Analysis and Improvement on A Lightweight Two-factor Authentication Scheme for Wireless Body Area Networks in Health-care IoT

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Abstract: Recently, medical and healthcare associations have gradually begun to use the Internet of Things and wireless sensor networks to monitor, collect data, and use wireless body area networks (WBANs) to communicate with patients. However, due to the characteristics of wireless networks that can freely access data on public channels, WBANs face some problems in the security and privacy protection. At the same time, some authentication schemes for wireless body area networks have also been proposed. In this paper, we carefully analyze Fotouhi et al.'s authentication scheme for wireless body area networks in health-care IoT and find that Fotouhi et al.'s scheme is vulnerable to several weaknesses. The main shortcoming of Fotouhi et al.'s scheme is that it takes up too much storage space of each entity during the registration and authentication phase. To overcome the shortcomings of Fotouhi et al.'s scheme, we propose an improved scheme. In our improved scheme, each entity will store less data than Fotouhi et al.'s scheme in the registration phase. Furthermore, we make the gateway node store as little data as possible by adding some key information to the transmitted messages in the authentication phase of the improved scheme. These measures can greatly save a lot of storage space and improve efficiency. We also investigate the security of the improved scheme in informal analysis and formal analysis.

Keywords: WBAN, Healthcare, Authentication scheme, Safety.

1. Introduction

The wireless body area network (WBAN) can perform real-time medical care monitoring and support through various intelligent medical sensors in or around the patient. These networks are especially helpful for elderly people who need long-term care and do not need to be hospitalized. However, the security of messages transmitted between patients and doctors is also an issue. An adversary can eavesdrop, intercept, modify, or replay data stored in mobile devices or sensors. Therefore, it is very important to ensure the security of transmitted messages. In addition, due to the power limitation of sensor nodes in the human body, efficiency and lightweight are also challenges for WBANs.

Recently, some authentication schemes to the security and privacy issues in WBANs have been proposed [1-14]. Fotouhi et al. [15] proposed a lightweight two-factor authentication scheme and claimed that the proposed protocol can meet the perfect forward security, key compromise impersonation resiliency, and other security requirements for health-care authentication schemes. We find the application scenarios of Fotouhi et al.'s scheme is different from common authentication schemes for WBANs [1-14]. In Fotouhi et al.'s scheme there are three kind participants, a gateway, sensors and users. The gateway, a sensor and a user want share a session key. But, the sensor and the user cannot communicate directly. It is undeniable that Fotouhi et al.'s scheme can resist the replay attacks and tracking attacks by updating the temporary identities of users and sensors, which also avoid the verification of timestamps.

However, in this paper, we find that Fotouhi et al.'s scheme is vulnerable to several weaknesses. Firstly, there is too much data storage in registration phase. Secondly, some identities data missing in some submitted messages in authentication

phase. Finally, more data are needed stored in authentication phase. So, Fotouhi et al.'s scheme is difficult to execute effectively and will take up a lot of storage space. On the basis of analyzing to Fotouhi et al.'s scheme, we propose an improvement on Fotouhi et al.'s scheme. In the registration phase of the improved scheme, each of our entities will store less data and ensure that there are no missing messages in the messages transmitted between entities. Meanwhile, in the authentication phase the gateway node store as little data as possible. We also investigate the security of the improved scheme in informal analysis and formal analysis.

The rest of the paper is organized as follows. In Section 2, we briefly review Fotouhi et al.'s scheme and analyze its weaknesses in Section 3. The improved protocol is proposed in Section 4. Security cryptanalysis is given in Section 5. Finally, the article is concluded in Section 6.

2. Review of Fotouhi et al.'s Scheme

In this section, we review Fotouhi et al.'s [15] authentication scheme for wireless body area networks in health-care IoT. Fotouhi et al.'s scheme consists of four phases: Initialization, registration, login and authentication, and the password change phase. Here, we only review the first three phases. Table 1 lists all the notations used in this paper.

Table 1: Notations and their importance

Symbol	Description
U_i, ID_i, PW_i	user and her/his identity and password respectively
GID_j, G_j	identity and secret key of jth gateway GW _j , respectively
SN_k, SID_k	kth sensor and its identity respectively
N_1	number of the sensor set
SG_k	shared secret key between sensor and the corresponding gateway
sk_u, sk_g, sk_s	common session keys generated by the user, gateway and sensor
M_i	messages in authentication phase

CID_i, QID_k	user's and sensor's temporary pseudonyms respectively
$R_u, R_g, R_s, R_x, R_y, R_z$	temporary random numbers
$h(.)$	collision-resistant cryptographic one-hash function
$\oplus$	exclusive-or operation
$\parallel$	concatenation operation

2.1 Initialization Phase

In this phase, assume that each gateway is a trusted party, and every message will be transmitted through the gateways identified with GID_j . Each gateway generates a secret key called G_j and selects a collision-resistant cryptographic hash function $h(.)$ to initialize the wireless body area network or networks.

2.2 Registration Phase for Sensor

In this phase, each sensor node called SN_k has an identifier SID_k . And, each set of sensors who belong to same network have same network identifier N_1 . Also each sensor and the corresponding gateway GW_j communicate with each other directly and share a common secret key SG_k which is equal to $h(SID_k \parallel G_j \parallel N_1)$, and the following operations are performed:

Step 1. GW_j selects two random numbers R_y and R_z and a pseudo-identity QID_k for each sensor.

Step 2. GW_j injects $\{SID_k, SG_k, GID_j, R_y, R_z, QID_k\}$ into SN_k .

Step 3. GW_j also stores $\{SID_k, QID_k, N_1, R_y, h(R_z)\}$ in its database. Then, the sensor will be installed in the intended place.

2.3 Registration Phase for User

In this phase, the user, U_i registers with the gateway, GW_j and the following operations are performed:

Step 1. U_i selects an identity, ID_i and the corresponding password, PW_i and a secret random nonce R_0 to compute masked password $HPW_i = h(PW_i \parallel R_0)$ and sends ID_i and HPW_i to GW_j via a secure channel.

Step 2. If ID_i has already been unregistered, GW_j generates a pseudo-identity CID_i and a random number R_x for U_i and stores them with ID_i and HPW_i in its database. Then, it computes $A_1 = h(CID_i \parallel R_x \parallel GID_j \parallel G_j) \oplus HPW_i$ and $A_2 = h(ID_i \parallel G_j) \oplus h(ID_i \parallel HPW_i)$ and sends A_1, A_2, GID_i, GID_j to U_i via a secure channel.

Step 3. U_i calculates $A_3 = h(ID_i \parallel PW_i) \oplus R_0$ and stores $A_1, A_2, A_3, CID_i, GID_i$ into his/her mobile device. Now U_i is ready to be authenticated through an insecure channel as described below.

2.4 Login and Authentication Phase

In this phase, U_i, GW_j , and SN_k carry out mutual authentication to set up a session key. The detailed description of the authentication phase are as follows:

Step 1. the U_i selects intended sensor and insert ID_i and PW_i to the mobile device which calculates $R_0 = A_3 \oplus h(ID_i \parallel PW_i)$ and $HPW_i = h(PW_i \parallel R_0)$. Then, it generates a random number R_u and selects sensor's corresponding SID_k and computes $B_1 = A_1 \oplus HPW_i$, $B_2 = B_1 \oplus HPW_i \oplus R_u$, $B_3 = SID_k \oplus h(ID_i \parallel R_u)$, $B_4 = h(CID_i \parallel GID_j \parallel SID_k \parallel B_1 \parallel ID_i \parallel R_u)$. Then, the message M_1 containing CID_i, GID_j, B_2, B_3 and B_4 is sent to GW_j .

Step 2. GW_j checks GID_j and CID_i and fetches the corresponding ID_i, R_x and HPW_i from its database, if they exist. Then, it computes $B_1 = h(CID_i \parallel R_x \parallel GID_j \parallel G_j)$ and $R_u = B_2 \oplus B_1 \oplus HPW_i$ and generates two random numbers R_g and R_z^{new} . Afterwards, GW_j obtains SID_k by calculating $B_3 \oplus h(ID_i \parallel R_u)$ and gets R_y from its database. Then, it generates a new pseudonym QID_k^{new} for the sensor. In the following, GW_j computes $SG_k = h(SID_k \parallel G_j \parallel N_1)$, $S = h(SG_k \parallel GID_j)$, $B_5 = (R_u \oplus HPW_i) \oplus S \oplus R_y$, $B_6 = R_g \oplus S \oplus SID_i \oplus R_y$, $B_7 = QID_k^{new} \oplus R_g \oplus R_y$, $B_8 = h(R_g \parallel R_y \parallel S) \oplus R_z^{new}$, $B_9 = h(QID_k \parallel B_7 \parallel B_8 \parallel SG_k \parallel R_u \oplus HPW_i \parallel R_g)$ and sends the message $M_2 = (QID_k, B_5, B_6, B_7, B_8, B_9)$ to the sensor.

Step 3. After receiving the message, the sensor first checks the QID_k and calculates $S = h(SG_k \parallel GID_j)$, $(R_u \oplus HPW_i) = B_5 \oplus S \oplus R_y$ and $R_g = B_6 \oplus S \oplus SID_i \oplus R_y$. Then if B_9 is correct, it generates a random number R_s and computes $R_z^{new} = h(R_g \parallel R_y \parallel S) \oplus B_8$, $QID_k^{new} = B_7 \oplus R_g \oplus R_y$. After generating $B_{10} = R_g \oplus S \oplus R_z$, it stores QID_k^{new} , R_z^{new} and $R_y^{new} = h(R_y)$ and generates the common session key $SK_s = h(R_u \oplus HPW_i \parallel R_g \parallel R_s)$. Finally the sensor generates $B_{11} = h(SG_k \parallel R_g) \oplus h(R_y) \oplus R_s$, $B_{12} = h(B_{10} \parallel B_{11} \parallel SK_s \parallel SID_k \parallel GID_j \parallel R_s)$ and sends $M_3 = (B_{10}, B_{11}, B_{12})$ to the GW_j as the response.

Step 4. On receiving the response from sensor, the GW_j computes $R'_y = h(R_y)$ in which R_y is fetched from DB and $R'_z = R_g \oplus S \oplus B_{10}$.

Then, it checks if $h(R_z) \stackrel{?}{=} h(R'_z)$ holds, it calculates $R_s = B_{11} \oplus h(SG_k \parallel R_g) \oplus R'_y$ and obtains the $SK_g = h(R_u \oplus HPW_i \parallel R_g \parallel R_s)$ as the common session key. Then, it checks B_{12} and generates a new CID_i for U_i and stores QID_k^{new} and

R_z^{new} . In addition, it replaces the R'_y with the previous R_y and $h(R_x)$ with the R_x .

In the following, GW_j computes:

$$B_{13} = h(CID_i^{new} \parallel h(R_x) \parallel GID_j \parallel G_j) \oplus h(R_u \parallel HPW_i),$$

$$B_{14} = h(R_u \parallel ID_i) \oplus R_g,$$

$$B_{15} = h(R_u \parallel R_g \parallel HPW_i) \oplus R_s,$$

$$B_{16} = h(h(ID_i \parallel G_j) \parallel R_s) \oplus CID_i^{new},$$

$B_{17} = h(sk_g \parallel ID_i \parallel B_{13} \parallel CID_i^{new})$ and finally forwards them to the U_i with the message $M_4 = (B_{13}, B_{14}, B_{15}, B_{16}, B_{17})$.

Step 5. U_i 's mobile device retrieves R_g and R_s by calculating, $R_g = B_{14} \oplus h(R_u \parallel ID_i)$, $R_s = B_{15} \oplus h(R_u \parallel R_g \parallel HPW_i)$, and U_i 's new pseudonym from $CID_i^{new} = B_{16} \oplus h((A_2 \oplus h(ID_i \parallel HPW_i)) \parallel R_s)$. Then it computes $SK_u = h(R_u \oplus HPW_i \parallel R_g \parallel R_s)$ to get the common session key.

After checking B_{17} , it stores CID_i^{new} and A_1^{new} which are derived by calculating $A_1^{new} = B_{13} \oplus h(R_u \parallel HPW_i)$.

3. Cryptanalysis of Fotouhi et al.'s Scheme

This section shows that Fotouhi et al.'s scheme has some security drawbacks.

3.1 Too Much Data Storage in Registration Phase

In registration phase of Fotouhi et al.'s scheme, the gateway GW_j must store data $\{SID_k, QID_k, N_1, R_y, h(R_z)\}$ for a sensor SN_k .

The gateway GW_j also must store $\{CID_i, ID_i, R_x, HPW_i\}$ for a sensor U_i .

However, the scheme is oriented to multiple users and multiple servers, it will take up too much storage space for the gateway to store users and sensors registration data.

3.2 Some Identities Data Missing in Submitted Messages in Authentication Phase

This scheme cannot efficiently work because some identities data missing in submitted the messages. For example, at step 2 in authentication phase, the message:

$$M_2 = (QID_k, B_5, B_6, B_7, B_8, B_9)$$

From the gateway GW_j to the sensor SN_k , due to the gateway identity GID_j missing in M_2 , the target sensor SN_k does not know the message sent from GID_j . So, SN_k cannot compute $s = h(SG_K \parallel GID_j)$ without GID_j . Such, next operations cannot be executed.

Similarly, due to flaws in messages M_3 at step 3 in authentication phase:

$$M_3 = (B_{10}, B_{11}, B_{12})$$

From the sensor SN_k to the gateway GW_j , due to the sensor temporary identity QID_k and the user temporary identity CID_i missing in M_3 . The gateway GW_j does not know the message from target sensor SN_k , so the gateway GW_j cannot compute $R'_y = h(R_y)$ without QID_k . In addition, if CID_i is missing, the gateway GW_j cannot update CID_i to CID_i^{new} by computing $B_{13} = h(CID_i^{new} \parallel h(R_x) \parallel GID_j)$. Such, next operations cannot be executed.

Finally, due to flaws in messages M_4 at step 4 in authentication phase,

$$M_4 = (B_{13}, B_{14}, B_{15}, B_{16}, B_{17})$$

From the gateway GW_j to the user U_i , the user U_i cannot compute $CID_i^{new} = B_{16} \oplus h((A_2 \oplus h(ID_i \parallel HPW_i)) \parallel R_s)$ without A_2 . Due to the user U_i store A_2 with the gateway identity GID_j , however the gateway identity GID_j missing in M_4 . So, the user U_i cannot find A_2 by the gateway identity GID_j to compute $CID_i^{new} = B_{16} \oplus h((A_2 \oplus h(ID_i \parallel HPW_i)) \parallel R_s)$. Such, next operations cannot be executed.

3.3 More Data are Needed Stored in Authentication Phase

After the gateway GW_j receives the response message M_3 sent by the target sensor SN_k , GW_j starts to perform corresponding calculations:

$$R'_z = R_g \oplus s \oplus B_{10}$$

at step 4.

But, it needs random number R_g and s previously generated by GW_j at step 2. So, GW_j must store R_g and QID_k at step 2. Unfortunately, GW_j does not store R_g with QID_k at step 2.

Furthermore, at step 4 it needs random number R_u and HPW_i for the following computation

$$SK_g = h(R_u \oplus HPW_i \parallel R_g \parallel R_s)$$

But, at step 2 GW_j does not store R_u and HPW_i .

To sum up, the authentication of Fotouhi et al.'s scheme cannot work without the storage of R_g , QID_k , R_u and HPW_i by GW_j at step 2.

4. Improved Scheme

In order to overcome the flaws of the Fotouhi et al.'s scheme, an improved scheme is proposed. Same as Fotouhi et al.'s scheme, the gateway GW_j , the sensor SN_k and the user U_i in the improved scheme want share a session key. But, the sensor SN_k and the user U_i cannot communicate directly. The proposed scheme contains the following three phases:

Initialization phase, registration, phase and authentication phase.

4.1 Initialization Phase

This phase is as same as that of the Fotouhi et al.'s scheme. So, it is omitted.

4.2 Registration of Sensor

Each sensor SN_k with its identity SID_k belongs to network identifier N_1 . Also SN_k and GW_j share a common secret key $SG_k = h(SID_k \| G_j \| N_1)$, GW_j selects a pseudo-identity QID_k for SN_k and injects $\{SID_k, SG_k, GID_j, QID_k\}$ into SN_k . GW_j also stores $\{SID_k, QID_k, N_1, GID_j\}$ in its database. Then, the sensor will be installed in the intended place.

4.3 Registration Phase for User

A user, U_i registers herself/himself to the gateway GW_j by the following operations:

Step 1. the U_i selects an identity, ID_i and the corresponding password, PW_i and a secret random nonce R_0 to compute masked password:

$$HPW_i = h(PW_i \| R_0)$$

and sends ID_i and HPW_i to GW_j via a secure channel.

Step 2. If ID_i has already been unregistered, GW_j generates a pseudo-identity CID_i for U_i and stores them with ID_i and HPW_i in its database. Then, it computes:

$$A_1 = h(CID_i \| GID_j \| G_j) \oplus HPW_i$$

and sends $\{A_1, CID_i, GID_j\}$ to U_i via a secure channel.

Step 3. U_i calculates:

$$A_2 = h(ID_i \| PW_i) \oplus R_0$$

and stores $\{A_1, A_2, CID_i, GID_j\}$ into his/her mobile device.

4.4 Authentication Phase

U_i , GW_j , and SN_k carry out mutual authentication to set up a session key. The detailed description of the authentication phase are as follows:

Step 1. the U_i selects intended sensor SN_k and insert ID_i and PW_i to the mobile device which calculates

$$R_0 = A_2 \oplus h(ID_i \| PW_i), \quad HPW_i = h(PW_i \| R_0).$$

Then, U_i generates a random number R_u and computes:

$$B_1 = A_1 \oplus HPW_i \oplus R_u, \\ B_2 = SID_k \oplus h(R_u), \quad B_3 = h(CID_i \| GID_j \| SID_k \| R_u).$$

Then, U_i sends the message $M_1 = (CID_i, GID_j, B_1, B_2, B_3)$ to GW_j .

Step 2. On receiving GW_j the message M_1 from U_i , GW_j computes:

$$R_u = B_1 \oplus h(CID_i \| GID_j \| G_j)$$

and generates a random numbers R_g . Afterwards, GW_j calculates:

$$SID_k = B_2 \oplus h(R_u), \quad B_3^* = h(CID_i \| GID_j \| SID_k \| R_u)$$

check $B_3^* \stackrel{?}{=} B_3$, if it holds, continue the operation, otherwise terminate the session. Then, GW_j generates a new pseudonym QID_k^{new} for the sensor SN_k and a new pseudonym CID_i^{new} for the user U_i . Then, GW_j computes

$$SG_k = h(SID_k \| G_j \| N_1), \\ B_4 = (h(CID_i^{new} \| GID_j \| G_j) \| CID_i^{new}) \oplus R_u, \\ B_5 = (R_u \| R_g) \oplus h(SG_k \| CID_i), \\ B_6 = h(B_4 \| B_5 \| CID_i^{new}), \\ B_7 = QID_k^{new} \oplus h(R_u \| R_g), \\ B_8 = h(QID_k \| CID_i \| (R_u \| R_g) \| B_7 \| B_4)$$

and GW_j stores CID_i^{new} with CID_i , stores QID_k^{new} with $\{SID_k, QID_k, SG_k, N_1\}$. Then, GW_j sends the message $M_2 = (GID_j, QID_k, CID_i, B_4, B_5, B_6, B_7, B_8)$ to the sensor SN_k .

Step 3. After receiving the message M_2 , the sensor SN_k calculates:

$$R_u \| R_g = B_5 \oplus h(SG_k \| CID_i), \\ QID_k^{new} = B_7 \oplus h(R_u \| R_g) \\ B_8^* = h(QID_k \| CID_i \| (R_u \| R_g) \| B_7 \| B_4)$$

Then check $B_8^* \stackrel{?}{=} B_8$, if it holds, SN_k generates a random number R_s and computes the common session key:

$$SK_s = h(R_u \| R_g \| R_s)$$

Then, SN_k generates:

$$B_9 = R_s \oplus QID_k^{new}, \quad B_{10} = h(QID_k^{new} \| SK_s)$$

and sends $M_3 = (QID_k, CID_i, B_4, B_5, B_6, B_9, B_{10})$ to the GW_j , then SN_k updates $\{SID_k, QID_k, SG_k, GID_j\}$ to $\{SID_k, QID_k^{new}, SG_k, GID_j\}$.

Step 4. On receiving the response message M_3 from sensor SN_k , the gateway GW_j first find QID_k^{new} and CID_i^{new} by QID_k and CID_i in M_3 . Then, GW_j computes:

$$R_s = B_9 \oplus QID_k^{new}, \quad B_6^* = h(B_4 \| B_5 \| CID_i^{new}).$$

and checks $B_6^* = B_6$ if it holds, GW_j computes:

$$R_u \parallel R_g = B_5 \oplus h(SG_k \parallel CID_i)$$

and the common session key sk_g and B_{10}^* :

$$sk_g = h(R_u \parallel R_g \parallel R_s), B_{10}^* = h(QID_k^{new} \parallel sk_g)$$

and checks $B_{10}^* = B_{10}$ if it holds, then, GW_j computes:

$$B_{11} = (R_g \parallel R_s) \oplus R_u, B_{12} = h(GID_j \parallel B_4 \parallel B_5 \parallel sk_g).$$

and GW_j sends the message $M_4 = (CID_i, GID_j, B_4, B_5, B_{11}, B_{12})$ to the user U_i . Then GW_j updates $\{SID_k, QID_k, SG_k, N_1\}$ to $\{SID_k, QID_k^{new}, SG_k, N_1\}$ and updates $\{CID_i, ID_i, HPW_i\}$ to $\{CID_i^{new}, ID_i, HPW_i\}$.

Step 5. On receiving the response message M_4 from the gateway GW_j , U_i 's mobile device calculates:

$$R_g \parallel R_s = B_{11} \oplus R_u, sk_u = h(R_u \parallel R_g \parallel R_s)$$

to get the common session key. Then, U_i 's mobile device computes:

$$B_{12}^* = h(GID_j \parallel B_4 \parallel B_5 \parallel sk_u)$$

and check $B_{12}^* = B_{12}$, if it holds, U_i 's mobile device calculates

$$h(CID_i^{new} \parallel GID_j \parallel G_j) \parallel CID_i^{new} = B_4 \oplus R_u, \\ A_1^{new} = h(CID_i^{new} \parallel GID_j \parallel G_j) \oplus HPW_i.$$

After that, U_i 's mobile device updates $\{A_1, A_2, CID_i, GID_j\}$ to $\{A_1^{new}, A_2, CID_i^{new}, GID_j\}$.

5. Security Analysis

5.1 Informal Security Analysis

This section shows that the improved scheme is well protected against relevant security threats. Firstly, like Fotouhi et al.'s scheme [15], Firstly, the improved scheme has absorbed the advantages of Fotouhi et al.'s scheme that can well resist the opponent's replay attacks and tracking attacks by updating the temporary identities of users and sensors, and also can avoid the verification of timestamps by the gateway stores the temporary identities which updated by users and sensors. next we will discuss separately that the improved protocol effectively solves the flaws about too much data storage in registration phase, some identities data missing in submitted messages in authentication phase, and more data are needed stored in authentication phase.

Firstly, in registration phase of the improved scheme, the sensor SN_k , the gateway GW_j and the user U_i just need to store:

$$\{SID_k, SG_k, GID_j, QID_k\} \\ \{SID_k, QID_k, N_1, GID_j\}, \{CID_i, ID_i, HPW_i\}$$

$$\{A_1, A_2, CID_i, GID_j\}$$

separately in their database. However in registration phase of the Fotouhi et al.'s scheme, the sensor SN_k , the gateway GW_j and the user U_i needs to store:

$$\{SID_k, SG_k, GID_j, R_y, R_z, QID_k\} \\ \{SID_k, QID_k, N_1, R_y, h(R_z)\}, \{CID_i, R_x, ID_i, HPW_i\} \\ \{A_1, A_2, A_3, CID_i, GID_j\}$$

in their database. Obviously, we can find that the amount of data stored in the sensor SN_k , the gateway GW_j and the user U_i in Fotouhi et al.'s scheme in the registration phase will be much larger than the amount of data stored in the improved scheme.

Secondly, in authentication phase of Fotouhi et al.'s scheme, some identities data missing in submitted messages between the sensor SN_k , the gateway GW_j and the user U_i , which will make Fotouhi et al.'s scheme unable to be effectively implemented. So, we need to fill in the missing data in submitted messages between the sensor SN_k , the gateway GW_j and the user U_i to ensure that Fotouhi et al.'s scheme can be executed normally.

Finally, there is more data need to be stored in authentication phase of Fotouhi et al.'s scheme. As analyzed by 3.3 in Cryptanalysis of Fotouhi et al.'s scheme above that the gateway GW_j need to store R_g , QID_k , R_u and HPW_i at step 2. in authentication phase of the improved scheme. Due to Fotouhi et al.'s scheme is oriented to multiple users and multiple servers, it means that a large amount of intermediate data needs to be stored when the gateway assists multiple users and multiple servers to communicate. However, in the authentication phase of our improved scheme, we can reduce the amount of data stored by the gateway GW_j by adding B_4 , B_5 , and B_6 .

$$B_4 = (h(CID_i^{new} \parallel GID_j \parallel G_j) \parallel CID_i^{new}) \oplus R_u,$$

$$B_5 = (R_u \parallel R_g) \oplus h(SG_k \parallel CID_i), B_6 = h(B_4 \parallel B_5 \parallel CID_i^{new}),$$

to the messages M_2 and M_3 . The gateway GW_j sends a message M_2 to the sensor SN_k in step 2 of the verification phase. After receiving the message M_2 , the SN_k will return B_4 , B_5 , and B_6 to the GW_j at step 3 in the authentication phase. In these two steps, B_4 and B_5 are used to transmit the protected information, while B_6 can be used at step 4 in the authentication phase. when the information B_4 and B_5 send back by the sensor SN_k to the gateway GW_j , B_6 can be used to verify B_4 and B_5 to prevent the message M_3 from being changed during transmission. This method not only enables the efficient execution of the program, but also saves the space for storing some intermediate data by the gateway GW_j .

In summary, the improved scheme completely overcomes the shortcomings of Fotouhi et al.'s scheme and retains the advantages of Fotouhi et al.'s scheme. In the improved scheme, neither the sensor SN_k nor the gateway GW_j nor the user U_i need to store large amounts of data in the registration phase. Meanwhile, less intermediate data needs to be stored

by the gateway GW_j in the authentication phase. Therefore, more storage space can be saved in our improved scheme.

5.2 Formal Security Analysis

5.2.1 Simulation for security verification with the AVISPA tool

We performed a formal security verification of the proposed scheme utilizing AVISPA simulation tool [16,17] to evaluate the safety of the authentication protocol against MITM and replay attacks, which is widely accepted for formal security analysis [18-20]. To perform AVISPA simulation tool, the environment and the session of security protocol must be implemented using the High Level Protocols Specification Language (HLPSL).

5.2.2 HLPSL specifications

We considered three basic roles: user U_i , gateway GW_j , and sensor SN_k . Then, we present session and environment utilizing HLPSL in Figure 1, which contains the security goals. The role specifications of U_i , GW_j , and SN_k are as shown in Figures 2-4.

```

role environment()
def=
    const
        ui,gw,sn,iagent,
        skuigw:symmetric_key,
        h:hash_func,
        idi,gidj:text,
        ui_gw_b12,gw_ui_b3,gw_gw_b6,gw_sn_b10,sn_gw_b8:protocol_id,
        sp1,sp2,sp3,sp4:protocol_id,
        snd,rcv:channel(dy)

    intruder_knowledge={ui,gw,sn,idi,gidj,h}
    composition
        session(ui,gw,sn,skuigw,h,snd,rcv)
        /session(i,gw,sn,skuigw,h,snd,rcv)
        /session(ui,i,sn,skuigw,h,snd,rcv)
        /session(ui,gw,i,skuigw,h,snd,rcv)

    end role

    goal
        secrecy_of sp1,sp2,sp3,sp4
        authentication_on ui_gw_b12
        authentication_on gw_ui_b3
        authentication_on gw_gw_b6
        authentication_on gw_sn_b10
        authentication_on sn_gw_b8

    end goal

    environment()

%Role for the session
role session(UI,GW,SN:agent,SKuigw:symmetric_key,H:hash_func,SND,RCV:channel(dy))
def=
    local
        SN1,SN2,SN3,RV1,RV2,RV3:channel(dy)
    composition
        user(UI,GW,SN,SKuigw,H,SN1,RV1)
        /gateway(UI,GW,SN,SKuigw,H,SN2,RV2)
        /sensornode(UI,GW,SN,SKuigw,H,SN3,RV3)

    end role
  
```

Figure 1: Role for environment and session in HLPSL.

```

%User
role user(UI,GW,SN:agent,SKuigw:symmetric_key,H:hash_func,SND,RCV:channel(dy))
played_by UI
def=
    local
        State:nat,
        IDi,PWi,R0,HPWi,A1,CIDi,GIDj,A2,Ru,B1,B2,SIDk,B3,B4,B5,B11:text,
        SK,B12,Rgrs,Rg,Rstext

    const
        sp1,sp2,sp3,sp4,ui_gw_b12,gw_ui_b3,gw_gw_b6,gw_sn_b10,sn_gw_b8:protocol_id

    init
        State:=0

    transition
        0.
            State:=0/RCV(start)=>
            State:=2/IDi:=new()
            /PWi:=new()/R0:=new()
            /HPWi:=H(PWi,R0)
            /SND((IDi,HPWi)_SKuigw)
            /secret([PWi],sp1,[UI])

        2.
            State:=2/RCV([A1',CIDi',GIDj']_SKuigw)=>
            State:=6/A2':=xor(H(IDi,PWi),R0)
            /R0':=xor(A2',H(IDi,PWi))
            /HPWi':=H(PWi,R0')
            /Ru':=new()
            /B1':=xor(xor(A1',HPWi'),Ru')
            /B2':=xor(SIDk,H(Ru'))
            /B3':=H(CIDi',GIDj',SIDk,Ru')
            /request(GW,UI,gw_ui_b3,Ru')
            /SND(CIDi',GIDj',B1',B2',B3')

        6.
            State:=6/RCV(CIDi',GIDj',B4',B5',B11',B12')=>
            State:=6/Rgrs':=xor(B11',Ru')
            /SK:=H(Ru,Rg,Rs)
            /secret([SK],sp4,[UI,GW,SN])
            /B12':=H(GIDj',B4',B5',SK)
            /witness(UI,GW,ui_gw_b12,B12')

    end role

%GateWay
role gateway(UI,GW,SN:agent,SKuigw:symmetric_key,H:hash_func,SND,RCV:channel(dy))
played_by GW
def=
    local
        State:nat,
        IDi,HPWi,CIDi,GIDj,A1,Gj,B1,B2,B3,Ru,Rg,SIDk,SGk,N1,B4,B5,B6,B7,B8:text,
        PWi,QIDk,B9,B10,RS,Rurg,SK,B11,B12,CIDinew,QIDknew:text

    const
        sp1,sp2,sp3,sp4,ui_gw_b12,gw_ui_b3,gw_gw_b6,gw_sn_b10,sn_gw_b8:protocol_id

    init
        State:=1

    transition
        1.
            State:=1/RCV({IDi'.HPWi'}_SKuigw)=>
            State:=3/IDi':=new()
            /GIDj':=new()
            /A1':=xor(H(CIDi'.GIDj'.Gj),HPWi')
            /secret({Gj},sp2,{GW})
            /SND({A1'.CIDi'.GIDj'}_SKuigw)

        3.
            State:=3/RCV(CIDi'.GIDj'.B1'.B2'.B3')=>
            State:=5/ Ru' := xor(B1',H(CIDi'.GIDj'.Gj))
            /Rg' := new()
            /SIDk' := xor(B2',H(Ru'))
            /B3' := H(CIDi'.GIDj'.SIDk'.Ru')
            /witness(GW,UI,gw_ui_b3,Ru')
            /SGk' := H(SIDk.Gj.N1)
            /CIDinew' := new()
            /QIDknew' := new()

            /B4' := xor(Ru',H(CIDinew'.GIDj'.Gj).CIDinew')
            /B5' := xor(H(SGk.CIDi'),(Ru'.Rg'))
            /B6' := H(B4'.B5'.CIDinew')
            /request(GW,GW,gw_gw_b6,B6')
            /B7' := xor(QIDknew',H(Ru'.Rg'))
            /B8' := H(QIDk.CIDi'.(Ru'.Rg').B7'.B4')
            /request(SN,GW,sn_gw_b8,B8')

            /SND(GIDj'.QIDk.CIDi'.B4'.B5'.B6'.B7'.B8')

        5.
            State:=5/RCV(QIDk.CIDi'.B4'.B5'.B6'.B9'.B10')=>
            State:=5/RS' := xor(B9',QIDknew)
            /Rurg' := xor(B5',H(SGk.CIDi'))
            /B6' := H(B4'.B5'.CIDinew)
            /witness(GW,GW,gw_gw_b6,B6')
            /SK' := H(Rurg'.RS')
            /B10' := H(QIDknew.SK)
            /witness(GW,SN,gw_sn_b10,B10')
            /B11' := xor(Ru',(Rg.Rs'))
            /B12' := H(GIDj'.B4'.B5'.SK)
            /SND(CIDi'.GIDj'.B4'.B5'.B11'.B12')

    end role
  
```

Figure 2: Role specification for user

```

%GateWay
role gateway(UI,GW,SN:agent,SKuigw:symmetric_key,H:hash_func,SND,RCV:channel(dy))
played_by GW
def=
    local
        State:nat,
        IDi,HPWi,CIDi,GIDj,A1,Gj,B1,B2,B3,Ru,Rg,SIDk,SGk,N1,B4,B5,B6,B7,B8:text,
        PWi,QIDk,B9,B10,RS,Rurg,SK,B11,B12,CIDinew,QIDknew:text

    const
        sp1,sp2,sp3,sp4,ui_gw_b12,gw_ui_b3,gw_gw_b6,gw_sn_b10,sn_gw_b8:protocol_id

    init
        State:=1

    transition
        1.
            State:=1/RCV({IDi'.HPWi'}_SKuigw)=>
            State:=3/IDi':=new()
            /GIDj':=new()
            /A1':=xor(H(CIDi'.GIDj'.Gj),HPWi')
            /secret({Gj},sp2,{GW})
            /SND({A1'.CIDi'.GIDj'}_SKuigw)

        3.
            State:=3/RCV(CIDi'.GIDj'.B1'.B2'.B3')=>
            State:=5/ Ru' := xor(B1',H(CIDi'.GIDj'.Gj))
            /Rg' := new()
            /SIDk' := xor(B2',H(Ru'))
            /B3' := H(CIDi'.GIDj'.SIDk'.Ru')
            /witness(GW,UI,gw_ui_b3,Ru')
            /SGk' := H(SIDk.Gj.N1)
            /CIDinew' := new()
            /QIDknew' := new()

            /B4' := xor(Ru',H(CIDinew'.GIDj'.Gj).CIDinew')
            /B5' := xor(H(SGk.CIDi'),(Ru'.Rg'))
            /B6' := H(B4'.B5'.CIDinew')
            /request(GW,GW,gw_gw_b6,B6')
            /B7' := xor(QIDknew',H(Ru'.Rg'))
            /B8' := H(QIDk.CIDi'.(Ru'.Rg').B7'.B4')
            /request(SN,GW,sn_gw_b8,B8')

            /SND(GIDj'.QIDk.CIDi'.B4'.B5'.B6'.B7'.B8')

        5.
            State:=5/RCV(QIDk.CIDi'.B4'.B5'.B6'.B9'.B10')=>
            State:=5/RS' := xor(B9',QIDknew)
            /Rurg' := xor(B5',H(SGk.CIDi'))
            /B6' := H(B4'.B5'.CIDinew)
            /witness(GW,GW,gw_gw_b6,B6')
            /SK' := H(Rurg'.RS')
            /B10' := H(QIDknew.SK)
            /witness(GW,SN,gw_sn_b10,B10')
            /B11' := xor(Ru',(Rg.Rs'))
            /B12' := H(GIDj'.B4'.B5'.SK)
            /SND(CIDi'.GIDj'.B4'.B5'.B11'.B12')

    end role
  
```

Figure 3: Role specification for gateway

```

%SensorNode
role sensornode(Ui,GW,SN:agent,SKuigw:symmetric_key,H:hash_func,SND,RCV:channel(dy))
played_by SN
def=

local
    State:=nat
    IDi,GIDj,QIDk,CIDi:B4'B5'B6'B7'B8',Rurg,SGk,RS,SK,Ru,Rg:text,
    PWi,B9,B10,QIDknew:text

const
    sp1,sp2,sp3,sp4,ui_gw,b12,gw_ui_b3,gw_gw_b6,gw_sn_b10,sn_gw_b8:protocol_id

init
    State:=4

transition
    4.
    State:=4/(RCV(GIDj:QIDk,CIDi:B4'B5'B6'B7'B8')=)>
    State:=1/(Rurg:=xor(B5',H(SGk,CIDi'))
    /\QIDknew:=xor(B7',H(Rurg))
    /\B8':=H(QIDk,CIDi'.Rurg'.B7'.B4')
    /\witness(SN,GW,sn_gw_b8,B8')
    /\Rs:=new()
    /\SK:=H(Ru,Rg,RS')
    /\secret((SK),sp3,(Ui,GW,SN))
    /\B9':=xor(Rs',QIDknew')
    /\B10':=H(QIDknew',SK')
    /\request(GW,SN,sn_gw_b10,B10')
    /\SND(QIDk,CIDi'.B4'.B5'.B6'.B9'.B10')

end role

```

Figure 4: Role specification for sensor

5.2.3 AVISPA Simulation Result

We show the AVISPA results to verify the safety of the proposed scheme using OFMC and CL-AtSe. The OFMC and the CL-AtSe checks whether the proposed scheme is safe. Consequently, Figure 5 shows that the proposed scheme is secure though AVISPA simulation.

```

% OFMC
% Version of 2006/02/13
SUMMARY
SAFE
DETAILS
BOUNDED_NUMBER_OF_SESSIONS
PROTOCOL
/home/span/span/testsuite/results/1.if
GOAL
as_specified
BACKEND
OFMC
COMMENTS
STATISTICS
parseTime: 0.00s
searchTime: 0.02s
visitedNodes: 8 nodes
depth: 3 plies

SUMMARY
SAFE

DETAILS
BOUNDED_NUMBER_OF_SESSIONS
TYPED_MODEL

PROTOCOL
/home/span/span/testsuite/results/1.if

GOAL
As Specified

BACKEND
CL-AtSe

STATISTICS
Analysed : 0 states
Reachable : 0 states
Translation: 0.54 seconds
Computation: 0.00 seconds

```

Figure 5: Analysis of AVISPA simulation using OFMC and CL-AtSe

6. Conclusion

In this paper, we find that Fotouhi et al.'s scheme is vulnerable to several weaknesses in the phase of registration and authentication. To overcome the shortcomings of Fotouhi et al.'s scheme, we propose an improved scheme. The improved scheme not only completely overcomes the shortcomings of Fotouhi et al.'s scheme but also retains the advantages of Fotouhi et al.'s scheme. Otherwise, the improved scheme has less computation cost.

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