A Novel Variable K-Pseudonym Scheme Applied to 5G Anonymous Access Authentication

Dong Ma¹, Xixiang Lyu¹, and Renpeng Zou¹[0000−0002−2759−1328]

Xidian University, Xifeng Road, Xi’an City, Shaanxi Province, China
xxlv@mail.xidian.edu.cn
rpzou@stu.xidian.edu.cn

Abstract. Anonymous access authentication schemes provide users with massive application services while protecting the privacy of users’ identity. The identity protection schemes in 3G and 4G are not suitable for 5G anonymous access authentication due to complex computation and pseudonym asynchrony. In this paper, we consider mobile devices with limited resources in the 5G network and propose an anonymous access authentication scheme without the Public Key Infrastructure. The anonymous access authentication scheme provides users with variable shard pseudonyms to protect users’ identities asynchronously. With the variable shared pseudonym, our scheme can ensure user anonymity and resist the mark attack, a novel attack aimed at the basic k-pseudonym scheme. Finally, we analyze the scheme with BAN logic analysis and verify the user anonymity.

Keywords: 5G · Anonymous Access Authentication · Variable k-pseudonym · Privacy

1 Introduction

With the development of mobile network technology, mobile networks [7] have become an indispensable part of people’s life. According to [6], there were 3.9 billion smartphones globally in 2016, which is estimated to rise to 6.8 billion by 2022. With smartphones, people can communicate with others easily and search for information quickly. However, due to the openness of wireless networks, users’ identities cannot be protected effectively [27,3]. Once a user’s International Mobile Subscriber Identification Number (IMSI) is intercepted, the adversary can track the user automatically and launch the man-in-the-middle attack (MITM) to steal the user’s private information. Moreover, because of the inherent mobility, users need to be authenticated frequently but without safe identity privacy protection.

As a result of lacking identity privacy protection, a user can be tracked by some organizations without the user’s authorization. What’s worse, the organizations may share the private information with other malicious parties which violate the user’s privacy. For example, a user authorizes a semi-trusted mobility
management entity (MME) to access his location information which is associated with his/her IMSI. MME may share the information to third parties such as the local tourist office and the advertising agencies, which will send their advertisements to nearby users without their authorizations.

For user identity privacy, there are some schemes in existing literature. 1) GSM system [18] uses Temporary Mobile Subscriber Identity (TMSI), instead of IMSI. Because a user need to update TMSI frequently at different Visitor Location Register (VLR) with his IMSI, the adversary can intercept and capture the user’s identity. 2) In 4G Long Term Evolution (LTE) Network [19,11], Globally Unique Temporary Identity (GUTI) is adopted as the temporary identity of the user equipment (UE) [13]. But the UE has to send IMSI to get or retrieve the temporary GUTI in some situations, so the UE’s identity is still at risk of being revealed. 3) Public-key based schemes are not suitable for the application scenario of 5G access authentication, because they need the support of Public Key Infrastructure (PKI) and execute some complex mathematical operations such as exponent operations and bilinear pairing operations [8]. Considering mobile devices are limited with resources, we present a shared key based anonymous access authentication scheme, which not only avoids complicated calculations, but also guarantees user anonymity.

Constrained by the existed structure of 5G access authentication and the limited capabilities of users, we propose a shared key based anonymous authentication scheme. Our contributions are as follows.

- We propose a 5G anonymous access authentication scheme based on shared keys. By the shared keys, UE and HSS can distinguish the valid shared pseudonym from the variable k-pseudonym sets, while the using pseudonym is still a secret for others, including MME.
- We present a robust anonymous access authentication scheme. Owing to the variable k-pseudonym sets, the UE can choose the suitable size of the k-pseudonym sets according to the actual network environment.
- We design the shared pseudonym to resist the intersection attack and the mark attack. The intersection attack and the mark attack will be described in Sect. 5. By the shared pseudonym, the UE utilizes a dynamic temporary identity, while the adversary cannot link the variable k-pseudonym sets with the UE’s identity, guaranteeing the robustness of our scheme.
- We analyze the scheme with BAN logic analysis. After the careful derivation process, we conclude that UE and HSS can reach an agreement on the UE’s identity, including the shared pseudonym.

**Organization of the Paper.** Sect. 2 reviews the related literatures. Sect. 3 provides the relevant background materials. In Sect. 4 we introduce the proposed protocol in detail. In Sect. 5 we analyze the security and logical correctness of our scheme, respectively. At the last section, we highlight some concluding remarks.
2 Related Works

Anonymous access authentication in mobile communication networks has captured attentions of researchers and practitioners recently [10,15,23]. In [1], researchers introduced DHIES (Diffie-Hellman Integrated Encryption Scheme) into authentication, protecting user identity. In [9], the authors introduced PKI into the EPS-AKA authentication process, which is adopted in 4G LTE Network. This change ensures user identity never being released as plaintext in untrusted networks.

Based on KP-ABE [12], authors in [2] suggest an implementation in which there is one global entity namely AuS (Authentication Server) for all operators. AuS has to generate the public key and a private key for each operator. In [15], considering that public-key based solutions have a higher cost both in terms of communication and computation, Khan et al. proposed a modified solution by using the identity based encryption (IBE). Since the public parameters have only local significance, several public keys need to be securely provisioned to the UE, increasing user burden.

In [21], Norrman et al. presented a new scheme by establishing a series of pseudonyms between UE and HSS. The solution can reduce impact on the bandwidth compared to public-key solutions. But when lost or asynchronous pseudonyms happen, the public-key technologies have also been considered as a potential approach to solving the problem.

To avoid the complex public-key calculations, Li et al. proposed an anonymous authentication scheme based on a shared key in [20]. Besides, the authors presented the enhanced Dolev-Yao model and introduced the intersection attack. By the static k-pseudonym set, they fixed the intersection attack basically. Inspired by this scheme, we try to design the shared pseudonym to construct variable k-pseudonym sets, resisting the intersection attack.

3 Background

In this section, we introduce some preliminaries including the basic k-pseudonym scheme and ZUC algorithms. The symbols used in the paper are shown in Table 1.

3.1 K-pseudonym Scheme

In the k-pseudonym scheme, a user sends the k-pseudonym set including his identity and the message encrypted by the shared key, a key obtained from server securely. The server traversals the shared keys according to the k identities in the identity set one by one and verify the authentication information respectively by the corresponding keys. Once the authentication information is verified correctly, the user is authenticated. Fig. 1 shows the authentication process of the k-pseudonym scheme.

1) user → server: a user sends an authentication request to the server.
Table 1: Notation Summary

| Symbol   | Description                                                                 |
|----------|-----------------------------------------------------------------------------|
| UE       | User Equipment                                                             |
| HSS      | Home Subscription Server                                                    |
| MME      | Mobility Management Entity                                                  |
| Key      | the shared key between a UE and the HSS                                     |
| IMSI     | International Mobile Subscriber Identification Number                        |
| H()      | a collision resistant hash function                                          |
| HMAC     | a collision resistant hash function with a cipher key                        |
| HMAC40   | a collision resistant hash function with a cipher key, select the high 40 bits of the output |
| $f_i()$  | the subfunctions of Milenage algorithm which is used in the authentication of 5G network |
| $P_0$    | the anchor shared pseudonym                                                 |
| $P_i$    | the shared pseudonym used in the i-th authentication                        |
| $\{P_i\}$ | a k-pseudonym set including $P_i$                                           |
| $SQN_{IMSI}$ | the SQN of IMSI                                                              |
| $SQN_0$  | the SQN of $P_0$                                                            |
| $count_i$| count the number of ZUC has been run in the i-th authentication             |

2) server → user: upon receiving the authentication request, the server generates a random number $N_1$ and sends it to the user as a challenge.

3) user → server: on receiving the random number $N_1$, the user generates a random number $N_2$, and calculates $M_1$ by Eq. (1).

$$M_1 = HMAC(N_1||N_2||C||Key|| (k − pseudonym set))$$  \hfill (1)

Then the user sends the k-pseudonym set including his real identity and other k-1 assistant pseudonyms, the random number $N_2$, and $M_1$ to the authentication server.

4) server → user: receiving the message from the user, the server calculates the corresponding $M'_1$ in Eq. (2), where each ID is an identity in the k-pseudonym set, $Key_{ID}$ is the shared key related with this identity. Finally, the server verifies whether $M'_1$ is equal to $M_1$.

$$M'_1 = HMAC(N_1||N_2||each ID||Key_{ID}|| (k − pseudonym set))$$  \hfill (2)

If $M'_1$ is equal to $M_1$, the server can determine that the corresponding ID is the user’s real identity and complete the authentication process. After that, the server calculates $M_2$ in Eq. (3).

$$M_2 = HMAC(N_2||Key)$$  \hfill (3)

In the end, the user calculates $M'_2 = HMAC(N_2||Key)$ according to the random number $N_2$ and the shared key. And then he verifies whether $M'_2$ is equal to $M_2$ received from the authentication server. If the verification is successful, the user and the server complete the mutual authentication and generate the session key $SK = PRNG(Key \oplus N_1 \oplus N_2)$, where $\oplus$ represents a xor operation.
3.2 ZUC Algorithm

As a stream cipher algorithm, the ZUC algorithm has been adopted as the kernel of the third set of the LTE cryptographic algorithms [26]. It consists of three layers and initializes the internal states by a 128-bit cipher key $K$ and a 128-bit initialization vector $IV$. In this paper, we use ZUC to generate the variable shared pseudonyms. Here we briefly introduce the process of ZUC.

- Linear feedback shift register (LFSR) is constructed from 16 register units, each holding 31 bits. And the feedback is defined by a primitive polynomial over the finite field $GF(2^{31} - 1)$.
- Bit reorganization (BR) extracts 128 bits from the states of the LFSR and forms four 32-bit words, where the first three words will be used by the nonlinear function $F$ in the bottom layer, and the last word will be involved in producing the keystream. It forms 4 of 32-bit words $X_0$, $X_1$, $X_2$, $X_3$, from the following 8 LFSR registers $s_0$, $s_2$, $s_5$, $s_7$, $s_9$, $s_{11}$, $s_{14}$, $s_{15}$.
- Nonlinear function ($F$) is based on two 32-bit registers $R_1$ and $R_2$. The operation of $F$ involves input from BR and uses two S-boxes $S_0$ and $S_1$. The mixing operations are the exclusive OR, the cyclic shift and the addition modulo $2^{32}$ (which takes the symbol $\oplus$ as the modulo $2^{32}$ addition). By $W=(X_0 \oplus R_1) \oplus R_2$, we get the keystream word $Z$ as $Z = W \oplus X_3$.

4 The Proposed Scheme

In this section, we introduce the variable k-pseudonym scheme in detail. Firstly, we design the shared pseudonyms with the help of ZUC. Next, we briefly introduce the variable k-pseudonym set construction. Then the detailed process of variable k-pseudonym scheme is described. Finally we adopt the anchor shared pseudonym $P_0$ in the recovery mechanism.
4.1 Shared Pseudonym

In the scheme, we use the predicable property of the pseudo-random sequence. We assume that UE and HSS can initialize ZUC with same shared information: the shared key $Key$ and the sequence number $SQN$. Then they can get the same pseudo-random sequence and generate the shared pseudonym synchronously but independently. Here follows the generation of the shared pseudonym.

1) Generate the initial parameters. ZUC is initialized by a 128-bit cipher key $K$ and a 128-bit initialization vector $IV$. In the scheme, we take the shared key as $K$, and get $IV$ by the Eq. (4).

$$\begin{align*}
\text{Rand} & = H(SQN_{IMSI}) \text{ or } H(SQN_{P_0}) \\
CK_0 & = f_3(\text{Key}, \text{Rand}) \\
IK_0 & = f_4(\text{Key}, \text{Rand}) \\
IV & = CK_{0H} \| IK_{0L}
\end{align*}$$

where $f_3$, $f_4$ is the subfunctions of Milenage algorithm $[24,17]$, which is used in the authentication of 5G network, $CK_{0H}$ means the high 64 bits of $CK_0$, $IK_{0L}$ means the low 64 bits of $IK_0$.

2) Update the shared pseudonym. As defined by 3GPP, IMSI is composed of three components: Mobile Country Code (MCC), Mobile Network Code (MNC), Mobile Subscriber Identification Number (MSIN). It is not necessary to change MCC and MNC, so we update the shared pseudonym by encrypting the MSIN of IMSI. Another thing we emphasize is that MSIN is 40 bits, so we need expand the 32-bit keystream output from ZUC to 40 bits. Thus we can encrypt the MSIN with the 40-bits expanded-keystream ($K_s$). Here we use XOR as the encrypt algorithm and $MSIN'$ is calculated by Eq. (5).

$$MSIN' = MSIN \oplus K_s$$

UE and HSS get the shared pseudonym $P_i$ by Eq. (6), where MCC and MNC are obtained from IMSI.

$$P_i = MCC \| MNC \| MSIN'$$

When a UE accomplish authentication with the shared pseudonym $P_i$, the UE and the HSS update the shared pseudonym $P_i$ to get the next shared pseudonym $P_{i+1}$. Fig. 2 shows the basic structure of updating the shared pseudonym.

4.2 Variable K-pseudonym Set Construction

For simplicity, it is a rational assumption that a UE can get enough available assistant identities from the HSS. If the UE has connected with the HSS, the HSS sends the updating shared pseudonyms which are used by others to the UE. Considering the situation that the UE is new for the HSS, the UE should generate the k-pseudonym sets by itself. Since the UE can generate the shared pseudonym by ZUC, similarly, he can generate assistant identities.
4.3 Authentication with Variable K-pseudonym Scheme

Here we briefly introduce the anonymous access authentication process with the variable k-pseudonym scheme. Fig. 3 shows the situation when a UE is new for the HSS.

1) UE → MME: when the UE is new for the HSS, the UE generates assistant identities to construct \{IMSI\}. Then the UE sends the k-pseudonym set \{IMSI\}, \(H_0 = HMAC(Key||IMSI)\), the identifier of the HSS \(HSS_ID\) to a MME.

2) MME → HSS: the MME forwards \{IMSI\}, \(H_0\) to the target HSS and replaces \(HSS_ID\) with its own \(SN_ID\).

3) HSS → MME: when receiving the authentication request, the HSS checks the \(SN_ID\) to confirm the MME. Then the HSS traverses those identities included in \{IMSI\} to find the UE’s IMSI by compared \(H'_0 = HMAC(Key_ID||ID)\) with \(H_0\), where ID is the identity in the \{IMSI\} and \(Key_ID\) is the key bounded with the ID. If the HSS cannot find the \(Key_ID\), then the HSS ignores the ID. Once finding an ID that makes \(H'_0 = H_0\) and is in \{IMSI\}, the HSS authenticate the UE. After that, the HSS calculates a authentication vector \(AV\) [4] by Eq. (7), helping the MME accomplish the final authentication. Finally, the HSS sends the \(AV\) to the MME. Here we define the \(SQN\) used in the first access authentication as \(SQN_{IMSI}\), which participates in the update of shared pseudonyms.

\[
AUTH = (SQN \oplus AK)||AMF||MAC
\]

\[
AV = Rand||XRES||K_{ASME}||AUTH
\]
4) MME → UE: upon receiving the authentication response, the MME gets \(\text{Rand}, \text{AUTH}\) and \(K_{ASME}\) from the AV. Then the MME assigns a 3 bits key identification \((KSI_{ASME})\) for \(K_{ASME}\) and sends \(\text{Rand}||\text{AUTH}||KSI_{ASME}\) to the UE.

5) UE → MME: when receives the authentication response, the UE checks \(MAC\) and \(SQN\) in the \(\text{AUTH}\). If they are matched, the UE calculates \(RES\) with \(f_2(\text{Rand}, \text{Key})\), where \(f_2\) is a secure function shared with the HSS. Finally the UE sends \(RES\) to the MME. Because only the UE and the HSS can calculate \(AK\) and get the \(SQN\), so they can initialize ZUC with the \(SQN_{IMSI}\) privately.

6) MME → UE: the MME compares \(RES\) with \(XRES\). If \(RES = XRES\), the MME sends an authentication complete signal to the UE. After the authentication finished, the UE and the MME have an agreement on \(K_{ASME}\), building a secure link between the UE and the MME.

7) UE ↔ HSS: if \(H'_0 \neq H_0\) or \(RES \neq XRES\), the authentication is interrupted. We assume that when the UE tries \(\{\text{IMSI}\}\) again, the UE must use the same k-pseudonym set \(\{\text{IMSI}\}\), which means the UE has to store the whole \(\{\text{IMSI}\}\) before the IMSI is authenticated. After the UE’s IMSI is authenticated, the UE and the HSS get the shared pseudonym \(P_i\) \((i \geq 1)\) synchronously. In the next access authentications, the UE can use the shared pseudonym \(P_i\) as his temporary identity, Fig. 4 briefly introduces the usage of the shared pseudonyms.
4.4 Recovery Mechanism

When the UE tries to connect with the target HSS, the authentication failure comes from two situations: 1) there are something wrong with the UE, such as miscalculation or signal distortion. The faults lead to the shared pseudonym $P_i$ is not match with the shared pseudonym $P'_i$ generated by the HSS. 2) the HSS loses $P'_i$, because of an unexpected cleanup of memory. In order to continue the UE’s access authentication process, we add the anchor shared pseudonym $P_0$, generated synchronously both at the UE and the HSS. The first we emphasize is that the values of $SQN_{IMSI}(SQN_{P_0})$ is protected by the USIM’s physical security features, which means the UE and the HSS can regard $SQN_{IMSI}(SQN_{P_0})$ as stable shared information [14]. According to this fact, we define the $P_0$ by Eq. (8).

$$P_0 = MCC||MNC||(MSIN \oplus HMAC_{40}(Key||SQN_{IMSI}))$$ (8)

Besides, the time delay between two continuous access authentication is longer than the time of updating the shared pseudonym, because the UE only needs to be authenticated when he is back online after rebooting device or turning off flight mode. So it is not necessary to consider the time delay caused by the generation of shared pseudonym between the UE and the HSS. In view of this situation, we assume access authentication failure just comes from situation (1) and (2).
After the UE’s IMSI is authenticated, the UE and the HSS calculate $P_0$ with $SQN_{IMSI}$. In other re-authentication situations, the UE and the HSS calculate $P_0$ with $SQN_{P_0}$. Once the authentication failure coming, we continue the access authentication by returning to the anchor shared pseudonym $P_0$. Moreover, $SQN_{P_0}$ ensures $P_0$ is variable at different authentication rounds, which means we can use a new $\{P_0\}$ to restart the access authentication, no need to store the old $\{P_0\}$.

5 SECURITY ANALYSIS

In this section, we first analyze the intersection attack and the mark attack. Then we verify the logical correctness of the scheme with BAN. Finally, we discuss user anonymity. After the complete security analysis, we conclude that the proposed scheme can resist the intersection attack and the mark attack, while guaranteeing good user anonymity.

5.1 The Intersection Attack

As considered in [20], the intersection attack shows a situation that an adversary can observe the k-pseudonym sets generated by the target UE, and associate those relevant k-pseudonym sets with the UE’s IMSI. If the UE changes the anonymous sets $\{IMSI\}$ at different time, the adversary can reduce the range of the IMSI or even confirm it. As is shown in Fig. 5a, the UE uses a k-pseudonym set $\{IMSI, B, C, D\}$ at time $T_1$, where IMSI represents the UE’s real identity.

![Diagram](image)

Fig. 5: 5a shows the the intersection attack; 5b avoid the intersection attack with anonymous set

set $\{IMSI, B, C, D\}$ at time $T_1$, where IMSI represents the UE’s real identity.
and others for the assistant identities in the k-pseudonym set. Next, if the UE uses a k-pseudonym set \{IMSI, B, E, F\} at time \(T_2\), the adversary links the two k-pseudonym sets to the UE and finds the common elements of the two sets. After analysis, the adversary can conclude that the real identity is included in \{IMSI, B\}. What’s more, if the UE uses a k-pseudonym set \{IMSI, D, G, H\} at time \(T_3\), the adversary can even get the UE’s IMSI with sufficient information. Under this assumption, if the adversary can get more k-pseudonym sets from the target UE, he will have higher possibility to get the UE’s IMSI.

In order to resist the intersection attack, Li et al. presented a static construction of the k-pseudonym sets in [20]. By this way, the UE employs the same k-pseudonym set during continuous anonymous access authentications. Although this method works on the enhanced Dolev-Yao model basically, there still has some questions worthy of consideration. The most important question is the robustness of the scheme. It is known that the Quality of Service (QoS) of UE is inversely proportional to the size of pseudonym set, because the larger set results more latency which downgrades QoS. If we select a large set for an unsafe environment, it will restrict the QoS in some relatively safe environments. But if we use a small set for an relative safe environment, it cannot guarantee the UE anonymity in a critical environment. So we conclude that the static construction of the k-pseudonym sets restricts the robustness of the scheme.

In the proposed scheme, we resist the intersection attack by the variable k-pseudonym sets. Taking into account the application scenarios of 5G anonymous access authentication, we adopt ZUC to generate the shared pseudonyms during next authentications. As is shown in Figure 5b, the UE uses a k-pseudonym set \{IMSI, B, C, D\} at time \(T_1\), and uses a k-pseudonym set \(\{P_1, B, E, F\}\) at time \(T_2\), where \(P_1\) represents the shared pseudonym of the UE. The adversary associates the two k-pseudonym sets, but he cannot get effective information about the UE’s IMSI, because the shared pseudonym changes in next authentications. By the shared pseudonym, the UE can choose the suitable size of k-pseudonym set and construct the variable k-pseudonym sets, improving the robustness of our scheme.

5.2 The Mark Attack

After the further study on the basic k-pseudonym scheme, we present a novel mark attack. In [20] to reduce user burden, the authors suggest that the HSS generates assistant identities and sends them to the UE. Moreover, in the enhanced Dolev-Yao model, the adversary can participate in the protocol as a legitimate user, which means he can mark his identity and distinguish it from a k-pseudonym set. Under this attack condition, the HSS cannot get rid of the marked assistant identities, while the UE also cannot discriminate between the normal assistant identities and the marked assistant identities. Once the UE constructs a k-pseudonym set with marked assistant identities, the adversary has a probability greater than \(\frac{1}{k}\) to get the IMSI. Here we assume that the adversary can mark a great deal of assistant identities, but not all assistant identities. For example, the HSS sends 100 assistant identities to the UE, and 20 of identities
are marked by the adversary, including B and C. As shown in Fig. 6a, the UE uses a k-pseudonym set \{IMSI, B, C, D\} at time \(T_1\) and B, C is marked, the adversary concludes that UE’s identity is in \{ID, D\}, a probability greater than \(\frac{1}{4}\). What’s worse, when B, C and D are all marked, the attacker can confirm the ID directly. The adversary marks more assistant identities, he has more possibility to get the UE’s identity.

In our proposal, the variable shared pseudonym is adopted to resist the mark attack. As illustrated in Figure 6b, the UE constructs a k-pseudonym set \{IMSI, B, C, D\} at time \(T_1\) and when B, C are marked, the adversary can get \{IMSI, D\}. And the UE uses a k-pseudonym set \{P_1, B, E, F\} at time \(T_2\), only B is marked. Then the attacker only conclude that UE’s identity is in \{P_1, E, F\}. In the best case, when the UE uses a k-pseudonym set \{P_2, D, G, H\} at time \(T_3\), without marked assistant identities, the adversary even cannot get the \{P_2\}. At \(T_1\), although our scheme has the same security as basic k-pseudonym scheme, \{IMSI\} only appears once in our system. In the subsequent authentications, \{P_i\} can use different assistant identities. After the analysis above, the UE’s IMSI is hidden by the variable shared pseudonym, so our scheme can resist the mark attack.

### 5.3 BAN Logic Analysis

BAN logical notation
BAN logical notation used in the paper as follows:
1) P, Q: the communication subject;
2) X, Y: the statement or message;
3) K: the cipher key;
4) P |≡ X: P believes X;
5) P ⊲ X: P sees X;
6) P |∼ X: P said X;
7) P ⇒ X: P controls X;
8) #(X): X is fresh;
9) P \xleftarrow{K} Q: K is the key shared by P and Q;
10) [X]_K: the ciphertext of X encrypted by the key K.

**BAN logical postulates**

1) Message-meaning rule:

\[
P |≡ Q \xleftarrow{K} P, P \bowtie [X]_K
\]

\[P |≡ Q |∼ X\] (9)

2) Nonce-verification rule:

\[
P |≡ #(X), P |≡ Q |∼ X
\]

\[P |≡ Q |≡ X\] (10)

3) Freshness rule:

\[
P |≡ #(X)
\]

\[P |≡ #(X,Y)\] (11)

4) Belief rule:

\[
P |≡ Q |≡ (X,Y)
\]

\[P |≡ Q |≡ X\] (12)

5) Session key rule:

\[
P |≡ #K, P |≡ Q |≡ X
\]

\[P |≡ P \xleftarrow{K} Q\] (13)

where X here is a necessary element of K.

6) Jurisdiction rule:

\[
P |≡ Q |⇒ X, P |≡ Q |≡ X
\]

\[P |≡ X\] (14)
Protocol Analysis

First, the protocol can be idealized as follows:

Premise P1: HSS $\equiv$ HSS $\stackrel{K_{ey}}{\leftrightarrow}$ UE
Premise P2: UE $\equiv$ HSS $\leftarrow\rightarrow$ UE
Premise P3: HSS $\equiv$ UE $\Rightarrow$ IMSI
Premise P4: HSS $\equiv$ UE $\Rightarrow$ $P_i (i \geq 1)$
Premise P5: HSS $\equiv$ SQN$_{IMSI}$
Premise P6: HSS $\equiv$ SQN$_{P_0}$
Premise P7: UE $\equiv$ # SQN$_{IMSI}$
Premise P8: UE $\equiv$ # SQN$_{P_0}$
Premise P9: UE $\equiv$ HSS $\Rightarrow$ SQN$_{IMSI}$
Premise P10: UE $\equiv$ HSS $\Rightarrow$ SQN$_{P_0}$

The protocol flows of our scheme:

1) UE $\rightarrow$ HSS: {IMSI}, UE $\stackrel{K_{ey}}{\leftrightarrow}$ HSS, [IMSI]$_{K_{ey}}$;
2) HSS $\rightarrow$ UE: SQN$_{IMSI}$ $\oplus$ AK;
3) UE $\rightarrow$ HSS: RES;
4) (the next authentication) UE $\rightarrow$ HSS: {$P_i$}, UE $\stackrel{K_{ey}}{\leftrightarrow}$ HSS, [$P_i$]$_{K_{ey}}$;

Next, our security goals are:

• UE $\equiv$ SQN$_{IMSI}$
• HSS $\equiv$ $P_i$
• UE $\equiv$ UE $\stackrel{SQN_{IMSI}}{\leftrightarrow}$ HSS
• HSS $\equiv$ UE $\stackrel{SQN_{IMSI}}{\leftrightarrow}$ HSS

Then, analyse our scheme:

1) Since the message-meaning rule in Eq. (9), we get:

$$HSS \equiv UE \stackrel{K_{ey}}{\leftrightarrow} HSS, HSS \ll [IMSI]_{K_{ey}}$$

$$HSS \equiv UE \ll IMSI$$

2) After the HSS authenticates the UE’s IMSI, the HSS sends an AV including SQN$_{IMSI}$ $\oplus$ AK, where AK can be calculated by Eq. (16).

$$AK = f_5(Rand, Key)$$

Although Rand is transmitted as plaintext, Key is a private part, which means only the UE and the HSS can share the SQN$_{IMSI}$. Here we regard SQN$_{IMSI}$ is encrypted by the Key, and according the message-meaning rule in Eq. (9), the nonce-verification rule in Eq. (10), the belief rule in Eq. (12) and the jurisdiction rule in Eq. (14), we get:

$$UE \equiv HSS \stackrel{K_{ey}}{\leftrightarrow} UE, UE \ll [SQN_{IMSI}]_{K_{ey}}$$

$$UE \equiv HSS \ll SQN_{IMSI}$$

$$UE \equiv #SQN_{IMSI}, UE \equiv HSS \ll SQN_{IMSI}$$

$$UE \equiv HSS \Rightarrow SQN_{IMSI}, UE \equiv HSS \Rightarrow SQN_{IMSI}$$

$$UE \equiv SQN_{IMSI}$$
3) When the HSS gets $RES$ from the UE, where $RES$ is defined by Eq. (18), the HSS knows that the authentication is completed. According to the message-meaning rule in Eq. (9) and the nonce-verification rule in Eq. (10), we get:

$$RES = f_2(Rand, Key)$$  \hspace{1cm} (18)

$$HSS \equiv UE \leftarrow^{Key} HSS, HSS \triangleleft \big[RAND\big]_{Key}$$

$$HSS \equiv UE \triangleright RAND$$  \hspace{1cm} (19)

In this process, because the UE needs to check $SQN_{IMSI}$ and then sends $RES$ to the HSS, the HSS believes that the UE recognizes $RAND$, only the UE believes $SQN_{IMSI}$ first. Taking into account the dependency relationship between $RAND$ and $SQN_{IMSI}$, we add a dependency relationship rule, shown in Eq. (20):

$$X \rightarrow Z, P \equiv Q \equiv X$$

$$P \equiv Q \equiv Z$$  \hspace{1cm} (20)

where $X \rightarrow Z$ means that $X$ depends on $Z$. From Eq. (19) and Eq. (20), we get:

$$RAND \rightarrow SQN_{IMSI}, HSS \equiv UE \equiv RAND$$

$$HSS \equiv UE \equiv SQN_{IMSI}$$  \hspace{1cm} (21)

4) For next authentications, the UE must has an agreement on the shared pseudonym $P_i$ with the HSS. Here we give the proof of the goal 3 and 4. According to Eq. (17), Eq. (21) and the session key rule in Eq. (13), we get:

$$UE \equiv \#(SQN_{IMSI}), UE \equiv HSS \equiv SQN_{IMSI}$$

$$UE \equiv UE \leftrightarrow^{SQN_{IMSI}} HSS$$

$$HSS \equiv \#(SQN_{IMSI}), HSS \equiv UE \equiv SQN_{IMSI}$$

$$HSS \equiv UE \leftrightarrow^{SQN_{IMSI}} HSS$$  \hspace{1cm} (22)

When the UE uses $P_i$ as his pseudonym, $P_i$ can be regarded as an encrypted IMSI which is protected by $SQN_{IMSI}$. According to Eq. (22), the message-meaning rule in Eq. (9), the nonce-verification rule in Eq. (10) and the jurisdiction rule in Eq. (14), we get:

$$HSS \equiv UE \leftrightarrow^{(Key,SQN_{IMSI})} HSS, HSS \triangleleft \big[IMSI\big]_{(Key,SQN_{IMSI})}$$

$$HSS \equiv UE \triangleright \big[IMSI\big]_{SQN_{IMSI}}$$

$$HSS \equiv \#(IMSI)_{SQN_{IMSI}}, HSS \equiv UE \triangleright \big[IMSI\big]_{SQN_{IMSI}}$$

$$HSS \equiv UE \equiv \big[IMSI\big]_{SQN_{IMSI}}$$

$$HSS \equiv \big[IMSI\big]_{SQN_{IMSI}}$$  \hspace{1cm} (23)

In the normal authentication, we get: $HSS \equiv P_i$ and $UE \equiv SQN_{IMSI}$, so the HSS can authenticate the UE’s IMSI and update $P_i$ with the UE synchronously.
5.4 The Anonymity of the UE’s Identity

In our scheme, the shared pseudonym is adopted to resist the intersection attack and the mark attack. With the variable k-pseudonym sets, the adversary cannot identify the shared pseudonym without the shared key. In the worst case, we use \{IMSI\} in the initial access authentication, which has the same anonymity with the basic k-pseudonym scheme. But we emphasize that the \{IMSI\} only appears once in our system and the adversary cannot recognize the initial authentication easily. In next authentications, the UE utilize the variable shared pseudonym as his temporary identity, so our scheme performs better in general. Even when the unsynchronised pseudonym comes, the UE can continue the access authentication with the $P_0$. Because the $Key$ and the $SQN_{IMSI}$ (or $SQN_{P_0}$) are the stable shared information between the UE and the HSS, it is a reasonable assumption that the UE and the HSS can get $P_0$ synchronously. Next, we analyze brute-force attack. In the scheme, we initialize ZUC with the $Key$ and the $SQN_{IMSI}$ (or $SQN_{P_0}$), and only the UE and the HSS can generate a series of relevant shared pseudonyms legally. Under such conditions, the probability of getting the UE’s IMSI (especially MSIN) by the exhaustive method is $\frac{1}{2^{40}}$. But if the attacker want trace or mark the UE, he also has to guess the shared key, which is the vital part to get the UE’s next shared pseudonym. This means the probability of recognizing UE’s current valid identity is $\frac{1}{2^{168}}$, where the $Key$ is 128 bits and MSIN is 40 bits.

6 Conclusions

In this paper, we propose a shared key based anonymous authentication scheme in 5G access authentication. And by the shared pseudonym, the UE can construct the variable k-pseudonym sets in subsequent access authentications. Moreover, owing to the variable k-pseudonym sets, our scheme can resist the intersection attack and the mark attack. We also give the shared pseudonym construction method and the recovery mechanism for the asynchronous situations. Finally, after BAN logic analysis, we conclude that the UE and the HSS can get the variable shared pseudonym ($P_i$) synchronous and privately. Besides, we hope to find some ways to improve the communication efficiency and reduce the communication latency.

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