MODULE 4

15.1 REMOTE USER-AUTHENTICATION PRINCIPLES

In most computer security contexts, user authentication is the fundamental building block and the primary line of defense. User authentication is the basis for most types of access control and for user accountability. RFC 4949 (*Internet Security Glossary*) defines user authentication as the process of verifying an identity claimed by or for a system entity. This process consists of two steps:

- **Identification step:** Presenting an identifier to the security system. (Identifiers should be assigned carefully, because authenticated identities are the basis for other security services, such as access control service.)
- **Verification step:** Presenting or generating authentication information that corroborates the binding between the entity and the identifier.

For example, user Alice Toklas could have the user identifier ABTOKLAS. This information needs to be stored on any server or computer system that Alice wishes to use and could be known to system administrators and other users.

A typical item of authentication information associated with this user ID is a password, which is kept secret (known only to Alice and to the system). If no one is able to obtain or guess Alice's password, then the combination of Alice's user ID and password enables administrators to set up Alice's access permissions and audit her activity. Because Alice's ID is not secret, system users can send her email, but because her password is secret, no one can pretend to be Alice.

In essence, identification is the means by which a user provides a claimed identity to the system; user authentication is the means of establishing the validity of the claim. Note that user authentication is distinct from message authentication. As defined in Chapter 12, message authentication is a procedure that allows communicating parties to verify that the contents of a received message have not been altered and that the source is authentic. This chapter is concerned solely with user authentication.

The NIST Model for Electronic User Authentication

NIST SP 800-63-2 (*Electronic Authentication Guideline,* August 2013) defines electronic user authentication as the process of establishing confidence in user identities that are presented electronically to an information system. Systems can use the authenticated identity to determine if the authenticated individual is authorized to perform particular functions, such as database transactions or access to system resources. In many cases, the authentication and transaction or other authorized function takes place across an open network such as the Internet. Equally authentication and subsequent authorization can take place locally, such as across a local area network.

SP 800-63-2 defines a general model for user authentication that involves a number of entities and procedures. We discuss this model with reference to Figure 15.1.

The initial requirement for performing user authentication is that the user must be registered with the system. The following is a typical sequence for registration. An applicant applies to a **registration authority (RA)** to become a **subscriber**

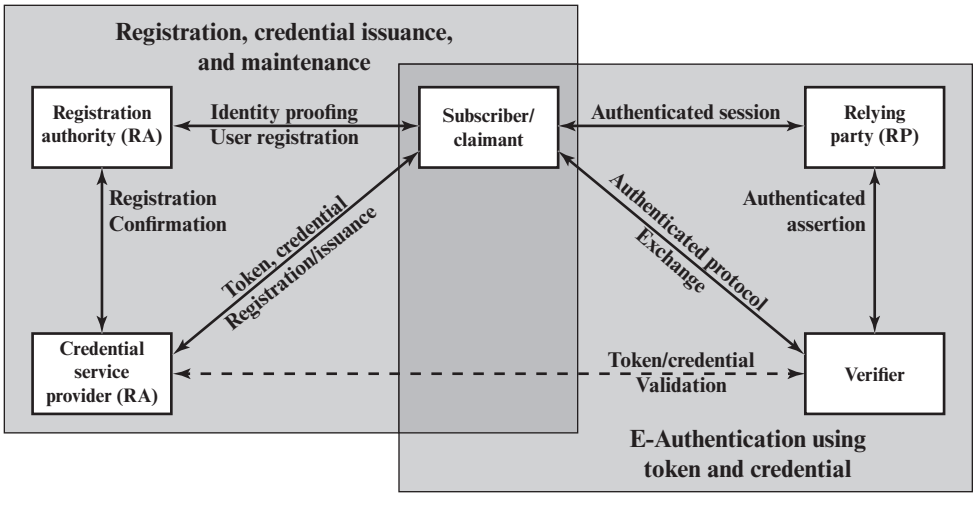

Figure 15.1 The NIST SP 800-63-2 E-Authentication Architectural Model

of a **credential service provider (CSP)**. In this model, the RA is a trusted entity that establishes and vouches for the identity of an applicant to a CSP. The CSP then engages in an exchange with the subscriber. Depending on the details of the overall authentication system, the CSP issues some sort of electronic credential to the subscriber. The **credential** is a data structure that authoritatively binds an identity and additional attributes to a token possessed by a subscriber, and can be verified when presented to the verifier in an authentication transaction. The token could be an encryption key or an encrypted password that identifies the subscriber. The token may be issued by the CSP, generated directly by the subscriber, or provided by a third party. The token and credential may be used in subsequent authentication events.

Once a user is registered as a subscriber, the actual authentication process can take place between the subscriber and one or more systems that perform authentication and, subsequently, authorization. The party to be authenticated is called a **claimant** and the party verifying that identity is called a **verifier**. When a claimant successfully demonstrates possession and control of a token to a verifier through an authentication protocol, the verifier can verify that the claimant is the subscriber named in the corresponding credential. The verifier passes on an assertion about the identity of the subscriber to the **relying party (RP)**. That assertion includes identity information about a subscriber, such as the subscriber name, an identifier assigned at registration, or other subscriber attributes that were verified in the registration process. The RP can use the authenticated information provided by the verifier to make access control or authorization decisions.

An implemented system for authentication will differ from or be more complex than this simplified model, but the model illustrates the key roles and functions needed for a secure authentication system.

Means of Authentication

There are four general means of authenticating a user's identity, which can be used alone or in combination:

- **Something the individual knows:** Examples include a password, a personal identification number (PIN), or answers to a prearranged set of questions.
- **Something the individual possesses:** Examples include cryptographic keys, electronic keycards, smart cards, and physical keys. This type of authenticator is referred to as a *token*.
- **Something the individual is (static biometrics):** Examples include recognition by fingerprint, retina, and face.
- **Something the individual does (dynamic biometrics):** Examples include recognition by voice pattern, handwriting characteristics, and typing rhythm.

All of these methods, properly implemented and used, can provide secure user authentication. However, each method has problems. An adversary may be able to guess or steal a password. Similarly, an adversary may be able to forge or steal a token. A user may forget a password or lose a token. Furthermore, there is a significant administrative overhead for managing password and token information on systems and securing such information on systems. With respect to biometric

authenticators, there are a variety of problems, including dealing with false positives and false negatives, user acceptance, cost, and convenience. For network-based user authentication, the most important methods involve cryptographic keys and something the individual knows, such as a password.

Mutual Authentication

An important application area is that of mutual authentication protocols. Such protocols enable communicating parties to satisfy themselves mutually about each other's identity and to exchange session keys. This topic was examined in Chapter 14. There, the focus was key distribution. We return to this topic here to consider the wider implications of authentication.

Central to the problem of authenticated key exchange are two issues: confidentiality and timeliness. To prevent masquerade and to prevent compromise of session keys, essential identification and session-key information must be communicated in encrypted form. This requires the prior existence of secret or public keys that can be used for this purpose. The second issue, timeliness, is important because of the threat of message replays. Such replays, at worst, could allow an opponent to compromise a session key or successfully impersonate another party. At minimum, a successful replay can disrupt operations by presenting parties with messages that appear genuine but are not.

[GONG93] lists the following examples of **replay attacks**:

1. The simplest replay attack is one in which the opponent simply copies a message and replays it later.
2. An opponent can replay a timestamped message within the valid time window. If both the original and the replay arrive within then time window, this incident can be logged.
3. As with example (2), an opponent can replay a timestamped message within the valid time window, but in addition, the opponent suppresses the original message. Thus, the repetition cannot be detected.
4. Another attack involves a backward replay without modification. This is a replay back to the message sender. This attack is possible if symmetric encryption is used and the sender cannot easily recognize the difference between messages sent and messages received on the basis of content.

One approach to coping with replay attacks is to attach a sequence number to each message used in an authentication exchange. A new message is accepted only if its sequence number is in the proper order. The difficulty with this approach is that it requires each party to keep track of the last sequence number for each claimant it has dealt with. Because of this overhead, sequence numbers are generally not used for authentication and key exchange. Instead, one of the following two general approaches is used:

- **Timestamps:** Party A accepts a message as fresh only if the message contains a **timestamp** that, in A's judgment, is close enough to A's knowledge of current time. This approach requires that clocks among the various participants be synchronized.

- **Challenge/response:** Party A, expecting a fresh message from B, first sends B a **nonce** (challenge) and requires that the subsequent message (response) received from B contain the correct nonce value.

It can be argued (e.g., [LAM92a]) that the timestamp approach should not be used for connection-oriented applications because of the inherent difficulties with this technique. First, some sort of protocol is needed to maintain synchronization among the various processor clocks. This protocol must be both fault tolerant, to cope with network errors, and secure, to cope with hostile attacks. Second, the opportunity for a successful attack will arise if there is a temporary loss of synchronization resulting from a fault in the clock mechanism of one of the parties. Finally, because of the variable and unpredictable nature of network delays, distributed clocks cannot be expected to maintain precise synchronization. Therefore, any timestamp-based procedure must allow for a window of time sufficiently large to accommodate network delays yet sufficiently small to minimize the opportunity for attack.

On the other hand, the challenge-response approach is unsuitable for a connectionless type of application, because it requires the overhead of a handshake before any connectionless transmission, effectively negating the chief characteristic of a connectionless transaction. For such applications, reliance on some sort of secure time server and a consistent attempt by each party to keep its clocks in synchronization may be the best approach (e.g., [LAM92b]).

One-Way Authentication

One application for which encryption is growing in popularity is electronic mail (email). The very nature of electronic mail, and its chief benefit, is that it is not necessary for the sender and receiver to be online at the same time. Instead, the email message is forwarded to the receiver's electronic mailbox, where it is buffered until the receiver is available to read it.

The "envelope" or header of the email message must be in the clear, so that the message can be handled by the store-and-forward email protocol, such as the Simple Mail Transfer Protocol (SMTP) or X.400. However, it is often desirable that the mail-handling protocol not require access to the plaintext form of the message, because that would require trusting the mail-handling mechanism. Accordingly, the email message should be encrypted such that the mail-handling system is not in possession of the decryption key.

A second requirement is that of **authentication**. Typically, the recipient wants some assurance that the message is from the alleged sender.

15.3 KERBEROS

Kerberos[4] is an authentication service developed as part of Project Athena at MIT. The problem that Kerberos addresses is this: Assume an open distributed environment in which users at workstations wish to access services on servers distributed throughout the network. We would like for servers to be able to restrict access to authorized users and to be able to authenticate requests for service. In this environment, a workstation cannot be trusted to identify its users correctly to network services. In particular, the following three threats exist:

1. A user may gain access to a particular workstation and pretend to be another user operating from that workstation.
2. A user may alter the network address of a workstation so that the requests sent from the altered workstation appear to come from the impersonated workstation.
3. A user may eavesdrop on exchanges and use a replay attack to gain entrance to a server or to disrupt operations.

In any of these cases, an unauthorized user may be able to gain access to services and data that he or she is not authorized to access. Rather than building in elaborate

[4]"In Greek mythology, a many headed dog, commonly three, perhaps with a serpent's tail, the guardian of the entrance of Hades." From *Dictionary of Subjects and Symbols in Art*, by James Hall, Harper & Row, 1979. Just as the Greek Kerberos has three heads, the modern Kerberos was intended to have three components to guard a network's gate: authentication, accounting, and audit. The last two heads were never implemented.

authentication protocols at each server, Kerberos provides a centralized authentication server whose function is to authenticate users to servers and servers to users. Unlike most other authentication schemes described in this book, Kerberos relies exclusively on symmetric encryption, making no use of public-key encryption.

Two versions of Kerberos are in common use. Version 4 [MILL88, STEI88] implementations still exist. Version 5 [KOHL94] corrects some of the security deficiencies of version 4 and has been issued as a proposed Internet Standard (RFC 4120 and RFC 4121).[5]

We begin this section with a brief discussion of the motivation for the Kerberos approach. Then, because of the complexity of Kerberos, it is best to start with a description of the authentication protocol used in version 4. This enables us to see the essence of the Kerberos strategy without considering some of the details required to handle subtle security threats. Finally, we examine version 5.

Motivation

If a set of users is provided with dedicated personal computers that have no network connections, then a user's resources and files can be protected by physically securing each personal computer. When these users instead are served by a centralized time-sharing system, the time-sharing operating system must provide the security. The operating system can enforce access-control policies based on user identity and use the logon procedure to identify users.

Today, neither of these scenarios is typical. More common is a distributed architecture consisting of dedicated user workstations (clients) and distributed or centralized servers. In this environment, three approaches to security can be envisioned.

1. Rely on each individual client workstation to assure the identity of its user or users and rely on each server to enforce a security policy based on user identification (ID).
2. Require that client systems authenticate themselves to servers, but trust the client system concerning the identity of its user.
3. Require the user to prove his or her identity for each service invoked. Also require that servers prove their identity to clients.

In a small, closed environment in which all systems are owned and operated by a single organization, the first or perhaps the second strategy may suffice.[6] But in a more open environment in which network connections to other machines are supported, the third approach is needed to protect user information and resources housed at the server. Kerberos supports this third approach. Kerberos assumes a distributed client/server architecture and employs one or more Kerberos servers to provide an authentication service.

[5]Versions 1 through 3 were internal development versions. Version 4 is the "original" Kerberos.
[6]However, even a closed environment faces the threat of attack by a disgruntled employee.

The first published report on Kerberos [STEI88] listed the following requirements.

- **Secure:** A network eavesdropper should not be able to obtain the necessary information to impersonate a user. More generally, Kerberos should be strong enough that a potential opponent does not find it to be the weak link.
- **Reliable:** For all services that rely on Kerberos for access control, lack of availability of the Kerberos service means lack of availability of the supported services. Hence, Kerberos should be highly reliable and should employ a distributed server architecture with one system able to back up another.
- **Transparent:** Ideally, the user should not be aware that authentication is taking place beyond the requirement to enter a password.
- **Scalable:** The system should be capable of supporting large numbers of clients and servers. This suggests a modular, distributed architecture.

To support these requirements, the overall scheme of Kerberos is that of a trusted third-party authentication service that uses a protocol based on that proposed by Needham and Schroeder [NEED78], which was discussed in Section 15.2. It is trusted in the sense that clients and servers trust Kerberos to mediate their mutual authentication. Assuming the Kerberos protocol is well designed, then the authentication service is secure if the Kerberos server itself is secure.[7]

Kerberos Version 4

Version 4 of Kerberos makes use of DES, in a rather elaborate protocol, to provide the authentication service. Viewing the protocol as a whole, it is difficult to see the need for the many elements contained therein. Therefore, we adopt a strategy used by Bill Bryant of Project Athena [BRYA88] and build up to the full protocol by looking first at several hypothetical dialogues. Each successive dialogue adds additional complexity to counter security vulnerabilities revealed in the preceding dialogue.

After examining the protocol, we look at some other aspects of version 4.

A Simple Authentication Dialogue In an unprotected network environment, any client can apply to any server for service. The obvious security risk is that of impersonation. An opponent can pretend to be another client and obtain unauthorized privileges on server machines. To counter this threat, servers must be able to confirm the identities of clients who request service. Each server can be required to undertake this task for each client/server interaction, but in an open environment, this places a substantial burden on each server.

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[7]Remember that the security of the Kerberos server should not automatically be assumed but must be guarded carefully (e.g., in a locked room). It is well to remember the fate of the Greek Kerberos, whom Hercules was ordered by Eurystheus to capture as his Twelfth Labor: "Hercules found the great dog on its chain and seized it by the throat. At once the three heads tried to attack, and Kerberos lashed about with his powerful tail. Hercules hung on grimly, and Kerberos relaxed into unconsciousness. Eurystheus may have been surprised to see Hercules alive—when he saw the three slavering heads and the huge dog they belonged to he was frightened out of his wits, and leapt back into the safety of his great bronze jar." From *The Hamlyn Concise Dictionary of Greek and Roman Mythology*, by Michael Stapleton, Hamlyn, 1982.

An alternative is to use an authentication server (AS) that knows the passwords of all users and stores these in a centralized database. In addition, the AS shares a unique secret key with each server. These keys have been distributed physically or in some other secure manner. Consider the following hypothetical dialogue:

$$\begin{aligned}
&\textbf{(1)}\ \mathrm{C} \rightarrow \mathrm{AS}: && ID_C \| P_C \| ID_V \\
&\textbf{(2)}\ \mathrm{AS} \rightarrow \mathrm{C}: && Ticket \\
&\textbf{(3)}\ \mathrm{C} \rightarrow \mathrm{V}: && ID_C \| Ticket \\
&Ticket = E(K_v, [ID_C \| AD_C \| ID_V])
\end{aligned}$$

where

$$\begin{aligned}
\mathrm{C} &= \text{client} \\
\mathrm{AS} &= \text{authentication server} \\
\mathrm{V} &= \text{server} \\
ID_C &= \text{identifier of user on C} \\
ID_V &= \text{identifier of V} \\
P_C &= \text{password of user on C} \\
AD_C &= \text{network address of C} \\
K_v &= \text{secret encryption key shared by AS and V}
\end{aligned}$$

In this scenario, the user logs on to a workstation and requests access to server V. The client module C in the user's workstation requests the user's password and then sends a message to the AS that includes the user's ID, the server's ID, and the user's password. The AS checks its database to see if the user has supplied the proper password for this user ID and whether this user is permitted access to server V. If both tests are passed, the AS accepts the user as authentic and must now convince the server that this user is authentic. To do so, the AS creates a **ticket** that contains the user's ID and network address and the server's ID. This ticket is encrypted using the secret key shared by the AS and this server. This ticket is then sent back to C. Because the ticket is encrypted, it cannot be altered by C or by an opponent.

With this ticket, C can now apply to V for service. C sends a message to V containing C's ID and the ticket. V decrypts the ticket and verifies that the user ID in the ticket is the same as the unencrypted user ID in the message. If these two match, the server considers the user authenticated and grants the requested service.

Each of the ingredients of message (3) is significant. The ticket is encrypted to prevent alteration or forgery. The server's ID (ID_V) is included in the ticket so that the server can verify that it has decrypted the ticket properly. ID_C is included in the ticket to indicate that this ticket has been issued on behalf of C. Finally, AD_C serves to counter the following threat. An opponent could capture the ticket transmitted in message (2), then use the name ID_C and transmit a message of form (3) from another workstation. The server would receive a valid ticket that matches the user ID and grant access to the user on that other workstation. To prevent this attack, the AS includes in the ticket the network address from which the original request came. Now the ticket is valid only if it is transmitted from the same workstation that initially requested the ticket.

A More Secure Authentication Dialogue Although the foregoing scenario solves some of the problems of authentication in an open network environment, problems remain. Two in particular stand out. First, we would like to minimize the number of times that a user has to enter a password. Suppose each ticket can be used only once. If user C logs on to a workstation in the morning and wishes to check his or her mail at a mail server, C must supply a password to get a ticket for the mail server. If C wishes to check the mail several times during the day, each attempt requires reentering the password. We can improve matters by saying that tickets are reusable. For a single logon session, the workstation can store the mail server ticket after it is received and use it on behalf of the user for multiple accesses to the mail server.

However, under this scheme, it remains the case that a user would need a new ticket for every different service. If a user wished to access a print server, a mail server, a file server, and so on, the first instance of each access would require a new ticket and hence require the user to enter the password.

The second problem is that the earlier scenario involved a plaintext transmission of the password [message (1)]. An eavesdropper could capture the password and use any service accessible to the victim.

To solve these additional problems, we introduce a scheme for avoiding plaintext passwords and a new server, known as the **ticket-granting server (TGS)**. The new (but still hypothetical) scenario is as follows.

Once per user logon session:

(1) C → AS: $ID_C \| ID_{tgs}$

(2) AS → C: $\mathrm{E}(K_c, Ticket_{tgs})$

Once per type of service:

(3) C → TGS: $ID_C \| ID_V \| Ticket_{tgs}$

(4) TGS → C: $Ticket_v$

Once per service session:

(5) C → V: $ID_C \| Ticket_v$

$$Ticket_{tgs} = \mathrm{E}(K_{tgs}, [ID_C \| AD_C \| ID_{tgs} \| TS_1 \| Lifetime_1])$$

$$Ticket_v = \mathrm{E}(K_v, [ID_C \| AD_C \| ID_v \| TS_2 \| Lifetime_2])$$

The new service, TGS, issues tickets to users who have been authenticated to AS. Thus, the user first requests a ticket-granting ticket ($Ticket_{tgs}$) from the AS. The client module in the user workstation saves this ticket. Each time the user requires access to a new service, the client applies to the TGS, using the ticket to authenticate itself. The TGS then grants a ticket for the particular service. The client saves each service-granting ticket and uses it to authenticate its user to a server each time a particular service is requested. Let us look at the details of this scheme:

1. The client requests a ticket-granting ticket on behalf of the user by sending its user's ID to the AS, together with the TGS ID, indicating a request to use the TGS service.

2. The AS responds with a ticket that is encrypted with a key that is derived from the user's password (K_c), which is already stored at the AS. When this response arrives at the client, the client prompts the user for his or her password, generates the key, and attempts to decrypt the incoming message. If the correct password is supplied, the ticket is successfully recovered.

Because only the correct user should know the password, only the correct user can recover the ticket. Thus, we have used the password to obtain credentials from Kerberos without having to transmit the password in plaintext. The ticket itself consists of the ID and network address of the user, and the ID of the TGS. This corresponds to the first scenario. The idea is that the client can use this ticket to request multiple service-granting tickets. So the ticket-granting ticket is to be reusable. However, we do not wish an opponent to be able to capture the ticket and use it. Consider the following scenario: An opponent captures the login ticket and waits until the user has logged off his or her workstation. Then the opponent either gains access to that workstation or configures his workstation with the same network address as that of the victim. The opponent would be able to reuse the ticket to spoof the TGS. To counter this, the ticket includes a timestamp, indicating the date and time at which the ticket was issued, and a lifetime, indicating the length of time for which the ticket is valid (e.g., eight hours). Thus, the client now has a reusable ticket and need not bother the user for a password for each new service request. Finally, note that the ticket-granting ticket is encrypted with a secret key known only to the AS and the TGS. This prevents alteration of the ticket. The ticket is reencrypted with a key based on the user's password. This assures that the ticket can be recovered only by the correct user, providing the authentication.

Now that the client has a ticket-granting ticket, access to any server can be obtained with steps 3 and 4.

3. The client requests a service-granting ticket on behalf of the user. For this purpose, the client transmits a message to the TGS containing the user's ID, the ID of the desired service, and the ticket-granting ticket.
4. The TGS decrypts the incoming ticket using a key shared only by the AS and the TGS (K_{tgs}) and verifies the success of the decryption by the presence of its ID. It checks to make sure that the lifetime has not expired. Then it compares the user ID and network address with the incoming information to authenticate the user. If the user is permitted access to the server V, the TGS issues a ticket to grant access to the requested service.

The service-granting ticket has the same structure as the ticket-granting ticket. Indeed, because the TGS is a server, we would expect that the same elements are needed to authenticate a client to the TGS and to authenticate a client to an application server. Again, the ticket contains a timestamp and lifetime. If the user wants access to the same service at a later time, the client can simply use the previously acquired service-granting ticket and need not bother the user for a password. Note that the ticket is encrypted with a secret key (K_v) known only to the TGS and the server, preventing alteration.

Finally, with a particular service-granting ticket, the client can gain access to the corresponding service with step 5.

5. The client requests access to a service on behalf of the user. For this purpose, the client transmits a message to the server containing the user's ID and the service-granting ticket. The server authenticates by using the contents of the ticket.

This new scenario satisfies the two requirements of only one password query per user session and protection of the user password.

The Version 4 Authentication Dialogue Although the foregoing scenario enhances security compared to the first attempt, two additional problems remain. The heart of the first problem is the lifetime associated with the ticket-granting ticket. If this lifetime is very short (e.g., minutes), then the user will be repeatedly asked for a password. If the lifetime is long (e.g., hours), then an opponent has a greater opportunity for replay. An opponent could eavesdrop on the network and capture a copy of the ticket-granting ticket and then wait for the legitimate user to log out. Then the opponent could forge the legitimate user's network address and send the message of step (3) to the TGS. This would give the opponent unlimited access to the resources and files available to the legitimate user.

Similarly, if an opponent captures a service-granting ticket and uses it before it expires, the opponent has access to the corresponding service.

Thus, we arrive at an additional requirement. A network service (the TGS or an application service) must be able to prove that the person using a ticket is the same person to whom that ticket was issued.

The second problem is that there may be a requirement for servers to authenticate themselves to users. Without such authentication, an opponent could sabotage the configuration so that messages to a server were directed to another location. The false server would then be in a position to act as a real server and capture any information from the user and deny the true service to the user.

We examine these problems in turn and refer to Table 15.1, which shows the actual Kerberos protocol. Figure 15.2 provides a simplified overview.

Table 15.1 Summary of Kerberos Version 4 Message Exchanges

(1)	$\mathbf{C} \rightarrow \mathbf{AS}$	$ID_c \| ID_{tgs} \| TS_1$
(2)	$\mathbf{AS} \rightarrow \mathbf{C}$	$\mathrm{E}(K_c, [K_{c,tgs} \| ID_{tgs} \| TS_2 \| Lifetime_2 \| Ticket_{tgs}])$
		$Ticket_{tgs} = \mathrm{E}(\mathrm{K}_{tgs}, [\mathrm{K}_{c,tgs} \| \mathrm{ID}_C \| \mathrm{AD}_C \| \mathrm{ID}_{tgs} \| \mathrm{TS}_2 \| \mathrm{Lifetime}_2])$

(a) Authentication Service Exchange to obtain ticket-granting ticket

(3)	$\mathbf{C} \rightarrow \mathbf{TGS}$	$ID_v \| Ticket_{tgs} \| Authenticator_c$
(4)	$\mathbf{TGS} \rightarrow \mathbf{C}$	$\mathrm{E}(K_{c,tgs}, [K_{c,v} \| ID_v \| TS_4 \| Ticket_v])$
		$Ticket_{tgs} = \mathrm{E}(\mathrm{K}_{tgs}, [\mathrm{K}_{c,tgs} \| \mathrm{ID}_C \| \mathrm{AD}_C \| \mathrm{ID}_{tgs} \| \mathrm{TS}_2 \| \mathrm{Lifetime}_2])$
		$Ticket_v = \mathrm{E}(\mathrm{K}_v, [\mathrm{K}_{c,v} \| \mathrm{ID}_C \| \mathrm{AD}_C \| \mathrm{ID}_v \| \mathrm{TS}_4 \| \mathrm{Lifetime}_4])$
		$Authenticator_c = \mathrm{E}(\mathrm{K}_{c,tgs}, [\mathrm{ID}_C \| \mathrm{AD}_C \| \mathrm{TS}_3])$

(b) Ticket-Granting Service Exchange to obtain service-granting ticket

(5)	$\mathbf{C} \rightarrow \mathbf{V}$	$Ticket_v \| Authenticator_c$
(6)	$\mathbf{V} \rightarrow \mathbf{C}$	$\mathrm{E}(K_{c,v}, [TS_5 + 1])$ (for mutual authentication)
		$Ticket_v = \mathrm{E}(\mathrm{K}_v, [\mathrm{K}_{c,v} \| \mathrm{ID}_C \| \mathrm{AD}_C \| \mathrm{ID}_v \| \mathrm{TS}_4 \| \mathrm{Lifetime}_4])$
		$Authenticator_c = \mathrm{E}(\mathrm{K}_{c,v}, [\mathrm{ID}_C \| \mathrm{AD}_C \| \mathrm{TS}_5])$

(c) Client/Server Authentication Exchange to obtain service

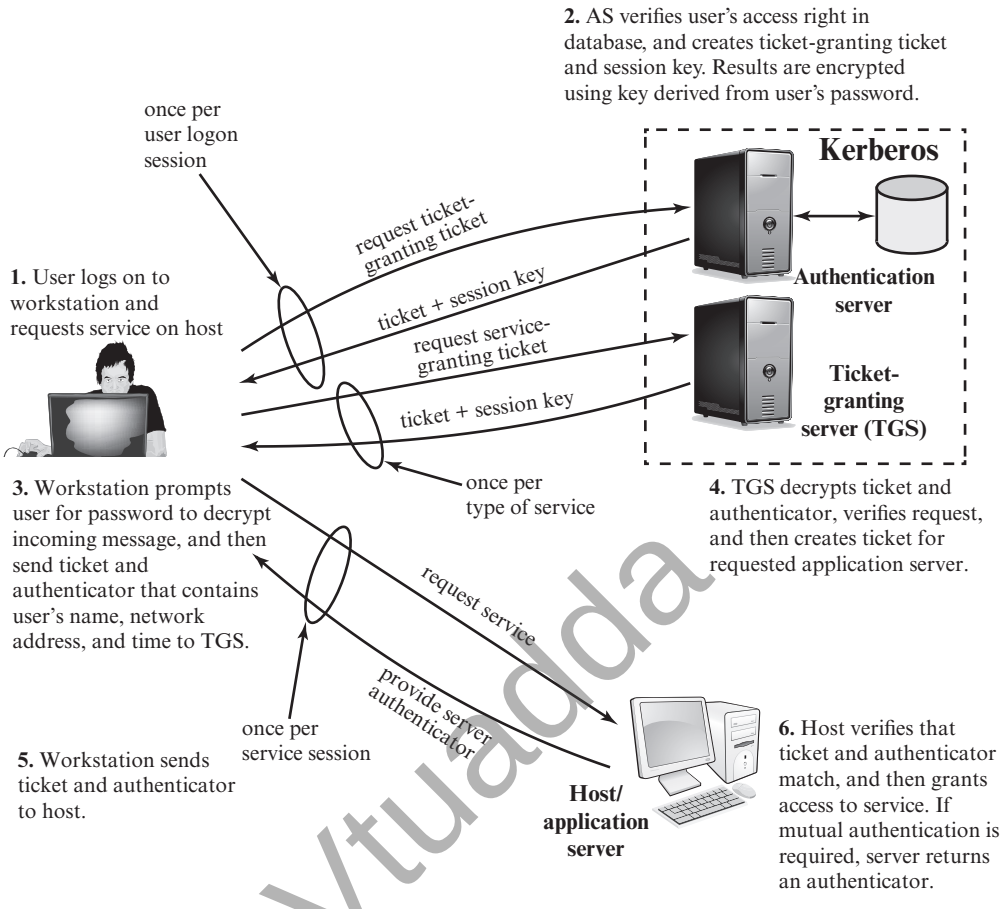


Figure 15.2 Overview of Kerberos

First, consider the problem of captured ticket-granting tickets and the need to determine that the ticket presenter is the same as the client for whom the ticket was issued. The threat is that an opponent will steal the ticket and use it before it expires. To get around this problem, let us have the AS provide both the client and the TGS with a secret piece of information in a secure manner. Then the client can prove its identity to the TGS by revealing the secret information—again in a secure manner. An efficient way of accomplishing this is to use an encryption key as the secure information; this is referred to as a session key in Kerberos.

Table 15.1a shows the technique for distributing the session key. As before, the client sends a message to the AS requesting access to the TGS. The AS responds with a message, encrypted with a key derived from the user's password (K_c), that contains the ticket. The encrypted message also contains a copy of the session key, $K_{c,tgs}$, where the subscripts indicate that this is a session key for C and TGS. Because this session key is inside the message encrypted with K_c, only the user's client can read it. The same session key is included in the ticket, which can be read only by the TGS. Thus, the session key has been securely delivered to both C and the TGS.

Note that several additional pieces of information have been added to this first phase of the dialogue. Message (1) includes a timestamp, so that the AS knows that the message is timely. Message (2) includes several elements of the ticket in a form accessible to C. This enables C to confirm that this ticket is for the TGS and to learn its expiration time.

Armed with the ticket and the session key, C is ready to approach the TGS. As before, C sends the TGS a message that includes the ticket plus the ID of the requested service [message (3) in Table 15.1b]. In addition, C transmits an authenticator, which includes the ID and address of C's user and a timestamp. Unlike the ticket, which is reusable, the authenticator is intended for use only once and has a very short lifetime. The TGS can decrypt the ticket with the key that it shares with the AS. This ticket indicates that user C has been provided with the session key $K_{c,tgs}$. In effect, the ticket says, "Anyone who uses $K_{c,tgs}$ must be C." The TGS uses the session key to decrypt the authenticator. The TGS can then check the name and address from the authenticator with that of the ticket and with the network address of the incoming message. If all match, then the TGS is assured that the sender of the ticket is indeed the ticket's real owner. In effect, the authenticator says, "At time TS_3, I hereby use $K_{c,tgs}$." Note that the ticket does not prove anyone's identity but is a way to distribute keys securely. It is the authenticator that proves the client's identity. Because the authenticator can be used only once and has a short lifetime, the threat of an opponent stealing both the ticket and the authenticator for presentation later is countered.

The reply from the TGS in message (4) follows the form of message (2). The message is encrypted with the session key shared by the TGS and C and includes a session key to be shared between C and the server V, the ID of V, and the timestamp of the ticket. The ticket itself includes the same session key.

C now has a reusable service-granting ticket for V. When C presents this ticket, as shown in message (5), it also sends an authenticator. The server can decrypt the ticket, recover the session key, and decrypt the authenticator.

If mutual authentication is required, the server can reply as shown in message (6) of Table 15.1. The server returns the value of the timestamp from the authenticator, incremented by 1, and encrypted in the session key. C can decrypt this message to recover the incremented timestamp. Because the message was encrypted by the session key, C is assured that it could have been created only by V. The contents of the message assure C that this is not a replay of an old reply.

Finally, at the conclusion of this process, the client and server share a secret key. This key can be used to encrypt future messages between the two or to exchange a new random session key for that purpose.

Figure 15.3 illustrates the Kerberos exchanges among the parties. Table 15.2 summarizes the justification for each of the elements in the Kerberos protocol.

Kerberos Realms and Multiple Kerberi A full-service Kerberos environment consisting of a Kerberos server, a number of clients, and a number of application servers requires the following:

1. The Kerberos server must have the user ID and hashed passwords of all participating users in its database. All users are registered with the Kerberos server.
2. The Kerberos server must share a secret key with each server. All servers are registered with the Kerberos server.

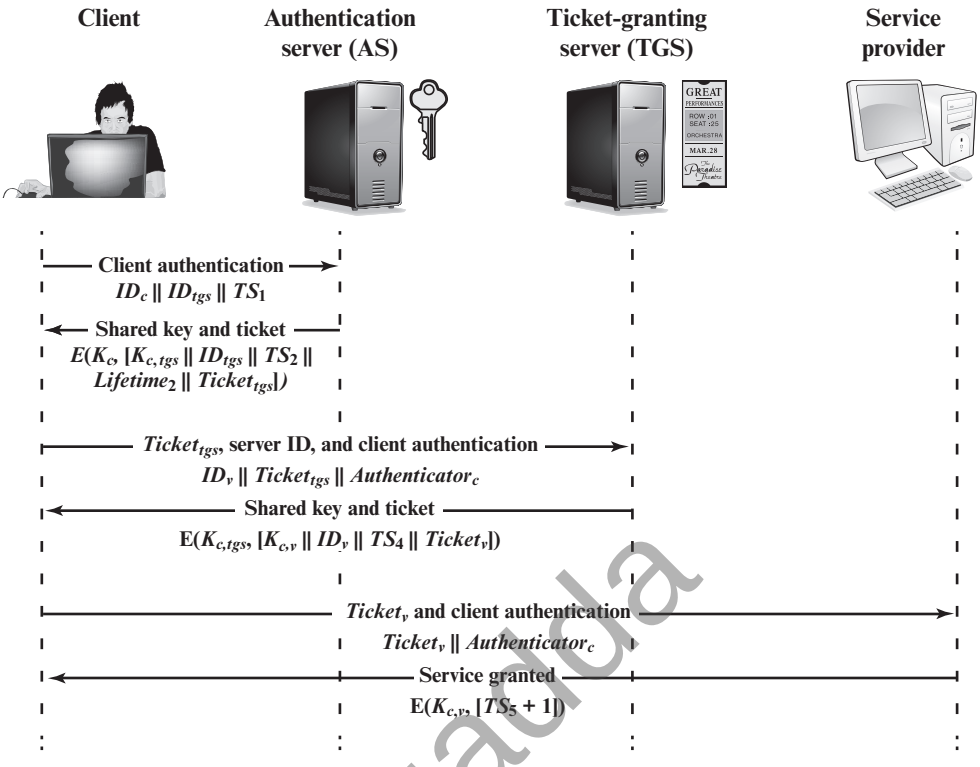


Figure 15.3 Kerberos Exchanges

Table 15.2 Rationale for the Elements of the Kerberos Version 4 Protocol

Message (1)	Client requests ticket-granting ticket.
ID_C	Tells AS identity of user from this client.
ID_{tgs}	Tells AS that user requests access to TGS.
TS_1	Allows AS to verify that client's clock is synchronized with that of AS.
Message (2)	AS returns ticket-granting ticket.
K_c	Encryption is based on user's password, enabling AS and client to verify password, and protecting contents of message (2).
$K_{c,\,tgs}$	Copy of session key accessible to client created by AS to permit secure exchange between client and TGS without requiring them to share a permanent key.
ID_{tgs}	Confirms that this ticket is for the TGS.
TS_2	Informs client of time this ticket was issued.
$Lifetime_2$	Informs client of the lifetime of this ticket.
$Ticket_{tgs}$	Ticket to be used by client to access TGS.

(a) Authentication Service Exchange

Message (3)	Client requests service-granting ticket.
ID_V	Tells TGS that user requests access to server V.
$Ticket_{tgs}$	Assures TGS that this user has been authenticated by AS.
$Authenticator_c$	Generated by client to validate ticket.

(*Continued*)

Table 15.2 Continued

Message (4)	TGS returns service-granting ticket.
$K_{c,\,tgs}$	Key shared only by C and TGS protects contents of message (4).
$K_{c,\,v}$	Copy of session key accessible to client created by TGS to permit secure exchange between client and server without requiring them to share a permanent key.
ID_V	Confirms that this ticket is for server V.
TS_4	Informs client of time this ticket was issued.
$Ticket_V$	Ticket to be used by client to access server V.
$Ticket_{tgs}$	Reusable so that user does not have to reenter password.
K_{tgs}	Ticket is encrypted with key known only to AS and TGS, to prevent tampering.
$K_{c,\,tgs}$	Copy of session key accessible to TGS used to decrypt authenticator, thereby authenticating ticket.
ID_C	Indicates the rightful owner of this ticket.
AD_C	Prevents use of ticket from workstation other than one that initially requested the ticket.
ID_{tgs}	Assures server that it has decrypted ticket properly.
TS_2	Informs TGS of time this ticket was issued.
$Lifetime_2$	Prevents replay after ticket has expired.
$Authenticator_c$	Assures TGS that the ticket presenter is the same as the client for whom the ticket was issued has very short lifetime to prevent replay.
$K_{c,\,tgs}$	Authenticator is encrypted with key known only to client and TGS, to prevent tampering.
ID_C	Must match ID in ticket to authenticate ticket.
AD_C	Must match address in ticket to authenticate ticket.
TS_3	Informs TGS of time this authenticator was generated.

(b) Ticket-Granting Service Exchange

Message (5)	Client requests service.
$Ticket_V$	Assures server that this user has been authenticated by AS.
$Authenticator_c$	Generated by client to validate ticket.
Message (6)	Optional authentication of server to client.
$K_{c,\,v}$	Assures C that this message is from V.
$TS_5 + 1$	Assures C that this is not a replay of an old reply.
$Ticket_v$	Reusable so that client does not need to request a new ticket from TGS for each access to the same server.
K_v	Ticket is encrypted with key known only to TGS and server, to prevent tampering.
$K_{c,\,v}$	Copy of session key accessible to client; used to decrypt authenticator, thereby authenticating ticket.
ID_C	Indicates the rightful owner of this ticket.
AD_C	Prevents use of ticket from workstation other than one that initially requested the ticket.
ID_V	Assures server that it has decrypted ticket properly.
TS_4	Informs server of time this ticket was issued.
$Lifetime_4$	Prevents replay after ticket has expired.
$Authenticator_c$	Assures server that the ticket presenter is the same as the client for whom the ticket was issued; has very short lifetime to prevent replay.
$K_{c,\,v}$	Authenticator is encrypted with key known only to client and server, to prevent tampering.
ID_C	Must match ID in ticket to authenticate ticket.
AD_C	Must match address in ticket to authenticate ticket.
TS_5	Informs server of time this authenticator was generated.

(c) Client/Server Authentication Exchange

Such an environment is referred to as a **Kerberos realm**. The concept of **realm** can be explained as follows. A Kerberos realm is a set of managed nodes that share the same Kerberos database. The Kerberos database resides on the Kerberos master computer system, which should be kept in a physically secure room. A read-only copy of the Kerberos database might also reside on other Kerberos computer systems. However, all changes to the database must be made on the master computer system. Changing or accessing the contents of a Kerberos database requires the Kerberos master password. A related concept is that of a **Kerberos principal**, which is a service or user that is known to the Kerberos system. Each Kerberos principal is identified by its principal name. Principal names consist of three parts: a service or user name, an instance name, and a realm name.

Networks of clients and servers under different administrative organizations typically constitute different realms. That is, it generally is not practical or does not conform to administrative policy to have users and servers in one administrative domain registered with a Kerberos server elsewhere. However, users in one realm may need access to servers in other realms, and some servers may be willing to provide service to users from other realms, provided that those users are authenticated.

Kerberos provides a mechanism for supporting such interrealm authentication. For two realms to support interrealm authentication, a third requirement is added:

3. The Kerberos server in each interoperating realm shares a secret key with the server in the other realm. The two Kerberos servers are registered with each other.

The scheme requires that the Kerberos server in one realm trust the Kerberos server in the other realm to authenticate its users. Furthermore, the participating servers in the second realm must also be willing to trust the Kerberos server in the first realm.

With these ground rules in place, we can describe the mechanism as follows (Figure 15.4): A user wishing service on a server in another realm needs a ticket for that server. The user's client follows the usual procedures to gain access to the local TGS and then requests a ticket-granting ticket for a remote TGS (TGS in another realm). The client can then apply to the remote TGS for a service-granting ticket for the desired server in the realm of the remote TGS.

The details of the exchanges illustrated in Figure 15.4 are as follows (compare Table 15.1).

(1) C → AS: $ID_c \| ID_{tgs} \| TS_1$

(2) AS → C: $E(K_c, [K_{c,tgs} \| ID_{tgs} \| TS_2 \| Lifetime_2 \| Ticket_{tgs}])$

(3) C → TGS: $ID_{tgsrem} \| Ticket_{tgs} \| Authenticator_c$

(4) TGS → C: $E(K_{c,tgs}, [K_{c,tgsrem} \| ID_{tgsrem} \| TS_4 \| Ticket_{tgsrem}])$

(5) C → TGS_{rem}: $ID_{vrem} \| Ticket_{tgsrem} \| Authenticator_c$

(6) TGS_{rem} → C: $E(K_{c,tgsrem}, [K_{c,vrem} \| ID_{vrem} \| TS_6 \| Ticket_{vrem}])$

(7) C → V_{rem}: $Ticket_{vrem} \| Authenticator_c$

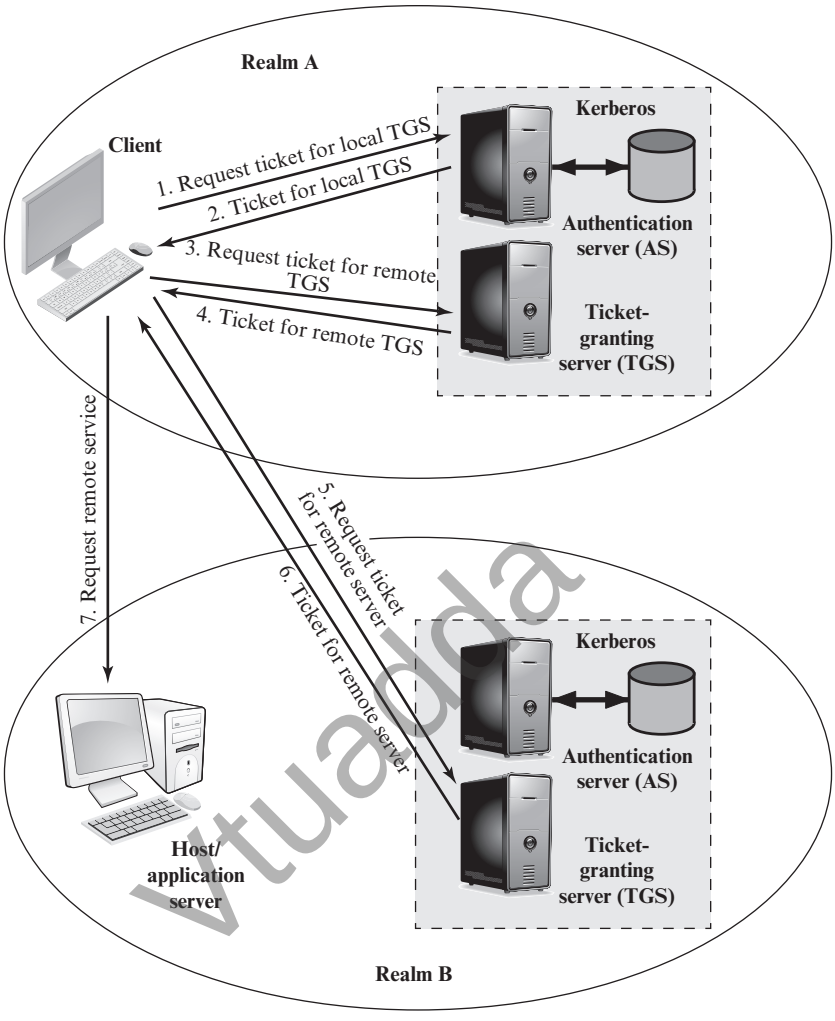


Figure 15.4 Request for Service in Another Realm

The ticket presented to the remote server (V_{rem}) indicates the realm in which the user was originally authenticated. The server chooses whether to honor the remote request.

One problem presented by the foregoing approach is that it does not scale well to many realms. If there are N realms, then there must be $N(N - 1)/2$ secure key exchanges so that each Kerberos realm can interoperate with all other Kerberos realms.

Kerberos Version 5

Kerberos version 5 is specified in RFC 4120 and provides a number of improvements over version 4 [KOHL94]. To begin, we provide an overview of the changes from version 4 to version 5 and then look at the version 5 protocol.

Differences between Versions 4 and 5 Version 5 is intended to address the limitations of version 4 in two areas: environmental shortcomings and technical deficiencies. Let us briefly summarize the improvements in each area.[8]

Kerberos version 4 was developed for use within the Project Athena environment and, accordingly, did not fully address the need to be of general purpose. This led to the following **environmental shortcomings**.

1. **Encryption system dependence:** Version 4 requires the use of DES. Export restriction on DES as well as doubts about the strength of DES were thus of concern. In version 5, ciphertext is tagged with an encryption-type identifier so that any encryption technique may be used. Encryption keys are tagged with a type and a length, allowing the same key to be used in different algorithms and allowing the specification of different variations on a given algorithm.
2. **Internet protocol dependence:** Version 4 requires the use of Internet Protocol (IP) addresses. Other address types, such as the ISO network address, are not accommodated. Version 5 network addresses are tagged with type and length, allowing any network address type to be used.
3. **Message byte ordering:** In version 4, the sender of a message employs a byte ordering of its own choosing and tags the message to indicate least significant byte in lowest address or most significant byte in lowest address. This techniques works but does not follow established conventions. In version 5, all message structures are defined using Abstract Syntax Notation One (ASN.1) and Basic Encoding Rules (BER), which provide an unambiguous byte ordering.
4. **Ticket lifetime:** Lifetime values in version 4 are encoded in an 8-bit quantity in units of five minutes. Thus, the maximum lifetime that can be expressed is $2^8 \times 5 = 1280$ minutes (a little over 21 hours). This may be inadequate for some applications (e.g., a long-running simulation that requires valid Kerberos credentials throughout execution). In version 5, tickets include an explicit start time and end time, allowing tickets with arbitrary lifetimes.
5. **Authentication forwarding:** Version 4 does not allow credentials issued to one client to be forwarded to some other host and used by some other client. This capability would enable a client to access a server and have that server access another server on behalf of the client. For example, a client issues a request to a print server that then accesses the client's file from a file server, using the client's credentials for access. Version 5 provides this capability.
6. **Interrealm authentication:** In version 4, interoperability among N realms requires on the order of N^2 Kerberos-to-Kerberos relationships, as described earlier. Version 5 supports a method that requires fewer relationships, as described shortly.

[8]The following discussion follows the presentation in [KOHL94].

Apart from these environmental limitations, there are **technical deficiencies** in the version 4 protocol itself. Most of these deficiencies were documented in [BELL90], and version 5 attempts to address these. The deficiencies are the following.

1. **Double encryption:** Note in Table 15.1 [messages (2) and (4)] that tickets provided to clients are encrypted twice—once with the secret key of the target server and then again with a secret key known to the client. The second encryption is not necessary and is computationally wasteful.
2. **PCBC encryption:** Encryption in version 4 makes use of a nonstandard mode of DES known as **propagating cipher block chaining (PCBC)**.[9] It has been demonstrated that this mode is vulnerable to an attack involving the interchange of ciphertext blocks [KOHL89]. PCBC was intended to provide an integrity check as part of the encryption operation. Version 5 provides explicit integrity mechanisms, allowing the standard CBC mode to be used for encryption. In particular, a checksum or hash code is attached to the message prior to encryption using CBC.
3. **Session keys:** Each ticket includes a session key that is used by the client to encrypt the authenticator sent to the service associated with that ticket. In addition, the session key may subsequently be used by the client and the server to protect messages passed during that session. However, because the same ticket may be used repeatedly to gain service from a particular server, there is the risk that an opponent will replay messages from an old session to the client or the server. In version 5, it is possible for a client and server to negotiate a subsession key, which is to be used only for that one connection. A new access by the client would result in the use of a new subsession key.
4. **Password attacks:** Both versions are vulnerable to a password attack. The message from the AS to the client includes material encrypted with a key based on the client's password.[10] An opponent can capture this message and attempt to decrypt it by trying various passwords. If the result of a test decryption is of the proper form, then the opponent has discovered the client's password and may subsequently use it to gain authentication credentials from Kerberos. This is the same type of password attack described in Chapter 21, with the same kinds of countermeasures being applicable. Version 5 does provide a mechanism known as preauthentication, which should make password attacks more difficult, but it does not prevent them.

The Version 5 Authentication Dialogue Table 15.3 summarizes the basic version 5 dialogue. This is best explained by comparison with version 4 (Table 15.1).

First, consider the **authentication service exchange**. Message (1) is a client request for a ticket-granting ticket. As before, it includes the ID of the user and the TGS. The following new elements are added:

[9]This is described in Appendix T.
[10]Appendix T describes the mapping of passwords to encryption keys.

Table 15.3 Summary of Kerberos Version 5 Message Exchanges

(1)	**C → AS**	$Options \| ID_c \| Realm_c \| ID_{tgs} \| Times \| Nonce_1$
(2)	**AS → C**	$Realm_C \| ID_C \| Ticket_{tgs} \| \mathrm{E}(K_c, [K_{c,tgs} \| Times \| Nonce_1 \| Realm_{tgs} \| ID_{tgs}])$
		$Ticket_{tgs} = \mathrm{E}(K_{tgs}, [Flags \| K_{c,tgs} \| Realm_c \| ID_C \| AD_C \| Times])$

(a) Authentication Service Exchange to obtain ticket-granting ticket

(3)	**C → TGS**	$Options \| ID_v \| Times \| Nonce_2 \| Ticket_{tgs} \| Authenticator_c$
(4)	**TGS → C**	$Realm_c \| ID_C \| Ticket_v \| \mathrm{E}(K_{c,tgs}, [K_{c,v} \| Times \| Nonce_2 \| Realm_v \| ID_v])$
		$Ticket_{tgs} = \mathrm{E}(K_{tgs}, [Flags \| K_{c,tgs} \| Realm_c \| ID_C \| AD_C \| Times])$
		$Ticket_v = \mathrm{E}(K_v, [Flags \| K_{c,v} \| Realm_c \| ID_C \| AD_C \| Times])$
		$Authenticator_c = \mathrm{E}(K_{c,tgs}, [ID_C \| Realm_c \| TS_1])$

(b) Ticket-Granting Service Exchange to obtain service-granting ticket

(5)	**C → V**	$Options \| Ticket_v \| Authenticator_c$
(6)	**V → C**	$\mathrm{E}_{K_{c,v}}[TS_2 \| Subkey \| Seq\ \#]$
		$Ticket_v = \mathrm{E}(K_v, [Flag \| K_{c,v} \| Realm_c \| ID_C \| AD_C \| Times])$
		$Authenticator_c = \mathrm{E}(K_{c,v}, [ID_C \| Relam_c \| TS_2 \| Subkey \| Seq\ \#])$

(c) Client/Server Authentication Exchange to obtain service

- **Realm:** Indicates realm of user
- **Options:** Used to request that certain flags be set in the returned ticket
- **Times:** Used by the client to request the following time settings in the ticket:
  - —**from**: the desired start time for the requested ticket
  - —**till**: the requested expiration time for the requested ticket
  - —**rtime**: requested renew-till time
- **Nonce:** A random value to be repeated in message (2) to assure that the response is fresh and has not been replayed by an opponent

Message (2) returns a ticket-granting ticket, identifying information for the client, and a block encrypted using the encryption key based on the user's password. This block includes the session key to be used between the client and the TGS, times specified in message (1), the nonce from message (1), and TGS identifying information. The ticket itself includes the session key, identifying information for the client, the requested time values, and flags that reflect the status of this ticket and the requested options. These flags introduce significant new functionality to version 5. For now, we defer a discussion of these flags and concentrate on the overall structure of the version 5 protocol.

Let us now compare the **ticket-granting service exchange** for versions 4 and 5. We see that message (3) for both versions includes an authenticator, a ticket, and the name of the requested service. In addition, version 5 includes requested times and options for the ticket and a nonce—all with functions similar to those of message (1). The authenticator itself is essentially the same as the one used in version 4.

Message (4) has the same structure as message (2). It returns a ticket plus information needed by the client, with the information encrypted using the session key now shared by the client and the TGS.

Finally, for the **client/server authentication exchange**, several new features appear in version 5. In message (5), the client may request as an option that mutual authentication is required. The authenticator includes several new fields:

- **Subkey:** The client's choice for an encryption key to be used to protect this specific application session. If this field is omitted, the session key from the ticket ($K_{c,v}$) is used.
- **Sequence number:** An optional field that specifies the starting sequence number to be used by the server for messages sent to the client during this session. Messages may be sequence numbered to detect replays.

If mutual authentication is required, the server responds with message (6). This message includes the timestamp from the authenticator. Note that in version 4, the timestamp was incremented by one. This is not necessary in version 5, because the nature of the format of messages is such that it is not possible for an opponent to create message (6) without knowledge of the appropriate encryption keys. The subkey field, if present, overrides the subkey field, if present, in message (5). The optional sequence number field specifies the starting sequence number to be used by the client.

Ticket Flags The flags field included in tickets in version 5 supports expanded functionality compared to that available in version 4. Table 15.4 summarizes the flags that may be included in a ticket.

Table 15.4 Kerberos Version 5 Flags

INITIAL	This ticket was issued using the AS protocol and not issued based on a ticket-granting ticket.
PRE-AUTHENT	During initial authentication, the client was authenticated by the KDC before a ticket was issued.
HW-AUTHENT	The protocol employed for initial authentication required the use of hardware expected to be possessed solely by the named client.
RENEWABLE	Tells TGS that this ticket can be used to obtain a replacement ticket that expires at a later date.
MAY-POSTDATE	Tells TGS that a postdated ticket may be issued based on this ticket-granting ticket.
POSTDATED	Indicates that this ticket has been postdated; the end server can check the authtime field to see when the original authentication occurred.
INVALID	This ticket is invalid and must be validated by the KDC before use.
PROXIABLE	Tells TGS that a new service-granting ticket with a different network address may be issued based on the presented ticket.
PROXY	Indicates that this ticket is a proxy.
FORWARDABLE	Tells TGS that a new ticket-granting ticket with a different network address may be issued based on this ticket-granting ticket.
FORWARDED	Indicates that this ticket has either been forwarded or was issued based on authentication involving a forwarded ticket-granting ticket.

The INITIAL flag indicates that this ticket was issued by the AS, not by the TGS. When a client requests a service-granting ticket from the TGS, it presents a ticket-granting ticket obtained from the AS. In version 4, this was the only way to obtain a service-granting ticket. Version 5 provides the additional capability that the client can get a service-granting ticket directly from the AS. The utility of this is as follows: A server, such as a password-changing server, may wish to know that the client's password was recently tested.

The PRE-AUTHENT flag, if set, indicates that when the AS received the initial request [message (1)], it authenticated the client before issuing a ticket. The exact form of this preauthentication is left unspecified. As an example, the MIT implementation of version 5 has encrypted timestamp preauthentication, enabled by default. When a user wants to get a ticket, it has to send to the AS a preauthentication block containing a random confounder, a version number, and a timestamp all encrypted in the client's password-based key. The AS decrypts the block and will not send a ticket-granting ticket back unless the timestamp in the preauthentication block is within the allowable time skew (time interval to account for clock drift and network delays). Another possibility is the use of a smart card that generates continually changing passwords that are included in the preauthenticated messages. The passwords generated by the card can be based on a user's password but be transformed by the card so that, in effect, arbitrary passwords are used. This prevents an attack based on easily guessed passwords. If a smart card or similar device was used, this is indicated by the HW-AUTHENT flag.

When a ticket has a long lifetime, there is the potential for it to be stolen and used by an opponent for a considerable period. If a short lifetime is used to lessen the threat, then overhead is involved in acquiring new tickets. In the case of a ticket-granting ticket, the client would either have to store the user's secret key, which is clearly risky, or repeatedly ask the user for a password. A compromise scheme is the use of renewable tickets. A ticket with the RENEWABLE flag set includes two expiration times: One for this specific ticket and one that is the latest permissible value for an expiration time. A client can have the ticket renewed by presenting it to the TGS with a requested new expiration time. If the new time is within the limit of the latest permissible value, the TGS can issue a new ticket with a new session time and a later specific expiration time. The advantage of this mechanism is that the TGS may refuse to renew a ticket reported as stolen.

A client may request that the AS provide a ticket-granting ticket with the MAY-POSTDATE flag set. The client can then use this ticket to request a ticket that is flagged as POSTDATED and INVALID from the TGS. Subsequently, the client may submit the postdated ticket for validation. This scheme can be useful for running a long batch job on a server that requires a ticket periodically. The client can obtain a number of tickets for this session at once, with spread out time values. All but the first ticket are initially invalid. When the execution reaches a point in time when a new ticket is required, the client can get the appropriate ticket validated. With this approach, the client does not have to repeatedly use its ticket-granting ticket to obtain a service-granting ticket.

In version 5, it is possible for a server to act as a proxy on behalf of a client, in effect adopting the credentials and privileges of the client to request a service from another server. If a client wishes to use this mechanism, it requests a ticket-granting

ticket with the PROXIABLE flag set. When this ticket is presented to the TGS, the TGS is permitted to issue a service-granting ticket with a different network address; this latter ticket will have its PROXY flag set. An application receiving such a ticket may accept it or require additional authentication to provide an audit trail.[11]

The proxy concept is a limited case of the more powerful forwarding procedure. If a ticket is set with the FORWARDABLE flag, a TGS can issue to the requestor a ticket-granting ticket with a different network address and the FORWARDED flag set. This ticket then can be presented to a remote TGS. This capability allows a client to gain access to a server on another realm without requiring that each Kerberos maintain a secret key with Kerberos servers in every other realm. For example, realms could be structured hierarchically. Then a client could walk up the tree to a common node and then back down to reach a target realm. Each step of the walk would involve forwarding a ticket-granting ticket to the next TGS in the path.

15.4 REMOTE USER-AUTHENTICATION USING ASYMMETRIC ENCRYPTION

Mutual Authentication

In Chapter 14, we presented one approach to the use of public-key encryption for the purpose of session-key distribution (Figure 14.9). This protocol assumes that each of the two parties is in possession of the current public key of the other. It may not be practical to require this assumption.

A protocol using timestamps is provided in [DENN81]:

1. A → AS: $ID_A \| ID_B$
2. AS → A: $\mathrm{E}(PR_{as}, [ID_A \| PU_a \| T]) \| \mathrm{E}(PR_{as}, [ID_B \| PU_b \| T])$
3. A → B: $\mathrm{E}(PR_{as}, [ID_A \| PU_a \| T]) \| \mathrm{E}(PR_{as}, [ID_B \| PU_b \| T]) \| \mathrm{E}(PU_b, \mathrm{E}(PR_a, [K_s \| T]))$

In this case, the central system is referred to as an authentication server (AS), because it is not actually responsible for secret-key distribution. Rather, the AS provides public-key certificates. The session key is chosen and encrypted by A; hence, there is no risk of exposure by the AS. The timestamps protect against replays of compromised keys.

This protocol is compact but, as before, requires the synchronization of clocks. Another approach, proposed by Woo and Lam [WOO92a], makes use of nonces. The protocol consists of the following steps.

1. A → KDC: $ID_A \| ID_B$
2. KDC → A: $\mathrm{E}(PR_{\mathrm{auth}}, [ID_B \| PU_b])$
3. A → B: $E(PU_b, [N_a \| ID_A])$
4. B → KDC: $ID_A \| ID_B \| \mathrm{E}(PU_{\mathrm{auth}}, N_a)$
5. KDC → B: $\mathrm{E}(PR_{\mathrm{auth}}, [ID_A \| PU_a]) \| \mathrm{E}(PU_b, \mathrm{E}(PR_{\mathrm{auth}}, [N_a \| K_s \| ID_B]))$

[11] For a discussion of some of the possible uses of the proxy capability, see [NEUM93b].

6. $B \rightarrow A$: $E(PU_a, [E(PR_{auth}, [(N_a \| K_s \| ID_B)]) \| N_b])$
7. $A \rightarrow B$: $E(K_s, N_b)$

In step 1, A informs the KDC of its intention to establish a secure connection with B. The KDC returns to A a copy of B's public-key certificate (step 2). Using B's public key, A informs B of its desire to communicate and sends a nonce N_a (step 3). In step 4, B asks the KDC for A's public-key certificate and requests a session key; B includes A's nonce so that the KDC can stamp the session key with that nonce. The nonce is protected using the KDC's public key. In step 5, the KDC returns to B a copy of A's public-key certificate, plus the information $\{N_a, K_s, ID_B\}$. This information basically says that K_s is a secret key generated by the KDC on behalf of B and tied to N_a; the binding of K_s and N_a will assure A that K_s is fresh. This triple is encrypted using the KDC's private key to allow B to verify that the triple is in fact from the KDC. It is also encrypted using B's public key so that no other entity may use the triple in an attempt to establish a fraudulent connection with A. In step 6, the triple $\{N_a, K_s, ID_B\}$, still encrypted with the KDC's private key, is relayed to A, together with a nonce N_b generated by B. All the foregoing are encrypted using A's public key. A retrieves the session key K_s, uses it to encrypt N_b, and returns it to B. This last message assures B of A's knowledge of the session key.

This seems to be a secure protocol that takes into account the various attacks. However, the authors themselves spotted a flaw and submitted a revised version of the algorithm in [WOO92b]:

1. $A \rightarrow KDC$: $ID_A \| ID_B$
2. $KDC \rightarrow A$: $E(PR_{auth}, [ID_B \| PU_b])$
3. $A \rightarrow B$: $E(PU_b, [N_a \| ID_A])$
4. $B \rightarrow KDC$: $ID_A \| ID_B \| E(PU_{auth}, N_a)$
5. $KDC \rightarrow B$: $E(PR_{auth}, [ID_A \| PU_a]) \| E(PU_b, E(PR_{auth}, [N_a \| K_s \| ID_A \| ID_B]))$
6. $B \rightarrow A$: $E(PU_a, [N_b \| E(PR_{auth}, [N_a \| K_s \| ID_A \| ID_B])])$
7. $A \rightarrow B$: $E(K_s, N_b)$

The identifier of A, ID_A, is added to the set of items encrypted with the KDC's private key in steps 5 and 6. This binds the session key K_s to the identities of the two parties that will be engaged in the session. This inclusion of ID_A accounts for the fact that the nonce value N_a is considered unique only among all nonces generated by A, not among all nonces generated by all parties. Thus, it is the pair $\{ID_A, N_a\}$ that uniquely identifies the connection request of A.

In both this example and the protocols described earlier, protocols that appeared secure were revised after additional analysis. These examples highlight the difficulty of getting things right in the area of authentication.

One-Way Authentication

We have already presented public-key encryption approaches that are suited to electronic mail, including the straightforward encryption of the entire message for confidentiality (Figure 12.1b), authentication (Figure 12.1c), or both (Figure 12.1d). These approaches require that either the sender know the recipient's public key

(confidentiality), the recipient know the sender's public key (authentication), or both (confidentiality plus authentication). In addition, the public-key algorithm must be applied once or twice to what may be a long message.

If confidentiality is the primary concern, then the following may be more efficient:

$$A \rightarrow B: \quad E(PU_b, K_s) \| E(K_s, M)$$

In this case, the message is encrypted with a one-time secret key. A also encrypts this one-time key with B's public key. Only B will be able to use the corresponding private key to recover the one-time key and then use that key to decrypt the message. This scheme is more efficient than simply encrypting the entire message with B's public key.

If authentication is the primary concern, then a digital signature may suffice, as was illustrated in Figure 13.2:

$$A \rightarrow B: \quad M \| E(PR_a, H(M))$$

This method guarantees that A cannot later deny having sent the message. However, this technique is open to another kind of fraud. Bob composes a message to his boss Alice that contains an idea that will save the company money. He appends his digital signature and sends it into the email system. Eventually, the message will get delivered to Alice's mailbox. But suppose that Max has heard of Bob's idea and gains access to the mail queue before delivery. He finds Bob's message, strips off his signature, appends his, and requeues the message to be delivered to Alice. Max gets credit for Bob's idea.

To counter such a scheme, both the message and signature can be encrypted with the recipient's public key:

$$A \rightarrow B: \quad E(PU_b, [M \| E(PR_a, H(M))])$$

The latter two schemes require that B know A's public key and be convinced that it is timely. An effective way to provide this assurance is the digital certificate, described in Chapter 14. Now we have

$$A \rightarrow B: \quad M \| E(PR_a, H(M)) \| E(PR_{as}, [T \| ID_A \| PU_a])$$

In addition to the message, A sends B the signature encrypted with A's private key and A's certificate encrypted with the private key of the authentication server. The recipient of the message first uses the certificate to obtain the sender's public key and verify that it is authentic and then uses the public key to verify the message itself. If confidentiality is required, then the entire message can be encrypted with B's public key. Alternatively, the entire message can be encrypted with a one-time secret key; the secret key is also transmitted, encrypted with B's public key. This approach is explored in Chapter 19.

17.1 WEB SECURITY CONSIDERATIONS

The World Wide Web is fundamentally a client/server application running over the Internet and TCP/IP intranets. As such, the security tools and approaches discussed so far in this book are relevant to the issue of Web security. However, the following characteristics of Web usage suggest the need for tailored security tools:

- Although Web browsers are very easy to use, Web servers are relatively easy to configure and manage, and Web content is increasingly easy to develop, the underlying software is extraordinarily complex. This complex software may hide many potential security flaws. The short history of the Web is filled with examples of new and upgraded systems, properly installed, that are vulnerable to a variety of security attacks.
- A Web server can be exploited as a launching pad into the corporation's or agency's entire computer complex. Once the Web server is subverted, an attacker may be able to gain access to data and systems not part of the Web itself but connected to the server at the local site.

- Casual and untrained (in security matters) users are common clients for Web-based services. Such users are not necessarily aware of the security risks that exist and do not have the tools or knowledge to take effective countermeasures.

Web Security Threats

Table 17.1 provides a summary of the types of security threats faced when using the Web. One way to group these threats is in terms of passive and active attacks. Passive attacks include eavesdropping on network traffic between browser and server and gaining access to information on a Web site that is supposed to be restricted. Active attacks include impersonating another user, altering messages in transit between client and server, and altering information on a Web site.

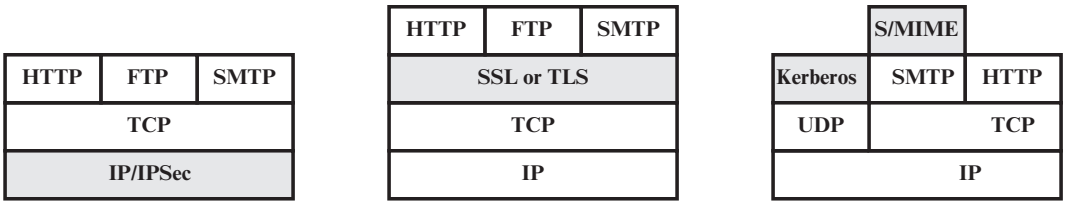
Another way to classify Web security threats is in terms of the location of the threat: Web server, Web browser, and network traffic between browser and server. Issues of server and browser security fall into the category of computer system security; Part Six of this book addresses the issue of system security in general but is also applicable to Web system security. Issues of traffic security fall into the category of network security and are addressed in this chapter.

Web Traffic Security Approaches

A number of approaches to providing Web security are possible. The various approaches that have been considered are similar in the services they provide and, to some extent, in the mechanisms that they use, but they differ with respect to their scope of applicability and their relative location within the TCP/IP protocol stack.

Table 17.1 A Comparison of Threats on the Web

	Threats	Consequences	Countermeasures
Integrity	• Modification of user data • Trojan horse browser • Modification of memory • Modification of message traffic in transit	• Loss of information • Compromise of machine • Vulnerability to all other threats	Cryptographic checksums
Confidentiality	• Eavesdropping on the net • Theft of info from server • Theft of data from client • Info about network configuration • Info about which client talks to server	• Loss of information • Loss of privacy	Encryption, Web proxies
Denial of Service	• Killing of user threads • Flooding machine with bogus requests • Filling up disk or memory • Isolating machine by DNS attacks	• Disruptive • Annoying • Prevent user from getting work done	Difficult to prevent
Authentication	• Impersonation of legitimate users • Data forgery	• Misrepresentation of user • Belief that false information is valid	Cryptographic techniques



(a) Network level (b) Transport level (c) Application level

Figure 17.1 Relative Location of Security Facilities in the TCP/IP Protocol Stack

Figure 17.1 illustrates this difference. One way to provide Web security is to use IP security (IPsec) (Figure 17.1a). The advantage of using IPsec is that it is transparent to end users and applications and provides a general-purpose solution. Furthermore, IPsec includes a filtering capability so that only selected traffic need incur the overhead of IPsec processing.

Another relatively general-purpose solution is to implement security just above TCP (Figure 17.1b). The foremost example of this approach is the Secure Sockets Layer (SSL) and the follow-on Internet standard known as Transport Layer Security (TLS). At this level, there are two implementation choices. For full generality, SSL (or TLS) could be provided as part of the underlying protocol suite and therefore be transparent to applications. Alternatively, TLS can be embedded in specific packages. For example, virtually all browsers come equipped with TLS, and most Web servers have implemented the protocol.

Application-specific security services are embedded within the particular application. Figure 17.1c shows examples of this architecture. The advantage of this approach is that the service can be tailored to the specific needs of a given application.

17.2 TRANSPORT LAYER SECURITY

One of the most widely used security services is **Transport Layer Security (TSL)**; the current version is Version 1.2, defined in RFC 5246. TLS is an Internet standard that evolved from a commercial protocol known as **Secure Sockets Layer (SSL)**. Although SSL implementations are still around, it has been deprecated by IETF and is disabled by most corporations offering TLS software. TLS is a general-purpose service implemented as a set of protocols that rely on TCP. At this level, there are two implementation choices. For full generality, TLS could be provided as part of the underlying protocol suite and therefore be transparent to applications. Alternatively, TLS can be embedded in specific packages. For example, most browsers come equipped with TLS, and most Web servers have implemented the protocol.

TLS Architecture

TLS is designed to make use of TCP to provide a reliable end-to-end secure service. TLS is not a single protocol but rather two layers of protocols, as illustrated in Figure 17.2.

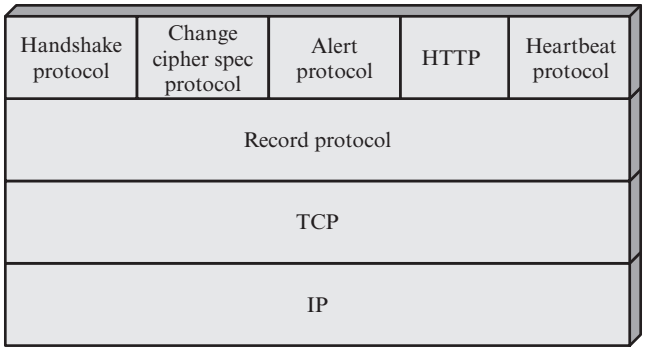


Figure 17.2 TLS Protocol Stack

The TLS Record Protocol provides basic security services to various higher-layer protocols. In particular, the **Hypertext Transfer Protocol (HTTP)**, which provides the transfer service for Web client/server interaction, can operate on top of TLS. Three higher-layer protocols are defined as part of TLS: the Handshake Protocol; the Change Cipher Spec Protocol; and the Alert Protocol. These TLS-specific protocols are used in the management of TLS exchanges and are examined later in this section. A fourth protocol, the Heartbeat Protocol, is defined in a separate RFC and is also discussed subsequently in this section.

Two important TLS concepts are the TLS session and the TLS connection, which are defined in the specification as follows:

- **Connection:** A connection is a transport (in the OSI layering model definition) that provides a suitable type of service. For TLS, such connections are peer-to-peer relationships. The connections are transient. Every connection is associated with one session.
- **Session:** A TLS session is an association between a client and a server. Sessions are created by the Handshake Protocol. Sessions define a set of cryptographic security parameters, which can be shared among multiple connections. Sessions are used to avoid the expensive negotiation of new security parameters for each connection.

Between any pair of parties (applications such as HTTP on client and server), there may be multiple secure connections. In theory, there may also be multiple simultaneous sessions between parties, but this feature is not used in practice.

There are a number of states associated with each session. Once a session is established, there is a current operating state for both read and write (i.e., receive and send). In addition, during the Handshake Protocol, pending read and write states are created. Upon successful conclusion of the Handshake Protocol, the pending states become the current states.

A session state is defined by the following parameters:

- **Session identifier:** An arbitrary byte sequence chosen by the server to identify an active or resumable session state.
- **Peer certificate:** An X509.v3 certificate of the peer. This element of the state may be null.

- **Compression method:** The algorithm used to compress data prior to encryption.
- **Cipher spec:** Specifies the bulk data encryption algorithm (such as null, AES, etc.) and a hash algorithm (such as MD5 or SHA-1) used for MAC calculation. It also defines cryptographic attributes such as the hash_size.
- **Master secret:** 48-byte secret shared between the client and server.
- **Is resumable:** A flag indicating whether the session can be used to initiate new connections.

A connection state is defined by the following parameters:

- **Server and client random:** Byte sequences that are chosen by the server and client for each connection.
- **Server write MAC secret:** The secret key used in MAC operations on data sent by the server.
- **Client write MAC secret:** The symmetric key used in MAC operations on data sent by the client.
- **Server write key:** The symmetric encryption key for data encrypted by the server and decrypted by the client.
- **Client write key:** The symmetric encryption key for data encrypted by the client and decrypted by the server.
- **Initialization vectors:** When a block cipher in CBC mode is used, an initialization vector (IV) is maintained for each key. This field is first initialized by the TLS Handshake Protocol. Thereafter, the final ciphertext block from each record is preserved for use as the IV with the following record.
- **Sequence numbers:** Each party maintains separate sequence numbers for transmitted and received messages for each connection. When a party sends or receives a "change cipher spec message," the appropriate sequence number is set to zero. Sequence numbers may not exceed $2^{64} - 1$.

TLS Record Protocol

The TLS Record Protocol provides two services for TLS connections:

- **Confidentiality:** The Handshake Protocol defines a shared secret key that is used for conventional encryption of TLS payloads.
- **Message Integrity:** The Handshake Protocol also defines a shared secret key that is used to form a message authentication code (MAC).

Figure 17.3 indicates the overall operation of the TLS Record Protocol. The Record Protocol takes an application message to be transmitted, fragments the data into manageable blocks, optionally compresses the data, applies a MAC, encrypts, adds a header, and transmits the resulting unit in a TCP segment. Received data are decrypted, verified, decompressed, and reassembled before being delivered to higher-level users.

The first step is **fragmentation**. Each upper-layer message is fragmented into blocks of 2^{14} bytes (16,384 bytes) or less. Next, **compression** is optionally applied. Compression must be lossless and may not increase the content length by more than

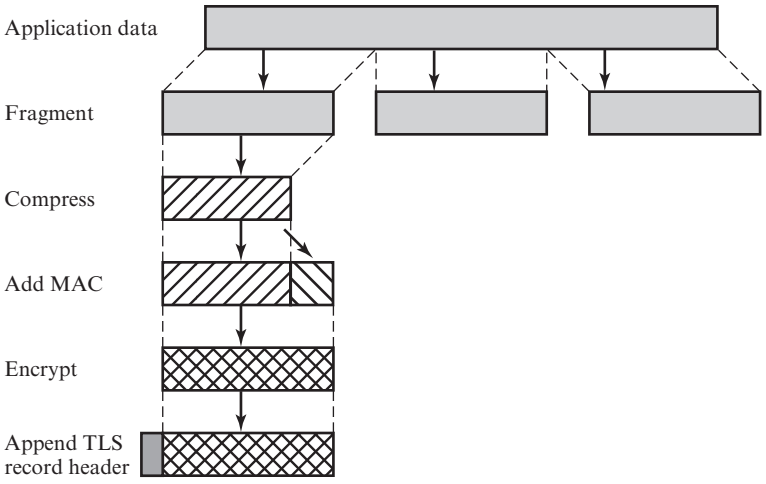


Figure 17.3 TLS Record Protocol Operation

1024 bytes.[1] In TLSv2, no compression algorithm is specified, so the default compression algorithm is null.

The next step in processing is to compute a **message authentication code** over the compressed data. TLS makes use of the HMAC algorithm defined in RFC 2104. Recall from Chapter 12 that HMAC is defined as

$$\text{HMAC}_K(M) = \text{H}[(K^+ \oplus \text{opad}) \| \text{H}[(K^+ \oplus \text{ipad}) \| M]]$$

where

H = embedded hash function (for TLS, either MD5 or SHA-1)
M = message input to HMAC
K^+ = secret key padded with zeros on the left so that the result is equal to the block length of the hash code (for MD5 and SHA-1, block length = 512 bits)
ipad = 00110110 (36 in hexadecimal) repeated 64 times (512 bits)
opad = 01011100 (5C in hexadecimal) repeated 64 times (512 bits)

For TLS, the MAC calculation encompasses the fields indicated in the following expression:

HMAC_hash(MAC_write_secret, seq_num || TLSCompressed.type ||
TLSCompressed.version || TLSCompressed.length || TLSCompressed.fragment)

The MAC calculation covers all of the fields XXX, plus the field `TLSCompressed.version`, which is the version of the protocol being employed.

Next, the compressed message plus the MAC are **encrypted** using symmetric encryption. Encryption may not increase the content length by more than 1024 bytes,

[1]Of course, one hopes that compression shrinks rather than expands the data. However, for very short blocks, it is possible, because of formatting conventions, that the compression algorithm will actually provide output that is longer than the input.

so that the total length may not exceed $2^{14} + 2048$. The following encryption algorithms are permitted:

Block Cipher		Stream Cipher	
Algorithm	**Key Size**	**Algorithm**	**Key Size**
AES 3DES	128, 256 168	RC4-128	128

For stream encryption, the compressed message plus the MAC are encrypted. Note that the MAC is computed before encryption takes place and that the MAC is then encrypted along with the plaintext or compressed plaintext.

For block encryption, padding may be added after the MAC prior to encryption. The padding is in the form of a number of padding bytes followed by a one-byte indication of the length of the padding. The padding can be any amount that results in a total that is a multiple of the cipher's block length, up to a maximum of 255 bytes. For example, if the cipher block length is 16 bytes (e.g., AES) and if the plaintext (or compressed text if compression is used) plus MAC plus padding length byte is 79 bytes long, then the padding length (in bytes) can be 1, 17, 33, and so on, up to 161. At a padding length of 161, the total length is $79 + 161 = 240$. A variable padding length may be used to frustrate attacks based on an analysis of the lengths of exchanged messages.

The final step of TLS Record Protocol processing is to prepend a header consisting of the following fields:

- **Content Type (8 bits)**: The higher-layer protocol used to process the enclosed fragment.
- **Major Version (8 bits):** Indicates major version of TLS in use. For TLSv2, the value is 3.
- **Minor Version (8 bits):** Indicates minor version in use. For TLSv2, the value is 1.
- **Compressed Length (16 bits):** The length in bytes of the plaintext fragment (or compressed fragment if compression is used). The maximum value is $2^{14} + 2048$.

The content types that have been defined are `change_cipher_spec`, `alert`, `handshake`, and `application_data`. The first three are the TLS-specific protocols, discussed next. Note that no distinction is made among the various applications (e.g., HTTP) that might use TLS; the content of the data created by such applications is opaque to TLS.

Figure 17.4 illustrates the TLS record format.

Change Cipher Spec Protocol

The Change Cipher Spec Protocol is one of the four TLS-specific protocols that use the TLS Record Protocol, and it is the simplest. This protocol consists of a single message (Figure 17.5a), which consists of a single byte with the value 1. The sole purpose of this message is to cause the pending state to be copied into the current state, which updates the cipher suite to be used on this connection.

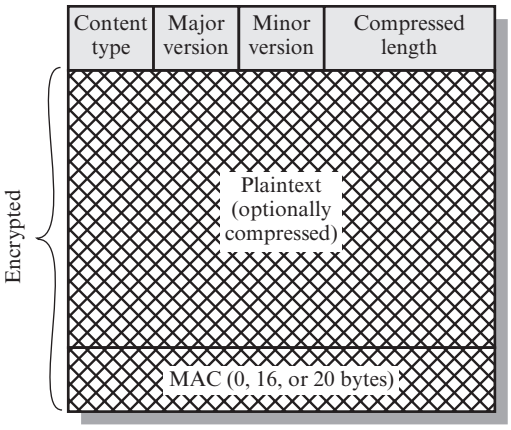


Figure 17.4 TLS Record Format

Alert Protocol

The Alert Protocol is used to convey TLS-related alerts to the peer entity. As with other applications that use TLS, alert messages are compressed and encrypted, as specified by the current state.

Each message in this protocol consists of two bytes (Figure 17.5b). The first byte takes the value warning (1) or fatal (2) to convey the severity of the message. If the level is fatal, TLS immediately terminates the connection. Other connections on the same session may continue, but no new connections on this session may be established. The second byte contains a code that indicates the specific alert. The following alerts are always fatal:

- **unexpected_message:** An inappropriate message was received.
- **bad_record_mac:** An incorrect MAC was received.
- **decompression_failure:** The decompression function received improper input (e.g., unable to decompress or decompress to greater than maximum allowable length).
- **handshake_failure:** Sender was unable to negotiate an acceptable set of security parameters given the options available.
- **illegal_parameter:** A field in a handshake message was out of range or inconsistent with other fields.

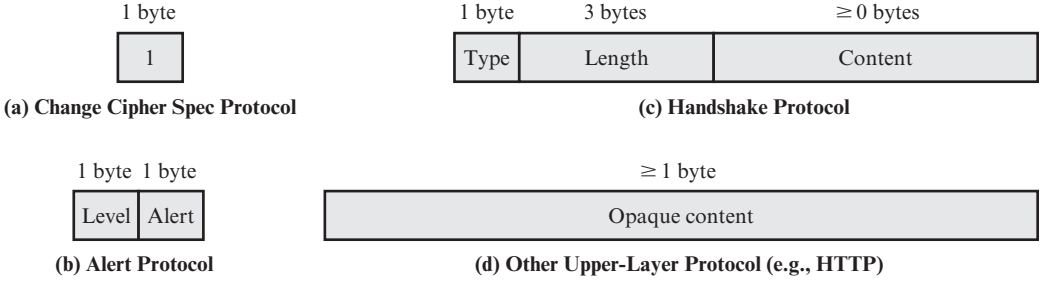


Figure 17.5 TLS Record Protocol Payload

- **decryption_failed:** A ciphertext decrypted in an invalid way; either it was not an even multiple of the block length or its padding values, when checked, were incorrect.
- **record_overflow:** A TLS record was received with a payload (ciphertext) whose length exceeds $2^{14} + 2048$ bytes, or the ciphertext decrypted to a length of greater than $2^{14} + 1024$ bytes.
- **unknown_ca:** A valid certificate chain or partial chain was received, but the certificate was not accepted because the CA certificate could not be located or could not be matched with a known, trusted CA.
- **access_denied:** A valid certificate was received, but when access control was applied, the sender decided not to proceed with the negotiation.
- **decode_error:** A message could not be decoded, because either a field was out of its specified range or the length of the message was incorrect.
- **export_restriction:** A negotiation not in compliance with export restrictions on key length was detected.
- **protocol_version:** The protocol version the client attempted to negotiate is recognized but not supported.
- **insufficient_security:** Returned instead of handshake_failure when a negotiation has failed specifically because the server requires ciphers more secure than those supported by the client.
- **internal_error:** An internal error unrelated to the peer or the correctness of the protocol makes it impossible to continue.

The remaining alerts are the following.

- **close_notify:** Notifies the recipient that the sender will not send any more messages on this connection. Each party is required to send a close_notify alert before closing the write side of a connection.
- **bad_certificate:** A received certificate was corrupt (e.g., contained a signature that did not verify).
- **unsupported_certificate:** The type of the received certificate is not supported.
- **certificate_revoked:** A certificate has been revoked by its signer.
- **certificate_expired:** A certificate has expired.
- **certificate_unknown:** Some other unspecified issue arose in processing the certificate, rendering it unacceptable.
- **decrypt_error:** A handshake cryptographic operation failed, including being unable to verify a signature, decrypt a key exchange, or validate a finished message.
- **user_canceled:** This handshake is being canceled for some reason unrelated to a protocol failure.
- **no_renegotiation:** Sent by a client in response to a hello request or by the server in response to a client hello after initial handshaking. Either of these messages would normally result in renegotiation, but this alert indicates that the sender is not able to renegotiate. This message is always a warning.

Handshake Protocol

The most complex part of TLS is the **Handshake Protocol**. This protocol allows the server and client to authenticate each other and to negotiate an encryption and MAC algorithm and cryptographic keys to be used to protect data sent in a TLS record. The Handshake Protocol is used before any application data is transmitted.

The Handshake Protocol consists of a series of messages exchanged by client and server. All of these have the format shown in Figure 17.5c . Each message has three fields:

- **Type (1 byte):** Indicates one of 10 messages. Table 17.2 lists the defined message types.
- **Length (3 bytes):** The length of the message in bytes.
- **Content (≥ 0 bytes):** The parameters associated with this message; these are listed in Table 17.2.

Figure 17.6 shows the initial exchange needed to establish a logical connection between client and server. The exchange can be viewed as having four phases.

Phase 1. Establish Security Capabilities Phase 1 initiates a logical connection and establishes the security capabilities that will be associated with it. The exchange is initiated by the client, which sends a **client_hello message** with the following parameters:

- **Version:** The highest TLS version understood by the client.
- **Random:** A client-generated random structure consisting of a 32-bit timestamp and 28 bytes generated by a secure random number generator. These values serve as nonces and are used during key exchange to prevent replay attacks.
- **Session ID:** A variable-length session identifier. A nonzero value indicates that the client wishes to update the parameters of an existing connection or to create a new connection on this session. A zero value indicates that the client wishes to establish a new connection on a new session.

Table 17.2 TLS Handshake Protocol Message Types

Message Type	Parameters
`hello_request`	null
`client_hello`	version, random, session id, cipher suite, compression method
`server_hello`	version, random, session id, cipher suite, compression method
`certificate`	chain of X.509v3 certificates
`server_key_exchange`	parameters, signature
`certificate_request`	type, authorities
`server_done`	null
`certificate_verify`	signature
`client_key_exchange`	parameters, signature
`finished`	hash value

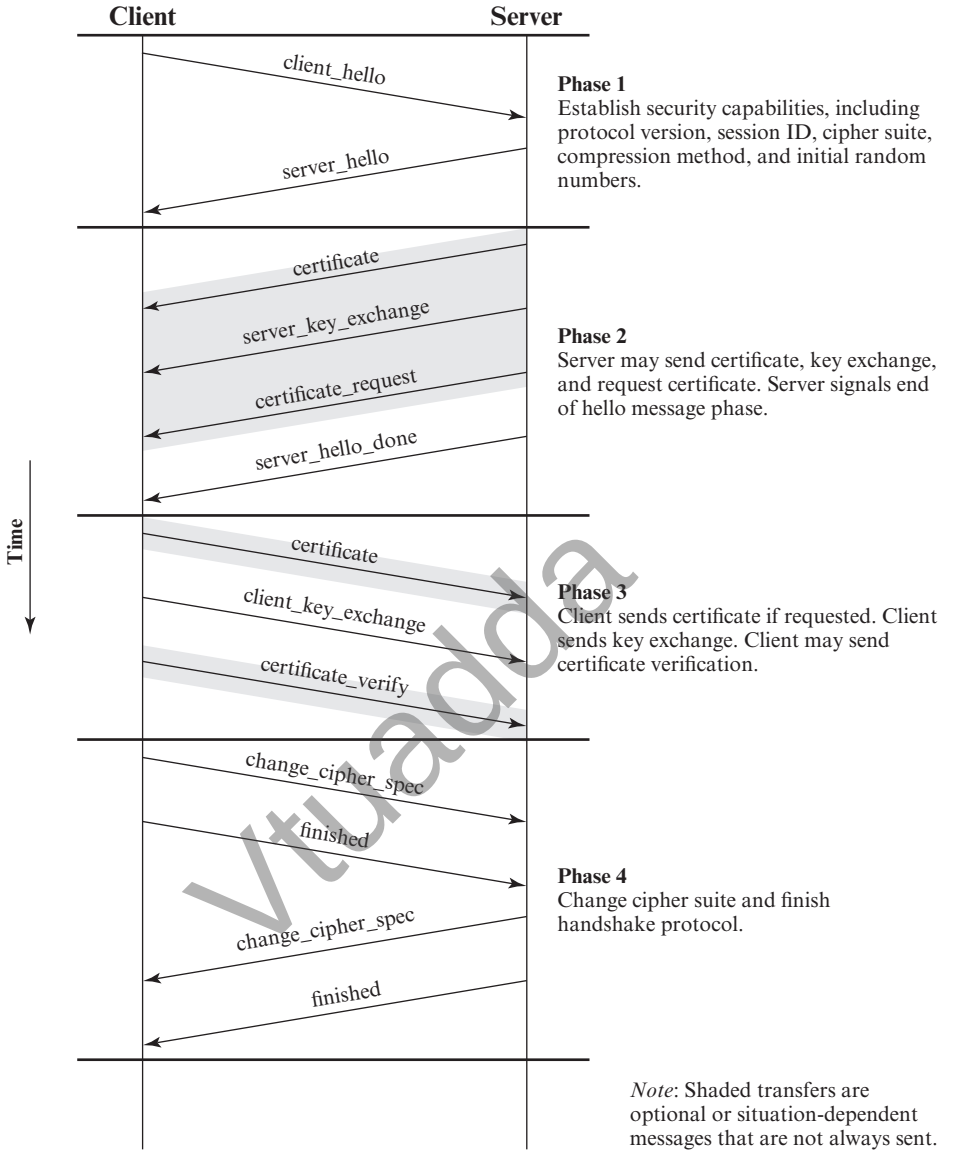


Figure 17.6 Handshake Protocol Action

- **CipherSuite:** This is a list that contains the combinations of cryptographic algorithms supported by the client, in decreasing order of preference. Each element of the list (each cipher suite) defines both a key exchange algorithm and a CipherSpec; these are discussed subsequently.
- **Compression Method:** This is a list of the compression methods the client supports.

After sending the `client_hello message`, the client waits for the **`server_hello message`**, which contains the same parameters as the `client_hello`

`message`. For the `server_hello message`, the following conventions apply. The Version field contains the lowest of the version suggested by the client and the highest supported by the server. The Random field is generated by the server and is independent of the client's Random field. If the SessionID field of the client was nonzero, the same value is used by the server; otherwise the server's SessionID field contains the value for a new session. The CipherSuite field contains the single cipher suite selected by the server from those proposed by the client. The Compression field contains the compression method selected by the server from those proposed by the client.

The first element of the Ciphersuite parameter is the key exchange method (i.e., the means by which the cryptographic keys for conventional encryption and MAC are exchanged). The following key exchange methods are supported.

- **RSA:** The secret key is encrypted with the receiver's RSA public key. A public-key certificate for the receiver's key must be made available.
- **Fixed Diffie–Hellman:** This is a Diffie–Hellman key exchange in which the server's certificate contains the Diffie–Hellman public parameters signed by the certificate authority (CA). That is, the public-key certificate contains the Diffie–Hellman public-key parameters. The client provides its Diffie–Hellman public-key parameters either in a certificate, if client authentication is required, or in a key exchange message. This method results in a fixed secret key between two peers based on the Diffie–Hellman calculation using the fixed public keys.
- **Ephemeral Diffie-Hellman:** This technique is used to create ephemeral (temporary, one-time) secret keys. In this case, the Diffie–Hellman public keys are exchanged and signed using the sender's private RSA or DSS key. The receiver can use the corresponding public key to verify the signature. Certificates are used to authenticate the public keys. This would appear to be the most secure of the three Diffie–Hellman options because it results in a temporary, authenticated key.
- **Anonymous Diffie–Hellman:** The base Diffie–Hellman algorithm is used with no authentication. That is, each side sends its public Diffie–Hellman parameters to the other with no authentication. This approach is vulnerable to man-in-the-middle attacks, in which the attacker conducts anonymous Diffie–Hellman with both parties.

Following the definition of a key exchange method is the CipherSpec, which includes the following fields:

- **CipherAlgorithm:** Any of the algorithms mentioned earlier: RC4, RC2, DES, 3DES, DES40, or IDEA
- **MACAlgorithm:** MD5 or SHA-1
- **CipherType:** Stream or Block
- **IsExportable:** True or False
- **HashSize:** 0, 16 (for MD5), or 20 (for SHA-1) bytes
- **Key Material:** A sequence of bytes that contain data used in generating the write keys
- **IV Size:** The size of the Initialization Value for Cipher Block Chaining (CBC) encryption

Phase 2. Server Authentication and Key Exchange The server begins this phase by sending its certificate if it needs to be authenticated; the message contains one or a chain of X.509 certificates. The **certificate message** is required for any agreed-on key exchange method except anonymous Diffie–Hellman. Note that if fixed Diffie–Hellman is used, this certificate message functions as the server's key exchange message because it contains the server's public Diffie–Hellman parameters.

Next, a **server_key_exchange message** may be sent if it is required. It is not required in two instances: (1) The server has sent a certificate with fixed Diffie–Hellman parameters; or (2) RSA key exchange is to be used. The server_key_exchange message is needed for the following:

- **Anonymous Diffie–Hellman:** The message content consists of the two global Diffie–Hellman values (a prime number and a primitive root of that number) plus the server's public Diffie–Hellman key (see Figure 10.1).
- **Ephemeral Diffie–Hellman:** The message content includes the three Diffie–Hellman parameters provided for anonymous Diffie–Hellman plus a signature of those parameters.
- **RSA key exchange (in which the server is using RSA but has a signature-only RSA key):** Accordingly, the client cannot simply send a secret key encrypted with the server's public key. Instead, the server must create a temporary RSA public/private key pair and use the server_key_exchange message to send the public key. The message content includes the two parameters of the temporary RSA public key (exponent and modulus; see Figure 9.5) plus a signature of those parameters.

Some further details about the signatures are warranted. As usual, a signature is created by taking the hash of a message and encrypting it with the sender's private key. In this case, the hash is defined as

$$\text{hash}(\text{ClientHello.random} \parallel \text{ServerHello.random} \parallel \text{ServerParams})$$

So the hash covers not only the Diffie–Hellman or RSA parameters but also the two nonces from the initial hello messages. This ensures against replay attacks and misrepresentation. In the case of a DSS signature, the hash is performed using the SHA-1 algorithm. In the case of an RSA signature, both an MD5 and an SHA-1 hash are calculated, and the concatenation of the two hashes (36 bytes) is encrypted with the server's private key.

Next, a nonanonymous server (server not using anonymous Diffie–Hellman) can request a certificate from the client. The **certificate_request message** includes two parameters: certificate_type and certificate_authorities. The certificate type indicates the public-key algorithm and its use:

- RSA, signature only
- DSS, signature only
- RSA for fixed Diffie–Hellman; in this case the signature is used only for authentication, by sending a certificate signed with RSA
- DSS for fixed Diffie–Hellman; again, used only for authentication

The second parameter in the certificate_request message is a list of the distinguished names of acceptable certificate authorities.

The final message in phase 2, and one that is always required, is the **server_done message**, which is sent by the server to indicate the end of the server hello and associated messages. After sending this message, the server will wait for a client response. This message has no parameters.

Phase 3. Client Authentication and Key Exchange Upon receipt of the `server_done` message, the client should verify that the server provided a valid certificate (if required) and check that the `server_hello` parameters are acceptable. If all is satisfactory, the client sends one or more messages back to the server.

If the server has requested a certificate, the client begins this phase by sending a **certificate message**. If no suitable certificate is available, the client sends a `no_certificate` alert instead.

Next is the **client_key_exchange message**, which must be sent in this phase. The content of the message depends on the type of key exchange, as follows:

- **RSA:** The client generates a 48-byte *pre-master secret* and encrypts with the public key from the server's certificate or temporary RSA key from a server_key_exchange message. Its use to compute a *master secret* is explained later.
- **Ephemeral or Anonymous Diffie–Hellman:** The client's public Diffie–Hellman parameters are sent.
- **Fixed Diffie–Hellman:** The client's public Diffie–Hellman parameters were sent in a certificate message, so the content of this message is null.

Finally, in this phase, the client may send a **certificate_verify message** to provide explicit verification of a client certificate. This message is only sent following any client certificate that has signing capability (i.e., all certificates except those containing fixed Diffie–Hellman parameters). This message signs a hash code based on the preceding messages, defined as

```
CertificateVerify.signature.md5_hash
    MD5(handshake_messages);
Certificate.signature.sha_hash
    SHA(handshake_messages);
```

where `handshake_messages` refers to all Handshake Protocol messages sent or received starting at `client_hello` but not including this message. If the user's private key is DSS, then it is used to encrypt the SHA-1 hash. If the user's private key is RSA, it is used to encrypt the concatenation of the MD5 and SHA-1 hashes. In either case, the purpose is to verify the client's ownership of the private key for the client certificate. Even if someone is misusing the client's certificate, he or she would be unable to send this message.

Phase 4. Finish Phase 4 completes the setting up of a secure connection. The client sends a **change_cipher_spec message** and copies the pending CipherSpec into the current CipherSpec. Note that this message is not considered part of the Handshake Protocol but is sent using the Change Cipher Spec Protocol. The client then immediately sends the **finished message** under the new algorithms, keys, and secrets.

The finished message verifies that the key exchange and authentication processes were successful. The content of the finished message is:

$$\text{PRF}(\text{master\_secret}, \text{finished\_label}, \text{MD5}(\text{handshake\_messages}) \| \text{SHA-1}(\text{handshake\_messages}))$$

where `finished_label` is the string "client finished" for the client and "server finished" for the server.

In response to these two messages, the server sends its own `change_cipher_spec` message, transfers the pending to the current CipherSpec, and sends its finished message. At this point, the handshake is complete and the client and server may begin to exchange application-layer data.

Cryptographic Computations

Two further items are of interest: (1) the creation of a shared master secret by means of the key exchange; and (2) the generation of cryptographic parameters from the master secret.

Master Secret Creation The shared master secret is a one-time 48-byte value (384 bits) generated for this session by means of secure key exchange. The creation is in two stages. First, a `pre_master_secret` is exchanged. Second, the `master_secret` is calculated by both parties. For `pre_master_secret` exchange, there are two possibilities.

- **RSA:** A 48-byte pre_master_secret is generated by the client, encrypted with the server's public RSA key, and sent to the server. The server decrypts the ciphertext using its private key to recover the pre_master_secret.
- **Diffie–Hellman:** Both client and server generate a Diffie–Hellman public key. After these are exchanged, each side performs the Diffie–Hellman calculation to create the shared pre_master_secret.

  Both sides now compute the `master_secret` as

  master_secret =

  PRF(pre_master_secret, "master secret", ClientHello.random ‖ ServerHello.random)

where `ClientHello.random` and `ServerHello.random` are the two nonce values exchanged in the initial hello messages.

The algorithm is performed until 48 bytes of pseudorandom output are produced. The calculation of the key block material (MAC secret keys, session encryption keys, and IVs) is defined as

key_block =

PRF(SecurityParameters.master_secret, "key expansion", SecurityParameters.server_random ‖ SecurityParameters.client_random)

until enough output has been generated.

Generation of Cryptographic Parameters CipherSpecs require a client write MAC secret, a server write MAC secret, a client write key, a server write key, a client write IV, and a server write IV, which are generated from the master secret in that order. These parameters are generated from the master secret by hashing the master secret into a sequence of secure bytes of sufficient length for all needed parameters.

The generation of the key material from the master secret uses the same format for generation of the master secret from the pre-master secret as

$$\begin{aligned}\text{key\_block} = \text{MD5}(&\text{master\_secret} \parallel \text{SHA}(\text{'A'} \parallel \text{master\_secret} \parallel \\ &\text{ServerHello.random} \parallel \text{ClientHello.random})) \parallel \\ \text{MD5}(&\text{master\_secret} \parallel \text{SHA}(\text{'BB'} \parallel \text{master\_secret} \parallel \\ &\text{ServerHello.random} \parallel \text{ClientHello.random})) \parallel \\ \text{MD5}(&\text{master\_secret} \parallel \text{SHA}(\text{'CCC'} \parallel \text{master\_secret} \parallel \\ &\text{ServerHello.random} \parallel \text{ClientHello.random})) \parallel \ldots\end{aligned}$$

until enough output has been generated. The result of this algorithmic structure is a pseudorandom function. We can view the `master_secret` as the pseudorandom seed value to the function. The client and server random numbers can be viewed as salt values to complicate cryptanalysis (see Chapter 21 for a discussion of the use of salt values).

Pseudorandom Function TLS makes use of a pseudorandom function referred to as PRF to expand secrets into blocks of data for purposes of key generation or validation. The objective is to make use of a relatively small, shared secret value but to generate longer blocks of data in a way that is secure from the kinds of attacks made on hash functions and MACs. The PRF is based on the data expansion function (Figure 17.7) given as

$$\begin{aligned}\text{P\_hash}(\text{secret}, \text{seed}) = &\text{HMAC\_hash}(\text{secret}, \text{A}(1) \parallel \text{seed}) \parallel \\ &\text{HMAC\_hash}(\text{secret}, \text{A}(2) \parallel \text{seed}) \parallel \\ &\text{HMAC\_hash}(\text{secret}, \text{A}(3) \parallel \text{seed}) \parallel\end{aligned}$$

where A() is defined as

$$\begin{aligned}\text{A}(0) &= \text{seed} \\ \text{A}(i) &= \text{HMAC\_hash}(\text{secret}, A(i-1))\end{aligned}$$

The data expansion function makes use of the HMAC algorithm with either MD5 or SHA-1 as the underlying hash function. As can be seen, `P_hash` can be iterated as many times as necessary to produce the required quantity of data. For example, if `P_SHA256` was used to generate 80 bytes of data, it would have to be iterated three times (through A(3)), producing 96 bytes of data of which the last 16 would be discarded. In this case, `P_MD5` would have to be iterated four times, producing exactly 64 bytes of data. Note that each iteration involves two executions of HMAC, each of which in turn involves two executions of the underlying hash algorithm.

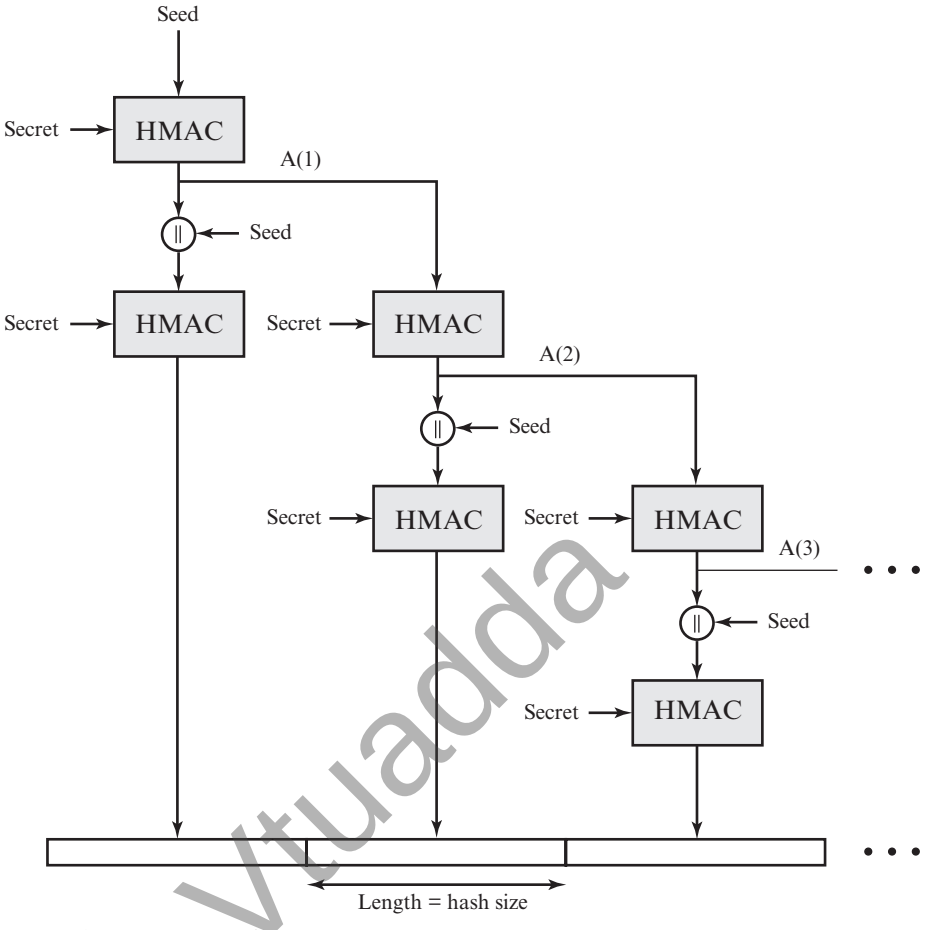


Figure 17.7 TLS Function `P_hash(secret, seed)`

To make PRF as secure as possible, it uses two hash algorithms in a way that should guarantee its security if either algorithm remains secure. PRF is defined as

$$\text{PRF(secret, label, seed)} = \text{P\_<hash>(secret, label} \parallel \text{seed)}$$

PRF takes as input a secret value, an identifying label, and a seed value and produces an output of arbitrary length.

Heartbeat Protocol

In the context of computer networks, a heartbeat is a periodic signal generated by hardware or software to indicate normal operation or to synchronize other parts of a system. A heartbeat protocol is typically used to monitor the availability of a protocol entity. In the specific case of TLS, a Heartbeat protocol was defined in 2012 in RFC 6250 (*Transport Layer Security (TLS) and Datagram Transport Layer Security (DTLS) Heartbeat Extension*).

The Heartbeat protocol runs on top of the TLS Record Protocol and consists of two message types: `heartbeat_request` and `heartbeat_response`. The use of the Heartbeat protocol is established during Phase 1 of the Handshake protocol (Figure 17.6). Each peer indicates whether it supports heartbeats. If heartbeats are supported, the peer indicates whether it is willing to receive `heartbeat_request` messages and respond with `heartbeat_response` messages or only willing to send `heartbeat_request` messages.

A `heartbeat_request` message can be sent at any time. Whenever a request message is received, it should be answered promptly with a corresponding `heartbeat_response` message. The `heartbeat_request` message includes payload length, payload, and padding fields. The payload is a random content between 16 bytes and 64 Kbytes in length. The corresponding `heartbeat_response` message must include an exact copy of the received payload. The padding is also random content. The padding enables the sender to perform a path MTU (maximum transfer unit) discovery operation, by sending requests with increasing padding until there is no answer anymore, because one of the hosts on the path cannot handle the message.

The heartbeat serves two purposes. First, it assures the sender that the recipient is still alive, even though there may not have been any activity over the underlying TCP connection for a while. Second, the heartbeat generates activity across the connection during idle periods, which avoids closure by a firewall that does not tolerate idle connections.

The requirement for the exchange of a payload was designed into the Heartbeat protocol to support its use in a connectionless version of TLS known as Datagram Transport Layer Security (DTLS). Because a connectionless service is subject to packet loss, the payload enables the requestor to match response messages to request messages. For simplicity, the same version of the Heartbeat protocol is used with both TLS and DTLS. Thus, the payload is required for both TLS and DTLS.

SSL/TLS ATTACKS

Since the first introduction of SSL in 1994, and the subsequent standardization of TLS, numerous attacks have been devised against these protocols. The appearance of each attack has necessitated changes in the protocol, the encryption tools used, or some aspect of the implementation of SSL and TLS to counter these threats.

Attack Categories We can group the attacks into four general categories:

- **Attacks on the handshake protocol:** As early as 1998, an approach to compromising the handshake protocol based on exploiting the formatting and implementation of the RSA encryption scheme was presented [BLEI98]. As countermeasures were implemented the attack was refined and adjusted to not only thwart the countermeasures but also speed up the attack [e.g., BARD12].
- **Attacks on the record and application data protocols:** A number of vulnerabilities have been discovered in these protocols, leading to patches to counter the new threats. As a recent example, in 2011, researchers Thai Duong and Juliano Rizzo demonstrated a proof of concept called BEAST (Browser Exploit Against SSL/TLS) that turned what had been considered only a theoretical vulnerability

into a practical attack [GOOD11]. BEAST leverages a type of cryptographic attack called a chosen-plaintext attack. The attacker mounts the attack by choosing a guess for the plaintext that is associated with a known ciphertext. The researchers developed a practical algorithm for launching successful attacks. Subsequent patches were able to thwart this attack. The authors of the BEAST attack are also the creators of the 2012 CRIME (Compression Ratio Info-leak Made Easy) attack, which can allow an attacker to recover the content of web cookies when data compression is used along with TLS [GOOD12]. When used to recover the content of secret authentication cookies, it allows an attacker to perform session hijacking on an authenticated web session.

- **Attacks on the PKI:** Checking the validity of X.509 certificates is an activity subject to a variety of attacks, both in the context of SSL/TLS and elsewhere. For example, [GEOR12] demonstrated that commonly used libraries for SSL/TLS suffer from vulnerable certificate validation implementations. The authors revealed weaknesses in the source code of OpenSSL, GnuTLS, JSSE, ApacheHttpClient, Weberknecht, cURL, PHP, Python and applications built upon or with these products.
- **Other attacks:** [MEYE13] lists a number of attacks that do not fit into any of the preceding categories. One example is an attack announced in 2011 by the German hacker group The Hackers Choice, which is a DoS attack [KUMA11]. The attack creates a heavy processing load on a server by overwhelming the target with SSL/TLS handshake requests. Boosting system load is done by establishing new connections or using renegotiation. Assuming that the majority of computation during a handshake is done by the server, the attack creates more system load on the server than on the source device, leading to a DoS. The server is forced to continuously recompute random numbers and keys.

The history of attacks and countermeasures for SSL/TLS is representative of that for other Internet-based protocols. A "perfect" protocol and a "perfect" implementation strategy are never achieved. A constant back-and-forth between threats and countermeasures determines the evolution of Internet-based protocols.

TLSv1.3

In 2014, the IETF TLS working group began work on a version 1.3 of TLS. The primary aim is to improve the security of TLS. As of this writing, TLSv1.3 is still in a draft stage, but the final standard is likely to be very close to the current draft. Among the significant changes from version 1.2 are the following:

- TLSv1.3 removes support for a number of options and functions. Removing code that implements functions no longer needed reduces the chances of potentially dangerous coding errors and reduces the attack surface. The deleted items include:
  - –Compression
  - –Ciphers that do not offer authenticated encryption
  - –Static RSA and DH key exchange
  - –32-bit timestamp as part of the Random parameter in the client_hello message

–Renegotiation
–Change Cipher Spec Protocol
–RC4
–Use of MD5 and SHA-224 hashes with signatures

- TLSv1.3 uses Diffie–Hellman or Elliptic Curve Diffie–Hellman for key exchange and does not permit RSA. The danger with RSA is that if the private key is compromised, all handshakes using these cipher suites will be compromised. With DH or ECDH, a new key is negotiated for each handshake.
- TLSv1.3 allows for a "1 round trip time" handshake by changing the order of message sent with establishing a secure connection. The client sends a Client Key Exchange message containing its cryptographic parameters for key establishment before a cipher suite has been negotiated. This enables a server to calculate keys for encryption and authentication before sending its first response. Reducing the number of packets sent during this handshake phase speeds up the process and reduces the attack surface.

These changes should improve the efficiency and security of TLS.

19.3 EMAIL THREATS AND COMPREHENSIVE EMAIL SECURITY

For both organizations and individuals, email is both pervasive and especially vulnerable to a wide range of security threats. In general terms, email security threats can be classified as follows:

- **Authenticity-related threats:** Could result in unauthorized access to an enterprise's email system.
- **Integrity-related threats:** Could result in unauthorized modification of email content.
- **Confidentiality-related threats:** Could result in unauthorized disclosure of sensitive information.
- **Availability-related threats:** Could prevent end users from being able to send or receive email.

A useful list of specific email threats, together with approaches to mitigation, is provided in NIST SP 800-177 (*Trustworthy Email*, September 2015) and is shown in Table 19.3.

SP 800-177 recommends use of a variety of standardized protocols as a means for countering these threats. These include:

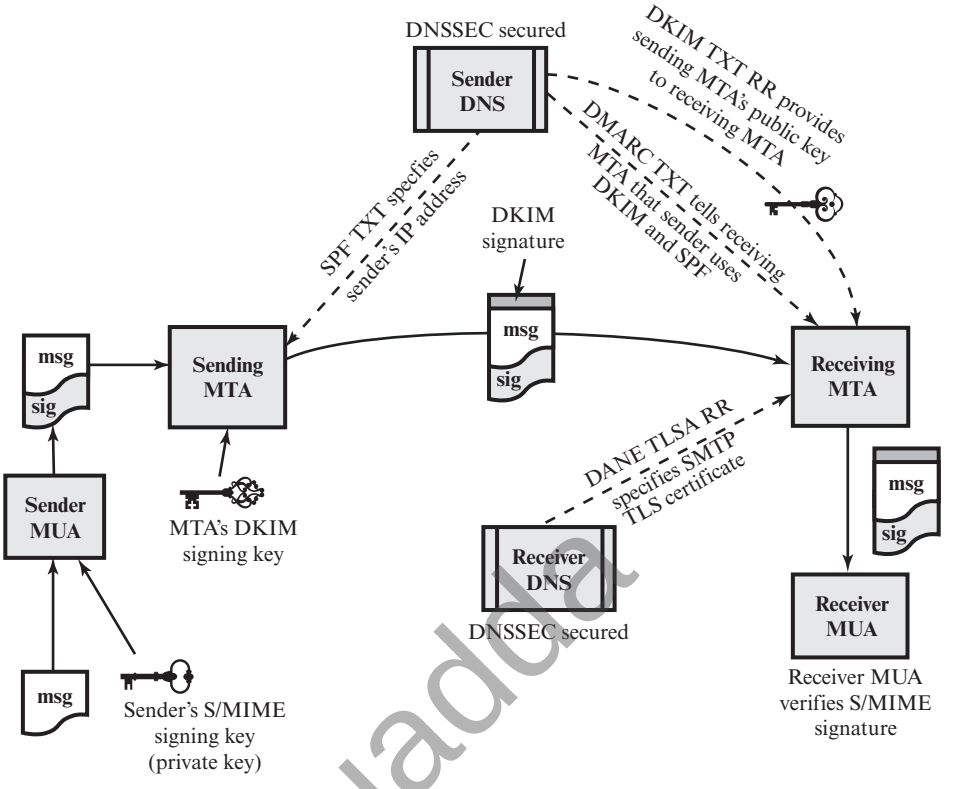
- **STARTTLS:** An SMTP security extension that provides authentication, integrity, non-repudiation (via digital signatures) and confidentiality (via encryption) for the entire SMTP message by running SMTP over TLS.
- **S/MIME:** Provides authentication, integrity, non-repudiation (via digital signatures) and confidentiality (via encryption) of the message body carried in SMTP messages.
- **DNS Security Extensions (DNSSEC):** Provides authentication and integrity protection of DNS data, and is an underlying tool used by various email security protocols.
- **DNS-based Authentication of Named Entities (DANE):** Is designed to overcome problems in the certificate authority (CA) system by providing an alternative channel for authenticating public keys based on DNSSEC, with the

Table 19.3 Email Threats and Mitigations

Threat	Impact on Purported Sender	Impact on Receiver	Mitigation
Email sent by unauthorized MTA in enterprise (e.g., malware botnet)	Loss of reputation, valid email from enterprise may be blocked as possible spam/phishing attack.	UBE and/or email containing malicious links may be delivered into user inboxes.	Deployment of domain-based authentication techniques. Use of digital signatures over email.
Email message sent using spoofed or unregistered sending domain	Loss of reputation, valid email from enterprise may be blocked as possible spam/phishing attack.	UBE and/or email containing malicious links may be delivered into user inboxes.	Deployment of domain-based authentication techniques. Use of digital signatures over email.
Email message sent using forged sending address or email address (i.e., phishing, spear phishing)	Loss of reputation, valid email from enterprise may be blocked as possible spam/phishing attack.	UBE and/or email containing malicious links may be delivered. Users may inadvertently divulge sensitive information or PII.	Deployment of domain-based authentication techniques. Use of digital signatures over email.
Email modified in transit	Leak of sensitive information or PII.	Leak of sensitive information, altered message may contain malicious information.	Use of TLS to encrypt email transfer between servers. Use of end-to-end email encryption.
Disclosure of sensitive information (e.g., PII) via monitoring and capturing of email traffic	Leak of sensitive information or PII.	Leak of sensitive information, altered message may contain malicious information.	Use of TLS to encrypt email transfer between servers. Use of end-to-end email encryption.
Unsolicited Bulk Email (UBE) (i.e., spam)	None, unless purported sender is spoofed.	UBE and/or email containing malicious links may be delivered into user inboxes.	Techniques to address UBE.
DoS/DDoS attack against an enterprises' email servers	Inability to send email.	Inability to receive email.	Multiple mail servers, use of cloud-based email providers.

result that the same trust relationships used to certify IP addresses are used to certify servers operating on those addresses.

- **Sender Policy Framework (SPF):** Uses the Domain Name System (DNS) to allow domain owners to create records that associate the domain name with a specific IP address range of authorized message senders. It is a simple matter for receivers to check the SPF TXT record in the DNS to confirm that the purported sender of a message is permitted to use that source address and reject mail that does not come from an authorized IP address.
- **DomainKeys Identified Mail (DKIM):** Enables an MTA to sign selected headers and the body of a message. This validates the source domain of the mail and provides message body integrity.
- **Domain-based Message Authentication, Reporting, and Conformance (DMARC):** Lets senders know the proportionate effectiveness of their SPF and DKIM policies, and signals to receivers what action should be taken in various individual and bulk attack scenarios.



DANE = DNS-based Authentication of Named Entities
DKIM = DomainKeys Identified Mail
DMARC = Domain-based Message Authentication, Reporting, and Conformance
DNSSEC = Domain Name System Security Extensions
SPF = Sender Policy Framework
S/MIME = Secure Multi-Purpose Internet Mail Extensions
TLSA RR = Transport Layer Security Authentication Resource Record

Figure 19.4 The Interrelationship of DNSSEC, SPF, DKIM, DMARC, DANE, and S/MIME for Assuring Message Authenticity and Integrity

Figure 19.4 shows how these components interact to provide message authenticity and integrity. Not shown, for simplicity, is that S/MIME also provides message confidentiality by encrypting messages.

19.4 S/MIME

Secure/Multipurpose Internet Mail Extension (S/MIME) is a security enhancement to the MIME Internet email format standard based on technology from RSA Data Security. S/MIME is a complex capability that is defined in a number of documents. The most important documents relevant to S/MIME include the following:

- **RFC 5750, S/MIME Version 3.2 Certificate Handling:** Specifies conventions for X.509 certificate usage by (S/MIME) v3.2.

- **RFC 5751, S/MIME) Version 3.2 Message Specification:** The principal defining document for S/MIME message creation and processing.
- **RFC 4134, Examples of S/MIME Messages:** Gives examples of message bodies formatted using S/MIME.
- **RFC 2634, Enhanced Security Services for S/MIME:** Describes four optional security service extensions for S/MIME.
- **RFC 5652, Cryptographic Message Syntax (CMS):** Describes the Cryptographic Message Syntax (CMS). This syntax is used to digitally sign, digest, authenticate, or encrypt arbitrary message content.
- **RFC 3370, CMS Algorithms:** Describes the conventions for using several cryptographic algorithms with the CMS.
- **RFC 5752, Multiple Signatures in CMS:** Describes the use of multiple, parallel signatures for a message.
- **RFC 1847, Security Multiparts for MIME—Multipart/Signed and Multipart/Encrypted:** Defines a framework within which security services may be applied to MIME body parts. The use of a digital signature is relevant to S/MIME, as explained subsequently.

Operational Description

S/MIME provides for four message-related services: authentication, confidentiality, compression, and email compatibility (Table 19.4). This subsection provides an overview. We then look in more detail at this capability by examining message formats and message preparation.

Authentication Authentication is provided by means of a digital signature, using the general scheme discussed in Chapter 13 and illustrated in Figure 13.1. Most commonly RSA with SHA-256 is used. The sequence is as follows:

1. The sender creates a message.
2. SHA-256 is used to generate a 256-bit message digest of the message.

Table 19.4 Summary of S/MIME Services

Function	Typical Algorithm	Typical Action
Digital signature	RSA/SHA-256	A hash code of a message is created using SHA-256. This message digest is encrypted using SHA-256 with the sender's private key and included with the message.
Message encryption	AES-128 with CBC	A message is encrypted using AES-128 with CBC with a one-time session key generated by the sender. The session key is encrypted using RSA with the recipient's public key and included with the message.
Compression	unspecified	A message may be compressed for storage or transmission.
Email compatibility	Radix-64 conversion	To provide transparency for email applications, an encrypted message may be converted to an ASCII string using radix-64 conversion.

3. The message digest is encrypted with RSA using the sender's private key, and the result is appended to the message. Also appended is identifying information for the signer, which will enable the receiver to retrieve the signer's public key.
4. The receiver uses RSA with the sender's public key to decrypt and recover the message digest.
5. The receiver generates a new message digest for the message and compares it with the decrypted hash code. If the two match, the message is accepted as authentic.

The combination of SHA-256 and RSA provides an effective digital signature scheme. Because of the strength of RSA, the recipient is assured that only the possessor of the matching private key can generate the signature. Because of the strength of SHA-256, the recipient is assured that no one else could generate a new message that matches the hash code and, hence, the signature of the original message.

Although signatures normally are found attached to the message or file that they sign, this is not always the case: Detached signatures are supported. A detached signature may be stored and transmitted separately from the message it signs. This is useful in several contexts. A user may wish to maintain a separate signature log of all messages sent or received. A detached signature of an executable program can detect subsequent virus infection. Finally, detached signatures can be used when more than one party must sign a document, such as a legal contract. Each person's signature is independent and therefore is applied only to the document. Otherwise, signatures would have to be nested, with the second signer signing both the document and the first signature, and so on.

Confidentiality S/MIME provides confidentiality by encrypting messages. Most commonly AES with a 128-bit key is used, with the cipher block chaining (CBC) mode. The key itself is also encrypted, typically with RSA, as explained below.

As always, one must address the problem of key distribution. In S/MIME, each symmetric key, referred to as a content-encryption key, is used only once. That is, a new key is generated as a random number for each message. Because it is to be used only once, the content-encryption key is bound to the message and transmitted with it. To protect the key, it is encrypted with the receiver's public key. The sequence can be described as follows:

1. The sender generates a message and a random 128-bit number to be used as a content-encryption key for this message only.
2. The message is encrypted using the content-encryption key.
3. The content-encryption key is encrypted with RSA using the recipient's public key and is attached to the message.
4. The receiver uses RSA with its private key to decrypt and recover the content-encryption key.
5. The content-encryption key is used to decrypt the message.

Several observations may be made. First, to reduce encryption time, the combination of symmetric and public-key encryption is used in preference to simply using public-key encryption to encrypt the message directly: Symmetric algorithms

are substantially faster than asymmetric ones for a large block of content. Second, the use of the public-key algorithm solves the session-key distribution problem, because only the recipient is able to recover the session key that is bound to the message. Note that we do not need a session-key exchange protocol of the type discussed in Chapter 14, because we are not beginning an ongoing session. Rather, each message is a one-time independent event with its own key. Furthermore, given the store-and-forward nature of electronic mail, the use of handshaking to assure that both sides have the same session key is not practical. Finally, the use of one-time symmetric keys strengthens what is already a strong symmetric encryption approach. Only a small amount of plaintext is encrypted with each key, and there is no relationship among the keys. Thus, to the extent that the public-key algorithm is secure, the entire scheme is secure.

Confidentiality and Authentication As Figure 19.5 illustrates, both confidentiality and encryption may be used for the same message. The figure shows a sequence in which a signature is generated for the plaintext message and appended to the message. Then the plaintext message and signature are encrypted as a single block using symmetric encryption and the symmetric encryption key is encrypted using public-key encryption.

S/MIME allows the signing and message encryption operations to be performed in either order. If signing is done first, the identity of the signer is hidden by the encryption. Plus, it is generally more convenient to store a signature with a plaintext version of a message. Furthermore, for purposes of third-party verification, if the signature is performed first, a third party need not be concerned with the symmetric key when verifying the signature.

If encryption is done first, it is possible to verify a signature without exposing the message content. This can be useful in a context in which automatic signature verification is desired, as no private key material is required to verify a signature. However, in this case the recipient cannot determine any relationship between the signer and the unencrypted content of the message.

Email Compatibility When S/MIME is used, at least part of the block to be transmitted is encrypted. If only the signature service is used, then the message digest is encrypted (with the sender's private key). If the confidentiality service is used, the message plus signature (if present) are encrypted (with a one-time symmetric key). Thus, part or all of the resulting block consists of a stream of arbitrary 8-bit octets. However, many electronic mail systems only permit the use of blocks consisting of ASCII text. To accommodate this restriction, S/MIME provides the service of converting the raw 8-bit binary stream to a stream of printable ASCII characters, a process referred to as 7-bit encoding.

The scheme typically used for this purpose is Base64 conversion. Each group of three octets of binary data is mapped into four ASCII characters. See Appendix X for a description.

One noteworthy aspect of the Base64 algorithm is that it blindly converts the input stream to Base64 format regardless of content, even if the input happens to be ASCII text. Thus, if a message is signed but not encrypted and the conversion is applied to the entire block, the output will be unreadable to the casual observer, which provides a certain level of confidentiality.

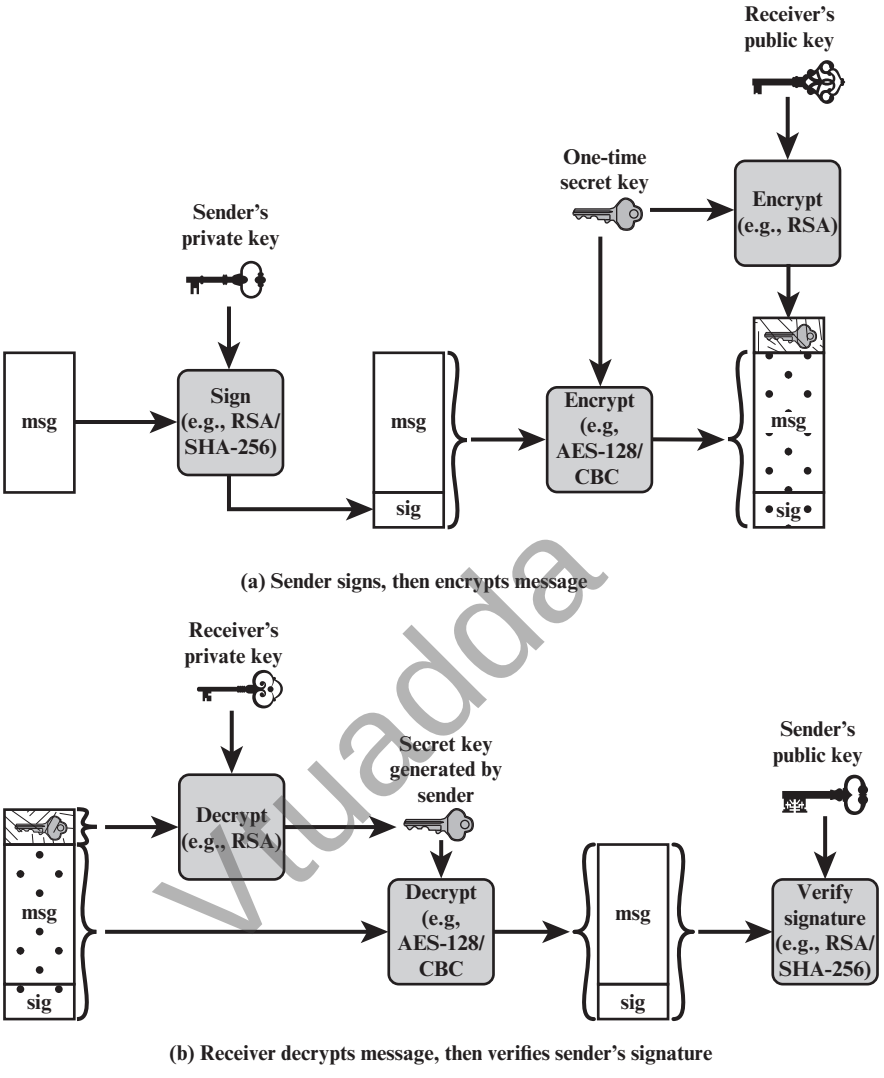


Figure 19.5 Simplified S/MIME Functional Flow

RFC 5751 also recommends that even if outer 7-bit encoding is not used, the original MIME content should be 7-bit encoded. The reason for this is that it allows the MIME entity to be handled in any environment without changing it. For example, a trusted gateway might remove the encryption, but not the signature, of a message, and then forward the signed message on to the end recipient so that they can verify the signatures directly. If the transport internal to the site is not 8-bit clean, such as on a wide area network with a single mail gateway, verifying the signature will not be possible unless the original MIME entity was only 7-bit data.

Compression S/MIME also offers the ability to compress a message. This has the benefit of saving space both for email transmission and for file storage. Compression

can be applied in any order with respect to the signing and message encryption operations. RFC 5751 provides the following guidelines:

- Compression of binary encoded encrypted data is discouraged, since it will not yield significant compression. Base64 encrypted data could very well benefit, however.
- If a lossy compression algorithm is used with signing, you will need to compress first, then sign.

S/MIME Message Content Types

S/MIME uses the following message content types, which are defined in RFC 5652, Cryptographic Message Syntax:

- **Data:** Refers to the inner MIME-encoded message content, which may then be encapsulated in a SignedData, EnvelopedData, or CompressedData content type.
- **SignedData:** Used to apply a digital signature to a message.
- **EnvelopedData:** This consists of encrypted content of any type and encrypted-content encryption keys for one or more recipients.
- **CompressedData:** Used to apply data compression to a message.

The Data content type is also used for a procedure known as clear signing. For clear signing, a digital signature is calculated for a MIME-encoded message and the two parts, the message and signature, form a multipart MIME message. Unlike SignedData, which involves encapsulating the message and signature in a special format, clear-signed messages can be read and their signatures verified by email entities that do not implement S/MIME.

Approved Cryptographic Algorithms

Table 19.5 summarizes the cryptographic algorithms used in S/MIME. S/MIME uses the following terminology taken from RFC 2119 (*Key Words for use in RFCs to Indicate Requirement Levels*, March 1997) to specify the requirement level:

- **MUST:** The definition is an absolute requirement of the specification. An implementation must include this feature or function to be in conformance with the specification.
- **SHOULD:** There may exist valid reasons in particular circumstances to ignore this feature or function, but it is recommended that an implementation include the feature or function.

The S/MIME specification includes a discussion of the procedure for deciding which content encryption algorithm to use. In essence, a sending agent has two decisions to make. First, the sending agent must determine if the receiving agent is capable of decrypting using a given encryption algorithm. Second, if the receiving agent is only capable of accepting weakly encrypted content, the sending agent must decide if it is acceptable to send using weak encryption. To support this decision process, a sending agent may announce its decrypting capabilities in order of preference for any message that it sends out. A receiving agent may store that information for future use.

Table 19.5 Cryptographic Algorithms Used in S/MIME

Function	Requirement
Create a message digest to be used in forming a digital signature.	MUST support SHA-256 SHOULD support SHA-1 Receiver SHOULD support MD5 for backward compatibility
Use message digest to form a digital signature.	MUST support RSA with SHA-256 SHOULD support —DSA with SHA-256 —RSASSA-PSS with SHA-256 —RSA with SHA-1 —DSA with SHA-1 —RSA with MD5
Encrypt session key for transmission with a message.	MUST support RSA encryption SHOULD support —RSAES-OAEP —Diffie–Hellman ephemeral-static mode
Encrypt message for transmission with a one-time session key.	MUST support AES-128 with CBC SHOULD support —AES-192 CBC and AES-256 CBC —Triple DES CBC

The following rules, in the following order, should be followed by a sending agent.

1. If the sending agent has a list of preferred decrypting capabilities from an intended recipient, it SHOULD choose the first (highest preference) capability on the list that it is capable of using.
2. If the sending agent has no such list of capabilities from an intended recipient but has received one or more messages from the recipient, then the outgoing message SHOULD use the same encryption algorithm as was used on the last signed and encrypted message received from that intended recipient.
3. If the sending agent has no knowledge about the decryption capabilities of the intended recipient and is willing to risk that the recipient may not be able to decrypt the message, then the sending agent SHOULD use triple DES.
4. If the sending agent has no knowledge about the decryption capabilities of the intended recipient and is not willing to risk that the recipient may not be able to decrypt the message, then the sending agent MUST use RC2/40.

If a message is to be sent to multiple recipients and a common encryption algorithm cannot be selected for all, then the sending agent will need to send two messages. However, in that case, it is important to note that the security of the message is made vulnerable by the transmission of one copy with lower security.

S/MIME Messages

S/MIME makes use of a number of new MIME content types. All of the new application types use the designation PKCS. This refers to a set of public-key cryptography specifications issued by RSA Laboratories and made available for the S/MIME effort.

We examine each of these in turn after first looking at the general procedures for S/MIME message preparation.

Securing a MIME Entity S/MIME secures a MIME entity with a signature, encryption, or both. A MIME entity may be an entire message (except for the RFC 5322 headers), or if the MIME content type is multipart, then a MIME entity is one or more of the subparts of the message. The MIME entity is prepared according to the normal rules for MIME message preparation. Then the MIME entity plus some security-related data, such as algorithm identifiers and certificates, are processed by S/MIME to produce what is known as a PKCS object. A PKCS object is then treated as message content and wrapped in MIME (provided with appropriate MIME headers). This process should become clear as we look at specific objects and provide examples.

In all cases, the message to be sent is converted to canonical form. In particular, for a given type and subtype, the appropriate canonical form is used for the message content. For a multipart message, the appropriate canonical form is used for each subpart.

The use of transfer encoding requires special attention. For most cases, the result of applying the security algorithm will be to produce an object that is partially or totally represented in arbitrary binary data. This will then be wrapped in an outer MIME message and transfer encoding can be applied at that point, typically base64. However, in the case of a multipart signed message (described in more detail later), the message content in one of the subparts is unchanged by the security process. Unless that content is 7 bit, it should be transfer encoded using base64 or quoted-printable so that there is no danger of altering the content to which the signature was applied.

We now look at each of the S/MIME content types.

EnvelopedData An application/pkcs7-mime subtype is used for one of four categories of S/MIME processing, each with a unique smime-type parameter. In all cases, the resulting entity, (referred to as an *object*) is represented in a form known as Basic Encoding Rules (BER), which is defined in ITU-T Recommendation X.209. The BER format consists of arbitrary octet strings and is therefore binary data. Such an object should be transfer encoded with base64 in the outer MIME message. We first look at envelopedData.

The steps for preparing an envelopedData MIME entity are:

1. Generate a pseudorandom session key for a particular symmetric encryption algorithm (RC2/40 or triple DES).
2. For each recipient, encrypt the session key with the recipient's public RSA key.
3. For each recipient, prepare a block known as `RecipientInfo` that contains an identifier of the recipient's public-key certificate,[1] an identifier of the algorithm used to encrypt the session key, and the encrypted session key.
4. Encrypt the message content with the session key.

[1]This is an X.509 certificate, discussed later in this section.

The RecipientInfo blocks followed by the encrypted content constitute the envelopedData. This information is then encoded into base64. A sample message (excluding the RFC 5322 headers) is given below.

```
Content-Type: application/pkcs7-mime; smime-type=enveloped-
       data; name=smime.p7m
Content-Transfer-Encoding: base64
Content-Disposition: attachment; filename=smime.p7m

rfvbnj756tbBghyHhHUujhJhjH77n8HHGT9HG4VQpfyF467GhIGfHfYT6
7n8HHGghyHhHUujhJh4VQpfyF467GhIGfHfYGTrfvbnjT6jH7756tbB9H
f8HHGTrfvhJhjH776tbB9HG4VQbnj7567GhIGfHfYT6ghyHhHUujpfyF4
0GhIGfHfQbnj756YT64V
```

To recover the encrypted message, the recipient first strips off the base64 encoding. Then the recipient's private key is used to recover the session key. Finally, the message content is decrypted with the session key.

SignedData The signedData smime-type can be used with one or more signers. For clarity, we confine our description to the case of a single digital signature. The steps for preparing a signedData MIME entity are as follows.

1. Select a message digest algorithm (SHA or MD5).
2. Compute the message digest (hash function) of the content to be signed.
3. Encrypt the message digest with the signer's private key.
4. Prepare a block known as SignerInfo that contains the signer's public-key certificate, an identifier of the message digest algorithm, an identifier of the algorithm used to encrypt the message digest, and the encrypted message digest.

The signedData entity consists of a series of blocks, including a message digest algorithm identifier, the message being signed, and SignerInfo. The signedData entity may also include a set of public-key certificates sufficient to constitute a chain from a recognized root or top-level certification authority to the signer. This information is then encoded into base64. A sample message (excluding the RFC 5322 headers) is the following.

```
Content-Type: application/pkcs7-mime; smime-type=signed-
       data; name=smime.p7m
Content-Transfer-Encoding: base64
Content-Disposition: attachment; filename=smime.p7m

567GhIGfHfYT6ghyHhHUujpfyF4f8HHGTrfvhJhjH776tbB9HG4VQbnj7
77n8HHGT9HG4VQpfyF467GhIGfHfYT6rfvbnj756tbBghyHhHUujhJhjH
HUujhJh4VQpfyF467GhIGfHfYGTrfvbnjT6jH7756tbB9H7n8HHGghyHh
6YT64V0GhIGfHfQbnj75
```

To recover the signed message and verify the signature, the recipient first strips off the base64 encoding. Then the signer's public key is used to decrypt the message digest. The recipient independently computes the message digest and compares it to the decrypted message digest to verify the signature.

Clear Signing Clear signing is achieved using the multipart content type with a signed subtype. As was mentioned, this signing process does not involve transforming the message to be signed, so that the message is sent "in the clear." Thus, recipients with MIME capability but not S/MIME capability are able to read the incoming message.

A multipart/signed message has two parts. The first part can be any MIME type but must be prepared so that it will not be altered during transfer from source to destination. This means that if the first part is not 7 bit, then it needs to be encoded using base64 or quoted-printable. Then this part is processed in the same manner as `signedData`, but in this case an object with `signedData` format is created that has an empty message content field. This object is a detached signature. It is then transfer encoded using base64 to become the second part of the multipart/signed message. This second part has a MIME content type of application and a subtype of pkcs7-signature. Here is a sample message:

```
Content-Type: multipart/signed;
   protocol="application/pkcs7-signature";
   micalg=sha1; boundary=boundary42

—boundary42
Content-Type: text/plain

This is a clear-signed message.

—boundary42
Content-Type: application/pkcs7-signature; name=smime.p7s
Content-Transfer-Encoding: base64
Content-Disposition: attachment; filename=smime.p7s

ghyHhHUujhJhjH77n8HHGTrfvbnj756tbB9HG4VQpfyF467GhIGfHfYT6
4VQpfyF467GhIGfHfYT6jH77n8HHGghyHhHUujhJh756tbB9HGTrfvbnj
n8HHGTrfvhJhjH776tbB9HG4VQbnj7567GhIGfHfYT6ghyHhHUujpfyF4
7GhIGfHfYT64VQbnj756
—boundary42—
```

The protocol parameter indicates that this is a two-part clear-signed entity. The `micalg` parameter indicates the type of message digest used. The receiver can verify the signature by taking the message digest of the first part and comparing this to the message digest recovered from the signature in the second part.

Registration Request Typically, an application or user will apply to a certification authority for a public-key certificate. The application/pkcs10 S/MIME

entity is used to transfer a certification request. The certification request includes `certificationRequestInfo` block, followed by an identifier of the public-key encryption algorithm, followed by the signature of the `certificationRequestInfo` block, made using the sender's private key. The `certificationRequestInfo` block includes a name of the certificate subject (the entity whose public key is to be certified) and a bit-string representation of the user's public key.

Certificates-Only Message A message containing only certificates or a certificate revocation list (CRL) can be sent in response to a registration request. The message is an application/pkcs7-mime type/subtype with an smime-type parameter of degenerate. The steps involved are the same as those for creating a `signedData` message, except that there is no message content and the `signerInfo` field is empty.

S/MIME Certificate Processing

S/MIME uses public-key certificates that conform to version 3 of X.509 (see Chapter 14). S/MIME managers and/or users must configure each client with a list of trusted keys and with certificate revocation lists. That is, the responsibility is local for maintaining the certificates needed to verify incoming signatures and to encrypt outgoing messages. On the other hand, the certificates are signed by certification authorities.

User Agent Role An S/MIME user has several key management functions to perform.

- **Key generation:** The user of some related administrative utility (e.g., one associated with LAN management) MUST be capable of generating separate Diffie–Hellman and DSS key pairs and SHOULD be capable of generating RSA key pairs. Each key pair MUST be generated from a good source of nondeterministic random input and be protected in a secure fashion. A user agent SHOULD generate RSA key pairs with a length in the range of 768 to 1024 bits and MUST NOT generate a length of less than 512 bits.
- **Registration:** A user's public key must be registered with a certification authority in order to receive an X.509 public-key certificate.
- **Certificate storage and retrieval:** A user requires access to a local list of certificates in order to verify incoming signatures and to encrypt outgoing messages. Such a list could be maintained by the user or by some local administrative entity on behalf of a number of users.

Enhanced Security Services

RFC 2634 defines four enhanced security services for S/MIME:

- **Signed receipts:** A signed receipt may be requested in a `SignedData` object. Returning a signed receipt provides proof of delivery to the originator of a message and allows the originator to demonstrate to a third party that the recipient received the message. In essence, the recipient signs the entire original message plus the original (sender's) signature and appends the new signature to form a new S/MIME message.

- **Security labels:** A security label may be included in the authenticated attributes of a `SignedData` object. A security label is a set of security information regarding the sensitivity of the content that is protected by S/MIME encapsulation. The labels may be used for access control, by indicating which users are permitted access to an object. Other uses include priority (secret, confidential, restricted, and so on) or role based, describing which kind of people can see the information (e.g., patient's health-care team, medical billing agents).
- **Secure mailing lists:** When a user sends a message to multiple recipients, a certain amount of per-recipient processing is required, including the use of each recipient's public key. The user can be relieved of this work by employing the services of an S/MIME Mail List Agent (MLA). An MLA can take a single incoming message, perform the recipient-specific encryption for each recipient, and forward the message. The originator of a message need only send the message to the MLA with encryption performed using the MLA's public key.
- **Signing certificates:** This service is used to securely bind a sender's certificate to their signature through a signing certificate attribute.

19.5 PRETTY GOOD PRIVACY

An alternative email security protocol is Pretty Good Privacy (PGP), which has essentially the same functionality as S/MIME. PGP was created by Phil Zimmerman and implemented as a product first released in 1991. It was made available free of charge and became quite popular for personal use. The initial PGP protocol was proprietary and used some encryption algorithms with intellectual property restrictions. In 1996, version 5.x of PGP was defined in IETF RFC 1991, *PGP Message Exchange Formats*. Subsequently, OpenPGP was developed as a new standard protocol based on PGP version 5.x. OpenPGP is defined in RFC 4880 (*OpenPGP Message Format*, November 2007) and RFC 3156 (*MIME Security with OpenPGP*, August 2001).

There are two significant differences between S/MIME and OpenPGP:

- **Key Certification:** S/MIME uses X.509 certificates that are issued by Certificate Authorities (or local agencies that have been delegated authority by a CA to issue certificates). In OpenPGP, users generate their own OpenPGP public and private keys and then solicit signatures for their public keys from individuals or organizations to which they are known. Whereas X.509 certificates are trusted if there is a valid PKIX chain to a trusted root, an OpenPGP public key is trusted if it is signed by another OpenPGP public key that is trusted by the recipient. This is called the *Web-of-Trust*.
- **Key Distribution:** OpenPGP does not include the sender's public key with each message, so it is necessary for recipients of OpenPGP messages to separately obtain the sender's public key in order to verify the message. Many organizations post OpenPGP keys on TLS-protected websites: People who wish to verify digital signatures or send these organizations encrypted mail

need to manually download these keys and add them to their OpenPGP clients. Keys may also be registered with the OpenPGP public key servers, which are servers that maintain a database of PGP public keys organized by email address. Anyone may post a public key to the OpenPGP key servers, and that public key may contain any email address. There is no vetting of OpenPGP keys, so users must use the Web-of-Trust to decide whether to trust a given public key.

NIST 800-177 recommends the use of S/MIME rather than PGP because of the greater confidence in the CA system of verifying public keys.

Appendix P provides an overview of PGP.