A Privacy-Preserved E2E Authenticated Key Exchange Protocol for Multi-Server Architecture in Edge Computing Networks

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This work was supported in part by the Chang Gung Memorial Hospital under Grant CMRPGD0183 and Grant CMRPD3D0063, in part by the Ministry of Science and Technology in Taiwan under Grant MOST-105-2923-E-182-001-MY3, Grant MOST-107-2221-E-182-006, and Grant MOST-108-2221-E-182-011, in part by the Healthy Aging Research Center, Chang Gung University from the Featured Areas Research Center Program within the Framework of the Higher Education Sprout Project by the Ministry of Education (MOE) in Taiwan, under Grant EMRPD1H0481, Grant EMRPD1H0421, and Grant EMRPD1H0551.

ABSTRACT Edge computing has played an important role in enabling 5G technology which supports a great number of connected narrow-band IoT devices. In an edge computing architecture enabled with global mobile network, edge or IoT devices are wirelessly connected to the edge of the network. Data acquisition and processing will be handled at or close to the edge of the network in a distributed way. Since edge computing is a heterogeneous distributed interactive system with multiple domains and entities, it might suffer from potential attacks and threats. To provide a trusted edge computing, there must have a robust scheme that allows all participants to mutually authenticate in a secure and privacy-preserved way. With the rapid development of IoT technologies, mobile networks and edge computing architecture, single server has been unable to meet the needs of users. In this paper, we propose a privacy-preserved end-to-end password-based authenticated key exchange protocol for multi-server architecture in edge computing networks. Our protocol allows an end user to use an easy-to-remember password to login to the server, then through foreign agent compute a shared key with another end user for specific use of services. The proposed protocol provides strong user anonymity during communication process. Besides, the proposed protocol is proved to be secure using BAN logic and AVISPA tool. Furthermore, performance analysis shows that the proposed protocol gains stronger security and better computational efficiency. Providing lightweight computation with short key size of ECC, our work is a solution to lower latency and improve efficiency in edge computing networks.

INDEX TERMS Edge computing, IoT, end-to-end, privacy protection, password-based, key exchange.

I. INTRODUCTION

Development of ubiquitous computing technologies and wireless sensing devices has driven various innovative services and applications of the Internet of Things (IoT), such as smart home, smart healthcare, smart city, intelligent transportation, and etc. IoT is a global and heterogeneous infrastructure comprising a number of functional blocks based on existing and evolving interoperable wireless information and communication technologies [1] such as 2G / 3G / 4G, WiFi, Bluetooth, etc. Functional blocks include internet-enabled sensing devices, communication, services, management, security, and applications [2]. It enables advanced intelligent context-aware services by interconnecting physical things, virtual things or hybrid things. Recently, Internet of Everything (IoE) focused on the intelligent connection of people, processes, data, and everything has been introduced. The proliferation of the IoE and 5G network architecture [3]
enables powerful collaborative computation, data processing, and rich service interface for the devices. However, traditional centralized cloud computing model for IoE will inefficiently support IoE-based application services due to the following problems: (i) Multi-sources data processing requirements of massive data at the edge of network might not be met. (ii) The communicational bandwidth and speed might be a bottleneck due to large scale of user access. (iii) It is a big challenge to deal with user privacy and users’ sensitive data in edge devices. Therefore, it is desired to combine existing cloud computing and edge computing to efficiently deal with the massive data processing problems at the edge of the network [2].

In an edge computing architecture, data acquisition and processing will be handled at or close to the edge of the network in a distributed way. It can offload the computation and communication burden and gain better quality of service. In the other word, edge computing enables storing and processing data at the edge of the network [4]. Thereby, edge computing addresses heavyweight computation problem from cloud computing [5]. Thus, edge computing has played an important role in enabling 5G technology, where narrow-band (NB) IoT devices are the essential entity. However, since edge computing is a heterogeneous distributed interactive system with multiple domains and entities, it might suffer from potential security issues and challenges in processing massive data. These issues and challenges include data security, secure computation, secure transmission, entity authentication, access control, privacy protection [2]. To provide a trusted edge computing, it should allow all participants to mutually authenticate for withstanding potential threats. Figure 1 presents communication in an edge computing network. Users may request to use services from providers (home servers or foreign agents). Besides, end users can communicate with each other to compute conversation key for specific purpose. Since this communication is carried out via a public channel, it is threatened to various attacks, such as man-in-the-middle attack [6], replay attack [7], impersonation attack [8], stolen verifier attack [9] and so on. An adversary can access message and steal desired information. Besides, identity anonymity [10] is very important to user. Therefore, a robust authentication scheme securing this communication is essential. Recently, a lot of works have been conducted to address security and privacy for sensitive information distributed using IoT devices in mobility networks or edge computing networks [11]–[15].

An edge computing architecture enabled with global mobility network provides effective global roaming services for personal communicating users and IoT devices. Through the universal roaming technology, legitimate mobile users can enjoy ubiquitous services [16] and manage IoT devices. A global mobility network includes three communicating parties: mobile user, home server and foreign agent. Mobile user in global mobility networks access service provider using IoT devices. User can directly use service from home server. Besides, he/she can communicate with foreign agent to obtain the service through home server [17]. With the rapid development of mobility network technology, people can use various services through mobile devices anytime and anywhere with edge computing. In order to address user security and privacy, lots of authentication and key exchange protocols used for global mobility networks have been introduced [18]–[21]. For instance, replay attack was prevented in [22], [23].

Furthermore, Sood [24] proposed a smart identity authentication protocol based on a dynamic identity card, which is obtained from improvement of Bellovin and Merritt [25]’s protocol. Sood used congruent multiplication and exponent to calculate user identity and password, then stores these in a verification table. However, Sood’s protocol is not free from stolen verifier attack when attacker steals the verification table. Therefore, some scholars have proposed password-based authentication mechanism without verification table to withstand this attack [26], [27].

Recently, Gope and Hwang [16] proposed a strong anonymity mutual authentication and key agreement scheme
for global mobile networks. Mobile communication architecture introduced in their work provided a cross-domain server mutual authentication method. However, server in Gope and Hwang’ protocol needs to maintain a verification table at registration center, which causes certain threats. Their work did not introduce a strong two-factor authentication. Besides, Gope and Hwang’s scheme cannot achieve the goal of end-to-end communication.

With the rapid development of IoT technologies, global mobile networks and edge computing networks, single server has been unable to meet the needs of users. The number of servers has increased remarkably to provide more services for the end user [28]. The conventional schemes allow user to access service only with a single server. More servers will lead to more identities and passwords that user must remember, which causes considerable inconvenience. It is not secure that user uses the same set of identities and passwords to register with different servers. Therefore, many researchers have proposed identity authentication mechanism suitable for a multi-server environment so that user can obtain services from multiple servers using a single password. A multi-server architecture in the edge computing network allows users to access service without complicated registration and authentication. For instance, Li et al. [29] proposed a secure dynamic identity based authentication protocol with smart card for multi-server architecture.

In this paper, we propose a privacy-preserved end-to-end authenticated key exchange protocol for multi-server architecture in distributed edge computing networks. The proposed protocol allows a mobile user to use an easy-to-remember password to login and authenticate different servers in the network. Edge computing network enables 5G technology architecture that supports a massive number of connected NB-IoT devices. The users of these devices may want to directly connect to each other for specific purposes such as sharing services, establishing common subscriptions, etc. To this end, our proposed scheme allows end users to communicate with each other and compute a shared key through the help of home server and foreign agent. User privacy is protected during communication process. Multi-server architecture introduced in our work deals with the overhead. Besides, Elliptic Curve Cryptography (ECC) with small key size is employed in our scheme. Hence, the proposed scheme favors end-to-end communication and is well suited for 5G enabled edge computing networks. Our proposed scheme is favored by the help of smart card, which can provide personal identification, authentication, data storage, and application processing [30].

The rest of this paper is organized as follows. Section II, we briefly review Gope and Hwang’s scheme. Section III, we propose a privacy-preserved end-to-end authenticated key exchange protocol for multi-server architecture in edge computing networks. Section IV and Section V, we respectively present formal and informal security analysis of the proposed protocol. Section VI, we compare performance of the proposed protocol with its related works. Section VII, an implementation of the proposed protocol is described. Finally, the conclusions and future research directions are given in Section VIII.

II. REVIEW OF GOPE AND HWANG’S SCHEME

In this section, we briefly describe Gope and Hwang’s scheme, which consists of three phases: registration phase, mutual authentication and key agreement phase, and password update phase. After that, we point out some weaknesses of their protocol.

A. REGISTRATION PHASE

Step 1 — Mobile user (MU) sends registration information to home agent (HA). They perform the following sub-steps.

Step 1-1: MU submits his/her identity ID_M to HA via a secure channel.

Step 1-2: HA generates a random number n_h and then computes K_{uh} = h(ID_M || n_h) ⊕ ID_h.

Step 1-3: HA generates a set of unlinkable pseudo-IDs PID = \{pid_1, pid_2, ..., \}, where for each pid_i ∈ PID, pid_j = h(ID_M || r_i || K_{uh}), r_i a random number.

Step 1-4: HA generates a unique track sequence number Tr_{seq}, which is basically a sequence number of 64-bit.

Step 1-5: HA stores K_{uh} and ID_M in its database.

Step 1-6: HA stores K_{uh}, PID, Tr_{seq}, h(·) in the smart card and sends smart card to MU.

Step 2 — The shared key K_{uh} between mobile user MU and home agent HA is stored in smart card.

Step 2-1: MU chooses a password PSW_M and submits it to the smart card.

Step 2-2: Smart card computes K_{uh}^{*} = K_{uh} ⊕ h(ID_{M} || PSW_{M}).

Step 2-3: MU replaces K_{uh} and K_{uh}^{*} with PID and PID^{*} respectively. Then smart card contains \{ K_{uh}^{*}, PID^{*}, Tr_{seq}, h(·) \}.

B. MUTUAL AUTHENTICATION AND KEY AGREEMENT (MAKA) PHASE

Step 1 — Smart card computes the shared key K_{uh} of mobile user MU and home agent HA with the legitimate ID_M and PSW_M, and sends an authentication request to foreign agent FA.

Step 1-1: MU inserts his/her smart card into the reader and enters his/her identity ID_M and password PSW_M.

Step 1-2: Smart card generates two random numbers N_m, N_m’ and computes P = N_m ⊕ N_m’.

Step 1-3: Smart card computes K_{uh} = K_{uh}^{*} ⊕ h(ID_{M} || PSW_{M}), AID_{M} = h(ID_{M} || K_{uh} || N_m || Tr_{seq}), where Tr_{seq} denotes the most recent track sequence number, received from the home agent HA. In case of loss of synchronization, the user needs to choose one of the unused pid^{*} then submits his/her identity ID_M and password PSW_{M} and computes
Formulate the following sub-steps.

Step 1-4: MU forms $M_{B1} = \{AID_M, \{N_m||p\}E_{K_{ah}}, Tr_{seq}, (N'_m||Q)E_{K_{fh}}\}$, and sends request message $M_{B1}$ to HA.

Step 2 — FA sends MU’s authentication request information to HA. Foreign agent FA performs the following sub-steps.

Step 2-1: FA generates two random numbers $N_f, N'_f$ and computes $Q = N_f \oplus N'_f$.

Step 2-2: FA computes $V_1 = h(M_{B1}||K_{fh}||N_f) \oplus Q$.

Step 2-3: FA forms a message $M_{B2} = \{AID_M, \{N'_m||p\}E_{K_{lah}}, Tr_{seq}, (N'_m||E_{K_{ah}}, V_1)\}$, and send $M_{B2}$ to HA.

Step 3 — After receiving the $M_{B2}$, HA verifies the legitimacy of the mobile user MU and the foreign agent FA. HA performs the following sub-steps.

Step 3-1: HA checks whether the track sequence number $Tr_{seq}$ is valid.

Step 3-2: HA decrypts $(N'_m||p)E_{K_{lah}}$ and $(N'_m||Q)E_{K_{fh}}$ with shared key $K_{lah}$ and $K_{fh}$.

Step 3-3: HA computes and verifies the parameters $V_1, AID_M$.

Step 3-4: HA computes $x = (N'_m||N_f)E_{K_{ah}}, Tr = h(K_{ah}||ID_M||N'_m) \oplus Tr_{seq} = h(x||K_{fh}||N_f), y = h(N'_m||K_{ah}||N_f), V_3 = h(y||N'_m||K_{ah}||Tr)$. Verify the correctness of $V_3$.

Step 3-5: HA sends $M_{B3} = \{x, Tr, V_3\}$ to FA.

Step 4 — After receiving $M_{B3}$ transmitted by HA, FA authenticates HA and establishes a conversation key with MU. FA performs the following sub-steps.

Step 4-1: FA decrypts $x$ using $K_{fh}$, checks the integrity of $x$, and verifies $N_f$ by computing and comparing $V_2$ with $V_2$.

Step 4-2: FA computes the session key $SK = N_m \oplus N_f$.

Step 4-3: FA forms a response message $M_{B4} = \{y, Tr, V_3\}$ and sends $M_{B4}$ to MU.

Step 5 — After receiving $M_{B4}$ transmitted by FA, MU authenticates HA and FA, then establishes a conversation key with FA. MU performs the following sub-steps.

Step 5-1: Using $y$ and $Tr$ from $M_{B4}$, MU computes $V_3^*$. Then, it verifies if $V_3^*$ is equal.

Step 5-2: Using $y$ and $Tr$ from $M_{B4}$, MU computes $N_f = h(N'_m||K_{ah}||y, Tr_{seq}) = h(K_{ah}||ID_M||N'_m) \oplus Tr$, and $SK = N_m \oplus N_f$.

Step 5-3: MU updates $Tr_{seq} = Tr_{seq}\_new$.

### C. PASSWORD UPDATE PHASE

**Step 1** — MU needs to insert his/her identity $ID_M$ and current password $PSW_M$ to smart card. Then computes $K_{ah} = K_{ah}^* \oplus h(ID_M||PSW_M), PID = PID^* \oplus h(ID_M||PSW_M)$. After verifying user’s legitimacy, MU enters the new password $PSW_{M\_new}$.

**Step 2** — Using the new password, smart card computes $K_{ah}^{**} = K_{ah}^* \oplus h(ID_M||PSW_{M\_new}^*), PID^{**} = PID^* \oplus h(ID_M||PSW_{M\_new}^*)$.

### III. THE PROPOSED PROTOCOL

Our proposed protocol includes four roles/actors: user $U_i$, user $U_j$, remote server $SR_i$ and remote server $SR_n$. The proposed protocol consists of six phases: system initialization phase, smart card registration phase, server registration phase, login phase, mutual authentication & key exchange phase, and
password update phase. During the protocol, all of the parties including \( U_i \), \( FA_p \), \( S_m \), \( U_j \), \( FA_q \), \( S_n \) participate in the communication that lets the user \( U_i \) and \( U_j \) compute a conversation key. For simplicity, only communication among \( U_i \), \( FA_p \), \( S_m \) is described. Table 1 describes notations and cryptographic functions used in this paper.

### A. SYSTEM INITIALIZATION PHASE

In system initialization phase, based on elliptic curve cryptography proposed by the National Institute of Standards and Technology (NIST) [31], the system generates a curve \( E_p(a, b) \) with a point \( G_{(1, 1)} \). It then computes public key for each server using the secret key \( k \), \( V = kG \). Besides, \( f \) is the symmetric key the home server and the foreign agent. Home server registers to certificate authority CA and obtains their own certificate, signature, public key and private key.

### B. SMART CARD REGISTRATION PHASE

The user \( U_i \) sends registration information to the smart card, the user \( U_i \) and the smart card performs following steps (shown in Figure 2).

**Step 1** — \( U_i \) enters \( ID_{U_i} \), \( PW_{U_i} \), to smart card.  
**Step 2** — Smart card generates \( r_i\), then computes \( A_{i} = H(PW_{U_i}) \oplus H(r_i||ID_{U_i}) \).  
**Step 3** — Smart card stores \( r_i \) and \( A_i \).

### C. SERVER REGISTRATION PHASE

The user first logs in to the smart card then performs server registration. As shown in Figure 3, the user \( U_i \) and the server \( S_m \) perform the following steps.

**Step 1** — \( U_i \) transmits the registration information to \( S_m \) through smart card. \( U_i \) and \( S_m \) perform the following sub-steps.  
**Step 1-1:** \( U_i \) enters \( SID_{i,m} \) to smart card.  
**Step 1-2:** Smart card generates random number \( SPW_{i,m} \), then computes \( SA_{i,m} = H(SPW_{i,m}) \oplus H(r_i||SID_{i,m}) \).  
**Step 1-3:** \( U_i \) transmits \( SID_{i,m} \) and \( SA_{i,m} \) to server \( S_m \).  
**Step 2** — \( S_m \) computes a shared value with \( U_i \).  
**Step 2-1:** \( S_m \) computes \( u_{m,i} = H(SID_{i,m}||x_m) \) and \( B_{m,i} = u_{m,i} \oplus SA_{i,m} \).  
**Step 2-2:** \( S_m \) computes \( u_{m,i} \) and \( SA_{i,m} \) in flash drive and smart card respectively.

### D. LOGIN PHASE

In login phase, the user \( U_i \) first logs in to smart card for verification. As shown in Figure 4, the user \( U_i \) logs in to the server \( S_m \), then the user \( U_i \), the smart card, the foreign agent \( FA_p \), and the server \( S_m \) jointly perform the following steps to complete the procedure in which the user \( U_i \) can
User $U_i$  

1. Enter ID$_{U_i}$, PW$_{U_i}$ to smart card  
2. $A_i' = H(PW_{U_i}) \oplus H(r_i || ID_{U_i})$  
3. $A_i = A_i' \oplus A_i$, verify user $U_i$’s legitimacy  
4. Enter SID$_{i,m}$ to smart card  
5. $u_{im} = B_{im} \oplus$ SA$_{im}$  
6. Generate random numbers $a_{im}, s_{im}$  
7. $R_{im} = a_{im} \ast G = (t_{im1}, t_{im2})$  
8. $C_{im1} = s_{im} \ast G$  
9. $Y_{im} = (y_{im1}, y_{im2}) = s_{im} \ast V_m$  
10. $c_{im21} = y_{im1} \ast (u_{im} || SID_{i,m}) \oplus T_{im} \mod p$  
11. $c_{im22} = y_{im2} \ast r_{im1} \mod p$  
12. $c_{im2} = y_{im2} \ast r_{im2} \mod p$  
13. $C_{im2} = (c_{im21}, c_{im22}, c_{im23})$

\[
C_{im1}, C_{im2}, T_{im}, \theta_{pm}
\]

FIGURE 4. Login phase.

log in to the server $S_m$ and compute conversation key with the user $U_i$.

Step 1 — $U_i$ enters ID$_{U_i}$, PW$_{U_i}$ to smart card.

Step 2 — Smart card computes $A_i' = H(PW_{U_i}) \oplus H(r_i || ID_{U_i})$.

Step 3 — Smart card compares $A_i'$ and its $A_i$, then verifies the legitimacy of user $U_i$.

Step 4 — User $U_i$ inserts his/her smart card, then enters SID$_{i,m}$. Using $B_{m,i}$ from flash drive, smart card calculates shared secret number $u_{im} = B_{m,i} \oplus$ SA$_{i,m}$.

Step 5 — Smart card generates two random numbers $a_{im}, s_{im}$.

Step 6 — Smart card computes $R_{i,m} = a_{im} \ast G = (r_{i,m1}, r_{i,m2})$, $C_{i,m1} = s_{im} \ast G$, $Y_{i,m} = (y_{i,m1}, y_{i,m2}) = s_{im} \ast V_m$, $c_{i,m21} = y_{i,m1} \ast (u_{im} || SID_{i,m}) \oplus T_{i,m} \mod p$, $c_{i,m22} = y_{i,m2} \ast r_{i,m1} \mod p$, $c_{i,m2} = y_{i,m2} \ast r_{i,m2} \mod p$, $C_{i,m2} = (c_{i,m21}, c_{i,m22}, c_{i,m23})$.

Step 7 — User $U_i$ transmits $C_{i,m1}, C_{i,m2}, T_{i,m}$ to foreign agent $FA_p$.

Step 8 — Foreign agent $FA_p$ generates two random numbers $Nf_p, Nf_p'$, computes $Q_p = Nf_p \oplus Nf_p'$, $\theta_{pm} = E_{fp}(Q_p || Nf_p')$, $c_{i,m21} = c_{i,m21} \oplus Nf_p$, $c_{i,m2} = (c_{i,m21}, c_{i,m22}, c_{i,m23})$, and transmits $\{ C_{i,m1}, C_{i,m2}, T_{i,m}, \theta_{pm} \}$ to server $S_m$.

E. MUTUAL AUTHENTICATION AND KEY EXCHANGE PHASE

1) MUTUAL AUTHENTICATION AND EXCHANGE PHASE BETWEEN SERVERS

As shown in Figure 5, mutual authentication and key exchange process between two servers is described as follows.

Step 1 — Server $S_m$ and $S_n$ respectively authenticate the legitimacy of user $U_i$ and $U_j$. The following sub-steps are performed by server $S_m$.

Step 1-1: $S_m$ computes $Z_{m,i} = (z_{m,i1}, z_{m,i2}) = k_m C_{i,m1}$.

Step 1-2: $S_m$ decrypts $\theta_{pm}$ to get $Q_p$, $Nf_p'$, and computes $c_{i,m21} = c_{i,m21} \oplus Nf_p'$.

Step 1-3: $S_m$ computes $u_{im} || SID_{i,m} = T_{i,m} \oplus c_{i,m21} * z_{m,i1}^{-1} \mod p$.

Step 1-4: $S_m$ uses above SID$_{i,m}$ and its secret number $x_m$ to compute $u_{m,i} = H(SID_{i,m} || x_m)$.

Step 1-5: $S_m$ confirms $u_{m,i} = u_{i,m}$ to verify user $U_i$’s legitimacy. If there is a match, $U_i$ is confirmed to be a legitimate user.

Step 1-6: $S_m$ employs the Elliptic Curve Cryptography to obtain $R_{i,m} = (c_{i,m22} \ast z_{m,i2}^{-1} \mod p, c_{i,m23} \ast z_{m,i2}^{-1} \mod p)$.

Step 2 — After $S_m$ and $S_n$ authenticate the legitimacy of $U_i$ and $U_j$, Server $S_m$ performs the following sub-steps.

Step 2-1: $S_m$ chooses random number $b_{m,i}$ and computes $W_{m,i} = b_{m,i} \ast G$.

Step 2-2: $S_m$ computes $Y_{m,i} = Nf_p \ast R_{i,m} \ast b_{m,i}$.

Step 2-3: $S_m$ calculates signature $\delta_m = Sig_{k_m}(Y_{m,i})$.

Step 2-4: $S_m$ transmits $\delta_m, Cert_m$ to $S_n$ for verification.

Step 3 — Server $S_m$ first verifies $\delta_m, Cert_m$ received from the server $S_n$. After verifying $S_n$’s identity, server $S_m$ uses received numbers to compute the following computations.

Step 3-1: $S_m$ computes $K_{m,i} = b_{m,i} \ast Y_{n,j} = Nf_q \ast a_{j,n} \ast b_{n,j} \ast b_{m,i} \ast G$. 
Step 3-2: \( S_m \) computes \( \beta_{m,i} = H(Y_{m,i} || \text{SID}_{m,i} || \text{ID}_{S_m}) \),
\[ \theta_{m,i} = E_{R_{m,i}}(W_{m,i} || \text{SID}_{m,i} || \beta_{m,i} || N_f^m || N_f^p) \]
\[ \theta_{m,p} = E_{f_{p,m}}(\theta_{m,i}) \]

2) AUTHENTICATION PHASE AMONG SERVER, FOREIGN AGENT AND USER
As shown in Figure 6, authentication process among the server, foreign agent and user is described as follows.

Step 1 — Server \( S_m \) transmits \( \theta_{m,p} \) to foreign agent \( FA_p \).
Step 2 — \( FA_p \) computes \( \theta_{m,i} = D_{f_{p,m}}(\theta_{m,p}) \), and transmits \( \theta_{m,i}, Q_p \) to \( U_i \).

Step 3 — \( U_i \) and \( U_j \) respectively verify \( S_m \) and \( S_n \), then compute a conversation key. \( U_i \) performs the following sub-steps.

Step 3-1: \( U_i \) computes \( W_{m,i} || \text{K}_{m,i} || \beta_{m,i} || N_f^m || N_f^p \) = \( D_{R_{m,i}}(\theta_{m,i}) \).
Step 3-2: \( U_i \) verifies whether \( N_f^p \oplus N_f^p \neq Q_p \).
Step 3-3: \( U_i \) computes: \( Y_{i,m} = N_f^m \oplus a_{i,m} \oplus W_{m,i} = N_f^p \oplus a_{j,m} \oplus b_{n,j} \oplus G \).
Step 3-4: \( U_i \) computes \( \beta_{i,m} = H(Y_{i,m} || \text{K}_{m,i} || \text{SID}_{m,i} || \text{ID}_{U_i}) \).
Step 3-5: \( U_i \) compares \( \beta_{i,m} \) with the received \( \beta_{m,j} \). If there is a match, the server \( S_m \) is legitimate.
TABLE 2. The notation used for logical analysis.

| Symbols | Description |
|---------|-------------|
| $P, Q$  | Principals  |
| $C$     | Communicating channel |
| $X, Y$  | Messages |
| $C(X)$  | The message $X$ is transited via channel $C$ |
| $r(C) / w(C)$ | The set of readers/writers of channel $C$ |
| $P[X]$  | $P$ believes statement $X$. The construct is central to the logic |
| $P < C(X)$ | $P$ sees $C(X)$. The message $X$ is transited via channel $C$ and can be observed by $P$. $P$ must be a reader of channel $C$ to read message $X$ |
| $P|\neg X$ | $P$ once said $X$. $P$ at some time sent a message including $X$ |
| $P < X | C$ | $P$ sees $X$ via $C$. The message $X$ is transited via channel $C$ and can be received by $P$ |
| $(X)_K$ | $X$ is hashed with the key $K$ |
| $P \leftrightarrow Q$ | $P$ and $Q$ may use the shared key $K$ to communicate. Here $K$ will never be discovered by any principals expect for $P$ and $Q$ |
| $#(X)$  | The formula $X$ is fresh, $X$ has not been sent in a message at any time before |

Step 3-6: Using $K_{m,i}$ sent by $S_m$, $U_i$ computes his/her conversation key $K_i = N_{f_p} * a_{t,m} * K_{m,i} = N_{f_p} * N_{f_q} * a_{i,m} * a_{j,n} * b_{m,n} * b_{m,i} * G$. $K_j$ is similarly computed by $U_j$ at the same time.

**IV. FORMAL SECURITY ANALYSIS**

**A. LOGICAL ANALYSIS USING BAN LOGIC**

This section describes the logical analysis of the proposed protocol by using BAN logic, which was defined and presented by [32], [33]. Table 2, Table 3 and Table 4 [32]–[34] respectively defines the notations, assumptions and rules used in this analysis. On the basis of the assumptions and logical analyses, the proposed protocol must realize the following four goals of authentication and key agreement as follows.

(G1) $U_i \equiv U_i \leftrightarrow K_i \rightarrow U_j$: User $U_i$ believes that $K_i$ is a symmetric key shared between $U_i$ and $U_j$.

(G2) $U_j \equiv U_i \leftrightarrow K_i \rightarrow U_j$: User $U_j$ believes that $K_i$ is a symmetric key shared between $U_i$ and $U_j$. 

**FIGURE 7.** Password update phase.
(G3) \( U_i \equiv U_j \equiv U_k \leftarrow K_j \): User \( U_i \) believes that \( U_j \) is convinced of \( K_j \) is a symmetric shared key between \( U_i \) and \( U_j \).

(G4) \( U_j \equiv U_i \equiv U_k \leftarrow K_j \): User \( U_j \) believes that \( U_i \) is convinced of \( K_j \) is a symmetric shared key between \( U_i \) and \( U_j \).

To accomplish Goal 1, firstly, we must prove \( a_{i,m}, N_f, p \), and \( K_{m,i} \) are trusted by \( U_i \). According to [32]–[34], the proposed protocol is described in logic with the following steps.

Step 1 — \( FA_p \leftarrow s_{i,m} \ast G, y_{i,m} \ast (u_{i,m} || S_{i,m}) \oplus T_{i,m} \mod p, y_{i,m} \ast r_{i,m} \mod p, T_{i,m} \mod p \)

Step 2 — \( S_m \leftarrow s_{i,m} \ast S_{i,m} \oplus T_{i,m} \mod p \)

Step 3 — \( FA_p \leftarrow ((W_{m,i} || [K_{m,i}||β_{m,i}||N_f||N_f'||R_{m,i}]) \leftarrow S_m) \)

We have that

\[ U_i \equiv a_{i,m} \rightarrow U_j \] (1)

\[ U_i \equiv N_f \rightarrow U_i \] (2.1)

must hold because of interpretation (13) and assumption (A5). Next, to accomplish Eq (2.1) and (2.2), we have that

\[ S_m \equiv (FA_p || (N_f \rightarrow FA_p, s_{i,m} \ast G, y_{i,m} \ast u_{i,m} || S_{i,m}) \oplus T_{i,m} \mod p, y_{i,m} \ast r_{i,m} \mod p, T_{i,m} \mod p) \]

\[ \rightarrow \rightarrow (FA_p) \] (3.1)

\[ FA_p \equiv (S_m || (\rightarrow (W_{m,i} || [K_{m,i}||β_{m,i}||N_f||N_f'||R_{m,i}]) \rightarrow S_m) \]

\[ U_i \equiv (FA_p || (N_f \rightarrow FA_p, Q_p, (W_{m,i} || [K_{m,i}||β_{m,i}||N_f||N_f'||R_{m,i}]) \rightarrow N_f \rightarrow FA_p) \] (3.2)

\[ U_i \equiv (FA_p || (K_m \rightarrow FA_p, Q_p, (W_{m,i} || [K_{m,i}||β_{m,i}||N_f||N_f'||R_{m,i}]) \rightarrow K_m \rightarrow FA_p) \] (3.3)

\[ S_m \equiv (FA_p || (N_f \rightarrow FA_p) \] (4.1)

\[ FA_p \equiv (S_m || (\rightarrow (W_{m,i} || [K_{m,i}||β_{m,i}||N_f||N_f'||R_{m,i}]) \rightarrow S_m) \] (4.2)

\[ U_i \equiv (FA_p || (N_f \rightarrow FA_p) \] (4.3)

and

\[ U_i \equiv (FA_p || (K_m \rightarrow FA_p) \] (4.4)

must hold because of assumptions (A3), (A6) and the rationality rule (R1). To accomplish Eq (4.1), (4.2), (4.3) and (4.4) we have that

\[ S_m \equiv (\#(N_f \rightarrow FA_p) \] (5.1)

\[ FA_p \equiv \#((W_{m,i} || [K_{m,i}||β_{m,i}||N_f||N_f'||R_{m,i}) \rightarrow S_m) \] (5.2)

\[ U_i \equiv (\#(N_f \rightarrow FA_p) \] (5.3)

and

\[ U_i \equiv (K_{m,i} \rightarrow FA_p) \] (6.1)

must hold because of the freshness rules (F1), (F2) and assumption (A4). To accomplish Eq (5.1), (5.2), (5.3) and (6.1), we have that

\[ FA_p \equiv (W(C_{FA_p}, S_m) = [FA_p, S_m]) \] (7.1)

\[ S_m \equiv (W(C_{FA_p}, S_m) = [FA_p, S_m]) \] (7.2)

\[ FA_p \equiv (W(C_{FA_p}, U_i) = [FA_p, U_i]) \] (7.3)

\[ S_m \in r(C_{FA_p}, S_m) \] (8.1)

\[ FA_p \in r(C_{FA_p}, S_m) \] (8.2)

\[ U_i \in r(C_{FA_p}, U_i) \] (8.3)

\[ S_m \equiv (C_{FA_p, S_m}(N_f \rightarrow FA_p) \] (9.1)

\[ FA_p \equiv (C_{FA_p, S_m}((W_{m,i} || [K_{m,i}||β_{m,i}||N_f||N_f'||R_{m,i}) \rightarrow S_m) \] (9.2)

\[ U_i \equiv (C_{FA_p, U_i}(N_f \rightarrow FA_p) \] (9.3)

and

\[ U_i \equiv (C_{FA_p, U_i}(K_{m,i} \rightarrow FA_p) \] (9.4)

must hold because of the interpretation rule (I1), the seeing rules (S1), (S2), assumptions (A1), (A2). By using interpretation rule (13), we have \( U_i \equiv K_i = a_{i,m} \ast N_f \ast K_{m,i} \).

Subsequently, using the same arguments of assumptions, rules, symmetric keys, we have \( K_{m,i} = b_{m,i} \ast Y_{n,j} \) trusted by \( S_m \), and \( Y_{n,j} = N_f \ast R_{j,n} \ast b_{n,j} \) trusted by \( S_m \). Particularly for \( Y_{n,j} \), the trust from Certificate Authority is needed, which is regarded as an assumption.

Finally, we have that the proposed protocol realizes

Goal 1: \( U_i \equiv U_j \rightarrow K_i \)

Similarly, we have that the proposed scheme realizes

Goal 2: \( U_j \equiv U_i \leftarrow K_i \rightarrow U_j \) by using the same arguments of Goal 1.

To accomplish Goal 3, we have that

\[ U_j \equiv ((U_j || (U_i \leftarrow K_i \rightarrow U_j) \rightarrow (U_j \equiv U_i \leftarrow K_i \rightarrow U_j)) \] (10)

and

\[ U_i \equiv (U_j || (U_i \leftarrow K_i \rightarrow U_j) \] (11)

must hold because of the rationality rule (R1) and assumption (A3). To accomplish Eq (11), we have that

\[ U_i \equiv \#(U_i \leftarrow K_i \rightarrow U_j) \] (12)

must hold because of the freshness rules (F1), (F2) and assumption (A4). To accomplish Eq (12), we have that

\[ U_i \leftarrow C_{U_i, U_j}(U_i \leftarrow K_i \rightarrow U_j) \] (13)

\[ U_i \equiv (w(C_{U_i, U_j} = \{U_i, U_j \}) \] (14)
TABLE 3. The assumptions of the proposed protocol.

| Assumptions | Explanation |
|-------------|-------------|
| (A1) $A \in r(C_{A,B})$ | $A$ can read from channel $C_{A,B}$ |
| (A2) $A \equiv (w(C_{A,B}) = \{A, B\}$ | $A$ believes that $A$ and $B$ can write on $C_{A,B}$ |
| (A3) $A \equiv (B||-\phi \to \phi)$ | $A$ believes that $B$ only says what it believes |
| (A4) $A \equiv \#(N_A)$ | $A$ believes that $N_A$ is fresh |
| (A5) $A \equiv a_{i,m} \to A$ | $A$ believes that $a_{i,m}$ is its secret number |
| (A6) $A \equiv A \leftrightarrow B$ | Server $A$ believes that $f$ is a symmetric key shared between $A$ and $B$ |

TABLE 4. The inference rules of the logic of the proposed protocol.

| Rules | Explanation |
|-------|-------------|
| (S1) $P < C(X), P \equiv r(C)$ | $P \equiv (P < X|C), P < X$ If $P$ receives and reads $X$ via $C$, then $P$ believes that $X$ has arrived on $C$ and $P$ sees $X$ |
| (S2) $P < (X,Y), P < X, P < Y$ | If $P$ sees a hybrid message $(X, Y)$, then $P$ sees $X$ and $Y$ separately |

**Seeing rules**

**Interpretation rules**

| (I1) $P \equiv (w(C) = \{P, Q\})$ | $P \equiv (P < X|C) \to Q \to X$ If $P$ believes that $C$ can only be written by $P$ and $Q$, then $P$ believes that if $P$ receives $X$ via $C$, then $Q$ said $X$ |
| (I2) $P \equiv (Q \to (X,Y))$ | $P \equiv (Q \to X), P \equiv (Q \to Y)$ If $P$ believes that $Q$ said a hybrid message $(X, Y)$, then $P$ believes that $Q$ has said $X$ and $Y$ separately |

| (I3) $U_i \equiv (a_{i,m} \to U_j), U_i \equiv (N_{f_{p}}, P_{A_p}, U_j \equiv (K_{m}, i \to S_{m})$ | $P \equiv (K_{i} = a_{i,m} * N_{f_{p}} * K_{m,i})$ If $U_i$ believes that $a_{i,m}$ is a secret number, and that $N_{f_{p}}$ and $K_{m,i}$ are components from $F_{A_p}$ and $S_{m}$ respectively, then $U_i$ believes that $K_{i}$ is a symmetric key shared between $U_i$ and $U_j$ |

| (F1) $P \equiv (Q \to X), P \equiv \#(X)$ | $P \equiv (Q \to X)$ If $P$ believes that another $Q$ said $X$ and $P$ also believes that $X$ is fresh, then $P$ believes that $Q$ has recently said $X$ |
| (F2) $P \equiv \#(X), P \equiv \#(X,Y)$ | If $P$ believes that a part of a mixed message $X$ is fresh, then it believes that the whole message $(X, Y)$ is fresh |

| (R1) $P \equiv (\Phi_1 \to \Phi_2), P \equiv \Phi_1$ | $P \equiv \Phi_2$ If $P$ believes that $\Phi_1$ implies $\Phi_2$ and $P$ believes that $\Phi_1$ is true, then $P$ believes that $\Phi_2$ is true |

and

$$U_i \in r(C_{U_i, U_j})$$  \hspace{1cm} (15)$$

must hold because of the interpretation rule (I1), the assumptions (A1), (A2) and the seeing rules (S1) and (S2).

Thus, the proposed protocol realizes

**Goal 3: $U_i \equiv U_j \equiv U_i \leftrightarrow U_j$.**

Similarly, using the same arguments of Goal 3, the proposed protocol realizes **Goal 4: $U_j \equiv U_i \equiv U_i \leftrightarrow U_j$.**

Therefore, our proposed protocol realizes Goal 1, 2, 3 and 4.

**B. SECURITY VERIFICATION USING AVISPA TOOL**

We verify our scheme using widely accepted Automated Validation of Internet Security Protocols and Applications.
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FIGURE 8. The HLPSL specification of the user.

(AVISPA) tool [35]. AVISPA tool executes the simulated protocol specified by HLPSL language [36]. For verifying cryptographic protocol, AVISPA tool includes four backends as follows.

- **On-the-fly Model-Checker (OFMC)**
- **Constraint Logic based Attack Searcher (CL-AtSe)**
- **SAT-based ModelChecker (SATMC)**
- **Tree Automata based on automatic approximations for the analysis of security protocols (TA4SP)**

In accordance with our proposed protocol, three roles including the user U, the server S, and the foreign agent FA are defined in the specification, HLPSL of which are shown in Figure 8, Figure 9 and Figure 10 respectively. Besides, session role, environment role and goals are also specified in HLPSL (shown in Figure 11). Since elliptic curve key generation is not supported in AVISPA, public key, private key and session key of ECC are predefined as Ks, inv(Ks) and Rus respectively. We consider six secrecy goals and two authentication properties for verification of our scheme.

- **secrecy of g1**: SIDim is kept secret to the U and the S.
- **secrecy of g2**: SAim is kept secret to the U and the S.
- **secrecy of g3**: SPWim is kept secret to the U.
- **secrecy of g4**: Bmi is kept secret to the U and the S.
- **secrecy of g5**: Nfp is kept secret to the U, the S and the F.
- **secrecy of g6**: Nfp1 is kept secret to the U, the S and the F.
- **authentication on u_s_tim**: The server S authenticates the user U based on Tim’ received from the message of the user U.
- **authentication on s_u_b1mi**: The user U authenticates the user U based on B1mi’ received from the message of the server S.

As show in Figure 12, the analysis results of the proposed protocol using OFMC confirm that the stated security properties are satisfied for a bounded number of sessions as specified in the environment role. Therefore, the proposed protocol is safe against various attacks, which are specifically described in Section V.

V. INFORMAL SECURITY ANALYSIS

The primary purpose of our propose protocol is to provide conversation key for two users. In other words, the secure shared key K of the user U, V and is computed through verification and authentication of the home servers S, and foreign agents FA, FA. The details of semantic security analysis of our proposed protocol are presented as follows.

A. PROVIDES ROBUST VERIFICATION

In Step 1 of login phase, the smart card computes A’i = H(PWUi ⊕ H(r, ||IDUi)), then confirms A1 and A’i. The user is verified to be legitimate if there is match, otherwise the smart
card rejects the request. In Step 1 of the mutual authentication and key exchange phase, the server $S_m$ decrypts $C_{i,m}$ and $C'_{i,m}$ using $k_{m}$ to obtain $u_{i,m}$ and $SID_{i,m}$. The server $S_m$ then computes $u_{m,i} = H(SID_{i,m}||X_m)$ using $S_m$ and confirms $u_{m,i}=u_{i,m}$. Similarly, if there is a match, legitimate user is confirmed. Besides, in Step 2 of the mutual authentication and key exchange phase, public key of the server $S_o$ is verified by using certificate $Cert_o$. In Step 5 of the mutual authentication and key exchange phase, the user uses $R_{i,m}$ to decrypt $\theta_{m,i}$ and then obtains $W_{m,i}$. After that, he/she calculates $Y_{i,m} = a_{i,m} \ast W_{m,i}$. $\beta_{i,m} = H(Y_{i,m}||SID_{i,m}||ID_{U_i}||ID_{S_m})$. The user then confirms $\beta_{i,m}$ and $\beta_{m,i}$ to verify the server $S_m$. Hence, our protocol provides a robust verification of communicating participants.

B. PROVIDES MUTUAL AUTHENTICATION

In Step 1 of the mutual authentication and key exchange phase, $u_{m,i}$ is computed to verify the user. Also, in this phase, both of the servers’ signatures are verified by the corresponding certificates. In Step 5 of the mutual authentication and key exchange phase, the user decrypts $\theta_{m,i}$ and computes $\beta_{i,m} = H(Y_{i,m}||SID_{i,m}||ID_{U_i}||ID_{S_m})$. The user then confirms $\beta_{m,i}$ and $\beta_{m,i}$ to verify the server $S_m$. Hence, our protocol provides a robust verification of communicating participants.
\[ \beta_{i,m} \text{ to verify the legitimacy of the server } \mathcal{S}_m. \] Hence, our work provides a full mutual authentication during proposed protocol.

### C. PROVIDES STRONG USER ANONYMITY

The \( \mathcal{ID}_{U_i} \) of the user is securely stored in the smart card at registration, and only used when the smart card verify legitimacy of the user by computing \( A'_i = H(\mathcal{PW}_{U_i}) \oplus H(r_i || \mathcal{ID}_{U_i}) \). Even the server does not know of \( \mathcal{ID}_{U_i} \). The user registers and logins to the server using \( \mathcal{SID}_{i,m} \) instead of his/her original \( \mathcal{ID}_{U_i} \). After that, the server uses \( \mathcal{SID}_{i,m} \) to compute \( u_{m,i} \) and \( b_{m,i} \) for further authentication. The identity \( \mathcal{SID}_{i,m} \) is not available openly and is only known to the user and server. Even if \( A_i \) or \( SA_{i,m} \) are leaked out, attacker cannot obtain \( \mathcal{ID}_{U_i} \) or \( \mathcal{SID}_{i,m} \) respectively since these identities are protected by one-way hash function. On the other hand, in the mutual authentication phase, the attack does not know of \( k_m \), so he/she cannot decrypt \( C_{i,m,21} \) to obtain \( \mathcal{SID}_{i,m} \). Besides, suppose the attacker compromises \( \beta_{i,m} \), he/she still cannot know of \( \mathcal{SID}_{i,m} \) since \( \beta_{i,m} \) is a hash value. Hence, our scheme provides a strong user anonymity.

### D. PROVIDES FORWARD SECRECY

Assume \( Y_{m,i} \) or \( Y_{i,m} \) is known to the attacker. Owning to discrete logarithm problem, the secret numbers \( a_{i,m}, b_{m,i} \) will not be calculated. Moreover, \( a_{i,m} \) and \( b_{m,i} \) are randomly generated to compute session key and conversation key. These keys are different in every login time. Therefore, the attacker cannot derive correct keys from previous ones. Hence, this protocol achieves the forward secrecy.

### E. PROVIDES PASSWORD UPDATE

In the proposed protocol, we provide password update facility. In password update phase, the user enters current \( \mathcal{PW}_{U_i} \) for verification. After that, he/she can enter \( \mathcal{PW}'_{U_i} \) to update his/her password. The user is recommended to update his/her periodically for better security.

### F. RESISTS PASSWORD GUESSING ATTACK

In this case, the attacker tries to guess the password from known parameters. Suppose the attacker obtains \( A_i \) in the smart card. He/she then tries to guess \( \mathcal{PW}_{U_i} \) from \( A_i = H(\mathcal{PW}_{U_i}) \oplus H(r_i || \mathcal{ID}_{U_i}) \). However, due to one-way hash value, it is not possible for the attacker to guess the correct password \( \mathcal{PW}_{U_i} \). Hence, our scheme can resist password guessing attack.

### G. RESISTS IMPERSONATION ATTACK

Assume the attacker knows of identity of the user and attempts to send a login request to the server \( \mathcal{S}_m \). Unless the attacker simultaneously steals \( SA_{i,m} \) (stored in the smart card), he/she cannot impersonate the user.
H. RESISTS MAN-IN-THE-MIDDLE ATTACK

In this case, the attacker tries to tamper with $C_{i,m_1}$, $C_{i,m_2}$, $T_{i,m}$ of login request message. However, due to aforesaid impersonation attack resistance, he/she cannot compute correct $u_{i,m}$ and then the server $S_m$ will reject the login request. Besides, in the mutual authentication and key exchange phase, assume the attacker attempts to access $\theta_{m,i}$, but he/she does not have $R_{i,m}$ to decrypt $\theta_{m,i}$ and $b_{m,i}$, to compute $\beta_{m,i}$ respectively. Therefore, the attacker cannot act as a middleman in any cases, and our protocol is secure against man-in-the-middle attack.

I. RESISTS REPLAY ATTACK

Replay attack occurs when the attacker intercepts the message stolen from the last session then retransmits it to the server. In Step 1 of the mutual authentication and key exchange phase of our scheme, timestamp $T_{i,m}$ is used to resist replay attack. Specifically, $c_{i,m_{21}}$ is generated with $T_{i,m}$ by XOR operation. The sever uses $T_{i,m}$ included in the message to check whether the message is resent. Only one message including the correct timestamp within $c_{i,m_{21}}$ is accepted. Besides, the server will reject any message with incorrect timestamps. Therefore, our proposed protocol is free from replay attack.
J. RESISTS STOLEN SMART CARD ATTACK
Smart card stores random numbers $r_i$, $A_i$ and $SA_i,m$. In some cases, the smart card may be lost or stolen. However, the attack cannot impersonate the user since he/she does not have correct password $PW_{U_i}$. As mentioned, our protocol can provide anonymous identity and resist password guessing attack. Therefore, the stolen smart card is useless without correct $ID_{U_i}$ and $PW_{U_i}$. On the other hand, even if the attacker obtains $r_i$, $A_i$, $SA_i,m$, unless he/she can steal $B_{m,i}$ stored in the flash drive at the same time, the attacker cannot impersonate the legitimate user to send the login request. Hence, stolen smart card attack is avoided in the proposed protocol.

VI. PERFORMANCE ANALYSIS
In this section, the proposed scheme is compared with the related works to judge its competence and functioning. According to Table 5, we can see that Sood [24] and Li et al. [29] cannot resist stolen smart card attack, which is resisted by our proposed protocol. Besides, our proposed protocol can resist man-in-the-middle attack, which is a threat in the protocols of Sood [24], Jiang et al. [20], Li et al. [29] and Gope and Hwang [16]. Our proposed protocol is secure against replay attack to which Jiang et al. [20] and Li et al. [29]’s protocols are vulnerable. Unlike ours, Sood [24], Li et al. [29] and Gope and Hwang [16] lacks a strong two-factor authentication. In addition, Jiang et al. [20], Li et al. [29] and Gope and Hwang [16] cannot prevent stolen verifier attack. Unlike Li et al. [29], our proposed protocol can resist server impersonation attack. Also, our proposed protocol can resist user impersonation attack that is a threat to Sood [24] and Li et al. [29]. Other than immense properties of security, our scheme bears a reasonable computational cost. As shown Figure 13, the logarithm to base 2 is defined as the running time of each scheme obtained from Table 6. Specifically, the comparative value is $\log_2 x$, where $x$ is the rough estimation of running time of each scheme when $n$ (number of servers) increases from 1 to 1000. When $n$ gradually increases, our proposed protocol is explicitly more efficient than protocols of Sood [24], Jiang et al. [20] and Gope and Hwang [16], which were designed for single-server architecture. Only protocol of Li et al. [29], which was also proposed for multi-server architecture, has less running time than ours. However, as mentioned above, Li et al. [29]’s protocol is not accomplished, which is unsafe against well-known attacks. Our scheme is even more efficient than Sood [24]’s in single-server architecture environment. Unlike all of the previous work, our protocol can favor the end-to-end communication between the end users. Therefore, such computational cost is rational.
VII. IMPLEMENTATION OF THE PROPOSED PROTOCOL

In this section, our proposed protocol is implemented with user-controlled single sign-on mechanism. Single sign-on (SSO) is a property that allows user to authenticate mobile application or web application with single username and password to access multiple applications that uses the same authentication provider [37]. SSO is consistent with multi-server architecture introduced in this paper, where user can access multiple edge servers to obtain services. In this scenario, we describe user interface of SSO system designed by Ubiquitous Security and Applications Laboratory (USA Lab.), Chang Gung University (CGU). The library of this system is written using Go Programming Language. Our system illustration includes four phases, namely, smart card registration phase, smart card login phase, server creation phase and account registration phase. In smart card registration phase (shown in Figure 14), user creates an account with identity d0540011, which is subsequently used for smart card login phase (shown in Figure 15). After having smart card login to system, the user has to create server. As shown in Figure 16, we use smart card’s identity and password to create the server CGMH. After that, the user creates some more servers, namely, CGMH blockchain, CGU, GOOGLE, etc. (shown in Figure 17). Finally, in account registration phase, he/she uses ID, password and arbitrary IDs to register accounts for multiple servers so as to use potential applications developed by CGU (the applications were not described in this illustration). As show in Figure 18, smart card identity d0540011, password and user identity 01011992 are used to create an account. The user can also check the detailed information of the created accounts. Figure 19 shows that he/she has created eight accounts with two identities 01011992 and 29071991, and four servers CGU,
communication or conference key distribution in 5G-IoT is IoT or edge devices, secure authentication protocol for group level of communication. Also, with the increasing number of protocol is a good direction for providing a higher security edge computing network attract more and more attention enabling 5G technology. Thereby, security and privacy in proposed protocol is suitable to edge computing.

With small key size is employed in our protocol. Thereby, our protocol gains stronger security and better efficiency. Moreover, Elliptic Curve Cryptography previous works, the proposed protocol gains stronger security and better efficiency. Moreover, Elliptic Curve Cryptography with small key size is employed in our protocol. Thereby, our proposed protocol is suitable to edge computing.

VIII. CONCLUSION
In this paper, we propose a privacy-preserved end-to-end authenticated key exchange protocol for multi-server architecture in edge computing networks. The proposed protocol is implemented with single sign-on (SSO) property and multi-server architecture. Our protocol allows mobile users to use a single easy-to-remember password to login to multiple servers then compute a conversation key for themselves during their end-to-end communication in 5G enabled NB-IoT networks. User privacy is preserved during communication process in our proposed protocol. As compared with previous works, the proposed protocol gains stronger security and better efficiency. Moreover, Elliptic Curve Cryptography with small key size is employed in our protocol. Thereby, our proposed protocol is suitable to edge computing.

Edge computing architecture plays an important role in enabling 5G technology. Thereby, security and privacy in edge computing network attract more and more attention from research community. Biometric-based authentication protocol is a good direction for providing a higher security level of communication. Also, with the increasing number of IoT or edge devices, secure authentication protocol for group communication or conference key distribution in 5G-IoT is an interesting topic for future work.

ACKNOWLEDGMENT
The authors would like to thank anonymous referees for their valuable suggestions.

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