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A Distributed Authentication Scheme Based on Smart Contract for Roaming Service in Mobile Vehicular Networks

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***Abstract*—Secure and real-time communication is an essential condition in mobile vehicular networks, and this requires secure authentication and seamless access enabled by roaming services. As a security inspector, roaming authentication ensures that legitimate users can access the network securely. However, today's roaming authentication protocols authenticate users with the help of centralized authentication servers, leading to the risk of the single point of failure and roaming fraud. The massive device access in 5G networks further exacerbates the losses when problems occur. In light of it, we propose a decentralized fraud-proof roaming authentication framework based on blockchain. We leverage smart contracts to implement a roaming authentication protocol, including user/AP registration, authentication, and revocation. For higher efficiency, we utilize the Bloom filter for the revocation process. In addition, we design an unforgeable and undeniable billing scheme based on hash chain technology. Security and performance analysis show that the proposed roaming authentication scheme can provide the required security features while incurring an acceptable authentication delay.**

***Index Terms*—distributed authentication, roaming authentication, mobile vehicular network, blockchain, smart contract**

I. Introduction

In recent years, with the rapid development of electric vehicles and wireless mobile networks, mobile vehicle networks have gained wide attention and significant development [1, 2]. The emergency of vehicular networks has enabled various new applications, e.g., real-time traffic and road-block analysis, traffic signal control, road examination, city event updates, etc [3, 4]. Seeing that no application can be independent of secure and real-time communication, efficient and secure roaming authentication is indispensable [5]. Besides, several communication types are usually considered in mobile vehicular networks, e.g., vehicle to vehicle (V2V), vehicle to infrastructure (V2I), and vehicle to pedestrian (V2P), and so on. Thus, the roaming and authentication service should be adaptive to heterogeneous networks, including, for example, vehicular networks, wireless networks, and cellular networks. All these factors lead to a dramatic increase in the importance and complexity of roaming services, and the demand for scalability is also increasing. According to Kaleido Intelligence, 5G data roaming traffic generated by mobile devices and IoT applications will exceed 500 Petabytes in 2024 [6]. Thereupon, roaming authentication, as a security barrier for roaming services that guarantees users' secure access and prevents fraudulent use of services, has gained extensive investigation.

So far, according to the number of participating entities, roaming authentication protocols fall into two categories: three-party roaming authentication schemes, e.g., the work in [7], and two-party roaming authentication schemes, e.g., the work in [8]. A typical three-party roaming authentication scheme involves three participants: a roaming user, a visiting foreign server and a home server. First, a user sends the access credentials to the foreign server, and then the foreign server forwards the credentials to the home server. Finally, the home server verifies the credentials and notifies the foreign server of the result. The three-party scheme relies on the home server's real-time participation, causing high authentication delays and the risk of a single point of failure. For example, the home server is vulnerable to denial of service (DoS) attacks, which may cause the collapse of the entire roaming system.

In two-party authentication schemes, a foreign server can directly authenticate a roaming user without the participation of the home server, thereby reducing the authentication delay compared with three-party schemes. To achieve this, two-party schemes adopt a public key system for authentication, hence bringing additional overhead for key management such as establishing a public key infrastructure (PKI). Moreover, roaming users have to store the public key of each visited network server for authentication, which is a heavy burden for mobile devices when the number of networks increases. Besides, in practice, roaming partnerships between different service operators are not changeless but dynamically established or revoked. However, on the basis of traditional two-party schemes, a service operator needs to notify all its' responding users when partnership changes, which brings a significant system overhead. What's more, two-party schemes generally distinguish foreign users from home users and use different protocols to authenticate different types of users, making the protocols not universal. In a word, although

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two-party schemes are superior to three-party schemes in terms of authentication efficiency, there are still significant shortcomings such as the complexity of the system architecture and inflexibility of partnership changes.

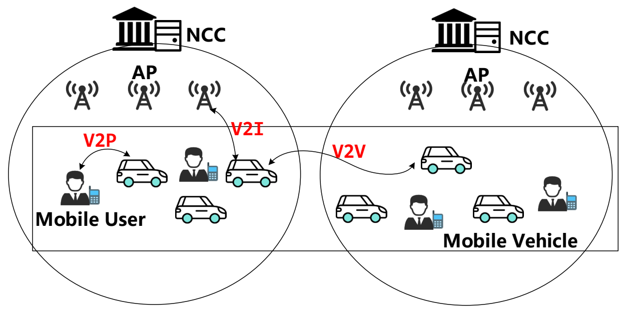

Fig. 1. Architecture of the mobile vehicular network and the communication types.

With the development of cryptocurrencies such as Bitcoin [9], blockchain technology has been proven both theoretically and practically to be able to guarantee the security of decentralized systems through cryptography and consensus mechanisms. Recently, there have been some schemes that introduce blockchain to build security facilities and implement key technologies [10–12]. Considering the risk of single point of failure of centralized authentication and the semi-trust relationships between different network operators, we introduce blockchain for users and access points (APs) registration, revocation, and authentication. Our main idea is to record the credentials and revocation information on the blockchain, and utilize smart contract to automatically provide users/APs with authentication services, thus achieving distributed and direct mutual authentication between users and APs. It is to be noted that the blockchain has limitations in both storage capabilities and data querying, and meanwhile blockchain confirmation could cause high latency. To this end, we leverage the Bloom filter for storage optimization and mapping tables for efficient querying. In addition to the authentication phase, secure and efficient billing is also worthy of attention. In order to prevent operators from cheating for higher billing revenues or prevent users from payment evasion, we design a billing scheme based on hash chain. In summary, we make the following contributions:

1) We propose a blockchain-based distributed authentication framework for roaming services in mobile vehicular networks. By leveraging blockchain smart contracts for registration and verification, our proposed system enables universal and direct mutual authentication between roaming users and access points (APs) independent of the adopted protocols of each underlying network, thus adaptive to the heterogeneous mobile vehicular network.
2) To achieve secure and efficient revocation checking, we leverage the Bloom filter to record revoked users/APs so that the revocation verification can be implemented by the storage-limited smart contracts, therefore supporting the huge user scale of 5G mobile network.
3) In order to prevent operators from cheating for higher billing revenues or users deceiving to avoid payment, we design an unforgeable and undeniable billing scheme based on the hash chain technology.
4) We analyze the security of our proposed scheme in theory. In addition, we make a prototype implementation and evaluate the performance. Security and performance analysis show that our proposed scheme provides the required security while incurring an acceptable performance overhead.

II. Related Work

Roaming, as a key service of wireless mobile networks, has been widely studied in academia and industry. According to the number of participating entities, roaming authentication protocols can be classified into two categories: three-party roaming authentication schemes and two-party roaming authentication schemes. Three-party roaming authentication schemes require the cooperation of the roaming user, the foreign server, and the home server. In 3G/4G networks, the foreign server forwards a user's authentication request to the home server, and then the home server authenticates the user based on the pre-shared key mechanism. Aiming at reducing the computation and communication overhead and enhancing the security and robustness of the authentication protocols, researchers have proposed a number of roaming schemes.

In 2004, Zhu and Ma [7] first proposed a three-party roaming authentication scheme. This scheme guarantees one-way authentication of the server to the user, and the session key is unilaterally generated by the user, thus causing a certain security risks. In addition, it cannot guarantee user anonymity. To take action against the problems, Lee *et al.* [13] proposed a new scheme to enhance security. However, Lee's scheme does not achieve actual backward security and anonymity. Thus, Wu *et al.* improved this scheme in [14]. Although Wu's scheme encrypts user identities, as in [15], the encrypted identities remain unchanged. Hence, the user identities are still traceable. In 2013, Jiang *et al.* [16] proposed an anonymous roaming protocol based on quadratic residual. A user's identity is encrypted and transmitted by the pre-stored large integer and quadratic residual algorithm. The server can restore the user's true identity according to the Chinese remainder theorem. However, this scheme cannot resist replay attacks [17].

In order to enhance anonymity and untraceability of a user's identity, smart card-based two-factor roaming authentication schemes, e.g., [18–23] were proposed. These schemes not only implement authentication through pre-shared keys, but also further enhance security with short passwords entered by users. Xie *et al.* [18] first proposed this type of scheme, but Xie's scheme cannot resist counterfeiting attacks. They therefore proposed a security-enhanced scheme *et al.* [19]. However, it fails to provide strong user anonymity, and it has inefficient typo-detection. It requires an online verification of the password and cannot be verified on smart cards. Gope *et al.* [20] used a pseudonym mechanism to enhance user anonymity. However, this scheme does not resist desynchronization attacks and requires smart cards with large storage capacity. Odelu *et al.* [21] designed a roaming scheme that puts password verification on a smart card, but it also creates password

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guessing attacks. Wu *et al.* [22] used the secret key of the home server to encrypt a user's real identity, but the secret key needs to be updated using a new random number sent by the home server after each authentication process. Thus, it cannot resist the desynchronization attack. Moreover, this scheme fails to provide untraceability of a user's identity and has inefficient typo-detection. Thus, Gupta *et al.* [23] proposed to encrypt the user's real identity through the quadratic residual algorithm, use fuzzy verifier [24] to speed up typo-detection, and set the error password threshold to resist password guessing attack. However, an attacker can forge a user and frequently initiate false authentication, hence causing legitimate users to be denied from services. Fotouhi *et al.* [25] designed a lightweight two-factor authentication protocol utilizing hash-chain technology to satisfy the forward secrecy requirement. Three-party schemes mentioned above are more or less problematic, and the latest two-factor schemes are also vulnerable to password guessing attacks or desynchronization attacks. In addition, the three-party scheme is a centralized authentication solution, which suffers from the single point of failure problem.

Two-party roaming authentication schemes enable a foreign server to directly authenticate roaming users without the participation of the home server. Compared with three-party schemes, two-party schemes avoid long delay caused by the home server. Yang *et al.* [8] initially proposed two secure two-party roaming authentication schemes. The first scheme is based on public-key cryptography. Although a user's identity is encrypted, the foreign server can decrypt it. Therefore, this scheme fails to provide strong anonymity. The second scheme uses a group signature algorithm to enhance anonymity so that even the foreign server cannot learn the user's true identity. However, the generation and verification of the group signature and the query of the revocation list consume a large amount of bilinear mapping calculations, and thus the computational overhead is huge. In addition, the private key of the revoked user will be disclosed, and the user's previous session will thereby be tracked, breaking the backward unlinkability. After that the work of He *et al.* [26] guaranteed backward unlinkability by giving each user multiple keys. As the number of keys increases, the backward unlinkability gradually increases. It is noted that the size of the revocation list also increases linearly with the number of keys, which makes the overhead of checking the revocation list more severe. Aiming at the problem of excessive revocation overhead, Liu *et al.* [27] introduced lifetime to a user's private key, and a foreign server can directly detect the expired user's group signature. This reduces the size of the revocation list to a certain extent, but it still fails to solve the user's active revocation problem. Yang *et al.* [28] designed a key update mechanism to reduce the computation and storage overhead of the revocation check process, but each revoked user will cause all other users to update their private keys. This increases the system overhead, and meanwhile breaks the user's independence. Xue *et al.* [29] proposed a batch verification mechanism for user authentication in space information network, significantly enhancing the handover efficiency. They further designed a group key-based handover authentication scheme in [30] based on the secret sharing technology and reduced the overhead of handover authentication. By adopting blockchain and smart contracts, Xue *et al.* [31] proposed a secure and efficient access control scheme of user subscription data in roaming scenarios, which can be decentralized without any trusted third party.

Considering that the calculation and revocation overhead of group signatures is too large, some roaming schemes based on identity-based cryptography (IBE) e.g., [32–34] have been proposed. These schemes provide user anonymity through a series of pseudonyms, but excessive and constantly updated pseudonyms, as well as expanded revocation lists, place a heavy burden on resource-constrained user devices. In summary, two-party schemes have some severe shortcomings. For example, the authentication process is implemented only by the foreign server, causing single point of failure problems. In addition, two-party schemes suffer from large computational overheads and therefore are not applicable to scenarios where devices are resource-constrained. Moreover, the key management process of two-party schemes is too cumbersome, and needs additional mechanisms to ensure key update and synchronization.

Recently researchers have introduced blockchain for secure authentication for mobile networks. Xu *et al.* [10] proposed an identity management and authentication scheme for mobile network that enables dynamic revocation based on redactable blockchain. But their scheme cannot help maintain the roaming relationship between operators in roaming scenarios. Tan *et al.* [11] designed a secure key management scheme based on blockchain for heterogeneous flying ad-hoc network. The scheme, therefore, is not adaptive to networks with operators on which our work focuses. Nguyen *et al.* [12] proposed BlockRoam which is a blockchain-based roaming management system for mobile networks. However, BlockRoam mainly concerns about the blockchain's consensus algorithm. The details of roaming authentication, including data structure, cryptography, authentication protocols, revocation protocols, and billing, are ignored. To our best knowledge, there is no practical scheme that enables secure and efficient mutual direct roaming authentication between users and APs for heterogeneous mobile networks, which is important in roaming scenarios as we explain in Section I.

TABLE I
A SUMMARY OF ROAMING AUTHENTICATION SCHEMES

3-party schemes	[7, 13–17]
smart-card-based schemes	[18–23]
2-party schemes	[8, 26–30]
IBE-based schemes	[32–34]
blockchain-based schemes	[10–12]

III. PRELIMINARIES

In this section, We first give a review of background information on blockchain and smart contract. Then, we introduce the principle of Bloom filter. At last, we briefly

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describe the definition of elliptic curve digital signature algorithm.

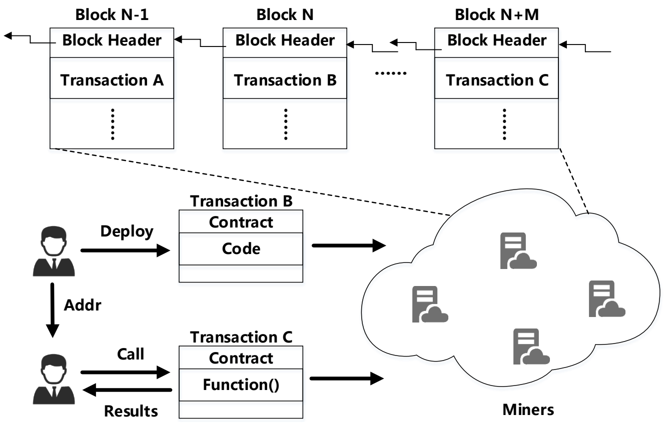

Fig. 2. The deployment and invocation of a smart contract

A. Blockchain and Smart Contract

Blockchain originates from Bitcoin [9], a distributed cryptocurrency proposed by Nakamoto. Nowadays, blockchain has gone beyond the scope of cryptocurrency and becomes a distributed tamper-proof ledger. The ledger is a chronologically ordered chain of blocks and each node of blockchain network holds a copy of the chain to prevent a single point of failure. Each block consists of a block body and a block header. The block body records the transactions or facts, which can be of any type such as token transfer transactions, smart contract transactions, health data, system logs, etc. In addition, the transactions are hashed into a Merkle hash tree. The block head records the root hash of the Merkle tree and the hash of the previous block, and hence those who attempt to tamper with the backdated transactions have to modify the target block and all the following blocks, which is considered difficult due to the consensus mechanism.

As a distributed system, blockchain guarantees consistency and synchronization among nodes through a consensus mechanism, ensuring that all nodes maintain the same copy of the blockchain. The consensus mechanism mainly consists of Proof of Work (PoW) [9, 35], Proof of Stake (PoS) [36, 37], and Practical Byzantine Fault Tolerance (PBFT) [38].

Ethereum [36] expands the functionality of the blockchain to support not only distributed cryptocurrencies but also more complex and flexible smart contracts. An Ethereum smart contract is simply a program that runs on the Ethereum blockchain. Once deployed, the program in the smart contract will be executed honestly. Users can design various complex functions utilizing smart contracts.

The deployment and invocation of a smart contract is shown in Fig. 2. A user sends a transaction to the blockchain via an externally owned account to generate a smart contract and save the address of the contract. All the miners will receive the transaction, and then deploy it in the blockchain through consensus. Anyone who knows the contract address can call the contract through a transaction. The contract will be executed by every miner. The execution results are stored in databases maintained by miners and returned to the caller after consensus.

B. Bloom Filter

A Bloom filter [39] is a space-efficient probabilistic data structure used to check whether an element is a member of a set. In formulation, a Bloom filter is an m-bit array andeach bit is initially set to zero. There are k hash functions, $Hash_i$, $1 \leq i \leq k$, used to map ID to a random number ranging from 1 to m. In the construction process of a Bloom filter, for all ID in the set, we calculate k hash values $Hash_i(ID)$ for $i \leq 1 \leq k$ as the index values, and set the mapping values of the corresponding positions in the array to be one. If multiple ID are mapped to the same position, the corresponding value remains one. In the query process of a Bloom filter, we need to calculate $hash_i(ID)$ for $1 \leq i \leq k$ to obtain the index values. If any of the mapping value in the array is zero, the ID is definitively not in the set. Otherwise, it is deemed to be in the set with a certain false positive rate which is shown as follows.

$$f = (1 - e^{-\frac{nk}{m}})^k, \tag{1}$$

where n is the number of elements in the data set. For more details, interested readers can refer to [39, 40].

C. Elliptic Curve Digital Signature Algorithm (ECDSA)

ECDSA is an instantiation of digital signature (DSA) by elliptic curve, which is generally specified by the following three algorithms in ANSI standard [41]:

- $EC.Keygen()$: The key generation algorithm generates a key pair for an entity. The key pair is computed under a particular set of elliptic curve domain parameters, which consists of a suitable chosen elliptic curve E defined over a finite field F_q of characteristic p, and a base point $G \in E(\mathbb{F}_q)$. To generate the secret/public key pair, the entity first selects a random integer d mod n, where n is a sufficiently large prime, then computes $Q = d \cdot G$. Thus, the key pair is (d, Q).
- $EC.Sign(d, m)$: The algorithm generates a signature for message m, which is implemented by the following steps:
  1) Select a random integer k $(1 \leq k \leq n-1)$;
  2) Compute $k \cdot G = (x_1, y_1)$ and $r = x_1 \mod n$. If $r = 0$, go to step (1);
  3) Compute $k^{-1} \mod n$, $e = Hash(m)$ and $s = k^{-1}(e + d \cdot r) \mod n$. If $s = 0$, go to step (1);
  4) The signature for message m is $\sigma = (r, s)$.
- $EC.Verify(Q, \sigma)$: The algorithm verifies the signature σ of m, which is implemented by the following steps:
  1) Verify whether r and s are two integers in the interval $[1, n-1]$. If yes, continue;
  2) Compute $e = Hash(m)$, $w = s^{-1} \mod n$, $u_1 = e \cdot w \mod$ n and $u_2 = r \cdot w \mod n$;
  3) Compute $X = u_1 \cdot G + u_2 \cdot Q$. If $X = \mathcal{O}$, reject the signature. Otherwise, compute $v = x_1 \mod n$ where $X = (x_1, y_1)$. Accept the signature if and only if $v = r$. For more details, we refer the interested readers to [41].

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IV. System Model, Security Model and Security Requirements

A. System Model

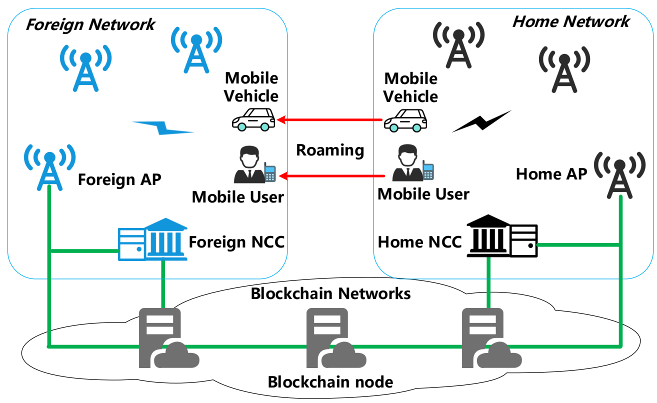

Fig. 3. System Model

The requirement of global network access for mobile users makes it necessary for wireless mobile networks to provide roaming services. The system model of a roaming service is illustrated in Fig. 3. The system consists of multiple domains, each of which contains a network control center (NCC), a number of access points (APs) and several blockchain nodes. The following illustrates the functions and roles of each entity.

- *NCC* is the management center of a network domain and is responsible for providing roaming services, including user/AP registration, authentication and revocation. It issues credentials for users/APs at the registration stage, provides related information for authentication, and updates revocation records. In addition, NCC deploys and maintains smart contracts to support roaming services.
- *Blockchain nodes* are maintained by their respective network operators, and collectively they form a global consortium blockchain. The blockchain maintains block information, runs smart contracts and verifies transactions.
- *APs*, as the entrance to the network, authenticate users through smart contracts and provides network access services for them.
- *Users* including e-vehicles and cellular users leave the home network to access a foreign network, and obtain the subscribed service through the roaming agreement.

B. Security Model

We assume that the network control center (NCC) is trustworthy for its domain users but is semi-trusted to other NCCs and their domain users. That is to say, an NCC is considered to follow the agreement to provide roaming services to users from other NCCs, but it is possible to misrepresent users' consumption. It is also assumed impossible for any adversary to compromise NCC. Besides, we assume that there exist a secure channel between APs and blockchain nodes, between NCC and its domain APs, and between NCC and its domain users. The secure channels can be constructed by the TLS or SSL protocol. At last, we assume that a polynomial time adversary, who can modify, interrupt or forge the messages exchanged between users and APs, tries to break the proposed roaming authentication protocol when users access to a foreign network.

C. Security Requirements

Our scheme should satisfy the following security requirements.

- ***Mutual Authentication***: The system should have the ability to detect unauthorized users' access and abort their requests. Meanwhile, users should have the ability to check the legitimacy of any access point.
- ***Key Establishment***: A random session key should be negotiated between a user and an AP to ensure the security of subsequent communications between them.
- ***Forward/Backward Secrecy***: It requires that the disclosure of the current session key would not affect the security of its future and previous session keys.
- ***Revocation Checking***: A roaming user may be revoked by the system (e.g., the user's subscription period has expired), and thus an AP should be able to find out whether a user is revoked.
- ***Unforgeability and undeniability of billing***: The foreign operator cannot forge billing information to charge more fees to the home operator. Users cannot deceive the amount of services received in order to reduce payments to the home operator.
- ***Robustness***: Even if the home NCC (HNCC) or the foreign NCC (FNCC) fails, the system can still run stably for a certain period of time.

V. Our Proposed Scheme

In this section, we give a detailed description of our scheme, which mainly consists of five phases: *System Initialization*, *User Authentication*, *Dynamic User Enrollment and Revocation*, *Roaming Partnership Establishment* and *Billing*.

A. Overview

Each NCC issues a set of smart contracts for roaming authentication. As illustrated in Fig. 4, the proposed smart contract framework is composed of a main contract (MC), an authentication contract (AC) and a revocation contract (RC). MC records the address of its related AC and a mapping table of other NCCs to their MC addresses. AC consists of two parts. The first part performs the authentication function and the second part stores the address of RC, which is used to verify whether a certificate has been revoked. By recording the addresses of AC and RC into MC, users and APs only need to store MC's address to complete the authentication process.

During system initialization phase, users and APs register with their HNCC, and the HNCC issues them credentials CR_U or CR_{AP} and the address of HNCC's MC. When a user accesses a foreign network, he/she generates an access request M_U based on his/her credential CR_U and sends

M_U to the AP. Upon receiving M_U, the AP verifies M_U's validity by invoking its HNCC's MC and sending a transaction TX_{in} constructed from M_U. MC then checking the mapping list to find the HNCC's MC with which the user registered and checks whether there is a roaming relationship with the HNCC. Then it invokes the related MC to invoke the user's corresponding AC. AC first checks whether the credential CR_U is valid, then invokes RC to check whether the entity has been revoked. For efficiency, RC maintains a bloom filter-based revocation list. If all are valid, MC will return $true$ to the AP, and then AP generates a response M_{AP} that includes a session key SK used for establishing a secure channel during the subsequent network access. If a mutual authentication is needed, the user can authenticate the AP based on M_{AP} in the same way.

B. System Initialization

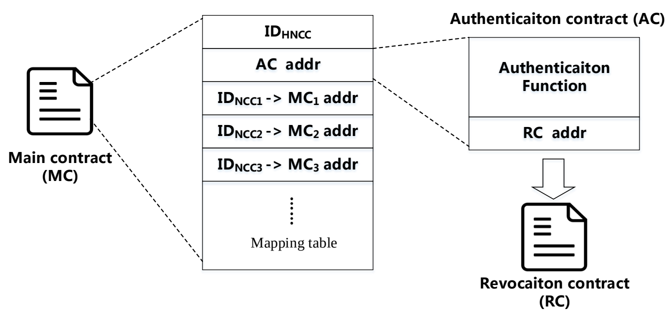

Fig. 4. The smart contract framework

1) User Registration: NCC generates a long-term ECDSA's secret key SK_{NCC} and a public key PK_{NCC}. Before a new user accesses a foreign network, he/she must register with HNCC to become a legal user. The user sends the identity ID_U to HNCC via a secure channel. HNCC generates ECDSA's private/public key pairs (SK_U, PK_U) for the user. Then, HNCC computes the credential by:

$$CR_U = EC.Sign(SK_{NCC}, ID_U||PK_U).$$

Finally, HNCC sends $\{ID_U, ID_{NCC}, SK_U, PK_U, CR_U, MADDR\}$ to the user via a secure channel where $MADDR$ is HNCC's MC address.

2) AP Registration: APs need to register with HNCC as well. The same as user registration, HNCC generates an ECDSA's private/public key pair (SK_{AP}, PK_{AP}) for the AP. Then, HNCC computes the credential by:

$$CR_{AP} = EC.Sign(SK_{NCC}, ID_{AP}||PK_{AP}).$$

Finally, HNCC sends $\{ID_{AP}, ID_{NCC}, SK_{AP}, PK_{AP}, CR_{AP}, MADDR\}$ to the AP.

C. User Authentication

The user authentication phase is implemented when a mobile user roams to a foreign network and accesses the network for obtaining services. In this phase, the AP and the user need to verify each other's legitimacy. If the verification is passed, a secure channel can be further established between them. The detailed steps are given as follows. (It's noted that we mainly focus on roaming authentication scheme in this paper, while authentication for accessing home network can also be achieved by implementing the following authentication processes.)

1) The user firstly generates an access request M_U and sends it to the corresponding AP. The details for generating M_U are illustrated in **Algorithm 1**.

Algorithm 1: Access Request Generation

Input: The user's identity ID_U, public key PK_U, private key SK_U, credential CR_U, and HNCC's identity ID_{NCC};
Output: Access request M_U;
Select a random number r_U;
Set $R_U = r_U \cdot G$;
Generate timestamp ts_U;
Set $T_U = h(R_U||ts_U)$;
Set $V_U = EC.sign(SK_U, T_U)$;
Set the access request message as $M_U = ID_U||PK_U||CR_U||R_U||ID_{NCC}||V_U||ts_U$;
return Access request M_U;

2) Upon receiving M_U, the AP verifies its validity and generates the access response message M_{AP} by implementing **Algorithm 2**. Firstly, the AP checks whether the timestamp ts_U is within an allowed range compared with its current time and then verifies whether T_U is valid. If both of them are positive, the AP then generates MC's input as $TX_{in} = ID_{NCC}||T'_U||ID_U||PK_U||CR_U||V_U$, and invokes its HNCC's MC by the stored $MADDR$ and sends TX_{in} for user authentication. MC's process is shown in **Algorithm 3**. As illustrated in Fig. 4, MC stores ID_{HNCC}, AC's address and the mapping table of ID_{NCC} to the corresponding MC's address. If ID_{NCC} is equal to ID_{HNCC}, MC calls AC (**Algorithm 4**) to verify whether the credential CR_U and signature V_U is valid. Otherwise, MC finds the mapping of ID_{NCC} to MC's address, and call the corresponding MC to verify TX_{in}. If the verification fails, the AP will receive a fail signal, and the access request will be rejected. Otherwise, the AP generates the access response M_{AP} as shown in **Algorithm 2**, and computes the session key $SK = r_{AP} \cdot R_U$. Finally, the AP sends M_{AP} to the user.
3) Upon receiving M_{AP}, the user's processing is the same as the AP's. Specifically, the user first checks the validity of ts_{AP} and T_{AP}, and then generates MC's input as $TX_{in} = ID_{NCC}||T'_{AP}||ID_{AP}||PK_{AP}||CR_{AP}||V_{AP}$, and invokes his/her HNCC's MC and sends TX_{in} for AP authentication. If the verification fails, the user will receive a false signal, and the access response will be rejected. Otherwise, the user computes the session key by $SK = r_U \cdot R_{AP}$ and establishes a secure channel with the AP.

Algorithm 2: Access Response Generation

Input: Access request M_U, MC's address $MADDR$;
Output: Access response M_{AP};
Check whether timestamp ts_U is within an allowed range;
Set $T_U' = h(R_U||ts_U)$;
Check whether T_U is equal to T_U';
if *ts_U or T_U is invalid* **then**
  Reject the access request;
  return false;
else
  Set $TX_{in} = ID_{NCC}||T_U'||ID_U||PK_U||CR_U||V_U$;
  Use TX_{in} as input to generate transaction and call HNCC's main contract;
  if $MC(TX_{in})$*==false* **then**
    Reject the access request;
    return false;
  else
    Select a random number r_{AP};
    Set $R_{AP} = r_{AP} \cdot G$;
    Generate timestamp ts_{AP};
    Set $T_{AP} = h(R_{AP}||ts_{AP})$;
    Set $V_{AP} = EC.sign(SK_{AP}, T_{AP})$;
    Set the access request message as $M_{AP} = ID_{AP}||PK_{AP}||CR_{AP}||R_{AP}||ID_{NCC}||V_{AP}||ts_{AP}$;
    Set $SK = r_{AP} \cdot R_U$;
    return Access response M_{AP};
  end
end

Algorithm 3: Main contract

Input: TX_{in};
Output: true or false;
Check whether ID_{NCC} is equal to ID_{HNCC};
if *equal* **then**
  return $AC(TX_{in})$
end
Check whether ID_{NCC} exists in address table;
if *inexistent* **then**
  return false;
else
  Find the mapping of ID_{NCC} to MC's address;
  return $MC(TX_{in})$
end

D. Dynamic User Enrollment and Revocation

Dynamic user enrollment means that the system allows a new user to join at any time after system initialization. This is an indispensable feature for any practical roaming authentication system. In our proposed scheme, when a new user wants to join the system, he/she only needs to perform the registration process to register with the HNCC.

Besides, some users may leave the system halfway due to key loss, illegal usage, etc. The authentication system should support revocation of these users. To this end, HNCC maintains a Bloom filter (RBF) to store all revoked users's identities ID_U. The RBF is preserved as a RBF array in the revocation contract (RC), and can be updated through modifying RC's variable. HNCC periodically (e.g., daily) updates the RBF based on the latest undo user by invoking RC to change the RBF array. As shown in **Algorithm 4**, when AC verifies the user's legitimacy, it invokes RC to check whether the user has been revoked. RC's procedure is illustrated in **Algorithm 5**. RC checks every bit in $Hash_i(ID_U)$. If any of them is zero, ID_U is definitively not in the revocation set. Otherwise, it judges that ID_U has been revoked with a certain probability of misjudgment. Considering that some ID_U may be misidentified as revocation, our scheme allows the AP to query the HNCC through the FNCC whether these ID_U have been revoked. It is worth noting that the AP's enrollment and revocation mechanism is the same as users'.

Algorithm 4: Authentication contract

Input: TX_{in};
Output: True or false;
Check the credential $CR_{U/AP}$ by $EC.Verify(PK_{NCC}, CR_{U/AP})$;
if *not passed* **then**
  return false;
end
Check signature $V_{U/AP}$ by $EC.Verify(PK_{U/AP}, V_{U/AP})$;
if *not passed* **then**
  return false;
else
  Call RC to check whether the entity has been revoked;
  if $RC(ID_{U/AP})$*==true* **then**
    return false;
  else
    return true;
  end
end

Algorithm 5: Revocation contract

Input: $ID_{U/AP}$;
Output: true or false;
Check whether $ID_{U/AP}$ is in the RBF;
for $i = 1{:}k$ **do**
  if $RBF[Hash_i(ID_U)] == 0$ **then**
    return false
  end
end
return true

E. Roaming Partnership Establishment

In practice, a roaming user can access a foreign network only if the home and the foreign network operators have

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signed a roaming agreement. However, the establishment of this partnership is not a one-step process, and instead, a network operator gradually decide to become a roaming partner with other network operators. In addition, different network operators may also cancel the partnership due to trust and interests. Therefore, our scheme is designed to support dynamic establishment and revocation of roaming partnerships.

In our proposed scheme, when two network operators decides to establish a roaming partnership, all they need to do is to update the corresponding items of the mapping table in their MC. Specifically, the HNCC adds the mapping of ID_{FNCC} to FNCC's MC address by sending a transaction to the blockchain network, and the FNCC also adds the mapping of ID_{HNCC} to HNCC's MC address. The revocation of the roaming partnership is just in a reversed way. HNCC and FNCC respectively erase the corresponding mapping. As thus, when AP belonging to FNCC invokes HNCC's MC for user/AP authentication, as shown in **Algorithm 3**, if ID_{FNCC} does not exist in the mapping table, user/AP will know that the HNCC and FNCC have not yet established a roaming partnership and will terminate the access process.

F. Billing

To prevent operators from cheating for higher billing revenues or from users' evasion of payment, we employ the hash chain technology for billing [8]. Specifically, after the user and the AP have established a secure channel, the AP stores the user's public key. The user first selects a random integer M and calculates a hash chain $h^{\tau}(M) = h(h(...h(M)))$, where τ denotes the maximum service (e.g., data traffic) of one communication session. Then, the user calculates the signature $\sigma_\tau = EC.Sign(SK_U, h^{\tau}(M)||h(ts))$, where ts is a timestamp. The user sends ($h^{\tau}(M)$, ts, σ_τ) to the AP. If ts and σ_τ are valid, the AP starts to provide network services to the user. After consuming a (pre-agreed) certain amount of service, the user provides the AP with the previous round's hash value $v = h^{\tau-1}(M)$. The AP then verifies whether $h(v) = h^{\tau}(M)$. If the verification fails, the AP stops the service. Otherwise, The user continues to receive the service and then provides the previous rounds' hash value periodically. When the session ends, the AP collects a set of hashes $h^{\tau}(M), h^{\tau-1}(M), ..., h^{\tau-n+1}(M)$. The AP then sends ($\sigma_\tau, ts, n, h^{\tau-n+1}(M), h^{\tau}(M)$) to NCC as a service provision proof. NCC saves these proofs in its database. At the end of the day, NCC sends all the proofs to HNCC and bills HNCC. HNCC can also charge users based on these proofs.

VI. Security Analysis

In this section, we theoretically analyze the security of our proposed scheme to verify whether the security requirements introduced in Section IV-C have been satisfied. Our analysis includes mutual authentication, key establishment and forward/backward secrecy, revocation checking, unforgeability and undeniability of billing, and resistance to some common attacks.

A. Mutual Authentication

Mutual Authentication means that a user and its accessing AP can verify each other's authenticity and legitimacy of the identity. Authenticity requires that an adversary cannot disguise as a valid user/AP, and legitimacy requires that the user/AP has registered to the corresponding HNCC and has not been revoked. Taking an AP authenticating a user as an example, the AP authenticates the user by verifying the challenge-response pair (T_U, V_U), where $T_U = h(R_U||ts_U)$ and $V_U = EC.Sign(SK_U, T_U)$. Since the ECDSA has been proven secure under the assumption that the discrete logarithm problem is hard without knowing the private key, it is infeasible to forge a valid signature on the fresh T_U without SK_U, thereby ensuring the authenticity. Moreover, a valid credential is signed by the HNCC with the private key SK_{NCC}, and SK_{NCC} is secretly held by NCC, adversaries therefore cannot forge a credential for themselves. And revoked users will be timely recorded to RC. The credential together with RC ensure the legitimacy. Similarly, the user authenticates the AP by the challenge-response pair (T_{AP}, V_{AP}).

B. Key establishment and forward/backward secrecy

In each session, the session key SK is computed from key negotiation parameters $R_U = r_u \cdot G$ and $R_{AP} = r_{AP} \cdot G$. Computing SK from these two parameters without knowing r_u and r_{AP} is equivalent to solve the discrete logarithmic problem (DLP), which is considered computationally infeasible. Therefore, the session key cannot be derived by any adversary. Besides, the key forward/backward secrecy is mainly achieved by the independence of the session key SK in different sessions. In our scheme, each session uses different fresh r_U and r_{AP} for key establishment, leading to the independence of the session keys. As thus, even if an adversary has obtained the current session key, he/she cannot derive the next or the previous session key.

C. Revocation Checking

Secure revocation checking requires that the AP should be able to find out whether a user requesting access has been revoked. Suppose that a revoked user RU tries to conceal its revocation when accessing an AP. RU should first generates M_{RU} and send it to the AP. The AP then calls the authentication contract (AC) to verify the information contained in M_{RU}. Note that, as Algorithm 4 shows, AC will invoke the revocation contract (RC) to check whether RU has been revoked. Since the revocation is recorded in the smart contract, RU can only conceal its revocation by modifying RC, which is considered impossible due to the blockchain consensus mechanism.

D. Unforgeability and undeniability of billing

The unforgeability of billing means that the FNCC charges as much for the service it provides. In our proposed scheme, the FNCC bills HNCC by providing the billing proofs $(\sigma_\tau, ts, n, h^{\tau-n+1}(M), h^{\tau}(M))$. On account of the hash chain, the FNCC cannot derive $h^{\tau-n'+1}(M)$ from $h^{\tau-n+1}(M)$ where $n' > n$. The roaming users will not conspire with FNCC to generate more billing proofs, because providing more billing proofs means that users have to pay more to HNCC. Thus, the FNCC cannot charge more than it provides. Besides, since the roaming user should provide $h^{\tau-n+1}(M)$ once finishing the nth service, the HNCC can then charge the user accordingly. Therefore, users cannot deny the received services.

E. Resistance to modification attacks

Suppose that an adversary intercepts and modifies a user's access request M_U. If the adversary aims at modifying R_U or ts_U, since he/she does not possess the user's private key SK_U, the adversary cannot compute a valid V'_U on a modified message T'_U. Therefore, the modified V_U cannot pass the signature verification $EC.Verify(PK_U, V_U)$. If the adversary modifies other parameters of M_U, since he/she does not possess the private key SK_{NCC}, he/she cannot compute a valid CR'_U on a modified user identity. Therefore, the modified M_U cannot pass the credential verification $EC.Verify(PK_{NCC}, CR_U)$. Similarly, for M_{AP}, if the adversary modifies R_{AP} or ts_{AP}, the modified M_{AP} cannot pass $EC.Verify(PK_{AP}, V_{AP})$. If the adversary modifies other parameters of M_{AP}, the modified M_{AP} cannot pass $EC.Verify(PK_{NCC}, CR_{AP})$. As a result, our scheme successfully prevents unauthorized modifications.

F. Resistance to replay attacks

It is noted that the access request message $M_U = ID_U||PK_U||CR_U||R_U||ID_{NCC}||V_U||ts_U$ contains a timestamp ts_U, which is included when computing T_U by $T_U = h(R_U||ts_U)$. Then, T_U is signed as $V_U = EC.Sign(SK_U, T_U)$. Because of the above steps, the timestamp cannot be modified and replaced. The access response message M_{AP} is also appended by a timestamp ts_{AP} and signed by $V_{AP} = EC.Sign(SK_{AP}, T_{AP})$. The AP will first check if ts_U is within the valid range, and if it expires, the AP rejects the access request. Besides, upon receiving the access response, the user will also check the timestamp ts_{AP}. Thus, any replaying message could be recognized by checking the timestamps and signatures. Therefore, the proposed scheme is able to resist replay attacks.

G. Resistance to man-in-the-middle attacks

A man-in-the-middle attacker tries to trick two parties into a three-party communication. In the roaming authentication phase, the attacker intercepts data packets communicated between the user and the AP, and attempts to modify the key negotiation parameters to crack the session key. During the access request, the key negotiation parameter $R_U = r_u \cdot G$ is hashed to $T_U = h(R_U||ts_U)$ and then signed as $V_U = EC.sign(SK_U, T_U)$. Therefore, the key negotiation parameter cannot be modified and replaced by the attacker. The key negotiation parameter $R_{AP} = r_{AP} \cdot G$ in the access response phase is also protected by signature $V_{AP} = EC.sign(SK_{AP}, T_{AP})$. Since the attacker cannot obtain the private key of the user and the AP, he/she cannot modify the key negotiation parameters and thus cannot perform a man-in-the-middle attack. Therefore, our scheme is secure against the man-in-the-middle attacks.

VII. Performance Analysis

In this section, we analyze the performance of our scheme in terms of authentication delay, revocation overhead and system fault tolerance. In order to test the performance of our scheme and compare it with other schemes, we measure the time to run basic cryptographic algorithms. In addition, we develop a prototype implementation of our scheme. The blockchain is based on Ganache [42] which is a personal blockchain for Ethereum development. The mobile user's and the AP's applications are developed using Javascript(node.js). User and APs interact with blockchain via web3.js 1.0. All experiments are completed with Inter(R) Core(TM) CPU i7-4790 @3.6GHz, 20GB RAM and Windows 7 Professional.

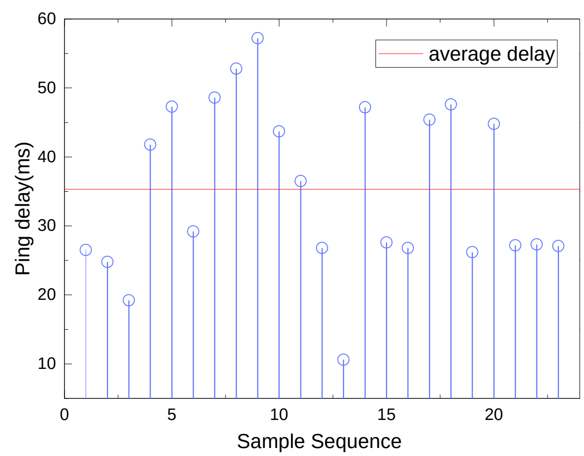

Fig. 5. Ping delay from user to cloud server

A. Authentication Delay

In this part, we evaluate the performance of the proposed scheme, including separate computation time of the main algorithms, communication delay, authentication delay, and the overall performance of the proposed authentication scheme. For cryptography, the exponential, elliptic curve and bilinear mapping operations are based on the PBC 0.5.14 library, and the rest of the algorithms are based on the OpenSSL 1.1.1 library. For communication overhead, as we cannot establish a real-world roaming system, but can only build a prototype system for evaluation, to get a more accurate simulation of the communication overhead in the real world, we crawled 4,967 bitcoin nodes worldwide and measured the ping delay from the user to these nodes, and used the average value as the communication delay in the subsequent experiments. For a more fine-grained result, we first measure the computation overhead of each main algorithm in our local machine, and then evaluate the overall performance in our Ganache-based prototype.

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The authentication delay is defined as the total time cost during the whole authentication process, including the time cost of computations and communication delay. TABLE II lists the computation time of related cryptographic operations. The communication delay includes the delay from user to FNCC T_{U-FNCC}, the delay from AP to FNCC $T_{AP-FNCC}$, and the delay from FNCC to HNCC T_{H-FNCC}. In this scheme, the delay from user or AP to the blockchain nodes is also involved, identified by T_{U-BLN} and T_{AP-BLN}. We assume that NCC is deployed in a cloud server. We measure the delay from the user to the cloud server to simulate T_{U-FNCC}. We select 23 nodes from major cloud server vendors in China for measurement, and measure the ping delay from user to these nodes. Each node is measured 10 times and we take the average delay as the result. As shown in Fig. 5, The ping delays are between 10ms and 60ms, and the average delay is 35.313ms. On this basis, it is reasonable to set $T_{U-FNCC} = T_{AP-FNCC} = 17.656$ms and $T_{H-FNCC} = 17.656$ms. As for the delay from user to blockchain nodes, we refer to the distribution of Bitcoin nodes. We crawled 4,967 bitcoin node IPs worldwide and measured the ping delay from the user to these nodes. The result is shown in Fig. 6. Experimental results show that the average ping delay is 226.405ms. Therefore, we set $T_{U-BLN} = T_{AP-BLN} = 113.202ms$.

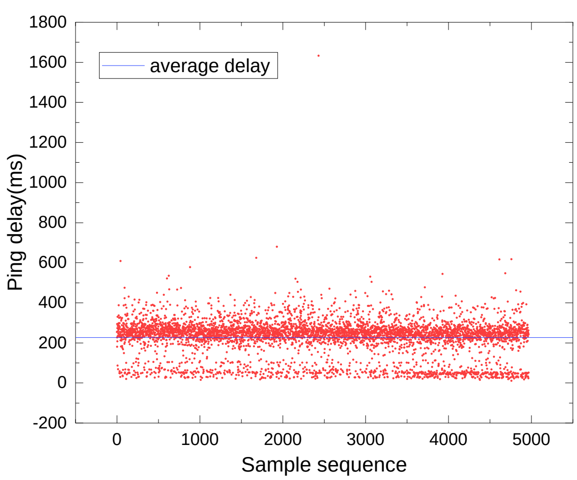

Fig. 6. Ping delay from user to Bitcoin node

We first analyze the computation delay of our scheme. In the process of user authentication, the protocol also checks whether the user is revoked at the same time. Therefore, the computation delay includes two parts, the first part is the time-consuming of ordinary cryptographic operations in the roaming authentication process, and the second part is the time-consuming of checking whether the user is revoked. TABLE III shows the comparison of typical schemes [8, 26, 27, 32, 43] in computation delay. As can be seen from TABLE III, in terms of both the ordinary computation delay and the revocation computation delay, our scheme is the lowest. Our scheme only requires 4 elliptic curve point multiplication operations, 2 ECDSA signature operations and 4 ECDSA signature verification operations during the authentication process. The delay for revocation computation includes two parts. The first part is to check whether the user is in the Bloom Filter that stores revocation information. After subsequent analysis, this part only needs to perform 10 hash operations, and the delay of the hash operation is negligible. Therefore, this delay is almost 0. The second part is the delay of HNCC querying the revocation list when a false detection occurs. After analysis, we concludes that the false positive rate is $\alpha = 1.58 \times 10^{-6}$, and more rigorous analysis and proof process will be explained in the following subsections. The false positive rate α is very low, and thus the second part delay is almost zero. It can also be seen from TABLE III that the common computation delay of the related schemes is low, within 100ms, and the revocation computation delay is greatly different. We refer to [27] by assuming that the annual user revocation scale is 1,000,000, and compare the revocation delay on this basis. Considering that the scale of user revocation is gradually increasing, the actual computation delay will be lower than when the user scale is at a peak of 1,000,000. When the number of revoked users is 1,000,000, the revocation computation delay of [8, 26, 27] is measured in minutes, which is beyond the user's tolerance. The reason is that in order to improve anonymity, these schemes perform complex cryptographic operations such as bilinear mapping for each entry of the revocation list during the revocation check. However, the revocation computation relay of the remaining schemes is in the order of milliseconds.

Then we analyze the communication delay of our scheme. The communication delay includes two parts, which are the communication time in the ordinary authentication process and the communication time in obtaining the revocation list. In the compared related schemes, the user's revocation list is pushed by the HNCC to the FNCC, and thus the FNCC can verify offline whether a user is revoked. Therefore, this part of other schemes takes zero time. The Bloom Filter revocation mechanism used in this solution has a natural false positive rate. In the case of a misjudgment, the user's revocation information needs to be obtained from the HNCC, and this part of the communication takes time. TABLE IV shows the communication delay comparison of related schemes. Due to the interaction with the blockchain and using the Bitcoin system as a reference example, our communication delay is greater than the rest. The communication delay of our scheme is around 450ms, but the remaining schemes can guarantee the communication delay within 100ms. In practice, users and APs may choose the nearest blockchain node for authentication, and hence the actual communication delayof our scheme may be lower.

Finally, we analyze the authentication delay of our scheme. It can be seen from TABLE IV that the total authentication delay of our scheme is about 460ms, which is higher than that of of the schemes of [32, 43], but far lower than the delay of the schemes of [8, 26, 27]. Overall, It is within the user's acceptable range.

Further, we build a prototype system of our scheme through the private chain Ganach to analyze the performance. We divide the authentication process into user request, AP contract call, AP response and user contract call. We measure the detailed processing time from four steps as shown in

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TABLE II
CRYPTOGRAPHY OPERATION COST

Operation	Exponentiation			Multiplication		ECDSA		Pairing
Domain	G	G_T	Bignum	G	G_T	$Sign$	$Verify$	
Symbol	T_{G_exp}	$T_{G_T\_exp}$	T_{exp}	T_{G_mul}	$T_{G_T\_mul}$	$T_{E.sign}$	$T_{E.verify}$	$Tpair$
Delay(ms)	1.086	0.131	0.328	1.095	0.112	0.248	0.502	0.679

TABLE III
COMPUTATION COST COMPARISON

	Computation delay(ms)	Revocation Computation delay
[26]	$29T_{G\_exp} + 11T_{G_T\_exp} + 7Tpair + T_{E.sign} + T_{E.verify} = 38.438$	$\lvert R_U\rvert \cdot T_{pair} = 11.317\text{min}$
[27]	$75T_{G\_exp} + 20T_{G_T\_exp} + 14Tpair + T_{E.sign} + T_{E.verify} = 94.326$	$0.4\lvert R_U\rvert \cdot T_{G\_exp} = 7.240\text{min}$
[8]	$16T_{G\_exp} + 7T_{G_T\_exp} + 7Tpair + T_{E.sign} + T_{E.verify} = 23.796$	$\lvert R_U\rvert \cdot 2T_{pair} = 22.633\text{min}$
[43]	$6T_{G_T\_exp} + 2Tpair + 4T_{G\_mul} + T_{E.sign} + T_{E.verify} = 13.004$	$\lvert R_U\rvert \cdot T_{map} > 0$
[32]	$T_{G_T\_exp} + Tpair + 9T_{G\_mul} + T_{E.sign} + T_{E.verify} = 12.37$	$\lvert R_U\rvert \cdot T_{map} > 0$
Ours	$4T_{G\_mul} + 2T_{E.sign} + 4T_{E.verify} = 6.884$	$\alpha\lvert R_U\rvert \cdot T_{map} \approx 0$

TABLE IV
AUTHENTICATION DELAY COMPARISON

	Total computation delay	Communication delay	Authentication delay
[26]	11.318min	$3 \cdot T_{U\text{-}FNCC} = 52.968$ms	11.319min
[27]	7.242min	$3 \cdot T_{U\text{-}FNCC} = 52.968$ms	7.243min
[8]	22.633min	$3 \cdot T_{U\text{-}FNCC} = 52.968$ms	22.634min
[43]	15.161ms	$3 \cdot T_{U\text{-}FNCC} = 52.968$ms	68.129ms
[32]	14.531ms	$3 \cdot T_{U\text{-}FNCC} = 52.968$ms	67.499ms
Ours	6.884ms	$4 \cdot T_{AP\text{-}BLN} + \alpha T_{AP\text{-}HNCC} \approx 452.808$	459.692ms

TABLE V. During the user request phase, the user needs to perform a dot multiplication, a hash and a signature operation and the total time is 1.242 ms. After receiving the user's access request, the AP performs a hash operation and then calls the MC from the blockchain. It costs 68.566 ms. It is worth noting that the MC will run locally in one of the blockchain nodes in a CALL manner, and no transaction will result in a consensus across the blockchain network. Therefore, it avoids the time of block consensus, such as 10 minutes for Bitcoin and 10 seconds for Ethereum. The AP response phase is similar to the user request phase, except that there is an additional dot multiplication operation. It costs 1.618 ms. Similarly, the user contract call phase has only one more point multiplication operation than the AP contract call phase. It costs 68.942 ms. The total time cost of computations is 140.368 ms, which is still within the user's acceptable range. However, the result is two orders of magnitude higher than the result shown in TABLE III. The main reason is that the contract calling process needs to perform some operations including cryptographic algorithms in the virtual environment of Ganach, which is exactly the bottleneck. Considering that the actual performance of the blockchain virtual machine is high, and with the development of software technology, this part of the delay will be effectively reduced.

TABLE V
PROCESSING TIME OF EVERY STEP IN AUTHENTICATION

	User	AP	User	AP
step detail	step 1 User request	step 2 AP call	step 3 AP response	step 4 User call
time	1.242ms	68.566ms	1.618ms	68.942ms

B. Revocation Overhead

During the roaming authentication stage, the AC calls the RC to check whether the user is revoked. The RC then queries the Bloom Filter to feed back the results. Due to the limitation of smart contract capacity, our solution increases the capacity of Bloom Filter by sub-contract storage. Ethereum limits the size of the smart contract to 24KB, we therefore set the size of the RC Bloom Filter to m=20KB. When m is fixed, we analyze the characteristics of the Bloom Filter to find a better setting, i.e., the false positive rate under different numbers of hashes (from 1 to 50) and revocation records (from 1 to 15000). We further analyze the revocation space overhead and compare our scheme with schemes based on revocation list when the number of revoked entities differs from 1 to $100,000$. Note that the revocation runtime overhead has been provided in Section VII-A.

Fig. 7 shows the relationship between the revocation false positive rate and the revocation entity size, n, and Bloom Filter hash times, k. It can be seen from Fig. 7 that when n is increased to about 5,000, choosing an appropriate k can keep the false positive rate at a low value. According to Eq. 1, when the size of the Bloom Filter is fixed, the larger the number of revoked entities, the higher the false positive rate. When n

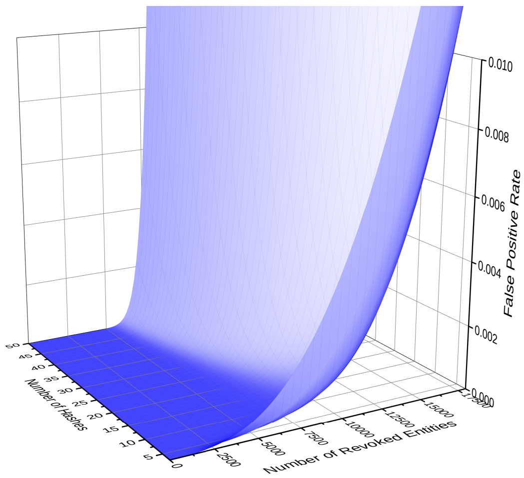

Fig. 7. Change of false positive rate

exceeds 5,000, the false positive rate increases significantly. Therefore, it is reasonable to set the maximum number of revocation entities stored in an RC Bloom Filter to 5,000. In practice, the scale of revocation entity gradually increases. We have to choose the appropriate k to ensure a low false positive rate. From Fig. 7, we can see that when k=10, the gradually increasing of n can still maintain a low false positive rate. Then, we select different n and analyze k. As shown in Fig. 8, when n is less than 5,000, the false positive rate takes the lowest value at k=10, and the lowest value is not much different. When n is higher than 5,000, the false positive rate can still reach the lowest value in different k values, but it increases significantly compared to when n <5,000. A smaller value of k can improve the efficiency of revoking query. Thus, we set k=10 and n to be less than 5,000. In summary, we set m=20KB, k=10, and make the capacity of an RC Bloom Filter 5,000. Finally, through Eq. 1, the maximum false positive rate is $\alpha = 1.58 \times 10^{-6}$.

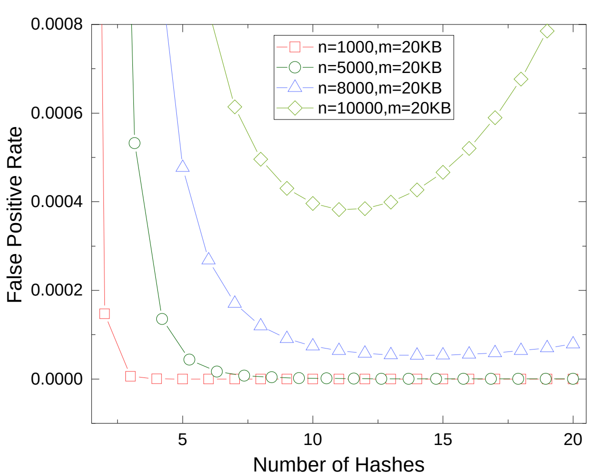

Fig. 8. Relationship between false positive rate and number of hashes

On the basis of the above, we further analyze the revocation performance of our scheme. Fig. 9 shows the relationship between the revocation space and the number of revoked entities. The revocation space based on Bloom Filter increases slowly with the number of revoked entities. For every 5,000 revoked users, our revocation space increases by 20KB. If based on the revocation list mechanism, referring to the paper [27], we set the entity ID size to 16. Compared with our scheme, the revocation space of these schemes is more drastic as the number of revoked entities increases. The required space is about 4 times of that of ours. Considering that the storage space of the blockchain is more valuable, our scheme can better improve the storage performance.

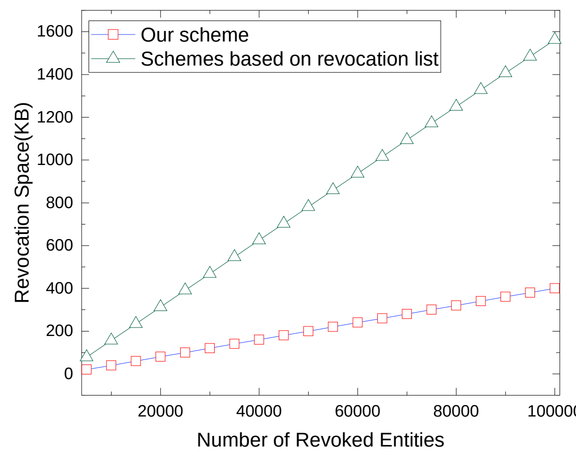

Fig. 9. Revocation space comparison

C. System Fault Tolerance

Our solution enhances the system's fault tolerance by introducing distributed blockchain nodes. In order to compare the fault tolerance rate of our scheme with other schemes, we assume that the main nodes of the system have the same failure probability, set to x, and assume there are 100 blockchain nodes. We compare the probability of roaming system failure of our proposed scheme with the three-party and two-party schemes under different node failure probabilities.

Fig. 10 shows how the probability of system failure changes as the probability of node failure increases. The main node of the two-party roaming scheme is the foreign server. If the foreign server fails, the roaming system will collapse. Therefore, the system failure probability is x, so the system failure probability increases linearly with the node failure probability. In addition to foreign server, the three-party roaming scheme also has the participation of the home server. Any node failure will cause the system to crash, so the probability of system failure is higher than the two-party scheme. The probability of system failure is $1-(1-x)^2 = 2x-x^2$. Our scheme involves blockchain nodes participating in authentication, and any blockchain node can authenticate the users or APs. The roaming system will only collapse if all blockchain nodes fail. When the scale of blockchain nodes reaches a certain level, our system will hardly fail. At a scale of 100 blockchain nodes, the system failure probability is x^{100}. As shown in Fig. 10, when the node failure probability is less than 1, our system failure probability is almost 0. Only when the node failure probability is close to 1, the system failure probability is close to 1, which is almost impossible to happen in practice. Therefore, our system has very high stability.

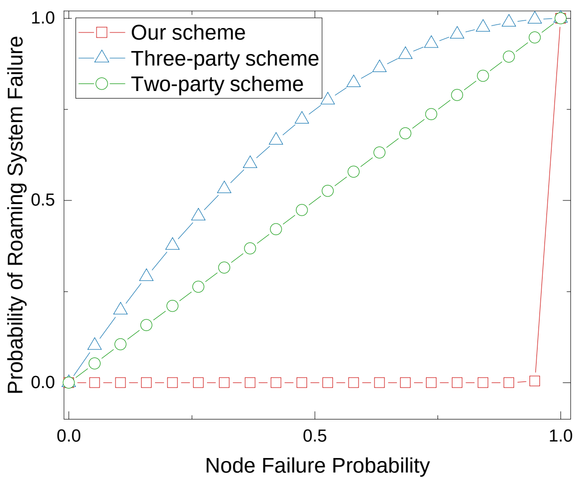

Fig. 10. Comparison of system fault tolerance

In addition, we analyze the fault tolerance of our roaming system under different node failure probabilities (NFP). We assume NFP=x and the number of nodes is k, then the roaming system crash probability is x^k. As shown in Fig. 11, as the NFP probability increases, the system quickly reaches high stability (the failure probability is close to 0). But no matter how big the NFP is, even as high as 90%, when the number of blockchain nodes increases to about 50, it will always stabilize. Therefore, our scheme has strong stability and fault tolerance.

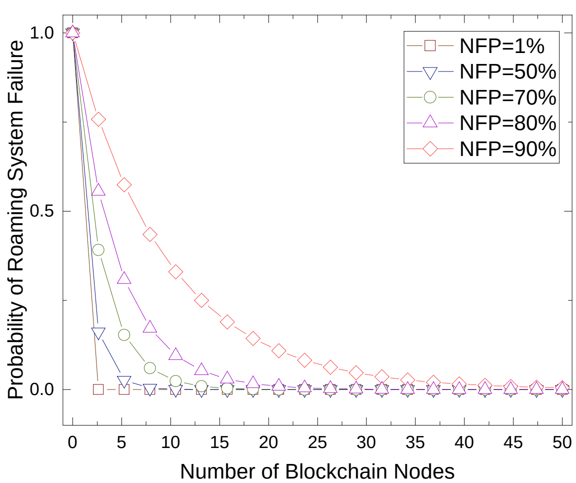

Fig. 11. System stability

VIII. Conclusion

In this work, by leveraging blockchain and smart contracts, we designed a distributed and secure roaming mechanism for mobile vehicle networks, which can be directly applied to other mobile network scenarios. In our scheme, we utilized smart contracts to implement roaming protocols including user/AP registration, authentication, and revocation, enabling secure and automatic roaming authentication. Considering blockchain's limitations on storage and computation, we introduced the Bloom filter to achieve more efficient revocation process. Moreover, we designed an unforgeable and undeniable billing scheme based on hash chain, preventing operators from cheating for higher billing revenues or users from payment evasion. Our security and performance analysis shows that the proposed scheme can provide the required security features while incurring an acceptable authentication delay.

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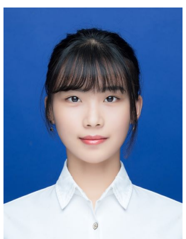

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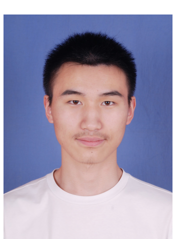

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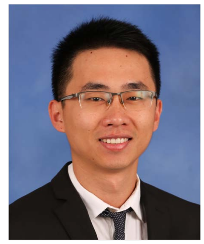

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