No. of Messages
Chunka et al. [16]	2560 bits	4
Amintoosi et al. [18]	1664 bits	4
Hajian et al. [27]	2144 bits	5
Ours	1837 bits	4

7.4. Results of Comparison

The results of the comparative analysis of PUFTAP-IoT and other papers in terms of security, computation cost, and communication cost are as follows. Although PUFTAP-IoT has a higher computational cost compared with authentication protocols in other papers, the communication cost is similar or lower. Moreover, from a security point of view, PUFTAP-IoT is safe against a variety of attacks and can provide security for guessing, brute-force, and device capture attacks using three-factor, PUF, *honey_list*, etc. Therefore, PUFTAP-IoT can provide very secure services to service users in the IoT environment, even though the computation cost is higher than other authentication protocols.

8. Conclusions

With the development of WSN and IoT, areas using IoT are gradually expanding. Therefore, a secure authentication protocol is required to provide secure IoT services. In this paper, we analyze the security vulnerabilities of two-factor and three-factor authentication protocols in various IoT-based environments. To compensate for the security vulnerabilities of these protocols, we proposed PUFTAP-IoT, which applied PUF, *honey_list*, and three-element technology. We used BAN logic to prove that PUFTAP-IoT can provide secure mutual authentication. We also demonstrated that PUFTAP-IoT can achieve Sean key security through the ROR model. In addition, the scyther simulation tool was used to show that the proposed protocol is safe against various attacks in a wireless network environment. In addition, as a result of the performance analysis of the protocol, it was found that it provides a more secure service in the IoT environment compared with other authentication protocols. In conclusion, PUFTAP-IoT is safer for real-world applications in IoT environments than other related technologies. In the future, based on the proposed protocol, we will analyze the network delay and through put of the protocol through programming and simulation and apply the developed protocol to the real environment to develop better protocols.

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References

1. Zhang, Y.; Zhao, H.; Xiang, Y.; Huang, X.; Chen, X. A key agreement scheme for smart homes using the secret mismatch problem. *IEEE Internet Things J.* **2019**, *6*, 10251–10260. [CrossRef]
2. Rashid, B.; Rehmani, M.H. Applications of wireless sensor networks for urban areas: A survey. *J. Netw. Comput. Appl.* **2016**, *60*, 192–219. [CrossRef]
3. Pierce, F.J.; Elliott, T.V. Regional and on-farm wireless sensor networks for agricultural systems in Eastern Washington. *Comput. Electron. Agric.* **2008**, *61*, 32–43. [CrossRef]
4. Wazid, M.; Bagga, P.; Das, A.K.; Shetty, S.; Rodrigues, J.J.P.C.; Park, Y. AKM-IoV: Authenticated key management protocol in fog computing-based Internet of vehicles deployment. *IEEE Internet Things J.* **2019**, *6*, 8804–8817. [CrossRef]
5. Kwon, D.; Yu, S.; Lee, J.; Son, S.; Park, Y. WSN-SLAP: Secure and lightweight mutual authentication protocol for wireless sensor networks. *Sensors* **2021**, *21*, 936. [CrossRef]
6. Fu, X.; Wang, Y.; Yang, Y.; Postolache, O. Analysis on cascading reliability of edge-assisted Internet of Things. *Reliab. Eng. Syst. Saf.* **2022**, *223*, 108463. [CrossRef]

7. Fu, X.; Pace, P.; Aloi, G.; Li, W.; Fortino, G. Cascade Failures Analysis of Internet of Things under Global/Local Routing Mode. *IEEE Sensors J.* **2021**, *22*, 1705–1719. [CrossRef]
8. Das, M.L. Two-factor user authentication in wireless sensor networks. *IEEE Trans. Wirel. Commun.* **2009**, *8*, 1086–1090. [CrossRef]
9. He, D.; Gao, Y.; Chan, S.; Chen, C.; Bu, J. An enhanced two-factor user authentication scheme in wireless sensor networks. *Ad Hoc Sensor Wirel. Netw.* **2010**, *10*, 361–371.
10. Kumar, P.; Lee, H.J. Cryptanalysis on two user authentication protocols using smart card for wireless sensor networks. In Proceedings of the Wireless Advanced, London, UK, 20–22 June 2011; pp. 241–245.
11. Turkanović, M.; Brumen, B.; Hölbl, M. A novel user authentication and key agreement scheme for heterogeneous ad hoc wireless sensor networks, based on the Internet of Things notion. *Ad Hoc Netw.* **2014**, *20*, 96–112. [CrossRef]
12. Amin, R.; Biswas, G.P. A secure light weight scheme for user authentication and key agreement in multi-gateway based wireless sensor networks. *Ad Hoc Netw.* **2016**, *36*, 58–80. [CrossRef]
13. Wu, F.; Xu, L.; Kumari, S.; Li, X.; Shen, J.; Choo, K.R.; Wazid, M.; Das, A.K. An efficient authentication and key agreement scheme for multi-gateway wireless sensor networks in IoT deployment. *J. Netw. Comput. Appl.* **2017**, *81*, 72–85. [CrossRef]
14. Shuai, M.; Yu, N.; Wang, H.; Xiong, L. Anonymous authentication scheme for smart home environment with provable security. *Comput. Secur.* **2019**, *86*, 132–146. [CrossRef]
15. Zou, S.; Cao, Q.; Wang, C.; Huang, Z.; Xu, G. A Robust Two-Factor User Authentication Scheme-Based ECC for Smart Home in IoT. *IEEE Syst. J.* **2021**, *16*, 4938–4949. [CrossRef]
16. Chunka, C.; Banerjee, S.; Goswami, R.S. An efficient user authentication and session key agreement in wireless sensor network using smart card. *Wirel. Pers. Commun.* **2021**, *117*, 1361–1385. [CrossRef]
17. Kalra, S.; Sood, S.K. Advanced password based authentication scheme for wireless sensor networks. *J. Inf. Secur. Appl.* **2015**, *20*, 37–46. [CrossRef]
18. Amintoosi, H.; Nikooghadam, M.; Shojafar, M.; Kumari, S.; Alazab, M. Slight: A lightweight authentication scheme for smart healthcare services. *Comput. Elec. Eng.* **2022**, *99*, 107803. [CrossRef]
19. He, D.; Kumar, N.; Chen J.; Lee, C.-C.; Chilamkurti, N.; Yeo, S.-S. Robust anonymous authentication protocol for health-care applications using wireless medical sensor networks. *Multimedia Syst.* **2015**, *21*, 49–60. [CrossRef]
20. Wu, F.; Xu, L.; Kumari, S.; Li, X. An improved and anonymous twofactor authentication protocol for health-care applications with wireless medical sensor networks. *Multimedia Syst.* **2017**, *23*, 195–205. [CrossRef]
21. Wang, C.; Xu, G.; Li, W. A secure and anonymous two-factor authentication protocol in multiserver environment. *Secur. Commun. Netw.* **2018**, *2018*, 1–15. [CrossRef]
22. Amin, R.; Islam, S.H.; Biswas, G.; Khan, M.K.; Leng, L.; Kumar, N. Design of an anonymity-preserving three-factor authenticated key exchange protocol for wireless sensor networks. *Comput. Netw.* **2016**, *101*, 42–62. [CrossRef]
23. Jiang, Q.; Zeadally, S.; Ma, J.; He, D. Lightweight three-factor authentication and key agreement protocol for internet-integrated wireless sensor networks. *IEEE Access* **2017**, *5*, 3376–3392. [CrossRef]
24. Ostad-Sharif, A.; Arshad, H.; Nikooghadam, M.; Abbasinezhad-Mood, D. Three party secure data transmission in IoT networks through design of a lightweight authenticated key agreement scheme. *Future Gener. Comput. Syst.* **2019**, *100*, 882–892. [CrossRef]
25. Mo, J.; Chen, H. A lightweight secure user authentication and key agreement protocol for wireless sensor networks. *Secur. Commun. Netw.* **2019**, *2019*, 1–17. [CrossRef]
26. Yu, S.; Park, Y. SLUA-WSN: Secure and lightweight three-factor-based user authentication protocol for wireless sensor networks. *Sensors* **2020**, *20*, 4143. [CrossRef]
27. Hajian, R.; Erfani, S.H.; Kumari, S. A lightweight authentication and key agreement protocol for heterogeneous IoT with special attention to sensing devices and gateway. *J. Supercomput.* **2022**, 1–43. [CrossRef]
28. Aghili, S.F.; Mala, H.; Shojafar, M.; Peris-Lopez, P. LACO: Lightweight three-factor authentication, access control and ownership transfer scheme for e-health systems in IoT. *Future Gener. Comput. Syst.* **2019**, *96*, 410–424.
29. Maes, R. Physically unclonable functions: Properties. In *Physically Unclonable Functions*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 49–80.
30. Juels, A.; Ristenpart, T. Honey encryption: Encryption beyond the brute-force barrier. *IEEE Secur. Privacy* **2014**, *12*, 59–62. [CrossRef]
31. Juels, A.; Ristenpart, T. Honey encryption: Security beyond the brute-force bound. In Proceedings of the Annual International Conference on the Theory and Applications of Cryptographic Techniques, Copenhagen, Denmark, 11–15 May 2014; pp. 293–310.
32. Burrows, M.; Abadi, M.; Needham, R. A logic of authentication. *ACM Trans. Comput. Syst.* **1990**, *8*, 18–36.
33. Abdalla, M.; Fouque, P.-A.; Pointcheval, D. Password-based authenticated key exchange in the three-party setting. In *Lecture Notes in Computer Science, Proceedings of the 8th International Workshop on Theory and Practice in Public Key Cryptography (PKC'05), Les Diablerets, Switzerland, 23–26 January 2005*; Springer: Berlin/Heidelberg, Germany, 2005; pp. 65–84.
34. Scyther Tool—Cas Cremers. Available online: https://people.cispa.io/cas.cremers/scyther/ (accessed on 23 July 2022).
35. Lamport, L. Password authentication with insecure communication. *Commun. ACM* **1981**, *24*, 770–772. [CrossRef]
36. Dolev, D.; Yao, A.C. On the security of public key protocols. *IEEE Trans. Inf. Theory* **1983**, *29*, 198–208. [CrossRef]
37. Kocher, P.; Jaffe, J.; Jun, B. Differential power analysis. In *Advances in Cryptology*; Springer Science+Business Media: Berlin, Germany; New York, NY, USA, 1999; pp. 388–397.

38. Aman, M.N.; Chua, K.C.; Sikdar, B. Mutual authentication in IoT systems using physical unclonable functions. *IEEE Internet Things J.* **2017**, *4*, 1327–1340. [CrossRef]
39. Frikken, K.B.; Blantonm, M.; Atallahm, M.J. Robust authentication using physically unclonable functions. In Proceedings of the International Conference on Information Security, Pisa, Italy, 7–9 September 2009; Springer: Berlin/Heidelberg, Germany, 2009; pp. 262–277.
40. Chatterjee, U.; Chakraborty, R.S.; Mukhopadhyay, D. A PUF-based secure communication protocol for IoT. *ACM Trans. Embedded Comput. Syst.* **2017**, *16*, 1–25. [CrossRef]
41. Dodis, Y.; Reyzin, L.; Smith, A. Fuzzy extractors: How to generate strong keys from biometrics and other noisy data. In *Lecture Notes in Computer Science, Proceedings of the International Conference on the Theory and Applications of Cryptographic Techniques, Interlaken, Switzerland, 2–6 May 2004*; Springer: Berlin/Heidelberg, Germany, 2004; pp. 523–540.
42. Juels, A.; Rivest, R.L. Honeywords: Making password cracking detectable. In Proceedings of the 2013 ACM SIGSAC Conference on Computer & Communications Security, Berlin, Germany, 4–8 November 2013; pp. 145–160.
43. Lee, J.; Yu, S.; Park, K.; Park, Y.; Park, Y. Secure three-factor authentication protocol for multi-gateway IoT environments. *Sensors* **2019**, *19*, 2358. [CrossRef]
44. Son, S.; Lee, J.; Park, Y.; Park, Y.; Das, A.K. Design of blockchain-based lightweight V2I handover authentication protocol for VANET. *IEEE Trans. Netw. Sci. Eng.* **2022**, *9*, 1346–1358. [CrossRef]
45. Oh, J.; Yu, S.; Lee, J.; Son, S.; Kim, M.; Park, Y. A secure and lightweight authentication protocol for IoT-based smart homes. *Sensors* **2021**, *21*, 1488. [CrossRef]
46. Yu, S.; Park, Y. A Robust Authentication Protocol for Wireless Medical Sensor Networks Using Blockchain and Physically Unclonable Functions. *IEEE Internet Things J.* **2022**. [CrossRef]
47. Kim, M.; Lee, J.; Oh, J.; Park, K.; Park, Y.; Park, K. Blockchain based energy trading scheme for vehicle-to-vehicle using decentralized identifiers. *Appl. Energy* **2022**, *322*, 119445. [CrossRef]
48. Lee, J.; Kim, G.; Das, A.K.; Park, Y. Secure and efficient honey list-based authentication protocol for vehicular ad hoc networks. *IEEE Trans. Netw. Sci. Eng.* **2021**, *8*, 2412–2425. [CrossRef]
49. Cremers, C.J. The scyther tool: Verification, falsification, and analysis of security protocols. In Proceedings of the International Conference on Computer Aided Verification, Princeton, NJ, USA, 7–14 July 2008; Springer: Berlin/Heidelberg, Germany, 2008; pp. 414–418.
50. Kilinc, H.H.; Yanik, T. A survey of SIP authentication and key agreement schemes. *IEEE Commun. Surv. Tutor.* **2013**, *16*, 1005–1023. [CrossRef]
51. Gope, P.; Sikdar, B. Lightweight and privacy-preserving two-factor authentication scheme for IoT devices. *IEEE Internet Things J.* **2019**, *6*, 580–589. [CrossRef]
52. Banerjee, S.; Odelu, V.; Das, A.K.; Chattopadhyay, S.; Rodrigues, J.J.; Park, Y. Physically secure lightweight anonymous user authentication protocol for internet of things using physically unclonable functions. *IEEE Access* **2019**, *7*, 85627–85644. [CrossRef]