On the Security of Wireless Network Access with Enhancements

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ABSTRACT

The security of the current 3G wireless protocols addresses the problems faced by the 2G systems, in addition to fulfilling the higher 3G security requirements mandated from operating in IP networks as well as voice networks. However, the approach adopted by the two most popular 3G mobile system forerunners, UMTS and cdma2000, leaves many areas for improvement. In this paper, we improve the security of the 3G protocols in network access by providing strong periodically mutual authentication, strong key agreement, and non-repudiation service in a simple and elegant way.

Categories & Subject Descriptors

K.6.5 [Security and Protection]: Authentication

General Terms

Security

Keywords

Security, 3G Mobile Network Security and Authentication

1. ACRONYMS

2G,3G,4G	The Second, Third, Fourth Generation
3GPP	3G Partnership Project
3GPP2	3G Partnership Project 2
A3	An authentication algorithm used in GSM
A5	An encryption algorithm used in GSM
A8	a key generation algorithm used in GSM
AES	Advanced Encryption System
AK	Anonymity Key
AKA	Authentication and Key Agreement
AV	Authentication Vector
CK	Cipher Key
CDMA	Code Division Multiple Access
cdmaOne	IS-95 based CDMA
cdma2000	IS-2000 based CDMA
COUNT	Call History Counter used in cdma2000
CS	Circuit Switching
ESA	Enhanced Subscriber Authentication
ESP	Enhanced Subscriber Privacy
FIPS	Federal Information Processing Standards
GSM	Global System for Mobile communications
HLR	Home Location Register
HMAC	keyed-Hash Message Authentication Code
IK	Integrity Key
IMT-2000	International Mobile Telecommunications 2000
Key K	A common secret key between MS and HLR
MS	Mobile Station
NIST	National Institute of Standards and Technology
PS	Packet Switching
RAND	A random number
SEQ	Sequence Number used in UMTS AKA
SSD	Shared Secret Data
UMTS	Universal Mobile Telecommunications System
VLR	Visitor Location Register

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2. INTRODUCTION

In recent years, due to technology advances, we have seen a phenomenal increase in the number of cellular users. As the demand increases, so does the importance of security in the cellular systems. This can be seen from many highly publicized incidents, e.g., the plain text communication among allied pilots during Kosovo war as reported by Washington Post, and the interception of House Speaker Newt Gingrich's cellular conference conversation. To provide protection, many different security areas are addressed, e.g., network access security provides users with secure access to the mobile services, network domain security provides secure exchanges of signaling data in the core network, application domain security provides users and providers with secure exchanges of application data, etc. [6]. Our emphasis in this paper is in the area of network access security.

For network access security, 2G mobile systems such as GSM and cdmaOne were designed to protect against external attacks. However, these designs have led to numerous interception attacks [5, 20, 24, 30]. The 3G wireless protocols must not only address the problems faced by the 2G systems but also provide strong security functionality to fulfill the 3G cellular requirements as defined in IMT-2000 [7], especially the required support over IP networks. Unfortu-

nately, the proposed security protocols for network access provided by the two most popular 3G cellular system forerunners, UMTS and cdma2000 (the descendants of GSM and cdmaOne, respectively), still leave many areas for improvement. In this paper, we address some of these areas and provide protocol enhancements on top of these two systems.

For clarity, here we specify the security standards to which we will be referring in this paper. The security architecture standard for UMTS is defined in [6]. For cdma2000, the latest published documentation on network access security can be found in [8, 9, 10].

One of the areas for improvement is the way in which a subscriber authenticates a network. 3G systems provide mutual authentication between a subscriber and a network, whereas 2G provides only subscriber authentication. To allow network authentication, UMTS uses a sequence number approach with which a subscriber can verify the freshness of an authentication request and thus prevent an attacker's replay. Instead of sequence numbers, we propose to use Lamport's one-time password/hash chaining technique [19] in both directions, to and from an MS, to establish periodically mutual authentication. Hash chaining provides strong periodical authentication and is used in many applications [3, 16, 17, 21]. Thus, by using this technique, our enhancement is efficient, elegant, and simple, and our periodically mutual authentication is strong.

Additionally, our enhancement can solve a billing dispute problem between an MS and a VLR. Neither UMTS nor cdma2000 address the issue of billing disputes, and thus there is no recourse to settle disputes when they arise. Note that a true non-repudiation service among HLR, MS, and VLR can only be achieved via a public-key system using digital signatures. In this paper, following UMTS and cdma2000, we adopt the symmetric key system with the assumption that both MS and VLR must trust HLR. However, unlike UMTS and cdma2000, our scheme can achieve non-repudiation between an MS and a VLR. That is, any dispute between an MS and a VLR can be resolved in our scheme. Specifically, we use keyed-Hash Message Authentication Code (HMAC) recently drafted by FIPS [14] on top of hash chaining to provide a non-repudiation service between an MS and a VLR to explicitly address the billing issue without complicating the existing protocols.

Previous work in this area includes a comparative study between UMTS and cdma2000 for the entire systems, but with little emphasis in the area of security [2, 13]. Rose [28] offered a high level general overview of wireless security between UMTS and cdma2000. Our detailed comparative study here emphasizes the subscriber authentication and key agreement procedures, as this becomes the basis for building our protocol enhancements. Al-Muhtadi et al. [1] proposed a lightweight component in mobile devices and a security server for authentication and call setup for 3G/4G systems. Their work can benefit from our enhanced protocol mentioned here to provide strong periodically mutual authentication and to simplify the implementation.

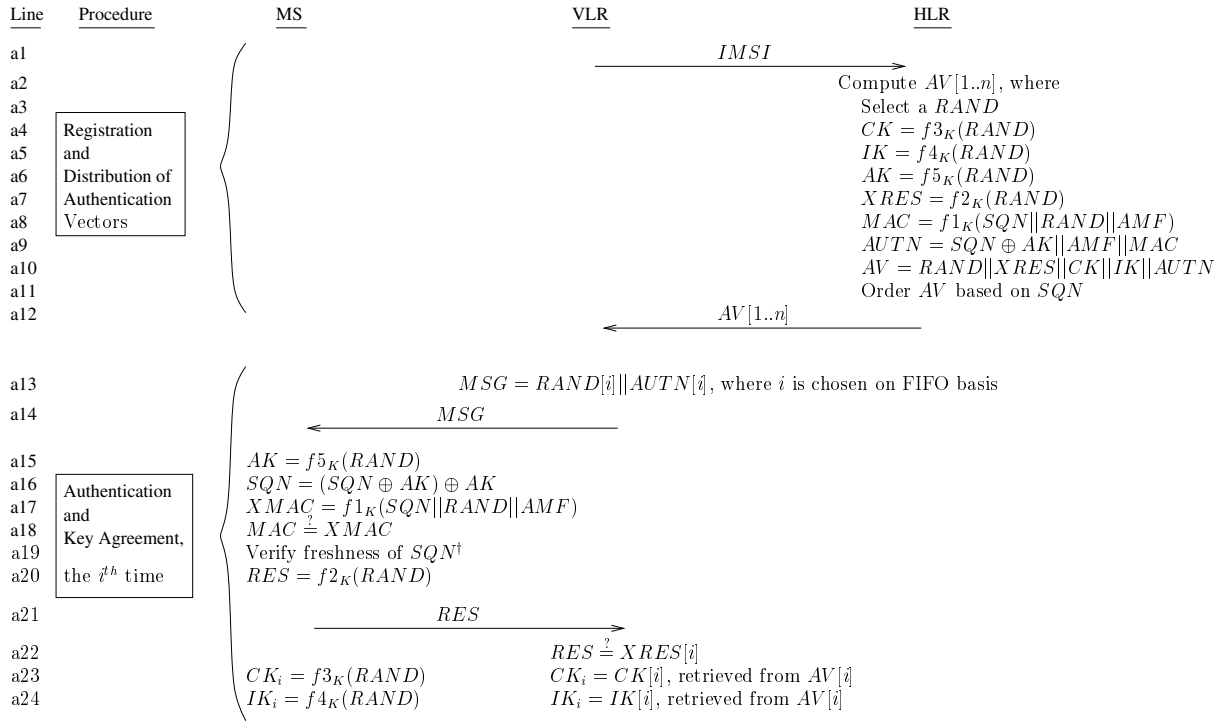
The remainder of this paper is organized as follows. Sections 3 and 4 describe detailed AKA procedure in UMTS and cdma2000, respectively. Section 5 describes our enhancements, and hash chaining and HMAC techniques that we adopt to achieve the improvements. Finally, section 6 provides conclusion and summary.

3. UMTS AUTHENTICATION AND KEY AGREEMENT

This section describes the registration and AKA procedures in UMTS [6], shown in Figure 1. For ease of reference, each line in the figure is provided with a line identification number. UMTS maintains the same challenge and response method as its 2G predecessor, GSM, to facilitate generation migration. In particular, during registration, an HLR prepares and sends a list of authentication vectors (AV) to a VLR (see lines $a2$ to $a12$ in Figure 1.) During AKA, a VLR uses an AV (lines $a13$ and $a14$) to authenticate an MS. Each AV is used once for each AKA invocation. If a VLR runs out of AVs, it can request more from the HLR. When an MS roams out of a VLR, the old VLR should transfer the leftover AVs to the new VLR. The standard [6] assumes that the communication links between VLRs are adequately secure.

The major differences in registration and AKA procedures between UMTS and GSM are (1) GSM allows only subscriber authentication, while UMTS provides both subscriber (line $a22$) and network (line $a19$) mutual authentications, and (2) UMTS can protect the integrity of signaling data (via IK_i in line $a24$), while GSM can not. For the network authentication, UMTS employs a complicated sequence number (SEQ) technique. Specifically, UMTS achieves these two extra functionalities by adding two extra fields in the AV, namely an authentication token (AUTN, line $a9$) and an integrity key (IK, line $a5$) on top of the triplet provided in GSM. An authentication token allows an MS to authenticate a VLR. The fields within the token include SEQ, anonymity key (AK), authentication management field (AMF), and message authentication code (MAC). Each authentication token is assigned a unique SEQ. When an MS receives an authentication token, it verifies that the corresponding SEQ has not been accepted before (line $a19$), thereby precluding replay by an attacker. To allow for out-of-order SEQs due to simultaneous registration in both CS and PS domains, MS maintains a list of SEQs that it has accepted. To prevent exposition of MS's identity and location, key AK can be used to conceal the SEQ. AMF is an authentication management field which can be used for purposes such as specifying a particular authentication algorithm used, etc. MAC is used to ensure the authenticity and integrity of the authentication token and the random challenge. The IK is used to protect the integrity of the control data. Readers are referred to the UMTS Security Architecture [6] for a detailed description of the AKA procedure.

The generation, allocation, verification, and management of SEQ is a complicated matter, especially with regard to the protection against an attack to force SEQ wrap around and the compromise of user identity confidentiality. Furthermore, with the consideration of re-synchronization failure recovery, SEQ complicates both protocol and implementation tremendously. (In re-synchronization failure recovery, an HLR and an MS try to re-synchronize SEQ due to synchronization failure in various scenarios such as simultaneous registration in CS and PS domains, user movement between VLRs which do not transfer leftover AVs, and super-charged networks where the mobility of an MS among various VLRs is very high.) In fact, in the UMTS Security Architecture [6], a 6-page appendix is necessary to describe the generation, allocation, verification, and management of SEQ.



† : The generation, allocation, verification, and management of SEQ (sequence number) are described in a 6-page appendix in UMTS security architecture standard [6].

Figure 1: Authentication and Key Agreement in UMTS

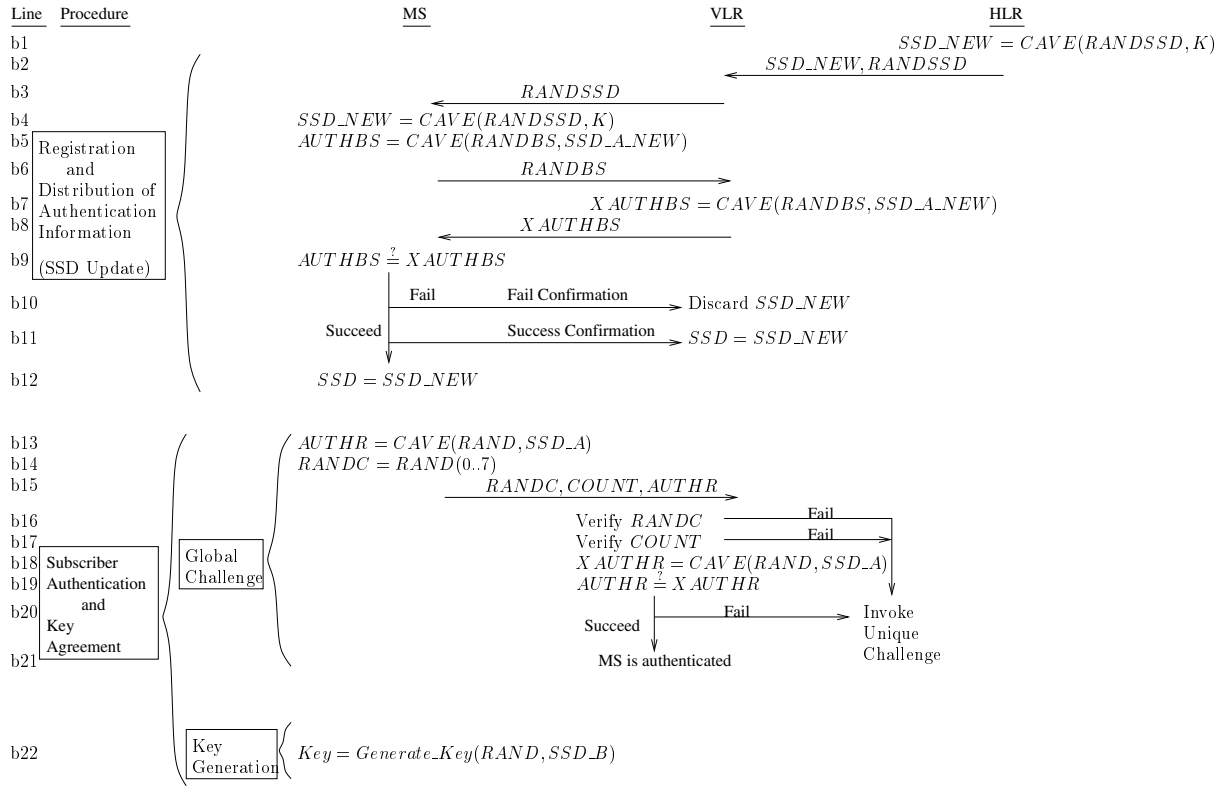
4. CDMA2000 SUBSCRIBER AUTHENTICATION AND KEY AGREEMENT

Cdma2000 is designed to be backward compatible with its predecessor cdmOne, therefore it inherits most of the cdmaOne security features. Specifically, for cdma2000, Figure 2 depicts the general registration and the subscriber authentication and key agreement procedures in the latest published documents on security [8, 9]. These standards show the same procedures as in cdmaOne.

In particular, during registration (invoked by the SSD update procedure, lines $b1$ to $b12$), the HLR selects a $RANDSSD$ and calculates a new SSD which can be shared with a VLR (lines $b1$ and $b2$.) The VLR then sends the $RANDSSD$ to an MS for it to derive the new SSD (lines $b3$ and $b4$.) To authenticate the VLR, an MS sends a base station challenge order (line $b6$) to the VLR. It is only when the VLR passes the challenge does the MS update to the new SSD (line $b12$).

During the subscriber authentication phase (lines $b13$ to $b21$), the MS invokes the global challenge procedure by first calculating a response $AUTHR$ using a globally broadcast challenge $RAND$ and SSD_A, the first portion of SSD. In line $b15$, the MS sends $RANDC$ (the first 8 bits of $RAND$), $COUNT$ (Call History counter used for clone prevention by keeping track the number of calls made by the MS), and $AUTHR$ to the VLR who will then verify the received values to authenticate the MS, (in lines $b16$ to $b21$). In case that the MS fails the global challenge, the VLR will invoke a unique challenge procedure with a unique random number specifically generated to challenge the MS (readers are referred to [8] for the details of the unique challenge procedure). Note that the subscriber authentication here is only one-way (i.e., the VLR authenticates the MS, but not vice versa). Only when the MS is successfully authenticated can the encryption key be generated. In line $b22$, the encryption key is calculated based on the $RAND$ and SSD_B, the second portion of SSD.

The predominant difference in the network access security between GSM and cdmaOne, and thus their descendants UMTS and cdma2000, is how the authentication data is prepared. In UMTS, an HLR prepares and sends a list of challenge and response vectors to the VLR to authenticate an MS; while in cdma2000, a derived shared secret data (SSD) from a common secret key K can be shared with a VLR so that the VLR itself can authenticate an MS locally. The HLR total control method adopted by UMTS is secure in that the HLR is the one that an MS trusts, however it is not convenient for a VLR as the VLR has to rely on the HLR to generate challenges and responses. On the other hand, cdma2000's VLR local method is convenient for a VLR but not as secure as UMTS, since an HLR does not have the total control in the communication between a VLR and an MS. This is most evident when there is a dispute between an MS and a VLR; an HLR has no easy way to settle the dispute as it has given the VLR the control. To lesson the degree of the problem, in cdma2000, an HLR can periodically change the value of the SSD (using the SSD Update procedure) to make the sharing with a VLR less problematic.



Note: In this figure, we only show the essential inputs to the CAVE algorithm. The detailed inputs can be found in [8] and [9].

Figure 2: Cdma2000 Subscriber Authentication and Key Agreement in documents C.S0004-A_v6.0 [8] and C.S0005-A_v6.0 [9]

To meet the 3G security challenges, cdma2000 will provide ESA and ESP enhancements [11]. However, the detailed steps in achieving these enhancements are still being worked out, although 3GPP2 has approved the following: (1) the adoption of openly reviewed algorithms such as Rijndael Encryption algorithm [9], the AES chosen by NIST, and (2) the adoption of 3GPP AKA with SHA-1 and Message Authentication Code as the hash and integrity functions for AKA operations [10]. SHA-1 is a hash function defined in FIPS "Secured Hash Standard" [15]. A message authentication code is generated by means of a hash function to ensure the authenticity and integrity of the transmitted messages. With the adoption of 3GPP AKA, it remains to be seen as to how cdma2000 handles both authentication styles (i.e., UMTS' HLR total control and cdma2000's VLR local control) smoothly. As of the writing of this paper, 3GPP2 has not published the details of this transaction.

5. ENHANCEMENTS

As can be seen from section 3, the approach adopted by UMTS to provide 3G AKA complicates the already complex wireless protocol. Here, we provide an elegant approach to achieve strong AKA on top of UMTS as well as cdma2000.

In the following, section 5.1 introduces a list of notations that we use in our enhanced protocol. Section 5.2 describes HMAC and hash chaining techniques. Section 5.3 describes our enhanced protocol, the advantages, and the time and space analysis.

5.1 Notation

- $t(x, y)$: HMAC with key x, and message y
- $p(x, y)$: Cipher key generation function with key x, and random data y
- $q(x, y)$: Integrity key generation function with key x, and random data y
- $r(x, y)$: Anonymity key generation function with key x, and random data y
- AK: Anonymity Key
- $RAND_H$: A random number selected by an HLR
- CK_H: The Cipher Key generated by an HLR, using HLR-selected $RAND_H$. An MS can also generate this when given a $RAND_H$.
- IK_H: The Integrity Key generated by an HLR, using HLR-selected $RAND_H$. An MS can also generate this when given a $RAND_H$.
- $CK_{i,m}$: The Cipher Key with id (i, m) generated by an MS and a VLR and for use between the MS and the VLR
- $IK_{i,m}$: The Integrity Key with id (i, m) generated by an MS and a VLR and for use between the MS and the VLR

- $f^m(b_i)$: One-way hash function with i^{th} random seed b_i and m^{th} composition, where $i \leq I$ and $m \leq M$, for use in authenticating an MS
- M: The maximum number of f hash chaining composition
- I: The maximum number of random seeds for f hash chaining
- $g^n(a_j)$: One-way hash function with j^{th} random seed a_j and n^{th} composition, where $j \leq J$ and $n \leq N$, for use in authenticating a VLR.
- N: The maximum number of g hash chaining composition
- J: The maximum number of random seeds for g hash chaining
- $\stackrel{?}{=}$: An equality comparison operator

5.2 Techniques

To enhance the 3G AKA protocol, we adopt two major techniques: keyed-Hash Message Authentication Code (HMAC) and hash chaining.

HMAC is very popular in the Internet community [25], and has been recently drafted by FIPS [14]. It is used for message authentication by means of a cryptographic hash function and a shared secret key. In a public-key system, a digital signature can be used to replace HMAC. The main components in HMAC are a hash algorithm and a key, and the most common form of HMAC is

$hash(key, hash(key, message))$.

Two of the most popular HMAC's are HMAC-MD5 [26] and HMAC-SHA [27].

Lamport's one-time password/hash-chaining was proposed in 1981, and has been used in many applications [3, 16, 17]. Let $f(x)$ be a one-way function and

$f^M(x) = f(f(\cdots(f(x)\cdots)))$

be the composition of M fs. During registration, the claimant (i.e., the one wishes to be authenticated) randomly selects an integer seed b, computes $f^M(b)$ and $HMAC$ of $f^M(b)$, and sends $f^M(b)$ and the $HMAC$ of $f^M(b)$ to the verifier (i.e., the one decides whether the claimant is who it is). Once registered, each hash chain can be used by the claimant to prove itself to the verifier M times. In the first visit, the claimant submits $f^{M-1}(b)$ to prove itself. The verifier checks the equality $f(f^{M-1}(b)) \stackrel{?}{=} f^M(b)$. If passed, the verifier updates $f^M(b)$ and stores $f^{M-1}(b)$ for the next visit; otherwise, the claimant is not authenticated. The claimant reveals $f^{M-1}(b)$, $f^{M-2}(b)$, $\cdots$, $f(b)$, and $b = f^0(b)$ in sequence to prove itself M times. The one-way hash chaining algorithm prevents all users, except the legitimate one, from computing backward values using the published one-way value.

Straightforward implementations of a hash chain such as storing all chain elements or iteratively hashing from a seed have $O(M)$ of combined memory and computational complexity for an M element chain. Recently, Jakobsson [18], and Coppersmith and Jakobsson [12] proposed a $log_2(M)$ space and access time mechanism, especially desired for low-cost applications such as mobile handsets, micro-payments, smart dust, authentications, and signatures (see [18, 12] for references therein.)

For the purpose of non-repudiation, the combination of $f^{M-m}(b)$ and the $HMAC$ of $f^M(b)$ (that is provided by the claimant during registration) can be used as a non-repudiation proof by the verifier as an evidence for all m visits made by the claimant. Specifically, for all m visits, the verifier only needs to store the most recently released f value (i.e., $f^{M-m}(b)$), and does not need to keep all other values that it has received (i.e., $f^M(b)$, $f^{M-1}(b)$, $\cdots$, $f^{M-m+1}(b)$) before the m^{th} visit. The verifier can produce a proof of the claimant's j^{th} visit, where $1 \leq j \leq m-1$, by simply computing $f^{m-j}(f^{M-m}(b))$. This desired feature is especially good for the applications (such as mobile handsets) with limited storage space.

To prolong the life time of a hash chain, an additional dimension can be added to the above scheme as follows. The claimant (1) randomly selects I seeds, $b_1, b_2, \cdots$, and b_I, (2) computes $f^M(b_1), f^M(b_2), \cdots$, and $f^M(b_I)$, and an HMAC on the concatenated message $f^M(b_1)||f^M(b_2)||\cdots||f^M(b_I)$, (3) sends the computed values in (2) to the verifier. Note that by using the concatenation of I hash chaining values as one single message, one message authentication code between an MS and an HLR is all that is needed for establishing the initial registration (see lines $c1$ and $c2$ in Figure 3).

A general discussion on one-way functions and one-way hash functions can be found in [29] and the implementation of these functions can be found in [4].

5.3 Protocol Enhancement

Figure 3 provides our registration and AKA enhancements on top of the two 3G forerunners, UMTS and cdma2000. For clarity, a set of protocol steps composed to achieve a unique functionality are grouped into a procedure. These procedures mirror those in Figures 1 and 2. The significance of this grouping indicates that our procedures can be used to replace with ease the corresponding UMTS and cdma2000 procedures.

5.3.1 Enhancement Details

In the following, we specify the assumption and explain each procedure and the corresponding steps.

- Assumptions: Just like in UMTS Security Architecture [6], we also assume that (1) the communication link between an HLR and a VLR is adequately secure, and (2) an MS shares a common secret key K with its HLR.

- Procedure: Registration and Distribution of Authentication Information

  This procedure is used when an MS first roams into a new visitor domain. The MS must send its HLR a set of data which is subsequently used by the VLR. Specifically, both MSG_1 and $HMAC_1$ (in lines c1 and c2) are sent from the MS via the VLR to the HLR. After the HLR verifies the authenticity of MSG_1, it then prepares MSG_2 to send to the VLR. In order for the MS to verify the authenticity of the VLR later on in the AKA phase, MSG_3 and $HMAC_3$ is prepared and sent by the VLR.

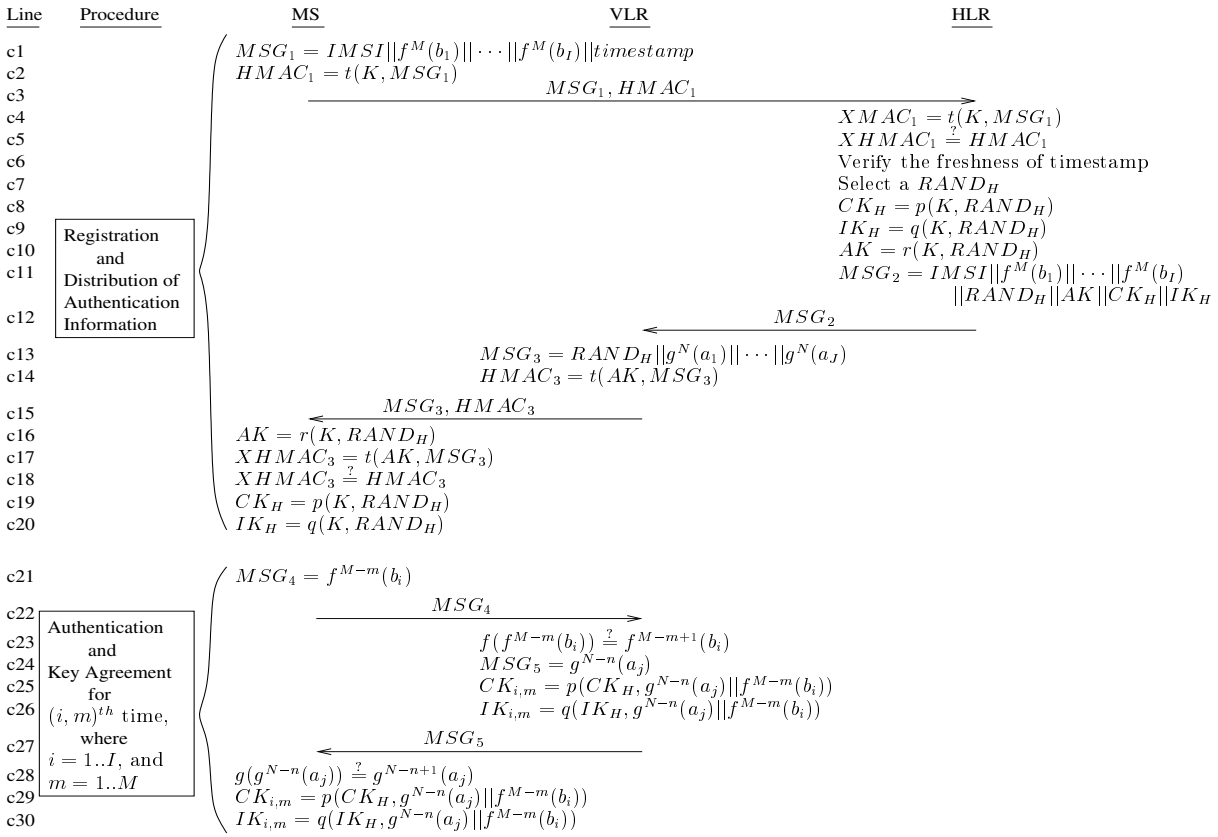


Figure 3: Enhanced Registration and AKA procedures

- Procedure: Authentication and Key Agreement

  This procedure is used by the MS and the VLR to mutually authenticate each other. Since each authentication uses one chain position, the MS can prove its identity to the VLR at most $I \times M$ times, whereas the VLR to the MS $J \times N$ times. The indices (i, m) and (j, n), where $i \leq I$, $m \leq M$, $j \leq J$, and $n \leq N$, are independent of each other as each side steps through its own hash chains at its own pace. Within each set of hash chains, it can be agreed that the chain with lower id (i.e., i and j) is used. If one side encounters problems in authenticating the other side, the verifier should send an error message with the problematic chain id to the claimant. The claimant then tries to authenticate itself to the verifier starting from the next fresh chain. For example, if the problematic chain id in f series is 8, then the MS should reveal $f^{M-1}(b_9)$ to the VLR to try to correct the authentication problem.

5.3.2 Advantages

The following list summarizes the advantages of our enhancements.

- Non-repudiation: For cases such as billing and dispute resolution between an MS and a VLR, the combination of $HMAC_1$ in line $c2$ and $f^{M-m}(b_i)$ can serve as a non-repudiation proof by a VLR as an evidence of m visits in the i^{th} chain made by an MS, and the combination of $HMAC_3$ in line $c14$ and $g^{N-n}(a_j)$ can serve as a non-repudiation proof by an MS as an evidence of n visits in the j^{th} chain made by a VLR. Note that due to the desired property of hash chaining, for each hash chain, the verifier only needs to keep the most recently released chain value (i.e., $f^{M-m}(b_i)$ kept by a VLR and $g^{N-n}(a_j)$ kept by an MS) as an evidence, (see section 5.2 for explanation.) This is good for mobile handsets because of their limited space constraint.

- Stronger mutual authentication: To achieve mutual authentication between an MS and a VLR, two hash chain sets are established, one for each direction. The one-way hash chaining algorithm prevents all users, except the legitimate one, from computing backward values using the published one-way value. Additionally, our method removes the assumption of secure channels between VLRs as there is no need to transfer leftover AVs. Therefore, this technique provides stronger mutual authentication than the current 3G protocols.

- Stronger periodical authentication: In UMTS [6], the periodical authentication is achieved by comparing a SEQ counter value between an ME and a VLR periodically. The SEQ is susceptible to synchronization failure. In our enhanced protocol, either a VLR or an MS can periodically request to authenticate the other by having the other side prove itself. It is only when the submitted value satisfies the hash chain property, is the claimant successfully authenticated. This way is

stronger than simply comparing the counter value.

- Stronger key agreement to protect against compromised data: The composition of session keys $CK_{i,m}$ and $IK_{i,m}$ for $(i,m)^{th}$ session are based on input values from all three entities involved, i.e, MS, VLR, and HLR. Therefore, if any of these input values is compromised by an attacker, the session can not proceed.

- Mutual authentication with no need for synchronization: Since there are two hash chain sets, one for each direction, and each side authenticates the other at its own pace, there is no need to synchronize these two chain sets.

- Authentication flexibility: Because of the feature of the mutual authentication with no need for synchronization, if it is necessary to provide only one-way authentication to function like a 2G system, one can simply omit the undesired set of chains.

- Simplicity and Elegance: Our enhancements do not use SEQ (sequence number) as in UMTS, or COUNT (call history counter) in cdma2000. As briefly mentioned in section 3, the management and record keeping of SEQ complicates both protocol and implementation tremendously. The management of a hash chain is simple and elegant compared to that of SEQ.

- Convenience and Security: By using a VLR's own hash chaining set, the VLR has the convenience of the local control in authenticating an MS. Yet an HLR still has the total control in security by means of the HLR-generated master keys CK_H and IK_H and non-repudiation services.

- Ease of handoff between VLRs: The roaming of an MS among VLRs is a case of *macro mobility*. For the roaming among base stations within the same VLR domain, known as *micro mobility*, methods such as Proactive Caching [22] can be used to reduce the connection delay. (We are currently working on extending the hash chaining technique to provide proactive caching for handoff in micro mobility.) In UMTS, when an MS roams out of a VLR domain, the old VLR must transfer the leftover authentication vectors to the new VLR. In our scheme, each MS and VLR pair has two unique sets of hash chains, one for each direction. That is, when an MS roams out of a VLR domain, the MS will establish two new sets of hash chains with a new VLR. The MS and the old VLR can still keep their old authentication states so that future connections can resume from the point where they leave each other. Thus, our scheme does not have leftover vector transferring problem as in UMTS. This feature is particularly attractive for a super-charged network where an MS moves around various VLRs frequently, or the cell sizes are small.

  For an MS who visits a VLR infrequently, an implementation of our enhancement can setup a time limit so that an established chain can be discarded due to a prolonged inactivity.

- Ease of re-synchronization: For any connection, if there is an authentication failure, the next fresh hash chain is used, thereby making re-synchronization between an MS and a VLR a trivial task.

6. CONCLUSION AND SUMMARY

Our main contributions in this paper are the enhancements on the authentication and key agreement protocol in the 3G network access security. To understand the basis of our enhancements, we provide an evolutionary and comparative study of this protocol in two most popular 3G cellular systems, UMTS and cdma2000.

The approaches adopted by the two 3G front runners aim to solve the 2G security problems and satisfy the higher 3G security requirements. Specifically, UMTS uses a sequence number approach to provide network authentication, a feature not in 2G. Cdma2000 has approved the adoption of the same technique. The sequence number record keeping and management complicate the already complex 3G implementation. In our study, we recommend to use a combination of hash chaining and keyed-Hash Message Authentication Code techniques instead. This combined approach not only simplifies both protocol and implementation, but also provides strong periodically mutual authentication, strong key agreement, and non-repudiation services in an elegant way.

Future work will provide a performance analysis of our enhancement.

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