An Efficient Three-Party Authentication and Key Agreement Protocol for Privacy-Preserving of IoT Devices in Mobile Edge Computing

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Abstract

The advancement of 5G communication technology and Internet of Things (IoT) technology has promoted the rapid development of Mobile Edge Computing (MEC). In mobile edge, all IoT devices adopt wireless communication technology. Therefore, it is particularly important to ensure the data security and privacy of the sender in the process of data transmission. At present, a lot of researchers have proposed a large number of schemes for the authentication of the user in MEC. However, there is no effective and lightweight solution for authentication among users, edge devices and cloud server. In this paper, an efficient three-party authentication and key agreement protocol without using bilinear pairings is designed. The proposed protocol realized authentication among users, edge devices and cloud server, and at the same time, three parties conduct key agreement to obtain a common session key. The security analysis shows that our protocol is secure and meets the security attributes such as session-key security, forward secrecy. The experiment shows that the computation cost is low in this protocol.

Keywords: Authentication, Key agreement, Three-party, IoT devices, MEC

1 Introduction

In recent years, with the rapid development of the Vehicular Ad-Hoc Network (VANETs) [1-2] and the Internet of Things (IoT) [3-4], a variety of smart devices have emerged, such as smart home, intelligent transportation, which undoubtedly make people’s life more convenient. However, most of the emerging applications on the market are complex application that generate large amounts of data. This will inevitably bring some problem such as limited resources and equipment. There are approximately 50 billion IoT devices in the world by 2020. The amount of data will grow exponentially every day. With the ever-increasing user requirements for network performance, such as network service quality and service request delay, it is difficult to use mobile device terminals with limited resources to meet them.

In order to deal with the above challenges, Mobile Edge Computing (MEC) [5-6] is proposed as a new paradigm. It can distribute computing ability and services in the cloud server to the edge of the network with geographical advantages, and provide real-time data analysis and intelligent processing nearby. At the same time, MEC can avoid the core network congestion effectively and reduce the service response delay. Therefore, it becomes the focus of academic and industrial research gradually. At present, researchers have carried out a large number of researches in the field of edge computing. The universally accepted edge computing schemes include micro-cloud computing, fog computing [7] and moving edge computing.

With the popularity of the IoT and the increasing power of mobile applications, the computing demands on user devices have reached unprecedented levels. In particular, the rapid development of 5G communication technology [8-9] and cloud computing technology [10] accelerate this process. Data generated by IoT devices can be sent to edge devices for processing through wireless communication technology [11]. If the processing capacity of edge devices is exceeded, data processing can be carried out through the cloud server. On the one hand, the communication delay of the system should be controlled within milliseconds. On the other hand, the safety of data transmission should be ensured. A typical architecture of MEC is illustrated in Figure 1. The structure can be roughly divided into three layers: IoT device layer, edge device layer and cloud server layer. The IoT devices can be mobile phones, cars, traffic lights, cameras and other devices. IoT devices can communicate with edge devices through edge networks (such as WiFi, 5g networks, etc.). Edge devices can communicate with cloud servers through the core network (such as IP, MPLS, etc.). Now, we face a lot of security challenges in the implementation of this process. Therefore, it is very important to design an efficient and secure three-party communication protocol.
1.1 Motivation

As we all know, security is one of the most important issues in MEC. Due to the use of wireless network communication mode, MEC is vulnerable to various attacks by adversary. For example, malicious users may intercept the information, or even modify the information, which brings great security risk to users. Some malicious users may send wrong messages to other users or edge devices, which may lead serious safety hazards. Therefore, how to ensure the security of communication among IoT devices, edge devices and cloud server is a problem worth to be discussed.

Privacy-preserving is another important issue needs to be addressed in MEC. When a user communicates with edge devices or cloud server, it is necessary to ensure its private information that is not disclosed (such as real identity). Some researchers have proposed conditional privacy-preserving scheme [12-13] based on this. Under the premise of ensuring user privacy, legal authentication of cloud servers, edge devices and users is worth studying.

Our contributions: In this paper, a privacy-preserving authentication and key agreement protocol among users, edge devices and cloud server is proposed. The main contributions are described as follows.

- **An efficient three-party authentication and key agreement protocol is proposed.** In this paper, a three-party authentication and key agreement protocol for users, edge devices and cloud server is designed. In addition, bilinear pairings is not adopted in this protocol, which greatly reduces the computational and communication overhead.

- **Conditional privacy-preserving is realized by the proposed protocol.** The real identity of the user is anonymized by the owner with a random number, which cannot be analyzed by other users and edge devices based on existing information. If the user is malicious, the trusted authority cloud server can track the real identity of the user according to the master key and its anonymous identity.

- **The protocol is secure under the security model.** We have made a formal security proof for the protocol, and the security proof shows that the protocol is secure under the DDH and CDH assumption.

1.2 Organization

The reminder of this paper is organized as follows. Section 2 analyzes the current research status. Section 3 describes the preliminaries in this paper. Section 4 describes the problem statement of this paper, including system model, security model and security definition. Section 5 presents three-party authentication and key agreement protocol in detail. Section 6 proves the security and analyzes the security attributes of the scheme. Section 7 evaluates the performance of the scheme through experiment result. Section 8 concludes the work of this paper.

2 Related Works

Nowadays, a lot of researchers have put forward their own scheme for authentication.

Cui et al. [14] proposed a privacy-preserving authentication scheme using cuckoo filter. In this scheme, the hash value of the signature that has been authenticated for the first time is stored in cuckoo filter. When the signature needs to be authenticated again, the hash value of the signature only needs to be compared with the hash value of the signature in Cuckoo filter. However, this scheme requires a large data structure to store the signature. In order to improve message filtering efficiency and reduce data storage overhead. Zhou et al. [15] proposed a lightweight multi-key privacy-preserving scheme for location-based services that includes a message filtering algorithm. In this scheme, Road Side Units (RSUs) evaluate the redundancy factor of each user’s message, so as to filter the duplicate message in the system according to the redundancy factor before information authentication. This way greatly reduced computation cost and communication cost. Moreover, the message is encrypted multiple times with different key, which increases the security of message and protects the privacy of user.

Lee et al. [16] proposed a three-party mutual authentication and key agreement protocol which based on Diffie-Hellman key exchange. Lv et al. [17] designed a novel
three-party authenticated key exchange protocol, which is more efficient with less computational overhead. At the same time, the use of one-time key solves the key escrow problem. However, the security level of the above two is not high, for example, neither of them achieves user anonymity and traceability. The three-party mutual authentication protocol can be applied to a variety of different scenarios. Chiou et al. [18] applied the three-party mutual authentication protocol into the medical environment and it satisfied more security requirements than above two. Jia et al. [19] applied the three-party mutual authentication protocol to the IoT healthcare system. Ma et al. [20] improved this protocol and applied it to VANETs, realizing mutual authentication among vehicles, fog nodes and cloud server, and reducing computational overhead.

Bagga et al. [21] proposed a new mutual authentication and key agreement protocol, which adopts two levels of authentication and key agreement, and realized the dynamic addition of vehicles and RSUs. Wazid et al. [22] applied user authentication and key agreement into the in Internet of Drones Deployment, which can be resistant against various known attacks through the formal security verification using the widely accepted AVISPA tool.

In order to support anonymity and traceability of vehicles at the same time, some researchers have adopted a conditional privacy-preserving mechanism. Mukherjee et al. [23] take advantage of lattice-based cryptography to design a conditional privacy-preserving authentication scheme. The scheme does not have fast computing power, but can also resist the quantum attack due to the hard lattice problem. Zhou et al. [24] proposed a roaming authentication scheme with conditional privacy-preserving function that is a cross-domain vehicle authentication scheme. Ali et al. [25] designed an identity-based conditional privacy-preserving scheme using bilinear pairing, which is mainly used to solve the authentication problem in V2V and V2I in VANETs. Tzeng et al. [26] proposed an identity-based privacy-preserving scheme, which support batch authentication and conditional privacy-preserving at the same time.

Since the user privacy key is managed uniformly by a trusted authority (TA) in the above scheme, there is a key escrow problem in these scheme. Zhang et al. [27] proposed a distributed aggregated privacy-preserving authentication scheme. One-time privacy key is adopted for communication between vehicles and low-level TA. However, the use of one-time private key will generate a lot of computational and communication overhead. Zhong et al. [28] proposed a privacy-preserving scheme based on certificateless aggregate signature, which not only solves the key escrow problem, but also reduces the computational and communication cost.

Group authentication is an important research field in VANETs. Han et al. [29] proposed an efficient self-certified and deniable group key agreement protocol. The protocol adopts deny negotiation to establish group communication to reduce the transmission of group keys, so as to achieve the effect of reducing vehicle authentication step. Jiang et al. [30] proposed an anonymous authentication scheme based on group signature. This scheme improves the efficiency of anonymous authentication of vehicles by adding region trust authority. Hsrouny et al. [31] designed a trust model based on group leader. The scheme evaluates the trust value of each vehicle, and selects a node with higher credibility as the group leader to manage the communication between vehicles.

3 Preliminaries

In this section, some of the preliminaries covered in this paper is described, including message authentication code and some complexity assumptions.

3.1 Message Authentication Code (MAC)

A message authentication code scheme consists of three algorithms: MAC.KeyGen, MAC.Mac and MAC.Verify. Firstly, the MAC.KeyGen algorithm evenly selects secret key from the key space. Secondly, input the string m under the algorithms MAC.Mac and output the tag τ. Thirdly, when the receiver receives the tag τ, inputs the information (m, τ) and runs MAC.Verify. If the output is 1, it means the verification is passed, otherwise, the verification fails.

3.2 Complexity Assumptions

(Computational Diffie-Hellman (CDH) Assumption). Let G represent a finite cyclic group of order n. The CDH problem is computing gab based on the given elements (g, g^a, g^b), where g and (a, b) represent the generator of G and the random number in Z_p, respectively. The probability of solving the CDH problem for any algorithm in probabilistic polynomial time (PPT) is negligible.

(Decisional Diffie-Hellman (DDH) Assumption). Let G represent a finite cyclic group of order n. The DDH problem is distinguishing g^c, g^a and g^b based on the given elements (g, g^a, g^b, g^c), where g and (a, b, c) represent the generator of G and the random number in Z_p, respectively. The probability of solving the DDH problem for any algorithm in PPT is negligible.

4 Problem Statement

In this section, we describe the system model, security model and security definition of the protocol. The specific description is as follows.

4.1 System Model

In this section, the architecture of system model of this paper is shown in Figure 2. The system model consists of three entities: the user, the edge device and the cloud server.

- **User**: Each user can be a smart furniture, mobile phone, vehicle and other IoT devices, which has less computing power. Users communicate with edge devices via the wireless communication technology. The user registers with the cloud server to obtain private key by using its identity.

- **Edge device**: The edge device is deployed at the roadside that has certain computing power, which is used for communication between the user and the cloud server. Edge device can negotiate a key with user and cloud server to generate a common session key. The edge device is a semi-trust participant.

- **Cloud server**: In system setup phase, the cloud server is used for generate the master private key and security parameter, which has strong computing power and storage capacity. When users and edge devices need to be
registered, the cloud server uses the master private key and their real identity to complete the calculation of the private key and sends it to them through a secure channel.

4.2 Security Model

We formulated a series of games between challenger $C$ and adversary $A$ to define our security model. Assume that participant $\prod_i \in \{U, ED, CS\}$ represents the $i$-th instance and $A$ represents the entire protocol. The $A$ can ask the $C$ oracle queries, and the $C$ can respond.

- $\text{Send}(\prod_i, m)$: If $A$ asks the query for the message $m$, the $C$ executes the specific steps of the protocol and returns the result.
- $\text{Execute}(\prod_U, \prod_{ED}, \prod_{CS})$: This oracle query models a passive eavesdropping attack. During the execution of the protocol, the $A$ can obtain the communication message between $\prod_U$, $\prod_{ED}$, and $\prod_{CS}$ through passive eavesdropping attack.
- $\text{Reveal}(\prod_i)$: This oracle query models the leakage of the session key. During the $A$’s query process, if the instance $\prod_i$ accepts, then outputs the session key, otherwise outputs $\bot$.
- $\text{Test}(\prod_i)$: This oracle query models the semantic security of the session key $Key$. When the $A$ sends a $\text{Test}()$ query to the $C$, the $C$ adopts a coin toss $b$. If $b = 1$, the $C$ sends the session key of instance $\prod_i$ to the $A$. If $b = 0$, the $C$ chooses a random number equals to the length of the session key and sends it to the $A$. After receiving the information, the $A$ will guess the value of $b$. If the result of the guess is always correct, the session key of the protocol is broken.

4.3 Security Definitions

Some security definitions are proposed for our protocol to provide strong security guarantees.

4.3.1 Definition

(Authentication Key Agreement (AKA) - security). Through the $C$’s $\text{Test}()$ query, the $A$ will guess the value of $b$ according to the query result and output the guess result $b’$. If $b’ = b$, it means that the semantic security of the session key of the protocol has been compromised. Let $\text{Success}(A)^{Key}$ represent the event where the $A$ guessed the value $b$ correctly and won the game. The advantage that the $A$ can break the semantic security of the session key by guessing the value $b$ correctly can be defined as

$$\text{Adv}_{A}^{Key} = |2 \Pr[\text{Succ}(A)^{Key}] - 1|.$$ 

Assuming that the advantage $\text{Adv}_{A}^{Key}$ is negligible for any PPT adversary, then the protocol $\mathcal{P}$ can be said to be AKA-secure.

4.3.2 Definition

(Privacy preservation). If the $A$ can obtain the ciphertext of the communication between the user, the edge device and the cloud server through $\text{Send}()$ query. Then when the $A$ cannot obtain the user’s private data through the calculation of the ciphertext, it is considered that the protocol $A$ has achieved privacy preservation.

5 Our Proposed Scheme

5.1 An Overview

In the system, both cloud server and edge devices have an ability to analyze data generated by IoT device. During the use
of an IoT device, edge devices will analyze the data generated by IoT devices and give corresponding instructions. When the data processing is beyond the processing capacity of the edge device, the cloud server has to process the data. Therefore, it is necessary to negotiate a common session key between the IoT device, the edge device, and the cloud server for subsequent data transfers. If the transmitted information is sensitive and the edge device does not have the right to view the message, the IoT device and the cloud server should negotiate a session key. In order to ensure the security of data transmission among IoT device, edge devices and cloud server. We have proposed an efficient three-party authentication and key agreement protocol. The protocol is mainly divided into the following parts: user registration, edge device registration, authentication and key agreement, user revocation and edge device revocation. The various notations and their descriptions listed in Table 1 are used in the paper for describing the phases.

5.2 System Setup

Take the security parameter \( k \) as input, the trust participant cloud server (CS) generates a multiplicative cyclic group \( G \) of \( q \) order with a generator \( g \). Next, CS chooses a random number \( x \) as the master private key, sets the system public key \( g_{pub} = g^x \). Then chooses five hash functions \( H_1, H_2, H_3, H_4, H_5 \), where \( H_1: \{0,1\}^* \rightarrow \mathbb{Z}_q^* \), \( H_2: G \rightarrow \{0,1\}^* \), \( H_3: G \times \{0,1\}^* \times \{0,1\}^* \rightarrow \mathbb{Z}_q \), \( H_4: G \rightarrow \mathbb{Z}_q \), \( H_5: \{0,1\}^* \times G \times G \rightarrow \mathbb{Z}_q \). The public parameter is defined as \( PP = \{g, g_{pub}, q, G, H_1, H_2, H_3, H_4, H_5\} \) and published publicly by CS.

**Table 1. Notations in our protocol**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q )</td>
<td>A large prime number</td>
</tr>
<tr>
<td>( G )</td>
<td>A multiplicative cyclic group with ( q ) order</td>
</tr>
<tr>
<td>( g )</td>
<td>A generator of ( G )</td>
</tr>
<tr>
<td>( H_1, H_2, H_3, H_4, H_5 )</td>
<td>Cryptographic hash functions</td>
</tr>
<tr>
<td>( x )</td>
<td>The master private key of system</td>
</tr>
<tr>
<td>( g_{pub} )</td>
<td>The public key of system</td>
</tr>
<tr>
<td>( SK_u, SK_{ED_j} )</td>
<td>The private key of user and edge device</td>
</tr>
<tr>
<td>( ID_u, ID_{ED_j} )</td>
<td>The real identity of user and edge device</td>
</tr>
<tr>
<td>( AID_i )</td>
<td>The anonymous identity of user</td>
</tr>
<tr>
<td>( AID_{i1} )</td>
<td>Anonymous identity part 1 of the ( i )-th user</td>
</tr>
<tr>
<td>( AID_{i2} )</td>
<td>Anonymous identity part 2 of the ( i )-th user</td>
</tr>
<tr>
<td>( T_{U_j}, T_{ED_j}, T_{CS}, T_{edj} )</td>
<td>Timestamp</td>
</tr>
<tr>
<td>( r, w_1, w_2, w_3, w_4 )</td>
<td>Random number selected from ( \mathbb{Z}_q )</td>
</tr>
<tr>
<td>( Key_1 )</td>
<td>Session key of user, edge device and cloud server</td>
</tr>
<tr>
<td>( Key_2 )</td>
<td>Session key of user and cloud server</td>
</tr>
</tbody>
</table>

5.3 User Registration

During the user \( U_j \) registration phase. The \( U_j \) wants to join the system, it is necessary to ask the CS for permission. Then the CS decides whether to assign a private key to the \( U_j \) according to the validity of the user’s information. The \( U_j \) sends a registration request to the CS with a real identity \( ID_{U_j} \). After the CS is verified, the master private key \( x \) and the hash function \( H_1 \) are used to compute

\[
SK_{U_j} = g^{1/xH_1(ID_{U_j})}.
\]

Then the CS stores the record \( \{ID_{U_j}, SK_{U_j}\} \) to the database and sends \( SK_{U_j} \) to the \( U_j \) through a secure channel.

5.4 Edge Device Registration

The Edge device \( ED_j \) register with the CS. The CS decides whether to assign a private key according to the validity of its identity. The \( ED_j \) sends a registration request to the CS with an identity \( ID_{ED_j} \). After the CS is verified, the master private key \( x \) and the hash function \( H_1 \) are used to compute

\[
SK_{ED_j} = g^{1/xH_1(ID_{ED_j})}.
\]

Then the CS stores the record \( \{ID_{ED_j}, SK_{ED_j}\} \) to the database and sends \( SK_{ED_j} \) to the \( ED_j \) through a secure channel.

5.5 Authentication and Key Agreement

In this phase, \( U_j \), \( ED_j \), and CS authenticate each other and negotiate two session keys to ensure the subsequent transfer of information. The process of authentication and key agreement is shown in Figure 3.

The \( U_j \) anonymizes its identity to prevent the disclosure of its real identity. The \( U_j \) chooses a random number \( r \) and computes anonymous identity \( AID_i = (AID_{i1}, AID_{i2}) \), where \( AID_{i1} = g^r \), \( AID_{i2} = ID_{U_j} \oplus H_2(g_{pub}^r) \).

Then the \( U_j \) chooses a random number \( w_1 \in \mathbb{Z}_q \), which is secure in this protocol. Then computes \( g_{U_j} = g^{w_1} \), \( \varphi_{U_j} = (SK_{U_j})^{w_1} \), \( \pi_{U_j} = H_3(g_{U_j}, ID_{U_j}, T_{U_j}, \varphi_{U_j}) \). Let \( T_{U_j} \) represent the current timestamp. The \( U_j \) sends \( \{\varphi_{U_j}, \pi_{U_j}, AID_i, T_{U_j}\} \) to \( ED_j \). After received the message, the \( ED_j \) first checks the freshness of \( T_{U_j} \). If it is not fresh, the message will be rejected by \( ED_j \). Otherwise, the \( ED_j \) chooses a random number \( w_2 \in \mathbb{Z}_q \) and computes \( g_{ED_j} = g^{w_2} \), \( \varphi_{ED} = (\varphi_{U_j})^{w_2} \), \( \varphi_{ED} = (SK_{ED_j})^{w_2} \), \( \pi_{ED} = H_3(g_{ED_j}, ID_{ED_j}, T_{ED_j}, T_{ED_j}, \varphi_{ED_j}) \). Let \( T_{ED_j} \) represent the current timestamp. \( ED_j \) sends \( \{\varphi_{U_j}, \varphi_{ED_j}, \varphi_{ED}, \pi_{U_j}, \pi_{ED), AID_i, ID_{ED_j}, T_{U_j}, T_{ED_j}\} \) to the CS.
When received the message, the CS first checks the freshness of \( T_{U_1} \) and \( T_{ED_j} \). If they are not fresh, the message will be rejected by the CS. Otherwise, the CS computes \( \pi_2 \) and \( \pi_{ED_j} \). The calculation process is shown as follows. The CS uses master private key \( x \) and hash function \( H_2 \) to calculate \( ID_{U_1} = \text{AI}D_{I2} \oplus H_2(\text{AI}D_{I1}^x) \). Then the CS calculates \( \tilde{g}_{U_1} = (\varphi_{U_1})^{x+H_2(\text{AI}D_{U_1}^x)} \), \( \tilde{g}_{ED_j} = (\varphi_{ED_j})^{x+H_2(\text{AI}D_{ED_j}^x)} \), \( W_{CS} = (\varphi_{UE})^{x+H_2(\text{AI}D_{U_1}^x)}, \pi_{U_1} = H_3(\tilde{g}_{U_1}, ID_{U_1}, T_{U_1}, \varphi_{U_1}), \pi_{ED_j} = H_3(\tilde{g}_{ED_j}, ID_{ED_j}, T_{ED_j}, \varphi_{ED_j}) \).

Next, the CS checks if both of \( \pi_{U_1} = \pi_{U_1} \) and \( \pi_{ED_j} = \pi_{ED_j} \) are true. If one of the two equations is not equal, the CS stops the process. Otherwise, the CS calculates the private key of user and edge device. Then the CS chooses two random numbers \( w_3, w_4 \in Z_q^* \) and computes \( W_{U_1} = (g^{w_3})^{w_3} = g^{w_2w_3}, W_{ED_j} = (g^{w_4})^{w_3} = g^{w_1w_3}, I_{U_1} = H_5(ID_{U_1}, SK_{U_1}, W_{ED_j}); S_2 = H_5(ID_{U_1}, SK_{U_1}, W_{U_1}), K_1 = (W_{CS})^{w_3}, K_2 = (\tilde{g}_{U_1})^{w_4}, Key_{y_2} = H_4(K_1), Key_{y_3} = H_4(K_2) \). Let \( T_{CS} \) represent the current timestamp. Among them, \( Key_3 \) is the common session key of the \( U_1 \), the \( ED_j \) and the \( CS \), and \( Key_{y_2} \) is the session key of both the \( U_1 \) and the \( CS \). The CS sends \( \{W_{U_1}, W_{ED_j}, W_{UC}, S_2, K_1, T_{CS}\} \) to \( ED_j \).

The \( ED_j \) first verifies the freshness of the timestamp \( T_{CS} \) after receiving the message. Then the \( ED_j \) uses its private key to calculates \( \tilde{S}_1 = H_5(ID_{ED_j}, SK_{ED_j}, W_{ED_j}) \) and checks whether \( \tilde{S}_1 = S_1 \) holds. If not, the \( ED_j \) aborts the request. Otherwise, the \( ED_j \) calculates \( K_3 = (W_{ED_j})^{w_2}, Key_{y_3} = H_4(K_1) \). Next, the \( ED_j \) generates a timestamp \( T_{edj} \) and sends \( \{W_{U_1}, W_{UC}, S_2, T_{edj}\} \) to the \( U_1 \).

The \( U_1 \) checks the freshness of the timestamp \( T_{edj} \). Then the \( U_1 \) uses its private key to calculates \( S_2 = H_5(ID_{U_1}, SK_{U_1}, W_{U_1}) \) and checks whether \( \tilde{S}_2 = S_2 \) holds. If not, the \( U_1 \) aborts the request. Otherwise, the \( U_1 \) calculates \( K_4 = (W_{UC})^{w_3}, Key_{y_2} = H_4(K_2) \).

5.6 User Revocation

If one user is found to be malicious, the CS can reveal the real identity of the user through its anonymous identity, and then revoke its identity. After the user is revoked, the user cannot enjoy the privilege of data analyzing by edge devices and CS. The CS runs \( MAC(\text{MAC}_g(m)) \) to generate a tag \( \tau \), where \( K = SK_{U_1}, m = (ID_{U_1}, SK_{U_1}, \text{revoke}) \) and then sends \( \tau \) to the user. In the end, the record \( (ID_{U_1}, SK_{U_1}) \) will be deleted by CS from the database. The output result of user operation algorithm \( MAC(\text{Verify}(\tau, m)) \), if it is 1, it means that the user has been revoked.

5.7 Edge Device Revocation

In the edge computing system, once the edge device is damaged or compromised, the CS needs to revoke it. During the revocation process, the CS will delete the record \( (ID_{ED_j}, SK_{ED_j}) \) from the database. Since the private key \( SK_{ED_j} \) is deleted from the database, the edge device cannot be legally authenticated.

6. Security Analysis

In this section, we first analyze the correctness of the protocol. Then, we give a formal security proof for the security of the protocol. Finally, we analyzed the security attributes of the protocol.
6.1 Correctness

The correctness of the three-party authentication. The parameter \( \varphi_{U1} \) generated by user is \( \varphi_{U1} = (SK_{U1})^{w1} = g^{xH_{1}(ID_{U1})} \), and the parameters \( \varphi_{EDj} \) generated by edge device is \( \varphi_{EDj} = (SK_{EDj})^{w2} = g^{xH_{1}(ID_{EDj})} \). The proof of authentication process is shown as follows.

\[
\begin{align*}
\hat{g}_{U1}^{-} &= (\varphi_{U1})^{-1}H_{1}(ID_{U1}) \\
&= (g^{xH_{1}(ID_{U1})})^{-1}H_{1}(ID_{U1}) \\
&= g^{-x} \\
&= g_{U1}, \\
\hat{\pi}_{U1} &= H_{3}(g_{U1}, ID_{U1}, T_{U1}, \varphi_{U1}) \\
&= H_{3}(g_{U1}, ID_{U1}, T_{U1}, \varphi_{U1}) \\
&= \hat{\pi}_{U1}, \\
\hat{g}_{EDj}^{-} &= (\varphi_{EDj})^{-1}H_{1}(ID_{EDj}) \\
&= (g^{xH_{1}(ID_{EDj})})^{-1}H_{1}(ID_{EDj}) \\
&= g^{-x} \\
&= g_{EDj}, \\
\hat{\pi}_{EDj} &= H_{4}(g_{EDj}, ID_{EDj}, T_{EDj}, \varphi_{EDj}) \\
&= H_{4}(g_{EDj}, ID_{EDj}, T_{EDj}, \varphi_{EDj}) \\
&= \hat{\pi}_{EDj}.
\end{align*}
\]

The correctness of three-party key agreement. The session key generated by CS, edge device and user are \( H_{4}(W_{CS}^{w3}), H_{4}(g_{U1}^{w1}), H_{4}(g_{EDj}^{w2}), H_{4}(W_{U1}^{w1}), H_{4}(W_{UC}^{w1}) \).

The parameters \( W_{CS}, W_{EDj}, W_{U1}, H_{4}(g_{U1}^{w1}) \) and \( H_{4}(W_{UC}^{w1}) \) are calculated as follows.

\[
\begin{align*}
W_{CS} &= (\varphi_{U1})^{-1}H_{1}(ID_{U1}) \\
&= (g^{xH_{1}(ID_{U1})})^{-1}H_{1}(ID_{U1}) \\
&= g^{-x} \\
W_{EDj} &= (g_{EDj})^{-x} = g^{-x}, \\
W_{U1} &= (g_{U1})^{-x} = g^{-x}, \\
(\hat{g}_{UC})^{-x} &= (W_{UC})^{-x} = g^{-x}.
\end{align*}
\]

Since \( W_{CS}^{w3} = W_{EDj}^{w2} = W_{U1}^{w1} = g^{w1w2w3} \) and \( (\hat{g}_{U1})^{w4} = (W_{UC})^{w1} = g^{w1w4} \), then we have the common session key \( \text{Key} = H_{4}(W_{CS}^{w3}) = H_{4}(W_{EDj}^{w2}) = H_{4}(W_{U1}^{w1}) \) and \( \text{Key} = H_{4}(g_{U1}^{w4}) = H_{4}(W_{UC}^{w1}) \). Therefore, the correctness of our protocol has been proven.

6.2 Formal Security Proof

In this subsection, the protocol \( A \) will be proven to be AKA secure under the security model.

**Theorem 6.1** The Key1 in our protocol is AKA-secure under the attack of any PPT A.

**Proof.** If \( A \) can break the protocol with a non-negligible probability \( \varepsilon \), then \( C \) can be constructed to solve the DDH assumption with a probability

\[
\varepsilon \geq \frac{1}{q_{se}} \sum_{j=1}^{5} (q_{se} + q_{se})^2.
\]

Given information \( (g, g^{a}, g^{b}, g^{c}) \), the C’s task is to judge whether equation \( g^{ab} = g^{c} \) is true or not based on the given information. The C chooses a number \( x \) randomly and set the system public key \( P_{pub} = g^{x} \). The public parameter \( PP = \{g, P_{pub}, q, g^{a}, g^{b}, g^{c}\} \) is sent to \( A \). Then the C assigns identities \( ID_{U1} \) and \( ID_{EDj} \) to the user and the edge device respectively. Next, the C calculates the private key for the user and the edge device respectively according to identity and the random value \( x \). The C receives the results of the A’s query and responds to it.

- **Send query:** The C generates and maintains a list \( L \) to record the results of the A’s query. The A can ask the Send query as below, and the C will respond.
  - **Send(\( \Pi_{U1} \)):** When receiving a query from A, the C chooses two numbers \( w_{1} \) and \( r \) randomly, computes \( A_{ID_{1}} = (A_{ID_{1}}, A_{ID_{2}}), A_{ID_{1}} = g^{r}, A_{ID_{2}} = ID_{U1} \ominus H_{2}(g_{pub}) \), \( u_{1} = g^{w_{1}}, \varphi_{U1} = (SK_{U1})^{w_{1}}, \pi_{U1} = H_{3}(g_{U1}, ID_{U1}, T_{U1}, \varphi_{U1}) \), and send the message \( M_{3} = \{A_{ID_{1}}, \varphi_{U1}, \pi_{U1}, T_{U1}\} \) to A.
  - **Send(\( \Pi_{EDj} \), \( \Pi_{M3} \)):** When receiving this query from A, the C chooses a number \( w_{2} \) randomly, computes \( g_{EDj} = g^{w_{2}}, \varphi_{UE} = (\varphi_{U1})^{w_{2}}, \varphi_{EDj} = (SK_{EDj})^{w_{2}}, \pi_{EDj} = H_{4}(g_{EDj}, ID_{EDj}, T_{EDj}, \varphi_{EDj}) \), and send the message \( M_{2} = \{\varphi_{U1}, \varphi_{UE}, \varphi_{EDj}, \pi_{U1}, \pi_{EDj}, A_{ID_{U}}, A_{ID_{EDj}}, T_{EDj}\} \) to A.
  - **Send(\( \Pi_{CS} \), \( \Pi_{M2} \)):** When received a query from the A, the C uses the above query results to make a judgment on the correctness of \( \pi_{U1} \) and \( \pi_{EDj} \). If both of them are correct, the C chooses two numbers \( w_{3} \) and \( w_{4} \) randomly, computes \( W_{U1} = (g_{EDj})^{w_{3}}, W_{EDj} = (g_{U1})^{w_{4}}, S_{1} = H_{s}(ID_{U1}, SK_{EDj}, W_{EDj}), S_{2} = H_{s}(ID_{U1}, SK_{U1}, W_{U1}), K_{1} = (W_{EDj})^{w_{3}}, Key_{1} = H_{4}(K_{1}), \) and send \( M_{3} = \{W_{U1}, W_{EDj}, S_{1}, S_{2}, T_{EDj}\} \) to A. Otherwise, the C rejects the query of the A and output ⊥.
  - **Send(\( \Pi_{U1} \), \( \Pi_{M3} \)):** When received a query from A, the C make a judgment on the correctness of \( S_{1} \). If it is correct, the C computes \( K_{1} = (W_{EDj})^{w_{3}}, Key_{1} = H_{4}(K_{1}) \), and send \( M_{4} = \{W_{U1}, S_{2}, T_{EDj}\} \) to A. Otherwise, the C rejects the query of the A and output ⊥.
Send(l, M1, M2, M3, M4): When received a query from the A, the C makes a judgment on the correctness of S2. If it is correct, the C computes K1 = (Wl)wM1, Key1 = H4(K1). Otherwise, the C rejects the query of the A and output ⊥. Then the message {M1, M2, M3, M4} is added to the list L.

Execute(l, l, l, l): When received this query, the C takes out the message {M1, M2, M3, M4} from the list L and return it to A.

Reveal(l): When the A asks this question, if the instance l agrees, the C will send the session key Key1 to the A. Otherwise, C outputs ⊥.

Test(l): When the A sends a Test(l) query to the C, the C adopts a coin toss b. If b = 1, the C sends the session key Key of instance l to the A. If b = 0, the C chooses a random number equal to the length of the session key and sends it to the A.

The proof includes four games (G0, G1, G2, G3), where εi indicates that the A guessed the value b correctly in the i-th game.

Game G0: This game simulates an ordinary attack by an A. Thus,

ε = |Pr[εi] − 1|.

(1)

Game G1: In this game, A can ask Hash query and Execute query to the C. When receiving query from the A, the C searches the list L and sends the results to the A. Otherwise, the C selects a random number and returns it to A. Since the C simulates a real attack, the advantage of the A in this game is indistinguishable from G0. Thus, we have

Pr[εi] = Pr[εi].

(2)

Game G2: In this game, A can ask various queries to the C as in G3. The difference from G1 is that when the hash query collides or the transcripts query collides, C will terminate the query. According to the birthday paradox, the probability of hash collision or transcripts collision is at most d0/2q and (qSε + qEε)2/2q respectively. Thus, we can conduct

|Pr[εi] − Pr[εi]| ≤ \sum_{j=1}^{q} q^2 + (qSε + qEε)² / 2q.

(3)

Game G3: This game simulates Send query. When receiving a query from A, the C responds with the following.

• When receiving a query from A, the C computes

\begin{align*}
g_{ul} = g^a \\ \varphi_{ul} = (g^a)^{\overline{w}(ul)}
\end{align*}

then assigns values to AIDl, πul, and TUL, respectively. Finally, the message \( M_1 = \{AID, g_{ul}, \varphi_{ul}, \pi_{ul}, TUL \} \) is sent to A.

• When receiving this query from A, the C computes

\begin{align*}
g_{edj} = g^b \\ \varphi_{ue} = (g^c)^{\overline{w}(ue)}
\end{align*}

\begin{align*}
g_{edj} = (g^b)^{\overline{w}(edj)}
\end{align*}

and \( \varphi_{edj} = \varphi_{ue}, \pi_{ul}, \pi_{edj} \), AIDv, DEDj, TUE, TEDj \) is sent to A.

• When received a query from A, the C chooses a random number \( w_3 \), computes \( W_{cp} = g^e \) and \( W_{ul} = g^{bw_3} \), \( W_{edj} = g^{aw_3} \). Then calculates \( S_1 \) and \( S_2 \). The C sets the values of \( K = g^{cw_3} \), and computes \( Key = H4(K) \). The C stores \( w_3 \) in the list L. Finally, the C sends the message \( M_3 = \{W_{ul}, W_{edj}, S_1, S_2, T_{cp} \} \) to A.

• When received a query from A, the C searches the list L for \( w_3 \). The C sets \( K = g^{cw_3} \) and \( T_{edj} \), calculates \( Key = H4(K) \). Finally, the C returns the message \( M_4 = \{W_{ul}, S_2, T_{edj} \} \) to A.

• When received a query from A, the C searches the list L for \( w_3 \). The C sets \( K = g^{cw_3} \), calculates \( Key = H4(K) \). If exists an A who can distinguish \( G2 \) from \( G3 \) successfully, then the C can use A as a subroutine to break the DDH difficulty assumption. I.e. if \( g^{cw_3} = g^{abw_3} \), then \( g^e = g^{ab} \).

The probability that the C chooses an instance is \( 1/2qS_ε \), therefore,

|Pr[εi] − Pr[εi]| ≤ \varepsilon \cdot qS_ε.

(4)

where \( \varepsilon \) represents the advantage of C in breaking the DDH assumption.

From (1) to (5), we can conduct

\begin{align*}
\varepsilon & \leq \frac{\sum_{i=1}^{q} \varepsilon^2 + (qS_ε + qE_ε)^2}{2q} + \varepsilon \cdot qS_ε.
\end{align*}

Therefore, we have

\begin{align*}
\varepsilon & \geq \frac{1}{qS_ε} (\varepsilon - \frac{\sum_{i=1}^{q} \varepsilon^2 + (qS_ε + qE_ε)^2}{2q}).
\end{align*}

Thus, the security of the protocol has been proven.

Theorem 6.2. The Key2 in our protocol is AKA-secure under the attack of any PPT A.

Proof. In our security model, A can obtain communication message among users, edge devices and cloud servers through eavesdropping. The A can obtain the message \( W_{uc} = g^{w_4} \) through Execute query. Then the A can obtain the user’s private key through Reveal query. A can compute the message \( g_{ul} = g^{w_3} \). Due to the hardness of CDH assumption and \( W_{ul}, W_{edj} \) are private, the A cannot calculate \( g^{w_{ul} w_4} \) according to \( g^{w_3} \) and \( g^{w_4} \).

6.3 Analysis of Security Requirement

In this subsection, we analyze the security requirements that the protocol meets.

(1) Mutual authentication: The cloud server can authenticate user and edge device respectively from the authentication request and response corresponding result. All the authentication messages are embedded in the authentication request. The cloud server authenticates
user and edge devices by checking whether the equations \( \pi_{U_1} = \pi_{U_1} \) and \( \pi_{ED_j} = \pi_{ED_j} \) are hold. At the same time, the user and edge device authenticate the cloud server by checking whether the equations \( S_2 = S_2 \) and \( S_1 = S_1 \) are true. Therefore, our protocol can support mutual authentication.

(2) **Anonymity:** The real identity of the user is anonymized by choosing random number \( r \). If one adversary wants to extract the real identity from the anonymous identity, it can calculate the real identity of the user from \( ID = AID_{ID} \oplus H_2(g_{pub}) \). The adversary need to computes \( g_{pub}^r = AID_{ID} x = g^{xy} \). The random number \( r \) and the master private key \( x \) are held by the user and the cloud server respectively, so that the adversary cannot calculate the real identity according to the anonymous identity of the user.

(3) **Traceability:** The cloud server is the legal holder of the master private key \( x \), and it can calculate the real identity of the vehicle according to the master private key from the anonymous identity.

(4) **Known-key security:** The session key \( Key \) contains random number \( w_1, w_2, w_3 \) and \( w_4 \) that are randomly selected by user, edge device and cloud server. So the different session key are independent of each other among protocol executions. Hence, our protocol support known-key security.

(5) **Session key security:** In our protocol, the session key \( Key_1 \) and \( Key_2 \) are calculated by formula \( Key_1 = H_4(g^{w_1w_2w_3}) \) and \( Key_2 = H_4(g^{w_4w_5w_6}) \), where the parameters \( w_1, w_2, w_3 \) and \( w_4 \) are random numbers. Therefore the adversary cannot calculate the session key according to the existing information.

(6) **Forward secrecy:** In our protocol, \( w_1, w_2, w_3 \) and \( w_4 \) are selected randomly in \( Z_n \). Therefore, the disclosure of the user’s private key will not lead to the disclosure of the session key, which ensures the communication security of the system.

(7) **Resistant against various kinds of attacks:** Our protocol is resistant to man-in-the-middle attack and replay attack as follows.

- **Man-in-the-middle attacks:** In our protocol, supposing that the adversary obtains the real identity of user and edge device successfully. The adversary chooses two random number \( w_1, w_2 \) and calculates \( g_{U_1} = g^{w_1}, g_{ED_j} = g^{w_2} \). However, the adversary cannot obtains \( \phi_{U_1} \) and \( \phi_{ED_j} \) without the private key of user and edge devices. Thus, the legitimate authentication information can not be forged.

- **Replay attacks:** The authentication information contains the timestamp, so the participants can resist the replay attacks according to the freshness of the timestamp.

- **Stolen verifier table attacks:** In our protocol, neither the user nor the edge devices need to generate a verifier table to store authentication message, they only need to store the private key and session key of their own. The adversary can not obtain the authentication message among the user, edge devices and cloud server by using stolen verifier table attack.

In this section, we analyze the performance of the protocol from the following two aspects: computation cost and communication cost.

### 7.1. Computation Cost

In this subsection, we analyze the computation cost of our protocol. For convenience, we define some execution time notations as follows.

- **\( T_{exp} \):** The execution time of exponential operations in multiplicative cyclic group.
- **\( T_{hb} \):** The execution time of a hash-to-point operation.
- **\( T_{hs} \):** The execution time of an ordinary hash operation.
- **\( T_{sm} \):** The execution time of a scalar multiplication operation in additive cyclic group.
- **\( T_{bp} \):** The execution time of a bilinear pairing operation \( e(P, Q) \), where \( P \) and \( Q \) belong to additive cyclic group.

We compared the computation cost of our protocol with Jia’s scheme [19] and Ma’s scheme [20]. The execution time of the cryptographic operations in our protocol is completed with the PBC library. Our hardware consists of an Intel(R) Core (TM) i5-9500 CPU with 3.00 GHz clock frequency, 8G memory and runs Windows 10 operation system. The execution time of the basic cryptographic operations are listed in Table 2.

The total computation cost of the participants (user \( U_1 \), edge device \( ED_j \) and cloud server \( CS \)) of our scheme, Jia’s scheme [19] and Ma’s scheme [20] are shown in Table 3.

For our scheme, \( U_1 \) needs perform six exponential operations, three ordinary hash operations and two hash-to-point operations. \( ED_j \) needs perform four exponential operations, two ordinary hash operations and one hash-to-point operation. \( CS \) needs perform eleven exponential operations, nine ordinary hash operations and two hash-to-point operations. Therefore, the total execution time of \( U_1, ED_j \) and \( CS \) is 11.3689ms, 7.5665ms and 20.7795ms.

<table>
<thead>
<tr>
<th>Cryptographic operation</th>
<th>Execution time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{exp} )</td>
<td>1.882</td>
</tr>
<tr>
<td>( T_{hb} )</td>
<td>0.0383</td>
</tr>
<tr>
<td>( T_{hs} )</td>
<td>0.0001</td>
</tr>
<tr>
<td>( T_{sm} )</td>
<td>8.006</td>
</tr>
<tr>
<td>( T_{bp} )</td>
<td>16.064</td>
</tr>
</tbody>
</table>

For the scheme of [19], \( U_1 \) needs perform six ordinary hash operations, two scalar multiplication operations and one bilinear pairing operation. \( FN_j \) needs perform four ordinary hash operations, two scalar multiplication operations and one bilinear pairing operation. \( CS \) needs perform eleven ordinary hash operations, three scalar multiplication operations and one bilinear pairing operation. The total execution time of \( U_1, FN_j \) and \( CS \) is 32.0766ms, 32.0764ms and 40.0831ms.

For the scheme of [20], \( U_1 \) needs perform four ordinary hash operations and three scalar multiplication operations. Fog node \( FN_j \) needs perform four ordinary hash operations and four scalar multiplication operations. \( CS \) needs perform eleven ordinary hash operations and ten scalar multiplication operations.

### 7. Performance Analysis

In this section, we analyze the performance of the protocol from the following two aspects: computation cost and communication cost.
operations. Therefore, the total execution time of \( U_i \), \( FN_j \) and \( CS \) is 24.0184ms, 32.0244ms and 80.0611ms.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>( U_i ) (ms)</th>
<th>( ED_j ) or ( FN_j ) (ms)</th>
<th>( CS ) (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our scheme</td>
<td>( 6T_{exp} + 3T_h + 2T_{kp} \approx 11.3689 )</td>
<td>( 4T_{exp} + 2T_h + T_{kp} \approx 7.5665 )</td>
<td>( 11T_{exp} + 9T_h + 2T_{kp} \approx 7.5665 )</td>
</tr>
<tr>
<td>Jia’s scheme</td>
<td>( 2T_{cm} + 6T_h + T_{ep} \approx 32.0766 )</td>
<td>( 2T_{cm} + 4T_h + T_{ep} \approx 32.0764 )</td>
<td>( 3T_{cm} + 11T_h + T_{ep} \approx 40.503 )</td>
</tr>
<tr>
<td>Ma’s scheme</td>
<td>( 3T_{cm} + 4T_h \approx 24.0184 )</td>
<td>( 4T_{cm} + 4T_h \approx 32.0244 )</td>
<td>( 10T_{cm} + 11T_h \approx 80.0611 )</td>
</tr>
</tbody>
</table>

### 7.2. Communication Cost

The performance evaluation result shows that the computation cost of our scheme on the user, edge device and cloud server is less than [19] and [20]. Compared with [20], our scheme uses less 12.6495, 24.4579 and 59.2816 milliseconds on user, edge device and cloud server. And our scheme uses less 20.7077, 24.5099 and 19.7235 milliseconds than [19] on user, edge device and cloud server.

The computation cost of edge device and cloud server increases with the growth of users as shown in Figure 4. It is worth noting that the computation cost of edge devices and the cloud server increases linearly with the increase of users.

The communication cost of user, edge device and cloud server is 1376bits, 6880bits and 3424bits, respectively.

For the scheme of [19], user needs to transmit the information \( \{A, P1D_i, N_i, T_i\} \) to fog node. Fog node needs to transmit the information \( \{A, B, P1D_i, N_i, L_j, T_u, T_f\} \) and \( \{B, C, Auth_i, T_c\} \) to cloud server and user, respectively. After cloud server verified the message, it needs to respond the message \( \{W_{U_i, W_{ED_j}}, W_{U_i, S_2}, S_2, T_{CS}\} \) to edge device. Therefore, the communication cost of user, edge device and cloud server is 1376bits, 6880bits and 3424bits, respectively.

For the scheme of [20], user needs to transmit the information \( \{AID_{U_i}, T_{U_i}, R_1, \alpha\} \) to fog node. Fog node needs to transmit the information \( \{AID_{U_i}, AID_{FN_j}, T_{U_i}, T_{FN_j}, R_1, R_2, R_3, D_{ID}\} \) and \( \{R_2, R_3, T_{CS}, Y\} \) to cloud server and user, respectively. After cloud server verified the message, it needs to respond the message \( \{R_2, R_2, T_{CS}, Y\} \) to fog node. So the communication cost is 1696bits, 5152bits and 1696bits, respectively.

For the scheme of [20], user needs to transmit the information \( \{AID_{U_i}, T_{U_i}, R_1, \alpha\} \) to fog node. Fog node needs to transmit the information \( \{AID_{U_i}, AID_{FN_j}, T_{U_i}, T_{FN_j}, R_1, R_2, R_3, D_{ID}\} \) and \( \{R_2, R_3, T_{CS}, Y\} \) to cloud server and user, respectively. After cloud server verified the message, it needs to respond the message \( \{R_2, R_2, T_{CS}, Y\} \) to fog node. So the communication cost is 1696bits, 5152bits and 1696bits, respectively.
of user, fog node and cloud server is 1696bits, 7200bits and 3744bits, respectively.

According to the analysis above, our scheme performs better than [19] and [20] on user side. On the edge device side and cloud server side, the communication overhead of our scheme is smaller than [20] and larger than [19]. Although the communication overhead of our scheme is inferior to [19] on edge device side and cloud server side, our scheme is also within the acceptable range due to the strong communication capabilities of the above two.

8. Conclusion

In this paper, an efficient and secure three-party authentication and key agreement protocol for privacy-preserving of IoT devices in MEC is put forward. The scheme realized three-party authentication and key agreement among users, edge devices and cloud server. Then, we prove the security of and analyze the security attributes of the protocol. The security analysis shows that our protocol secure and meets the security attributes such as session key security, forward secrecy. In the end, we evaluate the performance of the protocol, and the evaluation result shows that our protocol is more superior in terms of computation cost and communication cost.

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