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Remote user authentication in distributed networks and systems

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Remote User Authentication in Distributed Networks and Systems

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Dedicated to
My Parents & Grandparents

Declaration

This is to certify that the work reported in this thesis was done by the author, unless specified otherwise, and that no part of it has been submitted in a thesis to any other university or similar institution.

Jiangshan Yu
September 20, 2012

Abstract

Entity authentication is becoming more and more important. With widespread use of distributed computer networks, for example, cellular networks, virtual reality communities, World Wide Web, peer-to-peer networks and multiplayer online games, there is a need to be more vigilant about the security and privacy of users. One way to address the security and privacy concerns is remote user authentication and this is widely used in distributed systems for identifying users and servers. Remote user authentication is a means of identifying a user and verifying whether this user has permission to access the network services and resources. However, an attacker may impersonate a server to communicate with a user and then, the attacker is able to steal the user's information. Thereafter, the attacker can pass authentication with the real server by using the stolen information of the user. Therefore, mutual authentication is needed in order to prevent bogus server attacks. Other requirements of user authentication include ensuring the confidentiality of further exchanging messages, protecting user privacy, providing user anonymity and achieving unlinkability. In the complex environments of computer networks, however, it is a challenge to design efficient and secure mutual authentication protocols under such security requirements.

The research reported here aims to provide efficient and secure identification services with further security requirements for users in distributed systems and networks. In general, the identification services may require three factors, i.e., password, smart card and biometric characteristics. The authentication which based on password is called password-based authentication. Password-based authentication together with another factor, smart card, is called two-factor authentication. In which, a successful user authentication can be achieved if the user has a correct password together with a corresponding smart card. The biometric-based authentication mainly based on the biometric characteristics, for example, finger print, iris scan and a face, and it may also require a smart card. The three-factor authentication consists all of these three factors, i.e., password, smart card and biometric characteristics. There is another concept which belongs to two-factor authentication, called single sign-on (SSO). It enables a user to use a unitary secure credential (or token) to access multiple computers and systems where he/she has access permissions.

The contributions of this thesis are research on both single sign-on and three-factor authentication. In particular, this research will analyse the recent, supposed secure single sign-on scheme proposed in 2012 by Chang and Lee [CL12]. However, their scheme is actually not secure as we show that it fails to meet credential privacy and soundness of authentication. Based on this analysis, this research will suggest repairs to the scheme by employing the efficient verifiable encryption of RSA signature (RSA-VES) proposed by Ateniese [Ate99] for realising fair exchange of RSA signatures. In addition, this research will formalize the security model of single sign-on schemes with authenticated key exchange, and based on the model, a provably secure single sign-on scheme will be proposed. This scheme satisfies soundness, preserves credential privacy, meets user anonymity and supports session key exchange. For users who have higher security requirements, this research also proposes an improved generic framework, which is an efficiently systematic approach which upgrades two-factor authentication schemes to three-factor authentication schemes. This research also provides a provably secure concrete instantiation of the framework with comparison, practicability analysis, privacy discussion and formal security proof.

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Publications and Draft

1. Jiangshan Yu, Guilin Wang, and Yi Mu, "Provably Secure Single Sign-on Scheme in Distributed Systems and Networks", *The 11th IEEE International Conference on Trust, Security and Privacy in Computing and Communications*, June 25-27 2012, Liverpool, UK. (To Appear)

2. Guilin Wang, Jiangshan Yu, and Qi Xie, "Security Analysis of A Single Sign-On Mechanism for Distributed Computer Networks", *IEEE Transactions on Industrial Informatics*, July, 2012. (Provisionally accepted after second round review; the draft can be found in IACR Cryptology ePrint Archive 2012: 107)

3. Jiangshan Yu, Guilin Wang, Yi Mu, and Wei Gao, "An Efficient and Improved Generic Framework for Three-Factor Authentication with Provably Secure Concrete Instantiation". (The draft has been finished).

Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Overview of Cryptography

Classic cryptography is the techniques of hiding the meaning of a written text. It was first documented in the use of non-standard hieroglyphs by ancient Egyptians circa 1900 B.C., for secure communication in the presence of third parties, i.e. 'adversaries'. Since World War I it has been growing and effectively became synonymous with 'encryption' until the advent of modern cryptography.

Modern cryptography intersects with a number of different disciplines, like mathematics, computer science and electrical engineering. The algorithms designed for modern cryptography normally rely on computational hardness assumptions, for example, the difficulty of integer factorization in number theory. Theoretically, it is, indeed, possible to break these algorithms (e.g. by brute force attack) but it is unfeasible using known techniques and computational devices. So, the security of cryptographic algorithms and their applications are called computationally secure. Today, in terms of information security, the field of cryptography has been expanded from confidentiality and integrity to various aspects such as authentication, non-repudiation, trust and privacy.

Public key cryptography, also known as asymmetric cryptography, was invented in the late 1970s. It enables building secret communication using a public channel without the establishment of a prior secret key. In 1976, Diffie and Hellman [DH76] were first proposed a solution to address the problem of key distribution using public-key cryptography. Their idea involved using two distinct keys, one for plaintext encryption that can be made public, and one for ciphertext decryption which is kept private. Key generation requires that deducing the secret key from the public key is computationally unfeasible. Public key cryptosystems make authentication easy to achieve and have inspired a lot of research. As a result, a number of schemes for user authentication and message authentication have been devised.

1.2 User Authentication

User authentication is the process of individual identity confirmation, to ensure that an individual is really who he claims to be. Probably the earliest user authentication mechanism was based on passwords. This concept was first proposed by Lamport in 1981 [Lam81], and remains the most common mechanism for user authentication in computer systems and networks.

While such protocols have been widely used, a number of problems have appeared, for example, the poor selection of passwords, the shortcoming of capture by Trojans and the reuse of passwords. These can lead to attacks such as dictionary attacks. Dictionary attack is the method to break the password-based authentication scheme by systematically trying every likely word or the likely combination of words in a dictionary as a password. This attack works because that many users prefer to use some ordinary words as passwords. For example, the user's first name or his/her telephone number. A good remedy is the use of hardware authentication tokens together with passwords to enhance security. This is called two factor authentication, which has become popular, consisting of a password together with a hardware token which is usually a smart card.

Since Chang and Wu [CW91] introduced the remote user authentication scheme using smart cards in 1991, there are many two-factor authentication schemes which have been proposed. The security, however, could remain compromised since the smart card may be stolen, the range of possible password could be small and users may frequently forget or lose their passwords. Due to such concerns, biometric identification, which exploits the biometric features of the user to authenticate him/herself, has been introduced.

Biometric identification overcomes the flaws of two-factor authentication because biometric features have high entropy, cannot be forgotten and are rarely lost [JR03]. The first biometric authentication scheme was 'fuzzy commitment', proposed by Juels and Wattenberg [JW99] in 1999. This has inspired many subsequent researchers. One problem is that biometric features are not completely private since they may easily be 'stolen'; e.g. the fingerprint can be obtained from things the person has touched and the facial features may be obtained from a user's photograph. A way to alleviate these problems is to combine all three of these factors in what is called ‘three-factor authentication’.

Different techniques are selected depending upon the requirements of different services. For example, the security of Email is normally based on password only; the security of ATM services may require both a smart card and a personal identification number (PIN, as a password); and the higher level access control of financial organisations and the military usually require multiple factors.

1.3 Related Work

1.3.1 Password-Based Authentication

To thwart the compromise of password table, which is maintained by a server, many schemes [EKW74, LMM81] have been proposed using password hashing rather than the plain password in a directory table. This method protects passwords even when the directory table is disclosed. However, an adversary may impersonate a legal user to pass authentication by modifying the data in the directory table. Other schemes, such as [SKS+92, NSC+93, OR87, SY96, Syv93], attempt to ensure the authentication with the help of a trusted third party in networks, in which, the secret information (e.g. secret key) must be stored in a table on the server side. Thus, security is not reliable since leaking of the table could lead to system breakage.

1.3.2 Two-Factor Authentication

To eliminate the shortcomings of using directory tables, two-factor schemes which are based on both a password and a smart card have been proposed [CW91, CH93, OT89]. However, they all have drawbacks [YS99]. To resolve the problems in these schemes, Yang and Shieh [YS99] proposed two two-factor authentication schemes, one based on timestamp and the other based on random nonce. Both support easy password changing. Later, Chan and Cheng [CC02], and Fan *et al.* [FLZ02] found that the Yang-Schieh scheme is insecure against impersonation attack. To remedy this flaw, Shen, Lin and Hwang [SLH03], and Yang, Wang and Chang [YWC05] suggested improvements to the Yang-Schieh scheme. However, Yoon *et al.* [YKY05] identified attacks on the YWC-scheme [YWC05], and then improved the scheme. In 2006, however, Wang and Bao [WB06] pointed out that both the SLH-scheme [SLH03] and Yoon *et al.*'s scheme [YKY05] are vulnerable to impersonation attacks.

Single Sign-On

With the increasing usage of network services, a user may need to maintain more and more ID/password pairs for accessing different distributed service providers. This imposes a burden on users and service providers as well as the communication overhead of computer networks. To tackle this problem, a single sign-on (SSO) mechanism [Gro] has been introduced so that after obtaining a credential from a trusted authority, each legal user can use this single credential to authenticate itself and then access multiple service providers.

Intuitively, an SSO scheme should meet at least three basic security requirements: completeness, soundness and credential privacy. Completeness of authentication [BR93a] requires that: (a) both sides accept each other if they have matched the conversation; (b) the probability that one side accepts the other one who actually has not engaged in the matching conversation is negligible. Soundness means that an unregistered user without a credential should not be able to access the services offered by service providers. Credential privacy guarantees that colluding dishonest service providers should not be able to fully recover a user's credential and then impersonate the user to log in to other service providers.

Formal security definitions of SSO schemes were given in [HMSY10]. However, soundness of credential based authentication has not been formally studied yet despite its importance, and the preserving of both soundness and credential privacy is still a challenge in designing an SSO [WYX12].

In 2000, Lee and Chang [LC00] first proposed a user identification and key distribution scheme, actually an SSO scheme, maintaining user anonymity in distributed computer networks. Later, Wu and Hsu [WH04] pointed out that the Lee-Chang scheme is vulnerable to masquerading attacks and identity disclosure attacks. The former enable an adversary to impersonate a service provider to exchange the session key with users and then to obtain sensitive information in further communication. This is possible because of the one-way authentication in the Lee-Chang scheme. The second type of attack, which focuses on the user anonymity, can expose the identity of a user. Meanwhile, Yang *et al.* [YWB+04] showed that the Wu-Hsu scheme cannot preserve credential privacy either, since a malicious service provider can recover users' credentials, and they then proposed an improvement to overcome this limitation. In 2006, however, Mangipudi and Katti [MK06] pointed out that

Yang *et al.*'s scheme is insecure against DoS (Deniable of Service) attack and presented a new scheme. In 2009, Hsu and Chuang [HC09] demonstrated that both the Yang *et al.* and the Mangipudi-Katti schemes do not provide user anonymity since their schemes are vulnerable to identity disclosure attacks. To prevent such attacks, Hsu and Chuang proposed an RSA-based user identification scheme.

In [HMSY10], Han *et al.* proposed a generic SSO construction which relies on broadcast encryption plus zero knowledge (ZK) proof [FFS88] showing that the prover knows the corresponding private key of a given public key. So, implicitly, each user is assumed to have been issued a public key in a public key infrastructure (PKI). In the setting of an RSA cryptosystem, such ZK proof is very inefficient due to the complexity of interactive communications between the prover (a user) and the verifier (a service provider).

Recently, Chang and Lee [CL12] pointed out that the Hsu-Chuang scheme is vulnerable to impersonation attacks and the scheme requires additional time-synchronized mechanisms which have unstable latency in distributed networks. Then, they proposed a user anonymity preserving improvement with high efficiency. The scheme used random nonce to replace an additional time-synchronized mechanism, does not need PKI (Public key infrastructure) for users, and is suitable for mobile device users. Compared with Han *et al.*'s generic scheme, the Chang-Lee scheme has several attractive features: less underlying primitives without using broadcast encryption, high efficiency without resort to ZK proof and no requirement of PKI for users. Unfortunately, the analysis in Chapter 3 shows that the Chang-Lee scheme fails to provide proper user authentication and to preserve credential privacy since the knowledge proof of user authentication guarantees neither soundness nor credential privacy.

1.3.3 Biometric Authentication

To prevent the inherent drawbacks of passwords, biometric authentication has been proposed. In 1999, Juels and Wattenberg [JW99] proposed the first fuzzy commitment scheme, using Hamming distance to tolerate errors. Later, in 2002, Juels and Sudan [JS02] introduced a provably secure fuzzy vault scheme, in which a user chooses a long-bit secret key (treated as a biometric key) and hides it using the user's biometric template. The fuzzy vault scheme uses Euclidean distance measurement to tolerate errors. One year after, Clancy et. al [Cla03] proposed a secure smart card-based fingerprint authentication scheme, which was based on Juels and Sudan's fuzzy vault. In 2007, Nandakumar et. al [NJP07] proposed a fully automatic implementation by employing a fuzzy vault, using helper data to align unidentified fingerprints accurately. The improved scheme used both location and orientation attributes (x, y, θ) of a minutia point to record the biometric data, where (x, y) is the row and column that indicate the location in the image, and θ is the orientation in respect to the X-axis. The helper data are high curvature points extracted from the fingerprint orientation field, thus it neither affects the security nor leaks any information about the biometric template. Fuzzy vault has been widely accepted since the Euclidean distance measurement is suitable for the majority of biometric applications [WQ10].

Another famous scheme by Dodis *et al.* [DRS04], called 'fuzzy extractor', generates a pair including a secret key and a public key directly from the user's biometric template and uses Hamming distance, set difference and edit distance to tolerate errors. Other interesting works are briefly reviewed as follows. In 2008, Teoh and Ong [AT08] proposed a randomized dynamic quantization transformation (RDQT), which is based on fuzzy commitment, to binarize biometric data, satisfying randomness and uniqueness. Meanwhile, Sheng et.al [SHFD08] presented a template-free biometric-key generation, which can also generate a key directly from biodata.

1.3.4 Three-Factor Authentication

To achieve stronger security requirements, three-factor authentication has been introduced since the biometric features may not be completely private. In 2003, Kim *et al.* [KLY03] proposed two ID-based password authentication schemes, using smart card and fingerprints, without the use of public key directory tables. However, Scott [Sco04] pointed out that a passive eavesdropper without access to any smart cards, passwords, or fingerprints, could impersonate any identity to log in to the server after successfully eavesdropping legitimate log-on only once.

In 2004, Uludag *et al.* [UPJP04] surveyed various types of biometric cryptosystems, and they recommended using digital rights management (DRM) systems [JM03] to address the problems of biometric cryptosystems. In their methods, the cryptographic key is bound with biometric template then stored in a database. Thus, the key cannot be revealed without passing biometric authentication. However, the requirement of the biometric database has increased the cost and put users' privacy at risk. To protect users' privacy, in 2006 Bhargav-Spantze *et al.* [BSSB06, BSSM+07] proposed a novel privacy preserving two-phase multi-factor authentication scheme with biometrics, based on zero knowledge proof (ZKP), in which, user privacy is preserved by using the Petersen commitments. However, the scheme is very costly because the modular exponentiations and the database of all users' commitments are stored on the server side. In 2009, Fan and Lin [FL09] constructed an efficiency enhancing and privacy preserving three-factor authentication scheme, but it did not support free password changing and it had flaws in the formal proof. In their security proof, Theorem 2 defines that the protocol is a secure key exchange scheme if the public-key encryption scheme used in the protocol is secure against CCA2; however, in step 3 of the protocol, the session key material v is encrypted in a symmetric key scheme, and the session key $h(v)$ is only decided by the server, where $h(\cdot)$ is a hash function. Thus, if the symmetric key encryption scheme is insecure, then the protocol cannot provide secure key exchanging.

Recently, Li and Hwang [LH10] proposed an efficient biometric-based remote user authentication scheme using smart cards, without synchronized clocks. Later, Li *et al.* [LNM+11] pointed out that the Li-Huang scheme does not provide proper authentication since the scheme is vulnerable to man-in-the-middle attack. To address this shortcoming, they presented a further improvement. In 2011, however, Das *et al.* [Das11] found Li *et al.*'s improved scheme neither provided strong authentication nor supported easy password change. They then presented an improvement on Li *et al.*'s scheme. Our analysis, however, shows this scheme is vulnerable to the off-line guessing password attack. An adversary who has a smart card, can extract f_i,r_i,N from the smart card, where $f_i = h(BioData_i)$, $r_i = h(h(N||PW_i)||f_i)$. Then, the adversary can crack the user's password by matching $r_i = h(h(N||PW_i)||f_i)$ for every different PW_i in the password range.

In 2011, Huang *et al.* [HXC+11] proposed a generic framework for three-factor authentication, preserving security and privacy. The basic idea is to use fuzzy extractor to generate the biometric key from the biometric templates, and run twice a underlying two-factor authentication scheme. In the first time it runs the two-factor scheme as normal, and in the second time it uses the biometric key to replace the password and runs the underlying scheme again, thus achieving a three-factor scheme. This framework does not require any additional mechanism to enhance the underlying two-factor authentication protocol, and in the derived scheme, users need not show their biometric features to the server, and servers need not store any user information on a database. Thus, privacy is preserved and cost is reduced.

1.4 Challenges

The need for authentication of individual identity is a fundamental requirement in our society. In this computer age, single sign-on is a highly desirable solution for user authentication, suiting most common users since it reduces requirements for multiple logins and for remembering multiple IDs/passwords. This also alleviates forgotten password problems. Unfortunately, there are some shortcomings in the existing schemes such as (a) the inability to preserve user anonymity properly; (b) vulnerability to possible attacks, e.g. impersonation attacks; (c) a seeming absence of formal study and proof on soundness of the single sign-on; (d) the requirement for additional time-synchronized mechanisms; (e) lower efficiency and higher cost. Thus, it is a challenge to design an efficient and provably secure single sign-on scheme in distributed networks.

For users who have higher security requirements, three factor authentication is an ideal solution since it incorporates all advantages of password-based authentication, two-factor authentication and biometric authentication. An ideal three-factor authentication protocol can greatly ensure information confidentiality in distributed systems. However, the existing research on three-factor authentication is far from satisfactory and has a number of problems. The literature shows, for example, that corrupting biometric data is not only a privacy issue but is also related to the security of protocols; most existing solutions, and even their improved versions, have flaws which can lead to protocol breaking. Thus, it is a challenge to design a provably secure three-factor authentication scheme which preserves privacy in complex network environments.

1.5 Aims and Objectives

This thesis provides research into remote user authentication and focuses in particular on single sign-on and three-factor authentication. The aims of this thesis are as follows:

1. In the literature, several single sign-on schemes have been proposed. However, most of them have security flaws, and even worse, their improvements are also

insecure against possible attacks. Thus, this thesis aims to give an insight into the most recent SSO schemes identifying their flaws, issues and challenges.

2. The second aim of this thesis is to formalize the single sign-on and its security model to formally resolve the issues identified. Also, an efficient and provably secure single sign-on authentication scheme without the identified drawbacks will be provided according to the formal model.

3. A generic framework for three-factor authentication is the third aim of this thesis. The framework, which is efficient and practical, can upgrade two-factor authentication schemes to three-factor authentication schemes without additional requirements on the underlying schemes, and can preserve user privacy even when interfacing with a malicious server. Also, a concrete three-factor authentication scheme with formal security proof is needed.

1.6 Organisation of The Thesis

This thesis considers the use of single sign-on and three-factor authentication in the context of distributed environments. This chapter has reviewed the literature and the importance of user authentication and discussed the challenges and aims of this research.

Chapter 2 introduces five areas of background information relevant to the current research. The first part introduces some intractable problems with special focus on the discrete logarithm problem and the Diffie-Hellman problem. The chapter then reviews some cryptographic tools, encryption mechanisms and digital signatures. Finally, zero-knowledge proof-of-knowledge is discussed in the last part.

Chapter 3 first reviews the recent Chang-Lee scheme [CL12]. Chang and Lee claimed high security but this chapter demonstrates that the scheme is actually insecure as it fails to meet credential privacy and soundness of authentication. In particular, this chapter presents two impersonation attacks which also apply to another SSO scheme proposed by Hsu and Chuang [HC09], which inspired the design of the Chang-Lee scheme. This chapter then identifies the flaws in their security arguments to explain why attacks are possible against their SSO scheme. Moreover, by employing the efficient verifiable encryption of RSA signatures (RSA-VES) as proposed by Ateniese [Ate99], this chapter proposes an improvement for repairing the

Chang-Lee scheme. In addition, the formal study of the soundness of authentication has been identified as one open problem.

Chapter 4 formalizes the security model of the single sign-on schemes with authenticated key exchange. In particular, this chapter points out the difference between soundness and credential privacy, and combines them both into one definition. This part also proposes a provably secure single sign-on authentication scheme which satisfies soundness, preserves credential privacy, meets user anonymity and supports session key exchange. The proposed scheme is very efficient so that it is suitable for mobile devices in distributed systems and networks.

Chapter 5 reviews and improves a generic framework for three-factor authentication proposed by Huang et. al [HXC$^+$11] and then proposes a provably secure concrete instantiation according to the improved framework. Before reviewing Huang's framework, this part discusses two biometric identification schemes. Then, based on the discussion, this chapter suggests improvements to Huang's framework by employing fuzzy vault as first proposed by Juels and Sudan [JS02]. In addition, a concrete scheme is given by incorporating fuzzy vault and Yang's scheme [YWWD08] via the improved framework. This chapter also provides the practicability analysis of the derived scheme, then compares the scheme with other existing three-factor schemes and lastly, it also provides a formal security proof and a privacy discussion of the concrete instantiation.

Finally, Chapter 6 concludes this thesis with a summary of our proposed contributions, future work and new open problems for future research.

Chapter 2

Background

This chapter introduces five areas of fundamental background knowledge: intractable problems, cryptographic tools, encryption techniques, digital signatures and zero-knowledge proof of knowledge (ZKPK).

2.1 Intractable Problems

2.1.1 Discrete Logarithm Problem

The discrete logarithm problem [Mao04] is a significant element in a number of theoretical problems and is the core problem at the root of many difficulties encountered in cryptographic security assumptions.

Definition 2.1. (Discrete Logarithm Problem (DLP)) *In a cyclic group with generator g, the DLP is defined as follows.*
On input $(g, y) \in \mathbb{G}$, output a such that $y = g^a$.

2.1.2 Diffie-Hellman Problem

The Diffie-Hellman problem (DHP) was proposed by Diffie and Hellman [DH76]. The DHP can be divided into two related problems: computational DHP and decisional DHP.

Computational Diffie-Hellman (CDH) Problem

Definition 2.2. *In a cyclic group $\mathbb{G}$ of order p with generator g, pick integers $a, b \in \{0, 1, ..., p-1\}$ randomly and take g, g^a, g^b as input, the CDH problem is to compute g^{ab} without given the values of a and b.*

The CDH problem [DH76] is closely related to the DLP due to the open question of whether the DLP problem can be solved if CDH has been solved in $\mathbb{G}$.

Decisional Diffie-Hellman (DDH) Problem

The DDH problem has been proposed as a decisional version of the CDH problem.

Definition 2.3. *In a cyclic group $\mathbb{G}$ of order p with generator g, pick integers $a, b, z \in \{0, 1, ..., p-1\}$ randomly and given two distributions (g, g^a, g^b, g^z) and (g, g^a, g^b, g^{ab}), the DDH problem is to distinguish these two distributions. In other words, the problem is to decide whether $g^z = g^{ab}$ without knowing a, b and z.*

2.2 Cryptographic Tools

2.2.1 Cryptographic Hash Functions

A cryptographic hash function [Mao04], $H{:}\{0,1\}^* \rightarrow \{0,1\}^k$, is an algorithm which outputs the fixed k-length string for any arbitrary length input and has been widely employed in cryptographic schemes. In this thesis, all hash functions refer to the ideal cryptographic hash function which meets three main properties.

- The hash value is easy to compute for any given input message.
- It is unfeasible to find two distinct messages with the same hash value.
- It is unfeasible to recover a message from its hash value.

In 1986, Fiat and Shamir [FS86] first proposed the random oracle model (ROM), and later, it was formalized by Bellare and Rogaway [BR93b]. In the ROM, a hash function is modelled as a random oracle which is a theoretical black box. This black box answers every query with a random number selected from its output domain. In other words, the output of the hash function is treated as a randomness in the cryptographic security proof. However, one concern is that no hash function can be realized as a truly random function in the real world. Thus, some researchers have tried to prove schemes without the use of a random oracle. Despite this argument, the ROM is still popularly used in cryptographic security proofs. For example, Optimal Asymmetric Encryption Padding (OAEP) [BR94a] and one-mask Diffie-Hellman key exchange (OMDHKE) [BCP04] are provably secure in the ROM.

2.2.2 Time Stamp

In this thesis, the 'time stamp' means a digital time stamp. It is a proof showing that a digital event existed at a certain time and the event has not been changed since that time. In cryptography, it is normally employed to prevent message replay attacks. Time stamp is usually in two procedures: one is the signing procedure which binds the local clock code together with message and signs a signature on it; the other is the verifying procedure which convinces the receiver that the received message is valid only if the time stamp is being received for the first time.

The drawback of using the time stamp is the requirement of time synchronizing. This imposes restrictions on the use of time stamp. Thus, there are many schemes interested in using random nonce to achieve the same goal.

2.2.3 Diffie-Hellman Key Exchange

The Diffie-Hellman key exchange scheme is the first public key system, proposed by Diffie and Hellman in 1976 [DH76]. The scheme is widely accepted in public key systems to establish a session key. The session key enables two entities to communicate with each other over a public network with data integrity and confidentiality. The security of the Diffie-Hellman key exchange scheme is based on the computational Diffie-Hellman problem. The processes are as follows.

- **Initialization**. Two entities Alice and Bob agree on a cyclic group $\mathbb{G}$ with a generator g.
- **Key Exchange**. Alice and Bob choose secret random integers a and b respectively, calculate their own session key materials g^a and g^b respectively, and then send them to each other.
- **Key Agreement**. Alice and Bob calculate the session key by $(g^b)^a$ and $(g^a)^b$, respectively. Now, they share the same session key g^{ab} for further communication.

To prevent man-in-the-middle attacks, normally the session key material is bound together with the entity identity using cryptographic techniques, e.g. digital signature scheme.

2.3 Encryption Techniques

2.3.1 Symmetric Key Encryption

Symmetric key encryption is used to encrypt plaintext and decrypt ciphertext with the same secret key. The secret key is a shared secret between the sender and receiver such as a simple word, a name, or a random number. For example, the secret key can be the letters in the first column of the second page in the Bible. Since symmetric key encryption is more efficient than public key encryption, it is the favorite for protocol designing, e.g. Transport Layer Security (TLS) and Secure/Multipurpose Internet Mail Extensions (S/MIME). However, key sharing is a vulnerability of symmetric key encryption since that it requires a truly secure channel to share a key privately.

Symmetric key encryption can be classified into stream ciphers and block ciphers. The former is exceptionally fast but has a high cost and normally operates one bit at a time; the latter operates on a block of bits and has been used more frequently. An example of a stream cipher is the one-time pad [Mil82] introduced by Frank Miller in 1882. It has been proven that it is impossible to crack if used correct. RC4 is another example of a stream cipher, which was proposed by Ron Rivest of RSA Security in 1987 [Wik12a] and adopted in Secure Sockets Layer (SSL). The most well-known block cipher schemes are Data Encryption Standard (DES) which was published as FIPS PUB 46 in 1977 [oS77], Advanced Encryption Standard (AES) which was designed by Daemen and Rijmen [DR00] and published as U.S. FIPS PUB 197 in 2001 to supersede DES.

2.3.2 Asymmetric Key Encryption

Public encryption was first publicly introduced in the paper 'New Directions in Cryptography' [DH76] by Diffie and Hellman in 1976. Public key cryptosystems require two separate keys, one for plaintext encryption and one for ciphertext decryption. The encryption key can be published and the decryption key is kept secret.

Many classic asymmetric key encryption schemes have been widely adopted, e.g. RSA encryption [RSA78], ElGmagal encryption [ElG85], optimal asymmetric encryption padding (OAEP) [BR94b] and OAEP+ [Sho02].

RSA Encryption Scheme

The RSA cryptosystem is the best known and one of the most widely used public key cryptosystems. It was invented in 1978 by Rivest, Shamir and Adleman [RSA78]. There are two algorithms in RSA cryptosystem with two different keys for encryption and decryption. Anyone can access the encryption algorithm with a public key offered by the person who receives the messages. Thereafter, anyone can send encrypted messages (ciphertext) to the receiver. However, it is impossible to decrypt the ciphertext if only the public key is known. Thus, only the receiver who knows the private key can decrypt the ciphertext. The RSA encryption scheme consists of three parts, namely initialization, encryption and decryption.

- **Initialization**

  1. Select two distinct large primes p and q. Here, 'large' means from 1024 to 2048 bits or 308 to 616 decimal digits.
  2. Calculate $n = p \cdot q$ and $\phi(n) = (p-1) \cdot (q-1)$.
  3. Choose a random integer $e < \phi(n)$ such that $gcd(e, \phi(n)) = 1$ and publish the public key (n, e).
  4. Compute the integer d such that $e \cdot d \equiv 1 \mod \phi(n)$ and store the private key d.

- **Encryption**. Given a (block of) message $0 \leq m < n$, the ciphertext c is the least residue of $m^e \mod n$. That is $c \equiv m^e \mod n$.

- **Decryption**. To decrypt the ciphertext c, the plaintext can be recovered by calculating the least residue of $c^d \mod n$. That is $m \equiv c^d \mod n$, where $0 \leq m < n$.

The security of RSA closely related to the computationally unfeasible problem of large integer factorization. Informally, to decrypt c, we need private key d which was calculated by using the Euclidean algorithm with public key e and secret $\phi(n)$. Thus, we cannot get the private key without $\phi(n)$ as well as (p, q). Hence, to decrypt c without knowing d, we must factorize n. In the initialization, the p and q are large primes (1024-2048 bits) and thus, n is about 2048-4096 bits. Therefore, it is computationally unfeasible under today's knowledge to crack a well set-up RSA cryptosystem.

2.4 Digital Signatures

The digital signatures were introduced by Diffie and Hellman [DH76] and first formalized by Goldwasser, Micali and Rivest [GMR88]. It was invented to authenticate a signer of messages or documents, and to ensure that the messages have not been modified.

2.4.1 Formal Definition

Definition 2.4. (Digital signature) *A digital signature scheme consists of three algorithms:*

1. $KeyGen(\lambda)$*. Takes security parameter* λ *as input, outputs verifying/signing key pair* (PK, SK) *for a signer.*

2. $SGen(m, SK)$*. Takes message* m *and signing key* SK *of a signer as input, and outputs a signature* σ *on message* m*.*

3. $SVer(m, \sigma, PK)$*. Takes signer's public key* PK*, message* m *and signature* σ *as input, and outputs 'valid' iff the* σ *is signed by the signer on message* m*. Otherwise, it outputs 'invalid' for rejection.*

Formally, a signature scheme is called existentially unforgeable if any PPT adversary A can only win the following game, called Game-UFCMA, with a negligible probability [GMR84, GMR88].

Definition 2.5. (Game-UFCMA) *The Game-UFCMA has three phases which are defined as follows:*

- ***Initialization*** $(PK, SK) \leftarrow KeyGen(\lambda)$*. Given a security parameter* λ*, a verifying/signing key pair is generated by the key generation algorithm and adversary* A *is given the verifying key* PK*.*

- ***Query*** $\sigma_i \leftarrow SGen(SK, m_i)$*.* A *runs up to* q_{sign} *times to ask the signature signing oracle in an adaptive manner. Each time, the signing oracle will reply a signature* σ_i *for each message* m_i *chosen by* A*, where* $1 \leq i \leq q_{sign}$*.*

- ***Forge*** A *outputs a new message and signature pair* (m, σ)*.* A *wins if*

  1. $SVer(pk, m, \sigma) = 1$*, i.e.,* σ *is a valid signature for message* m *under the public key* PK*.*

2. $m \neq m_i$, for any $i \in \{1, \cdots, q_{sign}\}$.

2.4.2 RSA Signature Scheme

Since the concept of the digital signature was invented by Diffie and Hellman [DH76], many signature schemes have been proposed. The RSA signature scheme [RSA78] may be the earliest scheme, which comprises three algorithms defined as follows.

- $KeyGen(\lambda)$. Refer to the initialization phase of the RSA encryption scheme in 2.3.2.
- $SGen(m, d)$. To sign a message m, the signer generates the signature σ by computing $\sigma = h(m)^d \mod n$.
- $SVer(m, \sigma, e)$. Given a message m with a signature σ, the $SVer$ outputs *valid* iff $h(m) = \sigma^e \mod n$. Otherwise, it outputs *invalid*.

The primitive RSA signature scheme is not secure against certain attacks, e.g. common-modulus attacks against RSA [DK02]. The Common-Modulus Attack has been aimed at the case where two or more users of the RSA cryptosystem share the same RSA modulus n, which leads to (a) a user's secret key being able to recovered by another user; (b) a user factoring n; and (c) an attacker recovering the plaintext.

2.4.3 Schnorr Signature Scheme

As one of most frequently used signature schemes, the Schnorr signature scheme [Sch89, Sch91] is provably secure in a random oracle model under the assumption that the discrete logarithm problem is intractable [BP02, PS96, PS00, Mao04]. We now review the Schnorr signature scheme as follows.

- $KeyGen(\lambda)$. The scheme is defined in a cyclic group G of order q with a generator $g \in \mathbb{Z}_p^*$, where p and q are primes such that $q|p-1$, $q \geq 2^{160}$, and $p \geq 2^{1024}$. A secure hash function $h(\cdot)$ is also selected. The private key is x choosing from $\mathbb{Z}_q^*$, and the public key is $y = g^x \mod p$.
- $SGen(m, x)$. To sign message m with private key x, a signer picks a random integer $r \in \mathbb{Z}_q^*$, and outputs the signature $\sigma = (a, e, s)$ by computing $a = g^r \mod p$, $e = h(a, m)$ and $s = r + x \cdot e \mod q$.

- $SVer(m, \sigma, y)$. Given a signature $\sigma = (a, e, s)$ for message m with corresponding public key y, the verifier accepts this signature iff $e \equiv h(a, m)$ and $g^s \equiv ay^e \mod p$.

The security of the Schnorr mechanism is based on the intractability of discrete logarithm problem. The Schnorr signature scheme satisfies existential unforgeability under chosen message attack [GMR84]. Its security has been discussed and proven in [BP02, PS96, PS00, Mao04].

2.5 Zero-Knowledge Proof of Knowledge

Zero-knowledge proof was proposed by [GMR85] and discussed in detail in [GMR89]. It is an interactive protocol which enables a prover to convince a verifier the truth of an assertion, without revealing anything but the validity of proof. The zero-knowledge proof should satisfy three properties, namely completeness, soundness and zero-knowledge (ZK-ness). The completeness guarantees that the verifier will be convinced by a prover if the statement is true. The soundness ensures that the verifier will never be convinced by any prover if the statement is false. The ZK-ness requires that verifier can learn nothing but the fact.

Soon afterwards, a noninteractive zero-knowledge (NIZK) proof [CP92] was proposed and the proof of knowledge [BG92] was introduced. The proof of knowledge is an interactive proof, enables a prover to convince a verifier that he knows some secrets without showing the secrets to the verifier. If the proof of knowledge also satisfies the properties of zero knowledge proof, then it can be called zero-knowledge proof of knowledge (ZKPK).

2.5.1 RSA-based Verifiable Encryption of Signatures (RSA-VES)

Verifiable encryption of signatures (VES) was proposed in 1999 for fair exchange. VES comprises three parties, two users (namely Alice and Bob) and a trusted party. The basic idea of VES is that Alice who has a key pair of signature schemes signs a signature on a contract, encrypts it using the trusted party's public key, and uses the noninteractive signature-based proof of knowledge protocol [CP92] to convince Bob that she has encrypted the signature in the ciphertext and the trusted party can recover it from the proof materials. After validating the proofs, Bob sends his signature which is also on the contract to Alice and expects the signature from Alice. For the purpose of fair exchange, Alice should send her signature back to Bob after accepting Bob's signature. If she does not do so, Bob can also get her signature by sending Alice's proof materials together with his own signature to the trusted party who then recovers Alice's signature and sends it to Bob, and in the meanwhile, forwards Bob's signature to Alice. Thus, the fair exchange is achieved. In this thesis, we consider the case of RSA-VES such that the signer is working over a cyclic subgroup with unknown order, but the length of this order is publicly known. The RSA-VES, which is reviewed as follows, will be used in the chapter 3.

Initialization

Alice selects two large safe primes p and q to set $n = pq$. Namely, there are two primes p' and q' such that $p = 2p' + 1$ and $q = 2q' + 1$. Alice then computes her public key (e, n) where $e > 2$ is a prime, and her private key d such that $ed \equiv 1 \mod 2p'q'$. Alice also need to choose a cryptographic hash function $h(\cdot)$ such that $h : \{0,1\}^* \to \{0,1\}^k$, where $160 \leq k \leq n-1$. Now, Alice sends (e, n) to the trusted party and publishes $(e, n, h(\cdot))$.

Let $\mathbb{Q}_n$ be the subgroup of squares in $\mathbb{Z}_N^*$, whose order $\#G = p'q'$ is unknown to the public but its bit-length $l_G = |N| - 2$ is publicly known.

Upon receiving (e, n) from Alice, the trusted party checks its validity and randomly selects a $\overline{g} \in \mathbb{Z}_N^*$ if (e, n) is valid public key of Alice. To control the tightness of the ZK proof, a security parameter $\epsilon > 1$ is chosen. Then, the trusted party randomly selects a secret key x, computes and sends public parameters $g = \overline{g}^2 \mod n$ and $y = g^x \mod n$ to Alice. Finally, the trusted party publishes $(\epsilon, \overline{g}, g, y)$.

Proof Generation

First, Alice need to sign an RSA-based signature on message m by computing $\sigma = h(m)^{2d} \mod n$. To generate a proof of this signature, Alice first encrypts it as $K_1 = \sigma \cdot y^r \mod n$ and $K_2 = g^r \mod n$, where r is a random integer with binary length l_G. Secondly, Alice computes two commitments $a = (y^e)^{r_1} \mod n$ and $b = g^{r_1} \mod n$, where r_1 is a also random number such that $r_1 \in \pm\{0,1\}^{\epsilon(l_G+k)}$. Then, Alice computes the last part of proof (c, s) as $c = h(m||y^{er}||K_2||y^e||g||a||b)$ and $s = r_1 - c \cdot r$ (in $\mathbb{Z}$). Finally, Alice sends the proof $P = (K_1, K_2, a, b, c, s)$ as the whole proof to Bob.

Proof Verification

To verify the proof P, Bob calculates $W = \frac{K_1^e}{h(m)^2} \mod n$, $a' = (y^e)^s \cdot (W)^c \mod n$, $b' = g^s \cdot K_2^c \mod n$, and checks whether $(c, s) \in \{0,1\}^k \times \pm\{0,1\}^{\epsilon(l_G+k)+1}$ and $c = h(m||W||K_2||y^e||g||a'||b')$ holds. If it does hold, then Bob signs a signature σ' on hashed message $h(m)$ and sends it to Alice.

Fair Exchange

The $ZKPK$ is achieved until the last step. However, the RSA-VES was proposed for fair exchange. Thus, after Bob sends his signature to Alice, a signature from Alice is expected. If he has not received it, Bob can also obtain the signature with the help of the trusted party by the following steps.

First, Bob sends message m together with his signature σ' and the encrypted signature (K_1, K_2) to the trusted party. The trusted party verifies Bob's signature first and if it is valid, then decrypts the signature by computing $\sigma = \frac{K_1}{K_2^x}$. Finally, the trusted party sends σ to *Bob* and redirects σ' to Alice. Thus, fair exchange is achieved.

Chapter 3

Cryptanalysis of A Secure Single Sign-On Scheme

3.1 Introduction

With the wide spread use of distributed computer networks, it has become common to allow users to access various network services offered by distributed service providers [BX11]. Consequently, user authentication (also called user identification) [Lam81, LC00] plays a crucial role in distributed computer networks to verify if a user is legal and can therefore be granted access to the services requested. To avoid bogus servers, users usually need to authenticate service providers. After mutual authentication, a session key may be negotiated to keep the confidentiality of the data exchanged between a user and a service provider [LC00, JW09]. In many scenarios, the anonymity of legal users must be protected as well [LC00]. However, practice has shown that it is a big challenge to design efficient and secure authentication protocols with these security properties in complex computer network environments [CPS11].

Single sign-on (SSO) is a new authentication mechanism that enables a legal user with a single credential to be authenticated by multiple service providers in distributed computer network. Chang and Lee [CL12] made a careful study of the SSO mechanism. First, they argued that the Hsu-Chuang user identification scheme, actually an SSO scheme, has two weaknesses: (a) An outsider can forge a valid credential by mounting a credential forging attack since the Hsu-Chang scheme employs naive RSA signature without any hash function to issue a credential for any random identity selected by a user (In fact, this feature based on [YWB$^+$04].); and (b) the Hsu-Chuang scheme requires clock synchronization since it uses a time stamp. Then, Chang and Lee presented an interesting RSA-based SSO scheme, which is highly efficient in computation and communication (So it is suitable for mobile devices), and does not rely on clock synchronization by using a nonce instead of a time stamp. Finally, they presented a well-organized security analysis to show that their SSO scheme supports secure mutual authentication, session key agreement, and user anonymity.

This chapter, however, will demonstrate that their scheme is actually insecure as it fails to meet credential privacy and soundness of authentication. Specifically, we show that the Chang-Lee scheme [CL12] is actually insecure by presenting two impersonation attacks, i.e., *credential recovering attack* and *impersonation attack without credentials*. In the first attack, a malicious service provider who has communicated with a legal user twice can successfully recover the user's credential. Then, the malicious service provider can impersonate the user to access resources and services provided by other service providers. The other attack may enable an outside attacker without any valid credential to impersonate a legal user or even a nonexistent user to have free access to the services. These two attacks imply that the Chang-Lee SSO scheme fails to meet credential privacy and soundness, which are essential requirements for SSO schemes and authentication protocols. We also identify the flaws in their security arguments in order to explain why it is possible to mount our attacks against their scheme. Similar attacks can also be applied to the Hsu-Chuang scheme [HC09], on which the Chang-Lee scheme is based. Finally, to avoid these two impersonation attacks we propose an improved SSO scheme to enhance the user authentication phase of the Chang-Lee scheme. To this end, we employ the efficient RSA-based verifiable encryption of signatures (VES) proposed by Ateniese [Ate04] to verifiably and securely encrypt a user's credential. In fact, Ateniese's VES was originally introduced to realize fair exchange.

The rest of this chapter is organized as follows. The next section reviews the Chang-Lee scheme [CL12]. After that, we present two attacks against the Chang-Lee scheme in Section 3.3, and briefly analyse the Hsu-Chuang scheme [HC09] in Section 3.4. Then, the improved SSO scheme using VES is given in Section 3.5. Finally, Section 3.6 draws some conclusions.

3.2 Review of the Chang-Lee Scheme

The Chang-Lee single sign-on scheme [CL12] is a remote user authentication scheme, supporting session key establishment and user anonymity. In their scheme, RSA cryptosystems are used to initialize a trusted authority, called an $SCPC$ (smart

$SCPC$	The trusted authority
U_i, P_j	User and Service provider, respectively
ID_i, ID_j	The unique identity of U_i and P_j, respectively
e_X, d_X	The public/private RSA key pair of identity X
S_i	The credential of U_i created by $SCPC$
S_x	The long term private key of $SCPC$
S_y	The public key of $SCPC$
$E_K(M)$	A symmetric key encryption of plaintext M using a key K
$D_K(C)$	A symmetric key decryption of ciphertext C using a key K
$\sigma_j(M, SK_j)$	$\sigma_j(SK_j, M) \leftarrow SGen(m, SK)$ The signature σ_j on M signed by P_j with signing key SK_j via algorithm $SGen(\cdot)$
$SVer(M, \sigma_j, PK_j)$	The verifying of signature σ_j on M with public key PK_j
$h(\cdot)$	A given one way hash function
$\|\|$	The operation of concatenation

Table 3.1: Notations in the Chang-Lee Scheme

card producing center), and service providers, denoted as P_j's. The Diffie-Hellman key exchange technique is employed to establish session keys. In the Chang-Lee scheme, each user U_i applies a credential from the trusted authority $SCPC$, who signs an RSA signature for the user's hashed identity. After that, U_i uses a kind of knowledge proof to show that he/she is in possession of the valid credential without revealing his/her identity to eavesdroppers. Actually, this is the core idea of user authentication in their scheme and also the reason why their scheme fails to achieve secure authentication as we shall show shortly. On the other side, each P_j maintains its own RSA key pair for doing server authentication. The Chang-Lee SSO scheme consists of three phases: system initialization, registration, and user identification. Table 3.1 explains notations, and the details of the Chang-Lee scheme are reviewed as follows.

3.2.1 System Initialization Phase

The trusted authority $SCPC$ first selects two large safe primes p and q, and then sets $N = pq$. After that, $SCPC$ determines its RSA key pair (e, d) such that $ed = 1$

mod $\phi(N)$, where $\phi(N) = (p-1)(q-1)$. $SCPC$ chooses a generator $g \in \mathbb{Z}_n^*$, where n is also a large prime number. Finally, $SCPC$ publishes (e, g, n, N), keeps d as a secret, and erases (p, q) immediately once this phase has been completed.

3.2.2 Registration Phase

In this phase, each user U_i chooses a unique identity ID_i with a fixed bit-length, and sends it to $SCPC$. After that, $SCPC$ will return U_i the credential $S_i = (ID_i||h(ID_i))^d \mod N$, where $||$ denotes a concatenation of two binary strings and $h(\cdot)$ is a collision-resistant cryptographic one-way hash function. Here, both ID_i and S_i must be transferred via a secure channel.

At the same time, each service provider P_j with identity ID_j must maintain its own RSA public parameters (e_j, N_j) and private key d_j as does by $SCPC$.

3.2.3 User Identification Phase

To access the resources of service provider P_j, user U_i needs to go through the authentication protocol specified in Fig.3.1. Here, k and t are random integers chosen by P_j and U_i respectively; n_1, n_2 and n_3 are three random nonces; and $E(\cdot)$ denotes a symmetric key encryption scheme which is used to protect the confidentiality of user U_i's identity ID_i. We highlight this phase as follows.

- Upon receiving service request message m_1 from user U_i, service provider P_j generates and returns user message m_2 which is made up primarily by its RSA signature on (Z, ID_j, n_1). Once this signature is validated, it means that user U_i has authenticated service provider P_j successfully. Here, $Z = g^k \mod n$ is the temporal Diffie-Hellman (DH) key exchange material issued by P_j.

- After that, user U_i correspondingly generates his/her temporal DH key exchange material $w = g^t \mod n$ and issues proof $x = S_i^{h(K_{ij}||w||n_2)}$, where $K_{ij} = h(ID_i||k_{ij})$ is the derived session key and $k_{ij} = Z^t \mod n = w^k \mod n = g^{kt} \mod n$ is the raw key obtained by using the DH key exchange technique.

- Proof $x = S_i^{h(K_{ij}||w||n_2)}$ is used to convince P_j that U_i does hold valid credential S_i without revealing the value of S_i. Namely, after receiving message m_3 service provider P_j can confirm x's validity by checking if $SID_i^{h(K_{ij}||w||n_2)} \mod N = x^e$

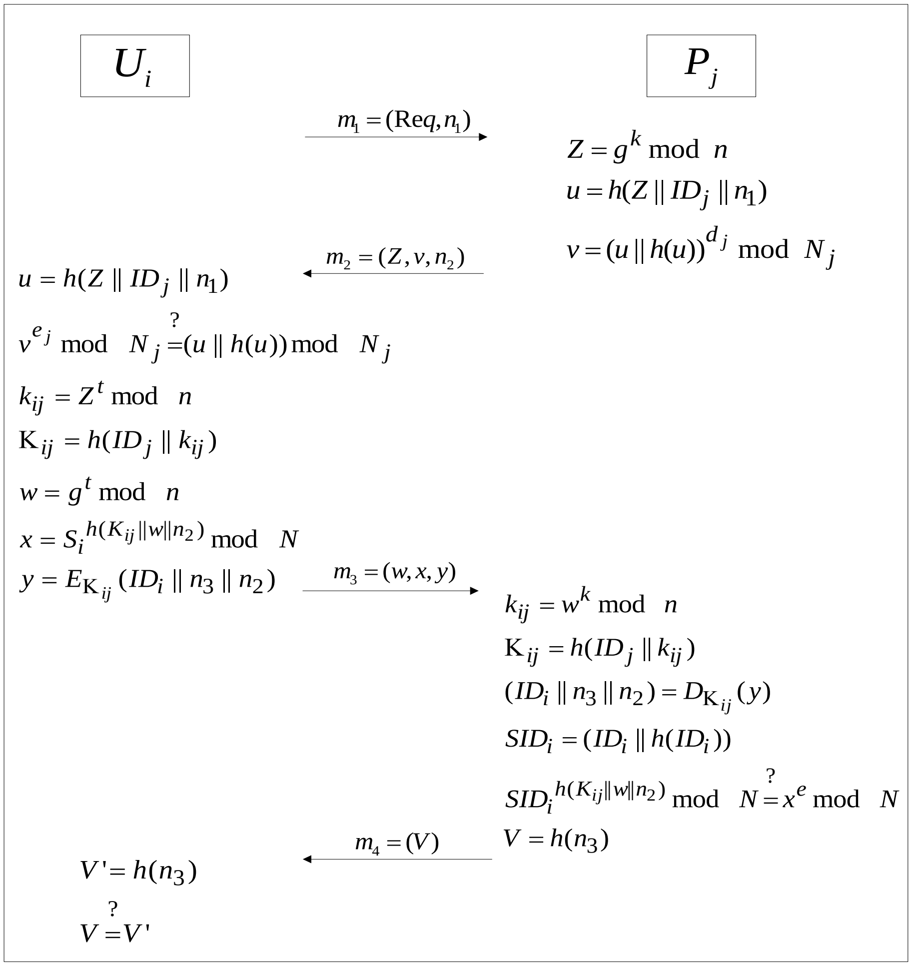


Figure 3.1: User Identification Phase of the Chang-Lee Scheme

mod N, where $SID_i = (ID_i || h(ID_i))$. Once this quality holds, it means that user U_i has been authenticated successfully by service provider P_j. It is worth noting that proof x is designed in a particular way so that except P_j and U_i, no one else can verify it as both U_i's identity ID_i and the newly established session key K_{ij} are used to produce x. This aims to achieve user anonymity as no eavesdropper can learn the values of ID_i and K_{ij}.

- Finally, message m_4 (i.e. $h(n_3)$) is employed to show that P_j has obtained message m_3 correctly, which implies the success of mutual authentication and session key establishment.

3.3 Attacks Against the Chang-Lee Scheme

As can be seen from the above, it seems that the Chang-Lee SSO scheme achieves secure mutual authentication since server authentication is done by using traditional RSA signature issued by service provider P_j and without valid credential S_i it looks impossible for an attacker to impersonate a legal user U_i by going through the user authentication procedure.

It can be seen from the following, however, that the Chang-Lee scheme is actually not a secure SSO scheme because there are two potential effective and concrete impersonation attacks. The first attack, the 'credential recovering attack', compromises the credential privacy in the Chang-Lee scheme as a malicious service provider is able to recover the credential of a legal user. The other attack, an 'impersonation attack without credentials', demonstrates how an outside attacker may be able to freely make use of resources and services offered by service providers, since the attacker can successfully impersonate a legal user without holding a valid credential and thus violate the requirement of soundness for an SSO scheme. In real life, these attacks may put both users and service providers at high risk.

We now first describe our attacks together with the assumptions required, justify why these assumptions are reasonable, and finally discuss why the security analysis and proofs given in [CL12] are not enough to guarantee the security of the Chang-Lee SSO scheme.

3.3.1 Credential Recovering Attack

Intuitively, the Chang-Lee SSO scheme seems to satisfy the requirement of credential privacy since receiving credential proof $x = S_i^{h_2} \mod N$, where h_2 denotes $h(K_{ij}||w||n_2)$, does not allow service provider P_j to recover user U_i's credential S_i by computing $S_i = x^{h_2^{-1}} \mod N$, where h_2^{-1} refers to $h_2^{-1} \mod \phi(N)$. In fact, the difficulty of calculating h_2^{-1} from the given (e, N, x, h) is the exact rationale why the RSA cryptosystem is secure, i.e., it should be intractable for an attacker to derive the RSA private key from the public key (and a given ciphertext). This is because here we could treat (h_2, h_2^{-1}) as another RSA public/private key pair w.r.t the same RSA modulus N. Moreover, directly recovering S_i from $x = S_i^{h_2} \mod N$ also looks impossible as this seems equivalent to decrypting the RSA ciphertext x w.r.t. the (ephemeral) public key h_2.

Nevertheless, there is a pitfall in the production of proof $x = S_i^{h_2} \mod N$ as here the same credential S_i is encrypted multiple times under different (ephemeral) public keys h_2 w.r.t. the same RSA modulus N. Consequently, under the assumption that malicious service provider P_j has run the Chang-Lee SSO scheme with the same user U_i twice, P_j will be able to recover U_i's credential S_i with high probability by using the extended Euclidean algorithm. Namely, P_j can solve S_i from two equations $x = S_i^{h_2} \mod N$ and $x' = S_i^{h'_2} \mod N$. The details of the attack, which share some features of common-modulus attacks against RSA [DK02], are given as follows:

1. After successfully running the Chang-Lee SSO scheme twice with the same user U_i, malicious service provider P_j stores all messages exchanged in these two instances, denoted as $(ID_i, x, K_{ij}, w, n_2, \cdots)$ for the first instance, and $(ID_i, x', K'_{ij}, w', n'_2, \cdots)$ for the second instance.

2. By denoting $h_2 = h(K_{ij}||w||n_2)$ and $h'_2 = h(K'_{ij}||w'||n'_2)$, P_j first checks if h_2 and h'_2 are co-prime, i.e. if $\gcd(h_2, h'_2) = 1$. In the case that $\gcd(h_2, h'_2) = 1$, P_j then runs the extended Euclidean algorithm to compute two integers a and b such that $a \cdot h_2 + b \cdot h'_2 = 1$ (in $\mathbb{Z}$). Finally, malicious P_j can recover U_i's credential S_i by computing

$$S_i = x^a \cdot x'^b \mod N. \tag{1}$$

   Eq. (1) is justified by the following equalities:

$$\begin{aligned} x^a \cdot x'^b \mod N &= (S_i^{h_2})^a \cdot (S_i^{h'_2})^b \mod N \\ &= S_i^{a \cdot h_2 + b \cdot h'_2} \mod N \\ &= S_i^1 \mod N \\ &= S_i. \end{aligned}$$

3. If $\gcd(h_2, h'_2) \neq 1$, P_j needs to run more instances with U_i so that it can get two instances such that $\gcd(h_2, h'_2) = 1$.

There are a number of comments to be made regarding the above attacks. First, it has a success rate of about 60% due for two reasons: (a) for two randomly selected integers u and v, the probability that $\gcd(u, v) = 1$ holds is $6/\pi^2 \approx 0.6$ [Ten95, Wei]; and (b) as the outputs of hash function h, h_2 and h'_2 can be regarded as random numbers. This means that after executing the Chang-Lee SSO scheme with the same user U_i twice, malicious P_j will be able to recover U_i's credential S_i with a probability of about 0.6. Consequently, it is easy to see that after running the scheme with U_i a couple of times, P_j can recover S_i almost certainly. Second, it is not hard to see that the above attack could be mounted by two or multiple malicious service providers who collude together once they put the values of h_2 together. Finally, the attack will lead to serious consequences since after recovering the valid credential of a legal user, malicious P_j can impersonate this user by running Chang-Lee SSO scheme in the same way as a legal user does to freely make use of the services offered by other service providers.

How could service provider P_j be malicious and then mount the above attack? On the one hand, the Chang-Lee SSO scheme specifies that $SCPC$ is the trusted party (refer to Section IV A [CL12]). So, this implies that service providers are not trusted parties and that they could be malicious. By agreeing with Yang *et al.* [YWB+04], when they said that "the Wu-Hsu's modified version cold not protect the user's token against a malicious service provider, ...", [CL12] also implicitly agrees that there is the potential for attacks from malicious service providers against SSO schemes. Moreover, if all service providers are assumed to be trusted, to identify him/herself user U_i can simply encrypt his/her credential S_i under the RSA public key of service provider P_i. Then, P_i can easily decrypt this ciphertext to get U_i's credential and verify its validity by checking if it is a correct signature issued by $SCPC$. In fact, such a straightforward scheme with strong assumption is much simpler, more efficient and has better security, at least against this type of attack.

On the other hand, according to the security models given in [YWB+04] and [HMSY10], malicious service providers could be attackers in SSO schemes. In fact, this is a traditional as well as prudential way to deal with trustworthiness, since we cannot simply assume that beside the trusted authority $SCPC$, all service providers are also trusted. The basic reason is that assuming the existence of a trusted party is the strongest supposition in cryptography but it is usually very costly to develop and maintain. In particular, Han *et al.* [HMSY10] defined collusion impersonation attacks as a way to capture the scenarios in which malicious service providers may recover a user's credential and then impersonate the user to login to other service providers. It is easy to see that the above credential recovery attack is simply a special case of collusion impersonation attack where a single malicious service provider can recover a user's credential.

3.3.2 Impersonation Attack Without Credentials

We now study the soundness of the Chang-Lee SSO scheme, which seems to satisfy this security requirement as well. The main reason is that to get valid proof x satisfying $SID_i^{h_2} \mod N = x^e \mod N$ for a random hash output h_2, there seems no other way but to compute x by $x = SID_i^{h_2 \cdot e^{-1}} \mod N$, i.e., $x = (SID_i^d)^{h_2}$ or $x = (S_i)^{h_2} \mod N$. Therefore, an attacker should not be able to log in to any service provider if it does not have the knowledge of either $SCPC$'s RSA private key d or user U_i's credential S_i.

Again, however, such a plausible discussion simply explains the rationale of the Chang-Lee SSO scheme but cannot guarantee its security w.r.t. the soundness. This is also the essential reason why the current focus of research in information security is on formal proofs which rigorously show the security of cryptosystems. Indeed, no one can formally prove that without knowing either $SCPC$'s RSA private key d or user U_i's credential S_i, it is unfeasible to compute a proof x that passes through authentication, as an outside attacker is able to get a shortcut if the $SCPC$'s RSA public key e is a small integer so that e's binary length is less than the output length of hash function h, i.e., $|e| < |h(\cdot)|$. The attack is explained in detail as follows:

1. To impersonate legal user U_i with identity ID_i for accessing service provider P_j, an attacker E first sends P_j request message m_1 normally, as U_i does.

2. Upon receiving message m_2 from P_j, E then checks P_j's signature and chooses a random integer t to compute (k_{ij}, K_{ij}, w). Before moving on to the next step, attacker E needs to check whether $h(K_{ij}||w||n_2)$ is divisible by e. If not, E has to choose another t or start a new session to satisfy this condition.

3. As $h(K_{ij}||w||n_2)$ is divisible by e, let $h(K_{ij}||w||n_2) = e \cdot b$ for some integer $b \in \mathbb{Z}$. Now, E computes x by $x = SID_i^b$, where $SID_i = ID_i||h(ID_i)$

4. Finally, E can impersonate user U_i to pass the authentication by sending $m_3 = (w, x, y)$ to P_j, since P_j will notice that $SID_i^{h(K_{ij}||w||n_2)} \mod N = x^e \mod N$. This is because we have: $SID_i^{h(K_{ij}||w||n_2)} \mod N = SID_i^{b \cdot e} \mod N = x^e \mod N$.

There are a number of things worth noting in regard to the above impersonation attack without credentials. First, the attack will succeed at a rate of about $1/e$ for one random number t in a new session. The reason is that $e|h(K_{ij}||w||n_2)$ holds with a probability of about $1/e$, since $|e| < |h(\cdot)|$ and the output of hash function h can be treated as random numbers. Consequently, if $e = 3$ the above attack can succeed once by trying about three values of t on average. Even if e is as large as $65537(= 2^{16} + 1)$, trying 65537 times to get a successful impersonation may not be difficult for attacker E as it may explore a machine, which can be much more powerful than a mobile device, to do the computations needed for each try, i.e., two modular exponentiations and two hash evaluations. Moreover, even when timeout is introduced into the Chang-Lee scheme it may be not a real obstacle for attacker E as it can initialize new sessions (w.r.t. the same or different identities).

Second, in the above attack we assume that e is a small integer and attacker E may know the value of one legal user's identity ID_i. This is reasonable as explained below. On the one hand, in the system initialization phase (Section IV-A) the Chang-Lee scheme only specifies that the trusted party $SCPC$ needs to set its RSA key pair (e, d) but does not give any limitation on the length of public exponent e. So, e could be a small integer with binary length less than the output length of hash function h, i.e., $|e| < |h(\cdot)|$. Moreover, in practice this is likely to happen because: (a) to speed up the RSA signature verification, some security standards (e.g. PKCS #1 [PKC]), academic papers (e.g. [Bon99]) and popular web sites ((e.g. wikipedia [Wik12b])) suggest that e can be set as 3 or 65537; and (b) as the Chang-Lee scheme is claimed to be efficient even for mobile devices in distributed networks, using small exponent e can provide further computational advantage for these devices as they usually have limited resources for computation and storage [XSK+05]. In addition, the security analysis given in [CL12] neither excludes the case of small e nor relies on the concrete procedure of setting $SCPC$'s RSA key pair (e, d).

On the other hand, in the Chang-Lee SSO scheme users' identities are not as crucial as their credentials, though the identities are transferred in ciphertext to provide user anonymity. So, users' identities could be known by an attacker due to reasons, such as users' negligence. At least service providers know users' identities. Moreover, even if users' identities are well protected so that attacker E cannot impersonate registered user U_i as above, E can freely forge an identity ID. This is possible because in the Chang-Lee scheme, each user selects his/her identity by following only one requirement: each identity is a string with fixed bit-length. Therefore, even an outside attacker E can use an arbitrary such string as an identity to mount the above attack, since the service providers are not provided any additional mechanism to check whether identity ID has been registered with $SCPC$. This also implies that if e is a small integer, E can even impersonate a nonexistent user to make use of the resources and services offered by service providers.

Finally, it must be emphasized that impersonation attacks without valid credentials seriously violate the security of SSO schemes as it allows attacker to be successfully authenticated without first obtaining a valid credential from the trusted authority after registration. In other words, it means that in an SSO scheme suffering these attacks there are alternatives which enable passing through authentication without credentials.

3.3.3 Discussion

In [CL12], Chang and Lee provided a well-organized security analysis to show that their SSO scheme is secure. However, the two impersonation attacks presented in the previous section mean that their SSO scheme is actually not secure. So, why is their analysis not enough to guarantee the security of their scheme? What is the security flaw in their scheme leading to the above attacks? And what could we learn from these attacks to prevent similar situations in the future design of SSO schemes? These are the topics of this section.

In [CL12], the security of the Chang-Lee SSO scheme has been analysed in three different ways: 1. BAN logic [BAN90] was used to show the correctness of the Chang-Lee scheme; 2. Informal security arguments were given to demonstrate that their scheme can resist some attacks, including impersonation attacks. 3. A formal security proof was given to prove that their scheme is a secure authenticated key exchange (AKE) protocol [BR93a]. However, these security analyses and proofs still do not guarantee the full security of the Chang-Lee scheme and there are a number of reasons for this. First, as early as the 1990s it was known that although BAN logic had been shown useful to identify some attacks, it could approve protocols which are actually unsound in practice because of some technical weaknesses in the logic [BM94]. Moreover, in [CL12] the authors did not give details to show how the BAN logic can be used to prove that their scheme guarantees mutual authentication. In fact, at the end of section V-A of [CL12], the authors claimed to be able to: "prove that U_i and P_j are able to authenticate each other using our protocol." but they provided no argument to show why each party could not be impersonated by an attacker. Second, the authors did discuss informally why their scheme could withstand impersonation attacks by considering two scenarios, for example, an attacker re-uses previous nonce n_2 to forge message m_3 or selects random credential S_i to compute SID_i by $SID_i = S_i^e \mod N$. However, such informal arguments neither strongly confirm their scheme's security against these two concrete attacks nor exclude the existence of other scenarios of impersonation attacks, such as those presented in previous sections. Finally, their formal proof about AKE only focuses on the session key security, i.e., an attacker with all reasonable resources is not able to know the session key established between the two parties under the computational Diffie-Hellman (CDH) assumption (refer to Theorem 1 in [CL12], not the security of mutual authentication. According to the definitions given by Bellare and Rogaway [BR93a], one fundamental requirement of a secure AKE protocol is that there be a secure mutual authentication in the first place.

From the above, we can see that it is the use of credential proof $x = S_i^{h_2} \mod N$ which leads to the above two attacks against the Chang-Lee SSO scheme. More specifically, $x = S_i^{h_2} \mod N$ is a kind of knowledge proof which shows that a prover (usually played by user U_i) knows credential S_i. However, this is not a secure proof as a malicious verifier (i.e. service provider P_j) can recover S_i and an outside attacker may be able to get authenticated without a credential. Based on this observation, a natural improvement on the Chang-Lee scheme would be to replace non-interactive proof x by a rigorous but interactive zero knowledge (ZK) proof [FFS88] that shows the prover's knowledge of secret $S_i = SID_i^d \mod N$ without revealing any additional information about credential S_i. In other words, using the verifiably encrypted signature introduced in [CM00], user U_i can encrypt his/her credential S_i under the public key of a trusted party and verifiably convince service provider P_j that the ciphertext does contain S_i w.r.t. U_i's identity ID_i without allowing P_j to get any additional information about credential S_i. Compared with two modular exponentiations used for generating and verifying proof x, however, ZK proofs for showing the possession of an RSA signature usually require hundreds of modulo exponentiations [ASW00, CM00] since these proofs rely on inefficient 'cut and choose' method, i.e., binary challenges.

From the two attacks presented above, we can learn that both credential privacy and soundness are crucial for SSO schemes. As mentioned in Section III-A, credential privacy has been studied in Yang et. al [YWB$^+$04] and Han *et al.* [HMSY10]. To the best of our knowledge, however, there is surprisingly, no existing research which has given a careful treatment of soundness. For example, Han *et al.* [HMSY10] did not investigate soundness, though they did carefully study how to formally define credential forgery and recovery attacks from outsiders, users, service providers and their potential collusion. According to the most traditional form of authentication, a user will be authenticated if he/she can provide a valid pair of user name and password (i.e. credential), and soundness is obviously satisfied because a user is not able to go through authentication without providing a valid credential which is registered and maintained by a server. In complex scenarios, like the Chang-Lee scheme, the situation may be less obvious and, in fact, quite challenging. For this reason, the problem remains an open one for future study. The question of formally defining the soundness of SSO/authentication schemes and rigorously proving them for concrete solutions remains an interesting and important one.

Finally, it must be noted that the analysis above shows only that the Chang-Lee SSO scheme fails to achieve secure authentication, without violating its security for achieving user anonymity and session key privacy.

3.4 Attacks on the Hsu-Chuang Scheme

In this section, we briefly highlight the difference between the Chang-Lee scheme [CL12] and the Hsu-Chuang scheme [HC09] to see why the above describe impersonation attacks apply to this latter as well. The two schemes have similar structures and use similar notations, but the technical details differ. In summary, the Hsu-Chuang scheme is differs from the Chang-Lee scheme in three ways. First, in the Hsu-Chuang scheme user U_i's credential S_i is a naive RSA signature signed by the trusted party $SCPC$, i.e., $S_i = ID_i^d \mod N$, where ID_i is U_i's identity selected by him/herself. Second, to authenticate itself, service provider P_j sends signature $u = g_j^{h(Z||T_1||ID_j)\cdot d_j} \mod N_j$, where Z is the DH key material generated by P_j, T_1 is the current timestamp, and ID_j is P_j's identity. Finally, for user authentication user U_i issues and sends proof $x = S_i^{h(K_{ij}||Z||w||T_2)} \mod N$ to P_j, who validates x by checking if $ID_i^{h(K_{ij}||Z||w||T_2)} = x^e \mod N$. For more detail, see [HC09] or Section II of [CL12].

As pointed out in [CL12], the Hsu-Chuang scheme is vulnerable to impersonation attack as an attacker can forge a valid credential S_i w.r.t. identity ID_i by simply selecting random $S_i \in \mathbb{Z}_N^*$ and then computing $ID_i = S_i^e \mod N$. This attack can be excluded if a specific encoding format is required for identities and the credential is issued by using a secure hash h, i.e., $S_i = h(ID_i)^d \mod N$, as in the Chang-Lee scheme. According to the discussion in Section III, the Hsu-Chuang scheme is still not secure even with such a countermeasure. The reason is that our two attacks against the Chang-Lee scheme apply to the Hsu-Chuang scheme as well. This means that the Hsu-Chuang scheme also fails to satisfy both credential privacy and soundness of authentication. In addition, there is another flaw in the Hsu-Chuang scheme. Attacker E can impersonate service provider P_j to cheat legal users, as the service authentication is conducted by using a non-traditional RSA signature, $u = g_j^{h(Z||T_1||ID_j)\cdot d_j} \mod N_j$. By communicating with P_j twice attacker E can get messages (Z, T_1, ID_j, u) and (Z', T_1', ID_j, u') so that $u = g_j^{h(Z||T_1||ID_j)\cdot d_j} \mod N_j$ and $u' = g_j^{h(Z'||T_1'||ID_j')\cdot d_j} \mod N_j$. Once $\gcd(h(Z||T_1||ID_j), h(Z'||T_1'||ID_j)) = 1$ (this holds with probability about 0.6), E can find two integers a and b such that $a \cdot h(Z||T_1||ID_j) + b \cdot h(Z||T_1||ID_j) = 1$. Hence, E can recover $g_j^{d_j} \mod N_j$ by computing $g_j^{d_j} \mod N_j = u^a u'^b \mod N_j$. After that, E can impersonate P_j to any legal user by using the value of $g_j^{d_j} \mod N_j$ to issue signature $u = (g_j^{d_j} \mod N_j)^{h(Z||T_1||ID_j)}$, without knowing P_j's RSA private key d_j.

3.5 Proposed Improvement

To overcome the flaws in the Chang-Lee scheme [CL12], an RSA-based verifiable encryption of signatures (RSA-VES) can be employed. This is an efficient primitive introduced in [Ate04] for realizing fair exchange of RSA signatures.

The basic idea of the improved scheme can be highlighted as follows. User U_i's credential is $S_i = h(ID_i)^{2d} \mod N$, i.e., SCPC's RSA signature on the square of the hashed user identity (in contrast to $S_i = h(ID_i)^d \mod N$ in [CL12]). For user authentication, U_i will encrypt his/her credential S_i using ElGamal encryption of SCPC's other public key $y = g^u$ by computing $P_1 = S_i \cdot y^r \mod N$ and $P_2 = g^r \mod N$, where $g \in \mathbb{Z}_N^*$ of big order and u is SCPC's secret decryption key. In this improvement, SCPC also plays the role of the trust authority in VES. To convince a service provider that (P_1, P_2) does encrypt his/her credential S_i (i.e. SCPC's RSA signature for ID_i), U_i must also provide an NZK proof x to show that he or she knows a secret r such that $\frac{P_1^e}{h(ID_i)^2} = (y^e)^r \mod N$ and $P_2 = g^r \mod N$. Such a proof x, is called 'proving the equality of two discrete logarithms in a group of unknown order' [Ate04], will convince the service provider without leaking any useful information about U_i's credential S_i. For server authentication, service providers can simply issue signatures as did [CL12], though the proposed changes give service providers the freedom to employ any secure signature scheme. The other procedures are the same as in the Chang-Lee scheme.

3.5.1 Initialization Phase

SCPC selects two large safe primes p and q to set $N = pq$. Namely, there are two primes p' and q' such that $p = 2p' + 1$ and $q = 2q' + 1$. SCPC now sets its RSA public/private key pair (e, d) such that $ed \equiv 1 \mod 2p'q'$, where e is a prime. Let Q_N be the subgroup of squares in $\mathbb{Z}_N^*$ whose order $\#G = p'q'$ is unknown to the public but its bit-length $l_G = |N| - 2$ is publicly known. SCPC randomly picks generator g of Q_N, selects an ElGamal decryption key u, and computes the corresponding public key $y = g^u \mod N$. In addition, for completing the Diffie-Hellman key exchange SCPC chooses generator $\overline{g} \in \mathbb{Z}_N^*$, where n is another large prime number. SCPC also chooses a cryptographic hash function $h(\cdot) : \{0,1\}^* \rightarrow \{0,1\}^k$, where security parameter k satisfies $160 \leq k \leq |N| - 1$. Another security parameter $\epsilon > 1$ is chosen to control the tightness of the ZK proof [GAT00]. Finally, SCPC publishes $(e, N, h(\cdot), \epsilon, g, y, \overline{g}, n)$, and keeps (d, u) secret.

3.5.2 Registration Phase

In this phase, upon receiving a register request, $SCPC$ gives U_i fixed-length unique identity ID_i, and issues credential $S_i = h(ID_i)^{2d} \mod n$. S_i calculated as SCPC's RSA signature on $h(ID_i)^2$ is an element of Q_N, which will be the main group we are calculating.

As in [CL12], each service provider P_j with identity ID_j should maintain a pair of signing/verifying keys for a secure signature scheme (not necessarily RSA). $\sigma_j(Msg, SK_j)$ denotes the signature σ_j on message Msg signed by P_j using signing key SK_j. $SVer(Msg, \sigma_j, PKj)$ denotes verifying of signature σ_j with public key PK_j, which outputs '1' or '0' to indicating if the signature is valid or invalid, respectively.

3.5.3 Authentication Phase

In this phase, RSA-VES is employed to authenticate a user, while a normal signature is used for service provider authentication. The details are illustrated in

Fig. 3.2 and further explained as follows:

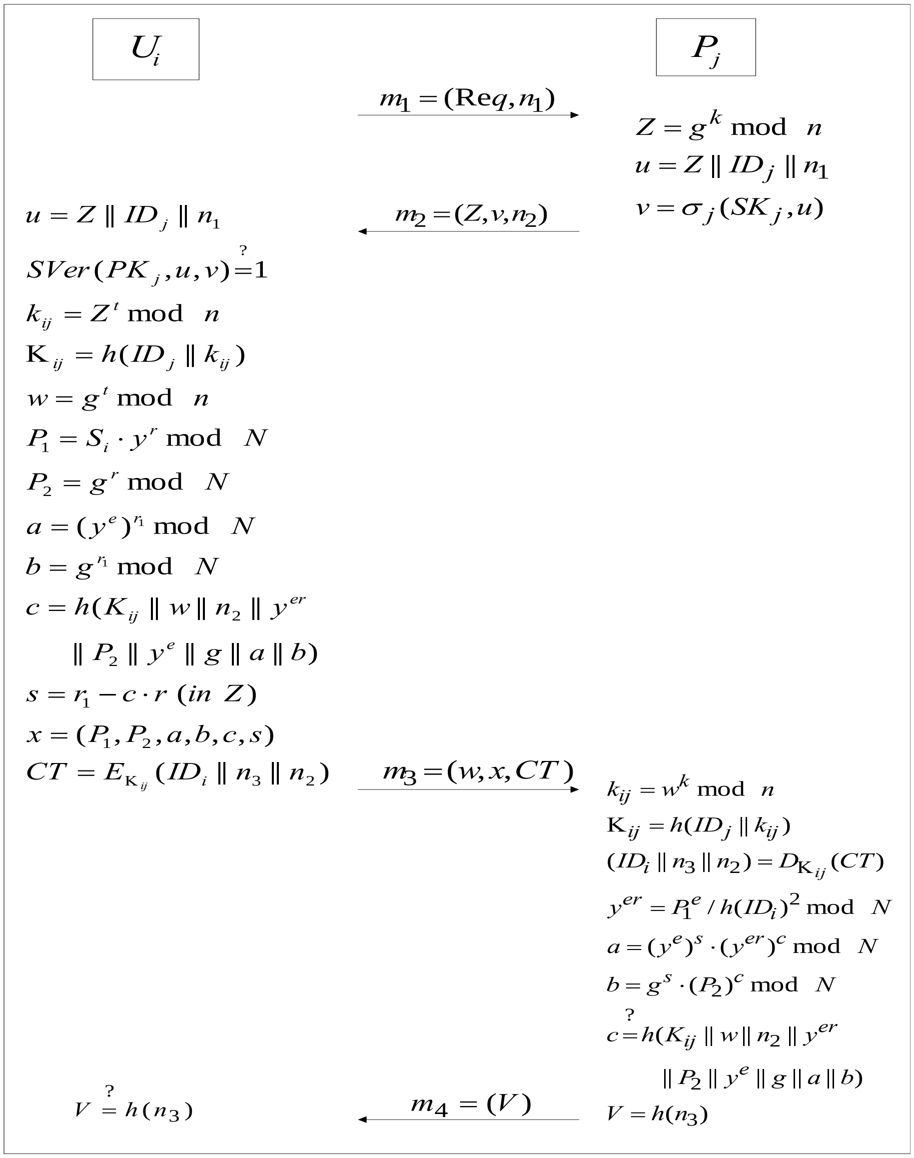


Figure 3.2: The Proposed Improved Scheme

1. U_i sends a service request with nonce n_1 to service provider P_j,

2. Upon receiving (Req, n_1), P_j calculates its session key material $Z = g^k \mod n$ where $k \in \mathbb{Z}_N^*$ is a random number, sets $u = Z||ID_j||n_1$, issues a signature $v = \sigma_j(u, SK_j)$, and then sends $m_2 = (Z, v, n_2)$ to the user, where n_2 is a nonce selected by P_j.

3. Upon receiving m_2, U_i sets $u = Z||ID_j||n_1$. U_i terminates the conversation if $SVer(u, v, PK_j) = 0$. Otherwise, U_i accepts service provider P_j because the

signature is valid. In this case, U_i selects a random number $t \in \mathbb{Z}_n^*$ to compute $w = g^t \mod n$, $k_{ij} = Z^t \mod n$, and the session key $K_{ij} = h(ID_j||k_{ij})$. For user authentication, U_i first encrypts his/her credential S_i as $P_1 = S_i \cdot y^r \mod N$, $P_2 = g^r \mod N$, where r is a random integer with binary length l_G. Next, U_i computes two commitments $a = (y^e)^{r_1} \mod N$ and $b = g^{r1} \mod N$, where $r_1 \in \pm\{0,1\}^{\epsilon(l_G+k)}$ is also a random number. After that, U_i computes the evidence showing that credential S_i has been encrypted in (P_1, P_2) under public key y. For this purpose, U_i calculates $c = h(K_{ij}||w||n_2||y^{er}||P_2||y^e||g||a||b)$ and $s = r_1 - c \cdot r$ (in $\mathbb{Z}$). Then, $x = (P_1, P_2, a, b, c, s)$ is the NIZK proof for user authentication. In fact, it is precisely, the processes of generating x which is the proof part of RSA-VES [Ate04]. Finally, U_i encrypts his/her identity ID_i, new nonce n_3, and P_j's nonce n_2 using session key K_ij to get ciphertext $CT = E_{K_{ij}}(ID_i||n_3||n_2)$, and thereafter sends $m_3 = (w, x, CT)$ to service provider P_j.

4. To verify U_i, P_j calculates $k_{ij} = w^k \mod n$, the session key $K_{ij} = h(ID_j||k_{ij})$, and then uses K_{ij} to decrypt CT and recover (ID_i, n_3, n_2). Then, P_j computes $y^{er} = P_1^e/h(ID_i)^2 \mod N$, $a = (y^e)^s \cdot (y^{er})^c \mod N$, $b = g^s \cdot (P_2)^c \mod N$, and checks if $(c, s) \in \{0,1\}^k \times \pm\{0,1\}^{\epsilon(l_G+k)}$ and $c = h(K_{ij}||w||n_2||y^{er}||P_2||y^e||g ||a||b)$. If the output is negative, P_j aborts the conversation. Otherwise, P_j accepts U_i and believes that they have shared the same session key K_ij by sending U_i $m_4 = (V)$ where $V = h(n_3)$.

5. After U_i receives V, he checks if $V = h(n_3)$. If this is true, then U_i believes that they share the same session key K_{ij}. Otherwise, U_i terminates the conversation.

3.5.4 Security Discussion

We now analyse the security of the improved SSO scheme by focusing on the security of the user authentication part, especially soundness and credential privacy due to two reasons. On the one hand, the unforgeability of the credential is guaranteed by the unforgeability of RSA signatures, and the security of service provider authentication is ensured by the unforgeability of the secure signature scheme chosen by each service provider. On the other hand, other security properties (e.g., user anonymity and session key privacy) are preserved, since these properties have been formally proved in [CL12] and the corresponding parts of the Chang-Lee scheme are kept unchanged.

Soundness requires that without holding valid credential S^* corresponding to a target user U^*, an attacker, who could be a collusion of users and service providers, has at most a negligible probability of generating proof x^* and going through user authentication by impersonating user U^*. The soundness of the above improved SSO scheme relies on the soundness of the NIZK proof, which also guarantees the soundness of RSA-VES, defined as the second property of Definition 1 in [Ate04]. Namely, if the user authentication part is not sound, i.e., an attacker can present valid proof x^* without holding the corresponding credential S^* in non-negligible probability, then this implies the NIZK proof of proving equality of two discrete logarithms in a group of unknown order is not sound, contradictory to the analysis given in Section 3.7 of [Ate04].

Credential privacy or credential irrecoverableness requires that there be a negligible probability of an attacker recovering a valid credential from the interactions with a user. Again this property can be deduced from the signature hiding property of RSA-VES, defined as the third property of Definition 1 in [Ate04]. Signature hiding means that an attacker cannot extract a signature from VES without help from the user who encrypted the signature or the trusted authority who can decrypt a VES. So, if this improved SSO scheme fails to meet credential privacy, it implies that Ateniese's RSA-VES fails to satisfy signature hiding, which is contrary to the analysis given in Section 3.7 of [Ate04]. In fact, soundness and signature hiding are the two core security properties to guarantee the fairness of digital signature exchange using VES.

More rigorous security proofs require to first formally define these two properties, and these are interesting topics for further study.

3.6 Conclusion

In this chapter, we demonstrated two effective impersonation attacks on Chang and Lee's single sign-on (SSO) scheme [CL12]. The first attack shows that their scheme cannot protect the privacy of a user's credential, and thus, a malicious service provider can impersonate a legal user in order to enjoy the resources and services from other service providers. The second attack violates the soundness of authentication by giving an outside attacker without credential the chance to impersonate even a non-existent user and then freely access resources and services provided by service providers. We also discussed why their well-organised security arguments are not strong enough to guarantee the security of their SSO scheme. In addition, we explained why Hsu and Chuang's scheme [HC09] is also vulnerable to these attacks. In addition, by employing an efficient verifiable encryption of RSA signatures introduced by Ateniese [Ate04], we proposed an improved the Chang-Lee scheme to achieve soundness and credential privacy. The unresolved problems for future work are to formally define authentication soundness and construct efficient and provably secure single sign-on schemes.

Chapter 4

A Provably Secure Single Sign-On Scheme

4.1 Introduction

As suggested in the previous chapter, it is necessary to formally define the soundness of authentication and to construct efficient and provably secure single sign-on schemes for mobile device users in distributed systems and networks. To design a secure SSO scheme, intuitively, there are three basic security requirements which should be considered: completeness, soundness and credential privacy. Completeness of authentication [BR93a] requires that: (a) both sides accept each other if they have matched the conversation; (b) the probability that one side accepts the other one who actually has not engaged in the matching conversation is negligible. Soundness means that an unregistered user without a credential should not be able to access the services offered by service providers. Credential privacy guarantees that colluding dishonest service providers should not be able to fully recover a user's credential and then impersonate the user to log in to other service providers. Soundness of credential based authentication, however, has not been formally studied yet although it is important, and the preserving of both soundness and credential privacy is still a challenge in designing SSO [WYX12].

In 2010, Han *et al.* [HMSY10] proposed a generic construction of SSO schemes. This construction relies on broadcast encryption plus zero knowledge (ZK) proof [FFS88] showing that the prover knows the corresponding private key of a given public key. So, implicitly, each user is assumed to have been issued a public key in a public key infrastructure (PKI). In the setting of an RSA cryptosystem, however, such ZK proof is very inefficient due to the complexity of interactive communications between the prover (a user) and the verifier (a service provider). In addition, the requirement of PKI services for each user imposes a heavy burden on the implementation of SSO scheme. The function of session key establishment is also desired in order to secure the further communication.

In order to solve these problems, this chapter first formally defines the single sign-on schemes with authenticated key exchange. Then, we propose an SSO scheme according to the formal model by exploiting the Schnorr signature due to its simplicity and unforgeability [GMR89, Mao04]. In particular, this scheme uses Schnorr signature to generate a user's credential and then, to authenticate him/her the user uses his/her credential as a private key to issue a Schnorr signature on some information generated in each session. As did in Chang-Lee scheme, a variant of Diffie-Hellman key exchange mechanism is employed to establish the session key. Furthermore, the security of the proposed protocol is discussed.

The rest of this chapter is organized as follows. The next section specifies a formal model for SSO with a unified definition of soundness and credential privacy. The proposed SSO scheme is given in section 4.3. The security of the proposed protocol is discussed in section 4.4. Finally, section 4.5 concludes this chapter.

4.2 Formal Model

In this section we present a formal model to define single sign-on schemes which support session key establishment. This model called authenticated key exchange single sign-on (AKESSO). This section also provides the security requirements of AKESSO. In particular, we list the components (e.g. syntax) of AKESSO, define correctness, describe an adversary model, and formally specify three security properties, including secure credential-based user authentication, secure credential-based service provider authentication, and session key security.

Definition 4.1. *An* ***authenticated key exchange single sign-on (AKESSO)*** *scheme is comprised of trusted credential provider (TCP), group of service providers P and group of users U. It consists of eight algorithms and protocol: initialization algorithm $Init(\cdot)$, identity generation algorithm $IdGen(\cdot)$, credential generation algorithm $CGen(\cdot)$, credential verification algorithm $CVer(\cdot)$, user proof generation algorithm $UPGen(\cdot)$, user proof verification algorithm $UPVer(\cdot)$, service provider proof generation algorithm $SPPGen(\cdot)$, and service provider proof verification algorithm $SPPVer(\cdot)$, and key exchange protocol $\prod$.*

1. *Init*(λ): *Taking security parameter* λ_0 *(or* λ_1*) as input, outputs the public/private key pair* (PK, SK) *for TCP (or* (PK_j, SK_j) *for* $P_j \in P$*).*

2. *IdGen*(RI_i): *Taking registration information* RI_i *as input, outputs unique identity* ID_i *for user* $U_i \in U$*.*

3. *CGen*(ID_i, SK): *Taking identity* ID_i *and TCP's private key* SK *as input, outputs credential* C_i *for user* U_i*.*

4. *CVer*(C_i, ID_i, PK): *Taking credential* C_i*, identity* ID_i*, and TCP's public key* PK *as input, outputs '1' or '0' for accepting or rejecting credential* C_i *respectively.*

5. *UPGen*(C_i, ID_i, PK, M): *Taking credential* C_i*, identity* ID_i*, TCP's public key* PK *and temporal message* M *generated in a session as input, outputs user proof* up_i *showing user* U_i*'s knowledge of credential* C_i*.*

6. *UPVer*(up_i, ID_i, PK, M): *Taking user proof* up_i*, identity* ID_i*, TCP's public key* PK*, and temporal message* M *generated in a session as input, outputs '1' or '0' for accepting or rejecting* up_i *as a valid credential proof w.r.t. identity* ID_i *respectively.*

7. *SPPGen*(SK_j, M'): *Taking service provider* P_j*'s private key* SK_j *and temporal message* M' *generated in a session as input, outputs service provider proof* spp_j *showing* P_j*'s knowledge of* SK_j*.*

8. *SPPVer*(spp_j, PK_j, M'): *Taking service provider proof* spp_j*,* P_j*'s public key* PK_j*, and temporal message* M' *generated in a session as input, outputs '1' or '0' for accepting or rejecting* spp_j *as a valid service provider proof w.r.t. public key* PK_j *respectively.*

9. $\prod$: *This is a key exchange protocol run by user* U_i *with private input* C_i *and service provider* P_j *with private input* SK_j*. After the completion of each protocol instance,* U_i *will output session key* K_{ij} *if he/she accepts* P_j*. Similarly, after the completion of each protocol instance* P_j *will output session key* K_{ji} *if it accepts* U_i*. (Ideally,* K_{ij} *and* K_{ji} *are expected to be the same value.)*

Remark 4.1. *The above definition focuses on public key based AKESSO with non-interactive proofs. It could be extended to support interactive proofs, where* sp_i *and*

ssp_j are generated by interactive protocols run by user U_i and service provider P_j. However, defining symmetric key based AKESSO is an area which is beyond the scope of this paper.

Remark 4.2. *Compared to Han et al.'s formal model given in [HMSY10], we require key exchange in AKESSO, and each user does not need to hold a public/private key pair. However, in Han et al.'s definition TCP (called IdP in their paper) is less trusted as it will not be able to impersonate any user: Each user will run a zero knowledge protocol to show that he/she knows the private key corresponding to the public key embedded in his/her credential.*

Before formally defining security properties, it is obvious that an AKESSO must be *correct*. Credential C_i generated by trusted credential provider TCP will be valid. User proof up_i issued properly by user u_i who holds a valid credential C_i, will be accepted by service provider P_j according to the $UPVer$ algorithm, service provider proof spp_j issued properly by P_j will be accepted by user U_i according to the $SPPVer$ algorithm, and U_i and P_j will accept each other and output the same session key if they honestly run the key exchange protocol $\prod$. Formally, we define correctness as the following:

Definition 4.2. ***(Correctness)*** *An AKESSO scheme is called correct if it satisfies all the following conditions:*

1. *For any RI_i and any key pair (PK, SK), if $ID_i \leftarrow IdGen(RI_i)$ and $C_i \leftarrow CGen(ID_i, SK)$, then $CVer(C_i, ID_i, PK) = 1$.*
2. *For any ID_i, any key pair (PK, SK) and any M, if $C_i \leftarrow CGen(ID_i, SK)$ and $up_i \leftarrow UPGen(C_i, ID_i, PK, M)$, then $UPVer(up_i, ID_i, PK, M) = 1$.*
3. *For any key pair (PK_j, SK_j) and any M', if $spp_j \leftarrow SPPGen(SK_j, M')$, then $SPPVer(spp_j, PK_j, M') = 1$.*
4. *For any user U_i with valid credential C_i and service provider P_j with private key SK_j, if both of them run the key exchange protocol $\prod$ honestly, then they will accept each other and output the same session key, i.e., $K_{ij} = K_{ji}$.*

Informally, an AKESSO scheme is secure if all the desired functionalities given in the above definition can be carried out only by the proper entities, i.e., not by attackers who are allowed to access all possible resources in a rigorously specified adversary model. In fact, we shall define the *security of SSO authentication* which corresponds to items 1) to 3), and *session key privacy* which corresponds to item 4).

To further define these security properties, we specify the **adversary model** as follows: Let $\prod_{TCP}$ be the trusted authority oracle with its key pair (SK, PK), $\prod_{U,P}^{i}$ be the user oracle simulating a set of all registered users, interacting with the service provider oracle in session i, and $\prod_{P,U}^{j}$ be the service provider oracle simulating a set of all registered service providers, interacting with the user oracle in session j. Probabilistic polynomial time (PPT) adversary A can ask the following oracle queries.

1. $\mathcal{O}_1$: $Register(\prod, U)$— Upon receiving this query, $\prod_{TCP}$ runs the $IdGen(RI_{A_i})$ and $CGen(ID_{A_i}, SK)$ algorithms, and outputs new user identity ID_{A_i} with corresponding credential C_{A_i} to A who can verify the credential by running $CVer(\cdot)$.

2. $\mathcal{O}_2$: $Register(\prod, P)$— Upon receiving this query, the system will run $Init(\lambda_1)$ and output P_{A_j}'s private/public key pair (SK_{A_j}, PK_{A_j}) together with identity SID_{A_j} to A.

3. $\mathcal{O}_3$: $Execute(U_i, P_j)$— Upon receiving this query, $\prod_{U,P}^{i}$ and $\prod_{P,U}^{j}$ will execute protocol as U_i and P_j in $\prod$, respectively. The exchanged messages between them will be recorded and sent to A. Here, we require that both U_i's credential and P_j's private key are not been corrupted by A via $\mathcal{O}_1$ and $\mathcal{O}_2$ oracles.

4. $\mathcal{O}_4$: $Send(U_i, m, f)$—This query sends the message m as message flow $f \in \{0, 1, \cdots, n\}$ to the user oracle $\prod_{U,P}^{i}$ which simulates a user U_i, and then, the oracle computes message honestly in $\prod$, and sends responses back to A, where n is the total number of messages transmitted in protocol $\prod$. If a user is the protocol initiator by default, A can also start a new session by asking $Send(U_i, \emptyset, 0)$, where $\emptyset$ denotes an empty set.

5. $\mathcal{O}_5$: $Send(P_j, m, f)$—This query sends the message m as message flow $f \in \{0, 1, \cdots, n\}$ to the user oracle $\prod_{P,U}^{i}$ which simulates a service provider P_j, and then, the oracle computes message honestly in $\prod$, and sends responses back to A. If a service provider is the protocol initiator by default, A can also start a new session by asking $Send(P_j, \emptyset, 0)$.

6. $\mathcal{O}_6$: *Reveal*$(\prod, i)$—This query models the leakage of session key in session i. This query only can be asked when a session key has been shared between a service provider and a user in session i.

Remark 4.3. *$\mathcal{O}_3$ simulates the real environment for passive attacker A who can eavesdrop all messages exchanged between U_i and P_j when executing protocol $\prod$. If A knows U_i's credential C_i and P_j's private key SK_j, oracle $\mathcal{O}_3$ is not necessary as A can run protocol $\prod$ by itself on their behalf. If A knows one of these two secrets but not both, A can run protocol $\prod$ with U_i (P_j) whose secret is not released by executing oracle $\mathcal{O}_4$ ($\mathcal{O}_5$).*

Remark 4.4. *$\mathcal{O}_4$ simulates the real environment for active attacker A who may obtain service provider P_j's private key SK_j, send message m as message flow $f \in \{0, 1, \cdots, n\}$ to target user U_i and then get the corresponding response. To answer this oracle, U_i will generate his/her response according to the specification of protocol $\prod$ and send it to A. Note that if U_i has not received all necessary previous messages that match this message with message flow f, this oracle request will be rejected, since it is meaningless to U_i. In fact, $\mathcal{O}_4$ also provides adversary A oracle access on algorithm $UPGen(\cdot)$ since $\prod_{U,P}^{i}$ will run $UPGen(\cdot)$ somehow in executing $\prod$. In our construction, $UPGen(\cdot)$ is the Schnorr signature generation algorithm. In this case, on the one hand, oracle $\mathcal{O}_4$ may be no stronger than the signing oracle in Game-UFCMA reviewed in section IV, since temporal message M, one input of algorithm $UPGen(\cdot)$, may be jointly decided by U_i and A (playing the role of P_j), rather than just by A. So, it may be hard for A to get U_i's user proof for any arbitrary message M. On the other hand, adversary A may, in fact, not be weaker than the forger in Game-UFCMA since besides $\mathcal{O}_4$ we also offer other oracle queries, which may increase A's attack capability.*

To formally define soundness and credential privacy, it is necessary to discuss the difference between them, since the majority of existing schemes only consider credential privacy. Credential privacy requires unforgeability and unrecoverability. The former guarantees that any PPT adversary A has only a negligible probability for successfully forging valid credential C_t of target user U_t in the credential generation phase, while the latter requires that in the user authentication phase, any A can only recover C_t with a negligible probability. Soundness is also critical in the user authentication phase as it ensures that there is a negligible probability that any

A without a valid credential can generate user proof up that passes through user authentication. The existing studies [HMSY10, CL12] only focus on whether a valid credential can be forged or recovered by attackers, but do not consider if a valid credential is definitely necessary for generating a valid user proof. We shall define these three properties as a single definition (but one for users and one for service providers).

Let $A^{\mathcal{O}}$ denotes adversary A who has access to all oracle queries in $\mathcal{O} = \{\mathcal{O}_i | i = 1, 2, \cdots, 6\}$ in the adversary model; let credential holder U_i with identity ID_i and credential C_i, and service provider P_j with identity SID_j and key pair (SK_j, PK_j) be two polynomial-time Turing machines. Let U_i and P_j interact with each other, and place A between U_i and P_j. ϵ denotes a negligible function. We define secure credential-based user authentication as follows:

Definition 4.3. ***(Secure credential-based user authentication (SCUA))*** *An AKESSO scheme achieves secure credential-based user authentication, if PPT adversary A has negligible advantage* $Adv^{SCUA}(A^{\mathcal{O}})$ *for creating a valid user proof without holding the corresponding credential. Formally, for any PPT A,* $Adv^{SCUA}(A^{\mathcal{O})} \triangleq \Pr[(ID_t, up_t, M) \leftarrow A^{\mathcal{O}} | UPVer(up_t, ID_t, PK, M) = 1] \leq \epsilon$ *with the following restrictions:*

- *A has not obtained credential* C_t *corresponding to* ID_t *via* $\mathcal{O}_1$ *-* $Register(\prod, U)$ *oracle; and*
- *A has not obtained valid user proof* up'_t *for message* M *by asking any oracle in* $\mathcal{O}$*, in particular* $\mathcal{O}_3$ *and* $\mathcal{O}_4$*.*

Similarly, the definition of secure service provider authentication is given below:

Definition 4.4. ***(Secure service provider authentication (SSPA))*** *An AKESSO scheme achieves secure service provider authentication if PPT adversary A has negligible advantage* $Adv^{SSPA}(A^{\mathcal{O}})$ *for forging a valid service provider proof without holding the corresponding service provider's private key . Formally, for any PPT A,* $Adv^{SSPA}(A^{\mathcal{O}}) \triangleq \Pr[(PK_t, M', spp_t) \leftarrow A^{\mathcal{O}} | SPPVer(PK_t, M', spp_t) = 1] \leq \epsilon$ *with the following restrictions:*

- *A has not obtained the private key* SK_t *corresponding to* SID_t *via* $\mathcal{O}_2$ *-* $Register(\prod, P)$ *oracle;*

- *A has not obtained valid service provider proof spp_t for message M' by asking any oracle in $\mathcal{O}$, in particular $\mathcal{O}_3$ and $\mathcal{O}_5$.*

Here, we review the freshness and test query $Test(\prod, i)$ for defining session key security [BR93a]. An adversary can get session keys by asking $\mathcal{O}_6$. We say the session key is *fresh* if and only if the $\mathcal{O}_6$ query has not been asked w.r.t. this session. In other words, the fresh session key must be unknown to the adversary. For simplicity, we call the test query $\mathcal{O}_7$, which is a game defined as follows:

- $\mathcal{O}_7$ — $Test(\prod, i)$: In protocol $\prod$, if $\prod_{U,P}^i$ and $\prod_{P,U}^i$ accept and share the same fresh session key in session i, upon receiving this query, by tossing coin b the correct session key is returned if $b = 0$, otherwise, a random session key is returned. A can only ask this query once and A needs to output one bit b' as the result of guessing b. A's advantage in attacking the session key security (SKS) of protocol $\prod$ is defined as $Adv_{\prod}^{SKS}(A^{\mathcal{O}'})$=$|2\Pr[b' = b] - 1|$, where $\mathcal{O}' = \mathcal{O} \cup \{\mathcal{O}_7\}$.

Session key security [BR93a] models adversary A's inability to distinguish the real session key and a random string, as formally defined below.

Definition 4.5. ***(Session Key Security)*** *We say an AKESSO satisfies session key security if for any PPT adversary A, $Adv_{\prod}^{SKS}(A^{\mathcal{O}'}) \leq \epsilon$, where $\mathcal{O}' = \mathcal{O} \cup \{\mathcal{O}_7\}$.*

Finally, we can give the definition of a secure authenticated key exchange single sign-on scheme.

Definition 4.6. ***(Secure Authenticated Key Exchange Single Sign-On Scheme)*** *An AKESSO scheme is called secure if it is correct and satisfies SCUA, SSPA, and session key security.*

4.3 Proposed Single Sign-On Scheme

This section presents a secure single sign-on scheme with user anonymity for remote user authentication in distributed systems and networks. We use a Schnorr signature [Sch89, Sch91] to overcome the drawbacks in the Chang-Lee scheme as their user proof cannot provide soundness and credential privacy while the Schnorr signature can. As a provably unforgeable signature scheme [PS00], Schnorr signature allows a signer to authenticate him/herself by signing a message without releasing

TCP	The trusted credential provider
P_j	A service provider
U_i	A user
SID_j	The unique identity of P_j
ID_i	The unique identity of U_i
C_i	The credential of U_i
x	The long term private key of TCP
y	The public key of TCP
$E_k(M)$	Symmetric encryption of message M using key k
$D_k(C)$	Symmetric decryption of ciphertext C using key k
$h(\cdot)$	A secure hash function

Table 4.1: Notations in the Proposed SSO Scheme

any other useful information about his/her private signing key. In the proposed scheme, the TCP first issues the credential for each user by signing the user's identity ID_i according to the Schnorr signature. Then, by treating his/her credential as another public/private key pair the user can authenticate him/herself by signing a Schnorr signature on a temporary message generated in the protocol. By contrast, each service provider maintains its own public/private key pair in any secure signature scheme so that it can authenticate itself to users by simply issuing a normal signature. Finally, as happens in the Chang-Lee scheme [CL12], the session key is established by running a variant of the Diffie-Hellman key exchange protocol, and user anonymity is guaranteed by symmetric key encryption. The notations used in the scheme are summarized in Table 4.1.

System Setup Phase: In this phase, TCP initializes his/her public and private parameters as a Schnorr signature scheme. First, TCP picks large primes p and q such that $q|p-1$, chooses generator g of large safe prime order q in cyclic group G. Then, TCP sets its private key $SK = x$, where $x \in \mathbb{Z}_q^*$ is a random number, and publishes its public key $PK = y$, where $y = g^x \mod p$.

Registration Phase: In this phase, the user asks TCP for registration, then TCP issues unique identity ID_i via $IdGen(RI_i)$ and signs a Schnorr signature (a, e, C) for user's identity as credential generation algorithm $CGen(ID_i, SK)$. C is kept secret by the user, while (a, e) will be made public. The details are given below.

- User Registration: When user U_i asks for registration, TCP selects unique identity ID_i and generates credential $C_i = (a, e, C)$ for U_i by selecting a randomness $r \in \mathbb{Z}_q^*$ and computing $a = g^r \mod p$, $e = h(a, ID_i)$, and $C = r + xe$

mod q. Then, TCP sends identity ID_i and credential C_i which is a Schnorr signature for ID_i to user U_i, where C should be kept secret.

- Service Provider Registration: Each P_j maintains a public/private key pair (PK_j, SK_j) of any secure signature scheme. Here, algorithms $SPPGen(\cdot)$ and $SPPVer(\cdot)$ are identical to the signature generation and verification algorithms respectively.

Authentication Phase: In this phase, to authenticate him/herself user U_i signs a Schnorr signature on the newly established session key K_{ij} using credential C the signing key, while U_i's session key material k_2 is used as the commitment. Note that the corresponding verification key of C is g^C, which can be recovered by computing $g^C = a \cdot y^e \mod p$. For service provider authentication, any provably secure signature scheme can be used to authenticate a service provider in the proposed scheme. The session key is established by using the modified Diffie-Hellman key exchange scheme which has been formally proved in [CL12], and user anonymity and unlinkability are preserved by using symmetric key encryption to encrypt a, e, and user's identity ID_i. The details of this phase are illustrated in Figure 4.1 and further explained below.

1. User U_i chooses random nonce n_1 and sends $M_1 = (Req, n_1)$ to P_j, where Req is a service request.

2. Upon receiving (Req, n_1), P_j picks random number $r_1 \in \mathbb{Z}_q^*$, computes its session key material $k_1 = g^{r_1} \mod p$, $u = h(k_1||SID_j||n_1)$ and signs u to get signature $v = SPPGen(SK_j, u)$, and sends $M_2 = (k_1, v, n_2)$ to the user.

3. User U_i first computes $u = h(k_1||SID_j||n_1)$ and verifies the signature v by checking if $SPPVer(PK_j, u, v) = 1$. If the output is "0", U_i terminates the protocol. Otherwise, U_i accepts service provider P_j's authentication, and then selects random number $r_2 \in \mathbb{Z}_q^*$ to compute $k_2 = g^{r_2} \mod p$, $k_{ij} = k_1^{r_2} \mod p$, and the session key $K_{ij} = h(SID_j||k_{ij})$. After that, U_i signs K_{ij} using his/her credential secret C by calculating $e_i = h(k_2, K_{ij})$, $z = r_2 + Ce_i \mod q$ and $\omega = E_K(ID_i||n_3||n_2||e||a)$, where n_3 is a nonce chosen by U_i. Finally, U_i sends $M_3 = (\omega, z, k_2)$ to service provider P_j.

4. To verify z, P_j first calculates $k_{ij} = k_2^{r_1} \mod p$, derives session key $K_{ij} = h(SID_j||k_{ij})$ and decrypt ω with K_{ij} to recover $ID_i||n_3||n_2||e||a$. Then, P_j

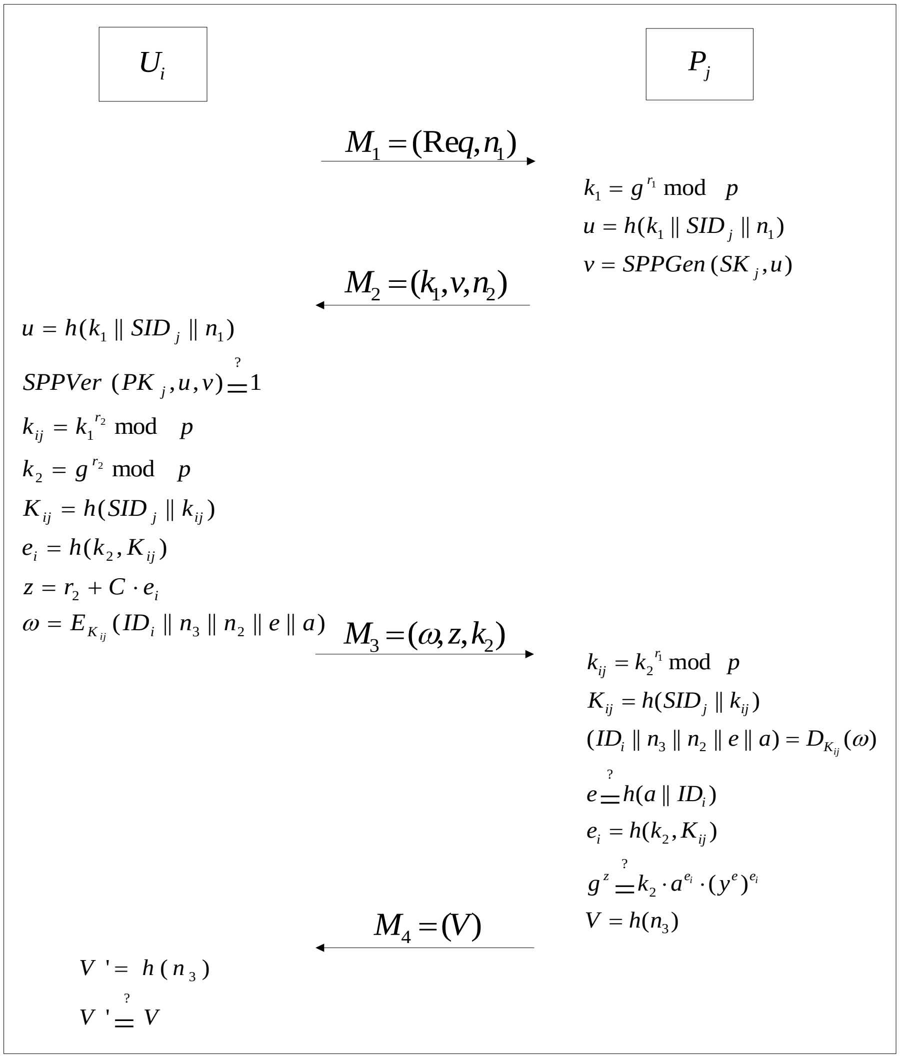


Figure 4.1: Participant Identification Phase of the Proposed SSO Scheme

checks if $e = h(a||ID_i)$. If this does not hold, P_j aborts the protocol. Otherwise, the service provider computes $e_i = h(k_2, K_{ij})$ and verifies z by checking if $g^z = k_2 \cdot a^{e_i} \cdot (y^e)^{e_i} \mod p$. If this holds, P_j accepts U_i's authentication, believes that they have shared the same session key K_{ij}, and sends $V = h(n_3)$ as M_4 to U_i.

5. User U_i computes $V' = h(n_3)$ and checks if $V' = V$. If this holds, U_i believes that he/she has shared the same session key K_{ij} with P_j.

4.4 Security Analysis

The proposed scheme employs the Schnorr signature scheme [Sch89, Sch91] to generate credentials for users, uses a modified Diffie-Hellman key exchange scheme to establish the session key, signs a Schnorr signature on the hashed session key for user authentication, uses any secure signature scheme for server authentication, and uses symmetric key encryption to ensure user anonymity. The secure authenticated key exchange single sign-on (AKESSO) scheme requires secure credential-based user authentication (SCUA), secure service provider authentication (SSPA), and a secure session key. To prove the security of the proposed AKESSO, it will only be necessary to prove SCUA and SSPA because (1) the proposed scheme only improves parts of key generation, user authentication and service provider authentication in the Chang-Lee scheme [CL12], while user anonymity and session key establishment have not been modified; and user anonymity and session key security have been proved in [CL12] and discussed in [WYX12] without revealing any problems. The following is a formal analysis of the security of the proposed AKESSO scheme.

Theorem 4.1. *(Correctness) The proposed construction is a correct AKESSO scheme according to Definition 2.*

Proof. This can be verified according to Definition 2 given in Section II. □

Informally, the proposed AKESSO scheme guarantees SSPA as each service provider employs a secure signature scheme. To prove SCUA, we need to show that Definition 4.3 holds for the proposed AKESSO scheme by assuming the unforgeability of the Schnorr signature scheme.

Theorem 4.2. *(Secure Credential-based User Authentication) In the proposed AKESSO scheme, if there is PPT adversary A who has non-negligible advantage $Adv^{SCUA}(A^{\mathcal{O}})$ as specified in Definition 3, then the Schnorr signature scheme is existentially forgeable under UFCMA attacks as defined in Section IV.*

Proof. As adversary A, with access to all oracles in $\mathcal{O} = \{\mathcal{O}_1, \cdots, \mathcal{O}_6\}$, has non-negligible advantage $Adv^{SCUA}(A^{\mathcal{O}})$, according to Definition 3 this implies that at least one of the following two cases is true:

- Case (1): With non-negligible probability ϵ_1, $A^{\mathcal{O}}$ is able to derive credential C_t corresponding to *unregistered* target identity ID_t.

- Case (2): With non-negligible probability ϵ_2, $A^{\mathcal{O}}$ is able to forge a valid user proof for new message M w.r.t. a *registered* target identity ID_i.

If either Case (1) or Case (2) is true, we can construct an algorithm B that is able to break the unforgeability of the Schnorr signature, where B runs $A^{\mathcal{O}}$ as a sub-program for fulfilling its purpose.

Case (1). Suppose that B is given a target Schnorr signature scheme with parameter $(p, q, h(\cdot))$ and public key $y = g^x \mod p$, where the private key x is not known to B. B's strategy for wining Game-UFCMA with non-negligible probability is to set up an AKESSO scheme for A and to simulate oracles in $\mathcal{O}$ so that A cannot distinguish the difference between this simulated environment and a real AKESSO scheme. Therefore, A will be able to successfully derive credential C_t for unregistered identity ID_t with probability ϵ_1. After that, B can adapt this credential into a forged Schnorr signature for a new message and thus break the unforgeability of the Schnorr signature scheme.

How does B sets up such a simulated AKESSO scheme for A. First, B sets y as the public key of TCP and gives y to B. Then, each oracle in $\mathcal{O}_i$ $(i = 1, \cdots, 6)$ can be simulated as follows. To simulate an $\mathcal{O}_1$ query, B can ask its own signing oracle to get Schnorr signature C_i for each identity ID_i and then reply (ID_i, C_i) to A. To simulate an $\mathcal{O}_2$ query, B can simply run $Init(\lambda_1)$ to get public/private key pair (SK_j, PK_j) for an identity SID_j, and then forward (SID_j, SK_j, PK_j) to A. As B knows all users' credentials and all service providers' private keys, it can simulate oracles $\mathcal{O}_3$, $\mathcal{O}_4$, $\mathcal{O}_5$ and $\mathcal{O}_6$ by executing the whole protocol $\prod$, running one move on behalf of a user, running one move on behalf of a service provider, and revealing a session, respectively. Note that as ID_t is an unregistered identity in this case, the corresponding user U_t will not be involved in any oracle $\mathcal{O}_i$ $(i = 1, \cdots, 6)$.

It is not difficult to see that the above simulated system is indistinguishable from a real system from A's point of view. Hence, A will be able to output credential C_t for target identity ID_t with non-negligible probability ϵ_1, where ID_t is not asked in $\mathcal{O}_1$ queries. Therefore, B will simply forward C_t as a forged Schnorr signature for message ID_t. Since ID_t is not asked in $\mathcal{O}_1$ queries, A does not ask ID_t in its signing oracle, i.e., ID_t is a new message for B. So, B's forged message-signature pair (ID_t, C_t) is valid according to the definition of Game-UFCMA (refer to Section IV). Moreover, B's success rate is exactly the same as A's, i.e., ϵ_1, which is non-negligible. Consequently, this means that B successfully breaks the unforgeability of the Schnorr signature scheme.

Case (2). This can be proved in a similar way to Case (1) but B will embed its target Schnorr signature scheme in the user proof generation algorithm for registered target user U_t with identity ID_t. Details are given as follows.

Suppose that B is given a target Schnorr signature scheme with parameter $(p, q, h(\cdot))$ and public key $y' = g^{x'} \mod p$, where private key x' is not known to B. First, B sets $y = g^x \mod p$ as the public key of TCP by selecting random number x as TCP's private key. For any identity ID_i except target identity ID_t, to answer an $\mathcal{O}_1$ query B can directly issue credential C_i for ID_i by generating a Schnorr signature for ID_i as B knows TCP's private key x. In contrast, B will take (a', e', x') as the credential C_t for target identity ID_t, where $e' \in \{0, 1, \cdots, q-1\}$ is a random number, $a' \in \mathbb{Z}_p^*$ is set as $a' = y' \cdot y^{-e'} \mod p$, and $h(a', ID_t)$ is set as e'. So, we have $g^{x'} = a' y^{h(e', ID_t)} \mod p$. Note that B does not know the value of x' and it will be not required to reveal C_t to A because ID_t is the target identity. In addition, here we can artificially fix the hash value for such a special input (a', ID_t) because the Schnorr signature is secure in random oracle where hash function can be viewed as random function [PS00]. All other oracles in $\mathcal{O}$ can be simulated as in Case (1), except A asks $\mathcal{O}_3$ and $\mathcal{O}_4$ queries in which U_t with identity ID_t is involved. In such scenarios, B can simulate U_t to output valid user proof up_t w.r.t. credential C_t by executing the whole protocol $\prod$ or running one move with necessary help from its own signing oracle w.r.t. public key y'.

Again, it is not difficult to see that the above simulated system is indistinguishable from a real system from A's point of view. Hence, with probability ϵ_2 A will be able to output valid user proof up_t for message M w.r.t. target identity ID_t, where M is not asked in $\mathcal{O}_3$ and $\mathcal{O}_4$ queries. Therefore, B can simply forward up_t as a forged Schnorr signature for message M. Since M is not asked in $\mathcal{O}_3$ and $\mathcal{O}_4$ queries, A does not ask M in its signing oracle, i.e., M is a new message for B. So, B's forged message-signature pair (up_t, M) is valid according to the definition of Game-UFCMA (refer to Section IV). Moreover, B's success rate is exactly the same as A's, i.e., ϵ_2, which is non-negligible. Consequently, this means that B successfully breaks the unforgeability of the Schnorr signature scheme. □

Remark 4.5. *In Case (1), $A^{\mathcal{O}}$ could directly forge C_t, recover C_t after executing protocol $\prod$ with user U_t or eavesdropping on the messages between U_t and some service providers, or derive C_t in any other possible way, though $A^{\mathcal{O}}$ is not allowed* *to obtain* C_t *by simply asking* $\mathcal{O}_1$ *oracle w.r.t.* ID_t*. Hence, if our AKESSO fails to satisfy the unforgeability or unrecoverability of the credential, then the Schnorr signature is forgeable. Similarly, in Case (2)* $A^{\mathcal{O}}$ *could directly forge user proof* up_t *without credential* C_t*, observe and adapt existing user proofs generated by* U_t *into user proof* up_t *for message* M*, or compute* up_t *in any other way, though* $A^{\mathcal{O}}$ *is not allowed to obtain any user proof for the same message* M *by simply asking* $\mathcal{O}_3$ *and* $\mathcal{O}_4$ *oracles w.r.t.* ID_t*. Hence, if our AKESSO fails to satisfy soundness of credential-based authentication [WYX12], then the Schnorr signature is forgeable.*

As the Schnorr signature scheme is proved to be secure under the discrete logarithm assumption [PS00], Theorem 4.2 assures that the proposed AKESSO scheme achieves secure credential-based user authentication under the discrete logarithm assumption.

Theorem 4.3. *(Secure Service Provider Authentication) In the proposed AKESSO, if there is PPT adversary A who has non-negligible advantage* $Adv^{SSPA}(A^{\mathcal{O}})$ *as specified in Definition 4, then the signature scheme employed by service providers is existentially forgeable under UFCMA attacks as defined in Section IV.*

Proof. Since a service provider proof is directly generated as a normal signature by the corresponding service provider, Theorem 4.3 can be formally proved as we did for Case (2) in Theorem 1. Note that here we do not need to discuss Case (1) as in Theorem 1, because each service provider is required to register its public/private key pair. □

Theorem 4.4. *According to Definition 6, the proposed AKESSO scheme is secure under the assumption that all digital signatures employed in the scheme are existentially unforgeable against UFCMA attacks as specified in Section IV.*

Proof. By Theorem 1, Theorem 2, Theorem 3 and session key security proved in [CL12], Theorem 4 holds according to Definition 6. □

4.5 Conclusion

Most existing single sign-on schemes have a number of security problems and are vulnerable to carious types of attacks. In this chapter, we first formalized an authenticated key exchange single sign-on scheme. In particular, we formally defined secure authentication for both users and service providers because this had not been done before [WYX12]. Then, a Schnorr mechanism based SSO scheme was proposed to overcome the drawbacks of the Chang-Lee scheme [CL12] while preserving its advantages. In this new scheme, to preserve credential generation privacy, the TCP signs a Schnorr signature [Sch89, Sch91] on user's identity; and to protect credential privacy and soundness, the user exploits his/her credential as a signing key to sign a Schnorr signature on the hashed session key. In fact, the Schnorr signature mechanism [Sch89, Sch91] is more efficient than the RSA mechanism which was employed by the Chang-Lee scheme. Thus, the proposed scheme reduces the computation cost, enhances confidentiality, while preserving soundness and credential privacy.

Chapter 5

A Generic Framework of Three-Factor Authentication

5.1 Introduction

Two factor authentication schemes were introduced in the previous two chapters. For the user who has high security requirements, however, two factor authentication schemes may be not secure enough. To resolve this problem, three factor authentication schemes have been introduced. Many existing three factor schemes, however, have security problems and privacy issues. In order to address this problem, Huang *et al.* [HXC$^+$11] proposed a generic framework for three factor authentication. This framework upgrades two factor authentication scheme to three factor authentication scheme without any additional requirement. It also preserves the privacy of user's biometric characteristics, while without the requirement of trusted devices. Huang *et al.*'s framework employs the 'fuzzy extractor' [DRS04] to generate a biometric key. The 'fuzzy extractor' uses Hamming distance, set difference and edit distance to tolerate errors. These distance measurements, however, have not been widely accepted by the majority of biometric applications [WQ10]. In addition, the process of Huang *et al.*'s framework can be reduced from running underlying scheme twice to running it once. Huang *et al.* also have not deeply analysed the practicalness and they have not provided a proper concrete scheme since that they put the above work in the future.

This chapter proposes an improved generic framework of three factor authentication which based on [HXC$^+$11]. This improved framework is more efficient and practical while remains all advantages of [HXC$^+$11]. According to the improved framework, a provably secure concrete instantiation is provided along with its implementation analysis and privacy discussion. In particular, we propose a security model for three-factor-based authentication schemes which support session key establishment. A formal proof of our concrete instantiation is also provided according to this security model.

The rest of this chapter is organised as follows. Section 5.2 reviews and discusses the two well known biometric identification mechanisms. After that, Section 5.3 reviews Huang *et al.*'s framework and then provides an improved generic framework for three-factor authentication. The concrete instantiation with analysis and comparison are given in Section 5.4, in which, formal security proof and privacy discussion of this instantiation are also provided. Finally, Section 5.5 concludes this chapter.

5.2 Biometric Identification Mechanisms

In 1999, Juels and Wattenberg [JW99] proposed the first biometric identification scheme, fuzzy commitment, using Hamming distance to tolerate errors. Later, in 2002, Juels and Sudan [JS02] introduced a provably secure 'fuzzy vault' scheme, in which, a user chooses a long-bit secret key (treated as a biometric key) in advance, and hides it using the user's biometric template. In the 'fuzzy vault', however, the Euclidean distance measurement is used to tolerate errors. In 2004, Dodis *et al.* [DRS04] proposed a provably secure 'fuzzy extractor' which generates a random pair strings R as a biometric key and a corresponding auxiliary string P directly from the user's biometric template. The 'fuzzy extractor' uses Hamming distance, set difference and edit distance to tolerate errors. The 'fuzzy vault' has been widely accepted since the Euclidean distance measurement is suitable for the majority of biometric applications [WQ10], while the distance measurements used in the 'fuzzy extractor' are not. This is also the reason why we choose the 'fuzzy vault' for biometric key generation. In 2008, Teoh and Ong [AT08] proposed a randomised dynamic quantisation transformation (RDQT), which is based on fuzzy commitment, to binarize biometric data, satisfying randomness and uniqueness. Meanwhile, Sheng et.al [SHFD08] presented a template-free biometric-key generation, which also can generate a key directly from a biometric template. This section reviews the 'fuzzy extractor' which has been employed by Huang *et al.*'s framework [HXC$^+$11], and the 'fuzzy vault' scheme which is employed in our proposed framework.

5.2.1 Fuzzy Extractor

The 'fuzzy extractor' has two procedures, a generation procedure (*Gen*) and a reproduction procedure (*Rep*). After a user scans his biometric features, the *Gen* extracts uniquely random R and corresponding auxiliary P from user's biometric template w. In the authentication phase, the inputs of *Rep* are P and unidentified biometric template w'; the output of *Rep* is the corresponding R iff the difference between w and w' is within an acceptable error tolerance. The error tolerance in the scheme depends on three error correcting techniques, namely Hamming distance, set difference and edit distance. The definition of the 'fuzzy extractor' was introduced by Dodis *et al.* [DRS04, DORS08]. To formally review this concept, we introduce the following notations.

- t: the fuzzyness of the 'fuzzy extractor';
- A, B: two probability distributions;
- M: a metric space on N points with distance function $dis(\cdot)$;
- m: the min-entropy of A given B, which can be calculated by computing the logarithm of average probability of value A given B;
- U_l: the uniform distribution on l-bit binary strings;
- $SD(A, B)$: the statistical distance between A and B such that $SD(A, B) = \frac{1}{2}\sum_v |\Pr(A = v) - \Pr(B = v)|$;

Definition 5.1. *An $(M, m, l, t, \epsilon) - fuzzy\ extractor$ is a pair of randomised procedures Gen and Rep, respectively, with the following properties:*

1. *Gen is a probabilistic generation procedure with input $w \in M$, which outputs public helper $P \in \{0, 1\}^*$ and an 'extracted' random string $R \in \{0, 1\}^l$. For any distribution W on M of min-entropy m, if $< R, P > \leftarrow Gen(W)$, then it requires that $SD(< R, P >, < U_l, P >) \leq \epsilon$.*
2. *Reproduction procedure Rep, can recover R, if and only if P and w' are provided as inputs, where $w' \in M$, satisfies $dis(w, w') \leq t$. Namely, if $< R, P > \leftarrow Gen(W)$, then $Rep(w', P) = R$*

The 'fuzzy extractor' provides a good insight into biometric identification since it extracts a unique random 'private' key directly from the user's biometric features. However, as a theoretical biometric key generation scheme for public key cryptosystem, the 'fuzzy extractor' has not been widely implemented since the distance measures in it are less accepted than the Euclidean distance measurement in biometric applications [WQ10].

5.2.2 Fuzzy Vault

In 2002, Juels and Sudan [JS02] proposed a cryptographic construction for data protection and user authentication by using fingerprints and smart cards, called the 'fuzzy vault'. The errors in the 'fuzzy vault' have been tolerated by the Euclidean distance measurement which has been widely accepted by the majority of biometric applications. The operations of the 'fuzzy vault' are described as follows.

First, a user's biometric features are scanned and his/her biometric template X is extracted. Then, s/he selects and uses a polynomial Pol to encrypt secret string K (treated as the biometric key) which has been chosen by the user in advance. The user evaluates Pol on all elements in X and chooses a large number of random chaff points which do not lie on Pol as the noise. The final vault V is the collection of the genuine minutiae points which lie on Pol and the chaff points which do not lie on Pol.

To recover secret string K from vault V, the user needs to offer his/her biometric template X', if the difference between X and X' is $|X - X'| < \epsilon$, where $X - X' = \{x | x \in X, x \notin X'\}$, then polynomial Pol can be reconstructed because a sufficient number of points on Pol can be identified and an error correcting scheme is used. Thus, K can be successfully recovered once Pol is available.

In 2003, Clancy et. al [Cla03] proposed a secure smart card-based fingerprint authentication scheme by using Juels and Sudan's 'fuzzy vault'. Later, in 2007, Nandakumar et. al [NJP07] proposed a fully automatic implementation by employing the 'fuzzy vault', and using helper data to align unidentified fingerprints accurately. The improved scheme used both location (x, y) and orientation attribute θ of a minutia point to record the biometric data, where (x, y) is the row and column indicates in the image as the location, and θ is the orientation on the X-axis. The helper data is high curvature points extracted from the fingerprint orientation field, thus it neither affects the security nor leaks any information about the biometric template.

One year later, Nagar, Nandakumar and Jain [NNJ08] improved the security and matching accuracy of Nandakumar et. al's fingerprint-based 'fuzzy vault' scheme by employing additional minutiae descriptors [Fen08], which capture local ridge orientation and ridge frequency information in the neighbourhood of a minutia. The results in [NNJ08] showed that the improved scheme reduces the false acceptance rate (FAR) and significantly increases the vault security. The operation of fingerprint based 'fuzzy vault' follows:

Let a locking/unlocking pair $(Lock, Unlock)$ is complete ϵ-fuzziness if the following holds. For every secret string k and every pair of biometric template sets (X, X'), such that $|X - X'| \leq \epsilon$ for integer ϵ, then $Unlock(X', Lock(X, k)) = k$ with overwhelming probability.

Vault Encoding (Lock):

1. $\xrightarrow[K,Pol]{X} \boxed{P_X(K)} \rightarrow L$

   Procedure $P_X(K)$ denotes that the 'fuzzy vault' encrypts user's secret K in polynomial Pol, and evaluates Pol on all elements in the user's biometric sample X, which is represented as an unordered set. The output of $P_X(K)$ is Locking set L;

2. $\xrightarrow[L]{CP} \boxed{\text{Gen}} \rightarrow V$

   The user selects chaff points CP which play the role of noise as the inputs of Gen, where chaff points CP do not lie on Pol, while L does. r denotes the number of points which lie on Pol in V, and s denotes the number of points which do not lie on Pol in V, where $s >> r$. The output of Gen is V such that $V = CP \cup L$.

Vault Decoding (Unlock):

1. $\xrightarrow[V,H]{X'H'} \boxed{\text{Rec}} \rightarrow Pol$

   For the user who requests to recover Pol, the 'fuzzy vault' first uses original helper data H and the requester's help data H' to adjust the orientation of the fingerprint, and then runs procedure Rec to reconstruct Pol from input V if the difference between X and the requester's extracted biometric template X' satisfies $|X - X'| < \epsilon$, where $X - X' = \{x | x \in X, x \notin X'\}$;

2. $\xrightarrow{Pol} \boxed{\text{De(Pol)}} \rightarrow K$

   The procedure $De(Pol)$ denotes the recovering algorithm which outputs the secret key K by giving the input polynomial Pol.

Here, r is the number of genuine points which lie on Pol in V, and this depends on the number of features which have been extracted from X. The security of the 'fuzzy vault' is in proportion to the number of chaff points. The degree of polynomial is presented as n. Parameter ϵ denotes error tolerance. Helper data H consists of the high curvature points and the ordinate value of vault V, and H does not leak the information of the user's biometric features [NJP07, NNJ08]. The security of the 'fuzzy vault' is based on (a) the difficulty in distinguishing the set of genuine minutiae points from a set of chaff points in vault V and (b) the difficulty to reconstruct the polynomial Pol in vault V.

5.3 A Generic Three-factor Authentication Framework

This section first reviews Huang *et al.*'s scheme, and then provides a more efficient and practical framework.

5.3.1 Review of Huang *et al.*'s Framework

Huang *et al.*'s framework employs the 'fuzzy extractor' to generate a uniquely long-bit random string as the biometric key of the user. By running the underlying two-factor scheme twice, a three-factor scheme is constructed. Specifically, the first running uses password and smart card as normal. Then, in the second time, the user replaces the password by a biometric key and runs the underlying protocol again, thus achieving a three-factor authentication. Huang *et al.*'s framework consists of three phases:

Registration:
The processes of registration includes the following steps:

1. User U_i chooses initial password PW_1;

2. Upon U_i scanning his/her biometric features, biometric template X is extracted, and then a pair (R, P) is outputted by running $Gen(X)$;

3. Let second password $PW_2 = h(R)$, where $h(\cdot)$ is a cryptographic hash function chosen by U_i.

4. $U_i\,[PW_1] \overset{2-Factor-Reg}{\Longleftrightarrow} S\,[SK_1] \rightarrow Data_1$;
   By running the underlying two-factor registration protocol (2-Factor-Reg), user U_i uses initial password PW_1 and server S uses secret key SK_1 to generate $Data_1$;

5. $U_i\,[PW_2] \overset{2-Factor-Reg}{\Longleftrightarrow} S\,[SK_2] \rightarrow Data_2$.
   $Data_2$ is generated by running the 2-Factor-Reg again, in which U_i uses PW_2 and S uses SK_2;

6. Server stores $Data_1$ and $Data_2$ in SC and gives it to U_i;

7. U_i updates SC by adding $Data_3 = (P, h(\cdot), Rep(\cdot))$ in it, where P is the auxiliary string for biometric key recovery, $h(\cdot)$ and $Rep(\cdot)$ are the descriptions of the corresponding hash function algorithm and the reproduction procedure, respectively.

The scheme supposes that PW_1, PW_2 will be deleted immediately from the server side upon completion of the corresponding steps because of the assumption that in this phase, the server is fully trusted.

Authentication:
User U_i' first inserts SC into the card reader and enters the password and scans his/her biometric features. We use X' to denote the extracted biometric template. The authentication phase is as follows.

1. The smart card computes R via $Rep(\cdot)$ and calculates $PW_2 = h(R)$. The identical R can be reproduced if and only if the difference between X and X' satisfying $dis(X, X') < t$;

2. $U_i'\,[PW_1, SC(Data_1)] \overset{2-Factor-Auth}{\Longleftrightarrow} S\,[SK_1]$;
   User U_i' with $(PW_1, Data_1)$ and S who with SK_1 execute the authentication phase (2-Factor-Auth) of the underlying two-factor authentication protocol;

3. $U_i'\,[PW_2, SC(Data_2] \overset{2-Factor-Auth}{\Longleftrightarrow} S\,[SK_2]$;
   U_i' and S run the 2-Factor-Auth again with PW_2, $Data_2$ and SK_2, respectively.

The user successfully passes user authentication iff S is accepted in both step 2 and step 3.

Password Changing:

The password can be changed by running password changing protocol (2-Factor-Password-Changing) in the underlying two-factor scheme after successfully logging and updating the SC accordingly. The biometrics can be changed by running step 2 and step 3 in the registration phase, then the user and server execute 2-Factor-Password-Changing and update the corresponding data in SC.

5.3.2 Improved Framework

Based on considerations of practicality, we use the 'fuzzy vault' to replace the 'fuzzy extractor' for biometric key generation, because the Euclidean distance measurement in the 'fuzzy vault' has been widely accepted by the majority of biometric applications, while the distance measures in the 'fuzzy extractor' have not [WQ10]. Moreover, to enhance the efficiency and reduce the computational cost, our improved framework reduces the process from running underlying two-factor authentication scheme twice to running it once by combining the password and biometric key together and hashing it as the password of the underlying scheme. We assume that the server in the registration phase is trusted. The details are specified as follows:

Three-Factor-Registration: The process of registration include the following steps:

1. User U_i chooses initial password PW_1, long-bit secret key (treated as the biometric key) PW_2, and computes $PW{=}h(PW_1||PW_2)$;

2. Upon U_i scanning his biometric features, the 'fuzzy vault' device extracts biometric template X with its helper data H from U_i's biometric features;

3. Taking X, PW_2, and polynomial Pol as inputs, $P_X(K)$ outputs locking set L, and the device then runs $Gen(CP, L){\rightarrow}V$;

4. $U_i\,[PW] \overset{2-factor-Reg}{\Longleftrightarrow} S\,[SK]\rightarrow Data_1$, where $PW{=}h(PW_1||PW_2)$.
   The user with PW and the server with SK run the registration phase of the underlying protocol.

5. Server stores $Data_1$ in smart card SC, and gives it to U_i;

6. U_i updates SC by adding $Data_2$ to it, where $Data_2 = (V, H, Rec(\cdot), De(\cdot), h(\cdot))$. $Rec(\cdot)$ and $De(\cdot)$ are the descriptions of the corresponding procedure in the fuzzy vault, and $h(\cdot)$ is the description of a hash function.

Three-Factor-Authentication:

To access services, user U_i' inserts SC to a card reader, which can extracts the data from the SC. Then, U_i' inputs PW_1 and scans his/her biometric features, the extracted biometric template is X' and its helper data is H'. The details are as follows:

1. The card reader extracts X', H' from U_i''s biometric features, and reproduces PW_2 by the following two steps:
   Firstly, the 'fuzzy vault' device reproduces Pol via the $Rec(\cdot)$ procedure, if and only if input X' satisfies $|X - X'| < \epsilon$;
   Then, to reconstruct PW_2, taking Pol as the input of $De(\cdot)$, which outputs PW_2.

2. The smart card calculates $PW{=}h(PW_1||PW_2)$;

3. $U_i'\,[PW, Data_1] \xLeftrightarrow{2-factor-Auth} S\,[SK]$;
   The user can successfully pass authentication if this step is success.

Three-Factor-Password-Changing:

The PW_1 can be changed by following steps.

1. After passing authentication, U_i' sends the password changing request, inputs new password PW_1'', and scans the biometric template.

2. The 'fuzzy vault' device will recover the PW_2 by using the 'fuzzy vault' decoding scheme.

3. The smart card calculates $PW'' = h(PW_1''||PW_2)$.

4. PW'' is taken as the password and runs the password changing phase of the underlying protocol.

Biometric key PW_2 can be changed in a similar way. For this purpose, U_i' chooses a new biometric key as PW_2'', then encrypts it via the 'fuzzy vault' device, outputs V'' and H'' which replaces current V and H of $Data_2$ in SC. The SC calculates $PW'' = h(PW_1||PW_2'')$, then takes PW'' as the password and runs the password changing phase of the underlying protocol. U_i' can also decide to use another finger to authenticate him. The process of finger changing is in a similar way.

5.4 Concrete Instantiation

Concrete instantiation chooses Yang *et al.*'s provably secure two-factor authentication protocol [YWWD08] as the underlying scheme. Yang's scheme employs the Diffie-Hellman key exchange protocol to establish the session key, and uses an asymmetric key encryption/decryption scheme to protect the transmitting messages. In the registration phase, the server creates a credential with a long-term secret key by using a pseudorandom function and sends it to the user who then does the exclusive-or operation (xor) on it along with his/her hashed password, and stores the outputs in a smart card. Thus, only the server which has the long term secret key can generate the credential and only the user who has the password and smart card can recover the credential. To pass user authentication, the user need to recover the credential and send it to the server after encrypting it by using a public key encryption scheme. For server authentication, a secure signature scheme has been employed. The notations used in the concrete instantiation are shown in Table 5.1.

ID_i	User's unique identity
SID	Server's unique identity
x	Server's long term secret key
SK, PK	Server's public key pair for encryption
SK', PK'	Server's key pair for signature scheme
PW_1	User's password.
PW_2	User's long-bit secret key
SC	Smart Card
H	Helper data used in the 'fuzzy vault'
C_i	Credential for U_i created by S
h	One way strong hash function. $\{0,1\}^* \rightarrow \{0,1\}^l$
$P_X(K), Gen(), Rec(), De()$	Defined as in the 'fuzzy vault'
PRF_x	$\{0,1\}^k \rightarrow \{0,1\}^k$ pseudorandom function keyed by server's long term secret key x.
sid	Session identifier.
CT	Cipher text.

Table 5.1: Notations in the Concrete Three-Factor Authentication

5.4.1 Concrete Protocol

The basic idea of our concrete protocol is that using PW such that $PW = h(PW_1||PW_2)$ as the password in Yang's scheme, where PW_1 is the password known by the user, PW_2 is the biometric key which can be recovered by providing the smart card and the corresponding biometric features. A user can pass authentication only if s/he provides the correct password, smart card, and the biometric features. Thus, a three-factor authentication scheme is achieved.

Registration

We assume the communication channel in this phase is secure.

1. User U_i obtains unique identity ID_i from server S, and then chooses password PW_1, polynomial Pol, and biometric key PW_2;

2. The 'fuzzy vault' device extracts the biometric template and helper data (X, H) from U_i's biometric features, and runs procedures $P_X(PW_2) \rightarrow L$ and $Gen(CP, L)$ to encrypt PW_2 in V. Then, it calculates $PW = h(PW_1||PW_2)$.

3. Server S generates credential C_i such that $C_i = PRF_x(h(ID_i))$, and hides it with initial password PW_{init} such that $B = C_i \oplus PW_{init}$.

4. S issues SC=\{ID_i, *SigData*, *AutData*, *EncData*\} to U_i. Here, *SigData* is the description of the signature algorithm together with related parameters; *AutData*=$\{B, V, H, h, Rec(), De()\}$; *EncData* is the description of an encryption algorithm together with the parameters. $h, Rec()$, and $De()$ are the description of the hash function and the 'fuzzy vault' procedures, respectively.

5. Upon receiving SC, U_i updates B by computing $B = C_i \oplus PW_{init} \oplus PW$.

Login-and-Authentication Phase

User U_i' inserts his/her smart-card in a card reader, inputs password PW_1' and scans his biometric features. The 'fuzzy vault' device extracts the biometric template and helper data X', H', then the 'fuzzy vault' device calculates $Pol = Rec(X', H', V, H)$, and $PW_2' = DeP(Pol)$. The smart card SC calculates C_i'=$B \oplus PW'$, where $PW' = h(PW_1'||PW_2')$. Then, the protocol runs as follows:

1. $U_i' \rightarrow S$: M_1=(ID_i, sid, g^a)

   User U_i' sends identity ID_i, session ID sid, and user's session key material g^a to S, where a is a random number chosen by U_i;

2. $S \rightarrow U_i'$: M_2=$(SID, sid, g^b, Sig_{SK'}(SID, ID_i, sid, g^a, g^b))$
   S sends his identity SID, session ID sid, and a signature with signing key SK' to U_i';

3. $U_i' \rightarrow S$: M_3=$(ID_i,\ sid,\ CT)$
   U_i checks the signature first. If it is not valid, U_i terminates the conversation. Otherwise, U_i computes $M_3 = (ID_i, sid, CT)$ and sends it to S, where CT=$E_{PK}(C_i', ID_i, SID, sid, g^a, g^b))$ and $E_{PK}(M)$ denotes the asymmetric key encryption on message M under public key PK;

4. After decrypting CT by using SK, S checks C_i', and rejects U_i if C_i'=$PRF_x(h(ID_i))$ does not hold. Otherwise, S accepts U_i, and believes that they share the same session key g^{ab}.

Password-Changing

The change of password PW_1 contains the following steps.

1. After successfully logging in, U_i chooses new password PW_1'.

2. U_i calculates $PW_{new} = h(PW_1'||PW_2)$ and $B_{new} = B \oplus PW \oplus PW_{new}$.

3. Replace B with B_{new} in the smart card.

The biometric key PW_2 and the biometric features can be changed in a similar way, in which case, the vault V and help data H also need to be updated on smart card.

5.4.2 Analysis of Implementation

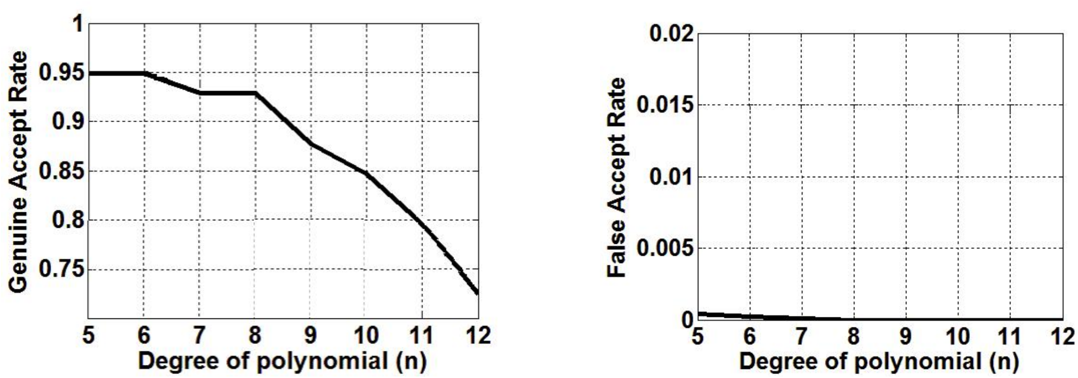
We first analyse the capacity of the smart card. During the registration phase, the point v_i in set V are presented as three-tuple $v_i = (x, y, \theta)$ $(i = \{1, 2, ..., r+s\})$, where (x, y) is the row and column coordinates in the image as the location, and θ is the orientation which respect to the X-axis. The number of points in vault V depends on r and s, where r is the number of points which lie on P and s denotes the number of points which do not lie on P (treated as chaff points or noise). Here, $s \approx 10r$. Nandakumar, Jain, and Pankanti [NJP07] showed that a 128-bit secret key requires an 8-degree polynomial to encrypt the key, and the lengths of x, y, θ are $6, 5, 5$, respectively, in field $F = GF(2^{16})$. Table 5.2, taken from [NJP07], shows the parameters in different databases:

Parameter	FVC2002-DB2	MSU-DBI
Image size	560 × 296 at 569 dpi resolution	640 × 480 at 500 dpi resolution
r in V	18-24	24-36
s in V	200-206	300-312
Total points in V	224	336
n	7-10	10-12
Length of secret key k	128-bit	128-bit
Length of V	448 Bytes	672 Bytes

Table 5.2: Parameters in Different Databases [NJP07]

The length of help data which depends on the points of maximum curvature in the flow curves can be ignored. Thus, only a half KB of the 'fuzzy vault' parameters needs to be stored in the smart card, and this is acceptable.

Now, we discuss the recognition rate of the 'fuzzy vault'. [NNJ08, NJP07] employ genuine acceptance rate (GAR) and false acceptance rate (FAR) to analyse the recognition accuracy. The results show that both GAR and FAR are influenced by n which is the degree of polynomial. The change of n affects both GAR and FAR; n is in an inverse proportion to GAR and FAR. Fig. 5.1 are the results of both GAR and FAR in the implementation provided in [NNJ08].



(a) Genuine Accept Rate (GAR) (b) False Accept Rate (FAR)

Figure 5.1: GAR and FAR of the 'Fuzzy Vault' [NNJ08]

Generally, the FAR is 10^{-4} when $n = 6$, and it tends to zero when n is increase to 8; all the results of GAR in the figure are practical even when $n = 12$, where GAR$>$ 70%. In fact, GAR may be also acceptable even it reduces to 30%, as this means that a genuine user can pass authentication successfully by trying three or four fingerprint identifications on average.

Properties / Name of scheme	Store Password or Biodata in DB	Cost		Change password freely	Biometrics privacy	Key Exchange	Security
		Registration phase	Login-and-Authentication phase				
Li and Hwang's scheme [LH10]	×	L1	L1	√	×	×	Vulnerable to man-in-the-middle attack
Li *et al.*'s scheme [LNM+11]	×	L1	L1	√	×	√	Fails to provide strong authentication
Das's scheme [Das11]	×	L1	L1	√	×	√	Vulnerable to Off-line guessing password attack
Kim-Lee-Yoo scheme [KLY03]	×	2 Exp	4 Exp	√	√	×	Vulnerable to impersonation attack
Bhargav -Spantze *et al.*'s scheme[BSSM+07, BSSB06]	√	3 Exp	5 Exp	×	√	×	Secure under three-factor requirements
Fan and Lin's scheme [FL09]	√	L1&L2	1 E/D	×	√	√	Secure under three-factor requirements
Proposed scheme	×	L1	1 DH; 1 Sig; 1 E/D	√	√	√	Secure under three-factor requirements

X: False
√: True
L1: The phase only contains the hash operation and exclusive operation
L2: The phase employs symmetric key encryption/decryption
E/D: The phase computes asymmetric key encryption and decryption
Exp: The phase calculates large modular exponentiation
Sig: The participator signs and verifies digital signature
DH: The plain Diffie-Hellman key exchange operation

Table 5.3: Comparison of Schemes

The comparison between our concrete instantiation and other three factor authentication schemes is given in Table 5.3. It is obviously that [LH10, LNM+11, Das11, KLY03] support free password changing, and [LH10, LNM+11, Das11] achieve lower computational cost. However, all of them have security flaws. Both [BSSM+07] and [FL09] are secure under the three-factor adversary model, but they do not support freely password changing and [BSSM+07] does not support session key exchange. Our derived protocol protects user privacy, supports easy password changing and session key establishment, although its computation cost is not low but still acceptable.

5.4.3 Formal Security Proof of Instantiation Protocol

The formal security proof of the factor-based authentication scheme has been introduced as an open problem and a challenging issue from the point of view of security analysis [HMZ+11], although some formal proofs have been provided [XZF09, XZJ11, FL09, CK01, BR93a, BPR00]. In [HXC+11] (even in its supplementary file) Huang *et al.* only provided informally security discussion. In [BR93a, BPR00, CK01], they provided generic models for formally proving the security of authenticated key exchange schemes, not for three-factor authentication schemes. So, the three-factor-based mutual authentication scheme which supports session key establishment has not been studied by these well-known models. This section proposes a security model for three-factor-based authenticated key exchange schemes. A formal proof of our proposed concrete scheme is also provided in our security model.

The basic idea of our concrete protocol is that a server creates credential C for a user via pseudorandom function $PRF(\cdot)$ with his/her long term secret key x, then the user encrypts it by doing the exclusive operation along with combined password and biometric key, which outputs encrypted credential B stored in the smart card. The user recovers the credential iff s/he provides the correct password and biometric features. For user authentication, the user encrypts and sends his/her identity and credential C' to the server. Upon receiving it, server calculates credential C with x according to user identity, and compares C and C'. If they have matched, then the server accepts the user's request. Otherwise, the server rejects it. Server authentication has been preserved by a secure signature scheme. Assumptions for security proofs are list below:

Assumptions:

1. The 'fuzzy vault' scheme in $\prod$ is secure due to [NJP07, NNJ08].

2. Information stored in smart card SC can be extracted by an attacker if he/she can obtain SC [Cla03].

3. No one has exactly the same biometric feature as others.

4. The case of a person without specific biometric features (such as a person without fingerprints) is ignored here since it is such a rare circumstance.

We place probabilistic polynomial time (PPT) adversary A, who can make queries to any instance, between user U_i in user set U and sever S_j in server set S. Let $\prod_{U,S}^{sid}$ denotes the user oracle, interacting with the server in session sid and $\prod_{S,U}^{sid}$ denotes the server oracle, interacting with user in the session sid. It is obvious that if protocol $\prod$ is secure when A knows two out of three factors, then $\prod$ is still secure when only one factor has been leaked to A. Therefore, we only consider the case of two corrupted factors. The oracle queries which can be made by A are defined as follows.

Adversary Model (*AM*):

1. $Register(\prod, S_j)$—Upon receiving this query from A, server oracle acts as S_j to run the registration phase with A, and issues identity ID_i and sends smart card SC to A.

2. $Execute(U_i, S_j, sid)$—This oracle query models all passive attackers who can eavesdrop on all messages transmitted between U and S in session sid in $\prod$. Upon receiving this query, $\prod_{U,S}^{sid}$ and $\prod_{S,U}^{sid}$ will execute protocol as U_i and S_j in $\prod$, respectively. The messages exchanged between them will be recorded and sent to A as responses.

3. $Send(U_i, S_j, sid, M_m, m)$—This query sends message M_m with sequence of message flow m to server oracle $\prod_{S,U}^{sid}$ which simulates S_j, and then, the oracle will compute a respond honestly in $\prod$, and send the response to A.

4. $Send(S_j, U_i, sid, M_{m'}, m')$—This query sends message $M_{m'}$ with sequence of message flow m' to user oracle $\prod_{U,S}^{sid}$ which simulates U_i, and then, the user oracle will compute a respond honestly in $\prod$, and send the response to A.

Upon receiving the query with $m' = \lambda$, where λ is an empty set, from A, the user oracle will start a new session and send a service request message to A.

5. *Reveal*$(\prod, U_i, S_j, sid)$—This query models the leakage of a session key in session *sid* between user U_i and server S_j. This query only can be made when a session key has been shared between the server and the user in session *sid*. Upon receiving this query, the user oracle will send the shared session key to A.

6. There are three corrupt queries:

   (a) *Corrupt*(U_i, pw, SC). Upon receiving this query, user oracle will send back the user U_i's password and the data stored in the smart card to the adversary;

   (b) *Corrupt*(U_i, pw, Bio). Upon receiving this query, user oracle will send back the user U_i's password and the biometric template to the adversary;

   (c) *Corrupt*(U_i, SC, Bio). Upon receiving this query, user oracle will send back the user U_i's biometric template and the data stored in the smart card to the adversary;

   In a concrete attack, A can only make one corrupt query in the target session.

7. *Test*(U_i, S_j, sid)— This query can be made by A only after a session key has been shared between U_i and S_j in a fresh session *sid*. If so, then a coin b is tossed, if it lands $b = 0$, then this test query oracle outputs the session key. Otherwise, a fixed-length random string is returned. A needs to outputs $b' = 0$ (or $b' = 1$) as the result of distinguishing the session key and a random string. A can only ask this query once.

The definitions of matching conversations, secure mutual authentication and secure key exchange [BR93a] are reviewed as follows.

Definition 5.2. *(Matching Conversations): Fix number of moves $R = 2\rho - 1$ and R-move protocol $\prod$. Run $\prod$ in the presence of adversary A in the AM and consider two oracles $\prod_{U,S}^{sid}$ and $\prod_{S,U}^{sid}$ that engage in conversations K and K', respectively. (τ, α, β) denotes that A is given response β back after asking α to an oracle at time τ. If $\alpha = \tau$, then it means that protocol $\prod$ starts a new session. Let $*$ denotes the final decision of R-move protocol $\prod$.*

1. *We say that K' is a matching conversation to K if there exist $\tau_0 \prec \tau_1 \prec \ldots \prec \tau_R$ and $\alpha_1, \beta_1, \ldots, \alpha_\rho, \beta_\rho$ such that K is prefixed by $(\tau_0, \lambda, \alpha_1)$, $(\tau_2, \beta_1, \alpha_2)$, $\ldots$, $(\tau_{2\rho-4}, \beta_{\rho-2}, \alpha_{\rho-1})$, $(\tau_{2\rho-2}, \beta_{\rho-1}, \alpha_\rho)$ and K' is prefixed by $(\tau_1, \alpha_1, \beta_1)$, $(\tau_3, \alpha_2, \beta_2)$, $\ldots$, $(\tau_{2\rho-3}, \alpha_{\rho-1}, \beta_{\rho-1})$.*

2. *We say that K is a matching conversation to K' if there exist $\tau_0 \prec \tau_1 \prec \ldots \prec \tau_R$ and $\alpha_1, \beta_1, \ldots, \alpha_\rho, \beta_\rho$ such that K' is prefixed by $(\tau_1, \alpha_1, \beta_1)$, $(\tau_3, \alpha_2, \beta_2)$, $\ldots$, $(\tau_{2\rho-3}, \alpha_{\rho-1}, \beta_{\rho-1})$, $(\tau_{2\rho-1}, \alpha_\rho, *)$ and K is prefixed by $(\tau_0, \lambda, \alpha_1)$, $(\tau_2, \beta_1, \alpha_2)$ $,\ldots,$ $(\tau_{2\rho-4}, \beta_{\rho-2}, \alpha_{\rho-1})$, $(\tau_{2\rho-2}, \beta_{\rho-1}, \alpha_\rho)$.*

Let $\prod_{U_i,S_j}^{sid}$ (or $\prod_{S_j,U_i}^{sid}$) denotes that the oracle who acts as user U_i (or server S_j) communicates with server S_j (or user U_i). Let $No-Matching^{A,U_i}(k)$ (or $No-Matching^{A,S_j}(k)$) be the event that there exist U_i, S_j and sid such that $\prod_{U_i,S_j}^{sid}$ (or $\prod_{S_j,U_i}^{sid}$) has accepted A as $\prod_{S_j,U_i}^{sid}$ (or $\prod_{U_i,S_j}^{sid}$), while $\prod_{S_j,U_i}^{sid}$ (or $\prod_{U_i,S_j}^{sid}$) has not engaged in a matching conversation. In other words, it is the event that user U_i (or server S_j) believes that server S_j (or user U_i) is communicating with him, but in fact, it is adversary A who impersonates server S_j (or user U_i).

Remark 5.1. *The above definition is defined for the case of $R = 2\rho - 1$ moves protocol. For the case of $R = 2\rho$ moves protocol, the definition can be changed trivially. So, we are not going to discuss it here.*

Definition 5.3. *(Secure Three-Factor Mutual Authentication (STMA)) We say that $\prod$ is a secure mutual authentication protocol if for any PPT adversary A in the AM, the following properties are satisfied.*

1. *If oracles $\prod_{U_i,S_j}^{sid}$ and $\prod_{S_j,U_i}^{i}$ have matched conversations, then they accept each other.*

2. *$\prod_{U_i,S_j}^{sid}$ accepted implies a matching conversation: the probability of $No-Matching^{A,U_i}(k)$ is negligible, where S_j should not be registered by A. (Secure server authentication)*

3. *$\prod_{S_j,U_i}^{sid}$ accepted implies a matching conversation: the probability of $No-Matching^{A,S_j}(k)$ is negligible, where U_i should not be registered by A. (Secure user authentication)*

Definition 5.4. *(Secure Three-Factor Authenticated Key Exchange (STAKE)) A Protocol $\prod$ is called $STAKE$ if the following properties hold for any adversary A in the AM:*

- *$\prod$ is a STMA protocol;*
- *if the session is fresh in protocol $\prod$, and both $\prod^{sid}_{U_i,S_j}$ and $\prod^{i}_{S_j,U_i}$ complete matching conversations, then they have shared the same session key;*
- *the advantage $Adv^A(k)$ is negligible.*

Note that:

1. Session freshness requires satisfying follow probabilities:
   - $\prod^{sid}_{U_i,S_j}$ and/or $\prod^{sid}_{S_j,U_i}$ accepted;
   - no queries to reveal the session key have been made to $\prod^{sid}_{U_i,S_j}$ or $\prod^{sid}_{S_j,U_i}$;
2. $Adv^A(k)$=$|Good - guess^A(k)] - \frac{1}{2}|$, where the Good-guess is the event such that A wins the game of AKE [BR93a];

To prove the security of our concrete scheme, we show that if A can successfully pass user or server authentication with a non-negligible probability, then we can construct a PPT Turing machine T to solve the hard problems by employing A with a non-negligible probability. The concrete protocol is reviewed as follows:

1. $U_i \rightarrow S$: M_1=(ID_i, sid, g^a)
2. $S \rightarrow U_i$: M_2=$(SID,\ sid,\ g^b,\ Sig_{SK'}(SID,\ ID_i,\ sid,\ g^a,\ g^b))$
3. $U_i \rightarrow S$: M_3=(ID_i, sid, CT), where CT=E_{PK} $(C'_i,\ ID_i,\ SID, sid, g^a, g^b)$
4. S checks credential C'_i. U_i will pass user authentication if and only if C'_i=PRF_x $(h(ID_i))$.
   Now, the shared session key is g^{ab}.

Lemma 5.1. *(Secure User Authentication) In the proposed protocol $\prod$, if the pseudorandom function (PRF) is replaced by an ideal random function, the public key encryption (PKE) scheme is secure against CCA2 attack, and $\prod^{sid}_{S_j,U_i}$ has accepted, then for any PPT adversary A in the AM, the probability of $No-Matching^{A,S_j}(k)$ is negligible.*

Proof. This can be proved by contradiction. If there exists an adversary A who can pass user authentication with non-negligible probability ϵ, then we can construct a PPT Turing machine T without known secret key x to solve a hard problem, i.e.

winning the game of PRF (Game-PRF), with a non-negligible probability by using A.

In the Game-PRF, a challenger sends two different plaintexts P_0 and P_1 to the PRF test query, then the PRF test query will answer with result $PRF_x(P_b)$ to the challenger, where b is the result of coin tossing. After that, the challenger needs to output $b' = 0$ or $b' = 1$ as its guess to value b. Let $\Pr_{adv}[PRF]$ be the advantage of guessing, which is defined as $\Pr_{adv}[PRF] = \Pr_{win} - \frac{1}{2}$, where $\Pr_{win}$ denotes the correct guessing rate. In this game, we give the challenger a power to ask the output of PRF by providing a message M_{pt}. Upon receiving this request, the PRF oracle $\prod_{PRF}$ will output a response $PRF_x(M_{pt})$ by using server's secret key x. Here we require that the asked message M_{pt} can not be sent as one of input to the PRF test query.

The basic idea is that to win Game-PRF, T simulates an environment of our concrete protocol to convince adversary A that this simulation is the real environment of concrete protocol execution. On the other side, A should only has a negligible probability to know the truth, i.e. this is not a real protocol environment but a simulation. In such a simulation, T communicates with A who has the ability to break our concrete protocol in some way in a session with session ID sid with a non-negligible probability. Then, in order to win Game-PRF, T will make use of A's ability to make the decision of which input message has been used to generate the output $PRF_x(P_b)$ with a non-negligible probability.

The simulation is constructed as follows. In the simulation, T answers all oracle queries made by A. To achieve this goal, T needs to setup (SK, PK) for the public key scheme and (SK', PK') for the signature scheme, while T does not know the value of long term secret key x which is for $\prod_{PRF}$. $\prod_{U_i,S_j}^{sid}$ denotes the user oracle who has password PW_1, smart-card SC, and corresponding biometric template X which can recover biometric key PW_2 with the SC. $\prod_{S_j,U_i}^{sid}$ denotes the server oracle who has PRF oracle $\prod_{PRF}$. In our concrete protocol, A can make the following queries:

- $Register(\prod, S_j)$—Upon receiving this query from A, T runs the registration phase with A with the help of $\prod_{PRF}$. In particular, T needs to record all identities which have been registered into what we called compromised table.

- $Execute(U_i, S_j, sid)$— In $\prod$, $\prod_{U_i,S_j}^{sid}$ and $\prod_{S_j,U_i}^{sid}$ generate and record all messages transmitted between U_i and S_j in session sid, then send these messages to A.

- $Send(U_i, S_j, sid, M_m, m)$— A can send M_1 to T, then T responds to M_2 by using SK' to sign a signature as the protocol specified. Upon receiving M_3 from A, T sends the result of user authentication according to M_1 and M_3 by using SK to decrypt the ciphertext and asking $\prod_{PRF}$ in order to verify the credential.

- $Send(S_j, U_i, sid, M_{m'}, m')$—Upon receiving a new session query $Send(S_j,U_i,sid, M_\lambda,\lambda)$, T asks $\prod_{U_i,S_j}^{sid}$ to send first message M_1 to A. After receiving corresponding message M_2, T checks the signature by using PK'. If the signature is valid, T asks $\prod_{PRF}$ and encrypts its output to form message M_3.

- $Corrupt(U_i, factor_a, factor_b)$— Upon receiving this query, $\prod_{U_i,S_j}^{sid}$ will send the corresponding two factors according to a and b, where $a, b \in \{pw, SC, Bio\}$ and $a \neq b$.

If A can pass user authentication successfully with a non-negligible probability without asking $\prod_{U_i,S_j}^{sid}$, there must exist a matching conversation between A and T who simulates server S_j if the following happens. First, A asks $Corrupt(U_i,factor_a, factor_b)$ to obtain two factors, then sends the first message to T who then responds with the second message. Finally, A forms the third message to T.

Now, we show how T makes use of A to win Game-PRF with non-negligible advantage as follows. We assume that A attacks at least once among q_s sessions, while T does not know which session A is going to attack. Now, T chooses a session out of q_s sessions randomly. Then, the probability of A passing user authentication in this session is $\frac{1}{q_s} \cdot \epsilon$.

To avoid the case that A found that this environment is only a simulation, in the rest $q_s - 1$ sessions, T redirects the identity ID_r, which is included in the first message, to oracle $\prod_{PRF}$ which will respond $PRF_x(ID_r)$ back to T. Then, T records this identity into the compromised table and checks whether A has passed the user authentication by matching $PRF_x(ID_r)$ with the credential which is encrypted in the third message. If they are matched, then T responds to A that T accepts A's login request. Otherwise, T rejects A's request. For these sessions, T just randomly guesses the value of b, so the probability that T wins the game is $\frac{1}{2}$.

To use A, after receiving first message $M_1 = (ID_{new}, sid, g^a)$, T forms $M_2 = (SID, sid, g^b,\ Sig_{SK'}(SID, ID_{new}, sid, g^a, g^b))$ by using SK' and sends it to A. If A

can successfully pass user authentication, s/he must be able to forge third message $M_3 = (ID_{new}, sid, CT)$, where $CT = E_{PK}(C'_{new}, ID_{new}, SID, sid, g^a, g^b)$. Now, T requires to start the Game-PRF by choosing two distinct messages $y_0 = h(ID_{new})$ and $y_1 = R_1$, and sends (y_0, y_1) to the PRF test query. The query responds $PRF_x(y_b)$ to T, then T decrypts CT to recover C'_{new} and checks whether the response is the same as C'_{new}. If it is, then it outputs $b' = 0$ as the guessed result of b. Otherwise, it outputs $b' = 1$.

We now analysis the probability of game winning. We assume that A forges user U_{new}, and passes user authentication successfully in polynomial time τ, with non-negligible probability ϵ, asking q_R times $Register(\prod, S_j)$, q_E times $Execute(U_i, S_j, sid)$, q_S times *send* query in q_s sessions. The formula of calculating probability $\Pr_{adv}[PRF]$ of three different corrupting cases should be the same but with different ϵ because we do not care how A can pass the user authentication. If A does not select this special session, the probability of game wining without the help of A is $\frac{1}{2}$. Otherwise, if A indeed attacks this special session chose by T, then the probability is concerned as follows. The probability of A pass authentication is ϵ, so the probability that we win the Game-PRF is $(\epsilon \cdot 1 + (1-\epsilon) \cdot \frac{1}{2})$. Because if A has passed authentication, then we have 100% probability to win the game. On the other side, A may also failed with the probability of $(1-\epsilon)$, in this case, we have $\frac{1}{2}$ probability to win the game. Thus,

$$\begin{aligned}
\Pr_{adv}[PRF] &= \frac{1}{q_s} \cdot (\epsilon \cdot 1 + (1-\epsilon) \cdot \frac{1}{2}) + \frac{q_{sq_s} - 1}{q_s} \cdot \frac{1}{2} - \frac{1}{2} \\
&= \frac{\epsilon + q_s}{2q_s} - \frac{1}{2} \\
&= \frac{\epsilon}{2q_s}
\end{aligned}$$

It is clear that $\Pr_{adv}[PRF]$ is non-negligible since ϵ is non-negligible, and T spends $\tau' = \tau + \tau_2$ time to win games, where τ_2 is the executing time of T interaction with the test query. It is obvious that both τ and τ'_2 are polynomial times, thus, τ' is also a polynomial time. Therefore, T can win Game-PRF with non-negligible advantage $\Pr_{adv}[PRF]$, and this contradicts assumption. □

Lemma 5.2. *(Secure Server Authentication) In proposed protocol $\prod$, if the signature scheme is unforgeable against adaptive chosen message attacks, and $\prod_{U_i,S_j}^{sid}$ has accepted, then for any PPT adversary A in the AM, the probability of $No-Matching^{A,U_i}(k)$ is negligible.*

Proof. This can be proved by contradiction. If A has been accepted by $\prod_{U_i,S_j}^{sid}$ with non-negligible probability of $No - Matching^{A,U_i}(k)$, then we can construct a PPT machine T which can win the Game-UFCMA [GMR88] by employing A.

In Game-UFCMA, there is a signature signing oracle $\prod_{Sign}$. A challenger who has got the PK' can make a signing query to a signature on any message M_i, and can also verify the signature by using PK'. Finally, the challenger outputs new message M_{new} which the signing oracle has not been asked to sign together with a forged signature. The challenger wins if the signature is valid for M_{new} under PK'. Let $\Pr_{win}[SIG]$ denotes the probability advantage of game winning.

The basic idea is that to win Game-UFCMA, T simulates an environment of our concrete protocol to convince adversary A that this simulation is the real concrete protocol. On the other side, A should only has a negligible probability to know the truce, i.e. this is not a real protocol environment but a simulation. In such simulation, T communicates with A who has the ability to successfully forge server's signature in a session with session ID *sid* with a non-negligible probability. Then, T will make use of A's ability to win Game-UFCMA with a non-negligible probability.

To use A, T need to simulate A's view as follows. In the simulation, T answers all oracle queries made by A. To achieve this goal, T needs to setup all parameters except signing key SK'. In our concrete scheme, A can ask following quires:

- $Execute(U_i, S_j, sid)$— In $\prod$, $\prod_{U_i,S_j}^{sid}$ and $\prod_{S_j,U_i}^{sid}$ generate and record all messages transmitted between U_i and S_j, then send them to A.

- $Send(U_i, S_j, sid, M, m)$— A can send M_1 to T, then T responds M_2 by asking the $\prod_{Sign}$ of $\prod_{S_j,U_i}^{sid}$. Upon receiving M_3 from A, T sends the result of user authentication according to M_1 and M_3.

- $Send(S_j, U_i, sid, M_{m'}, m')$—Upon receiving new session query $Send(S_j, M_\lambda, \lambda)$, T asks $\prod_{U_i,S_j}^{sid}$ to send first message M_1 to A. After receiving corresponding M_2, T checks the signature, and forms M_3 if the signature is valid.

If A can successfully pass server authentication with a non-negligible probability, there must exist a matching conversation between A and T who simulates user U_i if the following happens. In the simulation, first, T chooses message $M_1 = (T, sid, g^a)$, and sends it to A. If A can successfully pass server authentication, then A will form message $M_2 = (SID, sid, g^b, Sig_{SK'}(SID, T, sid, g^a, g^b))$ and send it to T.

To win the Game-UFCMA with A's help, T sends $M = (SID, T, sid, g^a, g^b)$ together with the signature in M_2 to the test query. We assume that A forges server S and passes server authentication successfully in polynomial time τ, with non-negligible probability ϵ, asking q_E times to $Execute(U_i, S_j, sid)$ and q_S times to send a query, which contains q_s times $Send(S_j, U_i, sid, M_{m'}, m')$. Let η be the probability of T winning Game-UFCMA when A has failed to pass server authentication. The probability is concerned as follows. In q_s times *send* query made by A, we choose one query to help us to answer the Game-UFCMA. The probability of A pass sever authentication is ϵ, so the probability of we win the Game-UFCMA is $(\epsilon \cdot 1 + (1-\epsilon) \cdot \eta)$. Because that if A has passed authentication, then we have 100% probability to win the game. On the other side, A may also failed with the probability of $(1-\epsilon)$, in this case, we have the probability of η to win the game. For the rest queries, the probability of game wining without the help of A is η. Thus,

$$\begin{aligned} \Pr_{win}[SIG] &= \frac{1}{q_s} \cdot (\epsilon \cdot 1 + (1-\epsilon) \cdot \eta) + \frac{q_s - 1}{q_s} \cdot \eta \\ &= \frac{\epsilon + \eta \cdot (q_s - \epsilon)}{q_s} \end{aligned}$$

It is clear that $\Pr_{win}[SIG]$ is non-negligible since ϵ is non-negligible. The time T spent to win the games is $\tau' = \tau + \tau_3$, where t_3 is the executing time of T spends in GAME-UFCMA. τ' is a polynomial time because both τ and τ_3' are polynomial times. Therefore, we can construct PPT machine T to win Game-UFCMA of the signature scheme, with non-negligible probability, and this is a contradiction. □

Theorem 5.3. *(Secure Three-Factor Mutual Authentication (STMA)) In proposed protocol $\prod$, if: (A) the PRF is replaced by an ideal random function and PKE scheme is secure against CCA2 attack; (B) the signature scheme is unforgeable against chosen message attack; (C) at least one of $\prod_{U_i,S_j}^{sid}$ and $\prod_{S_j,U_i}^{sid}$ has accepted; then for any PPT adversary A in the AM, the probabilities of both $No-Matching^{A_{U_i}}(k)$ and $No-Matching^{A_{S_j}}(k)$ are negligible.*

Proof. Obviously, the first condition of Definition 5.3 holds because it is easy to verify that our concrete protocol is correct. In addition, by Lemma 5.1 and Lemma 5.2, the second and third conditions of Definition 5.3 also hold. Therefore, Theorem 5.3 holds. □

Theorem 5.4. *(Secure Three-Factor Authenticated Key Exchange (STAKE)) In proposed protocol $\prod$, if (A) the PRF is replaced by an ideal random function and the*

PKE scheme is secure against $CCA2$ attack; (B) the signature scheme is unforgeable against chosen message attack; then for any PPT adversary A in the AM, the advantage $Adv^A(k)$ of A winning the game of $AKEP$ in a fresh session is negligible.

Proof. According to the Definition 5.4, $STAKE$ need to meet three conditions. The first condition is that protocol $\prod$ is required to satisfies $STMA$. This condition is achieved because Theorem 5.3. The second condition is that for a fresh session in protocol $\prod$, if complete conversations are matched, then the same session key must be shared between these two communicating parties. This condition is achieved because that in our concrete scheme, the key exchange is the plain two-move Diffie-Hellman protocol [CK01], and this condition is a well-known property and it was proved. For the third condition, the advantage $Adv^A(k) = |\Pr[Good - guess^A(k)] - \frac{1}{2}|$ is non-negligible due to [CK01]. Thus, $\prod$ is a secure three-factor authenticated key exchange protocol. □

5.4.4 Privacy Discussion

The proposed framework provides strong protection of user privacy. First, the server does not know any information about the user's biometric template since the user need not provide biometric features to the server. Second, the information in SC is also unable to leak biometric information to others. In SC, only vault V and helper data H are related to the biometric features, however, V has been added along with a large number of chaff points as noise. Thus, the probability of successfully recovering the biometric template is negligible due to [NJP07]. Moreover, helper data H in the 'fuzzy vault' does not reveal the user's biometric templates since they are global features which do not leak any information of local characteristics[NJP07] and two different finger templates can extract very similar helper data [NJP07].

A different PW_2 has been chosen, then a new V has been generated. In another words, the same biometric feature can encrypt different keys, and output different vault V. Thus, a user can use the same biometric feature in different servers with different biometric keys, and output different vault V.

5.5 Conclusion

The proposed improved framework for three-factor authentication is efficient and practical in distributed systems and networks. The framework upgrades two-factor authentication schemes to three-factor authentication schemes; the derived scheme protects user's privacy, and enhances security. In addition, a provably secure concrete authentication scheme has been provided with formal security proof and an analysis which shows the concrete scheme is more secure and practical.

Chapter 6

Conclusion

This chapter concludes the thesis in two parts: the summary of contributions and the promotion of open problems.

6.1 Contributions

This thesis focuses primarily on two techniques for remote user authentication: single sign-on and three-factor authentication. It aims: (a) to prevent attacks on SSO mechanisms by analysing and formally defining SSO mechanisms; (b) to provide a provably secure SSO scheme based on the proposed formal model and (c) to offer a generic framework of three-factor authentication with provably secure concrete instantiation for the user who has higher security requirements. The main contributions of this thesis are as follows:

- Chapter 3 first provides some new insights into a recent single sign-on scheme proposed by Chang and Lee [CL12]. Next, based on this analysis, Chapter 3 points out the shortcomings of the Chang-Lee scheme and identifies two potential attacks with an analysis of their success probability. In particular, these two impersonation attacks show that their scheme is actually insecure as it fails to meet credential privacy and soundness of authentication. This chapter also makes a carefully analysis on the issues of how to design single sign-on scheme. Finally, the drawbacks of the Chang-Lee scheme are overcome by employing the efficient verifiable encryption of RSA signatures (RSA-VES) which was proposed for fair exchange by Ateniese[Ate99].

- In Chapter 4, we have formalised the security model of single sign-on with authenticated key exchange. In particular, we have pointed out the difference between soundness and credential privacy. The proposed model presents a unified definition of formally specifying soundness and credential privacy for authenticated key exchange single sign-on (AKESSO). According to the formal model, this chapter proposes a provably secure single sign-on authentication scheme which satisfies soundness, preserves credential privacy, meets user anonymity, supports session key exchange. Due to its high efficiency, the scheme is suitable for mobile device users in distributed environments.

- Chapter 5 proposes an improved generic framework for three-factor authentication. This framework can upgrade a two factor authentication scheme to a three factor authentication scheme. The derived three-factor scheme is suitable for environments where the underlying two-factor scheme is specified. Compare with Huang *et al.*'s scheme [HXC$^+$11], the proposed generic framework enhances efficiency and it is more practical. A provably secure concrete instantiation of the generic framework is also provided. In particular, we have provided an performance analysis, a formal security proof and a privacy discussion of the concrete instantiation.

6.2 Open Problems

As mentioned in Chapter 3, the open problems are to formally define authentication soundness and construct efficient and provably secure single sign-on schemes. Han *et al.*'s model [HMSY10] requires additional PKI for users but it does not require the third party to be fully trusted. Our formal model of SSO does not require users holding publick key certificate, however, it may be not mature because it requires a fully trusted third party. So, another challenge is how to provide the same security level while reducing the trust level of the third party, and without requiring PKI for users. These challenges may be considered as a future work.

Bibliography

[ASW00] N. Asokan, Victor Shoup, and Michael Waidner. Optimistic fair exchange of digital signatures. *IEEE Journal on Selected Areas in Communications*, 18(4):593–610, April 2000.

[AT08] B.J. Teoh Andrew and Song Ong Thian. Secure biometric template protection via randomized dynamic quantization transformation. *IEEE International Symposium on Biometrics and Security Technologies*, 2008.

[Ate99] Giuseppe Ateniese. Efficient verifiable encryption (and fair exchange) of digital signatures. In *Proceedings of the 6th ACM conference on Computer and communications security*, CCS '99, pages 138–146, New York, NY, USA, 1999. ACM.

[Ate04] Giuseppe Ateniese. Verifiable encryption of digital signatures and applications. *ACM Trans. Inf. Syst. Secur.*, 7(1):1–20, 2004.

[BAN90] Michael Burrows, Martn Abadi, and Roger M. Needham. A logic of authentication. *ACM Trans. Comput. Syst.*, 8(1):18–36, 1990.

[BCP04] Emmanuel Bresson, Olivier Chevassut, and David Pointcheval. New security results on encrypted key exchange. In *Public Key Cryptography*, pages 145–158, 2004.

[BG92] Mihir Bellare and Oded Goldreich. On defining proofs of knowledge. In *CRYPTO*, pages 390–420, 1992.

[BM94] Colin Boyd and Wenbo Mao. On a Limitation of BAN Logic. In *Advances in Cryptology – EUROCRYPT '93*, volume 765 of *Lecture Notes in Computer Science*, pages 240–247. Springer Berlin / Heidelberg, 1994.

[Bon99] Dan Boneh. Twenty years of attacks on the RSA cryptosystem. *Notices of the American Mathematical Society*, 46(2):203–213, 1999.

[BP02] Mihir Bellare and Adriana Palacio. GQ and Schnorr identification schemes: Proofs of security against impersonation under active and concurrent attacks. *Advances in Cryptology CRYPTO 2002*, pages 162–177, 2002.

[BPR00] Mihir Bellare, David Pointcheval, and Phillip Rogaway. Authenticated key exchange secure against dictionary attacks. In *EUROCRYPT*, pages 139–155, 2000.

[BR93a] Mihir Bellare and Phillip Rogaway. Entity authentication and key distribution. In *CRYPTO*, pages 232–249, 1993.

[BR93b] Mihir Bellare and Phillip Rogaway. Random oracles are practical: A paradigm for designing efficient protocols. In *ACM Conference on Computer and Communications Security*, pages 62–73, 1993.

[BR94a] Mihir Bellare and Phillip Rogaway. Optimal asymmetric encryption. In *EUROCRYPT*, pages 92–111, 1994.

[BR94b] Mihir Bellare and Phillip Rogaway. Optimal asymmetric encryption. In *EUROCRYPT*, pages 92–111, 1994.

[BSSB06] Abhilasha Bhargav-Spantzel, Anna Cinzia Squicciarini, and Elisa Bertino. Privacy preserving multi-factor authentication with biometrics. In *Digital Identity Management*, pages 63–72, 2006.

[BSSM+07] Abhilasha Bhargav-Spantzel, Anna Cinzia Squicciarini, Shimon K. Modi, Matthew Young, Elisa Bertino, and Stephen J. Elliott. Privacy preserving multi-factor authentication with biometrics. *Journal of Computer Security*, 15(5):529–560, 2007.

[BX11] Leonard Barolli and Fatos Xhafa. Jxta-overlay: A p2p platform for distributed, collaborative, and ubiquitous computing, 2011.

[CC02] Chi-Kwong Chan and Lee-Ming Cheng. Cryptanalysis of timestamp-based password authentication scheme. *Computers & Security*, 21(1):74–76, 2002.

[CH93] C.-C. Chang and S.-J. Hwang. Using smart cards to authenticate remote passwords. *Computers and Mathematics with Applications*, 26(7):19 – 27, 1993.

[CK01] Ran Canetti and Hugo Krawczyk. Analysis of key-exchange protocols and their use for building secure channels. In *EUROCRYPT*, pages 453–474, 2001.

[CL12] Chin-Chen Chang and Chia-Yin Lee. A secure single sign-on mechanism for distributed computer networks. *IEEE Trans. Ind. Electron.*, 59(1):629–637, 2012.

[Cla03] T. Charles Clancy. Secure smartcard-based fingerprint authentication. In *ACM Workshop on Biometrics: Methods and Applications*, pages 45–52, 2003.

[CM00] Jan Camenisch and Markus Michels. Confirmer signature schemes secure against adaptive adversaries. In Bart Preneel, editor, *EUROCRYPT*, volume 1807 of *Lecture Notes in Computer Science*, pages 243–258. Springer, 2000.

[CP92] David Chaum and Torben P. Pedersen. Wallet databases with observers. In *CRYPTO*, pages 89–105, 1992.

[CPS11] Manuel Cheminod, Alfredo Pironti, and Riccardo Sisto. Formal vulnerability analysis of a security system for remote fieldbus access. *IEEE Trans. on Industrial Informatics*, 7(1):30–40, 2011.

[CW91] C.-C. Chang and T.-C. Wu. Remote password authentication with smart cards. *IEE Proceedings-E Computers and Digital Techniques*, 138(3):165 – 168, may 1991.

[Das11] Ashok Kumar Das. Cryptanalysis and further improvement of a biometric-based remote user authentication scheme using smart cards. *International Journal of Network Security and Its Applications (IJNSA)*, 3(2):13–28, 2011.

[DH76] Whitfield Diffie and Martin E. Hellman. New directions in cryptography. *IEEE Transactions on Information Theory*, 22(6):644–654, November 1976.

[DK02] Hans Delfs and Helmut Knebl. *Introduction to Cryptography: Principles and Applications*. Springer, 2002.

[DORS08] Yevgeniy Dodis, Rafail Ostrovsky, Leonid Reyzin, and Adam Smith. Fuzzy extractors: How to generate strong keys from biometrics and other noisy data. *SIAM J. Comput.*, 38(1):97–139, 2008.

[DR00] Joan Daemen and Vincent Rijmen. Rijndael for aes. In *AES Candidate Conference*, pages 343–348, 2000.

[DRS04] Yevgeniy Dodis, Leonid Reyzin, and Adam Smith. Fuzzy extractors: How to generate strong keys from biometrics and other noisy data. In *EUROCRYPT*, pages 523–540, 2004.

[EKW74] J. Arthur Evans, William Kantrowitz, and Edwin Weiss. A user authentication scheme not requiring secrecy in the computer. *Commun. ACM*, 17(8):437–442, August 1974.

[ElG85] Taher ElGamal. A public key cryptosystem and a signature scheme based on discrete logarithms. In George Blakley and David Chaumeditors, editors, *CRYPTO'85*, volume 196, pages 10–18. Springer, 1985.

[Fen08] Jianjiang Feng. Combining minutiae descriptors for fingerprint matching. *Pattern Recognition*, 41(1):342–352, 2008.

[FFS88] Uriel Feige, Amos Fiat, and Adi Shamir. Zero-knowledge proofs of identity. *Journal of Crytography*, 1(2):77–94, 1988.

[FL09] Chun-I Fan and Yi-Hui Lin. Provably secure remote truly three-factor authentication scheme with privacy protection on biometrics. *IEEE Transactions on Information Forensics and Security*, 4(4):933–945, 2009.

[FLZ02] Lei Fan, Jian-Hua Li, and Hong-Wen Zhu. An enhancement of timestamp-based password authentication scheme. *Computers & Security*, 21(7):665–667, 2002.

[FS86] Amos Fiat and Adi Shamir. How to prove yourself: Practical solutions to identification and signature problems. In *CRYPTO*, pages 186–194, 1986.

[GAT00] Marc Joye Giuseppe Ateniese, Jan Camenisch and Gene Tsudik. A practical and provably secure coalition-resistant group signature scheme. In *CRYPTO*, pages 255–270, 2000.

[GMR84] Shafi Goldwasser, Silvio Micali, and Ronald L. Rivest. A "paradoxical" solution to the signature problem (extended abstract). In *FOCS*, pages 441–448, 1984.

[GMR85] Shafi Goldwasser, Silvio Micali, and Charles Rackoff. The knowledge complexity of interactive proof-systems (extended abstract). In *STOC*, pages 291–304, 1985.

[GMR88] Shafi Goldwasser, Silvio Micali, and Ronald L. Rivest. A digital signature scheme secure against adaptive chosen-message attacks. *SIAM J. Comput.*, 17(2):281–308, 1988.

[GMR89] Shafi Goldwasser, Silvio Micali, and Charles Rackoff. The knowledge complexity of interactive proof systems. *SIAM J. Comput.*, 18(1):186–208, 1989.

[Gro] The Open Group. Security form on single sign-on. `http://www.opengroup.org/security/l2-sso.htm`.

[HC09] Chien-Lung Hsu and Yu-Hao Chuang. A novel user identification scheme with key distribution preserving user anonymity for distributed computer networks. *Inf. Sci.*, 179(4):422–429, 2009.

[HMSY10] Jinguang Han, Yi Mu, Willy Susilo, and Jun Yan. A generic construction of dynamic single sign-on with strong security. In *SecureComm*, pages 181–198, 2010.

[HMZ+11] Daojing He, Maode Ma, Yan Zhang, Chun Chen, and Jiajun Bu. A strong user authentication scheme with smart cards for wireless communications. *Computer Communications*, 34(3):367–374, 2011.

[HXC+11] Xinyi Huang, Yang Xiang, A. Chonka, Jianying Zhou, and Robert H. Deng. A generic framework for three-factor authentication: Preserving security and privacy in distributed systems. *IEEE Transactions on Parallel and Distributed Systems*, 22(8):1390 –1397, aug. 2011.

[JM03] Anil K. Jain and David Maltoni. *Handbook of Fingerprint Recognition.* Springer-Verlag New York, Inc., Secaucus, NJ, USA, 2003.

[JR03] Václav Matyás Jr. and Zdenek Ríha. Toward reliable user authentication through biometrics. *IEEE Security & Privacy*, 1(3):45–49, 2003.

[JS02] Ari Juels and Madhu Sudan. A fuzzy vault scheme. In *International Symposium on Information Theory (ISIT)*, page 408. IEEE Press, 2002.

[JW99] Ari Juels and Martin Wattenberg. A fuzzy commitment scheme. In *ACM Conference on Computer and Communications Security*, pages 28–36, 1999.

[JW09] Wen-Shenq Juang and Jing-Lin Wu. Robust and efficient authenticated key agreement in mobile communications. *Int. J. Mob. Commun.*, 7(5):562–579, April 2009.

[KLY03] Hyun-Sung Kim, Sung-Woon Lee, and Kee-Young Yoo. Id-based password authentication scheme using smart cards and fingerprints. *SIGOPS Oper. Syst. Rev.*, 37:32–41, October 2003.

[Lam81] Leslie Lamport. Password authentication with insecure communication. *Commun. ACM*, 24(11):770–772, Nov. 1981.

[LC00] Wei-Bin Lee and Chin-Chen Chang. User identification and key distribution maintaining anonymity for distributed computer networks. *Computer Systems Science and Engineering*, 15(4):113 –116, Aug. 2000.

[LH10] Chun-Ta Li and Min-Shiang Hwang. An efficient biometrics-based remote user authentication scheme using smart cards. *J. Netw. Comput. Appl.*, 33(1):1–5, January 2010.

[LMM81] Richard E. Lennon, Stephen M. Matyas, and Carl H. Meyer. Cryptographic authentication of time-invariant quantities. *IEEE TRANSACTIONS ON COMMUNICATIONS*, 29(6):773–777, June 1981.

[LNM+11] Xiong Li, Jian-Wei Niu, Jian Ma, Wen-Dong Wang, and Cheng-Lian Liu. Cryptanalysis and improvement of a biometrics-based remote user authentication scheme using smart cards. *Journal of Network and Computer Applications*, 34(1):73–79, 2011.

[Mao04] Wenbo Mao. *Modern cryptography: theory and practice*. HP Professional Series. Prentice Hall PTR, 2004.

[Mil82] F. Miller. *Telegraphic code to insure privacy and secrecy in the transmission of telegrams*. C.M. Cornwell, 1882.

[MK06] Kumar V. Mangipudi and Rajendra S. Katti. A secure identification and key agreement protocol with user anonymity (sika). *Computers & Security*, 25(6):420–425, 2006.

[NJP07] Karthik Nandakumar, Anil K. Jain, and Sharath Pankanti. Fingerprint-based fuzzy vault: Implementation and performance. *IEEE Transactions on Information Forensics and Security*, 2(4):744–757, 2007.

[NNJ08] Abhishek Nagar, Karthik Nandakumar, and Anil K. Jain. Securing fingerprint template: Fuzzy vault with minutiae descriptors. In *19th International Conference on Pattern Recognition, 2008. ICPR 2008.*, pages 1 –4, dec. 2008.

[NSC+93] B. Clifford Neuman, Stuart G. Stubblebine, B. Clifford, Neuman Stuart, and G. Stubblebine. A note on the use of timestamps as nonces. *Operating Systems Review*, 27:10–14, 1993.

[OR87] Dave Otway and Owen Rees. Efficient and timely mutual authentication. *SIGOPS Oper. Syst. Rev.*, 21(1):8–10, January 1987.

[oS77] National Bureau of Standards. *Data Encryption Standard*. FIPS-Pub.46., Department of Commerce, Washington D.C., U.S., January 1977.

[OT89] Eiji Okamoto and Kazue Tanaka. Identity-based information security management system for personal computer networks. *IEEE Journal on Selected Areas in Communications*, 7(2):290 –294, feb 1989.

[PKC] PKCS. Public key cryptography standards, PKCS #1 v2.1. RSA cryptography standard, draft 2, 2001. `http://www.rsasecurity.com/rsalabs/pkcs/`.

[PS96] David Pointcheval and Jacques Stern. Security proofs for signature schemes. In *EUROCRYPT*, pages 387–398, 1996.

[PS00] David Pointcheval and Jacques Stern. Security arguments for digital signatures and blind signatures. *Journal of Cryptology*, 13(3):361–396, 2000.

[RSA78] Ronald L. Rivest, Adi Shamir, and Leonard M. Adleman. A method for obtaining digital signatures and public-key cryptosystems. *Communnication of ACM*, 21:120–126, 1978.

[Sch89] Claus-Peter Schnorr. Efficient identification and signatures for smart cards. In *CRYPTO*, pages 239–252, 1989.

[Sch91] Claus-Peter Schnorr. Efficient signature generation by smart cards. *J. Cryptology*, 4(3):161–174, 1991.

[Sco04] Michael Scott. Cryptanalysis of an id-based password authentication scheme using smart cards and fingerprints. *SIGOPS Oper. Syst. Rev.*, 38:73–75, April 2004.

[SHFD08] Weiguo Sheng, Gareth Howells, Michael C. Fairhurst, and Farzin Deravi. Template-free biometric-key generation by means of fuzzy genetic clustering. *IEEE Transactions on Information Forensics and Security*, 3(2):183–191, 2008.

[Sho02] Victor Shoup. Oaep reconsidered. *J. Cryptology*, 15(4):223–249, 2002.

[SKS+92] Kehne Schonwalder, A. Kehne, J. Schonwalder, H. Langendorfer, and Tu Braunschweig. A nonce-based protocol for multiple authentications. *SIGOPS Oper. Syst. Rev.*, 26(4):84–89, October 1992.

[SLH03] Jau-Ji Shena, Chih-Wei Linb, and Min-Shiang Hwang. Security enhancement for the timestamp-based password authentication scheme using smart cards. *Computers & Security*, 22(7):591–595, 2003.

[SY96] Shiuh-Pyng Shieh and Wen-Her Yang. An authentication and key distribution system for open network systems. *SIGOPS Oper. Syst. Rev.*, 30(2):32–41, April 1996.

[Syv93] Paul Syverson. On key distribution protocols for repeated authentication. *Operating Systems Review*, 27:24–30, 1993.

[Ten95] Gerald Tenenbaum. Introduction to analytic and probabilistic number theory. *Cambridge studies in advanced mathematics*, 46, 1995.

[UPJP04] Umut Uludag, Sharath Pankanti, Anil K. Jain, and Salil Prabhakar. Biometric cryptosystems: Issues and challenges. In *Proceedings of the IEEE*, pages 948–960, 2004.

[WB06] Guilin Wang and Feng Bao. Cryptanalysis of timestamp-based password authentication schemes using smart cards. In *Proceedings of the 8th international conference on Information and Communications Security*, ICICS'06, pages 399–409, Berlin, Heidelberg, 2006. Springer-Verlag.

[Wei] Eric Weisstein. Relatively prime. mathworld-a wolfram web resource. `http://mathworld.wolfram.com/RelativelyPrime.html`.

[WH04] Tzong-Sun Wu and Chien-Lung Hsu. Efficient user identification scheme with key distribution preserving anonymity for distributed computer networks. *Computers & Security*, 23(2):120–125, 2004.

[Wik12a] Wikipedia. Rc4 — wikipedia, the free encyclopedia, 2012. [Online; accessed 23-May-2012].

[Wik12b] Wikipedia. RSA (algorithm) — wikipedia, the free encyclopedia, 2012. [Online; accessed 23-May-2012].

[WQ10] Yongdong Wu and Bo Qiu. Transforming a pattern identifier into biometric key generators. In *ICME*, pages 78–82, 2010.

[WYX12] Guilin Wang, Jiangshan Yu, and Qi Xie. Security analysis of a single sign-on mechanism for distributed computer networks. *IEEE Trans. Industrial Informatics*, accepted, July, 2012.

[XSK+05] Yuefei Xu, R. Song, L. Korba, Lihui Wang, Weiming Shen, and S. Lang. Distributed device networks with security constraints. *IEEE Trans. Industrial Informatics*, 1(4):217–225, 2005.

[XZF09] Jing Xu, Wen-Tao Zhu, and Dengguo Feng. An improved smart card based password authentication scheme with provable security. *Computer Standards & Interfaces*, 31(4):723–728, 2009.

[XZJ11] Jing Xu, Wen-Tao Zhu, and Wenting Jin. A generic framework for constructing cross-realm c2c-paka protocols based on the smart card. *Concurrency and Computation: Practice and Experience*, 23(12):1386–1398, 2011.

[YKY05] Eun-Jun Yoon, Woo-Hun Kim, and Kee-Young Yoo. Security enhancement for password authentication schemes with smart cards. In *Proceedings of the Second international conference on Trust, Privacy, and Security in Digital Business*, TrustBus'05, pages 311–320, Berlin, Heidelberg, 2005. Springer-Verlag.

[YS99] Wen-Her Yang and Shiuh-Pyng Shieh. Password authentication schemes with smart cards. *Computers & Security*, 18(8):727–733, 1999.

[YWB+04] Yanjiang Yang, Shuhong Wang, Feng Bao, Jie Wang, and Robert H. Deng. New efficient user identification and key distribution scheme providing enhanced security. *Computers & Security*, 23(8):697–704, 2004.

[YWC05] Chou-Chen Yanga, Ren-Chiun Wang, and Ting-Yi Chang. An improvement of the yang-shieh password authentication schemes. *Applied Mathematics and Computation*, 162(3):1391–1396, 2005.

[YWWD08] Guomin Yang, Duncan S. Wong, Huaxiong Wang, and Xiaotie Deng. Two-factor mutual authentication based on smart cards and passwords. *J. Comput. Syst. Sci.*, 74:1160–1172, November 2008.