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SPECIAL SECTION ON INTERNET-OF-THINGS ATTACKS AND DEFENSES: RECENT ADVANCES AND CHALLENGES

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On the Design of Secure and Efficient Three-Factor Authentication Protocol Using Honey List for Wireless Sensor Networks

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ABSTRACT The Internet of Thing (IoT) is useful for connecting and collecting variable data of objects through the Internet, which makes to generate useful data for humanity. An indispensable enabler of IoT is the wireless sensor networks (WSNs). Many environments, such as smart healthcare, smart transportation and smart grid, have adopted WSN. Nonetheless, WSNs remain vulnerable to variety of attacks because they send and receive data over public channels. Moreover, the performance of IoT enabled sensor devices has limitations since the sensors are lightweight devices and are resource constrained. To overcome these problems, many security authentication protocols for WSNs have been proposed. However, many researchers have pointed out that preventing smartcard stolen and off-line guessing attacks is an important security issue, and guessing identity and password at the same time is still possible. To address these weaknesses, this paper presents a secure and efficient authentication protocol based on three-factor authentication by taking advantage of biometrics. Meanwhile, the proposed protocol uses a honey_list technique to protect against brute force and stolen smartcard attacks. By using the honey_list technique and three factors, the proposed protocol can provide security even if two of the three factors are compromised. Considering the limited performance of the sensors, we propose an efficient protocol using only hash functions excluding the public key based elliptic curve cryptography. For security evaluation of the proposed authentication protocol, we perform informal security analysis, and Real-Or-Random (ROR) model-based and Burrows Abadi Needham (BAN) logic based formal security analysis. We also perform the formal verification using the widely-used Automated Validation of Internet Security Protocols and Applications (AVISPA) simulation software. Besides, compared to previous researches, we demonstrate that our proposed authentication protocol for WSNs systems is more suitable and secure than others.

INDEX TERMS Authentication, AVISPA, BAN logic, Internet of Things (IoT), ROR model, wireless sensor network, honey list.

I. INTRODUCTION

As the IoT notions has spread in recent years, vast quantities of sensors have been deployed for collecting and exchanging data in various fields related to IoT. An essential technological enabler of IoT is WSNs. WSNs collect user and device data and use these data for various applications such as remote health monitoring for patients, smart grid power usage monitoring, etc.

Figure 1 shows a WSN network model. Generally, WSNs consist of a series of dispersed sensor nodes, plenty distributed users, and one or more gateway nodes which have a powerful performance and play trusted parties. Each set of distributed sensor nodes is located in a specific area. And

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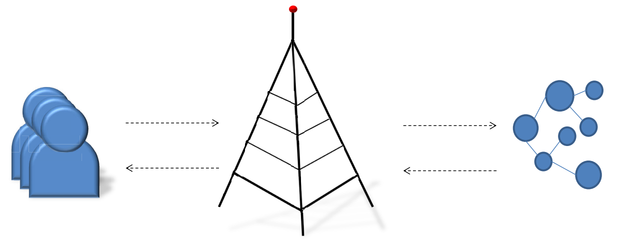

FIGURE 1. A generalizes model of WSNs.

a series of sensor nodes collect information data of human, device or environment and then they transmit data to the gateway node through open wireless channels. The gateway can access these data, and analysis of these data can help administrators and automated systmes make various functional decisions in real industrial environments. Generally, sensor nodes have limited communication, computing and storage capability. In addition, sensor nodes are easily compromised by attackers and cannot be guaranteed secure, because sensor nodes have limited physical security. Moreover, in WSNs, data are transmitted through open wireless channels and it causes security vulnerabilities that allow data can be captured by malicious attackers. If attackers capture these transmitted data, they can perform variable attacks i.e., man-in-the-middle, replay, privileged insider attacks and identity and password guessing attack and so on. Thus, various protocols have been developed in an attempt to guarantee the security of the transmitted data and the sensor node devices. However, traditional two factor authentication schemes remain vulnerable to guessing attacks according to [1]–[4]. They have been shown that attackers can guess identity and password from identity dictionary space $\mathcal{D}_{ID}$ and password dictionary space $\mathcal{D}_{PW}$ in real polynomial time. Therefore, in recent years, three-factor based mechanisms that use biometrics of users have been studied. Moreover, the honey_list technique can be used with three-factor to further protect the authentication protocol. Wang and Wang [34], Wang *et al.* [35] demonstrated that using biometrics and honey _list techniques can be safe, even if two of the three factors are compromised.

Recently, Chen *et al.* [5] suggested a privacy-preserving authentication protocol for WSNs. However, we demonstrate that the protocol of Chen *et al.* cannot be safe against stolen smartcard, off-line password and off-line identity guessing and replay attacks. Then, this paper proposes authentication protocol based three-factor utilizing biometrics and honey_list technique for WSNs.

A. MOTIVATION AND CONTRIBUTIONS

In WSNs environments, most authentication protocols are based on two-factor. Thus, they cannot prevent against simultaneously guessing identity and passwords. Furthermore, if users lose their smart cards or attackers steal smart cards, users are vulnerable to password guessing attack. Thus, this paper proposes a three factor authentication protocol to help ensure security of WSNs. The contributions of this paper include:

- This paper discovers that proposed protocol of Chen *et al.* [5] cannot provide security and is vulnerable to smartcard stolen, identity guessing, password guessing, and replay attacks. And also Chen *et al.*'s protocol cannot guarantee mutual authentication.
- This paper designs an authentication protocol based on three-factor for WSNs excluding elliptic curve cryptography (ECC), owing to the limited performance capability of sensor nodes. And we adopt the fuzzy-extractor for the biometric awareness. Moreover, we propose authentication protocol using honey_list technique to overcome malicious attacks including smartcard stolen attack and simultaneous guessing attack of identity and password.
- We analyze security using BAN logic, AVISPA software and ROR model for a formal security analysis. We conduct an informal analysis and we show security comparison, computational and communicational costs with previous related researches.

B. PAPER ORGANIZATION

We introduce previous interrelated researches in authentication for WSNs in Section II. Section III describes some preliminaries to show necessary backgrounds such as fuzzy extractor, honey_list and related notations. Sections IV and V review the suggested scheme of Chen *et al.* and analyze its security aspects. Section VI illustrates our proposed protocol for WSNs. Section VII demonstrates the security of the proposed protocol by performing a security analysis. Section VIII compares our efficiency and security features with other previous researches. In the end, we summarize and close the paper in Section IX.

II. RELATED WORKS

Authentication is considered as a primary security service which allows an entity to mutually authenticate with another entity [6]–[20].

Authentication protocols for WSNs have already been researched, and, here, we briefly review works involved in three aspects, i.e., lightweight authentication for WSNs, simultaneous guessing identity and password attack on protocol for WSNs and three-factor based protocol. Owing to the limitations of sensor nodes performance, efficiency communication and computation costs have become an important issue to design authentication protocols for WSNs. For this reason, several lightweight protocols for WSNs have been suggested.

In 2014, Turkanovic *et al.* [21] suggested key agreement scheme for WSNs. They used masked identities for users and sensors to protect real identities. Unfortunately, Amin and Biswas [22] discovered that their scheme cannot provide security. They discovered that Turkanovic *et al.*'s protocol doesn't guarantee safety against smartcard stolen, masquerade and off-line password guessing attacks. Amin and Biswas put forward a novel authentication protocol using a symmetric key to overcome security vulnerabilities of Turkanovic *et al.*'s protocol. Nevertheless, Srinivas *et al.* [23] pointed out that Amin and Biswas's authentication protocol cannot provide key security and also does not withstand impersonation, stolen smartcard attacks. To resolve these weaknesses, they suggested more efficient user authentication protocol to employing WSNs.

Unfortunately, some researchers have proved that password and smartcard based protocols are not safe against simultaneous guessing of identity and password. In 2016, Maitra *et al.* [24] proffered an authentication protocol for multiserver environment using a password and a smartcard. Nevertheless, Wang *et al.* [1] proved that Maitra *et al.*'s protocol is not safe against off-line guessing attack. They demonstrated that an attacker can conduct attack of simultaneous guessing identity and password through the Zipf's law [25]. Roy *et al.* [26] put forward a secure authentication protocol to employing IoT environment. They used a user's biometric to prevent various attacks. Unfortunately, Park [2] showed Roy *et al.*'s protocol is insecure against off-line identity guessing attack guessed password at the same time. And also, according to [3], [4], people easily want to choose identities and passwords that are easy to remember for convenience. Both identities and passwords must be taken from a very small dictionary space. Therefore, an attacker can guess identity and password of an user in polynomial time.

To prevent an adversary's simultaneous identity and password guessing attack, many researchers have suggested using a security three-factor authentication scheme. Biometric keys have several advantages compared with traditional passwords. They are unforgettable and they cannot be lost. Furthermore, they are difficult to fragile and difficult to copy. In 2016, Park and Park [28] discovered that the protocol of Chang *et al.* [27] cannot provide security such as perfect forward secrecy and password guessing attacks. Moreover Chan *et al.*'s protocol cannot provide accurate password updates. Thus, Park *et al.* proposed a three-factor based user authentication protocol for WSNs. They demonstrated that their protocol can provide more secure authentication by utilizing biometrics and elliptic curve cryptosystem. In 2018, Amin *et al.* [29] suggested a user authentication scheme for medical WSNs. They used a synchronous update mechanism to provide user anonymity. Nevertheless, Li *et al.* [30] figured out Amin *et al.*'s protocol cannot provide forward secrecy and also is not safe against denial of service attack. Therefore, they proposed three-factor based with forward secrecy for WMSN with ECC. And they also applied honey_list technique to provide security against device or smartcard stolen and brute-force attacks.

III. PRELIMINARIES

To improve the readability of this paper, we introduce the preliminary information of this paper: the basis of fuzzy-verifier; honey_ list; adversary model; and basic notations adopted in this paper.

A. HONEY LIST

Honey Encryption (HE) is an algorithm that can be used to protect data by strongly fooling unauthorized users if an attacker attempts to decrypt plain text using the wrong password or honeyword. When an adversary attempts to decrypt with multiple invalid passwords or honeywords, the HE process generates a fake valid message. HE [31], [32] is based on Distributed Transforming Encoding (DTE). HE manages plain-text space through DTE and includes encryption and decryption. The encryption process takes the space of a plain text message M as input and returns the S value of the n-bit string as output. The decryption process makes a conversion that is the value of the seed space S of the n-bit string into plain text. DTE encryption and decryption algorithms are as following figure:

In Figure 2, K is a key, H is a hash function, S is a seed, M is a message, C is a cipher-text and R is a random string. ←$ means uniform random assignment. Let the probability distribution over the message space $\mathcal{M}$ be p_m. And the message M is over the $\mathcal{M}$. If the $\mathcal{M}$ gets bigger, the p_m is going to lower. Thus, to assign the corresponding message rate, the DTE process takes a probability distribution theory.

$\mathrm{HEnc}(K, M)$	$\mathrm{HDec}(K, (R, C))$
$\mathrm{S} \leftarrow \$encode(M)$	$\mathrm{S}' \leftarrow H(R, K)$
$\mathrm{R} \leftarrow \$\{0,1\}^n$	$S \leftarrow C \oplus S'$
$S' \leftarrow H(R, K)$	$M \leftarrow decode(S)$
$C \leftarrow S' \oplus S$	return (M)
return (R, C)	

FIGURE 2. DTE encryption and decryption algorithms of honey encryption.

In this paper, *Honey_list* denotes honeywords. Honeywords mean false passwords and honeywords are kinds of honey encryption algorithm. The details of the honeyword generation algorithm are referred to [33]. Among the various methods used to prevent password guessing attack by using the *Honey_list* during the login phase [33], this paper applies the following method. We allow the login to proceed as usual, but the system tracks the login source. Moreover, the system ends the session when the number of items in the honey_ list exceeds the threshold. Wang and Wang [34], Wang *et al.* [36] demonstrated that simultaneously using a fuzzy-verifier and *Honey_list* techniques ensures that the system would be safe even if two of the three factors are attacked. In this paper, we use the fuzzy extractor instead of the fuzzy-verifier.

B. FUZZY EXTRACTOR

The fuzzy extractor [36] is a technology that uses a user biometric data through data extraction. The data extraction from biometrics normally has difficulty capturing real values due to various noises. To resolve this problem, the fuzzy extractor can help to extract random bit strings evenly without noises. The basic processes of the fuzzy extractor include generation and reproduction. In this paper, *Ge* denotes the generation process and *Re* denotes reproduction process.

- $Ge(BIO_i) =< R_i, P_i >$. To generate a key information, fuzzy extractor uses the generation process algorithm. Biometric data BIO_i is used as input, public reproduction P_i is a helper string and uniformly random string R_i is secret key data as an output.
- $Re(BIO'_i, P_i) = R_i$. To reproduce a secret string R_i, the reproduction algorithm is used by the fuzzy extractor. The inputs of reproduction process are P_i and user biometrics BIO_i. And the reproduction algorithm reproduces the original secret biometrics R_i. For restoring the equal R_i, the metric space distance between BIO_i and BIO'_i must be within the allowed specified error tolerance.

C. ADVERSARY MODEL

In the interest of analyze the security of the authentication protocol, it is necessary to first identify attacker's malicious attacks. We explicitly describe an adversary model consistent with reality by using the widely-accepted "Dolev-Yao threat model" [37] which introduces a simultaneous identity and password guessing attack. We assume capabilities of an adversary as follows.

- The adversary is in full control of transmitted messages through wireless public channels and can learn transmitted messages. Then, the adversary can eliminate, insert, eavesdrop or modify legitimate messages.
- The malicious adversary is able to get or pilfer a validate smartcard, and then the adversary can take out confidential values stored in the smartcard via a power analysis attacks [38], [39].
- The malicious adversary is able to damage some sensor nodes.
- The malicious adversary is able to register as a valid user and conduct a privileged-insider attack for guessing a user's password [40].
- The malicious adversary is able to get gateway's secret key when evaluating the system failure. Then, the adversary tries to previous session key.

We assume an adversary can conjecture registered legitimate user's identity or password. Moreover, we also follow the assumptions in [1]–[4]. We have assumption that the adversary can conjecture identity and password simultaneously. The adversary can choose random identity ID and random password PW from dictionary space of identity $\mathcal{D}_{ID}$ and space of password $\mathcal{D}_{PW}$. The space of identity and password is usually, $|\mathcal{D}_{ID}| < |\mathcal{D}_{PW}| < 10^6$. Therefore, the computational time complexity is very efficient.

D. NOTATIONS

Table 1 describes used the notations in this paper.

IV. REVIEW OF CHEN *et al.*'s PROTOCOL

We shortly examine the protocol developed by Chen *et al.*, which is composed of the user and sensor's registration phase, the login and authentication phase and the password change phase. Prior to registration, the gateway forms public parameters $\{n, a, b, p, G,$ and $h\}$ for the ECC and the gateway is published to the whole system. Additionally, the gateway generates a secret key X_{GWN}.

TABLE 1. Used notations in this paper.

Notations	Meanings
S_j, SID_j	jth sensor node and its identity
U_i, ID_i	ith user and his/her identity
GWN	Gateway node
HID_i, PID_j	Hidden identities of ith user and jth sensor, respectively
N_i, N_G	Random numbers of user and gateway, respectively
y	GWN's long-term secret key
G	The generator of ECC
X_{GWN}	GWN's master key
SK_{ij}	Session key shared by U_i, S_j
$h(\cdot)$	Hash function
$\|\|$	The conjugation symbol
$\oplus$	The exclusive-or operator

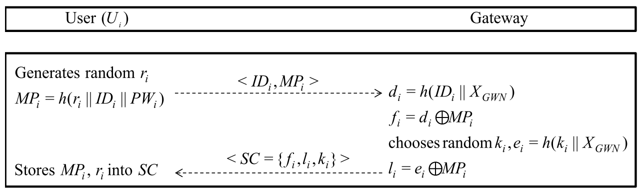

FIGURE 3. User registration phase of Chen *et al.*'s protocol.

A. REGISTRATION PHASE OF USERS AND SENSORS

At Chen *et al.*'s protocol, they have two registration phase, users and sensors. And the registration phase is through a closed channel.

- User registration: First, a user U_i picks out a unique ID_i and PW_i, then U_i randomly generates parameter r_i. Then, the user U_i calculates $MP_i = h(r_i||ID_i||PW_i)$ and transmits a composed message $\{ID_i, MP_i\}$ to a gateway GWN. After that, GWN calculates $d_i = h(ID_i||X_{GWN})$ and $f_i = d_i \oplus MP_i$. Next, GWN randomly chooses a number k_i and calculates $e_i = h(k_i||X_{GWN})$ and $l_i = e_i \oplus MP_i$. GWN stores values $\{f_i, l_i, k_i\}$ into a smartcard SC which is issued to the user. At last, U_i stores $\{MP_i, r_i\}$ into the SC. Figure 3 describes this phase.
- Sensor registration: A sensor S_j chooses a unique identity SID_j and transmits it to the gateway node GWN. After GWN receives SID_j, GWN calculates $x_j = h(SID_j||X_{GWN})$ and transmits it to the sensor. S_j keeps x_j in its private memory.

B. LOGIN AND AUTHENTICATION PHASE

When users needs to approach resources of sensor nodes, they have to login and authenticate with a gateway node. Then, the gateway authenticates the sensor nodes. And finally, users and sensors can have a shared session key. The detailed equations are as follows.

Step 1: An user U_i enters ID_i, PW_i and a smartcard. The smartcard calculates $MP'_i = h(r_i||ID_i||PW_i)$,

$d_i = f_i \oplus MP'_i$ and $e_i = l_i \oplus MP'_i$. Then, the smartcard chooses random number k_1 and timestamp T_1 and computes $A = k_1 \cdot G$. U_i gets a value k_i from the smartcard and chooses timestamp T_1. And then, U_i calculates $M_2 = h(A||ID_i||SID_j||d_i||T_1)$ and $M_1 = e_i \oplus (ID_i||SID_j||M_2)$ and sends a login request message $< A, k_i, M_1, T_1 >$ to a gateway GWN.

Step 2: After the gateway receives $< A, k_i, M_1, T_1 >$, the gateway GWN verifies the freshness of the timestamp and calculates $e'_i = h(k_i||X_{GWM})$, $(ID'_i||SID'_i||M'_2) = M_1 \oplus e'_i$, $d'_i = h(ID'_i||X_{GWN})$ and $M'_2 = h(A||ID'_i||SID'_i||d'_i||T_1)$. The gateway checks legitimate for comparing M'_2 and M_2. If they are valid, the gateway calculates $x'_j = h(SID'_j||X_{GWN})$ and chooses a timestamp T_2. Finally, the gateway computes $M_3 = h(A||SID'_j||x'_j||T_2)$ and sends a message $< A, M_3, T_2 >$ to a sensor nodes S_j.

Step 3: The sensor node verifies the freshness of T_2 after receiving $< A, M_3, T_2 >$. S_j calculates $M'_3 = h(A||SID'_j||x'_j||T_2)$ and checks whether $M_3 \stackrel{?}{=} M'_3$. If they are same values, S_j randomly chooses a number k_2. And then, S_j calculates $B = k_2 \cdot G$. S_j also calculates $M_4 = h(B||SK_{ij}||A)$ and $M_5 = h(x_j||M_3||M_4||B)$, and a shared session key $SK_{ij} = h(k_2 \cdot A)$. Then, it transmits $< B, M_4, M_5 >$ to GWN.

Step 4: GWN calculates $M'_5 = h(x_j||M_3||M_4||B)$ and verifies whether $M_5 \stackrel{?}{=} M'_5$. If they are valid, the gateway randomly chooses a number k_3, and calculates $e_{inew} = h(k_3||X_{GWN})$, $M_7 = h(e_{inew}||k_3||d'_i||T_1||M_4)$ and $M_6 = (e_{inew}||k_3||M_7) \oplus e'_i$. Then, the gateway sends a message $< B, M_6 >$ to U_i.

Step 5: U_i computes $(e_{inew}||k_3||M_7) = M_6 \oplus e'_i$, $SK'_{ij} = h(k_1 \cdot B)$, $M'_4 = h(B||SK'_{ij}||A)$. U_i then verifies whether or not M'_4 and M_4 are the same. If they are same values, U_i computes $M'_7 = h(e'_{inew}||k'_3||d_i||T_1||M'_4)$ and updates smartcard values $l_i = MP'_i \oplus e'_{inew}$ and $k_i = k'_3$.

C. PASSWORD CHANGE PHASE

The user is able to change the PW within k times in a period of T at Chen *et al.*'s protocol. For using a variable counter, their protocol counts the number of times which is a user incorrectly enter a password. If the user inputs an incorrect password over than k times, the password will not be allowed to enter. More detailed equations and steps are as follows.

Step 1: A validate user U_i inserts a smartcard and inputs ID_i and PW_i.

Step 2: The smartcard checks counter is smaller than k. If it is smaller than k, go Step 4, else, go Step 3.

Step 3: The smartcard checks if $|TW_{first} - T_{now}|$ is bigger than T. TW_{first} means the user enters a incorrect password for the first time. If it is bigger than T, go Step 4 and set counter=0. Otherwise, the user is not able to input a password.

Step 4: The smartcard calculates $h(r_i||ID_i||PW_i)$ and compares with MP_i stored in the smartcard. If they are same value, the smartcard allows to change password. Otherwise, go to Step 8.

Step 5: Check if counter is larger than 0, set counter is 0.

Step 6: The smartcard calculates $d_i = f_i \oplus MP_i$ and $e_i = l_i \oplus MP_i$.

Step 7: The user inputs a new password PW'_i. Then, the smartcard updates MP_i to $MP'_i = h(r_i||ID_i||PW'_i)$ and also updates $f'_i = d_i \oplus MP'_i$ and $l'_i = e_i \oplus MP'_i$. Finally, the user completes the password change.

Step 8: Set counter is counter + 1. If counter is 1, go to step 1 and TW_{first} is set to be now().

V. CRYPTANALYSIS OF CHEN *et al.*'s PROTOCOL

We discover security vulnerabilities of Chen *et al.*'s protocol in this section. They demonstrated that their protocol prevents user anonymity and off-line dictionary attack. Nevertheless, this paper discovers that their protocol is insecure to several attacks as following.

A. SMARTCARD STOLEN ATTACK

Section III-C introduced the adversary model used to obtain values stored in a smartcard. Therefore, an adversary can obtain stored values $\{MP_i, r_i, f_i, l_i, k_i(= k3)\}$ in a valid user's smartcard via a stolen smartcard attack.

B. OFF-LINE PASSWORD GUESSING ATTACK

In accordance with references [1]–[4], an adversary can conjecture ID_i and PW_i at a same time. From this assumption, the adversary can conjecture a legitimate user's ID_i and a PW_i as following.

Step 1: An adversary randomly selects a identity ID^* from an identity dictionary space $\mathcal{D}_{ID}$, and picks up a password PW^* from a password dictionary space $\mathcal{D}_{PW}$. And the adversary obtains smartcard values $\{MP_i, r_i, f_i, l_i, k_i(= k3)\}$.

Step 2: The adversary calculates $MP^* = h(r_i||ID^*||PW^*)$ to check the correctness of ID^* and PW^*.

Step 3: If MP^* and the stored value MP_i are the same, the adversary's guessing result is as successful. Else, the adversary returns to Step 1 and repeats until the adversary correctly guess the ID and password for the user.

$\mathcal{O}(|\mathcal{D}_{ID}| * |\mathcal{D}_{PW}| * T_h)$ is the computational time complexity of this procedure, where T_h is the hash computation cost. $|\mathcal{D}_{ID}|$ and $|\mathcal{D}_{PW}|$ denote the number of passwords and identities, respectively. According to Zipf's law [25], $|\mathcal{D}_{ID}| < |\mathcal{D}_{PW}| < 10^6$. Therefore, the off-line guessing attack is very efficient. Thus, the attack can be finished in the real polynomial time.

C. OFF-LINE IDENTITY GUESSING ATTACK

An adversary can conjecture a valid user's original ID_i as following steps.

Step 1: An adversary can obtain smartcard values $\{MP_i, r_i, f_i, l_i, k_i(= k3)\}$ by power analysis. Then, the adversary randomly chooses the identity ID^* in an identity dictionary space $\mathcal{D}_{ID}$.

Step 2: The adversary calculates $e_{inew} = MP_i \oplus l_i$ through obtained smartcard values. The adversary computes $d^* = f_i \oplus MP^i$ and $M_7 = h(e_{inew}||k_3||d^*||T_1||M_4)$ where T_1 and M_4 are obtained through channels. $e_i' = M_6 \oplus (e_{inew}|| k_3||M_7)$ where M_6 is obtained through channels.

Step 3: The adversary calculates $M_2' = h(A||ID^*||SID_j ||d_i'||T_1)$ using transmitted values SID_j, A, and T_1.

Step 4: The adversary calculates $M_1' = e_i' \oplus (ID^*||SID_j||M_2')$.

Step 5: The adversary compares the calculated value M_1' with the transmitted value M_1 to check the correctness of ID^*.

Step 6: If M_1' and stored value M_1 are same, adversary's guess results as successful. Otherwise, the adversary returns to Steps 1 and repeats until adversary correctly gets ID for the user.

D. USER IMPERSONATION ATTACK

If a malicious adversary can guess a user's identity according to V-C. The adversary can masquerade the user. The adversary extracts the value k_i stored in the smartcard and obtains transmitted values A and T_1. Then, the adversary can compute $M_{2_a} = h(A||ID_i||SID_j||d_i||T_1)$ and also the adversary can compute $M_{1_a} = e_i \oplus (ID_i||SID_j||M_{2_a})$ wherein $e_i' = M_6 \oplus (e_{inew}||k_3||M_7)$ where M_6 is obtained through channels. Thus, the adversary can impersonate the validate user.

E. REPLAY ATTACK

A malicious adversary attempts to impersonate a valid gateway for obtaining sensitive values of systems. At Chen *et al.*'s protocol, the adversary is able to generate a legitimate gateway's message by computed correct values.

Step 1: At a registration phase of sensors, an adversary chooses a sensor identity SID_j. Then, the adversary can obtain a legitimate $x_j = h(SID_j||X_{GWN})$.

Step 2: The adversary can compute $M_3 = h(A||SID_j'|| x_j'||T_2)$ in a login and authentication phase.

Step 3: Finally, the adversary can generate a legitimate message $< A, M_3, T_2 >$.

In conclusion, the adversary can generate a legitimate message to treat a sensor node.

And also, the adversary can conduct the man-in-the-middle attack. The adversary chooses a random nonce k_a then the adversary computes $A_a = k_a \cdot G$.

F. MUTUAL AUTHENTICATION

According to Sections V-C and V-D, an adversary can masquerade a valid user and also can compute a valid login request message. Therefore, Chen *et al.*'s protocol cannot provide secure mutual authentication.

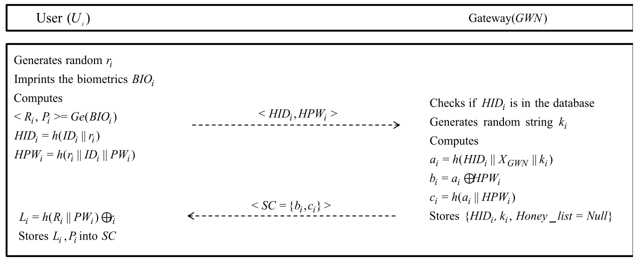

FIGURE 4. The user registration phase of proposed protocol.

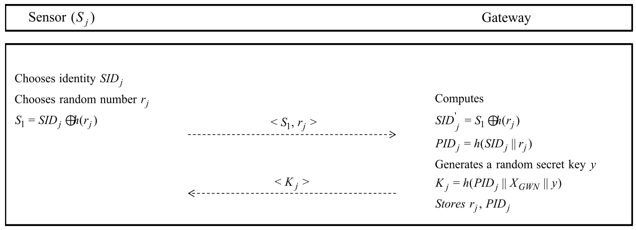

FIGURE 5. The sensor registration phase of the proposed protocol.

VI. PROPOSED PROTOCOL

To provide secure wireless IoT service via WSNs, we propose an authentication protocol based on three-factor with the biometrics. And also, our protocol uses "honey_ list" and "Fuzzy-extractor" techniques to maintain security even if two of the three factors are damaged by an malicious adversary. Before beginning of the registration phase, a gateway generates a secret key X_{GWN}.

A. REGISTRATION PHASE OF USERS AND SENSORS

To access WSNs service, an user U_i and a sensor S_j have to register with gateway. Figures 4 and 5 show the registration phase of users and sensors with detailed equations and steps as following.

- Registration phase of users: An user U_i selects unique ID_i and PW_i and U_i imprints the biometrics BIO_i. After that U_i randomly generates a nonce r_i. U_i calculates $< R_i, P_i >= Ge(BIO_i)$, $HID_i = h(ID_i||r_i)$ and $HPW_i = h(r_i||ID_i||PW_i)$ and transmits a registration request message $\{HID_i, HPW_i\}$ to a gateway GWN via a secure channel. The secure channel guarantees security against attacks. After receiving message $\{HID_i, HPW_i\}$, GWN checks that the HID_i is already registered in the database. If it is not, GWN generates a random string k_i and computes $a_i = h(HID_i||X_{GWN}||k_i)$, $b_i = a_i \oplus HPW_i$ and $c_i = h(a_i||HPW_i)$. After that, GWN stores HID_i with k_i and HPW_i and stores values $\{b_i, c_i\}$ into a smartcard SC. Then, it issues SC to the user. At last, U_i calculates $L_i = h(R_i||PW_i)$ and stores $\{L_i, P_i\}$ into the SC. The Figure 4 describes this phase.
- Registration phase of sensors: A sensor S_j chooses a its identity SID_j and a random nonce r_j. S_j computes $S_1 = SID_j \oplus h(r_j)$ sends S_1 and r_j to the gateway node GWN. After GWN receives registration request message, GWN computes $SID_j' = S_1 \oplus h(r_j)$ and $PID_j = h(SID_j||r_j)$. After that, GWN generates a random secret key y and

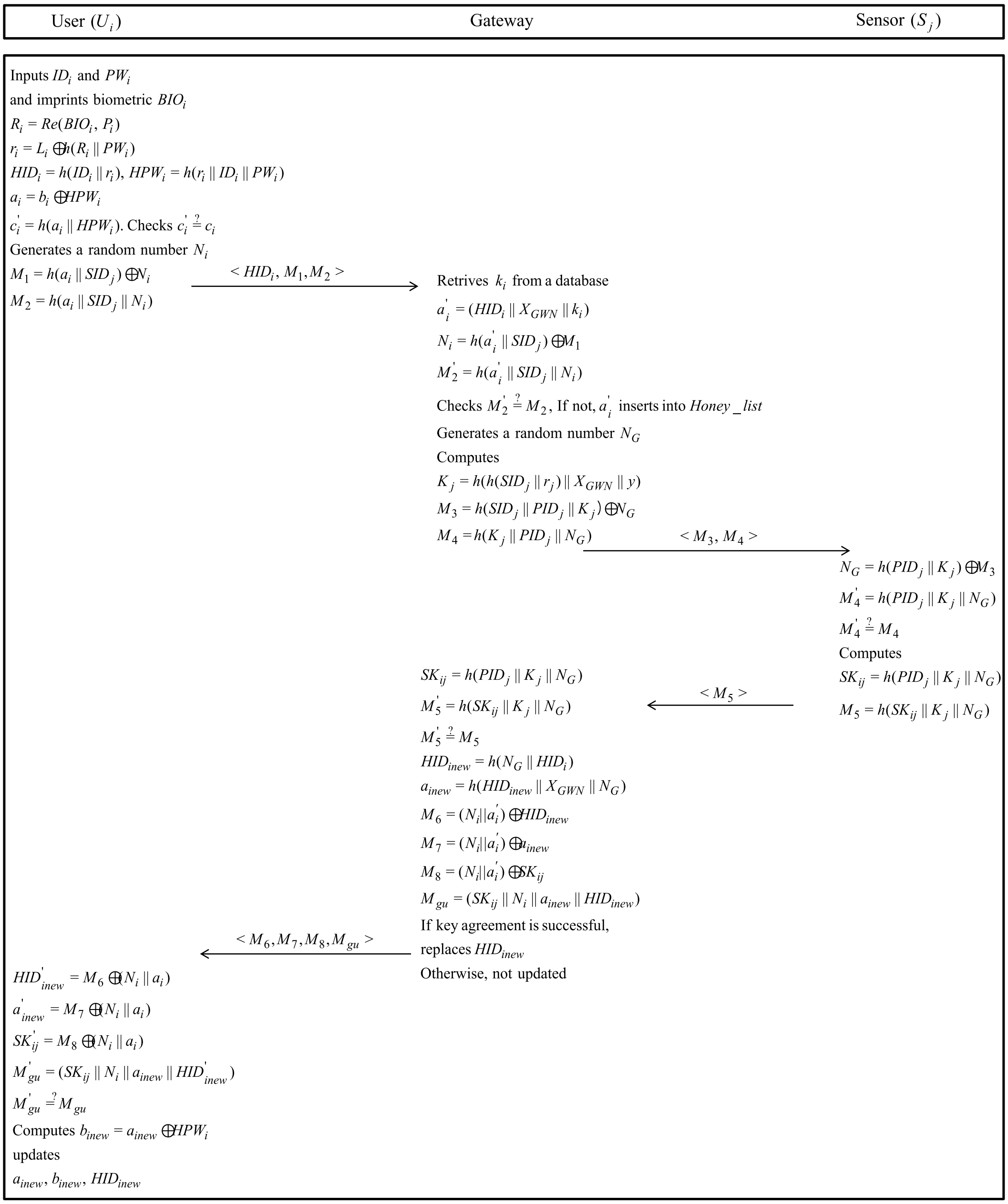

FIGURE 6. Login and authentication phase of the proposed protocol.

computes $K_j = h(PID_j||X_{GWN}||y)$ and stores r_j, PID_j in its private memory. Then, GWN sends K_j to the sensor. Figure 5 describes detailed steps.

B. LOGIN AND AUTHENTICATION PHASE

Users have to login and authenticate with the gateway and sensors to access information of sensors. Figure 6 shows the detailed steps of login and authentication phase. We also describe the detailed equations of login and authentication phase.

Step 1: User U_i inputs his/her unique identity ID_i and password PW_i and imprints a biometric BIO_i Then, U_i calculates $R_i = Re(BIO_i, P_i)$, $r_i = L_i \oplus h(R_i||PW_i)$, $HID_i = h(ID_i||r_i)$ and $HPW_i = h(r_i||ID_i||PW_i)$. U_i extracts $a_i = b_i \oplus HPW_i$ and computes $c_i' = h(a_i||HPW_i)$. And then, U_i computes $c_i' = h(a_i||HPW_i)$ and verifies whether c_i' and c_i are equal or not. If they are equal, U_i generates a random number N_i and computes $M_1 = h(a_i\,||SID_j)$ $\oplus N_i$ and $M_2 = h(a_i||SID_j||N_i)$. After that, U_i sends a login request message $< HID_i, M_i, M_2 >$ to a gateway node GWN.

Step 2: After GWN receives the login request message, GWN retrieves k_i from a database and computes $a_i' = (HID_i||X_{GWN}||k_i)$, $N_i = h(a_i'||SID_j) \oplus M_1$ and $M_2' = h(a_i||SID_j||N_i)$. GWN checks $M_2 \stackrel{?}{=} M_2'$.

If it is not equal, a_i' inserts into *Honey_list* or suspends the identify when the items in the *Honey_list* exceed a certain threshold. Otherwise, GWN computes $K_j = h(h(SID_j||r_j)||X_{GWN}||y)$, $M_3 = h(SID_j||PID_j||K_j) \oplus N_G$ and $M_4 = h(K_j||PID_j||N_G)$. Then, GWN sends $< M_3, M_4 >$ to a sensor node S_j.

Step 3: S_j computes $N_G = h(PID_j||K_j) \oplus M_3$, $M_4' = h(PID_j||K_j||N_G)$. S_j checks validation to compare M_4 with M_4'. If they are the same, S_j randomly generates a nonce N_j and calculates $SK_{ij} = h(PID_j||K_j||N_G)$ and $M_5 = h(SK_{ij}||K_j||N_G)$. Then, S_j sends $< M_5 >$ to GWN.

Step 4: After that, GWN calculates $SK_{ij} = h(PID_j||K_j||N_G)$ and $M_5' = h(SK_{ij}||K_j||N_G)$. GWN checks $M_5 \stackrel{?}{=} M_5'$. If it is equal, GWN computes $HID_{inew} = h(N_G||HID_i)$, $a_{inew} = h(HID_{inew}||X_{GWN}||N_G)$, $M_6 = (N_i\ ||a_i') \oplus HID_{inew}$, $M_7 = (N_i\ ||a_i') \oplus a_{inew}$, $M_8 = (N_i\ ||a_i') \oplus SK_{ij}$ and $M_{gu} = (SK_{ij}\ ||N_i\ ||a_{inew}\ ||HID_{inew})$. Then, GWN sends $< M_6, M_7, M_8, M_{gu} >$ to U_i. If session key agreement is successful, GWN updates HID_i to HID_{inew}. Otherwise, GWN keeps to store HID_i.

Step 5: U_i computes $HID_{inew}' = M_6 \oplus (N_i||a_i)$, $a_{inew}' = M_7 \oplus (N_i||a_i)$, $SK_{ij}' = M_8 \oplus (N_i||a_i)$ and $M_{gu}' = (SK_{ij}||N_i||a_{inew}||HID_{inew})$. U_i verifies whether M_{gu}' and M_{gu} are same value or not. If they are same value, U_i computes $b_{inew} = a_{inew} \oplus HPW_i$ and $c_{inew} = h(a_{inew}||HPW_i)$ and updates $a_{inew}, b_{inew}, c_{inew}$ and HID_{inew}. Finally, U_i, GWN and S_j authenticate each other and have the same session key.

C. PASSWORD CHANGE PHASE

If U_i wishes to change a password, U_i conducts the password change phase without the gateway's assistance. The detailed steps of the password change phase are as following.

Step 1: U_i imprints biometrics BIO_i and inputs his/her identity and password. And U_i sends ID_i, PW_i,and BIO_i to the smartcard.

Step 2: The smartcard calculates $< R_i, P_i >= Ge(BIO_i)$, $r_i = L_i \oplus h(R_i||PW_i)$ and $HPW_i = h(r_i||ID_i||PW_i)$ and $c_i^* = h(a_i||HPW_i)$. Then, smartcard makes a comparison between c_i^* and c_i stored value in the smartcard. If they are same values, the smartcard asks the user to supply a new password.

Step 3: The user enters a new password PW_i^{new} and sends it to the smartcard. Then, smartcard computes $HPW_i^{new} = h(r_i||ID_i||PW_i^{new})$, $L_i^{new} = h(R_i||PW_i^{new}) \oplus r_i$, $b_i^{new} = a_i \oplus HPW_i^{new}$ and $c_i^{new} = h(a_i||HPW_i^{new})$. After all computing, the smartcard updates $\{L_i^{new}, b_i^{new}, c_i^{new}\}$.

VII. SECURITY ANALYSIS OF THE PROPOSED PROTOCOL

This section shows that the suggested protocol has security to variable malicious attacks. And also, it shows that our protocol has a secure mutual authentication with key agreement by adopting BAN logic. Besides, we demonstrate that our proposed authentication protocol is secure to guessing attack, man-in-the-middle attack and replay attack employing ROR model and AVISPA.

A. INFORMAL SECURITY ANALYSIS

We describe how our protocol achieves security features in this section. And also, we demonstrate that our proposed authentication protocol can ensure safety session key agreement and mutual authentication.

1) OFF-LINE GUESSING ATTACK

If a user selects a password which is easy to guess, a malicious adversary is able to conjecture the user's ID_i and PW_i in real polynomial time. Nevertheless, in our authentication protocol, the adversary cannot conjecture user's ID_i and PW_i. The adversary can extract values $\{b_i, c_i, L_i, P_i\}$ stored in a smartcard through the power analysis attack. Then, the adversary can attempt to guess the legitimate user's ID_i and PW_i. b_i and c_i are masked with a_i and HPW_i. And also, a_i is masked with X_{GWN} and k_i. Therefore, the adversary cannot retrieve user's identity and password from b_i, c_i. Furthermore, if the adversary attempts to simultaneously guess identity and password, the adversary cannot guess them because of masking with user's biometric. Meanwhile, the honey_list can prevent to the times in off-line password guessing attack. In conclusion, our authentication protocol is secure to off-line guessing attack.

2) USER/SENSOR ANONYMITY

An adversary wants to obtain user's real identity for performing the tracing attack. In proposed authentication protocol, a true identity ID_i and SID_j of user and sensor are encrypted by a random number r_i and r_j. Meanwhile, HID_i is updated to HID_{inew} by GWN because HID_i is transmitted through a public channels. Therefore, the adversary cannot know the user's original ID_i and sensor's original identity SID_j.

3) FORGERY ATTACK

In our proposed protocol, all transmitted messages are concatenated with the random nonces N_i and N_G, and the secret parameters a_i and K_j. The messages are also encapsulated by the one-way collision-resistant cryptographic hash function. It is then impossible to compute correct messages M_1 and M_2 without a_i on the user side. Moreover, a_i consists of X_{GWN} and k_i which are unknown to the adversary. On the gateway side, M_3, M_4, M_6, M_7, M_8 and M_{gu} consist of a_i, N_i, N_G, PID_j and K_j which are unknown to the adversary. On the sensor side, M_5 is also masked with K_j and N_G. Therefore, our protocol is secure against forgery attack.

4) IMPERSONATION ATTACK

The impersonation attack is a particular case of forgery attack. As an adversary tries to impersonate each entity, the adversary has to compute legitimate messages. In the proposed protocol, transmitted messages over public channels are encrypted with random secrets N_i and N_G. The adversary tries to extract random numbers but the adversary cannot extract them. Meanwhile, M_3 is encrypted by K_j and PID_j. K_j and PID_j which are masked with random number r_j and secret keys X_{GWN}, y. In this way, the proposed protocol can be secure to impersonation attack.

5) DESYNCHRONIZATION ATTACK

Assuming a user does not receive the message $< M_6, M_7, M_8, M_{gu} >$ from a gateway because of attacks of adversary or unexpected termination, the adversary can perform the desychronization attack. However, the adversary cannot perform desychronization attack because the user checks whether M'_{gu} and M_{gu} are same or not. If it is not same, the session is terminated. Moreover, the gateway does not update HID_{inew} when the session is terminated. In conclusion, the proposed authentication protocol prevents to desynchronization attack.

6) SESSION KEY DISCLOSURE ATTACK

An adversary must know K_j and N_G to compute a valid session key SK_{ij}. But, K_j is encrypted with the gateway's master key X_{GWN}, secret key y and random number r_j. The adversary cannot extract a random nonce N_G. The adversary can also capture the message M_8 to compute SK_{ij}. However, the adversary does not know the correct random nonce N_i. Therefore, we can say that our proposed protocol can resist against session key disclosure attack.

7) TRACE ATTACK

In our proposed protocol, the user's real identity is hidden by HID_i. Moreover, HID_i is updated to HID_{inew} by GWN to protect against adversary's guessing. And all transmitted messages are changed in all each session because the messages include random numbers are changed in each session. Thus, the proposed protocol resists trace attack.

8) PRIVILEGED-INSIDER ATTACK

We assume that a user is privileged-insider attacker. Then, the privileged-insider attacker knows the registration information HID_i, HPW_i of a legitimate U_i over registration phase. Then, the attacker performs the power analysis attack for extracting stores values from a smartcard $\{b_i, c_i, L_i, P_i\}$. However, the attacker cannot guess correctly user's identity ID_i and password PW_i without having the biometric secret key R_i because of computationally expensive. In concluding, our authentication protocol can prevent privileged-insider attack.

9) SESSION SPECIFIC RANDOM NUMBER LEAKAGE ATTACK

In the proposed protocol, U_i and GWN generate session specific random numbers N_i and N_G. Even if N_i and N_G are compromised to the adversary, he/she cannot obtain sensitive information. At the login and authentication phase, M_1, M_6, M_7 and M_8 are masked with a_i. The secret parameter a_i consists of k_i and X_{GWN} which are unknown to the adversary. M_4 and M_5 are also masked with K_j, PID_j and SK_{ij}. The adversary cannot compute K_j, PID_j and SK_{ij} because they consist of r_j, X_{GWN} and y. Therefore, our proposed protocol prevents session specific random number leakage attack.

10) STOLEN VERIFIER ATTACK

The adversary can steal a legal registered user's information from the GWN and S_j. However, HID_i is updated to HID_{inew} for every session. Even if HID_i and k_i are compromised to the adversary, he/she cannot obtain entities' information. This is because the parameters including HID_i are masked with the gateway node's secret key X_{GWN}. If the adversary steals r_j and PID_j through stolen verifier attack, the adversary cannot still compute K_j and SK_{ij} as they are masked with X_{GWN}, y and N_G. Therefore, the proposed protocol can resist against stolen verifier attack.

11) MAN-IN-THE-MIDDLE ATTACK AND REPLAY ATTACK

We assume that the adversary can learn transmitted messages via open channel. However, the adversary cannot compute a valid login request message as mentioned at Section VII-A4. Moreover, the adversary cannot impersonate a legal registered user because the messages are refreshed in every session with random numbers N_i and N_G. In conclusion, our authentication protocol is secure to man-in-the middle and replay attacks.

12) DENIAL-OF-SERVICE (DoS) ATTACK

The adversary can conduct DoS attack for blocking to user's access for service. If the adversary intercepts the message $< M_6, M_7, M_8, M_{gu} >$ and replaces with $< M_6, M_7, M_8, M'_{gu} >$, where $M'_{gu} = M_{gu} \oplus N_a$ and N_a is a produced nonce by the adversary. However, our proposed protocol checks whether $M_{gu} \stackrel{?}{=} M'_{gu}$. Moreover, our proposed protocol can prevent desynchronization attack as Section VII-A5. Therefore, we can say our proposed protocol can prevent DoS attack.

13) KEY AGREEMENT AND MUTUAL AUTHENTICATION

All transmitted messages by each entity are authenticated through verification $M_2 \stackrel{?}{=} M'_2$, $M_4 \stackrel{?}{=} M'_4$, $M_5 \stackrel{?}{=} M'_5$ and $M_{gu} \stackrel{?}{=} M'_{gu}$. Moreover, Section VII-A7 shows that all transmitted messages are changed. All entities have authenticated each other, they compute the same session key. Thus, we can say our proposed authentication protocol can achieve secure key agreement and mutual authentication.

B. SECURITY ANALYSIS USING BAN LOGIC

This paper provides the proof which shows that the proposed protocol can provide mutual authentication by performing the BAN logic [41]. We describe basic notations of the BAN logic in the Table 2, and also illustrate logical rules, goals, assumptions and idealized forms. Then, we conduct the BAN logic to confirm the mutual authentication of our proposed protocol.

TABLE 2. The basic BAN logic notations.

Notations	Meaning
SK	The used session key in current authentication session
$\#S$	The statement S is **fresh**
$\sigma\mid\equiv S$	σ **believes** the statement S
$\sigma \lhd S$	σ **sees** the statement S
$\sigma\mid\sim S$	σ once **said** S
$< S >_F$	Formula S is **united** with formula F
$\{S\}_{Key}$	Encrypt the formula S **encrypted** the key Key
$\sigma \Rightarrow S$	σ **controls** the statement S
$\sigma \overset{Key}{\leftrightarrow} \omega$	σ and ω uses Key as **shared key** for communicating

1) LOGICAL RULES OF BAN LOGIC

The Logical rules of the BAN logic are:

1. Jurisdiction rule:

$$\frac{\sigma \mid\equiv \omega \mid\Longrightarrow S, \quad \sigma \mid\equiv \omega \mid\equiv S}{\sigma \mid\equiv S}$$

2. Nonce verification rule:

$$\frac{\sigma \mid\equiv \#(S), \quad \sigma \mid\equiv \omega \mid\sim S}{\sigma \mid\equiv \omega \mid\equiv S}$$

3. Message meaning rule:

$$\frac{\sigma \mid\equiv \sigma \overset{K}{\leftrightarrow} \omega, \quad \sigma \lhd \{S\}_K}{\sigma \mid\equiv B \mid\sim S}$$

4. Belief rule:

$$\frac{\sigma \mid\equiv (S, F)}{\sigma \mid\equiv S}$$

5. Freshness rule:

$$\frac{\sigma \mid\equiv \#(S)}{\sigma \mid\equiv \#(S, F)}$$

2) GOALS

The following goals are presented to demonstrate that the proposed protocol achieves secure mutual authentication:

Goal 1: $GWN| \equiv U_i| \equiv (N_i)$,

Goal 2: $GWN| \equiv (N_i)$,

Goal 3: $S_j| \equiv GWN| \equiv (N_G)$,

Goal 4: $S_j| \equiv (N_G)$,

Goal 5: $GWN| \equiv S_j| \equiv S_j \xleftrightarrow{SK_{ij}} GWN$,

Goal 6: $GWN| \equiv S_j \xleftrightarrow{SK_{ij}} GWN$,

Goal 7: $U_i| \equiv GWN| \equiv U_i \xleftrightarrow{SK_{ij}} GWN$,

Goal 8: $U_i| \equiv U_i \xleftrightarrow{SK_{ij}} GWN$.

3) IDEALIZED FORMS

The idealized forms are:

$M_1: \quad U_i \rightarrow GWN : (HID_i, SID_j, N_i)_{a_i}$

$M_2: \quad GWN \rightarrow S_j : (SID_j, PID_j, N_G)_{K_j}$

$M_3: \quad S_j \rightarrow GWN : (PID_j, N_G, K_j)_{X_{GWN}}$

$M_4: \quad GWN \rightarrow U_i : (HID_{inew}, a_{inew}, SK_{ij})_{N_i}$

4) ASSUMPTIONS

The following assumptions are generated for the initial state of the proposed protocol to achieve the BAN logic proof.

$A_1: \quad GWN| \equiv (U_i \xleftrightarrow{a_i} GWN)$

$A_2: \quad GWN| \equiv \#(N_i)$

$A_3: \quad S_j| \equiv (GWN \xleftrightarrow{K_j} S_j)$

$A_4: \quad S_j| \equiv \#(N_G)$

$A_5: \quad GWN| \equiv (S_j \xleftrightarrow{X_{GWN}} GWN)$

$A_6: \quad GWN| \equiv \#(K_j)$

$A_7: \quad U_i| \equiv (U_i \xleftrightarrow{N_i} GWN)$

$A_8: \quad U_i| \equiv \#(HID_{inew})$

$A_9: \quad GWN| \equiv U_i \Rightarrow (GWN \xleftrightarrow{a_i} U_i)$

$A_{10}: \quad S_j| \equiv GWN \Rightarrow (S_j \xleftrightarrow{K_j} GWN)$

$A_{11}: \quad GWN| \equiv S_j \Rightarrow (S_j \xleftrightarrow{SK_{ij}} GWN)$

$A_{12}: \quad U_i| \equiv GWN \Rightarrow (U_i \xleftrightarrow{SK_{ij}} GWN)$

5) PROOF USING BAN LOGIC

Main proofs using rules and assumptions of the BAN logic are as the following steps:

Step 1: S_1 can be obtained from M_1

$$S_1: GWN \lhd (SID_j, HID_i, N_i)_{a_i}.$$

Step 2: For obtaining S_2, we apply the message meaning rule with A_1

$$S_2: GWN| \equiv U_i| \sim (SID_j, HID_i, N_i).$$

Step 3: For obtaining S_3, we apply the freshness rule with A_2

$$S_3: GWN| \equiv \#(SID_j, HID_i, N_i).$$

Step 4: For obtaining S_4, we apply the nonce verification rule with S_2 and S_3

$$S_4: GWN| \equiv U_i \equiv (SID_j, HID_i, N_i).$$

Step 5: For obtaining S_5, we apply the belief rule

S_5: $GWN| \equiv U_i| \equiv (N_i)$. **(Goal 1)**

Step 6: S_6 can be obtained from M_2

S_6: $S_j \lhd (SID_j, PID_j, N_G)_{K_j}$.

Step 7: For obtaining S_7, we apply the message meaning rule with A_3

S_7: $S_j| \equiv GWN| \sim (SID_j, PID_j, N_G)$.

Step 8: For obtaining S_8, we apply the freshness rule with A_4

S_8: $S_j| \equiv \#(SID_j, PID_j, N_G)$.

Step 9: For obtaining S_4, we apply the nonce verification rule with S_7 and S_8

S_9: $S_j| \equiv GWN| \equiv (SID_j, PID_j, N_G)$.

Step 10: For obtaining S_{10}, we apply the belief rule

S_{10}: $S_j| \equiv GWN| \equiv (N_G)$. **(Goal 3)**

Step 11: S_{11} can be obtained from M_3

S_{11}: $GWN \lhd (PID_j, N_G, K_j)_{X_{GWN}}$.

Step 12: For obtaining S_{12}, we apply the message meaning rule with S_{11} and A_5

S_{12}: $GWN| \equiv S_j| \sim (PID_j, N_G, K_j)$.

Step 13: For obtaining S_{13}, we apply the freshness rule with A_6

S_{13}: $GWN| \equiv \#(PID_j, N_G, K_j)$.

Step 14: For obtaining S_{14}, we apply the nonce verification rule with S_{12} and S_{13}

S_{14}: $GWN| \equiv S_j| \equiv (PID_j, N_G, K_j)$.

Step 15: Since the session key $SK_{ij} = h(PID_j||K_j||N_G)$, from S_{14},

S_{15}:$GWN| \equiv S_j| \equiv S_j \overset{SK_{ij}}{\longleftrightarrow} GWN$. **(Goal 5)**

Step 16: S_{16} can be obtained from M_4

S_{16}: $U_i \lhd (HID_{inew}, a_{inew}, SK_{ij})_{X_{GWN}}$.

Step 17: For obtaining S_{17}, we apply the message meaning rule with S_{16} and A_7

S_{17}: $U_i| \equiv GWN| \sim (HID_{inew}, a_{inew}, SK_{ij})_{X_{GWN}}$.

Step 18: For obtaining S_{18}, we apply the freshness rule with S_{17} and A_8

S_{18}: $U_i| \equiv \#(HID_{inew}, a_{inew}, SK_{ij})$.

Step 19: For obtaining S_{19}, we apply the nonce verification rule with S_{17} and S_{18}

S_{19}: $U_i| \equiv GWN| \equiv (HID_{inew}, a_{inew}, SK_{ij})$.

Step 20: For obtaining S_{20}, we apply the belief rule

S_{20}: $U_i| \equiv GWN| \equiv (SK_{ij})$.

Step 21: From S_{20}, we can obtain S_{21}

S_{21}: $U_i| \equiv GWN| \equiv U_i \overset{SK_{ij}}{\longleftrightarrow} GWN$. **(Goal 7)**

Step 22: We apply the jurisdiction rule with S_5 and A_9 to obtain

S_{22}: $GWN| \equiv (N_i)$. **(Goal 2)**

Step 23: We apply the jurisdiction rule with S_{10} and A_{10} to obtain

S_{23}: $S_j| \equiv (N_G)$. **(Goal 4)**

Step 24: We apply the jurisdiction rule with S_{15} and A_{11} to obtain

S_{23}: $GWN| \equiv S_j \overset{SK_{ij}}{\longleftrightarrow} GWN$. **(Goal 6)**

Step 23: We apply the jurisdiction rule with S_{21} and A_{12} to obtain

S_{23}: $U_i| \equiv U_i \overset{SK_{ij}}{\longleftrightarrow} GWN$. **(Goal 8)**

C. FORMAL SECURITY VERIFICATION USING AVISPA SIMULATION

This section shows that our proposed protocol can be secure to man-in-the-middle and replay attacks by being universally adopted Automated Validation of Internet Security Protocols and Applications (AVISPA) simulation tool [42], [43]. The AVISPA simulation tool uses High-Level Protocol Specification Language (HLPSL) [44] to check if protocols are secure. The HLPSL inputs to one of four back-end models which are "On-the-Fly Model Checker (OFMC) [45]", "Constraint Logic-based Attack Searcher (CL-AtSE)" [46], "Tree automata based on Automatic Approximations for Analysis of Security Protocol (TA4SP)", and "SAT-based Model Checker (SATMC)". This input is converted to a format called "Intermediate Format (IF)", and output in a format called "Output format (OF)". The OF shows security analysis results of protocols. We provide similar simulation results as adopted in [47]–[49]. Figs. 7, 8 and 9 each describe *role* of user, gateway and sensor nodes. And the Figure 10 shows goals and environment of our proposed protocol. Then, according to goals, the results is shown in Fig 11. In CL-AtSe, the translation time has 0.09 seconds. And search time is 7.89 seconds for visiting 1,040 nodes in OFMC analysis. Two of the results all show that the proposed protocol is safe. Therefore, the proposed protocol can be secure to man-in-the-middle and replay attacks.

D. FORMAL SECURITY ANALYSIS UNDER ROR MODEL

We adopt the ROR model [50] to illustrate the semantic security of our suggested authentication protocol. This section demonstrates that our proposed protocol can achieve the session key security by employing the ROR model. We shortly describe the ROR model and present the proof of the session key security of protocol in Theorem 1. In this model, the proposed protocol has three participants $\mathcal{P}^t$, which are user $\mathcal{P}^{t_1}_{U_i}$, gateway $\mathcal{P}^{t_2}_{GWN}$ and sensor $\mathcal{P}^{t_3}_{S_j}$. And each participants have t^{th} denotes an instance of an executing participant. We assume that $\mathcal{P}^{t_1}_{U_i}$, $\mathcal{P}^{t_2}_{GWN}$ and $\mathcal{P}^{t_3}_{S_j}$ are instances t_1^{th} of the user, t_2^{th} of the gateway and t_3^{th} of the sensor, respectively. Moreover, we assume that an adversary $\mathcal{A}$ can modify, eliminate or insert or learn transmitted messages during the communication. Under the ROR model, the model defines various queries simulating a real attack like *Execute*, *CorruptSC*, *Reveal*, *Send* and *Test* queries. The detailed description of queries is as follows.

- *Execute*$(\mathcal{P}^{t_1}_{U_i}, \mathcal{P}^{t_2}_{GWN}, \mathcal{P}^{t_3}_{S_j})$: $\mathcal{A}$ performs this query to eavesdrop exchanged messages between wireless

```
%%%%%%%%%%%%user%%%%%%%%%%%%
role user(UA, GA, SA : agent, SKuaga : symmetric_key, H: hash_func,
SND, RCV : channel(dy))

played_by UA
def=
local State: nat,
   IDi, PWi, HIDi, HPWi, Ri, Pi, BIOi, Rii, Ki, Xgwn, Ai, Bi, Ci, Li,
SIDj, Y : text,
   S1, Ni, Ng, M1, M2, SKij, HIDinew, Rj, Kj, PIDj, Ainew, M3, M4,
M5, M6, M7, M8, Mgu: text
const sp1, sp2, sp3, sp4, sp5, ua_ga_ni, ga_sa_ng, ga_ua_ng, sa_ga_ng:
protocol_id
init State := 0
transition
%%%%%%%%%%%%Registration phase
1. State = 0 ∧ RCV(start) =|>
State' := 1 ∧ Ri' := new()
      ∧ HIDi' := H(IDi.Ri')  ∧ HPWi' := H(Ri'.IDi.PWi)
      ∧ SND({HIDi'.HPWi'}_SKuaga)
      ∧ secret({PWi}, sp1, {UA}) ∧ secret({HPWi'}, sp2, {UA,GA})
%%%%%%%%%%%%Recieve smartcard
2. State = 1 ∧ RCV
({xor(H(H(IDi.Ri'),Xgwn.Ki').H(Ri'.IDi.PWi)).H(H(H(IDi.Ri').Xgwn.Ki'
).H(Ri'.IDi.PWi))}_SKuaga)=|>
 State' := 2 ∧ Rii' := new() ∧ Pi' := new() ∧ Li':= xor(H(Rii'.PWi),Ri')
%%%%%%%%%%%%Login & Authentication phase
      ∧ Ni' := new()  ∧ M1' := xor(H(H(IDi.Ri').Xgwn.Ki'),Ni')
      ∧ M2' := H(H(H(IDi.Ri').Xgwn.Ki').SIDj.Ni')
      ∧ SND(M1'.M2'.H(IDi.Ri'))
      ∧ witness(UA,GA,ua_ga_ni,Ni')
3. State = 2 ∧ RCV(xor(Ni',H(Ng'.H(IDi.Ri'))).xor(Ni',
H(HIDinew'.Xgwn.Ng')).xor(Ni',
H(H(SIDj'.Rj').H(H(SIDj.Rj').Xgwn.Y').Ng')).(H(H(SIDj'.Rj').H(H(SIDj.
Rj').Xgwn.Y').Ng').Ni'.H(HIDinew'.Xgwn.Ng'))) =|>
State' := 3 ∧ SKij' :=  H(H(SIDj.Rj').H(H(SIDj.Rj').Xgwn.Y').Ng')
        ∧ request(GA,UA,ga_ua_ng,Ng')
end role
```

FIGURE 7. ***Role*** **of user.**

```
%%%%%%%%%%%%Gateway%%%%%%%%%%%%%
role gateway(UA, GA, SA : agent, SKuaga, SKsaga : symmetric_key, H:
hash_func, SND, RCV : channel(dy))
played_by GA
def=
local State: nat,
   IDi, PWi, HIDi, HPWi, Ri, Pi, BIOi, Rii, Ki, Xgwn, Ai, Bi, Ci, Li,
SIDj, Y : text,
   S1, Ni, Ng, M1, M2, SKij, HIDinew, Rj, Kj, PIDj, Ainew, M3, M4,
M5, M6, M7, M8, Mgu  : text
const sp1, sp2, sp3, sp4, sp5, ua_ga_ni, ga_sa_ng, ga_ua_ng, sa_ga_ng:
protocol_id
init State := 0
transition
1. State = 0 ∧ RCV({H(IDi.Ri').H(Ri'.IDi.PWi)}_SKuaga) =|>
 State' := 1 ∧ Ki' := new() ∧ Ai' := H(H(IDi.Ri').Xgwn.Ki')
       ∧ Bi' := xor(Ai',H(Ri'.IDi.PWi))  ∧ Ci' := H(Ai'.H(Ri'.IDi.PWi))
       ∧ SND({Bi'.Ci'}_SKuaga)
       ∧ secret({Xgwn,Ki},sp3,{GA})
2.State = 1 ∧ RCV({xor(SIDj,H(Rj')).Rj'}_SKsaga) =|>
State' := 2 ∧ PIDj' := H(SIDj.Rj')
        ∧ Y' := new()  ∧ Kj' := H(PIDj'.Xgwn.Y')
        ∧ SND({PIDj'.Kj'}_SKsaga)
        ∧ secret({Y'},sp4,{GA})   ∧ secret({Rj', Kj'},sp5,{SA,GA})
3. State = 2
∧ RCV(H(IDi.Ri').xor(H(H(IDi.Ri').Xgwn.Ki'),Ni').H(H(H(IDi.Ri').Xgw
n.Ki').SIDj.Ni')) =|>
State' := 3  ∧ Ng' := new() ∧ Y' := new() ∧ Rj' := new()
       ∧ Kj' := H(H(SIDj.Rj').Xgwn.Y')  ∧ M3' := H(SIDj.H(SIDj.Rj'))
       ∧ M4' := H(H(H(SIDj.Rj').Xgwn.Y').H(SIDj.Rj').Ng')
       ∧ SND(M3'.M4')
       ∧ witness(GA, SA, ga_sa_ng, Ng')
       ∧ request(UA, GA, ua_ga_ni,Ni')
4. State = 3
∧ RCV(H(H(H(SIDj'.Rj').H(H(SIDj.Rj').Xgwn.Y').Ng').H(H(SIDj.Rj').X
gwn.Y').Ng')) =|>
State' := 4 ∧ SKij' :=  H(H(SIDj.Rj').H(H(SIDj.Rj').Xgwn.Y').Ng')
       ∧ HIDinew' := H(Ng'.H(IDi.Ri'))
       ∧ Ainew' := H(HIDinew'.Xgwn.Ng')
       ∧ Ni' := new() ∧ Ri' := new()    ∧ M6' := xor(Ni',HIDinew')
       ∧ M7' := xor(Ni', Ainew')    ∧ M8' := xor(Ni', SKij')
       ∧ Mgu' := (SKij'.Ni'.Ainew')   ∧ SND(M6'.M7'.M8'.Mgu')
       ∧ witness(GA, UA, ga_ua_ng, Ng')
         ∧ request(SA, GA, sa_ga_ng,Ng')
end role
```

FIGURE 8. ***Role*** **of gateway.**

communicating entities U_i, GWN and S_j over public channels.

- *CorruptSC*: $\mathcal{A}$ can extract all stored sensitive parameters from the smartcard of the user to use the *CorruptSC* query.
- $Reveal(\mathcal{P}^t)$: $\mathcal{A}$ can reveal the session key SK_{ij}/SK_a between $\mathcal{P}^t$ and its partner in the current session.
- $Send(\mathcal{P}^t, M)$: This query is modeled as an active attack. $\mathcal{A}$ can transmit a message M to $\mathcal{P}^t$ and can also reply to the message accordingly.
- $Test(\mathcal{P}^t)$: This query corresponds to the security of the session key among with U_i, GWN and S_j following the ROR model. Before the game starts, a coin c without prejudice is flipped. According to the coin result, the following decision is made, Assume that $\mathcal{A}$ executes *Test* and the session key SK_{ij} and $SK_a$is fresh, $\mathcal{P}^t$ returns the session key for $c = 1$ or a random number if $c = 0$. Otherwise, it returns a null value ($\perp$).

Moreover, all communicating participants and $\mathcal{A}$ can access a collision-resistant hash function $h(\cdot)$ that is modeled as a random oracle, say *Hash*.

Wang *et al.* [25] demonstrated that the chosen passwords by users conform with the Zipf's law, which differs significantly from uniform distribution. We apply the Zipf's law for the formal analysis to prove the session key security. We show the detailed Theorem 1 is as in the following.

Theorem 1: We define the advantage probability of an adversary $\mathcal{A}$ running in polynomial time who can break the session key security of the proposed authentication protocol as $Adv_{\mathcal{A}}$. Then,

$$Adv_{\mathcal{A}} \leq \frac{q_h^2}{|Hash|} + 2\max\{C' \cdot q_{send}^{s'}, \frac{q_{send}}{2^{l_R}}\}$$

where q_h, q_{send} and $|Hash|$ mean "the amount of Hash queries, the amount of Send queries and the range space of the hash function", respectively, C' and s' mean the Zipf's parameters, and l_R is the number of bits in the biometric secret key b_i of U_i.

Proof: We provide the similar proof as adopted in [51]–[53], and we follow this proof. We proof the session key security through a sequence of four games, namely, GM_j, where $j \in [0, 3]$ wherein an event is defined in which $\mathcal{A}$ is able to accurately conjecture the random bit c in GM_j, which is defined by $Succ_{\mathcal{A},GM_j}$ and its advantage to win the game GM_j is defined by $Pr[Succ_{\mathcal{A},GM_j}]$. The detailed description of defined four games are as follows.

```
%%%%%%%%%%%%Sensor%%%%%%%%%%%%
role sensor(UA, GA, SA : agent, SKuasa, SKsaga : symmetric_key, H:
hash_func, SND, RCV : channel(dy))

played_by SA
def=
local State: nat,
    IDi, PWi, HIDi, HPWi, Ri, Pi, BIOi, Rii, Ki, Xgwn, Ai, Bi, Ci, Li,
SIDj, Y : text,
   S1, Ni, Ng, M1, M2, SKij, HIDinew, Rj, Kj, PIDj, Ainew, M3, M4,
M5, M6, M7, M8, Mgu: text

const sp1, sp2, sp3, sp4, sp5, ua_ga_ni, ga_sa_ng, ga_ua_ng, sa_ga_ng:
protocol_id
init State := 0
transition

1. State = 0 /\ RCV(start) =|>
State' := 1 /\ Rj' := new()
      /\ S1' := xor(SIDj, H(Rj'))
      /\ SND({S1'.Rj'}_SKsaga)

2. State = 1 /\ RCV({H(SIDj'.Rj').H(H(SIDj.Rj').Xgwn.Y')}_SKsaga) =|>
State' := 2
3. State = 2
/\ RCV(H(SIDj.H(SIDj.Rj')).H(H(PIDj'.Xgwn.Y').H(SIDj.Rj').Ng')) =|>
State' := 3 /\ SKij' := H(H(SIDj.Rj').H(H(SIDj.Rj').Xgwn.Y').Ng')
      /\ M5' := H(SKij'.H(H(SIDj.Rj').Xgwn.Y').Ng')
      /\ witness(SA, GA, sa_ga_ng,Ng')
         /\ SND(M5')
         /\ request(GA,SA, ga_sa_ng,Ng')

end role
```

FIGURE 9. ***Role*** **of sensor.**

- GM_0*:* This game is equivalent as the "real attack by $\mathcal{A}$ against the proposed protocol" in relation to the game GM_0. The randomly selected bit c is at the beginning of the game, Therefore, we get from the semantic security definition,

$$Adv_{\mathcal{A}} = |2Pr[Succ_{\mathcal{A},GM_0}] - 1| \tag{1}$$

- GM_1*:* This game is modeled that $\mathcal{A}$ can eavesdrop exchanged messages $< HID_i, M_1, M_2 >$, $< M_3, M_4 >$, $< M_5 >$ and $< M_6, M_7, M_8, M_{gu} >$ through an eavesdropping attack. These messages are intercepted by $\mathcal{A}$ over the login and authentication phase employing the *Execute* query. And next, $\mathcal{A}$ executes *Reveal* and *Test* queries to verify whether the derived session key SK_{ij}/SK_a between U_i, GWN and S_j is a real or random key. In our proposed protocol, we take notice of the session key which is constructed as $SK_{ij} = h(PID_j||K_j||N_G)$. To derive the session key, $\mathcal{A}$ have to need the secret identity PID_j of sensor and also random nonce N_j. And $\mathcal{A}$ must calculate the K_j with long term key X_{GWN} and short term secret key y which are unknown to $\mathcal{A}$. In conclusion, we obtain the truth that the $\mathcal{A}$ cannot have the GM_1's winning probability. Therefore, games GM_0 and GM_1 are indistinguishable, we then obtain,

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

- GM_2*:* In this game, *Hash* and *Send* queries are performed to model it calls an "active attack". The

```
%%%%Role for the session

role session(UA, GA, SA : agent, SKuaga, SKsaga : symmetric_key, H:
hash_func)

def=
local SN1, SN2, SN3, RV1, RV2, RV3: channel(dy)
composition
user(UA, GA, SA, SKuaga, H, SN1, RV1)
/\ gateway(UA, GA, SA, SKuaga, SKsaga, H, SN2, RV2)
/\ sensor(UA, GA, SA, SKuaga, SKsaga, H, SN3, RV3)
end role

role environment()
def=
const ua, ga, sa : agent,
skuaga, sksaga: symmetric_key,
h: hash_func,
sidj, hidi,idi: text,
ua_ga_ni, ga_sa_ng, ga_ua_ng, sa_ga_ng: protocol_id,
sp1,sp2,sp3,sp4,sp5: protocol_id

intruder_knowledge = {ua,ga,sa,sidj,hidi,idi,h}
composition
session(ua,ga,sa, skuaga, sksaga,h)/\session(i,ga,sa, skuaga, sksaga,h)
/\session(ua,i,sa, skuaga, sksaga,h)
/\session(ua,ga,i, skuaga, sksaga,h)

end role

goal
secrecy_of sp1, sp2, sp3, sp4, sp5
authentication_on ua_ga_ni
authentication_on ga_sa_ng
authentication_on ga_ua_ng
authentication_on sa_ga_ng
end goal

environment()
```

FIGURE 10. ***Role*** **of session, goal and environment.**

exchanged message $< HID_i, M_1, M_2 >$, the terms M_2 and HID_i are protected by *Hash*. Likewise, the terms M_3, M_4, M_5, M_{gu} are protected by hash function. In addition, All terms including M_1, M_6, M_7, M_8 are constructed the secret credentials and random numbers. Besides, deriving random numbers or secret values from the exchange messages are "computationally infeasible task" because of collision-resistant property. Thus, there are not collision happens if the *Hash* query is executed. As games GM_0 and GM_1 are indistinguishable except for the inclusion of the *Hash* query simulation in GM_2. We can obtain the following to adopt the birthday paradox results:

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

- GM_3*:* GM_3 is the final game which are executed with the *CorruptSC* query. According to *CorruptSC* query, $\mathcal{A}$ can extract stored sensitive values $\{b_i, c_i, L_i, P_i\}$ by performing the power analysis attack. Here, $HPW_i = h(r_i||ID_i||PW_i)$, $L_i = r_i \oplus h(R_i||PW_i)$, $b_i = a_i \oplus HPW_i$, $a_i = h(HID_i||X_{GWN}||k_i)$ and $c_i = h(a_i||HPW_i)$. Then, to derive the secret values r_i and k_i from a_i, L_i and HPW_i, $\mathcal{A}$ have to know the unknowns ID_i, PW_i, R_i and the

```
SUMMARY
 SAFE

DETAILS
 BOUNDED_NUMBER_OF_SESSIONS
 TYPED_MODEL

PROTOCOL
 /home/span/span/testsuite/results/wsn.if

GOAL
 As Specified

BACKEND
 CL-AtSe

STATISTICS

 Analysed    : 0 states
 Reachable   : 0 states
 Translation: 0.09 seconds
 Computation: 0.00 seconds
```

```
% OFMC

% Version of 2006/02/13

SUMMARY
  SAFE

DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
PROTOCOL
  /home/span/span/testsuite/results/wsn.if

GOAL
  as_specified
BACKEND
  OFMC
COMMENTS
STATISTICS
  parseTime: 0.00s
  searchTime: 7.89s
  visitedNodes: 1040 nodes
  depth: 9 plies
```

FIGURE 11. Result of simulation.

TABLE 3. Security Properties.

Security Properties	Amin and Biswas [22]	Amin *et al.* [29]	Chen *et al.*[5]	Ours
Smartcard stolen attack	x	x	x	o
Man-in-the-middle attack	o	o	o	o
Replay attack	o	o	x	o
Impersonation attack	x	o	x	o
Off-line guessing attack	x	o	x	o
User/sensor anonymity	x	o	x	o
Desynchronization	x	x	o	o
Privileged-insider attack	o	x	o	o
Mutual authentication	o	x	x	o

x : Insecure. o : Secure.

gateway's secret key X_{GWN}. Thus, it has computationally infeasible problem for $\mathcal{A}$ guessing the password of a legitimate user. Besides, the probability that $\mathcal{A}$ guesses the biometric key R_i of l_R bits is roughly $\frac{1}{2^{l_R}}$. Thus, in the absence of a password or biometric guessing attack, the games GM_2 and GM_3 are the same. In conclusion, by utilizing the Zipf's law on passwords, we have the next results:

$$|Pr[Succ_{\mathcal{A},GM_3}] - Pr[Succ_{\mathcal{A},GM_2}]| \leq \max\{C' \cdot q_{send}^{s'}, \frac{q_{send}}{2^{l_R}}\} \quad (4)$$

Due to all the games have been run, $\mathcal{A}$ must conjecture the exact bit c. Consequently, we can obtain below equation:

$$Pr[Succ_{\mathcal{A},GM_3}] = \frac{1}{2}. \quad (5)$$

We can obtain the following result from Eqs. (1) and (2):

$$\begin{aligned}\frac{1}{2}Adv_{\mathcal{A}} &= |Pr[Succ_{\mathcal{A},GM_0}] - \frac{1}{2}| \\ &= |Pr[Succ_{\mathcal{A},GM_1}] - \frac{1}{2}|. \end{aligned} \quad (6)$$

Again, Eqs. (5) and (6) give the below equation:

$$\frac{1}{2}Adv_{\mathcal{A}} = |Pr[Succ_{\mathcal{A},GM_1}] - Pr[Succ_{\mathcal{A},GM_3}]|. \quad (7)$$

We can obtain Eq. (8) by applying the triangular inequality with Eqs. (4), (5) and (7).

$$\begin{aligned}\frac{1}{2}Adv_{\mathcal{A}} &= |Pr[Succ_{\mathcal{A},GM_1}] - Pr[Succ_{\mathcal{A},GM_3}]| \\ &\leq |Pr[Succ_{\mathcal{A},GM_1}] - Pr[Succ_{\mathcal{A},GM_2}]| \\ &\quad + |Pr[Succ_{\mathcal{A},GM_2}] - Pr[Succ_{\mathcal{A},GM_3}]| \\ &\leq \frac{q_h^2}{2|Hash|} + \max\{C' \cdot q_{send}^{s'}, \frac{q_{send}}{2^{l_R}}\} \end{aligned} \quad (8)$$

Finally, we can obtain the required result of multiplying both sides of Eq. (8) with a multiple of 2:

$$Adv_P \leq \frac{q_h^2}{|Hash|} + 2\max\{C' \cdot q_{send}^{s'}, \frac{q_{send}}{2^{l_R}}\}.$$

Therefore, Theorem 1 is proved. □

TABLE 4. Computation and communication cost of login and authentication phase.

Protocol	User	Sensor	Gateway	Total cost	Communication cost
Amin and Biswas Case-1[22]	$7T_h$	$5T_h$	$8T_h$	$20T_h(10.0ms)$	408 bytes
Amin and Biswas Case-2[22]	$8T_h$	$5T_h$	$7T_h$	$20T_h(10.0ms)$	540 bytes
Amin *et al.* [29]	$12T_h$	$18T_h$	$6T_h$	$36T_h(18.0ms)$	404 bytes
Chen *et al.* [5]	$5T_h$+$2T_{mul}$	$4T_h$+$2T_{mul}$	$8T_h$	$17T_h$+$4T_{mul}(260.8ms)$	380 bytes
Ours	T_f+$6T_h$	$4T_h$	$9T_h$	T_f+ $19T_h(72.575ms)$	352 bytes

VIII. ANALYSIS OF SECURITY AND EFFICIENCY FEATURES

This section discusses security and efficiency aspects of the proposed protocol. We compare the security of our protocol with other related protocols and compare the performance, i.e., computation cost and communication cost with relevant protocols.

A. SECURITY FEATURES COMPARISON

This section compares the security features of our proposed protocol with related schemes [5], [22], [29]. The results of comparison are shown in Table 3. According to Table 3, All previously researches cannot resist the smartcard stolen attack, and also most of researches cannot prevent the desynchronization attack and cannot provide mutual authentication. Therefore, our proposed protocol provides superior security and functionality features according to comparison of results.

B. COMPUTATIONAL AND COMMUNICATION COSTS COMPARISON

We make the computation costs comparison between our proposed protocol and previous related works in this section. Table 4 describes the results of comparing the login and authentication phase. For comparison, we follow the experimental reported results in [54]. We define T_h, T_f and T_{mul} as the execution time needed for a hash function, a fuzzy extraction and an elliptic curve point multiplication, where T_{mul}, T_h and T_f are 63.075 ms, 0.5 ms and 63.075 ms, respectively. The exclusive-or (*XOR*) execution time is not included because it can be ignored in comparison with other operations. Our proposed protocol requires $T_f + 19T_h$ as the total cost. This is higher than Amin and Biswas's protocol and Amin *et al.*'s protocol. However, the computational demand for a sensor node is most lightweight than other related works. Also, our proposed protocol allows for a lighter computation than Chen *et al.*'s protocol. Thus, we can say that our proposed protocol is more efficient than related researches in WSN environment. We also compare the communication overheads with related protocols. For the comparison, we follow the assumption of Chen *et al.* [5]. Thus, we assume that the timestamp size is 4 bytes and the identity is 8 bytes, a random nonce is 20 bytes and the byte length of a point on the elliptic curve is 48 bytes. Besides, the hash output is 32 bytes. The sum of communicational cost also describes in Table 4. In conclusion, we can say our authentication scheme is more efficient compared to other related previous researched protocols.

IX. CONCLUDING REMARKS

Due to the development of the Internet, the number of objects connected to the IoT is increasing. Therefore, it is necessary to provide a secure service of IoT-enabled WSN that connects sensors of objects. Recently, previous researches and the protocol of Chen *et al.* are insecure to simultaneous ID and password guessing attacks, and Chen *et al.*'s protocol is also insecure to replay attack. To resolve these vulnerabilities, this paper provides a more efficient and secure three factor authentication protocol for WSNs using the honey list technique. We show that the proposed protocol is able to provide secure mutual authentication by employing the BAN logic. Moreover, we applied the broadly-accepted ROR model to prove that our protocol could achieve the session key security. Furthermore, we applied AVISPA simulation to show that the proposed protocol could prevent man-in-the-middle and replay attacks. This paper also provided the informal security analysis to demonstrate how the proposed authentication protocol is secure against impersonation, guessing, smartcard stolen, man-in-the-middle, replay, desynchronization and privileged-insider attacks. Furthermore, our protocol can provide mutual authentication and user/sensor anonymity. We also performed a performance analysis to show that our protocol is efficient. In conclusion, the proposed authentication protocol is more secure and efficient for application in practical WSN environment than other related schemes.

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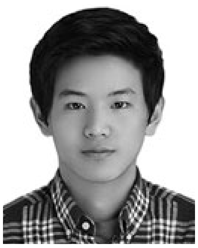

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