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# Flow field perception of a moving carrier based on an artificial lateral line system

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# Flow field perception of a moving carrier based on an artificial lateral line system


## Abstract

2020 by the authors. Licensee MDPI, Basel, Switzerland. At present, autonomous underwater vehicles (AUVs) cannot perceive local environments in complex marine environments, where fish can obtain hydrodynamic information about the surrounding environment through a lateral line. Inspired by this biological function, an artificial lateral line system (ALLS) was built on a moving bionic carrier using the pressure sensor in this paper. When the carrier operated with different speeds in the flow field, the pressure distribution characteristics surrounding the carrier were analyzed by numerical simulation, where the effect of the flow angle between the fluid velocity direction and the carrier navigation direction was considered. The flume experiment was carried out in accordance with the simulation conditions, and the analysis results of the experiment were consistent with those in the simulation. The relationship between pressure and fluid velocity was established by a fitting method. Subsequently, the pressure difference method was investigated to establish a relationship model between the pressure difference on both sides of the carrier and the flow angle. Finally, a back propagation neural network model was used to predict the fluid velocity, flow angle, and carrier speed successfully in the unknown fluid environment. The local fluid environment perception by moving carrier carrying ALLS was studied which may promote the engineering application of the artificial lateral line in the local perception, positioning, and navigation on AUVs.



## Disciplines

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# Secure Remote User Authenticated Key Establishment Protocol for Smart Home Environment

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**Abstract**—The Information and Communication Technology (ICT) has been used in wide range of applications, such as smart living, smart health and smart transportation. Among all these applications, smart home is most popular, in which the users/residents can control the various smart sensor devices of home by using the ICT. However, the smart devices and users communicate over an insecure communication channel, i.e., the Internet. There might be the possibility of various types of attacks, such as smart device capture attack, user, gateway node and smart device impersonation attacks and privileged-insider attack on a smart home network. An illegal user, in this case, can gain access over data sent by the smart devices. Most of the existing schemes reported in the literature for the remote user authentication in smart home environment are not secure with respect to the above specified attacks. Thus, there is need to design a secure remote user authentication scheme for a smart home network so that only authorized users can have access to the smart devices. To mitigate the aforementioned isses, in this paper, we propose a new secure remote user authentication scheme for a smart home environment. The proposed scheme is efficient for resource-constrained smart devices with limited resources as it uses only one-way hash functions, bitwise XOR operations and symmetric encryptions/decryptions. The security of the scheme is proved using the rigorous formal security analysis under the widely-accepted Real-Or-Random (ROR) model. Moreover, the rigorous informal security analysis and formal security verification using the broadly-accepted Automated Validation of Internet Security Protocols and Applications (AVISPA) tool is also done. Finally, the practical demonstration of the proposed scheme is also performed using the widely-accepted NS-2 simulation.

**Index Terms**—Smart home, user authentication, key agreement, provable security, AVISPA, NS2 simulation.

## 1 Introduction

The advancement of ICT and the Internet have provided the support for rapid growth in smart home environments. A smart home contains the advanced automation systems for monitoring and controlling of various smart devices. In a smart home, the residents can control various smart sensing devices such as temperature monitoring sensors, lighting equipments sensors, or occupancy sensors, etc. [1], [2], [3], [4]. The smart home environment provides a high level of comfort with reduced operational costs to provide safety and security to its residents [5]. One of the major advantages of this type of environment is for the elderly and disabled people in which these people get assistance in estimating their body parameters using smart gadgets [6]. A smart home is equipped with a number of smart devices ($SD_j$s), such as low-cost sensors, smart light controllers, smart window shutters, smart AC controllers various and surveillance cameras. Most of the $SD_j$s are resource-constrained having limited computational and communication power, and limited battery backup [5]. A smart home network can be implemented with the help of these $SD_j$s in which all $SD_j$s communicate over wireless channels using the home gateway node ($GWN$). The $GWN$ acts as a bridge between $SD_j$s and smart home user ($U_i$). The $GWN$ provides interoperability and control for the $SD_j$s and connects them to the external world using the Internet. This facilitates the $U_i$s to operate the smart home appliances remotely using the Internet-enabled smartphones, tablets, etc. anytime from anywhere in the world [5], [7].


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### 1.1 Network Model

The network model depicted in Fig. 1 consists of the smart home users $U_i$s who want to access smart devices $SD_j$s as per their requirements. Suppose there is a user $U_i$, who wants to access certain $SD_j$ (e.g. temperature & humidity sensor). To access that $SD_j$, $U_i$ first needs to register himself/herself at the trusted registration authority $RA$. Similarly, all $SD_j$s and the gateway node $GWN$ (which acts as the bridge between the $SD_j$ and $U_i$, and connects $SD_j$ to the external world using the Internet) are also registered at the $RA$. The $GWN$ is thus a special node

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that takes responsibility of controlling the network data, device and network interoperability and secure management [5]. The registration authority $(RA)$ is a trusted server and it is responsible for registering all the smart devices, users $U_i$'s and the $GWN$ securely. After the successful registration of $U_i$, $SD_j$ and $GWN$ securely, the $RA$ stores this useful information in the memory of smart phone $SP_i$ of $U_i$, and also in the memory of $SD_j$ and $GWN$, which are further used at the time of authentication and key establishment process. $U_i$, who wants to access a $SD_j$, sends an authentication request directly to the $GWN$ as both of them have already performed the registration phase at the $RA$. Three categories of mutual authentications happen: 1) between $U_i$ and $GWN$, 2) between $GWN$ and $SD_j$ and 3) between $U_i$ and $SD_j$. Moreover, $U_i$ and $SD_j$ establish a secret session key $SK_{ij}$ between them to protect the exchanged messages.

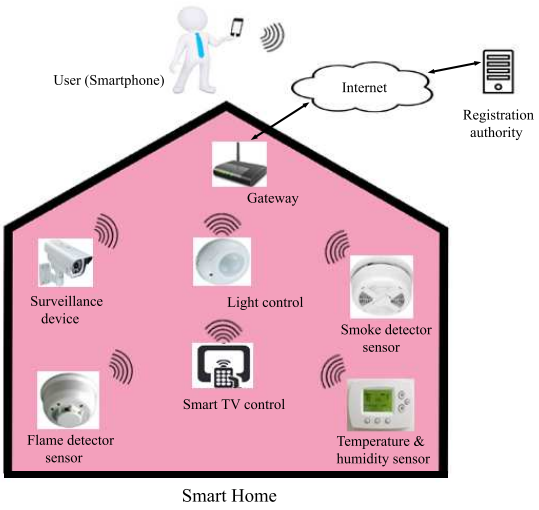


Fig. 1. Smart home environment (Adapted from [5])

### 1.2 Motivation

Consider the following scenario in smart home environment [8]. Recently, it is noticed that the major trend throughout Europe is the aging society, which is affected by an increasing life expectancy and decreasing birth rates. A large proportion of the European society will be not only from the group of people over 65, but also from a significant increase in the number of people over 80. The proportion of population aged over 65 and over is rising in all countries, however differences can be observed. It is also reported that "the ratio for Iceland, Ireland, Slovak Republic and Turkey lie well below the average for Europe, whereas the ratio for Finland, Germany, Greece, Italy and Sweden lie far above the average for Europe" [8].

The $SD_j$s in smart homes communicate over the insecure communication channels. There might be the possibility of various attacks in a smart home network. An illegal user (attacker), who can monitor the activities in a smart home, can break the security, and also can gain access over the $SD_j$s and other smart home appliances. For example, the attacker can watch the activities in the home by accessing the surveillance camera illegally where disabled people live in the smart home. Most of the existing authentication schemes reported in the literature in a smart home environment are not secure against various known attacks, such as smart device capture attack, user, gateway node and smart device impersonation attacks, and privileged-insider attack. Most of those schemes also fail to preserve traceability and anonymity properties of the users, the $GWN$ as well as of the smart devices $SD_j$s. Moreover, using the smart phone stolen attack, it is possible that an adversary $\mathcal{A}$ can capture a user's secret credentials, such as identity, password and biometrics key with the help of the extracted information stored in the smart phone. In addition, with the help of the user, gateway node and smart device impersonation attacks, $\mathcal{A}$ can create valid messages on the behalf of a user $U_i$, $GWN$ and smart device $SD_j$, respectively, and can send the corresponding messages to $U_i$, $GWN$ and $SD_j$ so that these messages are treated as valid by $U_i$, $GWN$ and $SD_j$, respectively. In a privileged-insider attack, an insider user of the $RA$ can act as an adversary. The privileged-insider of the $RA$ being an adversary can use the registration information of the users sent to the $RA$ by a legal $U_i$ during the registration phase and derive user's secret credentials, such as identity, password and biometrics key. However, the $GWN$ registration is usually performed in offline mode securely by the $RA$, and hence, an adversary can not compromise the sensitive information stored in the tamper-resistant $GWN$ device. Considering various possible attacks in a smart home environment, there is a great need to design a secure remote user authentication scheme suitable for a smart home network so that only authorized users can access the information collected by the deployed $SD_j$s.

### 1.3 Threat Model

- We have used the Dolev-Yao threat model [9] in our scheme. According to this model, any two communicating parties communicate over an insecure channel and the end-point entities such as $U_i$ and $SD_j$ are not considered as trusted entities. An adversary, say $\mathcal{A}$, can eavesdrop the exchanged messages, and also can modify or delete the message contents during transmission.
- It is assumed that an adversary can physically capture some smart devices equipped at the smart home which are not tamper-resistant, and can extract all the sensitive data stored in those devices.
- As in [5], we also assume that the $GWN$ is fully trusted and can not be compromised by an adversary. Otherwise, the whole network is compromised if the $GWN$ is compromised. For this purpose, as in Bertino *et al.*'s scheme [10], we also assume that the $GWN$ is equipped with the tamper-resistant device so that all the sensitive information including the cryptographic keying materials stored in it is protected from $\mathcal{A}$. Hence, the use of a tamper-resistant $GWN$ makes the security of the proposed scheme is strong enough. Though the attacks on tamper-resistant devices are possible, the attacker $\mathcal{A}$ needs a special equipment to perform attacks to extract the information. Since it is cheaper to install the $GWN$ than the special equipment, so $\mathcal{A}$ does not have economic incentives to mount such an attack [10]. Moreover, the $GWN$ can be physically secured by putting it under a locking system inside the smart home of a user so that the physical capture of the $GWN$ can be much difficult as compared to that for the smart devices.
- The $RA$ is also fully trusted and can not be compromised by an adversary.

### 1.4 Contributions

Based upon the above discussion, the following contributions are presented in this paper:

- We propose a new remote user authentication scheme for securing a smart home network. The proposed scheme allows three types of mutual authentications: 1) between a user $U_i$ and the $GWN$, 2) between the $GWN$ and a smart device $SD_j$, and 3) a user $U_i$ and a smart device $SD_j$. At the end, a symmetric session key is established between $U_i$ and $SD_j$, and they can use the established symmetric key for their future secure communications using a symmetric cipher (for example, the stateless CBC (Cipher Block Chaining) mode of the Advanced Encryption Standard (AES-128), known as AES-CBC [11], [12], [13]).
- The proposed scheme is suitable and efficient for resource-constrained $SD_j$s with limited resources as it uses only hash invocations, simple bitwise XOR operations and symmetric encryption/decryption operations.
- The security of the proposed scheme is proved using the formal security analysis under the widely-accepted ROR model [14], and also using the rigorous informal security analysis. The formal security discussed in Section 5.1 proves the semantic security of the proposed scheme against an adversary to get the session key between a user and a smart device in the smart home environment. On the other hand, using the informal security analysis, we have shown that the proposed scheme is secure against other possible known attacks, which are discussed in detail in Section 5.3.
- The formal security verification of the proposed scheme in Section 5.2 is done using the broadly-used AVISPA tool [15] and the simulation results show that it is also secure against replay and man-in-the-middle attacks.
- Finally, the practical demonstration of the proposed scheme is provided through the widely-accepted NS-2 simulation [16].

### 1.5 Roadmap of the Paper

The rest of the paper is structured as follows. We briefly discuss the relevant mathematical preliminaries in Section 2. A brief survey of various existing schemes proposed in the literature is given in Section 3. A new user authentication and session key agreement scheme for smart home environment is presented in Section 4. The rigorous formal and informal security analysis are given in Section 5. In addition, the formal security verification using the popular AVISPA tool is also given in this section. The practical demonstration of the proposed scheme using widely-accepted NS-2 simulation is given in Section 6. The performance comparison with the existing relevant schemes is given in Section 7. Finally, Section 8 concludes the article.

## 2 Mathematical Preliminaries

In this section, we briefly discuss the one-way cryptographic hash function and its properties, and also the indistinguishability of encryption under chosen plaintext attack (IND-CPA), which are necessary to analyze the security of the proposed scheme.

### 2.1 One-way Cryptographic Hash Function

A one-way cryptographic hash function $h$: $\{0,1\}^* \rightarrow \{0,1\}^l$ takes an arbitrary-length input, say $x \in \{0,1\}^*$, and outputs a fixed-length (say, $l$-bits) message digest $h(x) \in \{0,1\}^l$.

**Definition 1.** *As defined in [17], the formalization of an adversary $\mathcal{A}$'s advantage in finding hash collision is given by $Adv_{\mathcal{A}}^{HASH}(t) = Pr[(a,b) \leftarrow_R \mathcal{A}$: $a \neq b$ and $h(a) = h(b)]$, where $Pr[X]$ denotes the probability of an event $X$, and $(a,b) \leftarrow_R \mathcal{A}$ denotes the pair $(a,b)$ is randomly selected by $\mathcal{A}$. In this case, $\mathcal{A}$ is allowed to be probabilistic and the probability in the advantage is computed over the random choices made by $\mathcal{A}$ with the execution time $t$. By an $(\epsilon,t)$-adversary $\mathcal{A}$ attacking the collision resistance of $h(\cdot)$, it is meant that the runtime of $\mathcal{A}$ is at most $t$ and that $Adv_{\mathcal{A}}^{HASH}(t) \leq \epsilon$.*

### 2.2 Indistinguishability of Encryption Under Chosen Plaintext Attack

The indistinguishability of encryption under chosen plaintext attack (IND-CPA) is formally defined as follows [18], [19]:

**Definition 2.** *Let $SE/ME$ be the single/multiple eavesdropper respectively, and $OR_{ek_1}$, $OR_{ek_2}$, ..., $OR_{ek_N}$ be $N$ different independent encryption oracles associated with encryption keys $ek_1, ek_2, \ldots, ek_N$, respectively. The advantage functions of $SE$ and $ME$ are defined, respectively, as $Adv_{\Omega,SE}^{IND-CPA}(k) = |2Pr[SE \leftarrow OR_{ek_1}; (p_0,p_1 \leftarrow_R SE); \delta \leftarrow_R \{0,1\}; \beta \leftarrow_R OR_{ek_1}(p_\delta) : SE(\beta) = \delta] - 1|$, and $Adv_{\Omega,ME}^{IND-CPA}(k) = |2Pr[ME \leftarrow OR_{ek_1}, \ldots, OR_{ek_N}; (p_0,p_1 \leftarrow_R ME); \delta \leftarrow_R \{0,1\}; \beta_1 \leftarrow_R OR_{ek_1}(p_\delta), \ldots, \beta_N \leftarrow_R OR_{ek_N}(p_\delta): ME(\beta_1, \ldots, \beta_N) = \delta] - 1|$, where $\Omega$ is the encryption scheme. We call $\Omega$ is IND-CPA secure in the single (multiple) eavesdropper setting if $Adv_{\Omega,SE}^{IND-CPA}(k)$ (respectively, $Adv_{\Omega,ME}^{IND-CPA}(k)$) is negligible (in the security parameter $k$) for any probabilistic, polynomial time adversary $SE$ ($ME$).*

A deterministic encryption scheme means the same message, when it is encrypted twice, yields the same ciphertext. Thus, any deterministic encryption scheme is not IND-CPA secure [13]. There are five modes of symmetric encryption: Electronic Codebook (ECB), Cipher Block Chaining (CBC), Cipher Feedback (CFB), Output Feedback (OFB) and Counter (CTR). Out of these modes, ECB is not IND-CPA secure [13]. Since the adversary knows the Initialization Vector $(IV)$, CBC is essentially reduced to ECB, and hence, the stateful CBC is IND-CPA insecure [13]. On the other hand, in the stateless CBC, the $IV$ value is chosen at random for each message, and due to this property, the stateless CBC is IND-CPA secure [13]. If the stateless CBC of AES-128 symmetric encryption scheme is used for encryption/decryption purpose, it then becomes IND-CPA secure.

## 3 Related Work

Jeong *et al.* [20] presented a one-time password based user authentication scheme using smart card for smart home networks. Their scheme is lightweight as it uses one-way hash function operations. Their scheme does not provide mutual authentication between $GWN$ and smart device as well as between user and smart device. Their scheme does not provide traceability, and user anonymity properties as the user identity is sent in plaintext and also the messages can be easily traced by an adversary. Furthermore, their

scheme is insecure against stolen smart card attack and privileged-insider attack as the adversary can derive secret credentials of a user from the extracted information stored in the smart card. In addition, their scheme is not resilient against smart device physical capture attack.

Vaidya *et al.* [21] proposed a password based remote user authentication scheme for digital home network. Their scheme is also based upon lightweight computation modules such as hashed one-time password and hash-chaining methods. Similar to Jeong *et al.* [20], their scheme does not provide mutual authentication between $GWN$ and smart device as well as between user and smart device. Kim and Kim [22] analyzed Vaidya *et al.*'s scheme [21] and identified that it is vulnerable to password guessing attack and does not provide forward secrecy with lost smart card. They also proposed a new scheme which withstands the security weaknesses observed in Vaidya *et al.*'s scheme [21]. Vaidya *et al.*'s scheme [21] scheme is insecure against stolen smart card attack and privileged-insider attack as the adversary can derive secret credentials of a user from the extracted information stored in the smart card. In addition, their scheme is not resilient against smart device physical capture attack. Later, Vaidya *et al.* [23] also proposed an elliptic curve cryptography (ECC) based device authentication technique for smart energy home area network which requires more overheads as compared to the scheme in [21]. Kim-Kim's scheme [22] is however not resilient against privileged-insider attack, user impersonation attack and password guessing attack. In addition, Kim-Kim's scheme [22] also fails to preserve traceability and anonymity of user and smart device.

Hanumanthappa *et al.* [24] proposed a secure three-way authentication mechanism for user authentication and privacy preservation. In their mechanism, the users or service providers can check whether the device is compromised or not by the help of their proposed encrypted pass-phrases mechanism.

Santoso and Vun [25] proposed ECC based user authentication scheme for a smart home system. In their scheme, the mobile user can authenticate with the devices deployed in the smart home using a central node, called the home gateway. Similar to the schemes of Jeong *et al.* [20], Vaidya *et al.* [21], and Kim and Kim [22], their scheme does not provide traceability, and user anonymity properties. Furthermore, their scheme is insecure against stolen smart card attack and privileged-insider attack. In addition, their scheme is not resilient against smart device physical capture attack.

Chang and Le [26] recently proposed a two-factor user authentication scheme in wireless sensor networks (WSNs), which uses a user's password and smart card. Their scheme has two protocols: $\mathcal{P}_1$ and $\mathcal{P}_2$. While $\mathcal{P}_1$ is based on bitwise XOR and hash functions, $\mathcal{P}_2$ uses ECC along with bitwise XOR and hash functions. However, Das *et al.* [27] proved that both $\mathcal{P}_1$ and $\mathcal{P}_2$ are insecure against session specific temporary information attack and offline password guessing attack, while $\mathcal{P}_1$ is also insecure against session key breach attack. Moreover, they pointed out that both $\mathcal{P}_1$ and $\mathcal{P}_2$ are inefficient in authentication and password change phases. To erase the security limitations in $\mathcal{P}_1$ and $\mathcal{P}_2$, a new authentication and key agreement scheme using ECC in WSNs is presented [27].

Kumar *et al.* [5] presented a lightweight and secure session key establishment scheme for smart home network. To establish the mutual trust, each smart device control unit establishes a session key with the $GWN$ by using a short authentication token. However, their scheme does not preserve the $GWN$ anonymity and also the traceability properties. In addition, their scheme does not provide mutual authentication between user and smart device as well as between user and the $GWN$.

Li *et al.* [28] proposed an ECC based key establishment scheme for smart home energy management systems. Through the implementation, it is shown that their scheme is efficient with respect to execution time and memory usage. Han *et al.* [29] presented a secure key agreement scheme for ubiquitous smart home systems, which is particularly applicable to the consumer electronics devices in a smart home. The security and functionality features of the existing schemes summarized in Table 4 are also discussed in detail in Section 7.

TABLE 1
Notations used

| Notation | Description |
|---|---|
| $RA$ | Registration authority |
| $GWN$ | Gateway node |
| $SD_j$ | $j^{th}$ smart device in the home |
| $U_i$ | $i^{th}$ user |
| $SP_i$ | $U_i$'s smart phone |
| $ID_i$ | $U_i$'s identity |
| $ID_{SD_j}$ | $SD_j$'s identity |
| $PW_i$, $BIO_i$ | $U_i$'s password & personal biometrics, respectively |
| $T_i$ | Current timestamp |
| $\Delta T$ | Maximum transmission delay |
| $K_{GWN-U_i}$ | Secret key of $GWN$ for $U_i$ |
| $K_{GWN-SD_j}$ | Secret key of $GWN$ for $SD_j$ |
| $E_K(\cdot)/D_K(\cdot)$ | Symmetric encryption/decryption (for example, AES-CBC (128 bits) [12]) using key $K$ |
| $\sigma_i$ | Biometric secret key of $U_i$ |
| $\tau_i$ | Public reproduction parameter of $U_i$ |
| $t$ | Error tolerance threshold used in fuzzy extractor |
| $Gen$ | Fuzzy extractor probabilistic generation procedure |
| $Rep$ | Fuzzy extractor deterministic reproduction procedure |
| $h(\cdot)$ | One-way collision-resistant cryptographic hash function |
| $\|\|$, $\oplus$ | Concatenation and bitwise XOR operations, respectively |

## 4 The Proposed Scheme

We propose a new user authenticated key establishment scheme for the smart home environment. In the proposed scheme, we have a registration authority, several smart sensing devices, a gateway node $(GWN)$ and several users, who want to access the smart devices. First of all, the secure offline registration of each smart device and $GWN$ is done at the registration authority $(RA)$. Then a user, who wants to access the smart devices, needs to register at the registration authority providing his/her necessary information. Each user has a smart phone, which is capable to read the credential information such as the user's identity, password and biometric (fingerprint scanning etc.) provided by that user. The $GWN$ acts as an intermediary node. The legal user's authentication request goes to the $GWN$ and then the $GWN$ forwards the request to the requested smart device. The smart device sends response to the $GWN$ accordingly and then the $GWN$ forwards the response to the user. As discussed in the threat model provided in Section 1.3, the $GWN$ is fully trusted and all the sensitive informations stored in the $GWN$ are protected from an adversary [5]. Moreover, we assume that all the heterogeneous devices (i.e., $GWN$, users (smart phones) and smart devices) are synchronized with their clocks, and agree (mutually) on a maximum transmission delay $(\Delta T)$ to protect replay attacks in the proposed scheme [5].

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Our scheme has six phases: 1) offline smart device and gateway registration, 2) user registration, 3) login, 4) authentication and agreement, 5) biometric and password update, and 6) dynamic smart device addition. The notations presented in Table 1 are used in the proposed scheme. We assume that there are $m$ users and $n$ smart devices in the smart home environment. In addition, we assume that $n'$ additional smart devices can be added in the network through the dynamic smart device addition phase, where $n' << n$. We also use the fuzzy extractor to verify the biometrics. The fuzzy extractor is a tuple $\langle \mathcal{M}, l, t \rangle$, which is composed of the following two algorithms [30], [31]:

**Gen:** It is a probabilistic algorithm, which takes a biometric template $B_i$ from a given metric space $\mathcal{M}$ as input, and then outputs a biometric key $\sigma_i \in \{0,1\}^l$ and a public reproduction parameter $\tau_i$, that is, $Gen(B_i) = \{\sigma_i, \tau_i\}$, where $l$ denotes the number of bits present in $\sigma_i$.

**Rep:** This is a deterministic algorithm, which takes a noisy biometric template $B_i' \in \mathcal{M}$ and a public parameter $\tau_i$ and $t$ related to $B_i$, and then it reproduces (recovers) the biometric key $\sigma_i$. In other words, $Rep(B_i', \tau_i) = \sigma_i$ provided that the Hamming distance between $B_i$ and $B_i'$ is less than or equal to a predefined error tolerance threshold value $t$.

### 4.1 Offline Smart Device and Gateway Registration Phase

The offline smart device $(SD_j)$ and $GWN$ registration is done by the registration authority $(RA)$ in offline securely (for example, in person). For each $SD_j$ $(j = 1, 2, \ldots, n)$, the $RA$ selects a unique identity $ID_{SD_j}$ and also generates a unique random 1024-bit secret key $K_{GWN-SD_j}$ of $GWN$ for $SD_j$, and computes the corresponding temporal credential $h(ID_{SD_j}||K_{GWN-SD_j})$, and stores $\{ID_{SD_j}, h(ID_{SD_j}||K_{GWN-SD_j})\}$ into the memory of $SD_j$. The $RA$ further randomly generates the unique $GWN$'s identity $ID_{GWN}$ and a unique random 1024-bit secret key $K_{GWN-U_i}$ of $GWN$ for each user $U_i$ $(i = 1, 2, \ldots, m)$, and also selects the temporary identity $TID_i$ corresponding to each user $U_i$'s identity $ID_i$ into the memory of the $GWN$ after $U_i$'s successful registration phase described in Section 4.2. Finally, the $GWN$ and $SD_j$ contain the information $\langle \{(TID_i, ID_i, K_{GWN-U_i}) | i = 1, 2, \ldots, m\}, \{(ID_{SD_j}, K_{GWN-SD_j}) | j = 1, 2, \ldots, n\} \rangle$, and $\langle ID_{SD_j}, h(ID_{SD_j}||K_{GWN-SD_j}) \rangle$ for each user $U_i$ and smart device $SD_j$, respectively.

### 4.2 User Registration Phase

To access the services from a particular smart device $SD_j$, a user $U_i$ first needs to register with the $RA$ securely (for example, in person). The following steps are required for the $U_i$'s registration, which are also summarized in Fig. 2:

***Step REG1.*** $U_i$ chooses a unique identity $ID_i$ and a password $PW_i$, and generates 160-bit random secrets $a$ and $r$. $U_i$ also imprints his/her biometrics $BIO_i$ to the sensor of $SP_i$. The $SP_i$ applies the fuzzy extractor probabilistic generation function $Gen(\cdot)$ to generate secret biometric key $\sigma_i$ and public parameter $\tau_i$ as $Gen(BIO_i) = (\sigma_i, \tau_i)$ [31], [32], [33]. The $SP_i$ of $U_i$ calculates the masked password $RPW_i = h(PW_i||\sigma_i||a) \oplus r$, and sends the registration request $\langle ID_i, RPW_i \rangle$ to the $RA$ using a secure channel. Note that a privileged-insider user of the $RA$ being an adversary knows the registration information $\{ID_i, RPW_i\}$ to mount the privileged-insider attack.

***Step REG2.*** After receiving $\langle ID_i, RPW_i \rangle$ from $SP_i$, the $RA$ first generates a 1024-bit secret key $K_{GWN-U_i}$ of $GWN$ for $U_i$, and calculates $A_i = h(ID_i||K_{GWN-U_i}) \oplus RPW_i$. $RA$ also generates a temporary identity $TID_i$ corresponding to $ID_i$ for $U_i$ as discussed in the $GWN$ registration phase (Section 4.1). Finally, $RA$ sends the registration reply with information $\{A_i, TID_i\}$ to $U_i$ securely. Note that the privileged-insider user of the $RA$ being an adversary does not know the information $\{A_i, TID_i\}$ as these information are computed online by the $RA$.

***Step REG3.*** After receiving $\langle A_i, TID_i \rangle$ from the $RA$, $SP_i$ of $U_i$ computes parameters $B_i = h(ID_i||\sigma_i) \oplus a$, $RPW_i' = RPW_i \oplus r = h(PW_i||\sigma_i||a)$, $C_i = h(ID_i||RPW_i'||\sigma_i)$ and $A_i^* = A_i \oplus r = h(ID_i||K_{GWN-U_i}) \oplus RPW_i' = h(ID_i||K_{GWN-U_i}) \oplus h(PW_i||\sigma_i||a)$. Finally, $SP_i$ stores the information $\langle TID_i, A_i^*, B_i, C_i, \tau_i, h(\cdot), Gen(\cdot), Rep(\cdot), t \rangle$ in its memory, where $t$ is the error tolerance parameter used by the fuzzy extractor $Rep(\cdot)$ function.

At the end of this phase, the user $U_i$ erases $A_i$ from his/her smart phone $SP_i$ in order to avoid the privileged-insider attack as explained in Section 5.3.3. In addition, the $RA$ also deletes $A_i$ and $RPW_i$ from its database.

| **User** $(U_i)$/ **Smart phone** $(SP_i)$ | **Registration authority** $(RA)$ |
|---|---|
| Choose $ID_i$, $PW_i$, and imprint $BIO_i$. | |
| Generate 160-bit random secrets $a$, $r$. | Select 1024-bit $K_{GWN-U_i}$. |
| Compute $Gen(BIO_i) = (\sigma_i, \tau_i)$, | Compute |
| $RPW_i = h(PW_i||\sigma_i||a) \oplus r$. | $A_i = h(ID_i||K_{GWN-U_i}) \oplus RPW_i$. |
| $\langle ID_i, RPW_i \rangle$ | Generate temporary identity $TID_i$ |
| $\xrightarrow{\text{(via a secure channel)}}$ | corresponding to $ID_i$. |
| | $\langle A_i, TID_i \rangle$ |
| Compute $B_i = h(ID_i||\sigma_i) \oplus a$, | $\xleftarrow{\text{(via a secure channel)}}$ |
| $RPW_i' = RPW_i \oplus r = h(PW_i||\sigma_i||a)$, | |
| $C_i = h(ID_i||RPW_i'||\sigma_i)$, $A_i^* = A_i \oplus r$ | |
| $= h(ID_i||K_{GWN-U_i}) \oplus RPW_i'$. | |
| Delete $A_i$ from $SP_j$'s memory. | |
| Store $\{TID_i, A_i^*, B_i, C_i, \tau_i, h(\cdot),$ | Store $\{ID_i, TID_i\}$ in $GWN$'s database. |
| $Gen(\cdot), Rep(\cdot), t\}$ in $SP_j$'s memory. | Delete $A_i$ and $RPW_i$ from its database. |

Fig. 2. User registration phase

### 4.3 Login Phase

The login process of $U_i$ is performed as per the following steps:

***Step UL1.*** $U_i$ first provides his/her identity $ID_i$ and password $PW_i^*$ into the interface of the smart phone $SP_i$, and also provides his/her biometrics $BIO_i^*$ to the sensor of $SP_i$. $SP_i$ extracts the biometric key $\sigma_i^*$ as $\sigma_i^* = Rep(BIO_i^*, \tau_i)$ with the constraint that the Hamming distance between the original biometrics $BIO_i$ at the time of registration and entered current $BIO_i^*$ is less than or equal to $t$. $SP_i$ further computes $a^* = B_i \oplus h(ID_i||\sigma_i^*)$, $RPW_i^* = h(PW_i^*||\sigma_i^*||a^*)$ and $C_i^* = h(ID_i||RPW_i^*||\sigma_i^*)$. $SP_i$ then checks whether $C_i^* = C_i$. If it is valid, $U_i$ passes both password and biometric verification. Otherwise, the session is terminated immediately.

***Step UL2.*** $SP_i$ calculates $M_1 = A_i^* \oplus RPW_i^* = h(ID_i||K_{GWN-U_i})$. Then $SP_i$ generates a random nonce $r_{U_i}$ and the current timestamp $T_1$, and calculates parameters $M_2 = M_1 \oplus r_{U_i}$ and $M_3 = h(M_2||T_1||ID_i||TID_i||r_{U_i})$. Finally, $SP_i$ sends the login request message $\langle TID_i, M_2, M_3, T_1 \rangle$ to $GWN$ via an open channel.

### 4.4 Authentication and Key agreement Phase

On receiving the login request $\langle TID_i, M_2, M_3, T_1 \rangle$ from $SP_i$, following steps are performed by $U_i/SP_i$, $GWN$ and an accessed

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| **User** $(U_i)$/**Smart phone** $(SP_i)$ | **Gateway node** $(GWN)$ | **Smart device** $(SD_j)$ |
|---|---|---|
| $\langle TID_i, A_i^*, B_i, C_i, \tau_i,$ $h(\cdot), Gen(\cdot), Rep(\cdot), t\rangle$ | $\langle\{(TID_i, ID_i, K_{GWN-U_i})\|i = 1, 2, \ldots, m\},$ $\{(ID_{SD_j}, K_{GWN-SD_j})\|j = 1, 2, \ldots, n\}\rangle$ | $\langle ID_{SD_j}, h(ID_{SD_j}\|\|K_{GWN-SD_j})\rangle$ |
| Input $ID_i$, $PW_i^*$ & $BIO_i^*$. | Check if $\|T_1 - T_1^*\| \leq \Delta T$? | Check if $\|T_2 - T_2^*\| \leq \Delta T$? |
| Compute $\sigma_i^* = Rep(BIO_i^*, \tau_i)$, | If so, extract $ID_i$ and $K_{GWN-U_i}$ | If so, decrypt $M_7$ to retrieve |
| $a^* = B_i \oplus h(ID_i\|\|\sigma_i^*)$, | corresponding to $TID_i$. Compute | $(ID_i, ID_{GWN}, r_{U_i}^*, r_{GWN}, h(M_4))$ |
| $RPW_i^* = h(PW_i^*\|\|\sigma_i^*\|\|a^*)$, | $M_4 = h(ID_i\|\|K_{GWN-U_i})(= M_1)$ using | $= D_{h(ID_{SD_j}\|\|K_{GWN-SD_j})}[M_7]$. |
| $C_i^* = h(ID_i\|\|RPW_i^*\|\|\sigma_i^*)$. | extracted $ID_i$ & $K_{GWN-U_i}$, $r_{U_i}^* = M_2 \oplus M_4$, | Compute $M_9 = h[h(ID_{SD_j}\|\|K_{GWN-SD_j})$ |
| Check if $C_i^* = C_i$? If so, compute | $M_5 = h(M_2\|\|T_1\|\|ID_i\|\|TID_i\|\|r_{U_i}^*)$. | $\|\|T_2\|\|ID_i\|\|ID_{SD_j}\|\|ID_{GWN}\|\|r_{GWN}]$. |
| $M_1 = A_i^* \oplus RPW_i^* = h(ID_i\|\|K_{GWN-U_i})$. | Check if $M_5 = M_3$? | Check if $M_9 = M_8$? |
| Generate $r_{U_i}$ & $T_1$, and calculate | If matches, generate $r_{GWN}$ & $T_2$. | If so, generate $r_{SD_j}$ & $T_3$, and |
| $M_2 = M_1 \oplus r_{U_i}$, | Compute $M_6 = h(ID_{SD_j}\|\|K_{GWN-SD_j})$, | compute $SK_{ij} = h[ID_i\|\|ID_{SD_j}\|\|$ |
| $M_3 = h(M_2\|\|T_1\|\|ID_i\|\|TID_i\|\|r_{U_i})$. | $M_7 = E_{M_6}[ID_i, ID_{GWN}, r_{U_i}^*, r_{GWN}, h(M_4)]$, | $ID_{GWN}\|\|r_{U_i}^*\|\|r_{GWN}\|\|r_{SD_j}\|\|h(M_4)$ |
| $\langle TID_i, M_2, M_3, T_1\rangle$ | $M_8 = h(M_6\|\|T_2\|\|ID_i\|\|ID_{SD_j}\|\|ID_{GWN}\|\|r_{GWN})$. | $\|\|h(h(ID_{SD_j}\|\|K_{GWN-SD_j}))]$, |
| $\longrightarrow$ | $\langle M_7, M_8, T_2\rangle$ | $M_{10} = h(h(ID_{SD_j}\|\|K_{GWN-SD_j})\|\|T_3) \oplus r_{SD_j}$, |
| (via open channel) | $\longrightarrow$ | $M_{11} = h(SK_{ij}\|\|T_3)$, |
| | (via open channel) | $M_{12} = h(r_{SD_j}\|\|r_{GWN}\|\|ID_{SD_j}\|\|ID_{GWN}\|\|T_3)$. |
| | | $\langle M_{10}, M_{11}, M_{12}, T_3\rangle$ |
| | | $\longleftarrow$ |
| | Check if $\|T_3 - T_3^*\| \leq \Delta T$? | (via open channel) |
| | If so, compute $r_{SD_j}^* = M_{10} \oplus$ | |
| Check if $\|T_4 - T_4^*\| \leq \Delta T$? | $h[h(ID_{SD_j}\|\|K_{GWN-SD_j})\|\|T_3]$, | |
| If so, decrypt | $M_{13} = h(r_{SD_j}^*\|\|r_{GWN}\|\|ID_{SD_j}\|\|ID_{GWN}\|\|T_3)$. | |
| $D_{M_1}[M_{14}] = (r_{U_i}^*, r_{GWN}^*, r_{SD_j}^*,$ | Check if $M_{13} = M_{12}$? | |
| $ID_{SD_j}, ID_{GWN}, h(M_6))$. | If so, compute $M_{14} = E_{M_4}[r_{U_i}^*, r_{GWN}, r_{SD_j}^*,$ | |
| Check if $r_{U_i}^* = r_{U_i}$? | $ID_{SD_j}, ID_{GWN}, h(M_6)]$. | |
| If so, compute $SK'_{ij} = h[ID_i\|\|ID_{SD_j}$ | Generate $T_4$, select $TID_i^{new}$ and compute | |
| $\|\|ID_{GWN}\|\|r_{U_i}\|\|r_{GWN}^*\|\|r_{SD_j}^*$ | $M_{15} = TID_i^{new} \oplus h(TID_i\|\|M_4\|\|T_3\|\|T_4)$, | |
| $\|\|h(M_1)\|\|h(M_6)]$, | $M_{16} = h(M_{11}\|\|T_4\|\|r_{U_i}^*)$. | |
| $M_{17} = h(h(SK'_{ij}\|\|T_3)\|\|T_4\|\|r_{U_i})$. | $\langle M_{14}, M_{15}, M_{16}, T_3, T_4\rangle$ | |
| Check if $M_{17} = M_{16}$? If so, $U_i$ and $SD_j$ | $\longleftarrow$ | |
| establish session key $SK'_{ij}(= SK_{ij})$. | (via open channel) | |
| Compute $TID_i^{new} = M_{15} \oplus h(TID_i$ | | |
| $\|\|M_1\|\|T_3\|\|T_4)$. | | |
| Replace $TID_i$ with $TID_i^{new}$. | | |

Fig. 3. Summary of login, and authentication and key agreement phases

smart device $SD_j$ to establish a session key between $U_i$ and $SD_j$ for later secure communication:

***Step AUKA1.*** $GWN$ first checks the timeliness of $T_1$ by condition $|T_1 - T_1^*| \leq \Delta T$, where the maximum transmission delay is denoted by $\Delta T$ and $T_1^*$ is the reception time of the message $\langle TID_i, M_2, M_3, T_1\rangle$. If the condition matches, the $GWN$ searches the received $TID_i$ in its database and if it is found in the database, the $GWN$ extracts $ID_i$ and $K_{GWN-U_i}$ corresponding to $TID_i$ from its database, and calculates $M_4 = h(ID_i||K_{GWN-U_i})$ $(= M_1)$ using the extracted $ID_i$ and $K_{GWN-U_i}$, $r_{U_i}^* = M_2 \oplus M_4 = M_2 \oplus M_1$, $M_5 = h(M_2||T_1||ID_i||TID_i||r_{U_i}^*)$.

***Step AUKA2.*** $GWN$ checks if $M_5 = M_3$ holds. If it does not match, it terminates the authentication process. Otherwise $GWN$ generates a random nonce $r_{GWN}$ and timestamp $T_2$, and calculates parameters $M_6 = h(ID_{SD_j}||K_{GWN-SD_j})$, $M_7 = E_{M_6}[ID_i, ID_{GWN}, r_{U_i}^*, r_{GWN}, h(M_4)]$, $M_8 = h(M_6||T_2||ID_i||ID_{SD_j}||ID_{GWN}||r_{GWN})$. For computing $M_7$, if we use the stateless CBC of AES-128 (AES-CBC) symmetric encryption scheme, then the $GWN$ needs to set the $IV$ of CBC as $IV = h(M_6||T_1)$ so that it is random for each message in a particular session. Then $GWN$ sends the authentication request message $\langle M_7, M_8, T_2\rangle$ to $SD_j$ via an open channel.

***Step AUKA3.*** After receiving the message $\langle M_7, M_8, T_2\rangle$ from $GWN$, $SD_j$ checks the timeliness of $T_2$ by the criteria $|T_2 - T_2^*| \leq \Delta T$, where $T_2^*$ is the reception time of the message $\langle M_7, M_8, T_2\rangle$. If condition holds, $SD_j$ decrypts $M_7$ using the stored key $h(ID_{SD_j}||K_{GWN-SD_j})$ as $(ID_i, ID_{GWN}, r_{U_i}^*, r_{GWN}, h(M_4)) = D_{h(ID_{SD_j}||K_{GWN-SD_j})}[M_7]$. For decrypting $M_7$, $SD_j$ also needs to set the $IV$ of CBC as $IV = h(h(ID_{SD_j}||K_{GWN-SD_j})||T_1)$ $(= h(M_6||T_1))$.

***Step AUKA4.*** $SD_j$ calculates $M_9 = h[h(ID_{SD_j}||K_{GWN-SD_j})||T_2||ID_i||ID_{SD_j}||ID_{GWN}||r_{GWN}]$ and checks the condition $M_9 = M_8$. If it does not match, it terminates the authentication process. Otherwise, $SD_j$ generates a random nonce $r_{SD_j}$ and the current timestamp $T_3$, and computes the session key as $SK_{ij} = h[ID_i||ID_{SD_j}||ID_{GWN}||r_{U_i}^*||r_{GWN}||r_{SD_j}||h(M_4)||h(h(ID_{SD_j}||K_{GWN-SD_j}))]$. After that, $SD_j$ computes parameters $M_{10} = h(h(ID_{SD_j}||K_{GWN-SD_j})||T_3) \oplus r_{SD_j}$, $M_{11} = h(SK_{ij}||T_3)$ and $M_{12} = h(r_{SD_j}||r_{GWN}||ID_{SD_j}||ID_{GWN}||T_3)$. Then $SD_j$ sends the authentication reply message $\langle M_{10}, M_{11}, M_{12}, T_3\rangle$ to the $GWN$ via an insecure channel.

***Step AUKA5.*** Upon receiving authentication request message, $GWN$ checks the timeliness of $T_3$ by applying the criteria $|T_3 - T_3^*| \leq \Delta T$, where $T_3^*$ is the reception time of the message $\langle M_{10}, M_{11}, M_{12}, T_3\rangle$. If condition matches, $GWN$ computes $r_{SD_j}^* = M_{10} \oplus h[h(ID_{SD_j}||K_{GWN-SD_j})||T_3]$ and $M_{13} = h(r_{SD_j}^*||r_{GWN}||ID_{SD_j}||ID_{GWN}||T_3)$. The $GWN$ checks the condition $M_{13} = M_{12}$. If it does not match, the $GWN$ aborts the message. Otherwise, $GWN$ computes $M_{14}$ using previously computed $M_4 = h(ID_i||K_{GWN-U_i})$ as $M_{14} = E_{M_4}[r_{U_i}^*, r_{GWN}, r_{SD_j}^*, ID_{SD_j}, ID_{GWN}, h(M_6)]$. For encrypting the information in $M_{14}$ using the key $M_4$, we also use the stateless CBC of AES-128 (AES-CBC) symmetric encryption scheme and thus, the $GWN$ needs to set the $IV$ of CBC as $IV = h(M_4||T_4)$ so that it is random for each message in a particular session. The $GWN$ chooses current timestamp $T_4$ and generates a new temporary identity $TID_i^{new}$ corresponding to $ID_i$. The $GWN$ further computes $M_{15} = TID_i^{new} \oplus h(TID_i||M_4||T_3||T_4)$

and $M_{16} = h(M_{11} \,||T_4\, ||r^*_{U_i})$. The $GWN$ sends the message $\langle M_{14}, M_{15}, M_{16}, T_3, T_4\rangle$ to $U_i$ via insecure channel.

***Step AUKA6.*** After receiving the message $\langle M_{14}, M_{15}, M_{16}, T_3, T_4\rangle$, $SP_i$ of $U_i$ first checks the timeliness of $T_4$ with the condition $|T_4 - T^*_4| \leq \Delta T$, where $T^*_4$ is the reception time of the message. If condition matches, $U_i$ decrypts $M_{14}$ using pre-computed $M_1$ as $D_{M_1}\,[M_{14}] = (r^*_{U_i}, r^*_{GWN}, r^*_{SD_j}, ID_{SD_j}, ID_{GWN}, h(M_6))$. For decrypting $M_{14}$, $SD_j$ also needs to set the $IV$ of CBC as $IV = h(M_1||T_4)$ $(= h(M_4||T_4))$.

Then $SP_i$ checks if $r^*_{U_i} = r_{U_i}$. If they do not match, $SP_i$ terminates the authentication process. Otherwise, it computes the session key $SK'_{ij} = h[ID_i \,||ID_{SD_j}\, ||ID_{GWN}\, ||r_{U_i}\, ||r^*_{GWN}\, ||r^*_{SD_j}\, ||h(M_1)\, ||h(M_6)]$ and $M_{17} = h(h(SK'_{ij}\, ||T_3)\, ||T_4\, ||r_{U_i})$, and then matches if $M_{17} = M_{16}$. If it does not match, $SP_i$ terminates the session and discards the computed session key. Otherwise, message comes from the valid source and the computed session key $SK'_{ij}$ is authentic. Finally, $SP_i$ computes the new temporary identity as $TID^{new}_i = M_{15} \oplus h(TID_i\, ||M_1\, ||T_3\, ||T_4)$ and replaces $TID_i$ with $TID^{new}_i$ in its memory.

The login, and authentication and agreement phases are summarized in Fig. 3.

### 4.5 Password and Biometric Update Phase

The proposed scheme provides password and biometric update facility through which a legitimate user $U_i$ can update his/her password and biometrics for security reasons at any time after user registration phase without further involving the $RA$. Note that the biometric information of a given user $U_i$ is unique and unchanged as compared to the chosen password by that user $U_i$. However, we suggest the user $U_i$ to update his/her biometric information in the proposed scheme, if he/she desires to do so. This is required to protect strongly the offline password guessing attack to be considered in this phase as described by Huang *et al.* [34], which is discussed in detail in Section 5.3.11. This phase needs the following steps:

***Step PBU1.*** $U_i$ provides his/her identity $ID_i$, old password $PW^{old}_i$ to interface of the $SP_i$ and current his/her biometrics $BIO^{old}_i$ to the sensor of the $SP_i$. $SP_i$ then computes $\sigma^{old}_i = Rep(BIO^{old}_i,\ \tau_i)$, $a' = B_i \oplus h(ID_i||\sigma^{old}_i)$, $RPW^{old}_i = h(PW^{old}_i\, ||\sigma^{old}_i\, ||a')$ and $C^{old}_i = h(ID_i||\, RPW^{old}_i\, ||\sigma^{old}_i)$. $SP_i$ checks the condition $C^{old}_i = C_i$. If it matches, $U_i$ is the actual user; otherwise, the phase is terminated immediately.

***Step PBU2.*** $SP_i$ asks $U_i$ to enter a new password $PW^{new}_i$ and also imprint new biometrics $BIO^{new}_i$. The $SP_i$ then calculates $Gen(BIO^{new}_i) = (\sigma^{new}_i,\ \tau^{new}_i)$, $RPW^{new}_i = h(PW^{new}_i\, ||\sigma^{new}_i\, ||a')$, $B^{new}_i = h(ID_i||\sigma^{new}_i) \oplus a'$, $C^{new}_i = h(ID_i\, ||RPW^{new}_i\, ||\sigma^{new}_i)$ and $A^{new}_i = A^*_i \oplus RPW^{old}_i \oplus RPW^{new}_i$, $= h(ID_i||\, K_{GWN-U_i}) \oplus RPW^{new}_i = h(ID_i||\, K_{GWN-U_i}) \oplus h(PW^{new}_i\, ||\sigma^{new}_i\, ||a')$.

***Step PBU3.*** Finally, $SP_i$ replaces $\tau_i$, $A^*_i$, $B_i$, and $C_i$ with $\tau^{new}_i$, $A^{new}_i$, $B^{new}_i$, and $C^{new}_i$ in its memory, respectively.

The password and biometric update phase is also summarized in Fig. 4.

### 4.6 Dynamic Smart Device Addition Phase

To deploy a new smart device $SD^{new}_j$ in the existing smart home network, the $RA$ performs the following steps in offline:

***Step DA1.*** $RA$ first assigns a unique new identity $ID^{new}_{SD_j}$ and also generates a new secret key $K_{GWN-SD^{new}_j}$ of $GWN$ for $SD^{new}_j$. $RA$ further computes the temporal credential of $SD^{new}_j$ as $h(ID_{SD^{new}_j}||K_{GWN-SD^{new}_j})$.

| User $(U_i)$ | Smart phone $(SP_i)$<br>$\langle TID_i, A^*_i, B_i, C_i, \tau_i, h(\cdot), Gen(\cdot), Rep(\cdot), t\rangle$ |
|---|---|
| Provide $ID_i$, $PW^{old}_i$ & $BIO^{old}_i$. | Compute $\sigma^{old}_i = Rep(BIO^{old}_i, \tau_i)$,<br>$a' = B_i \oplus h(ID_i||\sigma^{old}_i)$,<br>$RPW^{old}_i = h(PW^{old}_i||\sigma^{old}_i||a')$,<br>$C^{old}_i = h(ID_i||RPW^{old}_i||\sigma^{old}_i)$.<br>Check if $C^{old}_i = C_i$?<br>If so, ask $U_i$ to provide new password & biometrics. |
| Provide $PW^{new}_i$ & $BIO^{new}_i$. | Compute $Gen(BIO^{new}_i) = (\sigma^{new}_i, \tau^{new}_i)$,<br>$RPW^{new}_i = h(PW^{new}_i||\sigma^{new}_i||a')$,<br>$B^{new}_i = h(ID_i||\sigma^{new}_i) \oplus a'$,<br>$C^{new}_i = h(ID_i||RPW^{new}_i||\sigma^{new}_i)$,<br>$A^{new}_i = A^*_i \oplus RPW^{old}_i \oplus RPW^{new}_i$,<br>$= h(ID_i||K_{GWN-U_i}) \oplus RPW^{new}_i$.<br>Finally, $SP_i$ replaces $\tau_i$, $A^*_i$, $B_i$ and $C_i$ with $\tau^{new}_i$, $A^{new}_i$, $B^{new}_i$ and $C^{new}_i$, respectively. |

Fig. 4. Summary of password and biometric update phase

***Step DA2.*** $RA$ stores the information $\{ID_{SD^{new}_j}, h(ID_{SD^{new}_j}\, ||K_{GWN-SD^{new}_j})\}$ into the memory of $SD_j$ before its deployment in the smart home. $RA$ also sends the information $\{ID_{SD^{new}_j}, K_{GWN-SD^{new}_j}\}$ to the $GWN$ securely, which are then stored in the database of the $GWN$.

Finally, $RA$ also needs to inform the existing users in the network about the deployment of new smart device $SD^{new}_j$ so that they can access the services from $SD^{new}_j$, if needed.

## 5 Security Analysis

In this section, we analyze the security of the proposed scheme using both formal and informal analysis.

### 5.1 Formal Security Analysis using Real-Or-Random Model

The widely-accepted Real-Or-Random (ROR) model [14] is used for formal security analysis of the proposed scheme.

#### 5.1.1 ROR Model

We follow the Abdalla *et al.*'s ROR model [14] for formal security analysis as done in [26]. According to our scheme, we have three participants in the smart home: smart device $SD_j$, user $U_i$ and $GWN$.

**Participants.** Let $\Pi^t_{SD_j}$, $\Pi^u_{U_i}$ and $\Pi^v_{GWN}$ be the instances $t$, $u$ and $v$ of $SD_j$, $U_i$ and $GWN$, respectively. These are called oracles [26].

**Accepted state.** An instance $\Pi^t$ is known to be accepted, if upon receiving the last expected protocol message, it goes into an accept state. The ordered concatenation of all communicated (sent and received) messages by $\Pi^t$ forms the session identification $(sid)$ of $\Pi^t$ for the current session.

**Partnering.** Two instances $\Pi^{t_1}$ and $\Pi^{t_2}$ are said to be partnered if the following three conditions are fulfilled simultaneously: 1) both $\Pi^{t_1}$ and $\Pi^{t_2}$ are in accept state; 2) both $\Pi^{t_1}$ and $\Pi^{t_2}$ mutually authenticate each other and share the same $sid$; and 3) $\Pi^{t_1}$ and $\Pi^{t_2}$ are mutual partners of each other.

**Freshness.** The instance $\Pi^u_{U_i}$ or $\Pi^t_{SD_j}$ is fresh, if the session key $SK_{ij}$ between $U_i$ and $SD_j$ has not revealed to an adversary $\mathcal{A}$ using the Reveal($\Pi^t$) query given below [26].

**Adversary.** It is assumed that $\mathcal{A}$ has fully control over all the

communications in a smart home. $\mathcal{A}$ has the ability to read, modify the exchanged messages, or can fabricate new messages and inject them into the network. Furthermore, $\mathcal{A}$ has access to the following queries [26]:

$Execute(\Pi^u, \Pi^v, \Pi^t)$: $\mathcal{A}$ can execute this query to obtain the messages exchanged between three legitimate participants $U_i$, $GWN$ and $SD_j$, which is further modeled as an eavesdropping attack.

$Reveal(\Pi^t)$: This query reveals the current session key $SK_{ij}$ generated by $\Pi^t$ (and its partner) to an adversary $\mathcal{A}$.

$Send(\Pi^t, msg)$: $\mathcal{A}$ runs this query to send a message, say $msg$, to a participant instance $\Pi^t$, and also receives a response message. It is modeled as an active attack.

$CorruptSmartPhone(\Pi^u_{U_i})$: It represents the smart phone $SP_i$ lost/stolen attack, which outputs the information stored in $SP_i$.

$CorruptSmartDevice(\Pi^t_{SD_j})$: This represents an attack in which secret $h(ID_{SD_j}||K_{GWN-SD_j})$ is disclosed to $\mathcal{A}$, which is applied to verify the security of the proposed scheme. As mentioned in [26], both $CorruptSmartPhone$ and $CorruptSmartDevice$ queries ensure the weak-corruption model in which temporary keys and the internal data of the participant instances are not corrupted.

$Test(\Pi^t)$: It represents the semantic security of a session key $SK_{ij}$ between $U_i$ and $SD_j$ following the indistinguishability in the ROR model [14]. An unbiased coin $b$ is flipped before start of the experiment, and its result is only known to $\mathcal{A}$ which is used to decide the output of the $Test$ query. If $\mathcal{A}$ runs this query, and the established session key $SK_{ij}$ is also new, then $\Pi^t$ returns $SK_{ij}$ in case $b = 1$ or a random number for $b = 0$; otherwise, it outputs $\perp$ (null).

Note that we impose a restriction that the adversary $\mathcal{A}$ has access to only limited number of $CorruptSmartPhone(\Pi^u_{U_i})$ and $CorruptSmartDevice(\Pi^t_{SD_j})$ queries, whereas he/she can access the $Test(\Pi^t)$ query many times. According to the threat model described in Section 1.3, the $GWN$ is trusted. Thus, $\mathcal{A}$ does not have any access to a corrupt query related to the $GWN$.

**Semantic security of session key.** According to the requirements of the ROR model [14], $\mathcal{A}$ needs to distinguish between an instance's real session key and a random key. $\mathcal{A}$ can make several $Test$ queries to either $\Pi^t_{SD_j}$ or $\Pi^u_{U_i}$. The output of $Test$ query should be consistent with respect to the random bit $b$. After the experiment is finished, $\mathcal{A}$ returns a guessed bit $b'$ and he/she can win the game if the condition $b' = b$ is met. Let $SUCC$ be an event that $\mathcal{A}$ win the game. The advantage $Adv^{AKE}_{\mathcal{P}}$ of $\mathcal{A}$ in breaking the semantic security of our authenticated key agreement (AKE) scheme, say $\mathcal{P}$ against deriving the session key $SK_{ij}$ between $U_i$ and $SD_j$ is given by $Adv^{AKE}_{\mathcal{P}} = |2.Pr[SUCC] - 1|$. In the ROR sense, $\mathcal{P}$ is secure if $Adv^{AKE}_{\mathcal{P}} \leq \psi$, where $\psi > 0$ is a sufficiently small real number.

**Random oracle.** As mentioned in [26], all communicating participants as well as $\mathcal{A}$ have access to a collision-resistant one-way cryptographic hash function $h(\cdot)$. $h(\cdot)$ is modeled by a random oracle, say $HO$.

### 5.1.2 Security Proof

Theorem 1 provides the semantic security of our proposed scheme under the widely-accepted ROR model [26], [35].

**Theorem 1.** *Let $\mathcal{A}$ be an adversary running in polynomial time $t$ against our scheme $\mathcal{P}$ in the random oracle, $D$ a uniformly distributed password dictionary and $l$ the number of bits present in the biometrics key $\sigma_i$. The advantage of $\mathcal{A}$ in breaking semantic security of our scheme is estimated as $Adv^{AKE}_{\mathcal{P}} \leq \frac{q_h^2}{|Hash|} + \frac{q_{send}}{2^{l-1}.|D|} + 2Adv^{IND-CPA}_{\Omega}(k)$, where $q_h$, $q_{send}$, $|Hash|$, $|D|$ and $Adv^{IND-CPA}_{\Omega,SE}(k)$ or $Adv^{IND-CPA}_{\Omega,ME}(k)$ are the number of $HO$ queries, the $Send$ queries, the range space of $h(\cdot)$, the size of $D$, and the advantage of $\mathcal{A}$ in breaking the IND-CPA secure symmetric cipher $\Omega$ (provided in Definition 2), respectively, and $Adv^{IND-CPA}_{\Omega}(k) = Adv^{IND-CPA}_{\Omega,SE}(k)$ or $Adv^{IND-CPA}_{\Omega,ME}(k)$.*

*Proof.* The proof is similar to that presented in the schemes [26], [35]. The sequence of five games, say $GM_i$, are defined in the security analysis, where $i = 0, 1, 2, 3, 4$. Assume that $SUCC_i$ be an event wherein an adversary $\mathcal{A}$ can guess the random bit $b$ in $GM_i$ correctly.

**$GM_0$:** This game corresponds to a real attack performed by $\mathcal{A}$ against our scheme $\mathcal{P}$ in the ROR sense. The bit $b$ is chosen at the beginning of $GM_0$. Hence, it follows that

$$Adv^{AKE}_{\mathcal{P}} = |2.Pr[SUCC_0] - 1|. \quad (1)$$

**$GM_1$:** This game represents an eavesdropping attack performed by the single/multiple eavesdropper $SE/ME$, say $\mathcal{A}$, where $\mathcal{A}$ can query $Execute(\Pi^u, \Pi^v, \Pi^t)$ oracle. At the end of the game, $\mathcal{A}$ makes queries to the $Test$ oracle. The output of $Test$ oracle determines whether it is the actual session key $SK_{ij}$ or a random number. Note that the session key $SK_{ij}$ is calculated by both $U_i$ and $SD_j$ as $SK_{ij} = h[ID_i||\ ID_{SD_j}\ ||ID_{GWN}\ ||r^*_{U_i}\ ||r_{GWN}\ ||r_{SD_j}\ ||h(M_4)\ ||h(h(ID_{SD_j}\ ||K_{GWN-SD_j}))]$, where $M_4 = h(ID_i\ ||K_{GWN-U_i})$. To calculate $SK_{ij}$, $\mathcal{A}$ must have $M_4$ and $h(ID_{SD_j}\ ||K_{GWN-SD_j})$, which further involve secret keys $K_{GWN-U_i}$ and $K_{GWN-SD_j}$. $\mathcal{A}$ also requires $ID_i$, $ID_{SD_j}$, $ID_{GWN}$, $r_{U_i}$, $r_{GWN}$ and $r_{SD_j}$ for calculating $SK_{ij}$, which are unknown to him/her. As a consequence, the chance of winning the game $GM_1$ for $\mathcal{A}$ is not increased by eavesdropping attack. It is then obvious that

$$Pr[SUCC_0] = Pr[SUCC_1]. \quad (2)$$

**$GM_2$:** By adding the simulations of the $Send$ and $HO$ oracles are added into $GM_1$, $GM_1$ is transformed into $GM_2$, which represents an active attack. In this game, the objective of $\mathcal{A}$ is to fool a participant to accept a modified message. $\mathcal{A}$ is permitted to make different $HO$ queries to examine the existence of the hash collisions. All the exchanged messages $\langle TID_i,\ M_2,\ M_3,\ T_1\rangle$, $\langle M_7,\ M_8,\ T_2\rangle$, $\langle M_{10},\ M_{11},\ M_{12},\ T_3\rangle$ and $\langle M_{14},\ M_{15},\ M_{16},\ T_3,\ T_4\rangle$ during the login and authentication phase contain the participant's identity, random nonce and timestamps. Hence, there is no collision when the $Send$ oracle is queried by $\mathcal{A}$. The results of the birthday paradox give

$$|Pr[SUCC_1] - Pr[SUCC_2]| \leq q_h^2/(2|Hash|). \quad (3)$$

**$GM_3$:** $GM_2$ is transformed into $GM_3$ by adding the simulation of $CorruptSmartPhone$ oracle. $\mathcal{A}$ can choose low-entropy passwords, and using the information stored into $SP_i$ he/she may try to acquire the user's password using the dictionary attack. Again, $\mathcal{A}$ may try to acquire the biometrics key $\sigma_i$ from the information stored in $SP_i$. We have used a strong fuzzy extractor in our scheme $\mathcal{P}$, which is capable to extract at most $l$ random bits and the guessing probability of $\sigma_i \in \{0,1\}^l$ by $\mathcal{A}$ is approximately $\frac{1}{2^l}$ [31]. It is also assumed that the system allows

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the limited number of wrong password inputs. Thus, we have the following result,

$$|Pr[SUCC_2] - Pr[SUCC_3]| \leq q_{send}/(2^l.|D|). \quad (4)$$

$GM_4$**:** $GM_3$ is transformed into $GM_4$, where $GM_4$ is the last game. It models an attack in which $\mathcal{A}$ can physically capture (compromise) a smart device $SD_j$ by adding the simulation of $CorruptSmartDevice$ oracle. $\mathcal{A}$ then knows the information $\{ID_{SD_j}, h(ID_{SD_j}||K_{GWN-SD_j})\}$ which is stored in $SD_j$. Let $\mathcal{A}$ also has all the eavesdropped messages $\langle TID_i, M_2, M_3, T_1\rangle$, $\langle M_7, M_8, T_2\rangle$, $\langle M_{10}, M_{11}, M_{12}, T_3\rangle$ and $\langle M_{14}, M_{15}, M_{16}, T_3, T_4\rangle$. Then, $\mathcal{A}$ tries to retrieve the information $\{ID_i, ID_{GWN}, r_{U_i}, r_{GWN}, h(M_4)\}$ by decrypting $M_7$ using $h(ID_{SD_j}||K_{GWN-SD_j})\}$ as $(ID_i, ID_{GWN}, r^*_{U_i}, r_{GWN}, h(M_4)) = D_{h(ID_{SD_j}||K_{GWN-SD_j})}[M_7]$. However, $\mathcal{A}$ can not decrypt $M_{14}$ as $M_4$ is unknown to him/her since as $M_{14} = E_{M_4}[r^*_{U_i}, r_{GWN}, r^*_{SD_j}, ID_{SD_j}, ID_{GWN}, h(M_6)]$. This implies that without having $M_4 = h(ID_i||K_{GWN-U_i})$ $(= M_1)$, it is quite difficult task for $\mathcal{A}$ to extract the information $\{r^*_{U_i}, r_{GWN}, r^*_{SD_j}, ID_{SD_j}, ID_{GWN}, h(M_6)\}$. Thus, computation of the session key $SK_{ij} = h[ID_i\ ||ID_{SD_j}\ ||ID_{GWN}\ ||r_{U_i}\ ||r_{GWN}\ ||r_{SD_j}\ ||h(M_1)\ ||h(M_6)]$ $(= SK'_{ij})$ is difficult as $\mathcal{A}$ needs the necessary information including $r_{SD_j}$ and $M_1$ $(= M_4)$ due to the IND-CPA secure symmetric cipher used in the proposed scheme for encryption/decryption. This concludes that

$$|Pr[SUCC_3] - Pr[SUCC_4]| \leq Adv^{IND-CPA}_{\Omega}(k). \quad (5)$$

In $GM_4$, all the random oracles are simulated. $\mathcal{A}$ is only left to guess the bit $b$ for winning the game after querying the $Test$ oracle. It is clear that $Pr[SUCC_4] = 1/2$.

From Equation (1), we get, $\frac{1}{2}.Adv^{AKE}_{\mathcal{P}} = |Pr[SUCC_0] - \frac{1}{2}|$. Using the triangular inequality, we have, $|Pr[SUCC_1] - Pr[SUCC_4]| \leq |Pr[SUCC_1] - Pr[SUCC_2]| + |Pr[SUCC_2] - Pr[SUCC_4]| \leq |Pr[SUCC_1] - Pr[SUCC_2]| + |Pr[SUCC_2] - Pr[SUCC_3]| + |Pr[SUCC_3] - Pr[SUCC_4]| \leq \frac{q_h^2}{2.|Hash|} + \frac{q_{send}}{2^l.|D|} + Adv^{ECDDHP}_{G_q}(t)$.

Using Equations (2) – (5), we have,

$$|Pr[SUCC_0] - 1/2| \leq q_h^2/(2.|Hash|) + q_{send}/(2^l.|D|) + Adv^{IND-CPA}_{\Omega}(k). \quad (6)$$

Finally, Equation (6) yields the required result:

$$Adv^{AKE}_{\mathcal{P}} \leq \frac{q_h^2}{|Hash|} + \frac{q_{send}}{2^{l-1}.|D|} + 2Adv^{IND-CPA}_{\Omega}(k).$$

□

### 5.2 Formal Security Verification using AVISPA

The proposed scheme is simulated for the formal security verification using the broadly-accepted Automated Validation of Internet Security Protocols and Applications (AVISPA) tool to exhibit that the proposed scheme withstands replay and man-in-the-middle attacks.

AVISPA integrates four back ends that implement different state-of-the-art automatic analysis mechanisms: (i) OFMC; (ii) CL-AtSe; (iii) SATMC; and (iv) TA4SP. The detailed description and functionality of these back ends are available in [15], [35], [36], [37], [38]. A security protocol requires to be implemented in the High Level Protocols Specification Language (HLPSL) [39], which is converted into intermediate format (IF) using the HLPSL2IF translator. The IF is then given as input to one of the four backends to produce output, which has various sections highlighting whether the designed scheme is safe or unsafe against an adversary.

```
role user (Ui, RA, GWN, SDj: agent, H : hash_func,
        SKuira : symmetric_key, Snd, Rcv: channel(dy))
played_by Ui
def=
local State: nat,  IDi, IDsdj, IDgwn, PWi, BIOi, RPWi, A: text,
  R, Kgwnui, Kgwnsdj, Rgwn, Rsdj, T1, M1, Rui, TIDi,TIDinew: text,
  M2, M3, T3, T4, Sigmai: text, Gen, Rep : hash_func
const ui_gwn_t1, ui_gwn_rui, gwn_ui_t4, gwn_ui_tidinew,sr1,sr2: protocol_id
init  State := 0
transition
1. State  = 0 /\ Rcv(start) =|>
% Registration phase
State' := 1  /\ A' := new() /\ R' := new()
          /\ secret({PWi, BIOi, A', R'}, sr1, Ui)
          /\ Sigmai' := Gen(BIOi) /\ RPWi' := xor(H(PWi.Sigmai'.A'), R')
% Send registration request securely to RA
          /\ Snd({IDi.RPWi'}_SKuira)
% Receive information securely from RA for SPi
2. State = 1/\Rcv({xor(H(IDi.Kgwnui),xor(H(PWi.Sigmai'.A'),R')).TIDi'}_SKuira)=|>
% Login phase
State' := 2 /\ secret({Kgwnui,Kgwnsdj}, sr2, GWN)
% Send login request to GWN via public channel
          /\ Rui' := new() /\ T1' := new()/\ M1' := H(IDi.Kgwnui)
          /\ M2' := xor(M1', Rui') /\ M3' := H(M2'.T1'.IDi'.TIDi'.Rui')
          /\ Snd(TIDi'.M2'.M3'.T1')
% Ui has freshly generated the values T1 and Rui for GWN
          /\ witness(Ui,GWN,ui_gwn_t1, T1')/\witness(Ui,GWN,ui_gwn_rui,Rui')
% Authentication and key agreement phase
% Receive authentication reply from GWN via public channel
3. State = 2 /\ Rcv({Rui'.Rgwn'.Rsdj'.IDi.IDsdj.IDgwn.
             H(H(IDsdj.Kgwnsdj))}_H(IDi.Kgwnui).
             xor(TIDinew', H(TIDi'.H(IDi.Kgwnui).T3'.T4')).
             H(H(H(IDi.IDsdj.IDgwn.Rui'.Rgwn'.Rsdj'.
             H(H(IDi.Kgwnui)).H(H(IDsdj.Kgwnsdj))).T3').T4'.Rui').T3'.T4')=|>
% Ui's acceptance of T4 and TIDinew generated for Ui by GWN
State' := 3/\request(GWN,Ui,gwn_ui_t4,T4')/\request(GWN,Ui,gwn_ui_tidinew,TIDinew')
end role
```

Fig. 5. The user $U_i$'s role in HLPSL

The registration, login, authentication and session key agreement phases of our scheme are implemented in HLPSL. In our implementation, four basic roles are defined: *registration authority*, *user*, *gateway node* and *smart device* for representing the $RA$, a user $U_i$, the $GWN$ and a smart device $SD_j$, respectively. The HLPSL role specification $user$ for $U_i$ is given in Fig. 5. $U_i$ as an initiator receives the start signal, updates its state from 0 to 1, and sends the registration request $\langle ID_i, RPW_i\rangle$ to the $RA$ using $Snd(\,)$ channel securely. The $RA$ accepts the registration request of $U_i$, and sends information $\langle A_i, TID_i\rangle$ to $U_i$ using $Snd(\,)$ channel securely. $U_i$ then receives information $\langle A_i, TID_i\rangle$ using $Rcv(\,)$ channel securely. $U_i$ sends the login request $\langle TID_i, M_2, M_3, T_1\rangle$ to the $GWN$ using public channel. The $GWN$ further sends the authentication request $\langle M_7, M_8, T_2\rangle$ to $SD_j$ using public channel. The $SD_j$ also sends reply message $\langle M_{10}, M_{11}, M_{12}, T_3\rangle$ to the $GWN$ using public channel. Finally, the $GWN$ sends authentication reply $\langle M_{14}, M_{15}, M_{16}, T_3, T_4\rangle$ to $U_i$ using public channel. Both $Snd(\,)$ and $Rcv(\,)$ public channels use Dolev-Yao threat model type [9]. So, an intruder (always denoted by $(i)$) can read, modify or delete the contents of exchanged messages. Similarly, we also have specified the roles for $RA$, $GWN$ and $SD_j$ in our HLPSL implementation.

In the session role specified in Fig. 6, all the basic roles are started with concrete arguments. Fig. 6 also consists of top level $environment$ role, which is the starting point for the execution. At the end, in the goal section, four authentication goals and two secrecy goals are specified.

The declaration $witness(Ui, GWN, ui\_gwn\_t1, T1')$ says that $U_i$ has freshly generated the current timestamp $T_1$ for

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$GWN$. The declaration $request(GWN, Ui, gwn\_ui\_t4, T4')$ expresses $U_i$'s acceptance of timestamp $T_4$ generated for $U_i$ by $GWN$. The declaration $secret(\{PWi, A', R'\}, sr1, Ui)$ also says that the information $PW_i$, $a$ and $r$ are only known to $U_i$. This is specified with protocol id $sr1$ in the goal section (given in Fig. 6).

```
role session (Ui, RA, GWN, SDj: agent, H: hash_func, SKuira: symmetric_key)
def=
 local  S1, R1, S2, R2, S3, R3, S4, R4: channel (dy)
 composition
   user (Ui, RA, GWN, SDj, H, SKuira, S1, R1)
/\ registrationauthority(Ui, RA, GWN, SDj, H, SKuira, S2, R2)
/\ gatewaynode (Ui, RA, GWN, SDj, H, SKuira, S3, R3)
/\ smartdevice (Ui, RA, GWN, SDj, H, SKuira, S2, R2)
end role

role environment()
def=
 const ui, ra, gwn, sdj: agent, h: hash_func, skuira: symmetric_key,
    kgwnui, kgwnsdj, idi, idsnj, idgwn, t1, t2, t3, t4, tidi, tidinew: text,
    gen, rep: hash_func, ui_gwn_t1, ui_gwn_rui, gwn_sdj_t2, gwn_sdj_rgwn,
    sdj_gwn_t3, sdj_gwn_rsdj, sr1, s2: protocol_id
intruder_knowledge ={t1, t2, t3, t4, h, gen, rep}
composition
 session(ui, ra, gwn, sdj, h, skuira) /\ session(i, ra, gwn, sdj, h, skuira)
/\ session(ui, i, gwn, sdj, h, skuira) /\ session(ui, ra, i, sdj, h, skuira)
/\ session(ui, ra, gwn, i, h, skuira)
end role

goal
 secrecy_of sr1, sr2
 authentication_on ui_gwn_t1, ui_gwn_rui, gwn_sdj_t2
 authentication_on gwn_sdj_rgwn, sdj_gwn_t3, sdj_gwn_rsdj
 authentication_on gwn_ui_t4, gwn_ui_tidinew
end goal
environment()
```

Fig. 6. The session, goal and environment roles in HLPSL

We have simulated our scheme using the widely-used OFMC and CL-AtSe backends. The executability check on non-trivial HLPSL specifications, replay attack check, and Dolev-Yao model check are verified in the proposed scheme. For more details on these verifications, one can refer to [31], [40]. The simulation results shown in Fig. 7 depicts that the proposed scheme is secure against replay as well as man-in-the-middle attacks.

```
% OFMC
% Version of 2006/02/13
SUMMARY
  SAFE
DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
PROTOCOL
  C:\progra~1\SPAN\testsuite
    \results\user_auth.if
GOAL
  as_specified
BACKEND
  OFMC
COMMENTS
STATISTICS
  parseTime: 0.00s
  searchTime: 7.75s
  visitedNodes: 1432 nodes
  depth: 8 plies
```

```
SUMMARY
  SAFE
DETAILS
  BOUNDED_NUMBER_OF_SESSIONS
  TYPED_MODEL
PROTOCOL
  C:\progra~1\SPAN\testsuite
    \results\user_auth.if
GOAL
  As Specified

BACKEND
  CL-AtSe

STATISTICS
  Analysed  : 8 states
  Reachable  : 0 states
  Translation: 0.14 seconds
  Computation: 0.00 seconds
```

Fig. 7. The results of the analysis using OFMC and CL-AtSe backends

## 5.3 Informal Security Analysis

The informal security analysis shows that the following other possible known attacks are prevented.

### 5.3.1 Traceability

In many applications, it is desirable that a user authentication should not allow an adversary to trace a user during login and authentication phases. Therefore, it also becomes important that the identity of the user should no be revealed to an adversary to preserve the privacy of that user in a network, especially in a smart home environment. The login request $\langle TID_i, M_2, M_3, T_1\rangle$ sent by $U_i$ to the $GWN$ is different each time due to the following reason. The smart phone $SP_i$ of $U_i$ computes $M_1 = A^* \oplus RPW_i^* = h(ID_i || K_{GWN-U_i})$, $M_2 = M_1 \oplus r_{U_i}$ and $M_3 = h(M_2 || T_1 || ID_i || TID_i || r_{U_i})$, where $T_1$ is current timestamp and $r_{U_i}$ random nonce of $U_i$. The involvement of $T_1$ and $r_{U_i}$ ensures that $M_2$ and $M_3$ are distinct for each session. Moreover, other exchanged messages $\langle M_7, M_8, T_2\rangle$, $\langle M_{10}, M_{11}, M_{12}, T_3\rangle$ and $\langle M_{14}, M_{15}, M_{16}, T_3, T_4\rangle$ are also different for each session due to the use of timestamps and random nonces. In addition, our scheme allows to update old $TID_i$ with a new $TID_i^{new}$ for each session while the message $\langle M_{14}, M_{15}, M_{16}, T_3, T_4\rangle$ is sent to $U_i$ by the $GWN$. After receiving the message, $SP_i$ of the user $U_i$ calculates $TID_i^{new} = M_{15} \oplus h(TID_i || M_1 || T_3 || T_4)$ and replaces $TID_i$ with $TID_i^{new}$ in its memory. Due to this, $TID_i$ in the login request messages are distinct for different sessions. Thus, our scheme avoids traceability of $U_i$ and $SD_j$ by an attacker.

### 5.3.2 Anonymity

Prior to sending the login request $\langle TID_i, M_2, M_3, T_1\rangle$ to the $GWN$, $U_i$ hides its identity $ID_i$ in $M_1 = A^* \oplus RPW_i^* = h(ID_i || K_{GWN-U_i})$, $M_2$ and $M_3$. The $GWN$ also hides the identities of $U_i$ and $SD_j$ as it computes $M_6 = h(ID_{SD_j} || K_{GWN-SD_j})$, $M_7 = E_{M_6}[ID_i, ID_{GWN}, r_{U_i}, r_{GWN}, h(M_4)]$ and $M_8 = h(M_6 || T_2 || ID_i || ID_{SD_j} || ID_{GWN} || r_{GWN})$ and $M_{14} = E_{M_4}[r_{U_i}, r_{GWN}, r_{SD_j}, ID_{SD_j}, ID_{GWN}, h(M_6)]$. $SD_j$ also hides its own identity by computing $M_{10} = h(h(ID_{SD_j} || K_{GWN-SD_j}) || T_3) \oplus r_{SD_j}$. If an attacker intercepts all the messages during login and authentication phases, he/she is unable to identify $ID_i$ and $ID_{SD_j}$ as these are protected by symmetric encryption and one-way cryptographic hash function $h(\cdot)$. Therefore, the user and smart device anonymity are preserved in our scheme.

### 5.3.3 Privileged-Insider Attack

Suppose $\mathcal{A}$ is a malicious insider user of the $RA$, who knows $ID_i$ and $RPW_i$, which were sent to $RA$ by $U_i$ during his/her registration phase. Note that $RPW_i = h(PW_i || \sigma_i || a) \oplus r$. We assume that $\mathcal{A}$ obtains the smart phone $SP_i$ of $U_i$ only after the user registration phase is finished. $\mathcal{A}$ can then extract all the information $\{TID_i, A_i^*, B_i, C_i, \tau_i, h(\cdot), Gen(\cdot), Rep(\cdot), t\}$ stored in $SP_i$ using the power analysis attacks [41]. Note that the user $U_i$ already deleted the information $A_i$ from its smart phone $SP_i$ at the end of the user registration phase described in Section 4.2. Hence, without having $A_i$, it is computationally hard for $\mathcal{A}$ to derive the secret $r$ as $r = A_i^* \oplus A_i$. As a result, without $r$, $\mathcal{A}$ can not derive $h(PW_i || \sigma_i || a) = RPW_i \oplus r$. Furthermore, without knowing $a$, it is computationally infeasible to derive the biometric key $\sigma_i$ as $h(ID_i || \sigma_i) = B_i \oplus a$. As a consequence, without having $a$, $\sigma_i$ and $K_{GWN-U_i}$, it is also computationally hard for $\mathcal{A}$ to guess correctly the password $PW_i$ of $U_i$ from $C_i = h(ID_i || RPW_i' || \sigma_i) = h(ID_i || (h(ID_i || K_{GWN-U_i}) \oplus h(PW_i || \sigma_i || a)) || \sigma_i)$. In summary, it is computationally hard for $\mathcal{A}$ to guess and verify correctly $PW_i$ and $\sigma_i$ from $RPW_i$, $A_i^*$, $B_i$ and $C_i$ due to the collision resistant property of $h(\cdot)$. Therefore, our scheme is secure against the privileged-insider attack.

#### 5.3.4 Stolen Smart Phone Attack

Suppose the smart phone $SP_i$ of $U_i$ is lost or stolen by an attacker $\mathcal{A}$. $\mathcal{A}$ can then extract all information $\langle TID_i, A_i^*, B_i, C_i, \tau_i, h(\cdot), Gen(\cdot), Rep(\cdot), t\rangle$ stored in $SP_i$ using the power analysis attacks [41]. Note that $B_i = h(ID_i||\sigma_i) \oplus a$, $RPW_i' = RPW_i \oplus r = h(PW_i \,||\sigma_i \,||a)$, $C_i = h(ID_i \,||RPW_i' \,||\sigma_i)$ and $A_i^* = A_i \oplus r = h(ID_i \,||K_{GWN-U_i}) \oplus RPW_i'$. To correctly guess $ID_i$ and $PW_i$ from $B_i$ and $C_i$ respectively, $\mathcal{A}$ needs to know both $a$ and $r$. Again, to know $a$ from $B_i$, $\mathcal{A}$ needs both $ID_i$ and $PW_i$. Thus, it is computationally infeasible for $\mathcal{A}$ to correctly guess both $ID_i$ and $PW_i$ as $ID_i$ and $PW_i$ are protected by the one-way hash function $h(\cdot)$. Therefore, our scheme is secure against such an attack.

#### 5.3.5 Session Key Security

The session key $SK_{ij} = h[ID_i|| \, ID_{SD_j} \,||ID_{GWN} \,||r_{U_i} \,||r_{GWN} \,||r_{SD_j} \,||h(M_4) \,||h(h(ID_{SD_j} \,||K_{GWN-SD_j}))]$ is calculated by both $U_i$ and $SD_j$. The message $\{M_{10}, M_{11}, M_{12}, T_3\}$ sent by $SD_j$ to $GWN$ contains session key $SK_{ij}$ as $M_{11} = h(SK_{ij} \,||T_3)$. Suppose an attacker $\mathcal{A}$ intercepts this message and tries to compute the session key $SK_{ij}' = h[ID_i \,||ID_{SD_j} \,||ID_{GWN} \,||r_{U_i} \,||r'_{GWN} \,||r'_{SD_j} \,||h(M_4) \,||h(h(ID_{SD_j} \,||K_{GWN-SD_j}))]$ by generating the random nonces $r'_{U_i}$, $r'_{GWN}$, $r'_{SD_j}$ and timestamp $T_3'$. However, the computation of $SK_{ij}'$ is not possible for $\mathcal{A}$ because he/she does not know the various identities $ID_i$, $ID_{SD_j}$, $ID_{GWN}$, secret key $K_{GWN-SD_j}$, $M_4' = h(ID_i \,||K_{GWN-U_i})$. Without the knowledge of these parameters, and due to the collision resistance property of $h(\cdot)$, it is very difficult for $\mathcal{A}$ to obtain $SK_{ij}'$. Therefore, our scheme preserves the session key security.

#### 5.3.6 User Impersonation Attack

Suppose there is an adversary $\mathcal{A}$, who has the lost/stolen smart phone $SP_i$ of a legal user $U_i$, and knows all the information stored in $SP_i$ by the help of power analysis attacks [41]. Assume that $\mathcal{A}$ intercepts $U_i$'s login request $\langle TID_i, M_2, M_3, T_1\rangle$ and tries to create another valid login request, say $\langle TID_i, M_2', M_3', T_1'\rangle$ on behalf of $U_i$, using the current timestamp $T_1'$ of his/her system. To compute $M_2'$, $M_1'$ is required to compute as $M_1' = A^* \oplus RPW_i^* = h(ID_i \,||K_{GWN-U_i})$. Suppose $\mathcal{A}$ generates random nonce $r'_{U_i}$. To calculate $M_2' = M_1' \oplus r'_{U_i}$ and $M_3' = h(M_2' \,||T_1'|| \, ID_i|| \, TID_i \,||r'_{U_i})$, $\mathcal{A}$ needs $ID_i$ and $K_{GWN-U_i}$, which are infeasible for him/her to obtain them. Due to the one-way hash function $h(\cdot)$, it is computationally infeasible for $\mathcal{A}$ to create valid login request $\langle TID_i, M_2', M_3', T_1'\rangle$ on behalf of $U_i$, even he/she knows the all information from the lost/stolen $SP_i$. So, it is clear that our scheme is secure against the user impersonation attack.

#### 5.3.7 GWN Impersonation Attack

Suppose an adversary $\mathcal{A}$ intercepts the messages $\langle M_7, M_8, T_2\rangle$ and $\langle M_{14}, M_{15}, M_{16}, T_3, T_4\rangle$, and attempts to create other valid messages, say $\langle M_7', M_8', T_2'\rangle$ and $\langle M_{14}', M_{15}', M_{16}', T_3', T_4'\rangle$ on behalf of the $GWN$, where $M_7 = E_{M_6}[ID_i, ID_{GWN}, r_{U_i}, r_{GWN}, h(M_4)]$, $M_6 = h(ID_{SD_j} \,||K_{GWN-SD_j})$, $M_4 = h(ID_i \,||K_{GWN-U_i})$ and $M_8 = h(M_6 \,||T_2 \,||ID_i \,||ID_{SD_j} \,||ID_{GWN} \,||r_{GWN})$, $M_{14} = E_{M_4}[r_{U_i}, r_{GWN}, r_{SD_j}, ID_{SD_j}, ID_{GWN}, h(M_6)]$, $M_{15} = TID_i^{new} \oplus h(TID_i \,||M_4 \,||T_3 \,||T_4)$, $M_{16} = h(M_{11} \,||T_4 \,||r_U)$. Suppose $T_2'$, $T_3'$, $T_4'$ and $r'_{U_i}$, $r'_{GWN}$, $r'_{SD_j}$ are the current timestamps and different random nonces generated by $\mathcal{A}$. To compute $M_7'$, $M_6'$, $M_4'$ and $M_8'$, the secret key $K_{GWN-SD_j}$, and various identities $ID_i$, $ID_{SD_j}$ and $ID_{GWN}$ are required. To calculate $M_{14}'$, $M_{15}'$ and $M_{16}'$, the secret key $K_{GWN-U_i}$, and various identities $TID_i$, $ID_i$, $ID_{SD_j}$ and $ID'_{GWN}$ are required. Moreover, the messages are protected by the one-way hash function $h(\cdot)$. Thus, $\mathcal{A}$ is not able to create other valid messages $\langle M_7', M_8', T_2'\rangle$, $\langle M_{14}', M_{15}', M_{16}', T_3', T_4'\rangle$ on behalf of the $GWN$. Therefore, the proposed scheme is secure against the $GWN$ impersonation attack.

#### 5.3.8 Smart Device Impersonation Attack

Suppose an adversary $\mathcal{A}$ intercepts the message $\langle M_{10}, M_{11}, M_{12}, T_3\rangle$ and attempts to create another valid message, say $\langle M_{10}', M_{11}', M_{12}', T_3'\rangle$ on behalf of the smart device $SD_j$, where $T_3'$ is the current timestamp of $\mathcal{A}$'s system when this message is created. Note that $M_{10}' = h(h(ID_{SD_j} \,||K_{GWN-SD_j}) \,||T_3') \oplus r'_{SD_j}$, $M_{11}' = h(SK_{ij}' \,||T_3')$, $SK_{ij}' = h[ID_i \,||ID_{SD_j} \,||ID_{GWN} \,||r'_{U_i} \,||r'_{GWN} \,||r'_{SD_j} \,||h(M_4) \,||h(h(ID_{SD_j} \,||K_{GWN-SD_j}))]$, $M_{12}' = h(r'_{SD_j} \,||r'_{GWN} \,||ID_{SD_j} \,||ID_{GWN} \,||T_3')$ and $M_4' = h(ID_i \,||K_{GWN-U_i})$, where $r'_{U_i}$, $r'_{GWN}$ and $r'_{SD_j}$ are the random nonces created by $\mathcal{A}$. To calculate $M_{10}'$, $M_{11}'$ and $M_{12}'$, the secret keys $K_{GWN-SD_j}$ and $h(ID_i \,||K_{GWN-U_i})$, and various identities $ID_i$, $ID_{SD_j}$ and $ID_{GWN}$ are necessary. Therefore, $\mathcal{A}$ is not able to create another valid message $\langle M_{10}', M_{11}', M_{12}', T_3'\rangle$ on behalf of $SD_j$. This confirms that the proposed scheme is secure against this attack.

#### 5.3.9 Resilience against Smart Device Capture Attack

Suppose a smart device $SD_j$ is physically captured by an attacker $\mathcal{A}$. Each $SD_j$ contains the information $\{ID_{SD_j}, h(ID_{SD_j} \,||K_{GWN-SD_j})\}$. Since each $K_{GWN-SD_j}$ is distinct, $h(ID_{SD_j} \,||K_{GWN-SD_j})$ is also distinct for each $SD_j$. If $\mathcal{A}$ tries to extract $K_{GWN-SD_j}$ from $h(ID_{SD_j}||K_{GWN-SD_j})$ using $ID_{SD_j}$, it is difficult task for $\mathcal{A}$ to compute $K_{GWN-SD_j}$ as $K_{GWN-SD_j}$ is a long 1024-bit secret key. However, $\mathcal{A}$ can know the session key $SK_{ij}$ shared with the legal user $U_i$, which is stored in $SD_j$'s memory. Thus, compromise of this particular smart device $SD_j$ in the smart home network does not lead to compromise of the session keys between that $U_i$ and other non-compromised smart devices $SD_l$'s as the stored $h(ID_{SD_l} \,||K_{GWN-SD_l})$ is distinct for $SD_l$. The proposed scheme is then unconditionally secure against this attack.

#### 5.3.10 Gateway Bypass Attack

In our scheme, both $U_i$ and $SD_j$ can not bypass the $GWN$ due to the following argument. $U_i$ can only send the login request through the $GWN$, and $SD_j$ can send the authentication response only through the $GWN$. Both $U_i$ and $SD_j$ also establish the session key $SK_{ij}$ through the $GWN$. When the $GWN$ receives login request from $U_i$, it computes $M_7 = E_{M_6}[ID_i, ID_{GWN}, r_{U_i}^*, r_{GWN}, h(M_4)]$ and $M_8 = h(M_6 \,||T_2 \,||ID_i \,||ID_{SD_j} \,||ID_{GWN} \,||r_{GWN})$ and sends $\langle M_7, M_8, T_2\rangle$ to $SD_j$, where $M_6 = h(ID_{SD_j} \,||K_{GWN-SD_j})$, and $T_2$ is the current timestamp generated by $U_i$. $U_i$ can not compute $M_6$ as he/she does not know $K_{GWN-SD_j}$ and it is only known to the $GWN$. Therefore, $U_i$ is not able to compute $M_7$ and $M_8$. When the $GWN$ receives authentication reply from $SD_j$, it computes $M_{14} = E_{M_4}[r_{U_i}^*, r_{GWN}, r_{SD_j}^*, ID_{SD_j}, ID_{GWN}, h(M_6)]$, $M_{15} = TID_i^{new} \oplus h(TID_i \,||M_4 \,||T_3 \,||T_4)$, $M_{16} = h(M_{11} \,||T_4 \,||r_{U_i}^*)$ and sends the message $\langle M_{14}, M_{15}, M_{16}, T_3, T_4\rangle$ to $U_i$. $SD_j$ can not compute $M_4$ as he/she does not know $K_{GWN-U_i}$. Therefore,

$SD_j$ can not compute $M_{14}$ and $M_{15}$. To compute $M_{16}$, even if $SD_j$ chooses current timestamp $T_4'$ to compute $M_{16} = h(M_{11} ||T_4' ||r_{U_i}^*)$, but he/she does not know the random nonce $r_{U_i*}$ of the user $U_i$. So, $SD_j$ can not compute $M_{14}$, $M_{15}$ and $M_{16}$. As a result, neither $U_i$ nor $GWN$ bypass the $GWN$ in our proposed scheme.

#### 5.3.11 Offline-Dictionary Attack

We consider an interesting attack scenario in our proposed scheme as illustrated by Huang *et al.* [34] to verify whether an adversary $\mathcal{A}$ can derive the password of a legal user $U_i$ or not. As in [34], we also consider the following attacking scenario as follows.

- At time $T_1$, suppose $U_i$ invokes the password and biometric update phase to change the password to $PW_{i1}$. At the end of this phase, the smart phone $SP_i$ of $U_i$ contains the information $\langle TID_i,\ A_i^*,\ B_i,\ C_i,\ \tau_i,\ h(\cdot),\ Gen(\cdot),\ Rep(\cdot), t\rangle$, where $A_i^* = h(ID_i ||K_{GWN-U_i}) \oplus h(PW_{i1} ||\sigma_{i1} ||a)$ and $\sigma_{i1}$ is the biometric key derived from the new biometrics $BIO_{i1}$ entered by $U_i$ at this time.
- At some time later (say, $T_2$), $U_i$ again changes his/her password $PW_1$ to a new password $PW_2$. At the end of this phase, the $SP_i$ of $U_i$ contains the information $\langle TID_i,\ A_i^{**},\ B_i,\ C_i,\ \tau_i,\ h(\cdot),\ Gen(\cdot),\ Rep(\cdot),\ t\rangle$, where $A_i^{**} = h(ID_i ||K_{GWN-U_i}) \oplus h(PW_{i2} ||\sigma_{i2} ||a)$ and $\sigma_{i2}$ is the biometric key derived from the new biometrics $BIO_{i2}$ entered by $U_i$ at this time $T_2$.
- A passive adversary $\mathcal{A}$ with smart phone can obtain the data stored in the smart phone at time $T_1$ and $T_2$.

Now, given $(A_i^*, A_i^{**})$, $\mathcal{A}$ can calculate $A_i^* \oplus A_i^{**} = h(PW_{i1} ||\sigma_1 ||a) \oplus h(PW_{i2} ||\sigma_{i2} ||a)$. By testing all password pairs in the password dictionary, $\mathcal{A}$ can try to find at least one pair $(pw_1, pw_2)$ such that $A_i^* \oplus A_i^{**} = h(pw_1 ||\sigma_{i1} ||a) \oplus h(pw_2 ||\sigma_{i2} ||a)$. However, to satisfy this condition, $\mathcal{A}$ further needs to guess correctly the biometric keys pair $(\sigma_{i1}, \sigma_{i2})$. In addition, $\mathcal{A}$ also needs the random secret $a$ which is only known to $U_i$. To derive $a$, $\mathcal{A}$ requires to guess the biometric key too. Thus, without having the biometric keys pair $(\sigma_{i1}, \sigma_{i2})$ and random secret $a$, it is computationally infeasible problem for $\mathcal{A}$ to verify whether the guessed passwords pair $(pw_1, pw_2)$ is correct or not. As a result, the proposed scheme has the ability to protect the offline-dictionary attack described in [34].

## 6 Practical Perspective: NS2 Simulation

The proposed scheme is simulated using the widely-accepted networking simulation tool, NS2 2.35 simulator [16] on Ubuntu 14.04 LTS platform.

### 6.1 Simulation Parameters

The various simulation parameters are given in Table 2. The network coverage area is taken as $400 \times 200\ m^2$. The communication ranges of the gateway node $(GWN)$ and smart devices $(SD_j)$ are taken as $200m$ and $50m$, respectively. The network simulation time is taken as 1800 seconds (30 minutes). The traditional Ad hoc On-Demand Distance Vector (AODV) routing protocol is used as the routing protocol. Two types of users are taken in the simulation: first type consists of the static users, who do not move (for example, some smart home users seat on the chair and access $SD_j$), while the second type has moving users (for example, somebody is walking in the garden and accessing $SD_j$, or somebody is driving the card and accessing $SD_j$). The speeds for these smart home users are considered as 2, 10 and 15 $mps$, respectively.

### 6.2 Simulation Environment

We have considered the following three network scenarios in the simulation. For all the scenarios, we have taken one $GWN$ and 50 $SD_j$s.

*Scenario 1.* In this case, we have taken two users ($U_i$s): one is static and other one is moving with 2 $mps$.

*Scenario 2.* In this case, we have taken three users ($U_i$s): one is static and other two are moving with the speeds of 2 $mps$ and 15 $mps$, respectively.

*Scenario 3.* In this case, we have taken eight users ($U_i$s): four are static and other four are moving with the speeds of 2 $mps$, 2 $mps$, 10 $mps$ and 15 $mps$, respectively.

Moreover, we assume that the bit lengths of the identity, hash output (if we use SHA-1 hash algorithm) and random number/nonce are 128, 160 and 128 bits, respectively. In each scenario, we have considered the following messages between different network entities: $\langle TID_i, M_2, M_3, T_1\rangle$, $\langle M_7, M_8, T_2\rangle$, $\langle M_{10}, M_{11}, M_{12}, T_3\rangle$ and $\langle M_{14}, M_{15}, M_{16}, T_3, T_4\rangle$ of sizes 480 bits, 960 bits, 512 bits and 1280 bits, respectively.

TABLE 2
Various simulation parameters

| Parameter | Description |
|---|---|
| Platform | Ubuntu 14.04 LTS |
| Network coverage area | $400 \times 200\ m^2$ |
| Network scenarios | 1, 2 and 3 |
| Number of users ($U_i$) | 2, 3, 8 for scenarios 1, 2, 3 |
| Number of gateway nodes ($GWN$) | 1 for all scenarios |
| Number of smart devices ($SD_j$) | 50 for all scenarios |
| Mobility | 2 $mps$, 10 $mps$, 15 $mps$ |
| Simulation time | 1800 seconds |
| Routing protocol | AODV |
| Communication range of $GWN$ | 200 $m$ |
| Communication range of $SD_j$ | 50 $m$ |

### 6.3 Simulation Results and Discussions

The network performance parameters, such as end-to-end delay (in seconds) and throughput (in bps) are calculated during the simulation.

#### 6.3.1 Impact on End-to-end Delay

The end-to-end delay $(EED)$ is calculated as the average time taken by the data packets to arrive at the destination from the source. The $EED$s of our scheme for different scenarios are given Fig. 8(a). The $EED$s are 0.29832, 0.28687 and 0.28637 seconds for the network scenarios 1, 2 and 3, respectively. Note that the $EED$ decreases in the scenarios 2 and 3, because in these scenarios we have considered more number of mobile users who are traveling towards the gateway node as compared to the scenario 1. For this reason, the $EED$ reduces as the distance between the gateway node and mobile users decreases which affects the reducibility of the $EED$s accordingly.

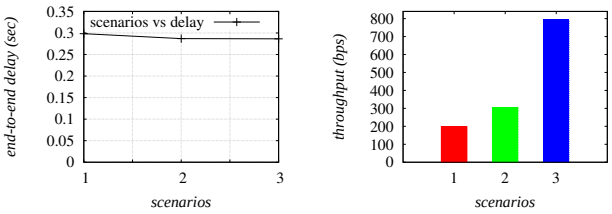


Fig. 8. (a) End-to-end delay (b) Throughput

### 6.3.2 Impact on Throughput

The throughput is measured as the number of bits transmitted per unit time. Fig. 8(b) depicts the network throughput (in bps) of our scheme under different network scenarios. The throughput values are $197.56$, $303.87$ and $793.78$ $bps$ for the scenarios $1$, $2$ and $3$, receptively. Note that the throughput increases with an increase in the number of users. Due to the large number of users, more number of messages are exchanged in the network, and as a result, the throughput also increases.

## 7 Performance Comparison

In this section, the proposed scheme is compared with related existing schemes of Kumar *et al.* [5], Vaidya *et al.* [21], Kim and Kim [22], Jeong *et al.* [20], and Santoso and Vun [25] during the login, and authentication and key agreement phases. Since the registration, and password and biometric update phases are not frequent, the costs involved in these phases are not discussed.

The communication costs of different existing schemes and our scheme are compared in Table 3. We have made a reasonable assumption that the identities are $128$ bits in length; random nonces are $128$ bits; timestamps are $32$ bits; plaintext/ciphertext block in symmetric encryption/decryption (using AES-CBC algorithm) is $128$ bits, and the hash digest is of $160$ bits (if we use SHA-1 as $h(\cdot)$ [42]). By considering these values, the communication costs for the schemes of Kumar *et al.*, Vaidya *et al.*, Kim-Kim, Jeong *et al.*, Santoso-Vun and our scheme are $1696$, $2272$, $4352$, $1568$, $4416$, and $3232$ bits, respectively. Note that in our scheme, the messages $MSG_1 = \langle TID_i, M_2, M_3, T_1\rangle$, $MSG_2 = \langle M_7, M_8, T_2\rangle$, $MSG_3 = \langle M_{10}, M_{11}, M_{12}, T_3\rangle$, $MSG_4 = \langle M_{14}, M_{15}, M_{16}, T_3, T_4\rangle$ are used. The cost of $M_7$ is $\lceil(128+ 128+ 128+ 128+ 160)\ /128\rceil \times 128 = 768$ bits. Similarly, $M_{14}$ needs $\lceil(128 +128 +128 +128 +128 +160)\ /128\rceil \times 128 = 896$ bits. So, the communication costs of different messages $MSG_1$, $MSG_2$, $MSG_3$ and $MSG_4$ are $480$ bits, $960$ bits, $512$ bits, and $1280$ bits, respectively. As a result, the total communication cost of the proposed scheme turns out to be $(480+ 960+ 512+ 1280) = 3232$ bits. Though our scheme requires more communication cost as compared to that for the schemes of Kumar *et al.*, Vaidya *et al.* and Jeong *et al.*, it is justified as our scheme supports additional functionality and security features (see Table 5).

In Table 4, we have used the notations $T_{exp}$, $T_E/T_D$, $T_h$, $T_{fe}$, $T_{mac}$ and $T_{hmac}$ to denote the computational time for modular exponentiation operation, symmetric encryption/decryption, hash function $h(\cdot)$ (using SHA-1 hashing algorithm), $Gen(\cdot)/Rep(\cdot)$, message authentication code (MAC) and hashed MAC, respectively. The bitwise XOR operation execution time is negligible, and we do not consider it as a performance evaluation parameter. The existing experimental values of these operations are given as follows in [43], [44]: $T_{exp}$, $T_h$, $T_E/T_D$, and $T_{fe}$ are $0.0192s$, $0.00032s$, $0.0056s$ and $0.0171s$, respectively. It is further assumed that $T_{mac} \approx T_{hmac} \approx T_h$. The computational costs of various schemes are given in Table 4. The total computational cost for our scheme is $22T_h+ 4T_E/T_D + T_{fe}$, whereas the computational cost for a smart device is $7T_h+ T_D \approx 7.84ms$ only. This indicates that our scheme is suitable for resource-constrained smart devices. The computation cost of our scheme is more than that for the schemes of Kumar *et al.*, Vaidya *et al.*, Kim-Kim and Jeong *et al.*, because we have used the fuzzy extractor for providing additional security level of the system as compared to other schemes. However, our scheme provides extra functionality features and security features, and the cost for a resource constrained smart device is low.

TABLE 3
Communication cost comparisons

| Scheme | Total messages | Total cost $(bits)$ |
|---|---|---|
| Kumar *et al.* [5] | 3 | 1696 |
| Vaidya *et al.* [21] | 2 | 2272 |
| Kim-Kim [22] | 2 | 4352 |
| Jeong *et al.* [20] | 2 | 1568 |
| Santoso-Vun [25] | 3 | 4416 |
| Our | 4 | 3232 |

TABLE 4
Computation costs comparison

| Scheme/phase | Total cost | Rough estimation |
|---|---|---|
| Kumar *et al.* [5] | $2T_h + T_{mac}$ $+1T_{hmac} + 2T_E/T_D$ | 12.48 ms |
| Vaidya *et al.* [21] | $20T_h + 3T_E/T_D$ | 23.20 ms |
| Kim-Kim [22] | $30T_h + 3T_E/T_D$ | 26.40 ms |
| Jeong *et al.* [20] | $10T_h + 3T_E/T_D$ | 20.00 ms |
| Santoso-Vun [25] | $2T_h + 3T_{exp}$ | 58.24 ms |
| Our | $22T_h + 4T_E/T_D + T_{fe}$ | 46.54 ms |

Finally, the functionality and security features comparison among our scheme and other schemes is shown in Table 5. The scheme of Vaidya *et al.* is insecure against privileged-insider, password guessing, and smart device capture attacks, and it does not have the traceability, user anonymity and smart device anonymity properties. Moreover, the dynamic smart device addition phase, offline smart device registration phase, formal security proof under standard model and formal security verification using AVISPA are not supported in their scheme. Kim-Kim's scheme is vulnerable to password guessing attack, password change attcak, privileged-insider attack, user impersonation attack through privileged-insider attack and smart device capture attack, and it does not have traceability, user anonymity and smart device anonymity properties. Additionally, the dynamic smart device addition phase, offline smart device registration phase, formal security proof under the ROR model and formal security verification using AVISPA are not available in Kim-Kim's scheme. Kumar *et al.* does not support traceability and gateway anonymity properties and it does not provide formal security proof under the ROR model. The schemes of Kumar *et al.*, Jeong *et al.* and Santoso-Vun also lack the functionality features, which are shown in Table 5. In summary, our scheme provides significantly better security and functionality features as compared to those for other existing schemes.

## 8 Conclusion

This paper presents a new scheme to address the user authentication issue in a smart home environment. The proposed scheme

TABLE 5
Security and functionality features comparison

| Functionality features | [5] | [21] | [22] | [20] | [25] | Our |
|---|---|---|---|---|---|---|
| $SFF_1$ | ✓ | × | × | × | × | ✓ |
| $SFF_2$ | × | × | × | × | ✓ | ✓ |
| $SFF_3$ | × | ✓ | ✓ | ✓ | × | ✓ |
| $SFF_4$ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $SFF_5$ | × | × | × | × | × | ✓ |
| $SFF_6$ | N/A | × | × | × | × | ✓ |
| $SFF_7$ | N/A | ✓ | × | × | × | ✓ |
| $SFF_8$ | ✓ | × | × | × | × | ✓ |
| $SFF_9$ | N/A | × | × | × | × | ✓ |
| $SFF_{10}$ | × | × | ✓ | ✓ | × | ✓ |
| $SFF_{11}$ | ✓ | × | × | × | × | ✓ |
| $SFF_{12}$ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $SFF_{13}$ | ✓ | × | × | × | ✓ | ✓ |
| $SFF_{14}$ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $SFF_{15}$ | N/A | × | ✓ | × | × | ✓ |
| $SFF_{16}$ | N/A | ✓ | × | × | × | ✓ |
| $SFF_{17}$ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $SFF_{18}$ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $SFF_{19}$ | ✓ | ✓ | ✓ | ✓ | × | ✓ |
| $SFF_{20}$ | ✓ | × | × | × | × | ✓ |
| $SFF_{21}$ | ✓ | × | × | × | × | ✓ |
| $SFF_{22}$ | N/A | ✓ | ✓ | ✓ | × | ✓ |
| $SFF_{23}$ | N/A | × | × | × | × | ✓ |
| $SFF_{24}$ | × | × | × | × | × | ✓ |
| $SFF_{25}$ | ✓ | × | × | × | × | ✓ |

*Note:* $SFF_1$: mutual authentication between $GWN$ and smart device; $SFF_2$: mutual authentication between user and smart device; $SFF_3$: mutual authentication between user and $GWN$; $SFF_4$: key agreement; $SFF_5$: traceability property; $SFF_6$: password guessing attack; $SFF_7$: password change attack; $SFF_8$: dynamic smart device addition phase; $SFF_9$: user anonymity property; $SFF_{10}$: $GWN$ anonymity property; $SFF_{11}$: smart device anonymity property; $SFF_{12}$: replay attack; $SFF_{13}$: privileged-insider attack; $SFF_{14}$: man-in-the-middle attack; $SFF_{15}$: stolen smart phone/smart card attack; $SFF_{16}$: user impersonation attack; $SFF_{17}$: smart device impersonation attack; $SFF_{18}$: GWN bypassing attack; $SFF_{19}$: DoS attack; $SFF_{20}$: resilient against smart device capture attack; $SFF_{21}$: offline smart device registration phase; $SFF_{22}$: password change phase; $SFF_{23}$: biometric update phase; $SFF_{24}$: formal security proof under ROR model; $SFF_{25}$: formal security verification using AVISPA.
✓: the scheme is secure or supports a particular functionality/security feature; ×: the scheme is not secure or does not support a particular functionality/security feature. $N/A$: not applicable in the scheme.

provides additional functionality features. The proposed scheme is secure against several known attacks, which are shown through random oracle model, informal security and AVISPA tool. The practical implementation of the proposed scheme is also demonstrated though the widely-accepted NS-2 simulator. Overall, the proposed scheme provides a better trade-off between security and functionality features provided in Table 5, and overheads as compared to other existing related schemes.

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