Intrusion Resilient and Real-Time Forensics

by

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Abstract

Intrusion to corporate network and unauthorized access to sensitive information can cause huge damage and intellectual property loss. In addition to intrusion, Denial of service (DoS)/Distributed DoS (DDoS) attack is also an eminent threat to an authentication server, which is used to guard access to firewalls, virtual private networks and resources connected by wired/wireless networks. Currently, most of the work has focused either on Intrusion Detection Systems (IDS)/Intrusion Prevention Systems (IPS), Anti-Malware, Network Access Control (NAC)/Network Access Protection (NAP), Firewall, or their combinations. However, either one has some weaknesses and cannot protect the network against intrusion thoroughly. In this dissertation, we proposed two security systems to protect network infrastructure against intrusion and data theft The first approach adopts distributing two-factor user secrets and authentication servers. A queueing model is utilized to analyze the performance of the proposed system. We also propose another innovative space-time evolving authentication scheme that includes users, processes, parent processes, applications and behaviors, as well as guarded information resources. This systems oriented methodology employs security agents to proactively acquire and guard logs, and reconstruct the space-time events of logs. A violation of ACL triggers a correlation engine to trace back related events in real-time to identify the attack, the attacker and the damage, including lost information in servers, hosts and devices. To test the performance, we first develop the system model, which includes Client, Security Agent, Super Security Agent, Authentication Server, and Database Server, using Java with JDK 1.6 against SQL injection attack and cross-site scripting attack. Later on, we simulate the system with Matlab and OPNET in large scale. The simulation results suggest that our proposed schemes are fast and effective against intrusion and data theft.

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Chapter 1

Introduction

In the rapidly exploring information era, everything goes electronically. Security and privacy become the major concerns of US government, education institute and commercial companies, especially the financial institutions. According to the Chronology of Data Breaches [1], 540,613,790 records (still increasing) breached since 2005, far more than 1,935 data breaches made public at that time.

Intrusion to corporate networks and unauthorized access to sensitive information can cause huge damage and intellectual property loss. According to recent study by McAfee [2], data theft and breaches from cybercrime may have cost businesses as much as $1 trillion globally in lost intellectual property, and expenditures for repairing the damage. Cybercriminal syndicates, such as the Russion Business Network (RBN), are becoming more professional and sophisticated in their approach. The same is true for the efforts of state-sponsored or terrorist groups. Recent reports from industry leader Verizon indicated that worldwide current security practices aren't making the grade. The firm's 2011 Data Breach Study [3] reports that 92% of breaches came from external sources - many capitalizing on user mistakes to install malware that is able to pull critical data from servers and applications.

To counter the attacks, the existing methods of protection adopt Intrusion Detection System (IDS)/Intrusion Prevention System (IPS), Anti-Malware, Network Access Control (NAC)/Network Access Prevention (NAP), Firewall, or their combinations. However, the frequency and sophistication of attacks on the Internet are rapidly increasing, which make intrusion detection and prevention really challenging.

In this chapter, we discuss the underlying technical challenges of intrusion resilience and network authentication. Then we explain the motivations for our work in intrusion

resilience and space-time evolving authentication. Last, the organization for the rest of the dissertation is presented.

1.1 Challenges for Network Authentication Protocols

It is challenging to implement an intrusion-resilient authentication protocol as the following properties need to be considered [5]:

- `Perfect Forward Secrecy (PFS)` is the property that ensures that a session key derived from a set of long-term public and private keys will not be compromised if one of the (long-term) private keys is compromised in the future.

- The `Privacy` property means that the protocol must not reveal the identity of a participant to any unauthorized party, including an active attacker who attempts to act as the peer. Clearly, it is not possible for a protocol to protect both the initator and the responder against an active attacker; one of the participants must always go first. In general, it is believed that the most appropriate choice is to protect the initator, since the initator is typically a relatively anonymous client, while the responder's identity may already be known. Conversely, protecting the responder's privacy may not be of much value (except perhaps in peer-to-peer communication): in many cases, the responder is a server with a fixed address or characteristics.

- `Memory-DDoS and Computation-DDoS`: Denial of service (DoS) or distributed DoS (DDoS) attack floods the authentication server with fake packets and causes the server to exhaust its resources for processing fake packets. When the resources of the authentication server are exhausted, a legitimate user's authentication requests cannot be processed. The major problem of DoS/DDoS attack is that the authentication server (or responder) needs to validate that the request is from a legitimate user (or initiator). However, the authentication server only has a limited CPU computation power and

restricted amount of memory. When attackers initiate sufficient requests, the authentication server cannot respond to legitimate requests. It is necessary to minimize the resources committed to a request before verifying that the request is from a legitimate source.

- The `Efficiency` property is worth discussing. In many protocols, key setup must be performed frequently enough that it can become a bottleneck to communication. The key exchange protocol must minimize computation as well as total bandwidth and round trips. Round trips can be especially an important factor when communicating over unreliable media, such as wireless.

The capabilities of hackers keep increasing. In the traditional adversary model, attackers can modify/record the communication, modify the messages transmitted, and initiate authentication requests with the server or forge response to authentication request from a legitimate user. With the rapid development of computer and electronics technology, attackers are able to do more than those prescribed in the traditional model. Thus, we use the term "strong adversary model" to reflect the evolving capabilities of computer hackers. In the strong adversary model, attackers can compromise either a user's client computer or the authentication server in addition to their capabilities in the traditional adversary model. If an attacker subverts the client computer or the server, all stored secrets for authentication are obtained by the adversary [4].

1.2 Challenges for Intrusion Resilience and Real-Time Forensics

The attacks have become more sophisticated in the last several years as the level of attack automation has increased. Sample and fully functional attack software is readily available on the Internet. Precompiled and ready to use programs allow novice users to launch relatively large scale attacks with little knowledge of the underlying security exploits. The advent of remote controlled networks of computers used to launch attacks has changed

the landscape and methods that a service provider must use. According to a study, 90% of the vulnerable hosts were infected, within the first 10 minutes of release and the infection doubling within 8.5 seconds [32].

There are always some new emerging threats. If the system or computer applications are not carefully written, attackers can exploit the vulnerabilities that are not discovered by the system administrator, thus cannot defend against zero-day attacks. After intrusion, malwares or trojans can be injected into the compromised host. Moreover, the mutation of the malware makes it even harder to detect such metamorphic and polymorphic malwares. Master Boot Record (MBR) malware is another recently found advanced and probably the stealthiest malware so far. It keeps the amount of system modifications to a minimum and is very challenging to detect from within the infected system. Secure boot is the heart and fundamental for application-level security [17].

It has become a well known problem that current intrusion detection systems (IDS) produce large volumes of alerts, including both actual and false alarms. As the network performance improves and more network-based applications are being introduced, the IDSs are generating increasingly overwhelming alerts. This problem makes it extremely challenging to understand and manage the intrusion alerts, let alone respond to intrusions timely. It is often desirable, and sometimes necessary, to understand attack strategies in security applications such as computer forensics and intrusion responses. For example, it is easier to predict an attacker's next move, and decrease the damage caused by intrusions, if the attack strategy is known during intrusion response. However, in practice, it usually requires that human users analyze the intrusion data manually to understand the attack strategy. This process is not only time-consuming, but also error-prone.

1.3 Motivation for Proposed Intrusion Resilient System

To build a system defending sophisticated attacks, a fully distributed intrusion resilient system is needed. Fig. 1.1 illustrates the architecture of our proposed system, which consists

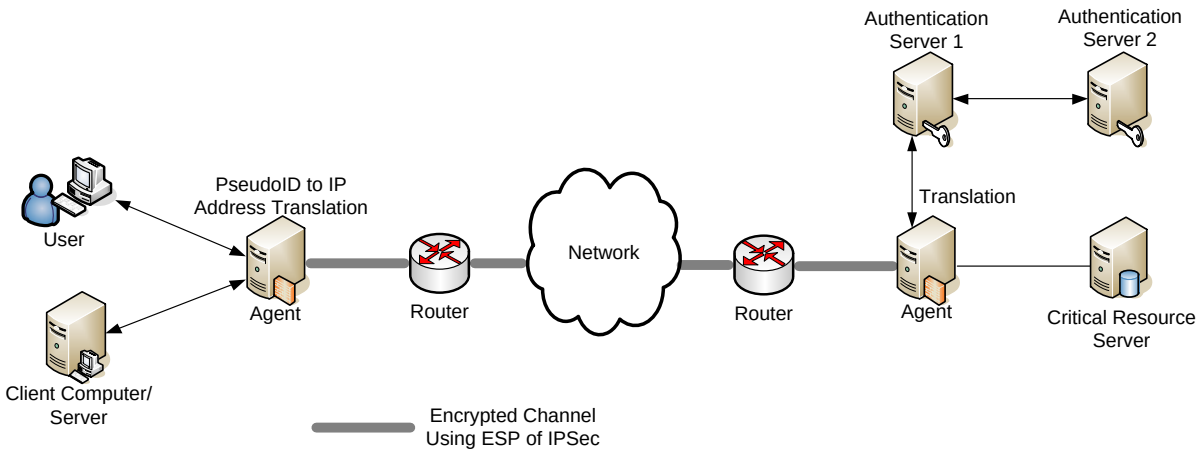


Figure 1.1: A fully distributed intrusion resilient system

of client/server computers, distributed agents and distributed Authentication Servers. A user/computer must register first using a PKI (Public Key Infrastructure) certificate and establish a shared secret with the Authentication Servers. Then a user/computer can use the shared secret for subsequent logins. Agents will control the access of a user/computer/agent to critical information/service available in the network. To counter the challenges mentioned above, we realize the necessary components in order to prove that the proposed system can provide

(a) Resilience to a strong inside adversary who can compromise a computer, a critical resource server, an agent and even Authentication Servers. Examples include an attacker compromises a client computer and cannot be authenticated by our system. An attacker compromises either Authentication Server 1 or 2 and cannot pretend to be a legitimate user. An attacker compromises both Authentication Server 1 and 2 and cannot pretend to be a legitimate user for the next time period. The self-healing will be demonstrated during the user's next login.

(b) Self-healing capability when a strong inside adversary compromises Authentication Servers.

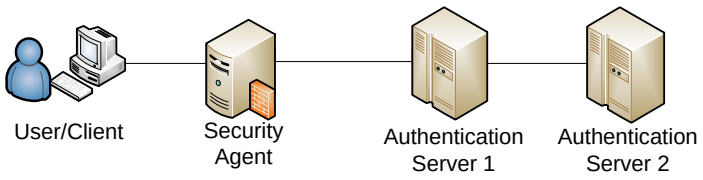


Figure 1.2: Concept of space separation

(c) Resistance to DDoS attacks. We will implement a DDoS attack by using multiple computers, which repetitively send in the first authentication request. The log in request of a legitimate user should be guaranteed during the DDoS attack.

(d) Access control and health monitoring capabilities of security agents in Trusted Network Connect (TNC)/Network Access Control (NAC)/Network Access Protection (NAP).

1.4 Motivation for Proposed Space-Time Authentication Scheme

Our goal is to build a robust and efficient system upon existing security technology and strengthen their weaknesses. The space-time concept is to separate login credentials and data in the realms of space and time in order to make system compromise exponentially more difficult. Thus, we propose our space-time evolving authentication scheme. The log creation and retrieval of every party involved should also be protected by the space-time evolving scheme.

The credential shared by the user and authentication server should be distributed in space to defend against single point failure problem (see Fig. 1.2). We cannot store the user credentials in one place, as if an attacker compromises the server, they have everything to access the critical resource.A sophisticated space separation concept is realized in a computer access system that has multiple authentication security agents. Imagine the online banking system that requires the user to authenticate with several authentication servers. The user must authenticate with each authentication server before access is granted to the banking

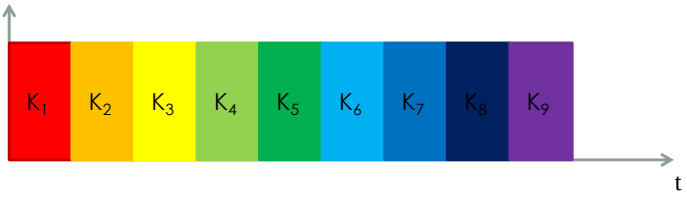


Figure 1.3: Concept of time evolving key

system. Each authentication server requires a unique password or other authentication credential from the user. Thus space separation of login credentials is accomplished.

Time separation of login credentials is achieved by making the key evolving in each time intervals (see Fig. 1.3). Only the owner of the key can derive the key for the next time interval; the party involved can only verify the key. User and host must have different keys, as user may login to different hosts. The key evolves in space as a packet propagating through agents and routers. The logs are also protected by the time evolving keys, which make our correlation and forensics part more secure.

Both space and time separation could fortify the system security. Thus, in this dissertation, we will describe the combination of space and time separation to achieve greater protection of critical network resources.

1.5 Dissertation Organization

This dissertation is divided into eight chapters. The first chapter provides the background information that is necessary to understand the rest of the work. The remaining chapters are the main contribution of our work.

In Chapter 2, we introduce the previous research on intrusion resilience, authentication and correlation. Although extensive work has been done to detect, mitigate and prevent the intrusions, there still exist some weaknesses in the current defense mechanisms.

In Chapter 3, we describe the technical details of the proposed intrusion resilient, DDoS-resistant authentication system (IDAS). We discuss how to distribute the secrets and authentication servers, how to achieve DDoS-resistance and self-healing properties. The performance evaluation of our proposed IDAS security system is presented in Chapter 4. The simulations are carried out from small scale to large scale like coast to coast and continent to continent.

In Chapter 5, the space-time evolving authentication scheme is investigated in detail. The concept of space and time separation is illustrated in this chapter. We can see how this separation strengthens the system security and protects the critical resources. After the space-time authentication, we present the correlation engine and real-time forensics in Chapter 6. The technique of how to correlate the logs on different parties and how to present real-time forensics are discussed. In Chapter 7, the system performance of our proposed space-time evolving authentication is examined. we talk about active attack chain, simulation network model and the simulation results.

Finally, in Chapter 8, we summarize the results of this dissertation and draw conclusions. Future research that could improve the system is also discussed in this chapter.

Chapter 2

Related Work

2.1 Related Work on Authentication

SSL (Secure Sockets Layer) protocol is widely used for authenticating users, services and equipment as well as protecting the confidentiality and integrity of the communication. IPSec (Internet Protocol Security) [7] is also widely used to form virtual private networks for protecting communication between computers and networks. However, both protocols suffer from intrusion and DDoS (distributed denial of service) attacks.

Furthermore, SSL and IPSec authentication services are critical to a network, because when an Authentication Server is paralyzed by DDoS attacks, the network is no longer usable. An authentication protocol must be computationally efficient when the requests to a server are made as well as does not create a state until the authentication is successful. It is well known that both SSL and IKEv1 (Internet Key Exchange version 1) of IPSec are not stateless protocols [23]. Even IKEv2 [8], which was touted as a stateless protocol, has the weakness of handling cookies in the multi-continental network and thus cannot defend a DDoS attack at a critical moment. A number of trace-back algorithms [15, 22] were proposed to stop the DDoS attacks at the source; however, it cannot prevent the "low and slow" attacks and cannot eliminate collateral damage inherited in SSL [27], IPSec and Kerberos [9]. The current version of Kerberos also has the problem of single point failure of centralized server. All authentication services is controlled by the centralized KDC (Key Distribution Center). If the attackers can compromise this authentication infrastructure, they can impersonate any user.

An insider attack can compromise a server, concentrator, router, or firewall, and all credential information can be exposed [6, 10–14]. Although intrusion detection and prevention

systems (IDS/IPS) are deployed to detect those attacks, the high false alarm rate, "low and slow" attacks, and knowledgeable insiders are difficult issues to tackle [16, 18–21].

An intrusion-resilient authentication protocol will be able to protect credential information when an insider compromises a computer. Since this computer only owns partial credential information, the protocol eliminates the single point of compromise [28]. Furthermore, this protocol can readily detect the use of partial credential information as an intrusion and indicate which part of the secret is exposed; consequently, the compromised computer can be recovered [26]. A DDoS-resistant protocol must not create a state nor perform computationally intensive operations when processing the incoming messages to the server until it is authenticated [5].

2.2 Related Work on DoS/DDoS

Service providers are under mounting pressure to prevent, monitor and mitigate DoS/DDoS attacks directed toward their customers and their infrastructure. The Internet is part of the critical national infrastructure but is unique in that it has no customary borders to safegard it from attacks.The number of Denial of Service(DoS) and Distributed Denial of Service (DDoS) attacks on the Internet has risen sharply in the last several years. Expectation level for service providers are also increasing as company revenues are directly tied to having reliable connectivity to the Internet. The financial industry is especially susceptible to DoS/DDoS attacks as millions of consumers move to electronic bill payments, purchases and on-line banking.

DoS attacks can be classified as logical attacks and resource exhaustion flooding attacks [30]. Logic attacks exploit security vulnerabilities to cause a server or service to crash or significantly reduce performance. Resource exhaustion flooding attacks cause the server's or network's resources to be consumed to the point where the service is no longer responding or the response is significantly reduced [31]. Logic attacks will be evaluated based on their effect on the network infrastructure and critical network services (DNS, BGP, RADIUS, etc).

A general method based initially on more secure packet forwarding among routers is proposed [3] as a solution to prevent DDoS attacks. The routers are modified to provide encryption, digital signatures, and authentication, enabling the tracing of a packet back to its origin and thus stopping further traffic at the closest intelligent router point. Every group of collaborating routers is called a "hardened network". The hardened routers should be implemented at the border and access point of an Autonomous System. When arriving at the first hardened router, the packet's payload is encrypted together with one byte of its IP address and the last hardened router before the host will decrypt it. Even though this system provides more secure and private communication between the routers involved, a tremendous amount of complexity is introduced, increasing cost, delay and bandwidth parameters. In addition, knowledge of the last router is critical as it decrypts the initial packet. Thus, a single point of failure and consequently a less reliable information system is created.

In another defense method based on measuring traffic levels, a DDoS module is attached to a given server making it a virtual server [6]. The module relies on a buffer through which all incoming traffic enters. Traffic level is continuously monitored and when it shoots to high levels, most incoming packets will be dropped. The module thus attempts to isolate the server from the attack. It first aims to detect the beginning of the attack at time t when the buffer becomes congested. Then the module, which can detect all active sources, attempts to identify the source of the attack by using statistical properties of traffic flow between t and $t + \tau$. Illegitimate traffic is recognized by its higher mean of traffic level and can thus be effectively suppressed. However, this approach may cause some level of delay and degradation on the service.

Hop-count filtering [4] and path identification mechanism [8] are also used to defend against spoofed DDoS attacks. In Hop-count filtering, the system relies on the fact that the number of hops between source and destination is indirectly indicated by the TTL field in an IP packet. Linking the source IP with the sadistical number of hops to reach

the destination can be used as a reference to assess the authenticity of the claimed IP source. Path identification mechanism is a method that acts to mitigate illegitimate traffic by marking packets deterministically to detect IP address spoofing. It consists of two parts: Marking and Filtering. The former consists of concatenating the MD5 hash of the next node's IP address with the current node's IP address. The result is computed on each router and placed in the IP identification field of the IP header, with newer values replacing older ones when the field's 16 bits are entirely used. The increasing sophistication of the attack and changing of the reflective attack path make the attack path hard to identify, which makes these approaches less effective.

2.3 Related Work on Intrusion Detection and Prevention

Intrusion detection is one of the major techniques for protecting information systems. It has been an active research area for over 20 years since it was first introduced in the 1980s [34]. Generally, intrusion detection systems can be roughly classified as anomaly detection and signature detection systems [33]. Anomaly detection involves building the normal behavior profile for systems. The behaviors that deviate from the profile are considered as intrusions. Signature detection looks for malicious activities by searching particular patterns on the data against a predefined signature database. Recently, a new type of intrusion detection has emerged. It is called specification based intrusion detection. Normally, this kind of detection technique defines specifications for network protocols, and any activities that violate specifications are considered as being suspicious. All intrusion detection has a lower false positive rate, but it is intended for detecting known attacks. Anomaly-based detection has the potential to detect novel attacks, but at the same time it suffers from a high false positive rate. Moreover, it is very hard to define normal behavior for a system.

Intrusion detection systems can also be classified as host-based and network-based, depending on the data source. A host-based intrusion detection system collects data such as system calls, log files and resource usage from a local machine. A network-based intrusion

detection system detects intrusion by looking at the network traffic. These two types of intrusion detection system are complementary, neither can be replaced by the other one.

Even through intrusion detection systems play an important role in protecting the network, organizations are more interested in preventing intrusion from happening or escalating. The intrusion prevention largely relies on the knowledge about the protected network and the understanding of attack behaviors. However, studying the attack behavior is a challenging job as the adversaries tend to change their behavior in order not to be identified. And at the same time, as new vulnerabilities are continually being discovered, the attacks may use new attack strategies.

2.4 Related Work on Forensics Correlation

Forensics correlation is related to two distinct activities: intrusion detection and network forensics. It is more important than ever that these two disciplines work together in a mutualistic relationship in order to avoid points of failure [35]. Alert correlation is defined as a process that contains multiple components with the purpose of analyzing alerts and providing high-level insight on the security state of the network under surveillance. One important use of alert correlation is to recognize the strategies or plans of different intrusions and infer the goals of attacks. Suppose that the next step or the ultimate goal of an attack can be identified by looking at the pattern of the intrusive behavior. We can take action to prevent the attack from escalating and therefore minimize the damage to the asset. Alert correlation provides a means to group different logically-connected alerts into attack scenarios, which allows the network administrator to analyze the attack strategies.

In the past few years, a number of correlation techniques have been proposed. Generally, they can be classified into the following categories:

- `Correlation Based on Feature Similarity`: These class of alert correlation approaches correlates alert based on the similarities of some selected features, such as source IP address, target IP address, and port number. Alerts with higher degree of

overall feature similarity will be correlated. One of the common weakness of these approaches is that they cannot fully discover the causal relationships between related alerts [36].

- `Correlation Based on Known Scenario:` This class of methods correlate alerts based on the known attack scenarios. An attack scenario is either specified by an attack language such as STATL [37] or LAMDBA [38], or learned from training datasets using data mining approach [39]. The idea of using data mining to support alarm investigation mines association rules over alarm bursts. Subsequently, alarms that are consistent with these association rules are deemed "normal" and get discarded. Some other techniques either use episode mining to guide the construction of custom-made filtering rules, or uses data mining techniques to learn correlation rules from hand-labeled training examples. Such approaches can uncover the causal relationship of alerts, however, they are all restricted to known situations.

- `Correlation Based on Prerequisite and Consequence Relationship`: This class of approaches is based on the observation that most alerts are not isolated, but related to different stages of attacks, with the early stages preparing for the later ones. Based on this observation, several studies [41, 43, 45] propose to correlate alerts using prerequisites and consequences of corresponding attacks. Such approaches require specific knowledge about the attacks in order to identify their prerequisites and consequences. Alerts are considered to be correlated by matching the consequences of some previous alerts and the prerequisites of later ones. In addition to the correlation method proposed by Ning et al., JIGSAW [41] and the MIRADOR [43] are two other approaches that use the similar paradigm. These approaches target recognition of multistage attacks and have the potential of discovering unknown attacks patterns. However, such approaches have one major limitation, that is they cannot correlate unknown attacks (not attack patterns) since its prerequisites and consequences are not defined. Even

for known attacks, it is difficult to define all prerequisites and all of their possible consequences.

- `Correlation Based on Neural Network`: This class of approaches are based on a neural network [33]. Some features are extracted and trained for the neural network. The distinguishing feature of this approach is that it uses a supervised learning method to gain knowledge from the training examples. Once trained, the correlation engine can determine the probability that two alerts should be correlated. Assigning correlation probability can help in constructing hyper-alert graphs and attack graphs that represent the real attack scenario. Alert graph matrix can encode correlation knowledge such as correlation strength and average time interval between two types of alerts. This knowledge is gained during the training process and is used by correlation engine to correlate future alerts. However, these approaches have no assurance of accuracy and exhibit extremely slow forensics.

2.5 Summary

The objective of this dissertation is to present solutions to protect critical information against theft, defend corporate network against DoS/DDoS attacks and improve security and efficiency in the forensics correlation process. This chapter overviewed a variety of existing approaches related to intrusion detection and prevention, authentication, and forensics correlation. Although these approaches may be effective in some circumstances, there are some drawbacks and limitations. For intrusion detection and prevention, the signature based approaches suffer from zero-day attack (an attack that never happened before), and the behavior based methods have the problem of false alarm. For the current authentication protocols, they have either single point of failure, too many authentication round trips, and many other problems. While current approaches of correlation and forensics have no assurance of accuracy and are time-consuming. In this dissertation, two security systems,

which are built upon existing technology, are introduced to provide intrusion resilience and real-time forensics.

Chapter 3

Intrusion-Resilient DDoS-Resistant Authentication System

In this chapter, an intrusion resilient, DDoS-resistant authentication system (IDAS) is introduced and explained in detail. Fig. 3.1 illustrates the architecture of the proposed IDAS security system, which consists of client/server computers, distributed agents and distributed Authentication Servers. A user/computer must register first using a PKI (Public Key Infrastructure) certificate and establish a shared secret with the Authentication Servers. Then a user/computer can use the shared secret for subsequent logins. Agents will control the access of a user/computer/agent to critical information/service available in the network. We realize the necessary components in order to prove that the IDAS can provide (1) resilience to a strong inside adversary who can compromise a computer, a critical resource server, an agent and even Authentication Servers; (2) self-healing capability when a strong inside adversary compromises Authentication Servers; (3) resistance to DDoS attacks; (4) access control and health monitoring capabilities of security agents in TNC (Trusted Network Control)/NAC (Network Access Control)/NAP (Network Access Protection).

3.1 Initial Registration

A new user or a new computer can be authenticated by using a PKI certificate only once during the first handshake protocol, which is called the registration protocol (as shown in Fig. 3.3). A secure tunnel is established for exchanging a shared seret that will be used for subsequent authentications. A JFK-like protocol [5] needs to be used only once for a new user/computer/agent in the registration process. After the first time registration, a shared secret can be carried by a user either using a token generator or a smart card. A

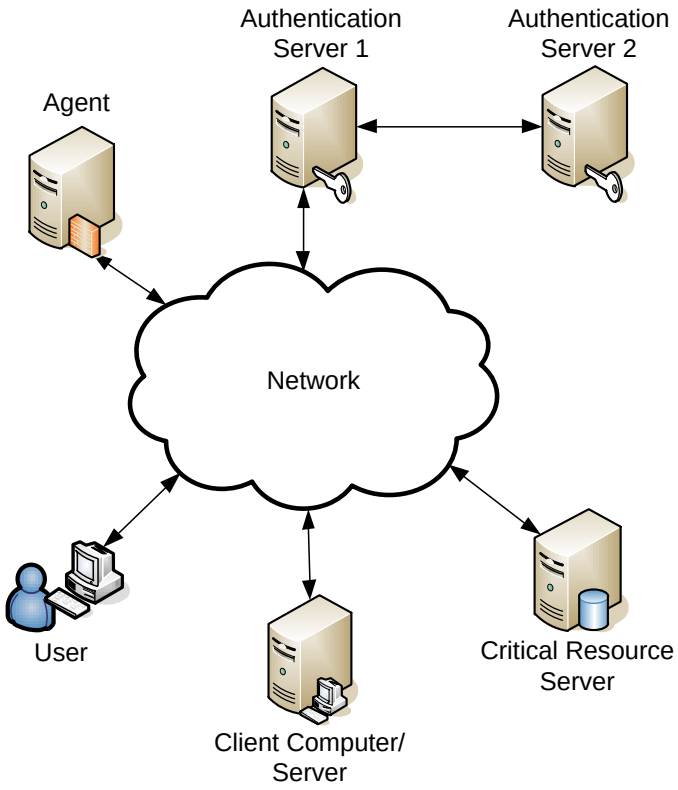


Figure 3.1: Overview of an intrusion-resilient, DDoS-resistant authentication system

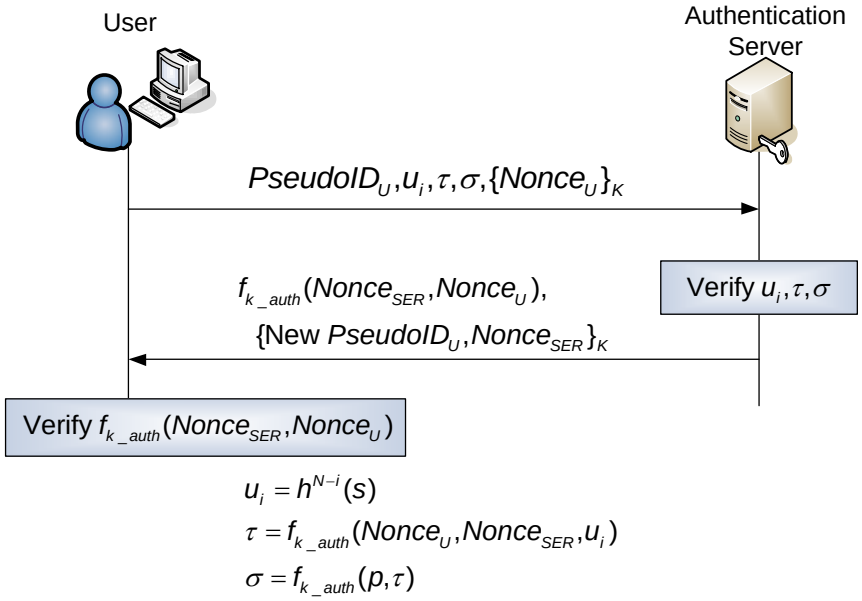


Figure 3.2: The user secret is distributed into two factors

computer/agnet will have the shared secret stored in itself and associated agent. The authentication of the subsequent login will be basd on the shared secret and the Authentication Servers only need hash operations for verifying the secret without creating any state. The identity if a user/computer/agent is changed after every successful login and every time period. The temporary identity is call a *PseudoID*. Distributed agents handle the updates of *PseudoID*.

3.2 Time-Dependent Secret and Self-Healing

Because the password is usually a low grade secret [25], the scheme may be vulnerable to password-guessing attacks. Instead, the scheme of hash chain iterations over a high grade secret (e.g. a 160-bit random number) is introduced to enhance the security [24, 26]. In the hash chain operation, a user begins with a random seed s. A hash function generates the secret sequence: $h(s), h(h(s)), \ldots, h^N(s)$. N is defined as the upper bound of the number of authentication sessions to be allowed for a single seed. Note that the superscript denotes the number of function iterations. In the initialization, the server stores the first hash chain value $u_0 = h^N(s)$. For the ith authentication session ($1 \leq i \leq N$), the user's device computes $u_i = h^{N-i}(s)$ and transmits it to the server. Then, the server checks whether the received u_i satisfies $h(u_i) = u_{i-1}$. If so, the server saves u_i for the next authentication session. The last authentication session in a hash chain cycle is the $(N-1)^{st}$ session, when $h(s)$ is transmitted to the server for verification. For a new hash chain cycle, the system restarts with a new hash chain seed $s^{'}$, and the server stores $h^N(s^{'})$.

The feature of the hash chain is the asymmetry that one side has the seed s and the other knows the value of the hash iterations over s. If an adversary compromises the server to obtain the stored u_{i-1}, the attacker cannot derive u_i required for the next authentication session because of the one-way property of cryptographic hash functions. This is a self-healing feature of the Authentication Server.

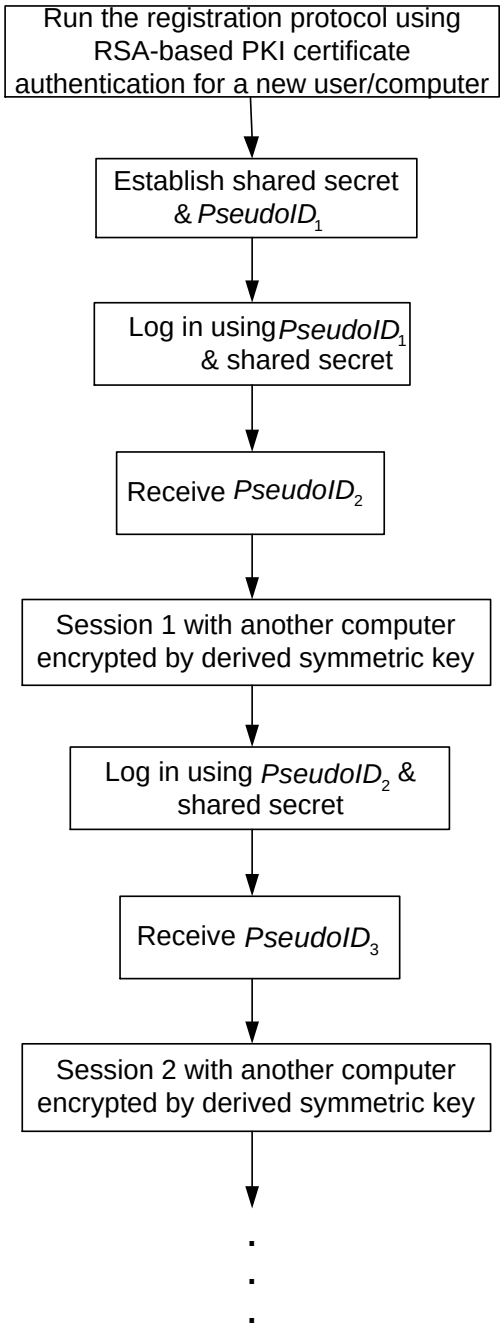


Figure 3.3: The authentication process includes two parts: registration process and symmetric key authentication

Notice that the iteration upper bound N must be optimal so that the re-generation of seed and delivery of $h^N(s^{'})$ will not occur often. If N is too large, the client computer will have to perform a large number of hash operations for the authentication attempts. We propose the method of automatic update of hash chain seed, where hash operations are applied to a random number seed to generate a sequence of random numbers as the hash chain seeds. And the client computer will let the server know the new hash chain value $h^N(s)$.

HMAC (RFC 2104 [29]) is the standard approach in cryptography to ensure the message integrity. In the context of our authentication protocol, HMAC can be viewed as a fixed-size output produced by two inputs (a message and a secret key). It is computationally infeasible to produce the valid code without the knowledge of the key.

3.3 Distribute Two-Factor User Secrets

A legitimate user shares a p, a hash chain value and a cryptographic key k_auth with the Authentication Server. The p represents a second factor for authentication and can be a password, a token, a biometrics or smart card. Partial secrets of the user are provided with two random number seeds: one is for the nonce generation, and the other for the hash chain seed. In the initial registration protocol, the device generates the first hash chain seed s, and delivers $h^N(s)$ to the server. Fig. 3.2 describes the essential cryptographic core for distributing a user secret into two parts.

Step 1: The user sends its identifier $PseudoID_u$ (a time-varying ID), $u_i = h^{N-i}(s)$ for the ith authentication session, $\tau = f_{k\_auth}(Nonce_U, Nonce_{SER}, u_i)$, $\sigma = f_{k\_auth}(p, \tau)$, and the nonce $Nonce_U$ (encrypted by a shared key K) to the Authentication Server. Notice that the p is never sent out onto the communication channel. After a new user registers in an Authentication Server, a shared secret, including $PseudoID_U$, $Nonce_{SER}$, k_auth, K and p, is given to the user and the computer in use; the user generates $Nonce_U$ and s, and computes

u_0; and $Nonce_U$ and u_0 are delivered to the Server. A secure channel established by the registration protocol is used to exchange the shared secret.

Step 2: Then the server uses $PseudoID_u$ to choose the private credentials of the user, authentication key k_auth and the p. The server then performs verification on the hash chain value $h^{N-i}(s)$, the first HMAC τ, and the second HMAC σ. If any of them fails, the handshake session will be dropped immediately; otherwise, the server decrypts $Nonce_U$, generates an encrypted nonce $Nonce_{SER}$, a new $PseudoID_u$ and the HMAC $f_{k\_auth}(Nonce_{SER}, Nonce_U)$, and then sends them to the device. This step resists both memory-DDoS and computation-DDoS since the HMAC computation is fast and no state is created before the verification of HMACs is successful.

Step 3: Because the device shares k_auth and knows the two *nonces*, it is able to verify the received HMAC. If the HMAC is valid, the device mutually authenticates the Authentication Server. A new $PseudoID_u$ is received and available for next user login. Otherwise, the device terminates the authentication immediately.

Notice that the traditional use of hash chain technique suffers from the synchronization problem, as it becomes vulnerable to an active adversary who intercepts and traps as-yet unused hash chain value ([25], pp.397). However, in our scheme, the hash chain has the HMAC protection. Without the HMAC key, replaying hash chain value will not let adversaries log onto the server. In practice, the user's computer, after Step 3, will immediately send a synchronization acknowledgement to the server. So, both sides will have the consistent knowledge about the iteration number of hash chain. In the case of adversary blocking the synchronization, the server updates the iteration number while storing the last successful one for authenticating a legitimate user.

In each hash chain cycle, $(N-1)$ authentication sessions are allowed. Here, we present the scheme of updating the hash chain value at the $(N-1)^{st}$ or the last authentication session of a hash chain cycle. Let the hash chain seed of current cycle be s_j and the one for

the next cycle be s_{j+1}. The new hash chain value $h^N(s_{j+1})$ piggybacks on Step 1,

$$h^{N-(N-1)}(s_j), h^N(s_{j+1}), \tau^{'}, f_{k\_auth}(p, \tau^{'}) \tag{3.1}$$

where $\tau^{'} = f_{k\_auth}(Nonce_U, Nonce_{SER}, h^{N-(N-1)}(s_j), h^N(s_{j+1}))$. The authentication key k_auth is crucial for the authenticity of the update $h^N(s_{j+1})$. Upon checking the first HMAC $\tau^{'}$, the server is able to discern whether the new hash chain value $h^N(s_{j+1})$ is intact and from the legitimate user. Then the server stores $h^N(s_{j+1})$ for the next $N-1$ authentication sessions of a new hash chain cycle. We give the expression for the hash chain in Step 1,

$$u_i = \begin{cases} h^{N-i}(s_0) & i = 1, \cdots, N-1 \\ h^{2N-1-i}(s_1) & i = N, \cdots, 2(N-1) \\ h^{3N-2-i}(s_2) & i = 2(N-1)+1, \cdots, 3(N-1) \\ \cdots & \cdots \end{cases} \tag{3.2}$$

where i denotes the index of authentication session and the superscripts of $h()$ denote the number of function iterations. Each hash chain cycle (distinguished by the subscript of s) consists of $N-1$ to 1. In summary, the device stores s_0 and the server receives $h^N(s_0)$ before any authentication attempt. At the jth authentication session (j is multiple of $(N-1)$), the piggyback operation is performed.

If an adversary compromises the device, the attacker does not know the p. If the attack initiates the authentication request to the server, the first HMAC τ in Step 1 will be correct since the code only requires the secrets stored in the device. Nevertheless, the second HMAC σ will fail because the correct code requires the p. The possible choice for the attack is to perform an online guessing attack. Note that an attacker without compromising the device cannot get the first HMAC τ correct because of the enormous search space of HMAC key k_auth. In this case both HMACs will be wrong. As a result, when the server detects that the first HMAC is correct and the second one is wrong, the server can infer that the device

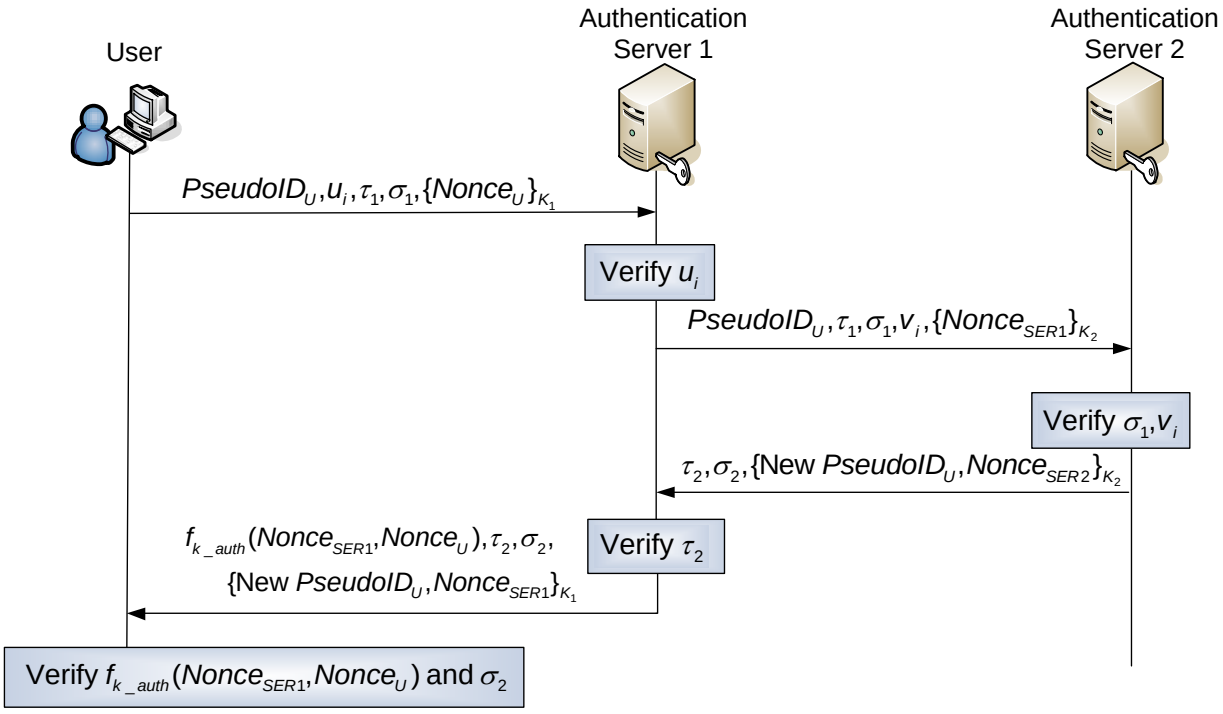
has been compromised - in practice the server will set up a threshold for the number of error occurrence as users may occasionally input wrong p. Since the correctness of one HMAC and the invalidity of the other HMAC correspond to the case of adversary compromising the device, we name the technique *mutual HMAC*.

If an adversary compromises the server, the attacker can learn the p and k_auth. Since the hash chain uses one-way function iteration over cryptographic random numbers, it is computationally infeasible for attackers to derive the hash chain value for the next authentication session. Consequently, the attacker cannot succeed in next authentication attempt. Notice that the strong adversaries may launch the phishing attack-set up a fake server and entice the users to log onto the bogus server. Our use of hash chain can mitigate the attack, as the adversaries have to connect with the users first and then use the hash chain value. Suppose the attackers phish to obtain the hash chain value for ith authentication session. Then, for the $(i+1)th$ authentication session, the attacker has to undergo the handshake with the user again. In this self-healing manner, the chance of exposing fake servers will be significantly increased.

The proposed mutual HMAC scheme combines the usage of a p, a key, and a hash chain in a computation-efficient manner to achieve a strong security level. If p is not used in the protocol, when an adversary compromises the device, the attacker can succeed in impersonating the user. If the HMAC key is not used in the protocol, the update of hash chain value might be tampered by the adversary. Thus, the server and the device will be out of synchronization for authentication. If the hash chain is not used in the protocol, the adversary compromising the server learns the secret HMAC key and p. Then the adversary can succeed in impersonating a user in the next authentication session.

3.4 Distribute Authentication Server into Two Servers

Fig. 3.4 illustrates the method of distributing the credential information of a user into two Authentication Servers and eliminates the single-point of compromising. Server 2 is



$$u_i = h^{N-i}(s) \qquad v_i = h^{N-i}(t)$$

$$\tau_1 = f_{k\_auth}(Nonce_U, Nonce_{SER1}, u_i) \qquad \tau_2 = f_{k\_auth}(Nonce_{SER1}, Nonce_{SER2}, v_i)$$

$$\sigma_1 = f_{k\_auth}(p, \tau_1) \qquad \sigma_2 = f_{k\_auth}(p, \tau_2)$$

Figure 3.4: Distribute authentication server secret into two servers

hidden from a user and only Server 1 can access Server 2. This arrangement makes it difficult to attack Server 2 directly and provides intrusion-resilient and self-healing features.

Step 1: Server 1 and Server 2 establish a secret hash chain using $v_i = h^{N-i}(t)$ through an initial registration protocol.

Step 2: User sends in $PseudoID_U$, u_i, τ_1, σ_1, $\{Nonce_U\}_{K_1}$ to Server 1, and Server 1 verifies u_i. Then Server 1 sends $PseudoID_U$, τ_1, σ_1, v_i, $\{Nonce_{SER1}\}_{K_2}$ to Server 2.

Step 3: Server 2 verifies $\sigma_1 = f_{k\_auth}(p, \tau_1)$ and v_i to ensure that the user has a correct p and Server 1 has a correct v_i. If both are correct, then Server 2 sends back New $PseudoID_u$, τ_2, σ_2, $\{Nonce_{SER2}\}_{K_2}$ to Server 1.

Step 4: Server 1 verifies $\tau_2 = f_{k\_auth}(Nonce_{SER1}, Nonce_{SER2}, v_i)$ to make sure that Server 2 knows k_auth and sends back

$$f_{k\_auth}(Nonce_{SER1}, Nonce_U), \tau_2, \sigma, \{Nonce_{SER1}, \text{New}PseudoID_U\}_{K_1} \tag{3.3}$$

Step 5: User verifies $f_{k\_auth}(Nonce_{SER1}, Nonce_U)$ and σ_2 to make sure that Server 1 and Server 2 are legitimate.

The above steps remove the single-point compromising vulnerability of critical user authentication information. It is useless for an attacker to compromise one of the two servers. If a strong inside attacker compromises both servers, one can pretend to be a user for the current period. For the next time period, the attacker loses the required hash chain value and the authentication system self heals.

3.5 Distribute Authentication Service for a Computer/Server/Agent

A client computer/server has its secret p distributed to a security agent during the registration process. The secrecy of p is provided by the Authentication Server and stored in an agent after a new computer/server is registered. The agent verifies the health state of the computer and demonstrates that the agent possesses the secret k_auth; this is a mutual

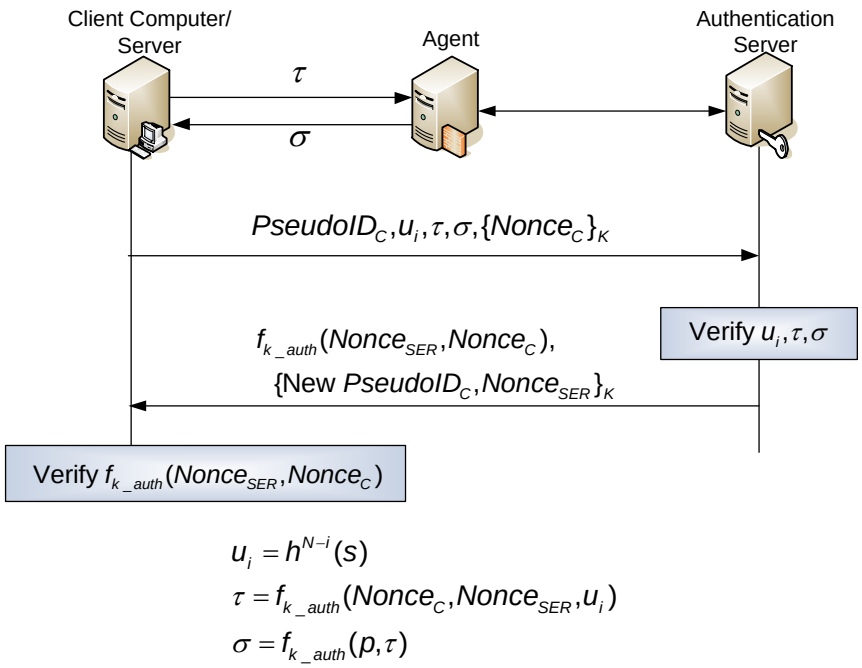


Figure 3.5: Part of the secret of a client computer/server is distributed to an agent

authentication to defend spoofed agent. Note that the secret p and other secrets such as s, $PseudoID_C$, k_auth and *nonces* are protected by the TPM (Trusted Platform Module) encryption and are difficult to be compromised by an attacker. The agent's blessing, which is a time-varying secret and difficult to forge, is used as part of the secret to obtain the authentication of the Authentication Server.

A computer/server/agent can have its secrets distributed in two Authentication Servers to avoid a single-point of compromising. A security agent is used to provide half of the secret, p, which is given by the Authentication Servers after the successful registration of the identity. The authentication secret is encrypted by the TPM on the motherboard. An agent monitors the health of a computer/server and, if the health is acceptable, provides a time-varying secret for mutual authentication, which is critical for protecting a computer and an agent. The time-varying secret will be used by the computer to obtain authentication from the Authentication Servers.

A security agent is a critical code that is running in a computer. An agent's access right and the health of the residing computer need to be controlled/monitored. Another agent is used to monitor the health of the current agent's residing computer and grants the access rights to it. Furthermore, Authentication Servers provide the necessary secret to both agents after the registration of the agent if another agent is available for monitoring it. The first agent that is granted trust by the Authentication Servers is the root security agent during the initiation of IDAS system. A tree structure is used for the connection of agents. A parent agent of a tree monitors the child agents' health and control access activities. An agent establishes a secure channel with its parent agent and child agents. The shared secrets for an agent are provided by the Authentication Servers in order to establish secure tree-type channels. A child agent follows the same procedure by using its parent agent as the agent for monitoring health and control activities. A tree structure based on the proximity makes the agent communication scalable to a large network.

This scheme requires that a computer/server logs in periodically independent of user's activity so that self healing and health monitoring can be effective to stop attacks.

3.6 Security Analysis

In the beginning of the dissertation, the desired properties of a good authentication system were presented. Here, in this section, we will give a security analysis of our proposed Intrusion Resilient DDoS-Resistant Authentication System (IDAS) to see if the properties are satisfied.

3.6.1 Resilient to Strong Adversary

In the proposed IDAS security system, it can protect against not only the passive eavesdropper, but also the strong adversaries with some secrets. Suppose the adversary has compromised the long-term encryption key K, or the key k_auth to compute HMAC τ or σ in the ith session (Assume it does not exceed the cap N). In the next session, the hash

chain value changes to $\mu_{i+1} = h^{N-(i+1)}(s)$. Because of one-way feature of the hash function, knowing μ_i cannot guarantee that the adversary can derive the next hash chain μ_{i+1}. The authentication server can still verify if this is an intruder or legitimate user by first comparing the hash chain value μ_i and $h(\mu_{i+1})$, as for legitimate user,

$$\begin{aligned} h(\mu_{i+1}) &= h(h^{N-(i+1)}(s)) \\ &= h^{N-(i+1)+1}(s) \\ &= h^{N-i}(s) \\ &= \mu_i \end{aligned} \tag{3.4}$$

If the $h(\mu_{i+1}) \neq \mu_i$, the request is rejected and the packet is discarded immediately. In our scheme, the hash chain value also has the HMAC protection. Without the HMAC key, replaying hash chain value will not let adversaries log onto the server.

Moreover, the 160-bit $Nonce_U$ and $Nonce_{SER}$ are also time varying. For the next round, new fresh $Nonce$ will be generated for authentication. Suppose the encryption K or HMAC key k_auth is exposed. The adversary relays the message $PseudoID_U, \mu_i, \tau, \sigma, \{Nonce_U\}_K$. If K is exposed, the adversary computes $\{Nonce_U\}_K$, but cannot compute the HMAC τ and σ without having the HMAC key k_auth. If HMAC key k_auth is compromised, the adversary can compute HMAC τ and σ, but cannot decrypt $\{Nonce_U\}_K$ and $\{\text{New}PseudoID_U, Nonce_{SER}\}_K$ without having key K. Even if both keys are compromised, the nonces are evolving from time to time. The adversary cannot pass the mutual authentication without compromising both User and Authentication Server.

3.6.2 DDoS Resistance

Denial of service (DoS) or distributed DoS (DDoS) attack floods the authentication server with fake packets and causes the server to exhaust its resources for processing fake packets. When the resources of the authentication server are exhausted, legitimate user's authentication requests cannot be responded. Denial of service relies on methods that exploit

the weaknesses of the network and attempts to reduce the ability of a responder to service users [47].

The major problem of DoS/DDoS attack is that the authentication server (or responder) needs to validate that the request is from a legitimate user (or initiator). However, even the most powerful authentication server has a limited CPU computation power and restricted amount of memory. When attackers initiate sufficient requests, the authentication server cannot respond to legitimate requests. It is necessary to minimize the resource committed to a request before verifying that the request is from a legitimate source.

Following the concept of a stateless protocol *"Do not create any state or do expensive computation before you can ensure that the received frame is legitimate"*, the idea of stateless server and stateless connection is proposed to defend against DoS/DDoS. If the server authenticates the user and verifies the user's $PseudoID_U$ without keeping states, the authentication scheme will be stateless. Moreover, the protocol is stateless since a frame with an incorrect hash chain value is only checked and no other computation resource is committed.

Extending the methods proposed by [28], a new user or a new computer can be authenticated by using a PKI certificate only once during the first handshake protocol, which is called the registration protocol. A secure channel is established for exchanging a shared secret that will be used for subsequent authentications. A JFK-like (JFK refers to Just Fast Keying) protocol [5] needs to be used only once for a new user/computer/agent as the registration. Even though registration protocol is not completely DDoS resistant in a multi-continent network, the threat is not eminent and can be easily prevented since the legitimate request is only from a new/computer/agent. After the first time registration, a shared secret can be carried by a user either using a token generator or a smart card. A computer/agent will have the shared secret stored in itself and associated agent. The authentication of the subsequent login will be based on the shared secret, and the Authentication Servers only need hash operations for verifying the secret without creating any state. If the hash generates a correct value of u_{i-1} using the received u_i, then the decryption of nonce is carried

out; otherwise, the received message is dropped. Therefore, this authentication process is efficient and DDoS resistant. Furthermore, mutual authentication is necessary in order to prevent spoof attack. This is achieved by using a shared secret key for the hashing process during authentication.

In our system, the legitimate user has its corresponding identifier $PseudoID_U$ (a time-varying ID). The authentication server will not do time-consuming decryption if the $PseudoID_U$ in the request is incorrect. Furthermore, we have the hash chain protection. Computing hash chain value and comparing the values are fast and efficient. Time-consuming decryption/encryption processes will be executed if and not if the $PseudoID_U, \mu_i, \tau, \sigma$ are all correct. There are no state and time-consuming jobs committed.

3.6.3 Efficiency

In many protocols, key setup must be performed frequently enough that it can become a bottleneck to communication. The key exchange protocol must minimize computation as well as total bandwidth required and round trips. Round trips can be especially an important factor when communicating over unreliable media, such as wireless. Using our protocols, only two round-trips are needed to set up a working security association. This is a considerable saving in comparison with existing protocols, such as IKE (Internet Key Exchange) [8].

3.7 Summary

In this chapter, an intrusion resilient, DDoS-resistant authentication system is proposed and explained in detail. The system achieves its goals by distributing two-factor user secrets, distributing authentication server into two servers, and distributing authentication services for a computer/server/agent. Even for strong adversaries, who can compromise the server and learn some secret, it is computationally infeasible for them to derive the secrets for next authentication session. The system is efficient as there is only one round trip in the

authentication. No expensive computation is committed before verifying the hash chains and HMACs. Thus, the system is also DDoS resistant. Our work is published in proceedings of two international conferences IEEE BROADNETS'07 [50] and ACM SPRINGSIM'08 [51].

Chapter 4

Performance Evaluation of Proposed IDAS System

In the beginning of this chapter, a queueing model is utilized to analyze the network traffic. The network delay and CPU utilization could be derived from the queueing model. Then, the simulations are carried out for small scale, as well as for long distance (coast to coast and continent to continent). The simulations results are encouraging even in the presence of massive attacks.

4.1 Queueing Model

In queueing theory, a queueing model is used frequently to analyze the queueing behavior in real queueing situation or computer system. There are many queueing models such as single-server queue, multiple-servers queue, open queue, and closed queue. In this dissertation, we adopts the classic BCMP queueing model (it is named after Baskett, Chandy, Muntz and Palacios [40]).

4.1.1 BCMP Queueing Network Model

To evaluate the performance of our proposed IDAS system, we need to build a queueing model first. The packets in the buffer either originate from legitimate users or from attackers. Hence, the total average number of packets N in the buffer is the sum of those originating from the legitimate users and those from the attackers N_a. The total number of requests from the legitimate users N_u consists of the number of authentication packets N_u^{auth} and the number of data packets N_u^{data}.

$$N = N_a + N_u^{auth} + N_u^{data} \tag{4.1}$$

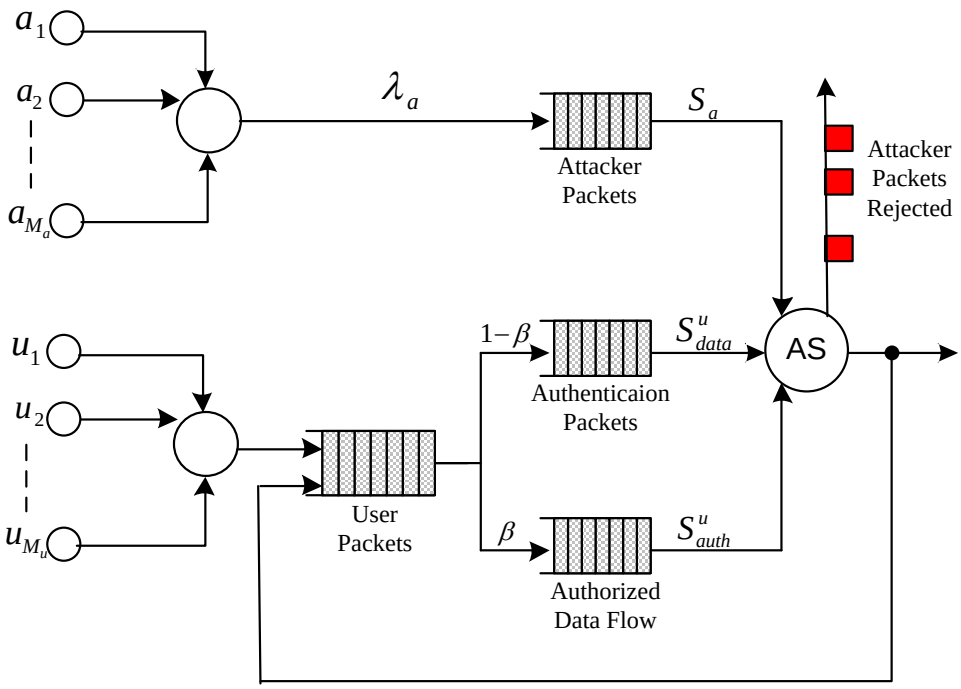


Figure 4.1: One Authentication Server Queueing Model

For simplicity, let class $r \in \{1, 2, 3\}$ denote the class of attacker packets, legitimate user authentication request packets and data packets from an authenticated user, respectively. λ_a and S_a are the arrival rate and service rate in the queue. We can represent the state of a BCMP queueing network as follows:

- Let N_r represent the number of class r customers waiting in the queue.
- The overall state is given by the vector $\overrightarrow{N} = (N_1, N_2, N_3)$ such that the total number of customers in the queueing networks is given by $N = \sum_{r=1}^{R} N_r$.

4.1.2 One Authentication Server Process Model

We assume $M = M_a + M_u$ as the total number of nodes, the ratios $\alpha_u = M_u/M$, and consequently the number of attacker nodes is $M_a = \alpha_a \times M = (1 - \alpha_u) \times M$. At time t, $\beta \times M_u$ nodes among the total legitimate user nodes M_u were authenticated and are sending normal authenticated data packets. Assume that the queue at the authentication server is

first come first served (FCFS), and jobs are load-dependent, Let V_r be the visit ratio for class r when the number of customers of class r is N_r, and μ_r is the service rate for class r. The fixed population is given by the vector $\overrightarrow{K} = (K_1, K_2, \cdots, K_R)$ and $K = \sum_{i=1}^{R} K_i$.

From the mean value analysis, if we define the average service demand for class r at authentication server as $D_r = V_r/\mu_r$, based on the arrival theorem [42], the expected response time R_r and expected waiting time W_r for a class r customer are given as follows:

$$E[R_r] = D_r(\sum_{j=1}^{R} E[N_j(\overrightarrow{K} - 1_j)] + 1) \tag{4.2}$$

$$E[W_r] = (E[N_r(K-1)])E[R_r] \tag{4.3}$$

where 1_j represents a unit-vector with a 1 one the j-th position. The overall service response time for authentication service can be expressed as

$$E[R] = \sum_{r=1}^{R} \eta_r E[R_r] \tag{4.4}$$

where

$$\eta_1 = \alpha_a, \eta_2 = (1-\beta)\alpha_u, \eta_3 = \beta\alpha_u. \tag{4.5}$$

Assume the server's processor capability is U_{cap} which means the CPU of the server can process as many as U_{cap} instructions per CPU clock cycle. Let I denote the number of instructions needed to complete an attacker job per unit time, and T denote time needed to process an instruction. We can compute the server CPU utilization U as:

$$U = \frac{IKE[R]}{TU_cap} = \frac{I\sum_{r=1}^{3} N_r \sum_{r=1}^{3} \eta_r E[R_r]}{TU_cap} \tag{4.6}$$

From the above derivation, we can also get the delay D at the authentication server as

$$E[D] = \sum_{r=1}^{3} \eta_r E[W_r] \tag{4.7}$$

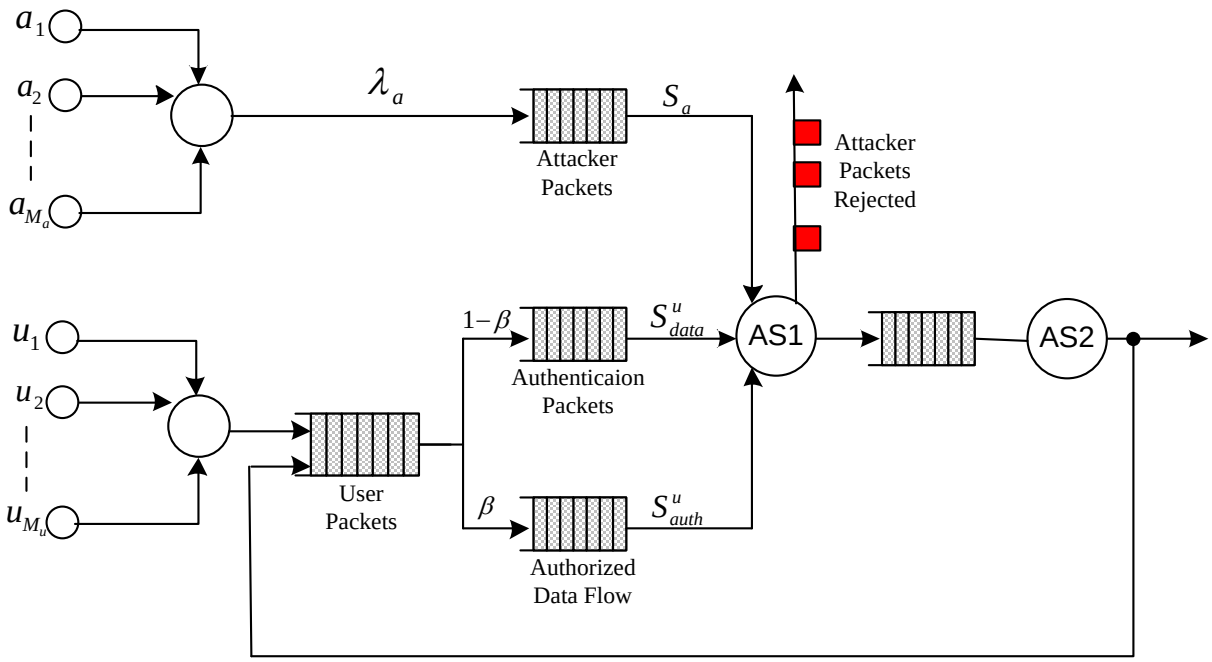


Figure 4.2: Two Authentication Servers Queueing Model

4.1.3 Two Authentication Servers Process Model

For two authentication server case, we can represent the state of BCMP queueing network model as follows:

- Let $\overrightarrow{N_i} = (N_{i,1}, N_{i,2}, N_{i,3})$ be the state of authentication servers.
- $N_{i,r}$ represents the number of class r customers waiting in the queue at authentication server $i = 1, 2$.
- The overall state is given by the vector $\overrightarrow{N} = (\overrightarrow{N}_1, \overrightarrow{N}_2, \overrightarrow{N}_3)$ and the overall number of customers in the queueing networks is given by $N_i = \sum_{r=1}^{3} N_{i,r}$, $R = 3$. The fixed population of jobs is given by the vector $\overrightarrow{K_i} = (K_{i,1}, K_{i,2}, \cdots, K_{i,R})$ and $K_i = \sum_{r=1}^{R} K_{i,r}$.
- Let $V_{i,r}$ be the visit ratios for class r at authentication server i, given number of class r customers $N_{i,r}$, and $\mu_{i,r}$ is the service rate for class r at authentication server i.

From the mean value analysis, if we define the average service demand for class r at authentication server i as $D_{i,r} = V_{i,r}/\mu_{i,r}$, based on the arrival theorem, the response time and waiting time for a class r customer at authentication server i is given as follows:

$$E[R_{i,r}] = D_{i,r}(\sum_{j=1}^{R} E[N_{i,j}(\overrightarrow{K_i} - 1_j)] + 1) \tag{4.8}$$

$$E[W_{i,r}] = (E[N_{i,r}(K_i - 1)])E[R_{i,r}] \tag{4.9}$$

The ovrall service response time for authentication server AS1 can be expressed as

$$E[R_1] = \sum_{r=1}^{R} \eta_{1,r} E[R_{1,r}] \tag{4.10}$$

where $\eta_{1,r}$ are given as

$$\eta_{1,1} = \alpha_a, \eta_{1,2} = (1-\beta)\alpha_u, \eta_{1,3} = \beta\alpha_u \tag{4.11}$$

The overall service response time for authentication server AS2 can be expressed as

$$E[R_2] = \sum_{r=1}^{R} \eta_{2,r} E[R_{2,r}] \tag{4.12}$$

where $\eta_{2,r}$ are given as $\eta_{2,1} = (1-\beta)\alpha_u$, $\eta_{2,2} = \beta\alpha_u$.

Assume the server's processor capability is U_cap which means the CPU of the server can process as much as U_cap instructions per CPU clock cycle. Let I denote the number of instructions needed to complete an attacker job per unit time. We can compute the server CPU utilization U as follows:

$$U_1 = \frac{IK_1E[R_1]}{TU_cap} = \frac{I\sum_{r=1}^{3} N_{1,r} \sum_{r=1}^{3} \eta_{1,r} E[R_{1,r}]}{TU_cap} \tag{4.13}$$

$$U_2 = \frac{IK_2E[R_2]}{TU_cap} = \frac{I\sum_{r=1}^{2} N_{2,r} \sum_{r=1}^{2} \eta_{2,r} E[R_{2,r}]}{TU_cap} \tag{4.14}$$

Table 4.1: Packet size of different payload

TYPE	SIZE(bytes)
IDAS Header	21
PseudoID Payload	6
Hash Chain Payload	20
First HMAC Payload $\tau = f_{k\_auth}(Nonce_U, Nonce_{SER}, \mu_i)$	20
Second HMAC Payload $\sigma = f_{k\_auth}(p, \tau)$	20
Nonce	20
Authentication Payload	32
Encrypted Payload	32
Attack IP Packet	86

From the above derivation, we can also get the delay D at the authentication server AS1

$$E[D] = \sum_{r=1}^{R} \eta_{1,r} E[W_{1,r}] \tag{4.15}$$

4.2 Performance Evaluation

4.2.1 Network Simulation Parameters

We run the simulation in OPNET Modeler 14.0.A PL2 version on a PC with Pentium 4, 2.20GHz CPU, 2GB RAM and running the Microsoft Windows XP operating system. Table 4.1 shows the packet size for different payload. We have a detailed documentation of IDAS packet format.

4.2.2 Simulation on Network within Short Distance

Simulation scenarios

By using OPNET Rapid Configuration in the Topology menu bar, we could set up a star topology rapidly. For a 1000 node case, a network diagram is shown in Fig. 4.3. After that, we could do the following steps to complete the simulation scenario setup:

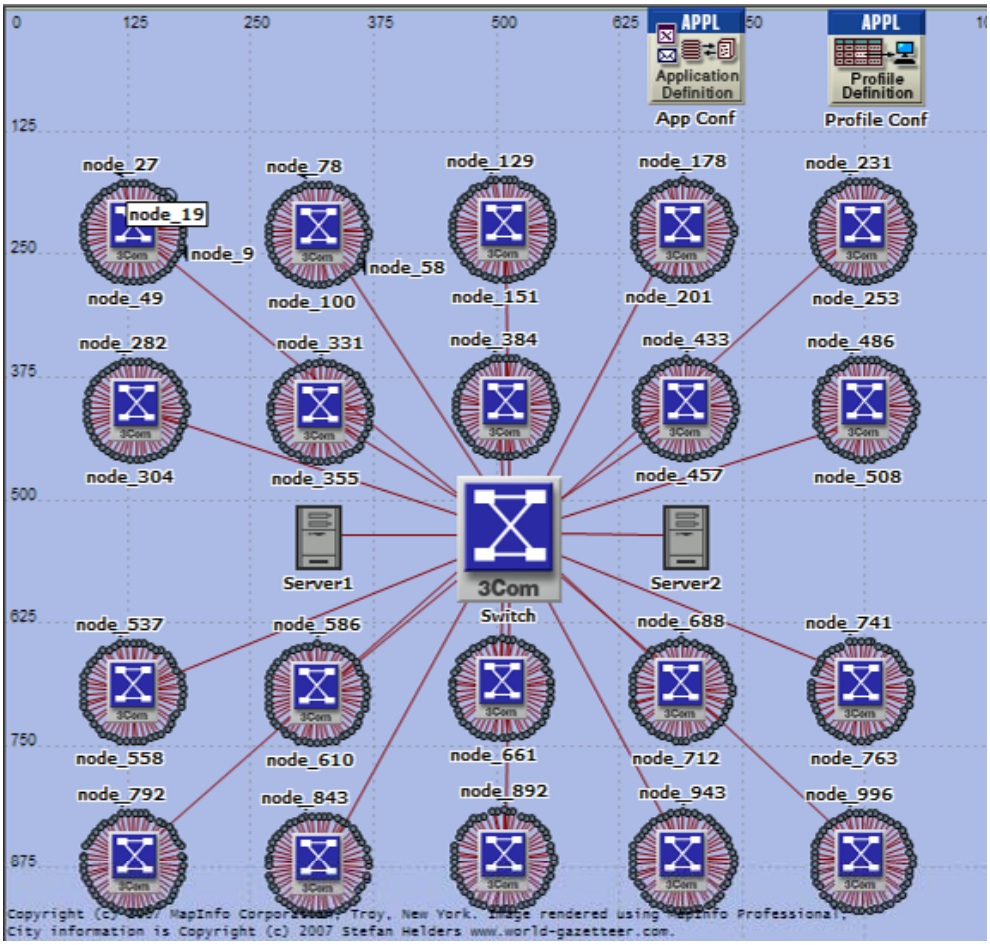


Figure 4.3: A 1000 node network diagram, which shows all nodes are connected to the authentication servers by switches using a 1 Gbps link

1) First of all, we should create the nodes to denote the user nodes, attacker nodes and servers.

   a) The server is Dell PowerEdge 1855, 1 CPU, 1 Core per CPU, 3.6GHz, 4GB RAM.

   b) Each node is a Dell Dimension 2400, 1 P4 CPU - 2.20 GHz, 512 MB RAM, and Buffer size is 512 KB.

   c) The switch is 3Com 3C_SSII_1100_3300_4s_ae52_e48_ge3 with 4 MB buffer/port and has the switch packet service rate of 1.2 M packets/sec.

   d) The NIC (Network Interface Controller) buffer size is 64 K bytes and OS buffer size is 4 M bytes.

2) Then, we set up the link between the nodes using a 1Gbps link.

3) After that, we should set up the traffic over the link by exponential inter-arrival process for the attacker and user nodes.

4) We use the built-in server model in Opnet for simulating authentication servers for processing the packets sent from attackers and users.

The user and attacker nodes are in the periphery of the star topology network, connecting to the central switch. Then the switch is connected to the authentication server 1 by a link of 1Gbps, and the server 1 connects to server 2 also via a 1Gbps link.

From our packet size of different payload definition in Table 4.1, the packet size from user to authentication server 1 is 107 bytes. The nodes will send the packet to authentication server 1 following the exponential distribution. In the scenario, we use random number generator to simulate the attackers and the legitimate users. Generate a random number x, using uniform distribution, $U[0 \sim 1]$. If $x > 0.1$, the node is assigned to simulate an attacker, else the node is assigned to simulate a legitimate user. So if there is a total 1000 nodes, there will be 100 legitimate user nodes and 900 attacker nodes.

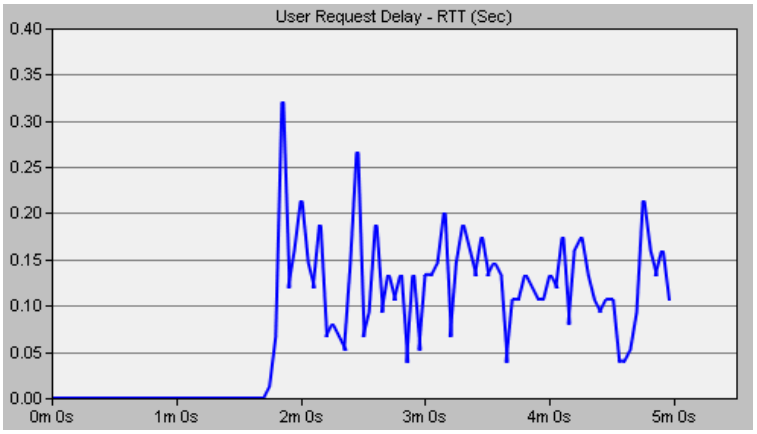


Figure 4.4: Legitimate user request RTT - under attack (100 user nodes and 900 attacker nodes)

Case 1 performance: 100 user nodes and 900 attacker nodes

The following results are based on the 1000 nodes, which has 10% legitimate user nodes and 90% attacker nodes. The total number of legitimate user nodes is 100, and the number of attacker nodes is 900. The initial random seed for the simulation is 128 (this is used for reproducing the simulation).

The exponential inter-arrival time for a user node is 0.001 sec. In a real world, a user sends an authentication request with a rate far less than 1 per minute. The 0.001 sec exponential inter-arrival time for a user node is actually equivalent to more than 10,000 users' traffic for authentication requests. 100 user nodes actually represent more than 1,000,000 users; thus, the load of authentication requests imposed on the authentication servers is beyond today's network load. The exponential inter-arrival time for an attacker node is 0.001 sec; thus the generated traffic fully utilizes the link from switch to Server 1 (close to 100%).

The simulation starts at 105 seconds, and the system is idle between time 0 to 105s. From Fig. 4.4, 4.5, 4.6, and 4.7, IDAS system performance is compared in the scenarios with attackers and without attackers. As shown in Fig. 4.8, the average time between an attack frame leaving a node and rejected by the server is short. During the appearance of

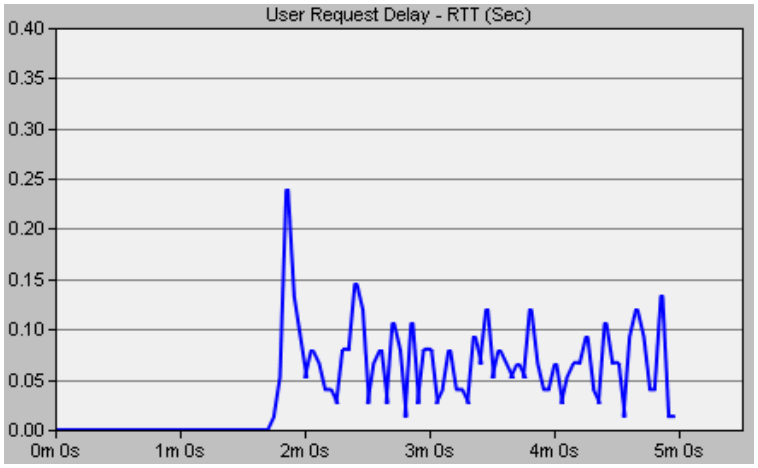


Figure 4.5: Legitimate user request RTT - without attack (1000 user nodes)

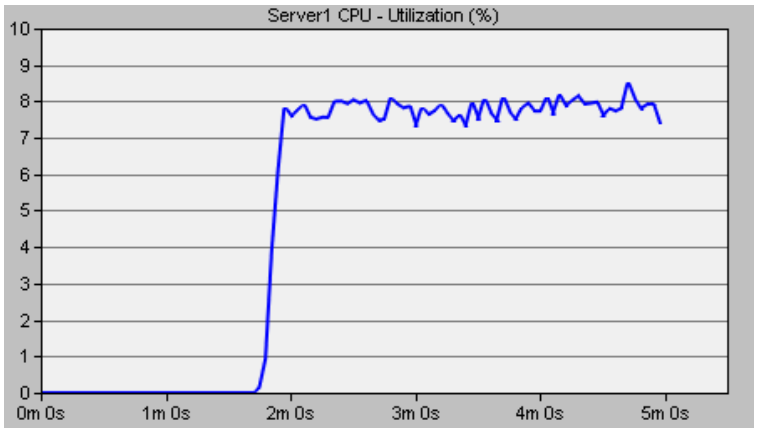


Figure 4.6: Server 1 CPU utillization - under attack (100 user nodes and 900 attacker nodes)

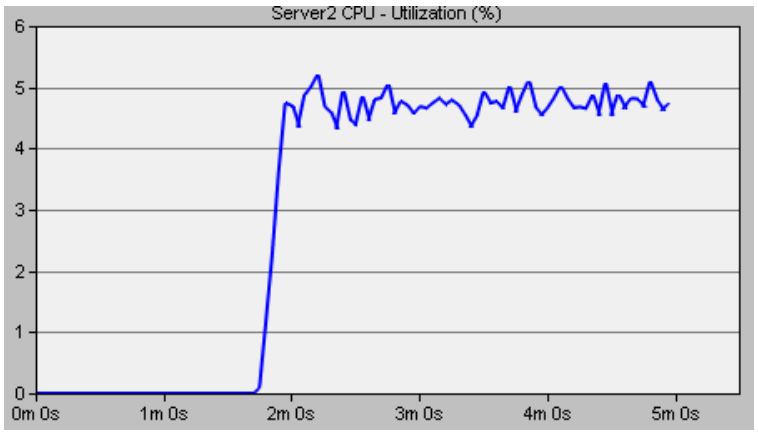


Figure 4.7: Server 2 CPU utilization - under attack (100 user nodes and 900 attacker nodes)

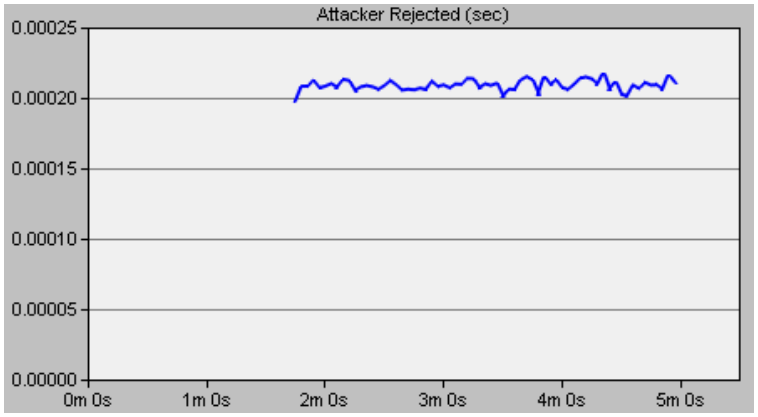


Figure 4.8: The average time between an attack frame leaving a node and rejected by the server (100 user nodes and 900 attacker nodes)

large volume attackers, the legitimate users cannot really sense the attack activities during authentication, as indicated by the slight increase of delay in Fig. 4.4 and 4.5. To illustrate the capability of servers under attack, as shown in Fig. 4.6 and 4.7, both servers have low utilization rate (peak at 8.5%) during the attack. They should be able to handle even more punishment.

Case 2 performance: 200 user nodes and 1800 attacker nodes

In comparison to Case 1, the Server 1 utilization rate is up to 13% from 8.5%. Both servers should have capabilities to take heavier DDoS punishment form more attackers. The peak RTT latency is increased from 0.325 ms (Case 1) to 0.35 ms (Case 2). This comparison further confirms IDAS scalability of providing normal authentication service to users even under heavy attacks without any collateral damage.

4.2.3 Simulation with Queueing Model for Long Distance Network

Simulation scenarios and parameters

Three scenarios were simulated:

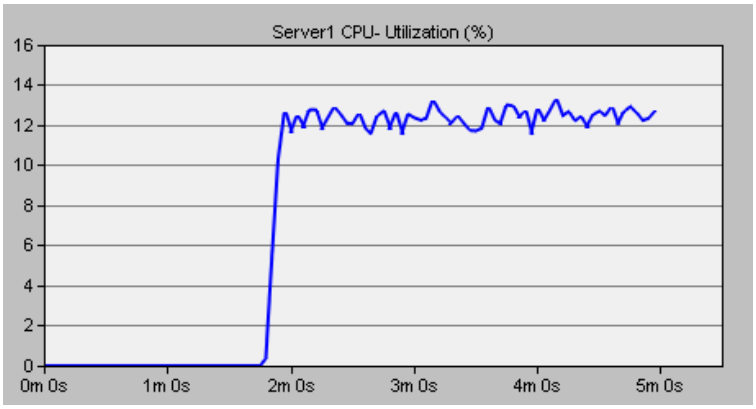


Figure 4.9: Server 1 CPU utillization - under attack (200 users and 1800 attackers)

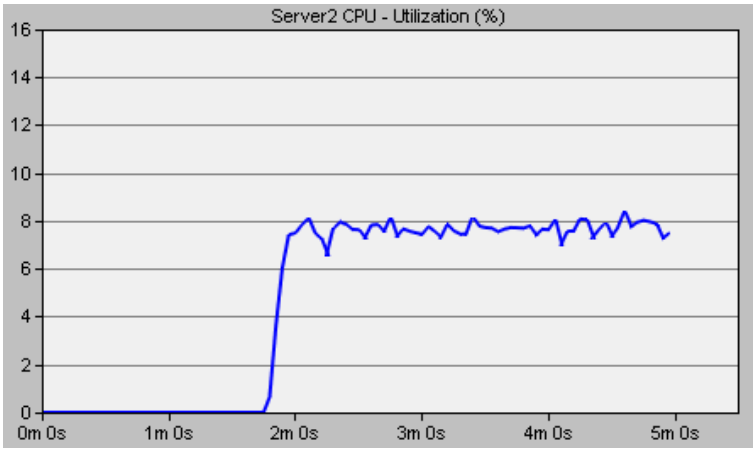


Figure 4.10: Server 2 CPU utilization - under attack (200 users and 1800 attackers)

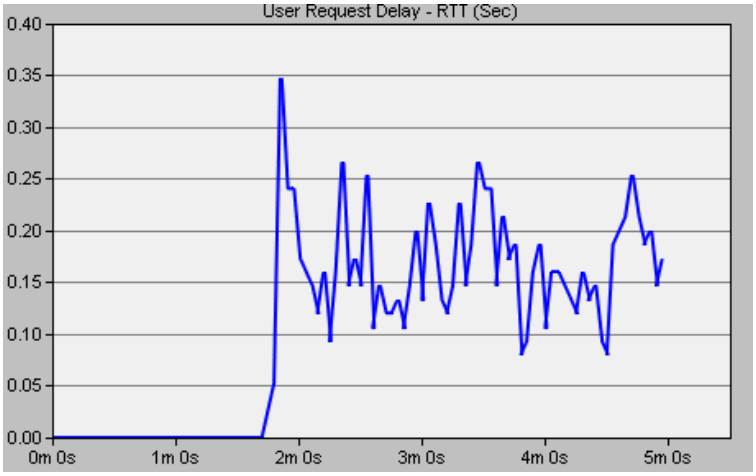


Figure 4.11: Legitimate user request RTT - under attack (200 users and 1800 attackers)

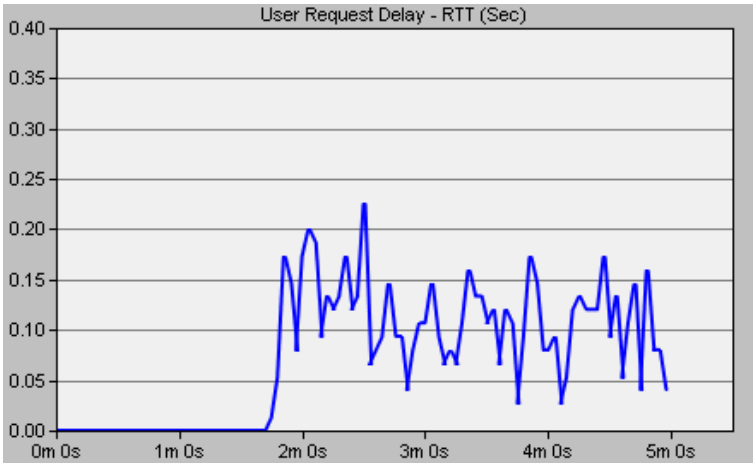


Figure 4.12: Legitimate user request RTT - without attack (2000 users)

1) One Authentication Server (AS) for a network spreading from coast to coast in North America continent as shown in Fig. 4.13.

2) One AS for a network spreading multiple continents as show in Fig. 4.14.

3) Two ASs for a network spreading multiple continents.

Following is the list of equipment that are used in the simulations:

- 15 switches: 3Com, model - 3C_SSII_1100_3300_4s_ae52_e48_ge3
- Authentication Server: Dell, model - Dell PowerEdge 1855 2 CPU, 1 Core Per CPU, 3600MHz, 8GB RAM, Microsoft Windows Server 2003 Standard x64 Edition System
- 200 laptops: Lenovo Thinkpad T43 Type 1871-48u: 1CPU, 1 Core(s) Per CPU, 1600MHz, 1GB RAM, WinXP System
- 800 desktops: Dell Precision Workstation 650: 1 CPU, 1 Core(s) Per CPU, 3200MHz, 1GB RAM, WinXP System
- Backbone Link and AS link: 10Gbps, model - 10Gbps_Ethernet_adv
- Computer's link to switch: 1 Gbps Ethernet

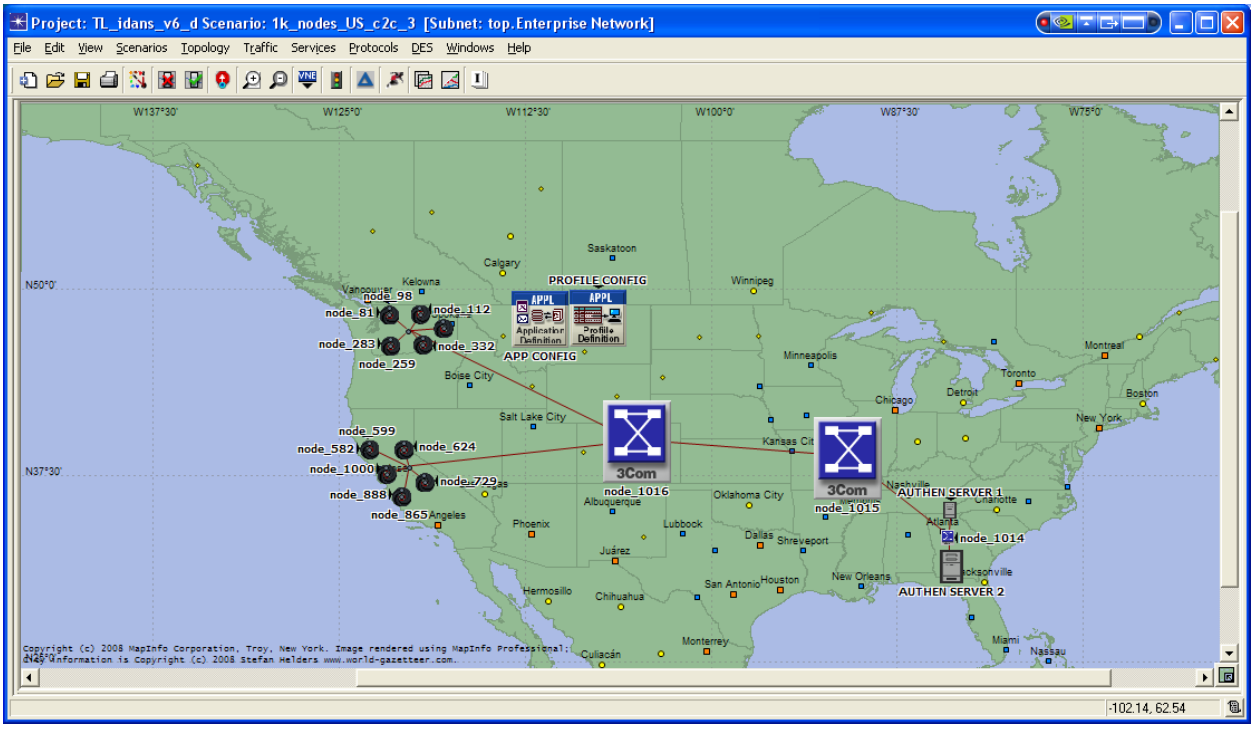


Figure 4.13: A network spreads over the north America continent

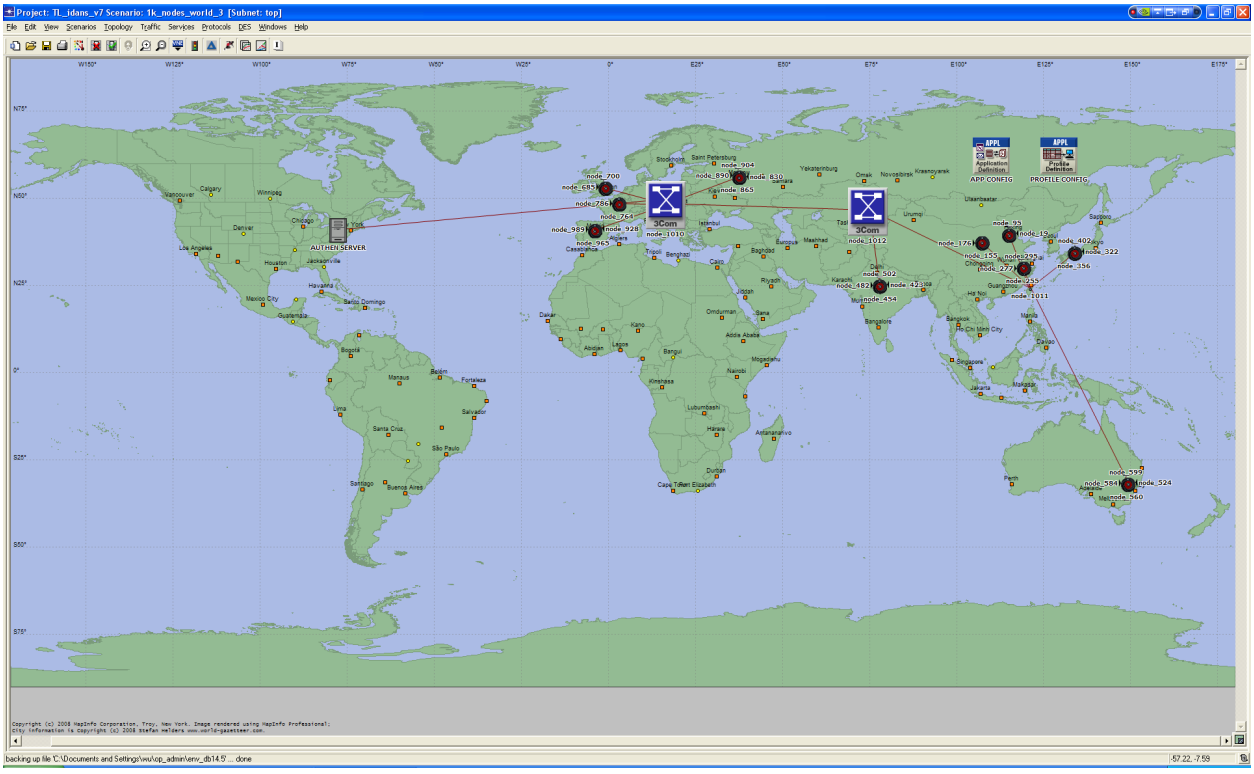


Figure 4.14: A network diagram spreads over multiple continents

Table 4.2: The arrival rates of user and attacker packets

	Packet arrival rate (per second)	Packet size(bytes)
User authentication request	0.0235	86
User data after authentication	1.667×10^3	512
Attacker packet (coast to coast)	6.847×10^5	86
Attacker packet (worldwide)	2.263×10^6	86

- Users: 100 nodes
- Attacker: 900 nodes
- Users and attackers are randomly distributed
- The attack rate and user packet rate is adjusted to fill the 10 Gbps backbone link to the AS

All packets are generated based on the Weibull Traffic Model. As shown in Table 4.2, legitimate user's average authentication request rate is 0.0235 per second, such as traveling in a mobile network. After authenticated, user's data packet has a mean arrival rate of 1.667×10^3. The attacker's packet rate is adjusted to fill up the 10 Gbps pipe to the authentication server (AS).

Simulation results and comparisons

The simulations of all traffic are launched at t= 105 second (s) as the default set by OPNET software. As shown in Table 4.3, when under massive DDoS attacks, the AS CPU utilization rate increases about 16%. The latency increases about 0.04 to 0.06 seconds (as shown in Table 4.4) that cannot be sensed by a legitimate user. There is no collateral damage to legitimate users during massive DDoS attacks.

To compare the simulation and modeling results, Fig. 4.15 and 4.16 show the CPU utilization and packet latency in a worldwide network, when the attacks were launched at t = 105 s against one authentication server. The comparisons between simulation result

Table 4.3: Server CPU Utilization Comparison (%) under Weibull Network Traffic Model. The two server simulation results is indicated by (d)

	CPU utilization (%) under attack	CPU utilization (%) without attack
Coast to coast	30.31	26.32
Worldwide	35.83	30.94
Worldwide (d)	11.78/8.32	10.21/7.56

Table 4.4: Network Delay (ms) Comparison under Weibull Network Traffic Model. The two-server simulation results are indicated by (d)

	Network delay (ms) under attack	Network delay (ms) without attack
Coast to coast	303.7	257.6
Worldwide	368.4	316.1
Worldwide (d)	145.1	113.2

and queueing model show a difference of 7% for CPU utilization, and a difference of 5% for packet latency, respectively. Fig. 4.17 and Fig. 4.18 illustrate the comparison results for two authentication server in worldwide scenario. The comparisons between simulation result and queueing model show a difference of 8% for CPU utilization, and a difference of 6% for packet latency respectively. We can see the agreement between simulation and modeling results is adequate.

4.3 Summary

In this chapter, the performance of proposed IDAS system is evaluated. To model network delay and CPU utilization of authentication servers, a BCMP queueing network is utilized to analyze the network. Later on, comprehensive simulations are carried out on different scenarios like coast to coast and continent to continent. The simulation results prove that the proposed system is fast and efficient to massive attacks. This work is published in proceeding of ACM SpringSim 2008 [51] and International Journal of Information and Computer Security [52].

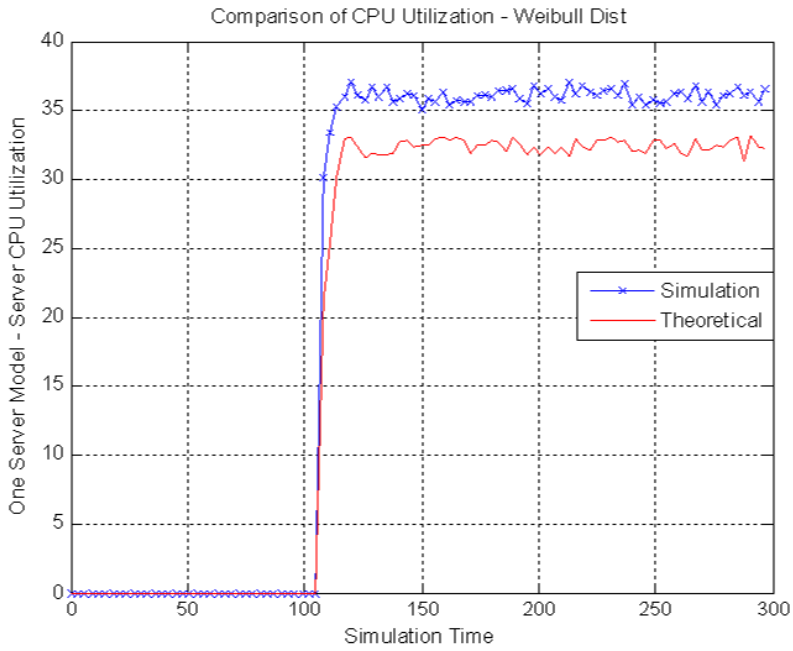


Figure 4.15: Comparison for CPU utilization (%) in worldwide one-AS scenario

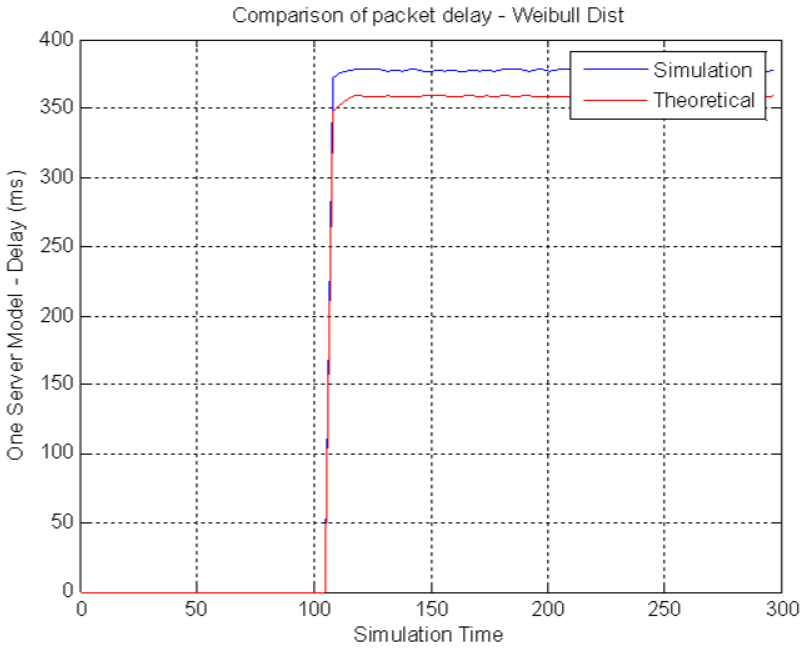


Figure 4.16: Comparison for packet latency (ms) in worldwide one-AS scenario

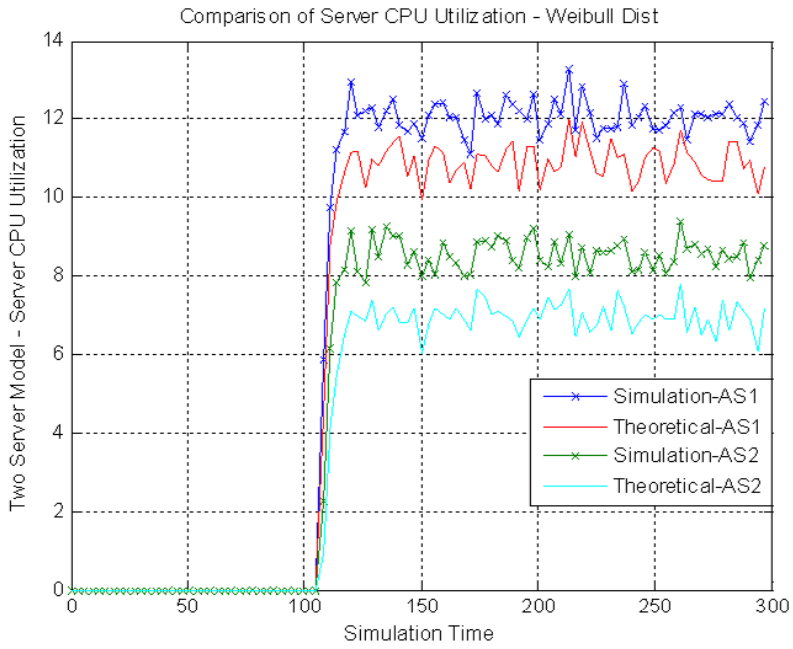


Figure 4.17: Comparison for CPU utilization (%) in worldwide two-AS scenario

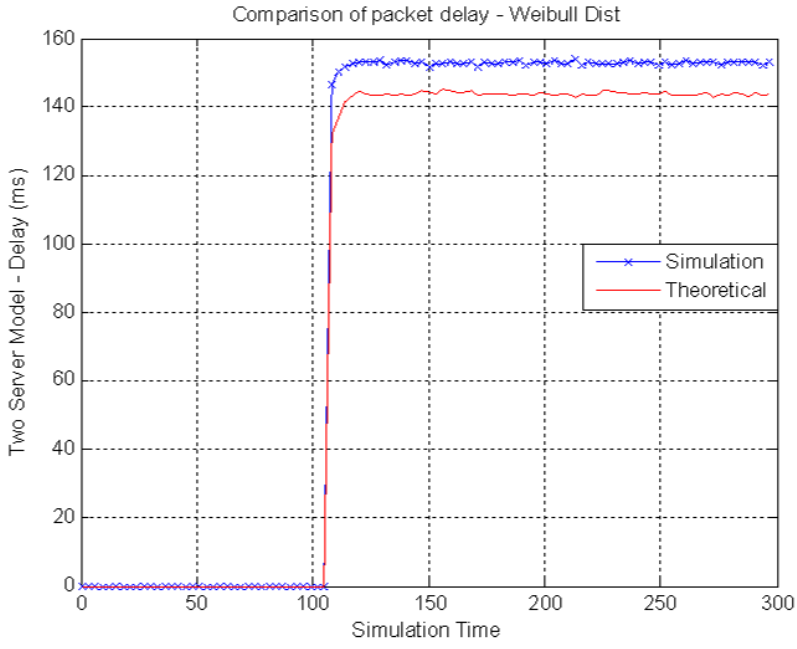


Figure 4.18: Comparison for packet latency (ms) in worldwide two-AS scenario

Chapter 5

Space-Time Evolving Authentication Scheme

The key concept of the this proposed scheme is space-time evolving. It means that the key evolves from time to time, and from location to location. Only the owner of the key can derive the key for the next time interval, while the party involved can only verify the key. User asset and host have different keys. The key also evolves in space as a packet propagating through agents and routers. All the related activities should be logged and the logs are protected by the space-time evolving keys.

Fig. 5.1 illustrates the architecture of our proposed space-time evolving authentication scheme. Security agent coordinates a group of user/client, while the super security agent coordinates a group of security agents. The incoming and outgoing requests of application server (in our case, database server) are also checked by the front security agent. The logs of every involved entity are stored and protected by the space-time evolving keys. To create or retrieve the logs, appropriate keys should be presented. Otherwise, the request is rejected and the activity is added to log.

First, we will list some notations used in our proposed space-time evolving authentication scheme.

5.1 Components

The key of proposed scheme is to protect and control access to sensitive data stored in the central Database Server. The user with a Badge uses a Client computer to log in to the database to access sensitive data. Both the user and the client must be registered beforehand. Access to the database is controlled by a group of the Security Agents (SA) and the Super Security Agent (SSA). When a User wishes to access sensitive data stored on

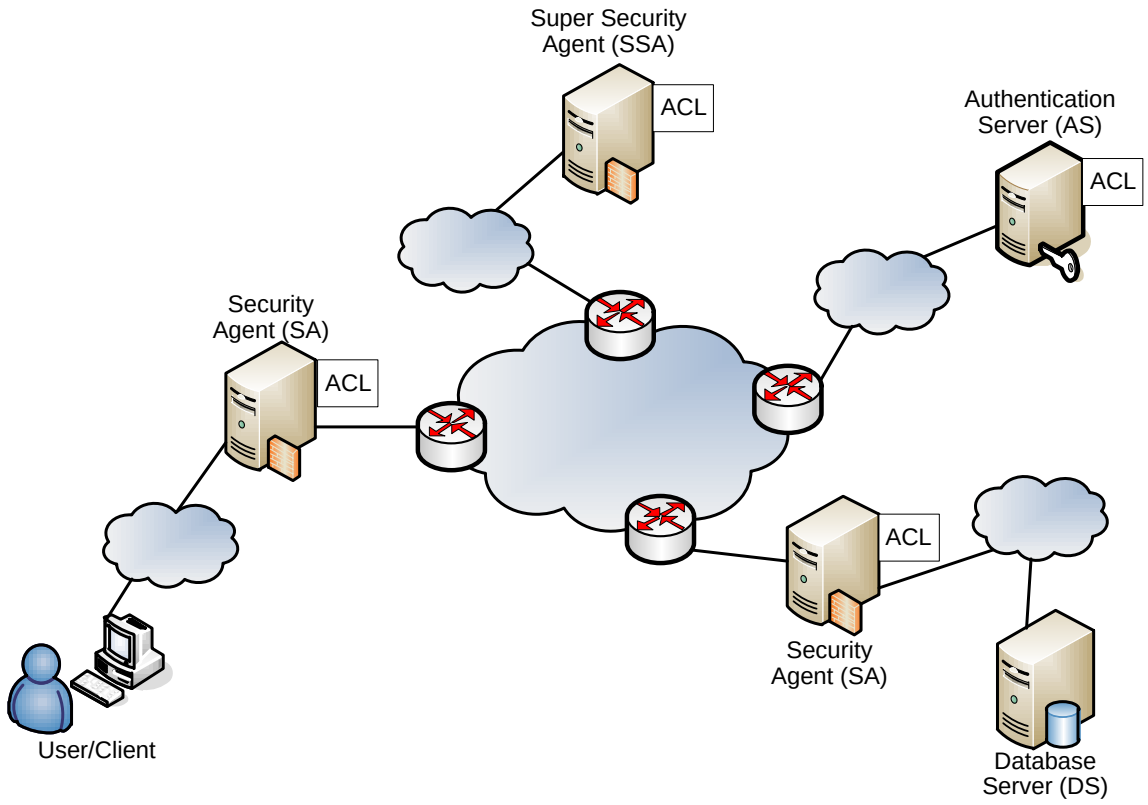


Figure 5.1: System architecture of our space-time evolving authentication scheme

Table 5.1: List of notations

U	User
C	Client Host
B	Badge
SA	Security Agent
SSA	Super Security Agent
AS	Authentication Server
DS	Database Server
$h_k(M)$	Keyed hash operation of message M using key k.
$\{M\}_k$	Encryption using symmetric key k
$h_k^2(M)$	Double keyed hash operation of message M.
ID_U	User identifier
S_U	User password
ID_C	Client Host identifier
ID_{SA}	Security Agent identifier
$OPT_{C,AS}$	One-time password of Client Host and Authentication Server
$OPT_{C,SA}$	One-time password from Client to Security Agent
$OPT_{SA,C}$	One-time password from Security Agent to Client
SN	A 32-bit sequence number
PID_U	User pseudo identifier
PID_C	Client Host pseudo identifier
PID_{SA}	Security Agent pseudo identifier
K^a	Authentication key
K^e	Encryption key
T_U	A timestamp generated by User
T_B	A timestamp generated by Badge
T_{SA}	A timestamp generated by Security Agent
T_{SSA}	A timestamp generated by Super Security Agent
T_{AS}	A timestamp generated by Authentication Server
$\mu_{U,AS}$	HMAC of User of Authentication Server
$A_{U,AS}$	Authenticator between User and Authentication Server
$V_{U,AS}$	Verifier between User and Authentication Server
$\mu_{C,AS}$	HMAC of Client and Authentication Server
$A_{U,AS}$	Authenticator between Client and Authentication Server
$V_{U,AS}$	Verifier between Client and Authentication Server
$\mu_{SA,AS}$	HMAC of Security Agent and Authentication Server
$A_{U,AS}$	Authenticator between Security Agent and Authentication Server
$V_{U,AS}$	Verifier between Security Agent and Authentication Server
$H_{C,SA}$	Authenticator of each packet.

the Database Server (DS), he must own a Badge (Smart Card) and a User password. These two security tokens are used in conjunction with a secret held by the Client in order to authenticate the User with the DS. The User/Client must authenticate with each of several SAs individually, with the authentication process being controlled and monitored by one of the SSAs. The authentication credentials change both per session and per packet.

The following are some components needed in the authentication process:

1) ID and PseudoID (PID)

   Both the User and the Client are assigned 160-bit permanent ID numbers upon registration with the authentication system. This allows the SAs, SSAs, and AS to identify who is attempting to login and to find the authentication information for that User and Client. In addition, the User and the Client are also assigned temporary Pseudo IDs (PID). These are randomly-generated IDs which are changed every login session. The PID is used to protect the real identity of User. When a User attempts to login to the authentication system, he must possess the correct permanent IDs for both User and Client as well as the correct PIDs for both User and Client. During login, the User and Client are identified by their PIDs, and Permanent IDs are verified later in the login process.

2) Timestamp (T)

   The timestamp is needed to record the time for every request. In our implementation, we adopt the Network Time Protocol (NTP) [48]. NTP is a protocol and software implementation for synchronizing the clocks of computer systems over packet-switched, variable-latency data networks. The 64-bit timestamp in our system is generated using $NTPv4\ T = NTPTimeReq()$.

3) Application ID (AppID) and Parent Application ID

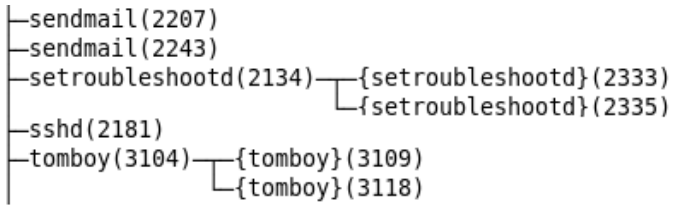


Figure 5.2: Application ID (AppID) and Parent AppID in Linux OS

For every application the operating system is assigned an application ID. Fig. 5.2 demonstrates the application ID and parent application ID in the Linux OS. In a chain of applications, an application also has its parent application, which the application originates from. In our system, when a User/Client wishes to communicate with the DS or another Client, the Client must first download a small application from an SA. This application is used to establish subsequent communication with the DS or another Client. This application must be downloaded for each new session. Each application that is dispensed by the SA has a random unique AppID. The SAs maintain logs detailing which AppIDs were issued to which Clients at which times.

When a Client sends a message, the packet contains two fields current AppID and Parent AppID. The current AppID field contains the AppID of the application that sent the packet. If the packet was created in response to an earlier packet received from another Client, then the Parent AppID field contains the AppID of the original packet. Otherwise, the Parent AppID field contains the same value as the current AppID field. For example, if Client A sends a message to Client B instructing Client B to send a different message to Client C, then the packet from Client A contains Client A's AppID in both the current AppID and Parent AppID fields. The packet sent from Client B to Client C will contain Client B's AppID in the current AppID field and Client A's AppID in the Parent AppID field. The current and Parent AppIDs will be utilized later during correlation and traceback.

4) One-Time Password (OPT)

The One Time Password (OTP) is a per packet password that authenticates the User or Client with an individual SA. The OTP is a hash of previously established keys that are shared between the Client or the User and each individual SA, and a sequence number. The Client or User has an authentication relationship with each SA; each relationship consists of an independently established set of keys and sequence number (space separation). The sequence number increments for each packet; thus, the OTP is different for each packet (time separation). Also, the keys are changed after each login session initiated by a Client or User (time separation). Possession of the correct keys, which are secrets, and the correct sequence number, which is not a secret, is necessary to correctly calculate the OTP.

5) Content ID and Authorization (Permissions)

Each piece of sensitive information on the Database is identified by a unique Content ID. A piece of sensitive information may exist in one place, or it may be split into several pieces with each piece having a unique Content ID and residing in different locations on a single Database or in locations across multiple Databases (space separation). When a User requests access to the sensitive information, he must possess all of the correct Content IDs. It is also possible to change these Content IDs over time (time separation).

Access to sensitive information is also controlled by means of authorization privileges (permissions). The SSAs maintain an access control list, which specifies which Clients and which Users are permitted to access which pieces of sensitive information. The SSAs also share this list with the SAs. Whenever an SA or an SSA handles an information access request, the calling Client/User is checked against the access control rules for that particular piece of information.

6) Security Ticket

When a sensitive data access request is sent from the User/Client to the Database, it must

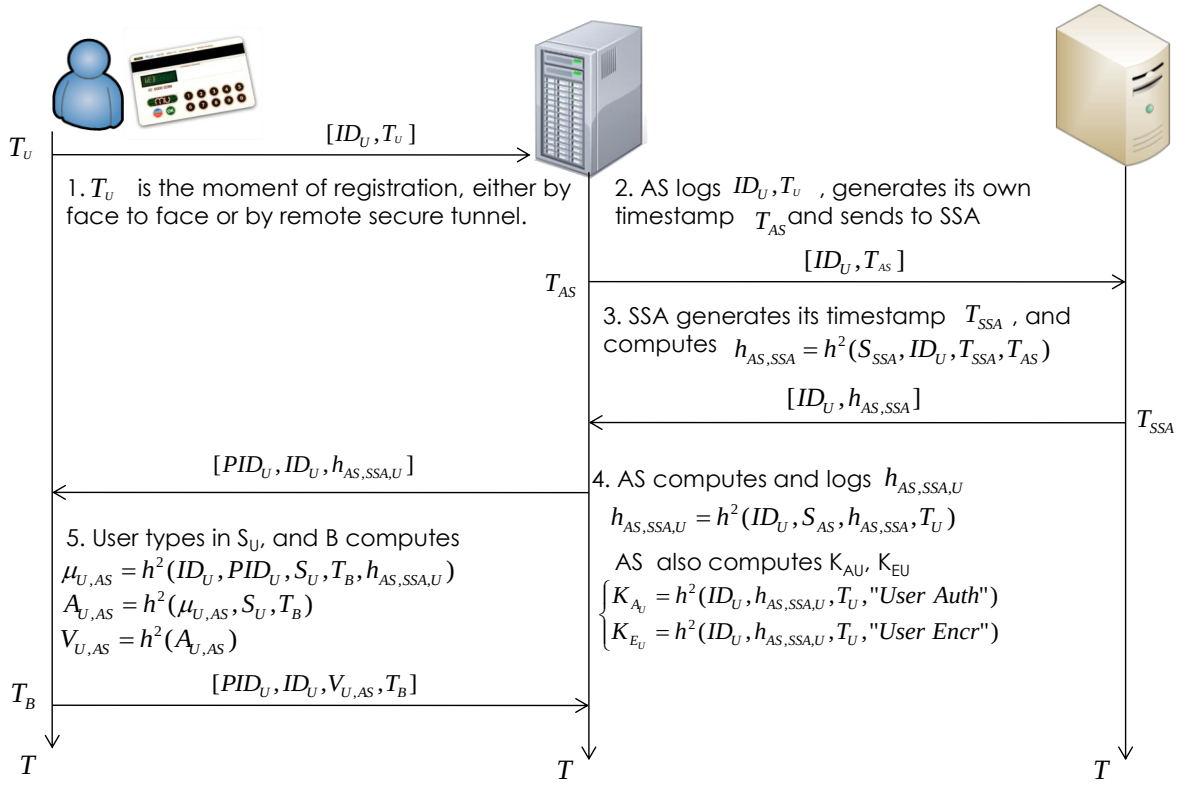


Figure 5.3: User Badge registration process

first clear the SA barrier and the SSA barrier. The packet must clear each of a number of SAs by passing PID, OTP, and authorization (permissions) checks. The packet also carries a Security Ticket; when an SA authenticates and authorizes a packet, it "stamps" the packet's Security Ticket before sending it to the next SA. This allows future SAs to verify which SAs the packet has previously cleared.

5.2 Registration Process

5.2.1 User Badge Registration

User with a Badge needs to register with AS and SSA first before mutual authentication stage. The registration process is processed either via face-to-face in the registration office, or via a remote secure tunnel. In either case, Users need to present enough identifications

to prove he/she has corresponding privilege to register. Here are the detailed registration process (see Fig. 5.3):

Step 1: User $\Longrightarrow$ AS

timestamp T_U is the moment of registration, and ID_U is the real identity of User. User delivers $[ID_U, T_U]$ to AS for registration.

Step 2: AS $\Longrightarrow$ SSA

After AS received User's request, it logs ID_U, T_U, generates its own timestamp T_{AS} and forwards the request $[ID_U, T_{AS}]$ to SSA.

Step 3: SSA

SSA logs ID_U, T_{SSA}, T_{AS}, and $h_{AS,SSA}$. It generates its own timestamp T_{SSA}, and computes

$$h_{AS,SSA} = h^2(S_{SSA}, ID_U, T_{SSA}, T_{AS}) \tag{5.1}$$

where S_{SSA} is the secret of SSA.

Step 4: AS $\Longleftarrow$ SSA

In this step, AS first computes and logs

$$h_{AS,SSA,U} = h^2(ID_U, S_{AS}, h_{AS,SSA}, T_U) \tag{5.2}$$

where $h_{AS,SSA}$ is received from SSA, and S_{AS} is the secret of AS. Then it computes authentication key K_U^a and encryption key K_U^e respectively.

$$K_U^a = h^2(ID_U, h_{AS,SSA,U}, T_U, \text{“User AUTH”}) \tag{5.3}$$

$$K_U^e = h^2(ID_U, h_{AS,SSA,U}, T_U, \text{“User ENCR”}) \tag{5.4}$$

After that, AS sends $[PID_U, ID_U, h_{AS,SSA,U}]$ to the User.

Step 5: User $\Longleftarrow$ AS

After User received response from AS, it types in S_U. The Badge B computes

$$\mu_{U,AS} = h^2(ID_U, PID_U, S_U, T_B, h_{AS,SSA,U}) \tag{5.5}$$

where S_U is the User secret, T_B is the current timestamp, and $h_{AS,SSA,U}$ is received from AS. It also computes

$$A_{U,AS} = h^2(\mu_{U,AS}, S_U, T_B) \tag{5.6}$$

$$V_{U,AS} = h^2(A_{U,AS}) \tag{5.7}$$

When User knows $\mu_{U,AS}$, $A_{U,AS}$, and $V_{U,AS}$, it sends $[PID_U, ID_U, V_{U,AS}, T_B]$ to the AS. AS will log the activity and stores the credentials from authentication process.
After the registration, AS has verifier $V_{U,AS}$ and shares authentication key K_U^a and encryption key K_U^e with the user. User can generate $OPT_{U,AS}$ with the keys.

5.2.2 Client Host Registration

Fig. 5.4 shows the registration of Client. The registration process is similar to User registration.

Step 1: Client $\Longrightarrow$ AS

timestamp T_C is the moment of registration, and ID_C is the real identity of Client. Client delivers $[ID_C, T_C]$ to AS for registration.

Step 2: AS $\Longrightarrow$ SSA

After AS received Client's request, it logs ID_C, T_C, generates its own timestamp T_{AS} and forwards the request $[ID_C, T_{AS}]$ to SSA.

Step 3: SSA

SSA logs ID_C, T_{SSA}, T_{AS}, and $h_{AS,SSA}$. It generates its own timestamp T_{SSA}, and computes

$$h_{AS,SSA} = h^2(S_{SSA}, ID_C, T_{SSA}, T_{AS}) \tag{5.8}$$

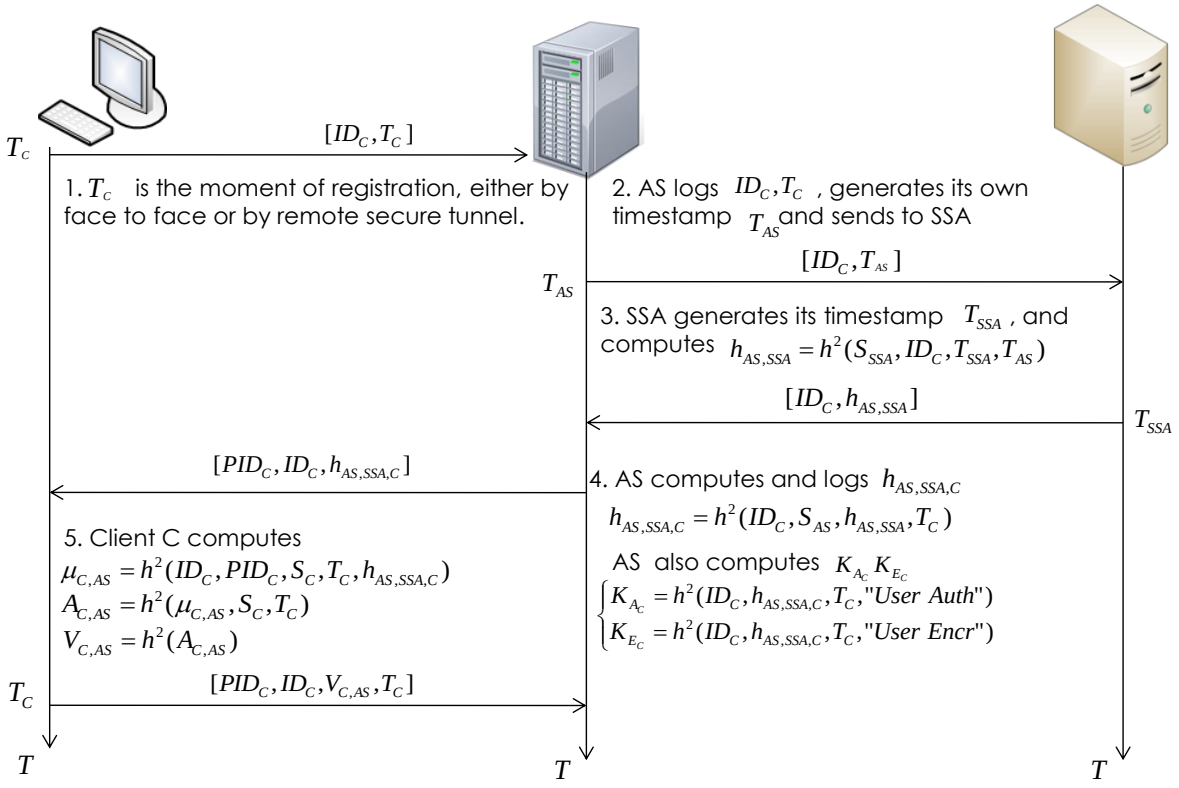


Figure 5.4: Client Host registration process

where S_{SSA} is the secret of SSA.

Step 4: AS $\Longleftarrow$ SSA

In this step, AS first computes and logs

$$h_{AS,SSA,C} = h^2(ID_C, S_{AS}, h_{AS,SSA}, T_C) \tag{5.9}$$

where $h_{AS,SSA}$ is received from SSA, and S_{AS} is the secret of AS. Then it computes authentication key K_C^a and encryption key K_C^e respectively.

$$K_C^a = h^2(ID_C, h_{AS,SSA,C}, T_C, \text{“Client AUTH”}) \tag{5.10}$$

$$K_C^e = h^2(ID_C, h_{AS,SSA,C}, T_C, \text{“Client ENCR”}) \tag{5.11}$$

After that, AS sends $[PID_C, ID_C, h_{AS,SSA,C}]$ to the Client.

Step 5: Client $\Longleftarrow$ AS

After Client received response from AS, it computes

$$\mu_{C,AS} = h^2(ID_C, PID_C, S_C, T_C, h_{AS,SSA,C}) \tag{5.12}$$

where S_C is the Client's secret, T_C is the current timestamp, and $h_{AS,SSA,C}$ is received from AS. It also computes

$$A_{C,AS} = h^2(\mu_{C,AS}, S_C, T_C) \tag{5.13}$$

$$V_{C,AS} = h^2(A_{C,AS}) \tag{5.14}$$

When Client knows $\mu_{C,AS}$, $A_{C,AS}$, and $V_{C,AS}$, it sends $[PID_C, ID_C, V_{C,AS}, T_C]$ to the AS. AS will log the activity and stores the credentials from authentication process.

After the registration, AS has verifier $V_{C,AS}$ and shares authentication key K_C^a and encryption key K_C^e with the Client. Client can generate $OPT_{C,AS}$ with the keys.

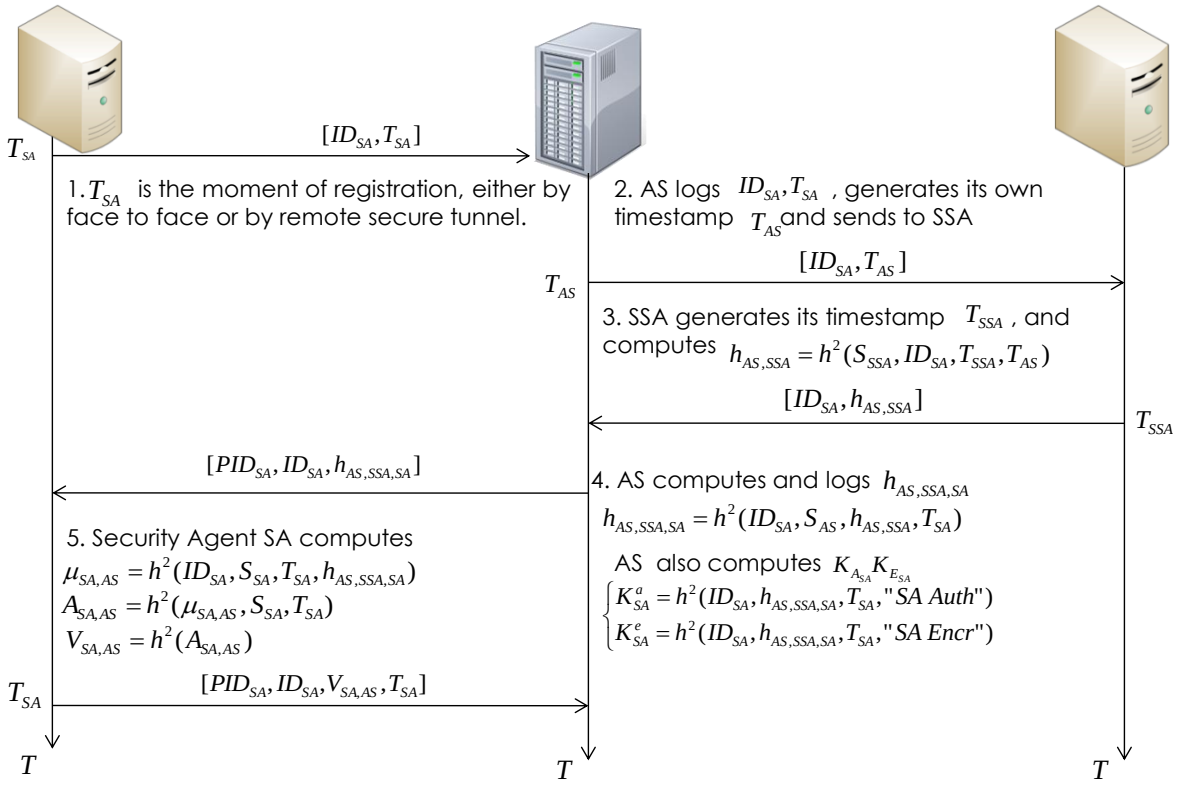


Figure 5.5: Security Agent registration process

5.2.3 Security Agent Registration

Fig. 5.5 shows the registration of Security Agent. The registration process is also similar to User registration and Client registration.

Step 1: SA $\Longrightarrow$ AS

timestamp T_{SA} is the moment of registration, and ID_{SA} is the real identity of Security Agent. Security Agent delivers $[ID_{SA}, T_{SA}]$ to AS for registration.

Step 2: AS $\Longrightarrow$ SSA

After AS received Security Agent's request, it logs ID_{SA}, T_{SA}, generates its own timestamp T_{AS} and forwards the request $[ID_{SA}, T_{AS}]$ to SSA.

Step 3: SSA

SSA logs ID_{SA}, T_{SSA}, T_{AS}, and $h_{AS,SSA}$. It generates its own timestamp T_{SSA}, and computes

$$h_{AS,SSA} = h^2(S_{SSA}, ID_{SA}, T_{SSA}, T_{AS}) \tag{5.15}$$

where S_{SSA} is the secret of SSA.

Step 4: AS $\Longleftarrow$ SSA

In this step, AS first computes and logs

$$h_{AS,SSA,SA} = h^2(ID_{SA}, S_{AS}, h_{AS,SSA}, T_{SA}) \tag{5.16}$$

where $h_{AS,SSA}$ is received from SSA, and S_{AS} is the secret of AS. Then it computes authentication key K^a_{SA} and encryption key K^e_{SA} respectively.

$$K^a_{SA} = h^2(ID_{SA}, h_{AS,SSA,SA}, T_{SA}, \text{“SA AUTH”}) \tag{5.17}$$

$$K^e_{SA} = h^2(ID_{SA}, h_{AS,SSA,SA}, T_{SA}, \text{“SA ENCR”}) \tag{5.18}$$

After that, AS sends $[PID_{SA}, ID_{SA}, h_{AS,SSA,SA}]$ to the Client.

Step 5: SA $\Longleftarrow$ AS

After SA received response from AS, it computes

$$\mu_{SA,AS} = h^2(ID_{SA}, PID_{SA}, S_{SA}, T_{SA}, h_{AS,SSA,SA}) \tag{5.19}$$

where S_{SA} is the SA's secret, T_{SA} is the current timestamp, and $h_{AS,SSA,SA}$ is received from AS. It also computes

$$A_{SA,AS} = h^2(\mu_{SA,AS}, S_{SA}, T_{SA}) \tag{5.20}$$

$$V_{SA,AS} = h^2(A_{SA,AS}) \tag{5.21}$$

When SA knows $\mu_{SA,AS}$, $A_{SA,AS}$, and $V_{SA,AS}$, it sends $[PID_{SA}, ID_{SA}, V_{SA,AS}, T_{SA}]$ to the AS. AS will log the activity and stores the credentials from authentication process.
After the registration, AS has verifier $V_{SA,AS}$ and shares authentication key K^a_{SA} and encryption key K^e_{SA} with the SA. SA can generate $OPT_{SA,AS}$ with the keys.

5.3 Authentication Process

5.3.1 Client Host Authentication

Mutual authentication between Client and AS occurs after registration process, during which AS has verifier $V_{C,AS}$ and shares authentication key K^a_{SA} and encryption key K^e_{SA} with the Client. We illustrate the mutual authentication process step by step.

Initialization

After the registration process, AS receives $V_{C,AS}$ from the Client and logs A_C

$$A_C = [PID_C, ID_C, V_{C,AS}, T_C, h_{AS,SSA,C}, K^a_C, K^e_C] \tag{5.22}$$

AS has the topological information of all SAs during the registration process, and assign SAs that can accept login to client. AS also maintains the mapping table dynamically. Given an ID_C, AS searches the associated SAs's ID. Suppose we have n SAs that can accept login from Client. There is mapping between SA and its ID $\{SA_1, SA_2, \cdots, SA_n\} \Longrightarrow \{ID_{SA_1}, ID_{SA_2}, \cdots, ID_{SA_n}\}$. Every SA coordinates a group Client. Given Client with ID_C, AS finds all the SAs's ID based on the SA ID and Client ID mapping table (see Table 5.2).

Mutual authentication

Client is equipped with Trusted Platform Module (TPM), which logs activity and maintains health status of the Client. With the assistance of TPM, the logs and status are protected against alteration by the the intruder.

Table 5.2: SA ID and Client ID mapping table

SA ID	Client ID
ID_{SA_1}	$[ID_{C_1}, ID_{C_3}, \cdots, ID_{C_{x_1}}]$
ID_{SA_2}	$[ID_{C_1}, ID_{C_6}, \cdots, ID_{C_{x_2}}]$
$\cdots$	$\cdots$
ID_{SA_n}	$[ID_{C_1}, ID_{C_7}, \cdots, ID_{C_{x_n}}]$

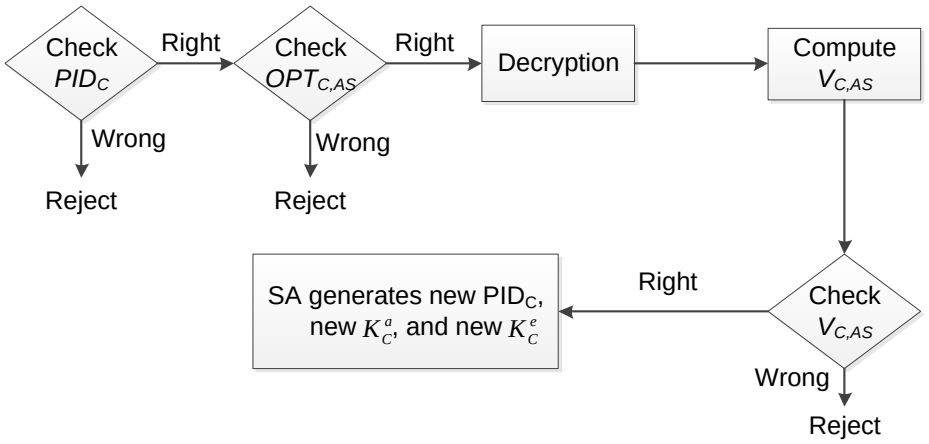


Figure 5.6: Flowchart of processing of Client request by SA

M1: C $\Longrightarrow$ SA

Client generates a timestamp T_C and sends M1 to SA

$$M1 = [SN_C, PID_C, OTP_{C,AS}, \{ID_C, T_C, A_{C,AS}, HS_C\}_{K_C^e}, H_{C,SA}] \tag{5.23}$$

where SN_C is a 32-bit sequence number of client request packet, HS_C is the health statement provided by Client's TPM, and the authentication of each packet is carried out by $H_{C,SA} = h_{K_C^a}$(sequence number, invariant header, encrypted payload). SA will do Challenge & Response occasionally to check Client's health status. For the first time login $OTP_{C,AS} = OTP_{C,SA} = h^2(K_C^a, K_C^e, SN_C)$, and they will be different after the first time login.

After receiving the login request from client, SA processes the request based on the flowchart in Fig. 5.6. If any stage of the request fails, the request will be rejected immediately and the packet is discarded. Otherwise, if the request is from a legitimate user, SA computes $OTP_{SA,C}$, generates new K_C^a and new K_C^e for next authentication session, and delivers to Client and AS respectively.

$$\text{new } K_C^a = h^2(ID_C, h_{AS,SSA,C}, \text{new } T_C, \text{“Client AUTH”}) \tag{5.24}$$

$$\text{new } K_C^e = h^2(ID_C, h_{AS,SSA,C}, \text{new } T_C, \text{“Client ENCR”}) \tag{5.25}$$

M2: C $\Longleftarrow$ SA

After computing the new K_C^a and new K_C^e, SA sends $M2$ to Client

$$M2 = [SN_{SA}, OTP_{SA,C}, \{\text{new } PID_C, \text{new } K_C^a, \text{new } K_C^e\}_{K_C^e}, H_{C,SA}] \tag{5.26}$$

Clients computes and checks $OTP_{SA,C}$. If it is correct, it will decrypt and get new PID_C and new keys for next login.

M3: SA $\Longrightarrow$ AS

SA also sends $M3$ to AS

$$M3 = [ID_C, T_C, A_{C,AS}, \text{new } PID_C, \text{new } K_C^a, \text{new } K_C^e]_{K_C^e} \tag{5.27}$$

AS stores the new PID_C, new authentication key K_C^a and new encryption key K_C^e. The activity should be logged by AS.

M4: C $\Longrightarrow$ SA

The payload is encrypted using the encryption key K_C^e together with the ID_C, new T_C, and new $V_{C,AS}$.

$$M4 = [SN_C, PID_C, OTP_{C,SA}, \{ID_C, \text{new } T_C, \text{new } V_{C,AS}, \text{payload}\}_{K_C^e}, H_{C,SA}] \tag{5.28}$$

where new T_C is the new timestamp generated by Client, and SN_C is the request sequence number. After received the packet, SA first checks PID_C. If PID_C is right then it proceeds to compute $OTP_{C,SA} = h^2(K_C^a, K_C^e, SN_C)$ and checks if the $OPT_{C,SA}$ matches the received one. If either one in the above two fails, the request is rejected immediately. Only when both PID_C and $OTP_{C,SA}$ can be verified, the payload is decrypted and SA sends new T_C and new $V_{C,AS}$ to AS.

A secure tunnel is established after successful mutual authentication. Each direction of the flow in a tunnel has a 32-bit sequence number as the counter of sent packets. The authentication of each packet is carried out by $H_{C,SA} = h_{K_C^a}(SN, \text{invariant header}, \text{encrypted payload})$. Moreover, SA establishes a secure tunnel to other SA in order to let User receive the service (SA requests ticket on behalf of User). After Client login, every packet should be authenticated. Every packet has a 32-bit sequence number (SN) in clear text header. Re-login of Client is required when SN is about to wraparound. Sender, either C or SA, uses the following fresh keys for every packet

$$K_C^{a*} = h^2(PID_C, K_C^a, SN, \text{“Client AUTH”}) \text{ where } SN = SN_C \text{ or } SN_{SA} \tag{5.29}$$

$$K_C^{e*} = h^2(PID_C, K_C^e, SN, \text{“Client ENCR”}) \text{ where } SN = SN_C \text{ or } SN_{SA} \tag{5.30}$$

The destination IP address is protected similar to ESP [49].

5.3.2 User and SA Authentication

User authentication occurs after Client authentication and establishes a secure tunnel inside the C-SA tunnel for accessing critical information. The process User or SA authentication is very similar to Client authentication, changing the corresponding ID and timestamp. A secure tunnel is established after successful SA mutual authentication. Each direction of the flow in a tunnel has a 32-bit sequence number as the counter of sent packets. The

authentication of each packet is carried out by $H_{SA,SSA}$. After SA login, every packet needs to be authenticated. Re-login is of SA is required when SN is about to wraparound.

5.4 Summary

In this chapter, the space-time evolving authentication scheme is presented. The system includes user, client host, security agent, super security agent, authentication server and database server. The security agent acts as a proxy between a client and other servers. It monitors and tracks the state transitions in ACL, and authenticate user and process according to ACL and AD (Active Directory). The super security agent coordinates a group of security agents. It monitors the health of security agents and track state transition in ACL. The space-time evolving concept is adopt to enhance the system securities. Only the owner of the key can derive the key for the next authentication session, while the parties involved can only verify the key. The registration and mutual authentication process are illustrated step by step. Once the mutual authentication process is finished, a secure tunnel is established inside Client-SA for user to communication with remote servers.

Chapter 6

Correlation Engine and Real-Time Forensics

6.1 Access Control List (ACL)

Access Control List (ACL) is used widely to control and grant access to certain objects in the computer systems. For each object, there is a list of permissions and operations that are allowed. We use Extensible Markup Language (XML) to define our ACL (see Fig. 6.1 for an example of ACL rule).

To control the access, the following components are used in our ACL (see Table 6.1). Entry SoH is the state of health, which is used to check if there are any modifications of current system and applications. Application ID (AppID) contains the credentials of an application, such as HMAC. Content ID contains comprehensive URL database and elements of application identification to limit unauthorized information transfer plus HMAC.

Fig. 6.2 illustrates the role and capability based access control. The subject on behalf of a user with a role's indicator will possess the necessary capabilities required by the role's responsibility. Upon execution of the program file or domain transition, the subject's capability state is recalculated based on the current security context. Note that the security context involves the program file being executed, the current role and the current domain. Based on the validity check conditions for an execute request, security manager verifies whether

Table 6.1: Components in the ACL

Username	Network Protocol	Network Path	Src IP address	Dst IP Address	Host Type	Host OS ID
Time	Current AppID	Parent AppID	Content ID	HMAC	PID	SoH

```
<rule id="match.rule.1">
<eventType> Logfile_Base </eventType>
  <match>
  <predicate>
     <![CDATA[&hostname == "client1"]]>
  </predicate>
  </match>
< triggerActions >
<action function="Discard"/>
</triggerActions >
</rule>
```

Figure 6.1: XML definition of an ACL rule

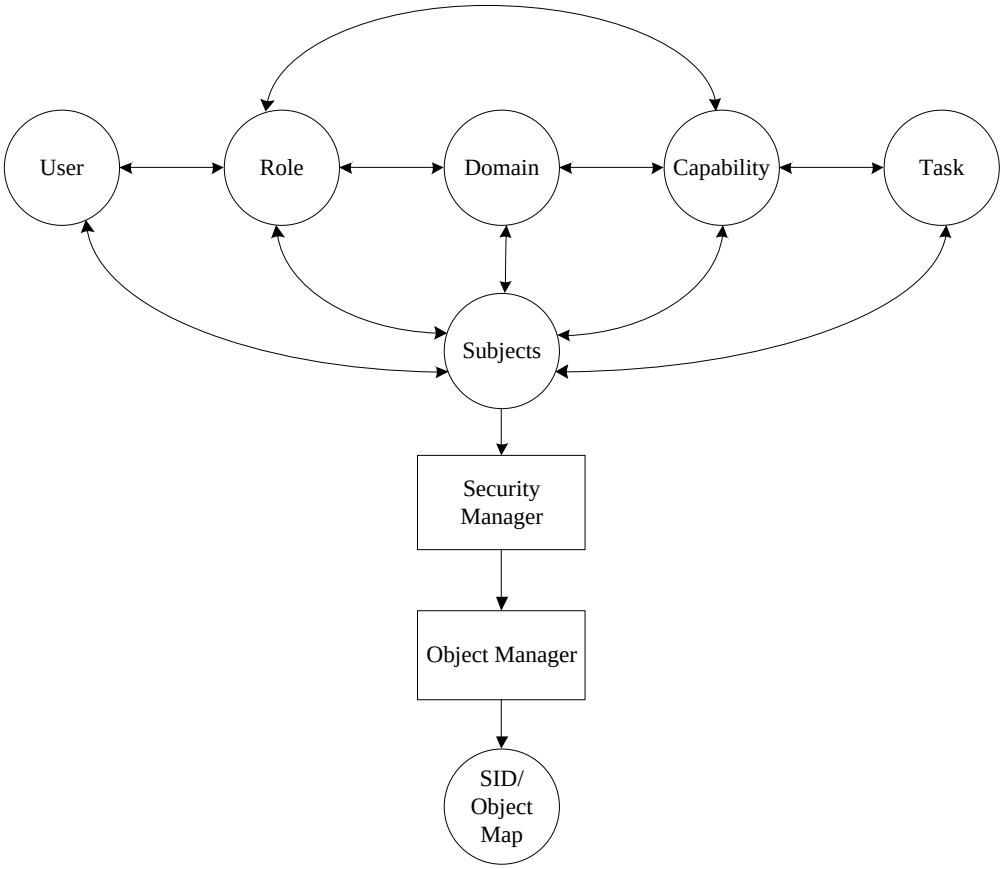


Figure 6.2: Role and capability access control

the mediation for the subject's current security context and capability state is valid. If the validity of the execute request has been verified by the algorithm, the appropriate process image, role, domain and capability state corresponding to this subject will be created or mediated.

To illustrate how ACL works in SA, SSA and AS (see Fig. 5.1), we give an example for Client's AJAX request. SA, SSA and AS with ACL verify Client's request according to ACL based on username, source/destination IP addresses, network path, time, AJAX script ID, parent AppID, and query field in the form. Moreover, they also verify inconsistency with currently active ACL (within a time interval) 1) nested/chained commands for accessing a target, involving multiple hosts, usernames, and applications; 2) one user in two separate locations at the same time; 3) modification/creation/deletion of logs. Authorization request is triggered if ACL requires the permission from SSA for critical information.

6.2 Logs Creation and Protection

Logs are the key information needed to correlate attacks and generate forensics report. All the related activities should be logged in User/Client, SA, SSA, AS and DS. Correlation Engine will collect the required logs from all the related entities.

6.2.1 Log Format

Maintaining a log with records for each packet received over an infinite period of time would be prohibitively expensive and time-consuming. Therefore, each SA and SSA maintains log records based on a sliding time window of length t, say t = 15 minutes. Logs are maintained for the most recent t time of traffic for fast availability; older logs are stored on a backup server.

The format of these log records is shown in Fig. 6.3. The record contains standard packet data such as source and destination IP addresses, packet sequence number, and packet arrival time. The record also contains the current and parent application IDs, which

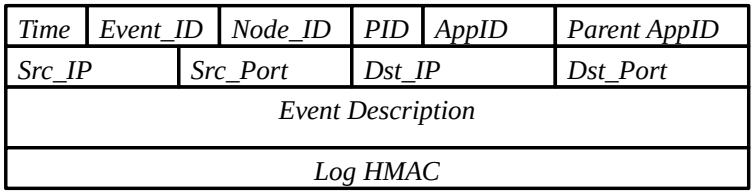


Figure 6.3: Log format

can indicate if a Client besides the one at the source IP address initiated this packet. The record also contains the packet type and the Content ID associated with the packet (if the packet is accessing data on the Database). Finally, the record contains the network path which specifies the IP addresses of all the machines (Clients, routers, SAs, etc.) the packet has touched on its route. All of this information is recorded so it can be used by the SSA to trace an attack packet to the origin of the Attacker (which will be discussed in a later section).

6.2.2 Log Protection

Logs need to be protected against malicious modifications. Each packet sent out from the user is authenticated by HMAC with space-time evolving key. All the activities associated with log entry creation and deletion are also logged. Fig. 6.4 illustrates the log protection scheme using space-time evolving key. User computes two logs HMAC $H_{User} = HMAC(K_U(t_0), \text{Data})$ and $H_{Client} = HMAC(b_{i-1}, \text{Data})$, where $K_U(t_0)$ is the user's space-time key K_U^e derived in chapter 5, and b_{i-1} is Client's hash chain value. The two HMACs are appended to the log entry. Then User sends the packet to SA. SA also computes its log HMAC using space-time key and nonce $H_{SA} = HMAC(K_{SA}(t_0), Nonce_{SA}, Data)$, and saves the packet with HMAC. $K_{SA}(t_0)$ is SA's space-time key K_{SA}^e derived in previous chapter. After that, SA forwards the packet to another SA or to AS.

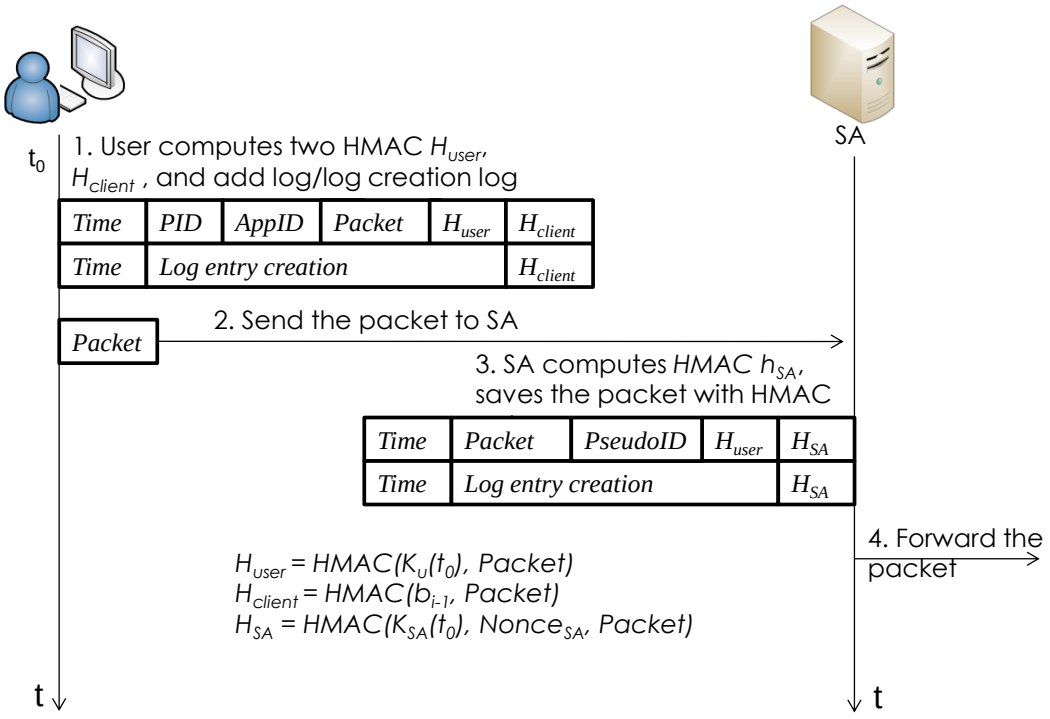


Figure 6.4: Log protection scheme

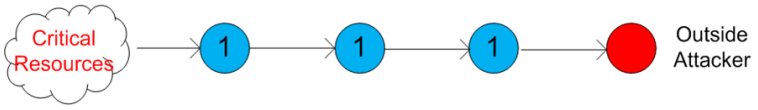


Figure 6.5: Attack chain from outside attacker

6.3 Correlation Engine and Real-Time Forensics

6.3.1 Correlation Engine

We use the event corresponding to the failure to attack critical resources as a starting point. Related logs are retrieved and analyzed. Correlation Engine (CE) traces the attack from the attack path to root attackers (see Fig. 6.5). A record contains root[ip,port,hostname,attack chain],time are generated to assist forensics processing. At every transition host in the attack path, analyze the inconsistencies and violations based on state transition diagram and privilege transition diagram. CE detection rules are as follows:

- Authentication failure: Compare timestamps in authentication failure logs. At a given time T, there are more than C (such as $C = 3$) authentication failure logs.
- Illegal privilege escalation: Analyze privilege related logs and check if there is any privilege escalation.
- State transition violation: Maintain state ID, S_{id}, and state transition diagram, and check if there is any violation with ACL.
- Loation/time inconsistency: Check if there is any location/time inconsistency.

6.3.2 Real-Time Forensics

All the log data and traffic data are stored in the database on the forensics security agent. The survey data are also saved in the agent. All these data will give guidance to the forensics analysis, data mining analysis, investigation target profiles, emergence response policy and even IDS signature pattern.

Super security agents integrate the forensics data and analyze them. It also guides the network packet filter and captures the behavior on the network monitor. It can launch the investigation program on the network investigator as the response to the sensitive attacks.

Network security agents are engines of the data gathering, data extraction and data secure transportation. It also gives the mechanism of digital signature to data integration, communication, command and control. Agents resident on the monitored host, and network log includes the possible misuse and potential risk origin in the network. System log includes the change of the register, file system, system directory, system process, open ports and system services. Important files include the evidence of misuse behavior. This data is useful to find the compromise procedure and discover the evidence of intrusion.

The network traffic data is fully captured to record the whole procedure of the intrusion and can be used to reconstruct the intrusion behavior. The main function of the security agent is obtaining information of some sensitive spots on the malicious list. The lists are imported from the analysis of forensics data and given by the super security agent. This function can be executed automatically. Surveying the domain name of an IP address will give some details of the origin of the malicious attacker. DNS surveying can acquire some useful information, such as location, email address, and phone number. Many tools are integrated in the system, such as ping, traceroute, nslookup, whois and so on.

LogDB stores the sensitive data gathered from the distributed TPMs. It can provide sensitive knowledge for the network monitor machine to pursue adaptive packet filtering and capture. TrafficDB are the data transformed from the raw network traffic captured by the network monitor machine. They are evidence of the network behavior on monitored host.

Some data mining approaches can be used on network forensics analysis. Data mining generally refers to the process of extracting models from large stores of data. We choose several algorithms in our research. Classification analysis can map a data item into one of several predefined categories. Link analysis will determine relationship between fields in the database. Finding out the correlations in forensics data will provide insight for discovering

attack behavior, for example, sequence analysis can help us understand the sequence of forensics events.

The survey result includes the intranet mapping topology data, which will be used for the intranet misuse trace back. The intranet mapping data includes IP address, MAC address, user name, geographic room number, email address and so on. Survey results can also include some internet survey data, such as domain name, possible geographic location, IP address, MAC address, phone number, email address, possible OS types and so on.

Presentation gives the statistics of the most possible attacking time, time span, penetrate tools, hacker techniques, IP address, the origin country of the attacker, attacking hops and so on. Some attacking characteristics can be estimated by the system, such as OS system and geographic location.

The forensics report is generated based on the event analysis and event correlation. It contains

- The activities associated with the user.
- The type of attacks launched.
- The location of attacks launched.
- The target of attacks.
- The location of log tampered.
- The asset was accessed.
- The flow of critical data.
- The space and time evolution of events that can be found, linked by consequence and proximity of space and time.

6.3.3 Network Topology Mapping

Another function is to scan the network for mapping topology. Mapping topology of the network may help to find fraudulent proxy server, ARP spoofing and trace back the location of the attack origin. Mapping the topology of the local area network will help to find the origin of the misuse behavior. The scan and survey result includes the topology of the network, the IP address, the MAC address, the possible geographic location of the IP, domain name, phone number, email address, possible OS types. IP trace back and mapping the IP to the geographic location are the most important approaches in the network investigator. The response is real time, so that once the IDS gives the alert, the network forensics server will send the command to the network investigator. Another approach that can be used is remote OS fingerprinting. It can obtain the general OS type of the target host. This is useful to estimate the experience level and the possible attack tools of the investigated object. The result also can serve as a digital evidence for future forensics. We can use nmap tools in the OS fingerprinting scan.

6.3.4 Traceback Root Attackers

When the intruder attempts to steal critical information, it will be caught in real-time. From the failure point, traceback procedure is taken to trace the root attackers. The attack traceback capability is two-fold: first, it can identify the origin of any detected attack, and second, it can detect all Slave Clients controlled by the attacker. When an attack is detected, a report is sent by the detecting SA or SSA to one of the SSAs. This SSA then initiates a traceback process to identify to source of the attack.

6.4 Summary

Logs are is the key to traceback the attacker. Some intruders may try to tamper the log to hide their activities. Thus, the logs of all involved parties are protected using the space-time evolving key. If there is any intrusion detected by the space-time authentication scheme,

or any violations of ACL, the correlation engine is trigger to traceback the attacker. The forensics report is generated based on the event analysis and event correlation. It includes the type of attack, the activities associate with the user, the flow of critical data, etc. The damage is also assessed and a recovery process is followed.

Chapter 7

Performance Evaluation for Proposed Space-Time Evolving Authentication Scheme

7.1 Active Attack Chain

It is necessary to demonstrate how the proposed scheme defends against various attacks. In general, it will be assumed that attacks will either seek to read sensitive information from the Database or overwrite sensitive information on the Database. Based on this assumption, several general attack scenarios can be formed and their likelihood of success measured against the security of the network.

The attacks can be classified into two types based on their approach (See Fig. 7.1). The inside attack launches attack to the critical resources directly inside the organization. The outside attack first compromises some Client Hosts inside the organization. A group of these Client Hosts form a "botnet". When an outside attacker launches their attack, it coordinates some comprised hosts as active attack path. An attacker may choose to use one or more compromised hosts to launch an attack in order to 1) make use of their login credentials, and 2) mask his own identity.

If the outside attack chain is greater than two or the inside attack is greater than one, the compromised host controls a group of hosts. The attack chain starts from the compromised hosts and selects attack path from hosts in its control.

There are three stages in the attack (see Fig. 7.2). First, the attacker scans the vulnerabilities inside an organization. If the security policy is loose, it is easy for attackers to penetrate into the network and compromise some hosts. In our implementation, we use either BufferOverflow or Phishing attack in this stage. Second, The outside attacker targets certain compromised hosts and uses them to send request to DS. In this stage, SQL Injection attack is used. Different SQL injection attack methods are tried to gain access to DS and

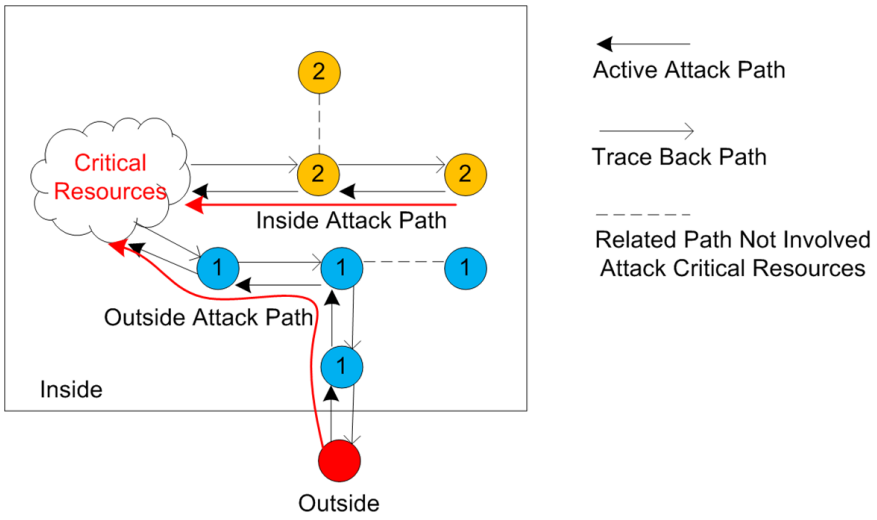


Figure 7.1: Two different approaches of attack

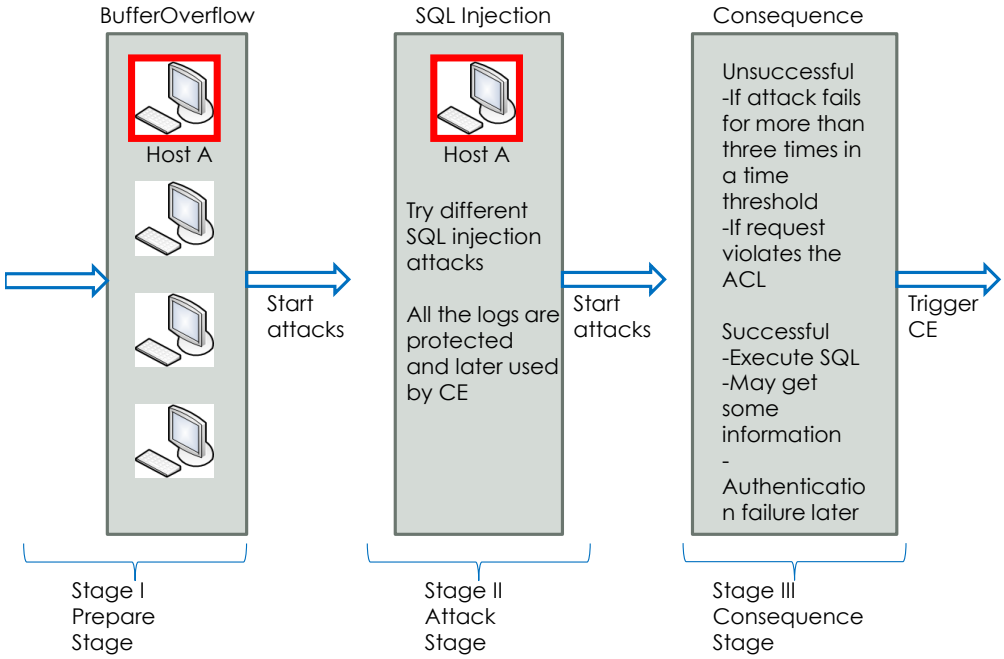


Figure 7.2: Three stages of attack

to retrieve critical information. All activities will be logged and protected. The logs will be used by CE (Correlation Engine) later. Third, there are two types of consequences in this stage, unsuccessful and successful. Unsuccessful attack means either an attack fails for more than three times in a time threshold, or the request violates the ACL. While successful attack means SQL query can be executed and may get some information. However, in the outgoing SA (there are two SAs in front end of critical resources, incoming and outgoing SA), the content and privilege will be checked based on the ACL. If the request cannot prove possession of right credential, the information cannot be retrieved outside the DS. If there is any violation or authentication failure in the above case, the CE is triggered and forensics processing is followed.

7.2 Network Model

We consider a network $NE = (S_D, S_A, H)$, where S_D is the set of security agents which are referred to as defenders, and S_A is the set of attackers. $H = (1, 2, \cdots, N_h)$ is the set of network host which may be attacked by the attackers, referred to as targets, and $A = (1, 2, \cdots, N_a)$ is the set of root attacker which is the source of all attacks.

The object of the attacker is to attack the targets and gain critical resources without being detected. $\mathbf{p} = (p_1, p_2, \cdots, p_{N_h})$ is the attack probability distribution over the target host set H, where p_i is the probability of successfully attacking target i. $\sum_{i \in H} p_i \leq P \leq 1$ represents the attackers' resource constraint.

In order to detect the attacks, SA monitors the target hosts with the probability $\mathbf{q} = (q_1, q_2, \cdots, q_{N_h})$, where q_i is the probability of monitoring target i. Monitor means that the defender security agent collects audit data and examines them for signs of security problems. We have $\sum_{i \in H} q_i \leq Q \leq 1$ that represents the defender's monitor resource constraint.

We setup a hierarchical network topology (see Fig. 7.3), which consists of host, star and group. Each star contains 100 hosts and each group has 10 stars. If we want to simulate

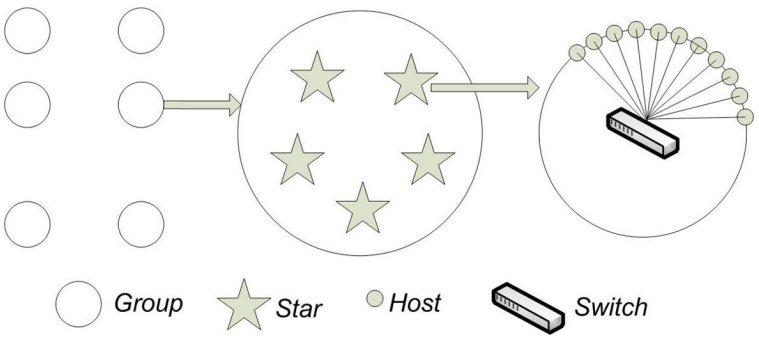


Figure 7.3: Network topology

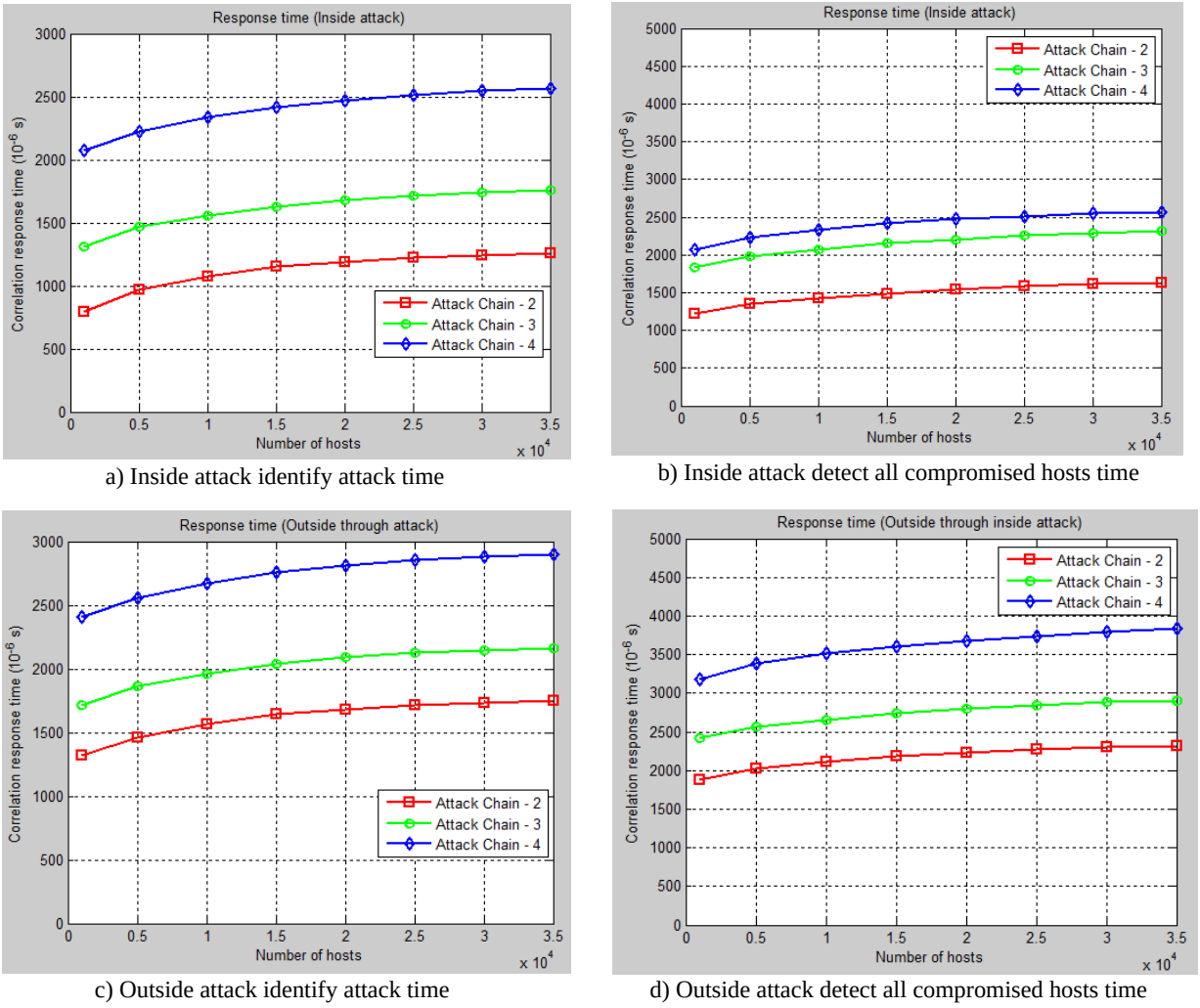
a network of an organization with hosts $[1k, 5k, 10k, 15k, 20k, 25k, 30k, 35k]$, then we have stars of $[10, 50, 100, 150, 200, 250, 300, 350]$ and group of $[1, 5, 10, 15, 20, 25, 30, 35]$.

7.3 Simulation Results

7.3.1 Fixed Attack Ratio

In this simulation scenario, we fix the attack ratio. Assume there are total of N_{host} hosts inside an organization. We set the ratio of hosts that are under attack to be $AttRatio = 0.3$, and ratio of the compromised hosts that are under attack to be $ComRatio = 0.1$.

During all simulations, background traffic was introduced into the network in order to simulate normal operating conditions. It was determined that introducing network traffic on the slower network connections did not affect the simulation results (and made the simulation running time prohibitively long). Therefore, all background traffic was introduced between the SAs and the SSAs. Background traffic equal to 625 kbps/Client was divided equally between SAs and the SSAs and sent from each SA to each SSA. An equal amount of traffic was sent from each SSA to each SA. This rate of background traffic ranged from a one-way 80% load on a 10 Gbps link for a full-sized network (35k Clients) to a much smaller load for smaller networks (0.8% load for a 1000 Client-network). This rate of background traffic affected both log search time during Attack Tracebacks (background traffic increased



a) Inside attack identify attack time

b) Inside attack detect all compromised hosts time

c) Outside attack identify attack time

d) Outside attack detect all compromised hosts time

Figure 7.4: Network topology

the number of log entries) and packet transit time in the Data Center (due to network congestion).

During the simulations, one of the statistics tracked was the Traceback time. Each time an attack was detected, the simulation time was recorded as $T1$ for that attack. When the SSA completed the traceback to identify the attacker, that time was recorded as $T2$. When the SSA completed the log search to identify all Slaves of that Attacker, that time was recorded as $T3$. These three times were used to compile statistics about the traceback speed of the IDACS system (which are shown in the following graphs). The two times of

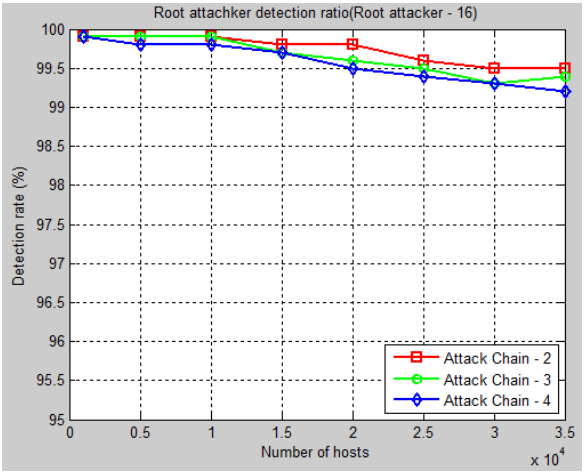
interest are the traceback time ($T2 - T1$) and the All Slaves Identified time ($T3 - T1$). It should be noted that for any given attack, ($T2 - T1$) will always be shorter than ($T3 - T1$), since $(T3 - T1) = (T2 - T1) + (T3 - T2)$.

One of the advantages of our system is its ability to identify the attacker and all the compromised hosts quickly. Fig. 7.4 shows the traceback response time for both inside attack and outside attack specified in the beginning of this chapter. We can see that attack traceback times are very short, with even the (T3 - T1) traceback time under 4 milliseconds. Even as the network size grows, the traceback time grows very slowly relative to the network size. This is because the simulation uses $log_2(n)$ (n is the size of the network) to calculate log search time, since there are currently log search methods that are better than $log_2(n)$. Because the attack traceback is so fast, our system can begin defensive or counterattack procedures before the attacker even realizes that the attack has been detected and blocked.

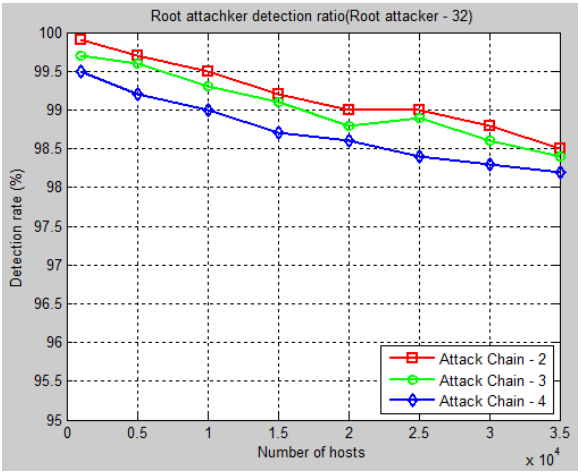
7.3.2 Fixed Root Attacker

In this simulation scenario, we fix the root attackers numbers. The attacks from root attacker consist of two phases. First, the root attacker scans the vulnerabilities of the target network. If there are any security holes, such hosts with vulnerabilities are compromised and under control by root attacker. Second, it coordinates an attack chain (in our simulations, we set the attack chain to be 2, 3 and 4). The attack chain means the path from root attacker to target resources (see Figure 7.1). As the number of root attackers increases, the number of compromised hosts increases exponentially.

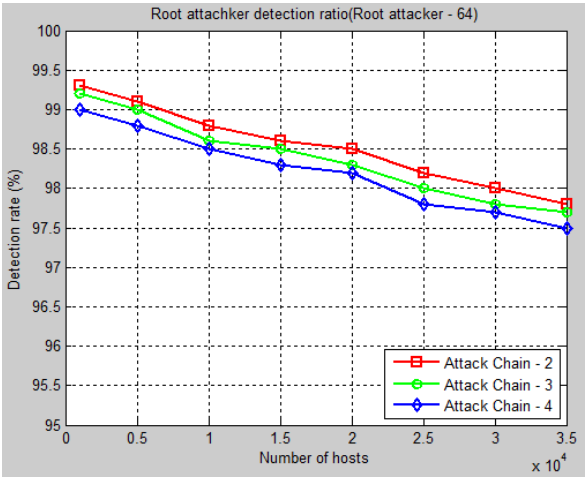
The attacks can be very sophisticated using different kind of attacks, such as SQL injection, buffer overflow, cross-site scripting (XSS), and phishing attacks. Moreover, it adopts different attack path, and sometimes it can even bypass the security check of SA. Fig. 7.5 shows the detection ratio of root attackers. As the root attackers increase, the detection ratio decreases a little bit because the number of compromised hosts increases



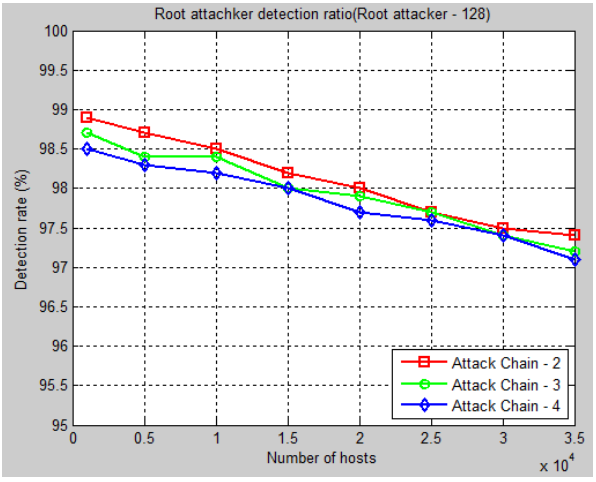
a) Number of root attacker: 16



b) Number of root attacker: 32



c) Number of root attacker: 64



d) Number of root attacker: 128

Figure 7.5: Detection ratio of root attacker

exponentially. Even with 128 root attackers and in a network of 35k hosts, our detection ratio is still above 97%.

If the attack packet did not possess the proper authentication or authorization parameters, any SA or SSA would detect the attack 100% of the time. In reality, however, some attacks would go undetected due to various attack methods (SQL injection, buffer overflow, etc.) Therefore, the security checks performed by the SAs and the SSA were governed by a set of "Fail to Detect Attack" probabilities. For example, if an attack packet failed the authorization check at a given SA, the outcome of this failure would be governed by a "Fail to Detect Attack" probability variable. If the variable was set to 50%, then there would be a 0.5 chance that the SA would still pass the attack packet through as if it had failed to detect the attack. This was done for two reasons. First, as mentioned earlier, this situation more closely reflects reality. Second, this situation can be used to demonstrate the performance of our system even if several barrier machines are compromised. As mentioned in the "Attack Scenarios" section, it is possible for any SA or SSA to be compromised by an attacker and forced to allow attack packets to pass through. Such a situation is reflected by adjusting the "Fail to Detect Attack" variable to 100%. In this simulation, normally functioning SAs and SSAs had these "Fail to Detect Attack" variables set to 0.5. This was done to demonstrate the strength of our system, even under "poor" performance conditions (in reality, this probability is expected to be much lower than 0.5), and also to allow some attacks to succeed in order to see the effect of other variables on network performance.

7.4 Summary

To evaluate the performance of proposed space-time evolving authentication scheme, simulations are carried out in different scenarios. The network increases from 1,000 hosts to 35,000 hosts. As the root attackers increase, the detection ratio decreases a little bit because the number of compromised hosts increases exponentially. Even with 128 root attackers and in a network of 35k hosts, our detection ratio is still above 97%. The simulation results of

correlation response time and detections ratio are both satisfactory. Part of the research is published on IEEE TrustCom 2011 [53].

Chapter 8

Conclusion and Future Work

With the rapid increase of security breaches into corporate networks, it is important to protect critical information against intruders. There are many variations of attacks and new forms of attack are still emerging, such as metamorphic and polymorphic malwares, zero-day attacks, and Boot Record malwares. The current protection schemes against unauthorized intrusions have some weaknesses and cannot protect the network efficiently and thoroughly. To protect the network against intrusion and DoS/DDoS attacks and provide real-time forensics, two security systems are proposed in this dissertation.

The first approach is an intrusion resilient, DDoS-resistant authentication system (IDAS). The IDAS system protects the network via time-dependent secret and self-healing properties of hash chain. We also distribute two-factor user secret using two HMACs and distribute the authentication server into two authentication servers. By using these methods, even strong adversaries can be detected and rejected immediately without influencing the performance of the current network. To demonstrate the performance, we carried out simulations from small scale inside a building to large scale like coast to coast and continent to continent. The simulation results suggest our proposed system is fast and efficient against intrusion and DDoS attacks.

The second approach is built upon the existing security technology and reduces its weakness. The center of the research is to guard critical information/resource against intrusion, and provide real-time forensics. The approach provides the last line of defense against theft of critical information/resource. We accomplish the intrusion detection and prevention using the innovative method

- Use the attempts of stealing the critical information as the entry point.

- Use an innovative ACL (Access Control List)
- Use a space-time evolving authentication scheme, including user, process, parent process, application, behavior, and guarded information/resource.

Moreover, this approach will also provide real-time forensics to help failure points recovery.

- Use a space-time evolving scheme to acquire and guard logs. The keys for log protection are changing from time to time, location to location.
- Violation of ACL (Access Control List) will trigger correlation engine.
- Real-time correlation of possible events to identify attack, attacker, damage (including lost information, servers, hosts and devices). The detailed forensics report will cover attack location, time, type of attack, type of target, etc.

Nevertheless, there are still some limitations and assumptions in the investigation on the proposed security systems, and we wish to further explore the challenges and problems in the near future.

- It is difficult to prove the capabilities of IDAS by actually implementing a full scale botnet due to financial constraints. In this dissertation, only simulation results are reported. In practice, we implement the system using Java in a laboratory setting with several computers. In the future, we may cooperate with big companies from industry to carry out large scale testing in real environments. Part of the research in this dissertation is sponsored by Northrop Grumman Corporation (NGC). In the first stage, the security systems are implemented using six computers, and are tested in large scale via simulation. As the simulation results are encouraging, NGC proposes to test the system in a real environment. There are hundreds of thousands hosts in NGC's Information Security Lab, which makes the test possible in the future.
- Distributing the server and secret enhances the system security and performance. We may distribute the authentication server to a bank of servers in different locations. In

the two-servers case of the proposed IDAS solution, the authentication services could be distributed to different locations, each location has two servers. The nearest in geographic location or the least utilized servers are chosen based on the request. By distributing the authentication servers, the authentication services could be guaranteed even when certain authentication servers are overwhelmed by coordinated large scale attacks. In this case, if the current authentication servers could not respond, the authentication request can be routed to another location.

- As many entities are involved in our system, the synchronization process is challenging. In this disssertation, Network Time Protocol (NTP) is chosen to synchronize the system. However, there are some limitations on this method. We would like to investigate more synchronization methods. Every request has its corresponding sequence number. The protected sequence number could be used to synchronize the service between a client host and an authentication server. Moreover, a beacon could be added in the request packet to indicate the status of the current request. These methods could be investigated in the near future to compare the performance and security with the current scheme.

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