A three-factor anonymous user authentication scheme for Internet of Things environments

Hakjun Lee\textsuperscript{a}, Dongwoo Kang\textsuperscript{b}, Jihyeon Ryu\textsuperscript{b}, Dongho Won\textsuperscript{c}, Hyoungshick Kim\textsuperscript{c}, Youngsook Lee\textsuperscript{d,∗}

\textsuperscript{a}Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon, Gyeonggi-do, South Korea
\textsuperscript{b}Department of Software, Sungkyunkwan University, Suwon, Gyeonggi-do, South Korea
\textsuperscript{c}Department of Computer Engineering, Sungkyunkwan University, Suwon, Gyeonggi-do, South Korea
\textsuperscript{d}Department of Cyber Security Department, Hankook University, Gunsan, Jeollabuk-do, South Korea

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\textbf{A B S T R A C T}

To accelerate the deployment of fifth-generation (5G) cellular networks, millions of devices are being connected to massive Internet of Things (IoT) networks. However, advances in the scale of connectivity on 5G networks may increase the attack surface of these devices, thereby increasing the number of attack opportunities. To address the potential security risks in IoT systems, one feasible security practice involves the development of secure and efficient user authentication schemes. In 2017, Dhillon and Kalra proposed a three-factor user authentication scheme for IoT. We noted that their scheme suffers from several security weaknesses. In this study, we specifically demonstrate that the scheme proposed by Dhillon and Kalra (1) is not secured from a stolen mobile device attack; (2) does not prevent a user impersonation attack; (3) does not provide a session key agreement; (4) does not have a contingency plan (e.g., a revocation phase) for situations where a user’s private key is compromised, or a mobile device is stolen or lost. We propose an improved three-factor user authentication scheme to resolve these security issues. Furthermore, we demonstrate that the proposed scheme provides desirable attributes for IoT environments and that its computation and communication costs are suitable for extremely low-cost IoT devices.

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1. Introduction

The Internet of Things (IoT) is composed of resource-constrained nodes, and these densely scattered nodes in IoT environments provide continuous service, irrespective of time and location. Currently, IoT has been adopted for many applications, including healthcare, smart home, smart factory, and smart city. Furthermore, the advent of the fifth-generation (5G) cellular network and its commercialization has birthed the anticipation of a hyperlink network to connect and share information not only between individual portable terminals but also between most (if not all) the objects we use in daily life. According to a study conducted by Park et al. [1], by the year 2020, approximately 50 billion sensor devices across the world will be connected to IoT networks, and the number of these devices is expected to increase exponentially with the commercialization of 5G networks. According to the 5G vision requirements of the International Telecommunication Union Radio Communication Standards Sector (ITU-R) [2], a massive IoT network accommodates approximately 1 million objects per km\(^2\) (1 per m\(^2\)).

The development of IoT and massive IoT has tremendous potential, but these environments expose devices to a wide range of vulnerabilities due to an increased attack surface. Therefore, to protect user privacy in IoT environments, security properties such as (1) data security, (2) virtual network security, (3) service availability, and (4) data integrity must be provided [3]. In the network architecture, secure user authentication and key distribution mechanisms utilizing cryptography must support these IoT security requirements [4]. In IoT network, user nodes and sensor nodes that interact with each other are exposed to various threats. To strengthen the security of the IoT network, user authentication schemes must guarantee the following security and functional requirements [5,6]:

\begin{itemize}
  \item (1) Data security: To prevent unauthorized access and modification of data.
  \item (2) Virtual network security: To prevent unauthorized access and modification of the virtual network.
  \item (3) Service availability: To ensure the availability of the service.
  \item (4) Data integrity: To prevent unauthorized modification of data.
\end{itemize}
1. User anonymity: The authentication scheme must maintain anonymity to ensure user privacy. In essence, an attacker cannot uncover the actual identity of the user.

2. Unlinkability: The scheme must prevent the attacker from tracking the activity of the user, thereby guaranteeing unlinkability and enhancing user privacy.

3. Mutual authentication: The scheme must provide mutual authentication for participants to verify each other’s legitimacy.

4. Session key agreement: In the authentication scheme, the session key used to encrypt and decrypt the message must be fresh, and forward secrecy must be assured.

5. Resilience to various attacks: The authentication scheme must achieve all key security goals and resist various known attacks.

When secret keys are exposed, all traffic in the network can be decrypted. Even when a key stored in physical memory is exposed through a side channel attack, a user authentication scheme must implement countermeasures that prevent the attacker from intruding and controlling the IoT network. The revocation mechanism is a simple and efficient countermeasure. With the revocation mechanism implemented, when a user’s private key is lost or stolen, the administrator issues a new key to the user.

Lately, numerous authentication schemes have been proposed for enhanced security. In 2007, Dhillon and Kalra [7] presented a three-factor remote user authentication scheme that is efficient in terms of computational cost in resource-constrained IoT environments. However, we discovered some security defects in their scheme. In this study, we perform an investigation of the security of their scheme using cryptanalysis and propose a new authentication scheme that resolves the security issues. Through security analysis, we demonstrate that the proposed scheme ensures all security requirements, and through performance analysis, we demonstrate that the scheme is suitable in terms of computational and communication cost for application in IoT environments.

The remainder of this paper is organized as follows: In Section 2, previous studies are explored. In Section 3, the preliminary knowledge for this study is introduced for an understanding of the background. In Section 4, Dhillon and Kalra’s scheme [7] is reviewed, and the cryptanalysis performed on the scheme is presented in Section 5. In Section 6, the proposed scheme is presented. In Section 7, we provide an informal and a formal security analysis of the proposed scheme. In Section 8, we present the performance comparisons with the related schemes. Finally, the conclusions of this study are presented in Section 9.

2. Related work

Since Lamport [8] first proposed a password-based authentication scheme, many related studies of two-factor authentication schemes have been proposed to improve the security and efficiency of various network environments [9–11]. In addition, two-factor authentication schemes using various cryptographic technologies such as symmetric key cryptography, asymmetric key cryptography, and hash functions have been studied to provide secure user authentication in a wireless sensor networks (WSNs) [12–16].

In 2006, Wong et al. [17] first proposed a lightweight and dynamic password-based user authentication scheme for securely accessing WSNs. However, Das [18] claimed that the scheme proposed by Wong et al. [17] has security drawbacks (e.g., it cannot resist many logged-in users with the same login ID attacks and stolen-verifier attacks). To enhance the security of the scheme proposed by Wong et al. [17], Das [18] proposed a two-factor user authentication scheme for strong authentication and session key establishment using the gateway (GW). Unfortunately, it was later revealed by Khan and Alghathbar [19] and He et al. [20] that the scheme proposed by Das [18] is vulnerable to various attacks, including impersonation, privileged-insider attacks, and GW-node bypassing, and it does not guarantee mutual authentication between the GW and sensor nodes. To resolve this security problem, Khan and Alghathbar [19] proposed an enhanced two-factor user authentication scheme and claimed that their scheme had several security advantages. However, Vaidya et al. [21] discovered that the Khan and Alghathbar scheme [19] is not secure against smart-card theft, forgery, and node capture attacks. In 2011, Yeh et al. [22] also reported vulnerabilities in the scheme presented by Das [18] and proposed a new user authentication scheme that uses smart cards for WSNs. Yeh et al. [22] applied the elliptic curve cryptography (ECC)-based mechanism to the scheme to make it suitable for higher security in WSNs. However, according to Xue et al. [23], the scheme proposed by Yeh et al. [22] not only requires additional storage overhead but also requires increased computational resources. Then, Xue et al. [23] proposed a new scheme with strengthened security, but Li et al. [24] reported that various security weaknesses still remained [23]; these included vulnerabilities to loss of a smart card, offline-password guessing, stolen-verifier, insider, and many logged-in users with the same login ID attacks. Turkanovic et al. [25] presented an improved mutual authentication scheme to resolve these security challenges, ensuring essential features such as mutual authentication, key agreement, password security, and low computational costs, using hash and exclusive-OR (XOR) operations. Farash et al. [26] found security failures in the scheme proposed by Turkanovic et al. [25]; they reported that the scheme does not guarantee untraceability and anonymity of the sensor node. To overcome these security vulnerabilities, Farash et al. [26] proposed a user authentication scheme for WSNs, tailored for IoT. However, Kumari et al. [27] reported that the scheme proposed by Farash et al. [26] violates user and sensor-node anonymity and is not secure against various attacks.

In Dhillon and Kalra’s study [7], they highlight that traditional two-factor authentication protocols are insecure in real-world situations when a password breach or loss of smart device occurs. Based on the IoT network model (See Section 3.1) applied to the schemes [25–27] described earlier in this section, Dhillon and Kalra [7] proposed a lightweight multi-factor user authentication scheme using password, biometric, and mobile device. They claimed that their scheme is secure against offline password guessing, password change, denial of service, stolen mobile device, and impersonation attacks. However, we found that their solution is also insecure from a user impersonation attack via a stolen mobile device attack, and it does not provide a session key agreement and a revocation plan.

In this study, we perform a security analysis to demonstrate the security failures of the Dhillon and Kalra’s scheme [7]. We then propose an improved lightweight authentication scheme that uses only XOR, hash, and symmetric cryptography and is suitable for IoT environments.

3. Preliminaries

3.1. Network model and authentication process

Currently, various IoT architecture models are being used to achieve security, scalability, and efficient computational cost. Xue et al. [23] introduced five resource-constrained communication mechanisms that address users, sensor nodes, and single or multiple gateways. We briefly describe the fifth network model applied to the Dhillon and Kalra’s scheme [7] and our scheme, which shares the session key between the mobile node MNj and the sensor node NJ. This mutual authentication is performed utilizing the
gateway GW, as shown in Fig. 1. The user authentication process is as follows:

1. MN sends a login and authentication request to N to access the IoT network.
2. Upon receipt of the request message, N sends the received request to GW for MN authentication.
3. GW checks the message received from N, authenticates MN, and responds to N.
4. N sends a response to MN, and then MN and N mutually establish a session key via authentication.

### 3.2. Bio-hash function

Biometrics provides a unique identification method for addressing security vulnerabilities in specific user credentials that can be forgotten or stolen, such as pins, passwords, and tokens. Imprint biometric characteristics vary slightly with each input for various reasons, such as dry or cracked skin, or the presence of dust on the imprint sensors [28]. To solve the problem of high false rejection rates, in 2004, Jin et al. [29] proposed a method of two-factor authentication based on inner products between tokenized pseudo-random numbers and user-specific fingerprint features. They created a user-specific compact code set called a bio-hash code. The bio-hash code randomly maps the biometric feature to a binary string using a user-specific token of pseudo-random numbers. The bio-hash has been applied to a variety of recently proposed schemes [30,31]. Bio-hash technology is efficient for biometrics-based multi-factor authentication schemes because it is suitable for small capacity devices [32].

### 4. Review of the dhillon and Kalra’s scheme

In this section, we review Dhillon and Kalra’s user authentication scheme [7], which consists of three steps: (1) registration, (2) login and authentication, and (3) the password change phase. Table 1 lists all the notations used in this paper.

#### 4.1. Registration phase for user

In this phase, MN, a mobile node seeking to access the IoT service through a smart device application, registers with the GW, and the following operations are performed:

1. MN selects its identity ID and password PW, inputs biometrics BIO, generates a random number r, and computes MR = h(r||PW), MI = h(r||ID), and MB = h(r||BIO).
2. MN sends a request, < MP, MI, MB >, via a secure channel.
3. After receiving the request message from MN, GW computes x = h(MI||KG), y = h(MP||KG), z = h(MB||KG), e = x || y, and f = x || z.
4. GW sends the response message, < MI, e, f, x, K >, to MN.
5. MN stores the received parameters along with r.

### 4.2. Registration phase for IoT node

In this phase, N registers with the GW, and the following operations are performed:

1. N chooses a random number r and computes MR = h(KGN||r||ID), MR = r ± KGN, and MP = r ± MR.
2. N sends the request, < NID, MP, MR, T >, to GW via a public channel.
3. GW checks the freshness of T. If it is fresh, GW computes MR = MP ± MR, T = NID ± MR, and MP = h(KGN||r||ID). GW then checks whether MP = MP. If it does, GW computes x = h(NID|||KG), y = h(MP||KG), and z = x || y.
4. Finally, GW sends the message, < z, y, T >, to N, via an insecure open wireless channel.
5. N checks the freshness of T. If it is fresh, N stores z and y in the memory storage.

### 4.3. Login and authentication phase

In this phase, MN, N, and GW carry out mutual authentication to set up a session key. The detailed description of the login and authentication phase is as follows:

1. MN inputs ID, BIO, and PW and computes MR = h(r||PW), MB = h(r||BIO), y = h(MP||KG), z = h(MB||KG), e = x || y, and f = x || z. MN then checks if y = x || y and z = x || z. If they are equal, MN generates a random number n and computes UN = h(y||z||KG||T) and UZ = n || x.
2. MN sends the authentication request M = < MI, e, f, UZ, UN, T > to N.
3. N checks the freshness of T. If it is fresh, N computes y = x || z and A = h(KGN||T || T ) ± y.
5.1. Kalra’s scheme

4.4. Password change phase

In this phase, MNl performs the following process to change the password stored in its host mobile device:

(a) MNl inputs $BIO_i$ and $PW_i$ and computes $MP_l^0 = h(r_i||PW_i)$, $MB_l = h(r_i||BIO_i)$, $x_l^0 = h(MP_l^0||KGU)$.

(b) MNl checks if $x_l^0 \neq y_l$ and $z_l^0 \neq z_l$. If they are equal, MNl selects a new password, $PW_{\text{new}}^l$.

(c) $MP_{\text{new}} = h(MP_l^0||KGU)$, and $e_{\text{new}} = x_l^0 \oplus y_{\text{new}}^0$.

Finally, MNl replaces the old $e_i$ with $e_{\text{new}}$.

5. Cryptanalysis of dhillon and Kalra’s scheme

In this section, we conduct cryptanalysis of the Dhillon and Kalra’s scheme [7]. For security analysis, we consider the following attacker capabilities:

1. The attacker $A$ can control the public channel by eavesdropping, inserting, deleting, altering, or intercepting public messages.
2. $A$ somehow acquires a user’s stolen or lost mobile device, he or she can perform a side channel attack to extract secret parameters from the device [33,34].
3. $A$ can enumerate all possible items offline in polynomial time in the Cartesian product $D_{id} \times D_{pw}$, where $D_{id}$ and $D_{pw}$ represent the dictionary spaces of the identity and password, respectively [35–37].

5.1. Stolen mobile device attack

In the Dhillon and Kalra’s scheme [7], $A$ can simultaneously obtains the identifier and password of MNl from the stolen or lost mobile device. $A$ can perform offline guessing attacks using the following process:

(a) $A$ extracts the secret parameters, $(M_{l1}, e_i, f_i, x_i, KGU, r_i)$, from the user’s mobile device.

(b) $A$ selects the candidate identity $ID_{l1}^*$, computes $MI_{l1}^* = h(r_i||ID_{l1}^*)$, and compares the extracted value with the calculated value, i.e., $MI_{l1} \neq MI_{l1}^*$.

(c) $A$ selects the candidate password $PW_{l1}^*$, computes $MP_{l1}^* = h(r_i||PW_{l1}^*)$ and $y_l^* = h(MP_{l1}^*||KGU)$, and compares the extracted value with the calculated value, i.e., $y_l \neq y_l^*$.

(d) If the measurements show that they are matched, $A$ has successfully found the correct identity and password. Otherwise, $A$ chooses another $ID_{l1}^*$ and $PW_{l1}^*$, and iterates steps (b) and (c) until the correct identity and password are found.

(e) $A$ extracts the password by $e_i \oplus y_l^*$ and compares $x_l \oplus z_l^*$. If they are the same, $A$ proceeds to the next step.

5.2. User impersonation attack

$A$ can impersonate a legitimate user using the $y_l^*$ and $z_l^*$ values through the guessing attack. Moreover, $A$ can more easily calculate $y_i$ and $z_i$ values only with $e_i$, $f_i$, and $x_i$ values extracted from the user’s mobile device without guessing $ID_{l1}^*$ and $PW_{l1}^*$ (e.g., $y_i^* = x_i \oplus e_i$ and $z_i^* = x_i \oplus f_i$).

The Dhillon and Kalra’s scheme [7] allows the impersonation of a legitimate user during the login authentication phase through the following process:

(a) $A$ inputs $ID_A$, $PW_A$ and $BIO_A$ and computes $MP_A = h(r_i||PW_A)$ and $MB_A = h(BIO_A||r_i)$.

(b) After this, $A$ skips the calculation of the other parameters and instead injects the $y_l^*$ and $z_l^*$ into the local verification process.

(c) If $A$ passes the local verification process, he or she generates a random number $n_A$ and computes $UN_A = h(y_l^*||z_l^*||KGU||T_1)$ and $UA_A = n_A \oplus x_i$.

(d) $A$ sends the authentication request, $Mi = (M_{l1}, e_i, f_i, x_i, UN_A, T_1 >)$, to $N_l$.

(e) Eventually, $N_l$ and $GW$ proceed with the rest of the login and authentication phase normally. Consequently, $A$ and $N_l$ establish a session key.

5.3. No provision for agreement of session key

In Dhillon and Kalra scheme [7], $MN_l$ and $N_l$ set up the session key $SK$, but they do not check to see whether the random numbers $n_l$ and $m_l$ included in the session key are correct, or they established the session key $SK$ correctly after the mutual authentication. The protocol of reference [38,39] provides a session key agreement. The reason for ensuring the agreement of the session key is as follows: If, for some reason, an error occurs in the parameter value used to establish the session key, an erroneous session key may cause a communication failure. For this reason, the two nodes that set up the session key must perform a mutual process of checking whether the session key has been correctly calculated.

5.4. No provision for revocation

Revealing a user’s stolen or lost mobile device is necessarily essential for authentication schemes in IoT environments [40]. If MNl’s legitimate mobile device is lost or stolen, an efficient revocation mechanism should be implemented to prevent future misuse of mobile devices and leakage of personal information. To support this mechanism, the server must maintain the users real identity.
to detect invalid mobile devices [41]. However, Dhillon and Kalra [7] did not consider this feature in their scheme.

6. Proposed scheme

We suggest a three factor anonymous user authentication scheme for IoT environments. The proposed scheme contains the following four phases: (1) registration, (2) login and authentication, (3) password change, and (4) user-revocation phase.

6.1. Registration of user

The registration phase of the proposed scheme for MN$_i$ is depicted in Fig. 2 and comprises the following operations:

(a) MN$_i$ selects $ID_i$, $PW_i$, and $BIO_i$, and computes $PW_B_i = h(ID_i || PW_i || B_IO_i)$ and $MID_i = h(ID_i || H(BIO_i))$.

(b) MN$_i$ sends $<ID_i, PW_B_i, MID_i>$ to GW via the secure channel.

(c) GW selects random numbers $r_{GU}$ and $r_D$ and computes $RID = E_{K_B}(ID_i)$, $PID = E_{K_G}(ID_i || r_{GU})$, $x_i = h(ID_i || PW_B_i)$, and $y_i = h(ID_i || PW_B_i || r_{GU}) || h(K_G || |ID_i||)$. GW stores a pair ($RID$, $MID_i$) in the database.

(d) GW sends $<PID_i, x_i, y_i, r_{GU}>$ to MN$_i$.

(e) Finally, MN$_i$ stores the received parameters, $<PID_i, x_i, y_i, r_{GU}>$, in the mobile device.

6.2. Registration of IoT node

The registration phase of the proposed scheme for the sensor node N$_j$ is depicted in Fig. 3 and consists of the following operations:

(a) N$_j$ selects random number $r_j$ and computes $MP_j = h(K_{GN} || r_j || N_ID_j)$, and $M1_j = r_j \oplus h(N_ID_j || K_{GN})$.

(b) N$_j$ sends $<N_ID_j, MP_j, M1_j>$ to GW via the public channel.

(c) GW computes $r^*_j = M1_j \oplus h(N_ID_j || K_{GN})$, $MP^*_j = h(K_{GN} || r^*_j || |N_ID_j||)$, $MP^*_j \equiv MP_j$, and $x_j = h(N_ID_j || K_{GN})$, and stores $<r^*_j, y_j, MP^*_j>$ in the memory.

(d) Store $<y_j>$ into the memory. GW computes $<y_j>$.

6.3. Login and authentication phase

In this phase, MN$_i$ and N$_j$ mutually authenticate each other with the support of GW to establish a session key. The login and authentication phase that are depicted in Fig. 4 are as follows:

(a) MN$_i$ inputs $ID_i$, $PW_{old}^i$, $PW_{new}^i$, and $BIO_i$, and computes $PW_{B_{old}}^i = h(PW_{old}^i || H(BIO_i))$ and $x_i = h(ID_i || PW_{B_{old}}^i)$.

(b) MN$_i$ checks whether $x_i$ and $x_{old}$ are the same. If they are not, MN$_i$ terminates this phase. Otherwise, MN$_i$ computes $A_i = y_i \oplus h(ID_i || PW_{B_{old}}^i || r_{GU})$, $PW_{B_{new}}^i = h(PW_{B_{new}}^i || H(BIO_i))$, $x_{new}^i = h(ID_i || PW_{B_{new}}^i)$, and $y_{new}^i = h(ID_i || PW_{B_{new}}^i || r_{GU}) \oplus A_i$.
Fig. 4. Login and authentication phase of the proposed scheme.

(c) Finally, MN_i replaces the old x^{old}_i and y^{old}_i with x^{new}_i and y^{new}_i, respectively.

6.5. Revocation phase

To recover the secret parameters, MN_i performs a revocation mechanism for the mobile device as follows:

(a) When MN_i hopes to revoke or reissue a secret parameter, he or she inputs an old identity ID^{old}_i, a new identity ID^{new}_i, a new password PW^{new}_i, and BIO_i into his or her mobile device. MN_i then computes PW^{new}_i = h(PW^{new}_i || H(BIO_i)), M^{new}_i = h(ID^{new}_i || H(BIO_i)), and MID^{new}_i = h(ID^{new}_i || H(BIO_i)).

(b) MN_i sends the revocation request message, < ID^{old}_i, ID^{new}_i, M^{old}_i, M^{new}_i, PW^{old}_i >, to GW via a secure channel.

(c) GW computes RID^{old}_D = E_{K_G}(ID^{old}_D) for verifying the identity of MN_i and then searches a pair (RID^{old}_D, MID^{old}_D) in the database to find a registered user. If the pairs (RID^{old}_D, MID^{old}_D) and (RID^{new}_D, MID^{new}_D) are equal, GW generates new random numbers r^{new}_D and r^{new}_S, computes P^{new}_i =
 confirm in device; secret 7.1.3. authentication each public

(43x196)

In the real process, the proposed scheme ensures a session key agreement.

7.1.6. Resistance to user impersonation attack

In the proposed scheme, \( A \) cannot disguise the user because the scheme resists a stolen mobile device attack through a local user verification process and mutual authentication. Therefore, as a secure session key agreement is guaranteed, the proposed scheme resists user impersonation attacks.

7.1.7. Resistance to replay attack

Even if \( A \) eavesdrops on messages \( M_{1-4} \) from the communication that is in the public channel and replays them, \( A \) cannot calculate the correct session key \( SK \). To compute the session key \( SK \), \( A \) would need to know \( n_i \) or \( m_i \), and to know these, \( A \) needs \( GW \)’s secret key \( K_{CI} \) and for \( K_{GU} \). As there is no way for \( A \) to know the secret keys of \( GW \) from the message transmitted through the public channel, the proposed scheme is safe from replay attacks.

7.1.8. Local user verification

At the login and authentication phase of the proposed scheme, the mobile device checks the legitimacy of the user. Users who have entered the correct \( ID_v \), \( PW_v \), and \( BIO_v \) through the user verification process can perform the following authentication procedure. Therefore, the proposed scheme can block unauthorized access of \( A \) because the individual \( BIO_{mi} \) is unique.

7.1.9. Resistance to stolen-verifier attack

In the proposed scheme, \( GW \) does not directly receive \( MN_i \’s \) credentials such as \( PW_{mi} \) and \( H(BIO_{mi}) \). Furthermore, \( GW \) maintains the database with \( RID_{i} \) encrypted with its private key to confirm the legitimacy of the user, i.e., even if \( A \) steals the user registered information from the database for impersonation, it is difficult for \( A \) to know the actual identity of \( MN_i \). Therefore, the proposed scheme is secure against stolen-verifier attacks.

7.1.10. Resistance to privileged-insider attack

The privileged-insider can attempt to impersonate a user by using a registration request message obtained at the user registration phase or additionally obtaining the stolen or lost mobile device of a user [47].

In the registration phase of the proposed scheme, \( MN_i \) sends \( ID_{i} \) and \( PW_{Bi} \), which contains \( PW_v \) and \( H(BIO_{mi}) \), to \( GW \). However, an insider in a \( GW \) cannot guess \( MN_i \’s \) \( PW_v \) without \( BIO_v \), which is unique to the user. Therefore, the proposed scheme resists stolen mobile device attacks. The insider needs \( BIO_v \) or the private key \( K_{CI} \) for \( MN_i \) to impersonate the user. It is impossible to determine \( BIO_v \), which is an individual’s biological characteristics, and if a security mechanism is applied that prevents insiders from knowing the secret key for users in \( GW \’s \) system, the insider cannot impersonate the user in any way.

Therefore, the insider cannot impersonate \( MN_i \) to access and communicate with \( N_i \) in the proposed scheme. Furthermore, in the password change phase of the proposed scheme, \( MN_i \) changes his or her password with \( PW_{Bi} \) without the help of \( GW \). The proposed scheme withstands privileged-insider attacks because it is impossible for the insider to know a \( MN_i \’s \) password.
7.1.11. User-friendly password change

A user’s password can be changed from his or her end without server intervention. We apply this mechanism to the proposed scheme to allow the user to replace an old password with a new one after the user verification phase is executed. Therefore, the proposed scheme provides a user-friendly password changing process.

7.1.12. Forward secrecy

The computed session key between MN_i and N_j can be corrupted by A. However, he or she cannot find significant correlations between the past, present, and future session keys because they contain random numbers n_i and m_j that are different in each session in the proposed scheme. Therefore, the proposed scheme guarantees forward security.

7.1.13. Resistance to sensor node impersonation attack

In this attack, we assume that A eavesdrops on the messages M_4 during the authentication and key agreement phase from the public channel and attempts to generate other messages M_4 = \langle PID_{new}^{'}, L_1, SV_j, T_2 \rangle to send them to MN_i. However, to generate M_4, A needs n_i and F_j. Therefore, A cannot impersonate a valid sensor node N_j in the proposed scheme. As a result, the proposed scheme is also secure against a sensor node impersonation attack.

7.1.14. Resistance to known session-specific temporary information attack

If the random numbers n_i and m_j are known to A, he or she can attempt to compute the session key SK = h(h(ID||n_i)||n_i||m_j). However, it requires the knowledge of ID_i or F_j = h(ID||n_i) from public messages M_2 and M_4. As we explained in Section 7.1.1, the proposed scheme ensures user anonymity through which ID_i is encrypted by the secret key K_{Gw}. In addition, F_j is protected by x_j that is not transmitted as plain text. There is no way for A to get ID_i and the related parameters involving SK. Therefore, the proposed scheme resists the known session-specific temporary information attack.

7.1.15. Provisional revocation phase

In the proposed scheme, MN_i sends a revocation request to GW with \langle ID_{old}^{'}, PID_{new}^{'}, MID_{old}^{'}, MID_{new}^{'}, PWB_{new}^{'}, \rangle when their mobile device is stolen or lost or when the secret parameters are exposed. Because GW maintains RID_i and MID_i in the database, when a revocation request is received from MN_i, GW computes RID_{old}^{'}, MID_{old}^{'}, and compares that the pairs (RID_i, MID_i) and (RID_{old}^{'}, MID_{old}^{'}) are same, to determine whether MN_i is a valid user. Since MID_i contains MN_i’s ID_i and BID_i, which is unique to the user, GW can only reissue the secret parameters to a legitimate user for recovery purposes. Thus, the proposed scheme can handle an unexpected case using provisional revocation.

7.2. Formal analysis using proverif

ProVerif is an automation tool for cryptographic protocol analysis, and it supports various cryptographic primitives such as symmetric and asymmetric encryptions, digital signatures, and hash functions. The principle by which ProVerif proves the security of a protocol by inputting and verifying the security attributes of the cryptographic primitives is introduced in the manual [48]. ProVerif is widely used by many researchers [49–51] to validate the security analysis of the key agreement and authentication schemes for various network environments. In this section, we verify the security of the proposed scheme using ProVerif, introduce ProVerif code as a description of the proposed scheme, and present the analysis results.

The execution of all the code described in Appendix A verifies the accuracy of all the events and queries and generates the simulation results presented in Fig. 5. All the authentication parameters, i.e., the queries and events between MN_i, N_j, and GW in the proposed scheme, perform successful mutual authentication and securely establish the session key as a result. Therefore, the proposed scheme can be considered secure for simulated attacks.

7.3. Formal analysis using the random oracle model

In this section, a formal security analysis of the proposed scheme is performed using a random oracle model. To this end, we first define a one-way hash function. A one-way hash function \( h: [0, 1]^* \rightarrow [0, 1]^n \) maps data of an input \( x \in [0, 1]^* \) of arbitrary size to a bit string of fixed size \( h(x) \in [0, 1]^n \). The properties of a one-way hash function are as follows:

1. **Pre-image resistance**: Given \( y = h(x) \), it is computationally difficult to find an input \( x \).
2. **Second pre-image resistance**: Given \( x \neq x' \), it is computationally difficult to find a different input \( x' \) such that \( h(x') = h(x) \).
3. **Collision resistance**: It is computationally difficult to find two different inputs \( x \) and \( x' \) such that \( h(x) = h(x') \).

**Theorem 1.** Assuming that the one-way hash function, \( h(\cdot) \), behaves like an oracle, the proposed scheme is proven secure against A because it guarantees secure protection of MN_i’s identity ID_i and GW’s private key K_G.

**Reveal:** Given the hash value \( y = h(x) \), the random oracle shall output the hash input value \( x \) unconditionally.

**Extract:** Given the encrypted message \( C = E_{K_d}(P) \), the random oracle shall output the plain text \( P \) unconditionally.

**Proof.** In the proposed scheme, we apply a method similar to that used for the formal security proof in [52,53]. We assume that A runs the experimental algorithm to derive \( ID_{mi} \) and \( K_d \) that are shown in Algorithm 1, EXP1^A_{HASH} for the proposed

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### Algorithm 1: Algorithm EXP1^A_{HASH}

1. Eavesdrop login request message \( (PID_i, U_j, U_j, T_j) \) of MN_i
2. Call the Reveal oracle.
   - Let \( (A'_i, PID'_i, n'_i) \leftarrow \text{Reveal}(U_j) \)
3. Computes \( U_j = n'_i \oplus A'_i \)
4. if \( (U_j = U_j) \) then
5. Call the Reveal oracle.
   - Let \( (K'_d, ID'_i) \leftarrow \text{Reveal}(A'_i) \)
6. Call the Extract oracle.
   - Let \( (ID'_j, T_j) \leftarrow \text{Reveal}(PID'_i) \)
7. if \( (ID'_j = ID'_i) \) then
8. Accept \( ID'_j \) as the correct identity
9. Compute \( PID'_j = E_{K'_d}(ID'_j, T_j) \)
10. if \( (PID'_j = PID'_i) \) then
11. Accept \( K'_d \) as the correct secret key
12. return 1 (Success)
13. else
14. return 0
15. end if
16. else
17. return 0
18. end if
19. else
20. return 0
21. end if
user authentication scheme. We define the success probability of $\text{EXP}_{\text{HASH}}^4$ as $\text{Success}^4_{\text{HASH}} = |\{\text{Pr}[\text{EXP}^4_{\text{HASH}} = 1]\}|$. The advantage function for this experiment becomes $\text{Adv}_{\text{HASH}}^4(t,q_R,q_E) = \max_i (\text{Success}^4_{\text{HASH}})$, where the maximum value is determined by the execution time $t$ and the number of queries $q_R$ and $q_E$ for the Reveal and Extract oracle, respectively. If $A$ can successfully break the property of the hash function provided in Definition 1, $A$ can directly derive $ID_1$ and $K_C$ by getting the desired input value of the hash function. We assume that the attacker performs the attack experiment detailed in Algorithm 1 after $A$ detects the participant’s full connection through the authentication request message transmitted in the public channel. However, it is difficult for $A$ to invert the input value against a given hash value contained in the acquired messages, i.e., $\text{Adv}_{\text{HASH}}^4(t,q_R,q_E) \leq \epsilon$ because $\text{Adv}_{\text{HASH}}^4(t,q_R,q_E)$ depends on $\text{Adv}_{\text{HASH}}^4(t)$. As $\text{Adv}_{\text{HASH}}^4(t,q_R,q_E) \leq \epsilon$ is negligible, we finally have $\text{Adv}_{\text{HASH}}^4(t,q_R,q_E) \leq \epsilon$, which is also negligible. Consequently, $A$ cannot acquire $ID_1$ and $K_C$. Therefore, the proposed scheme is proven secure against the adversary $A$ even if $A$ can have full communication control on the public channel. □

Theorem 2: Under the assumption that the one-way hash function $h(\cdot)$ behaves like an oracle, then the proposed scheme is proven secure against $A$ by protecting $ID_1$, $PW_1$, and $BIO_1$ of $MN_1$ and $K_C$ of $GW$.

Proof: We assume that $A$ executes the experimental algorithm $\text{EXP}_{\text{HASH}}^4$, which is detailed in Algorithm 2, to derive $ID_2$, $PW_2$, $BIO_2$, and $K_C$. $A$ exploits a side channel attack [33,54] to extract the secret parameters $PID_1$, $x_I$, $y_I$, and $r_{GU}$ from the mobile device. We define the success probability of $\text{EXP}_{\text{HASH}}^4$ as $\text{Success}^4_{\text{HASH}} = |\{\text{Pr}[\text{EXP}^4_{\text{HASH}} = 1]\}|$. The advantage function for this experiment becomes $\text{Adv}_{\text{HASH}}^4(t,q_R) = \max_i (\text{Success}^4_{\text{HASH}})$, where the maximum value is determined by the execution time $t$ and the number of queries $q_R$ and $q_E$ for the Reveal and Extract oracle. If $A$ can resolve the hash function problem, $A$ can directly derive $ID_{mi}$, $PW_{mi}$, $BIO_{mi}$, and $K_{mi}$. Consider the attack experiment shown in Algorithm 2. $A$ can successfully break the property of the hash function provided in Definition 2, $A$ can directly derive $ID_{mi}$, $PW_{mi}$, $BIO_{mi}$, and $K_{mi}$ by getting the desired input value of the hash function. However, it is difficult for $A$ to invert the input value against a given hash value contained in the extracted parameters, i.e., $\text{Adv}_{\text{HASH}}^4(t,q_R) \leq \epsilon$, $\forall \epsilon > 0$. We have $\text{Adv}_{\text{HASH}}^4(t,q_R,q_E) \leq \epsilon$, because $\text{Adv}_{\text{HASH}}^4(t,q_R,q_E)$ depends on $\text{Adv}_{\text{HASH}}^4(t)$. Because $\text{Adv}_{\text{HASH}}^4(t,q_R) \leq \epsilon$ is negligible, we finally have $\text{Adv}_{\text{HASH}}^4(t,q_R,q_E) \leq \epsilon$, which is also negligible. Consequently, $A$ cannot acquire $ID_2$, $PW_2$, $BIO_2$, and $K_C$. Therefore, the proposed scheme is proven secure against $A$ even if $A$ can obtain the secret parameters stored in the mobile device. □

7.4. Authentication proof using BAN logic

In this subsection, we use Burrows-Abadi-Needham (BAN) logic [55] to provide the proof that $MN_i$ and $N_j$ perform a valid mutual authentication and to verify that the distributed session key between them is fresh. BAN logic is a formal logic that proves the belief that each of the entities participating in the authentication protocol trusts each other based on the source, freshness, and reliability of the messages. Many researchers [56–59] use it to analyze the security of cryptographic protocols.

Algorithm 2: Algorithm EXP2$_{\text{HASH}}$

1. Extract the secret parameters, $<\text{PID}_1, x_I, y_I, r_{GU}>$, stored in the mobile device by the side channel attack.
2. Call the Reveal oracle. Let $(ID_2',PW_2') = \text{Reveal}(x_I)$
3. Call the Reveal oracle. Let $(PW_2',BIO_2') = \text{Reveal}(PW_2')$
4. Compute $z_I = h(ID_2')|PW_2'|r_{GU} \oplus y_I'$
5. Call the Reveal oracle. Let $(K_{C}',ID_{mi}') = \text{Reveal}(z_I)$
6. if $(ID_2 = ID_2')$ then
7. Accept $ID_{mi}'$ as the correct $ID_2$ of $MN_i$
8. Compute $\text{PID}_2' = K_{C}'(ID_2'|ID_{mi}')$
9. if $(\text{PID}_2 = \text{PID}_2')$ then
10. Accept $r_{GU}'$ and $K_{C}'$ as the correct $r_{GU}$ and $K_{C}'$ of $MN_i$
11. Compute $w_I = h(ID_2'|H(PW_2'|H(BIO_2'))|r_{GU}')$
12. Compute $y_I' = w_I \oplus h(K_{C}'|ID_{mi}')$
13. if $(y_I = y_I')$ then
14. Accept $PW_2'$ and $BIO_2'$ as the correct $PW_2$ and $BIO_2$ of $MN_i$
15. return 1 (Success)
16. else
17. return 0
18. end if
19. else
20. return 0
21. end if
22. else
23. return 0
24. end if

The basic notations of BAN logic is as follows.
(1) $U \to C$: $U$ sees condition $C$.
(2) $U \equiv C$: Condition $C$ is believed by $U$.
(3) $\neg(C)$: It makes a fresh $C$.
(4) $U \sim C$: $U$ expresses the condition $C$.
(5) $U \leftarrow S$: $U$ asks $S$ a secret key $K$.
(6) $U \Rightarrow C$: Condition $C$ is handled by $U$.
(7) $(C)_K$: $C$ is encrypted under key $K$.

To prove mutual authentication of the proposed scheme, we use the following five rules of BAN logic.

1. Rule 1: Message-meaning rule: $\frac{U_{\sim S},U_{\sim C} \times C}{U_{\sim S} \downarrow C}$. If $U$ trusts that the key $K$ is shared with $S$, $U$ sees the $C$ combined with $K$, then $U$ trusts $S$ once said $C$.
2. Rule 2: Nonce-verification rule: $\frac{U_{\sim S} \downarrow C \times U_{\sim C} \leftarrow C}{U_{\sim S} \sim C}$. If $U$ trusts that $S$’s freshness and $U$ trusts $C$ once said $C$, then $U$ trusts that $S$ trusts $C$.
3. Rule 3: Believe rule: $\frac{U_{\sim S} \downarrow C \times U_{\sim C} \leftarrow C}{U_{\sim S} \downarrow C}$. If $U$ trusts $C$ and $M$, $(C, M)$ are also trusted by $U$. 

Fig. 5. Results of ProVerif code for the proposed scheme.
(4) Rule 4: Freshness-conjunction rule: $U \leftarrow (C) \rightarrow (U \leftarrow C)$. If freshness of $C$ is trusted by $U$, then $U$ can trust the freshness of full condition.

(5) Rule 5: Jurisdiction rule: $\frac{U \leftarrow (C) \rightarrow (U \leftarrow C)}{U \leftarrow (C) \rightarrow (U \leftarrow C)}$: If $U$ trusts that $S$ has jurisdiction over $C$, and $U$ trusts that $S$ trusts a condition $C$, then $U$ also trusts $C$.

Since the main goal of the proposed scheme is to establish a session key between $MN_i$ and $N_j$ through mutual authentication, we must satisfy the following four goals.

1. **Goal 1**: $MN_i \leftarrow (MN_i \leftarrow N_j)$
2. **Goal 2**: $N_i \leftarrow (MN_i \leftarrow N_j)$
3. **Goal 3**: $MN_j \leftarrow (MN_j \leftarrow N_j)$
4. **Goal 4**: $N_j \leftarrow (MN_j \leftarrow N_j)$

The four messages transmitted in the proposed scheme can be converted into the idealized form as follows.

1. Using $M_1 = \langle PID_i, UN_i, UZ_i, T_i \rangle$, $MN_i \rightarrow N_j$: $UN_j = h(A_i \mid |PID_i|, |N_i|)$. This is reduced as $MSG_1: PID_i, A_i, T_i, 1_n$.
2. Using $M_2 = \langle M_1, NID_j, A_j, B_j \rangle$, $N_j \rightarrow GW: A_j = h(x_j) \oplus n_j$, $B_j = h(x_j) \oplus n_i$. This is reduced as $MSG_2: (M_1, NID_j, n_j)_s$.
3. Using $M_3 = \langle PID^{new}, G_j, R_j, H_j \rangle$, $GW_i \rightarrow N_j: G_j = F_j \oplus x_j$, $R_j = n_j^i \oplus n_j^m$, $H_j = h(x_j^i \mid |n_j^i| \mid |F_j|)$. This is reduced as $MSG_3: (F_j, n_j, n_j^m, KCN)_s$.
4. Using $M_4 = \langle PID^{new}, L_j, SV_j, T_j \rangle$, $N_j \rightarrow MN_j: L_j = h(\langle N_j \mid |N_j| \rangle) \oplus m \oplus SV_j = h(SK_j^i \mid T_i \mid T_j)$. This is reduced as $MSG_4: (PID_j, m_j, T_i, T_j)_n$.

To derive the goals of the proposed scheme, we define the following assumptions.

1. $A_1: MN_i \equiv \langle z \mid T_i \rangle$
2. $A_2: N_j \equiv \langle z \mid n_j \rangle$
3. $A_3: GW \equiv \langle z \mid KCN \rangle$
4. $A_4: N_j \equiv \langle z \mid T_2 \rangle$
5. $A_5: N_j \equiv \langle N_j \mid n_j \mid MN_i \rangle$
6. $A_6: GW \equiv \langle GW \mid N_j \rangle$
7. $A_7: N_j \equiv \langle N_j \mid x_j \mid GW \rangle$
8. $A_8: MN_j \equiv \langle MN_j \mid n_j \mid N_j \rangle$
9. $A_9: N_j \equiv \langle N_j \mid MN_j \leftarrow SK \mid N_j \rangle$
10. $A_{10}: N_j \equiv \langle N_j \mid MN_j \leftarrow SK \mid N_j \rangle$

We describe the main proof of the proposed scheme using the BAN logic rules, messages and assumptions as follows.

1. From $MSG_1$, we get $V_1: N_j \leftarrow (PID_i, A_i, T_i)_n$.
2. From $A_2$ and Rule 1, we get $V_2: N_j \leftarrow (MN_j \leftarrow (PID_i, A_i, T_i))_n$.
3. From $A_1$ and Rule 4, we get $V_3: N_j \equiv (MN_j \leftarrow (PID_i, A_i, T_i))_n$.
4. From $V_1$, $V_2$ and Rule 2, we get $V_4: N_j \leftarrow (MN_j \leftarrow (PID_i, A_i, T_i))_n$.
5. From $MSG_2$, we get $V_5: GW \equiv (M_1, NID_j, n_j)_s$.
6. Using $A_2$ and Rule 1, we get $V_6: GW \equiv N_j \leftarrow (MN_j \leftarrow (MN_j \leftarrow N_j))_s$.
7. From $A_2$ and Rule 4, we get $V_7: GW \equiv (MN_j \leftarrow (MN_j \leftarrow N_j))_s$.
8. From $V_5$, $V_6$ and Rule 2, we get $V_8: GW \equiv N_j \leftarrow (MN_j \leftarrow (MN_j \leftarrow N_j))_s$.
9. From $MSG_3$, we get $V_9: N_j \leftarrow (F_j, n_j, n_j, KCN)_s$.
10. From $A_2$ and Rule 1, we get $V_10: N_j \equiv GW \leftarrow (F_j, n_j, n_j, KCN)_s$.
11. From $A_2$ and Rule 4, we get $V_{11}: N_j \equiv z(F_j, n_j, n_j, KCN)_s$.
12. From $V_9$, $V_{10}$ and Rule 2, we get $V_{12}: N_j \equiv GW \leftarrow (F_j, n_j, n_j, KCN)_s$.
13. From $MSG_4$, we get $V_{13}: MN_i \leftarrow (PID_i, m_j, T_1, T_2)_n$.

(14) From $A_8$ and Rule 1, we get $V_{14}: MN_j \equiv N_j \leftarrow (PID_i, m_j, T_1, T_2)_n$.
(15) From $A_4$ and Rule 4, we get $V_{15}: MN_j \equiv z(PID_i, m_j, T_1, T_2)_n$.
(16) From $V_{13}$, $V_{14}$ and Rule 2, we get $V_{16}: MN_j \equiv N_j \leftarrow (PID_i, m_j, T_1, T_2)_n$.
(17) From $V_{12}$, $V_{16}$, and $SK = h(F_j \mid |n_j| \mid m_j)$, we get $V_{17}: MN_j \equiv (MN_j \leftarrow SK \mid N_j)_s$.
(18) From $V_{18}, V_9$, and $SK = h(IID_j \mid |n_j| \mid m_j)$, we get $V_{18}: N_j \equiv (MN_j \leftarrow SK \mid N_j)_s$.
(19) From $A_9$, $V_{17}$ and Rule 5, we get $V_{19}: MN_j \equiv N_j \equiv (MN_j \leftarrow SK \mid N_j)_s$ (Goal 3).
(20) From $A_{10}$, $V_{18}$ and Rule 5, we get $V_{20}: N_j \equiv MN_j \equiv (MN_j \leftarrow SK \mid N_j)_s$ (Goal 4).

From Goals 1, 2, 3, and 4 that we achieved above, we see that $MN_i$ and $N_j$ establish a session key through secure mutual authentication.

8. Performance analysis

In this section, we compare the computational and communication costs for the proposed scheme with other related schemes that have the same communication mechanism in IoT networks. We conducted a comparative analysis based on the computational cost and the amount of communication incurred during the login and authentication process.

We considered the 320-bit ECC (Elliptic multiplication) $T_e$, the 128-bit Advanced Encryption Standard (AES) algorithm $T_e$, and the 160-bit hash function $T_h$. We did not consider the XOR operation because it is negligible.

We assumed that the mobile node and gateway are computing environments on the following computing environments and evaluated the execution time of cryptographic operations. We refer to the experimental results of Abbasi-Nazhad-Mood and Nikooghadam [60] for each cryptographic execution time on the following sensor node:

1. Mobile node: Galaxy Note 9 Device, AP: Octa-Core Processor 2.7GHz + 1.7GHz, 8G memory, OS: Android 9.0, and Android Studio and Software Development Kits (SDK) tools.
2. Sensor node: LPC1768 Device, ARM Cortex-M3 (up to 100 MHz) processor, 512 kB flash memory, and 64 kB SRAM.
3. Gateway: CPU: Intel(R) Pentium(R) processor G4600 (3.60 GHz), 8G memory, OS: Win10 64bit, and Virtual Studio 2017 using the Crypto++ Library 8.1.

Based on our measurement results and the experimental results of Abbasi-Nazhad-Mood and Nikooghadam [60], the cryptographic time of the mobile node, sensor node, and gateway are as follows:

1. Mobile node: $T_e \approx 29.48\mu s, T_h \approx 76.2\mu s, T_{16} \approx 160.38\mu s$
2. Sensor node: $T_e \approx 1263\mu s$ and $T_h \approx 15.5\mu s$
3. Gateway: $T_e \approx 2226\mu s, T_h \approx 5.4097\mu s, T_{16} \approx 4.9465\mu s$

We summarize the results of the performance comparison in Table 3. It indicates that the Turkanovic et al.'s scheme [25] has significantly less computational complexity than other schemes. However, it has already been revealed by Farash et al. [26] that the Turkanovic et al. scheme [25] is vulnerable to various attacks. The computational costs of the schemes proposed by Das et al. [42], Chang et al. [43], Yang et al. [44], and Wu et al. [46] are inferior to that of the proposed scheme. Our comparison shows that the Banerjee et al.'s scheme [45] has the second-best performance. However, as shown in Table 2, their scheme does not include a revocation phase.

Using the method presented in [61,62], we compared the communications cost of the login and authentication phase. We assume that the lengths of the identity, timestamp, and random
number values are 128, 32, and 64 bits, respectively. The symmetric key encryption, the elliptic multiplication operation, and the hash function produce 256, 360, and 160 bits, respectively.

Table 4 summarizes the results of the comparison in terms of communication cost. The total communication cost of proposed scheme is 2112 bits, while the schemes of Das et al. [42], Turkanovic et al. [25], Chang et al. [43], Yang et al. [44], Banerjee et al. [45], Wu et al. [46], and Dhillon and Kalra [7] are 2368, 2688, 2048, 3712, 3200, 2592, and 2880 bits, respectively. The cost of the Chang et al.’s scheme [43] is less than the proposed scheme. However, their scheme is insecure, as previously mentioned.

We measured the performance of the proposed scheme using hardware approximations of mobile devices and sensor devices that can be used in real IoT environments. In the proposed scheme, the computation and communication costs of the mobile node and sensor node are slightly higher than those of some other schemes. However, this can be applied to extremely low-cost IoT devices because mobile nodes and sensor nodes use only XOR and hash operations for mutual authentication and session key establishment. Furthermore, the proposed scheme assures all security requirements. Therefore, the proposed scheme is suitable for application to IoT environments.

9. Conclusions

In this study, we report that the user authentication scheme of Dhillon and Kalra has some security pitfalls, and propose an enhanced scheme that solves these vulnerabilities and improves security. To prove the security strength of the proposed scheme, we performed informal and formal security analyses using the random oracle model, BAN logic, and ProVerif tool. The results of the analysis show that the proposed scheme is secure against various known attacks and satisfies all security requirements. Furthermore, we performed a comparative analysis of performance against other related schemes assuming the hardware specifications of mobile and sensor devices in a real IoT environment. The results of the analysis show that the proposed scheme is compatible with extremely low-cost IoT devices. Therefore, the scheme proposed in this study is practical for user authentication in IoT environments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Hakjun Lee: Conceptualization, Software, Writing - original draft. Dongwoo Kang: Formal analysis. Jihyeon Ryu: Resources, Investigation. Dongho Won: Methodology, Validation. Hyounghick Kim: Writing - review & editing. Youngsook Lee: Supervision.

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Appendix A

Fig. 6 presents the process definitions and identifiers of the proposed scheme. Here, we define the public and secure channels used between each party; predefined constants; secret key; session key; exclusive-OR, hash, and bio-hash functions; symmetric key cipher; and concatenation operation; and the start and end of communication between each node to be verified for the correspondence relationship of messages.

Fig. 7 shows the overall MN process code for the proposed scheme. We model the registration phase on lines 39–42 and the login and authentication phase on lines 43–60.

Fig. 8 shows the overall Nj process code for the proposed scheme. We model the registration phase on lines 62–67 and the login and authentication phase on lines 68–91.

(*......channels......*)
1 free ch:channel [private].
2 free chb:channel.
3 free chc:channel.
4
(*......constants......*)
5 free ID:bitstring [private].
6 free NID:bitstring.
7 free GW:bitstring.
8 free PW:bitstring [private].
9 free BIO:bitstring [private].
10
(*......secret key......*)
11 free KG:bitstring [private].
12 free KGN:bitstring [private].
13 free KG:bitstring [private].
14
(*......shared key......*)
15 free SK:bitstring [private].
16 free SKb:bitstring [private].
17
(*......functions......*)
18 fun concat(bitstring,bitstring) : bitstring.
19 fun syme(bitstring,bitstring):bitstring.
20 fun xor(bitstring,bitstring):bitstring.
21 fun h(bitstring):bitstring.
22 fun l(bitstring):bitstring.
23 reduc forall m:bitstring, key:bitstring; symd(syme(ma,key),key,ma).
24 equation forall p:bitstring, q:bitstring; xor(xor(p,q),q)=p.
25
(*......events......*)
26 event beginGateWay(bitstring).
27 event endGateWay(bitstring).
28 event beginIoTNode(bitstring).
29 event endIoTNode(bitstring).
30 event beginMNode(bitstring).
31 event endMNode(bitstring).
32
Fig. 6. ProVerif code for the overall mobile node process.

(*......MN’s process......*)
33 let pMNode=
34 let PWB = h(concat(PW,h(BIO))) in
35 let MID = h(concat(ID,h(BIO))) in
36 out(chi(ID,PWB,MID));
37 let (char(str1,str2,str3,str4,str5)) in
38
Fig. 7. ProVerif code for the overall mobile node process.

(*......IoT Node’s process......*)
39 let pAgent=
40 new r:bitstring.
41 let M1 = h(concat(KGN,concat(r1,NID))) in
42 let M2 = xor(r1,h(concat(NID,KGN))) in
43 out(chi(NID,M1));
44 in(chi(XY:bitstring));
45 in(chi(XM:bitstring));
46 let (XPID:bitstring,XUNI:bitstring,XUZ:bitstring,XT:bitstring) = XM in
47 event beginIoTNode(NID);
48 new nj:bitstring;
49 new NJ:bitstring;
50 let (XUNM:bitstring) = XM in
51 let x1 = xor(XY,h(concat(NID,concat(r1,KGN)))) in
52 let A1 = xor(h(x1), nj) in
53 let B1 = h(concat(x1,nj)) in
54 let M2 = concat(XUNM,concat(NID,concat(A1, B1))) in
55 out(chi(M2));
56 in(chi(XM:bitstring));
57 let (XPID:bitstring,XUNI:bitstring,XUZ:bitstring,XT:bitstring) = XM in
58 let F1 = xor(XG,x1) in
59 let ni" = xor(XR,nj) in
60 let H1 = h(concat(x1,concat(nj,concat(ni",F1")))) in
61 if H1 = XH1 then
62 new mj:bitstring;
63 new Tx:bitstring;
64 let L1 = xor(h(concat(NID,ni")),mj) in
65 let SKJ1 = h(concat(TF,concat(ni",mj))) in
66 let SV = h(concat(SKJ1,concat(Xt,T2))) in
67 let M4 = concat(XPID,concat(L1,concat(SV,T2))) in
68 out(chi(M4));
69 event endIoTNode(NID);
70
Fig. 8. ProVerif code for the overall mobile node process.
Fig. 9. ProVerif code for the overall mobile node process.

Fig. 10. ProVerif code for the overall mobile node process.

| 92 | (*......GW's process......*) |
| 93 | let pHAgent= |
| 94 | in(ch,\{XID|bitstring, XPWB|bitstring, XMID|bitstring\}); |
| 95 | new rGU|bitstring; |
| 96 | new rD|bitstring; |
| 97 | let RID=syme\{XIDI, KG\} in |
| 98 | let PID=syme\{concat\{XIDI, rGU\}, KG\} in |
| 99 | let xl=h\{concat\{XIDI, XPWB\}\} in |
| 100 | let yl=xor\{h\{concat\{XIDI, concat\{XPWB, rGU\}\}\}, h\{concat\{KG, XIDI\}\}\} in |
| 101 | out(ch,\{PID, yl, rGU\}); |
| 102 | let xI=XDI\{concat\{XIDI, XNID, KG\}\} in |
| 103 | let yI=xor\{XMI, \{concat\{XMI, xI, KG\}\}\} in |
| 104 | if MP|y=concat\{KG, rI', XIDI\} in |
| 105 | then |
| 106 | let xI'=h\{concat\{XIDI, KG\}\} in |
| 107 | let yI=xor\{xI', MP\} in |
| 108 | out(ch, yI)); |
| 109 | event beginGateWay(GW); |
| 110 | let (XNID|bitstring, XAP|bitstring, XJB|bitstring, XMM|bitstring) = XM In |
| 111 | let (XPPID|bitstring, XUNN|bitstring, UXU|bitstring, XTT|bitstring) = XM In |
| 112 | let xI''=h\{concat\{XIDI, XNID, KG\}\} in |
| 113 | let nI=xor\{nI, xI'I\} in |
| 114 | let B''=h\{concat\{xI', nI\}\} in |
| 115 | let (ID'|bitstring, rD'|bitstring) = symd\{XPPID, KG\} in |
| 116 | let A''=h\{concat\{ID', KG\}\} in |
| 117 | let nF=xor\{UXU, A\} in |
| 118 | let UNI'=h\{concat\{A', concat\{XPPID, nI'\}\}\} in |
| 119 | if UNI'=XUNN then |
| 120 | let F3=h\{concat\{ID', nI\}\} in |
| 121 | let GI=xor\{FI, nI\} in |
| 122 | let R2=xor\{nI', nI'\} in |
| 123 | let H3=h\{concat\{xI', concat\{nI, concat\{nI, nI'\}\}\}\} in |
| 124 | new Nr|bitstring; |
| 125 | let NPID=syme\{concat\{ID', Nr\}, KG\} in |
| 126 | let M3=concat\{NPID, concat\{GI, concat\{Ri, HI\}\}\} in |
| 127 | event endGateWay(GW). |

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