PART FIVE: MUTUAL TRUST

CHAPTER 14

KEY MANAGEMENT AND DISTRIBUTION

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Discuss the concept of a key hierarchy.
- Understand the issues involved in using asymmetric encryption to distribute symmetric keys.
- Present an overview of approaches to public-key distribution and analyze the risks involved in various approaches.
- List and explain the elements in an X.509 certificate.
- Present an overview of public-key infrastructure concepts.

The topics of cryptographic key management and cryptographic key distribution are complex, involving cryptographic, protocol, and management considerations. The purpose of this chapter is to give the reader a feel for the issues involved and a broad survey of the various aspects of key management and distribution. For more information, the place to start is the three-volume NIST SP 800-57, followed by the recommended readings listed at the end of this chapter.

14.1 SYMMETRIC KEY DISTRIBUTION USING SYMMETRIC ENCRYPTION

For symmetric encryption to work, the two parties to an exchange must share the same key, and that key must be protected from access by others. Furthermore, frequent key changes are usually desirable to limit the amount of data compromised if an attacker learns the key. Therefore, the strength of any cryptographic system rests with the *key distribution technique*, a term that refers to the means of delivering a key to two parties who wish to exchange data without allowing others to see the key. For two parties A and B, key distribution can be achieved in a number of ways, as follows:

1. A can select a key and physically deliver it to B.
2. A third party can select the key and physically deliver it to A and B.
3. If A and B have previously and recently used a key, one party can transmit the new key to the other, encrypted using the old key.
4. If A and B each has an encrypted connection to a third party C, C can deliver a key on the encrypted links to A and B.

Options 1 and 2 call for manual delivery of a key. For link encryption, this is a reasonable requirement, because each link encryption device is going to be exchanging data only with its partner on the other end of the link. However, for **end-to-end encryption** over a network, manual delivery is awkward. In a distributed system, any given host or terminal may need to engage in exchanges with many other

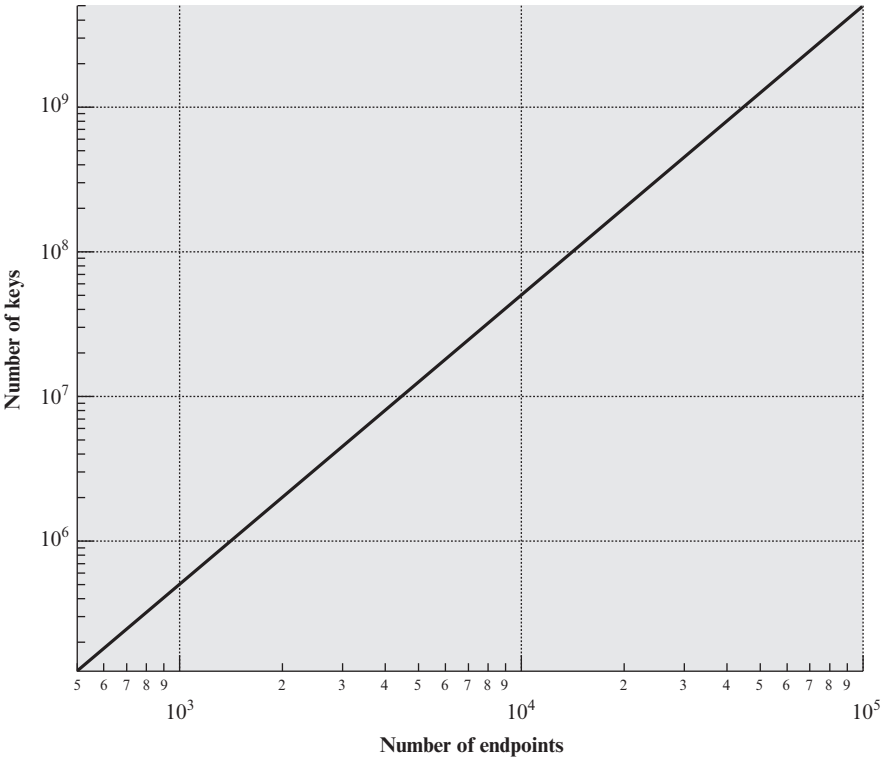


Figure 14.1 Number of Keys Required to Support Arbitrary Connections between Endpoints

hosts and terminals over time. Thus, each device needs a number of keys supplied dynamically. The problem is especially difficult in a wide-area distributed system.

The scale of the problem depends on the number of communicating pairs that must be supported. If end-to-end encryption is done at a network or IP level, then a key is needed for each pair of hosts on the network that wish to communicate. Thus, if there are N hosts, the number of required keys is $[N(N - 1)]/2$. If encryption is done at the application level, then a key is needed for every pair of users or processes that require communication. Thus, a network may have hundreds of hosts but thousands of users and processes. Figure 14.1 illustrates the magnitude of the key distribution task for end-to-end encryption.[1] A network using node-level encryption with 1000 nodes would conceivably need to distribute as many as half a million keys. If that same network supported 10,000 applications, then as many as 50 million keys may be required for application-level encryption.

Returning to our list, option 3 is a possibility for either link encryption or end-to-end encryption, but if an attacker ever succeeds in gaining access to one key, then all subsequent keys will be revealed. Furthermore, the initial distribution of potentially millions of keys still must be made.

[1]Note that this figure uses a log-log scale, so that a linear graph indicates exponential growth. A basic review of log scales is in the math refresher document at the Computer Science Student Resource Site at WilliamStallings.com/StudentSupport.html.

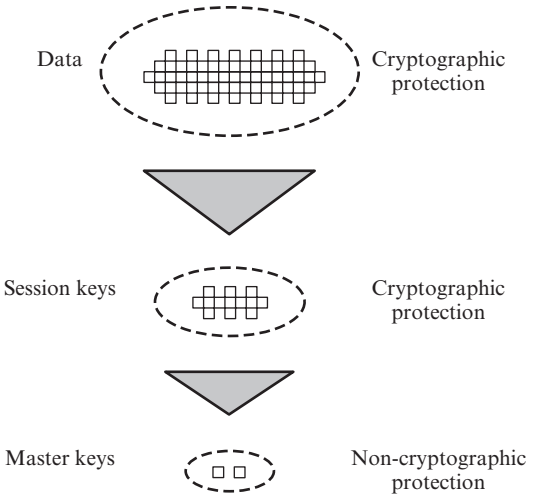


Figure 14.2 The Use of a Key Hierarchy

For end-to-end encryption, some variation on option 4 has been widely adopted. In this scheme, a key distribution center is responsible for distributing keys to pairs of users (hosts, processes, applications) as needed. Each user must share a unique key with the key distribution center for purposes of key distribution.

The use of a key distribution center is based on the use of a hierarchy of keys. At a minimum, two levels of keys are used (Figure 14.2). Communication between end systems is encrypted using a temporary key, often referred to as a **session key**. Typically, the session key is used for the duration of a logical connection, such as a frame relay connection or transport connection, and then discarded. Each session key is obtained from the key distribution center over the same networking facilities used for end-user communication. Accordingly, session keys are transmitted in encrypted form, using a **master key** that is shared by the key distribution center and an end system or user.

For each end system or user, there is a unique master key that it shares with the key distribution center. Of course, these master keys must be securely distributed in some fashion. However, the scale of the problem is vastly reduced. If there are N entities that wish to communicate in pairs, then, as was mentioned, as many as $[N(N - 1)]/2$ session keys are needed at any one time. However, only N master keys are required, one for each entity. Thus, master keys can be distributed in some non-cryptographic way, such as physical delivery.

A Key Distribution Scenario

The key distribution concept can be deployed in a number of ways. A typical scenario is illustrated in Figure 14.3, which is based on a figure in [POPE79]. The scenario assumes that each user shares a unique master key with the key distribution center (KDC).

Let us assume that user A wishes to establish a logical connection with B and requires a one-time session key to protect the data transmitted over the connection.

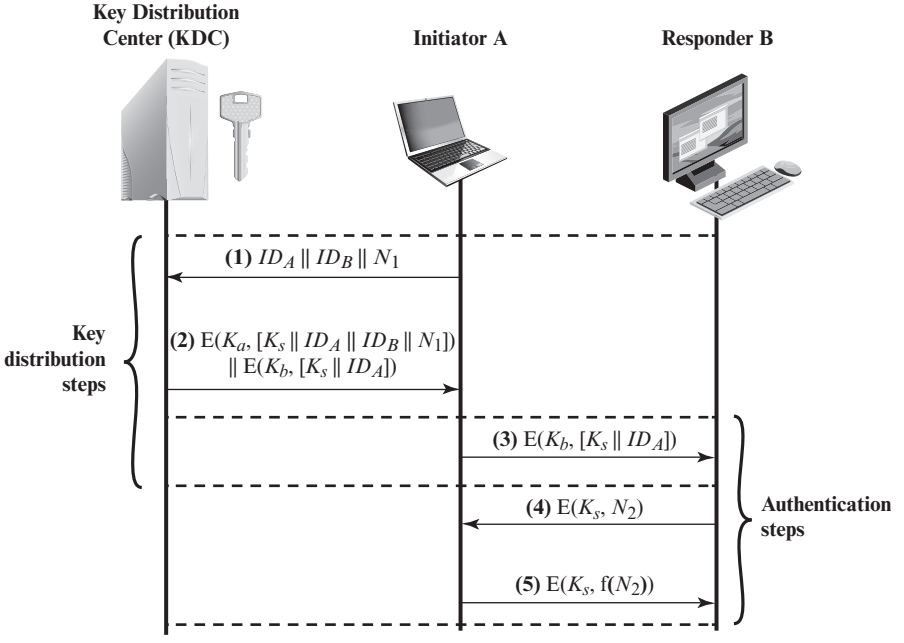


Figure 14.3 Key Distribution Scenario

A has a master key, K_a, known only to itself and the KDC; similarly, B shares the master key K_b with the KDC. The following steps occur.

1. A issues a request to the KDC for a session key to protect a logical connection to B. The message includes the identity of A and B and a unique identifier, N_1, for this transaction, which we refer to as a **nonce**. The nonce may be a timestamp, a counter, or a random number; the minimum requirement is that it differs with each request. Also, to prevent masquerade, it should be difficult for an opponent to guess the nonce. Thus, a random number is a good choice for a nonce.
2. The KDC responds with a message encrypted using K_a. Thus, A is the only one who can successfully read the message, and A knows that it originated at the KDC. The message includes two items intended for A:
   - The one-time session key, K_s, to be used for the session
   - The original request message, including the nonce, to enable A to match this response with the appropriate request

   Thus, A can verify that its original request was not altered before reception by the KDC and, because of the nonce, that this is not a replay of some previous request.

   In addition, the message includes two items intended for B:
   - The one-time session key, K_s, to be used for the session
   - An identifier of A (e.g., its network address), ID_A

   These last two items are encrypted with K_b (the master key that the KDC shares with B). They are to be sent to B to establish the connection and prove A's identity.

3. A stores the session key for use in the upcoming session and forwards to B the information that originated at the KDC for B, namely, $E(K_b,[K_s \| ID_A])$. Because this information is encrypted with K_b, it is protected from eavesdropping. B now knows the session key (K_s), knows that the other party is A (from ID_A), and knows that the information originated at the KDC (because it is encrypted using K_b).

At this point, a session key has been securely delivered to A and B, and they may begin their protected exchange. However, two additional steps are desirable:

4. Using the newly minted session key for encryption, B sends a nonce, N_2, to A.
5. Also, using K_s, A responds with f(N_2), where f is a function that performs some transformation on N_2 (e.g., adding one).

These steps assure B that the original message it received (step 3) was not a replay.

Note that the actual key distribution involves only steps 1 through 3, but that steps 4 and 5, as well as step 3, perform an authentication function.

Hierarchical Key Control

It is not necessary to limit the key distribution function to a single KDC. Indeed, for very large networks, it may not be practical to do so. As an alternative, a hierarchy of KDCs can be established. For example, there can be local KDCs, each responsible for a small domain of the overall internetwork, such as a single LAN or a single building. For communication among entities within the same local domain, the local KDC is responsible for key distribution. If two entities in different domains desire a shared key, then the corresponding local KDCs can communicate through a global KDC. In this case, any one of the three KDCs involved can actually select the key. The hierarchical concept can be extended to three or even more layers, depending on the size of the user population and the geographic scope of the internetwork.

A hierarchical scheme minimizes the effort involved in master key distribution, because most master keys are those shared by a local KDC with its local entities. Furthermore, such a scheme limits the damage of a faulty or subverted KDC to its local area only.

Session Key Lifetime

The more frequently session keys are exchanged, the more secure they are, because the opponent has less ciphertext to work with for any given session key. On the other hand, the distribution of session keys delays the start of any exchange and places a burden on network capacity. A security manager must try to balance these competing considerations in determining the lifetime of a particular session key.

For connection-oriented protocols, one obvious choice is to use the same session key for the length of time that the connection is open, using a new session key for each new session. If a logical connection has a very long lifetime, then it would be prudent to change the session key periodically, perhaps every time the PDU (protocol data unit) sequence number cycles.

For a connectionless protocol, such as a transaction-oriented protocol, there is no explicit connection initiation or termination. Thus, it is not obvious how often one needs to change the session key. The most secure approach is to use a new

session key for each exchange. However, this negates one of the principal benefits of connectionless protocols, which is minimum overhead and delay for each transaction. A better strategy is to use a given session key for a certain fixed period only or for a certain number of transactions.

A Transparent Key Control Scheme

The approach suggested in Figure 14.3 has many variations, one of which is described in this subsection. The scheme (Figure 14.4) is useful for providing end-to-end encryption at a network or transport level in a way that is transparent to the end users. The approach assumes that communication makes use of a connection-oriented end-to-end protocol, such as TCP. The noteworthy element of this approach is a session security module (SSM), which may consist of functionality

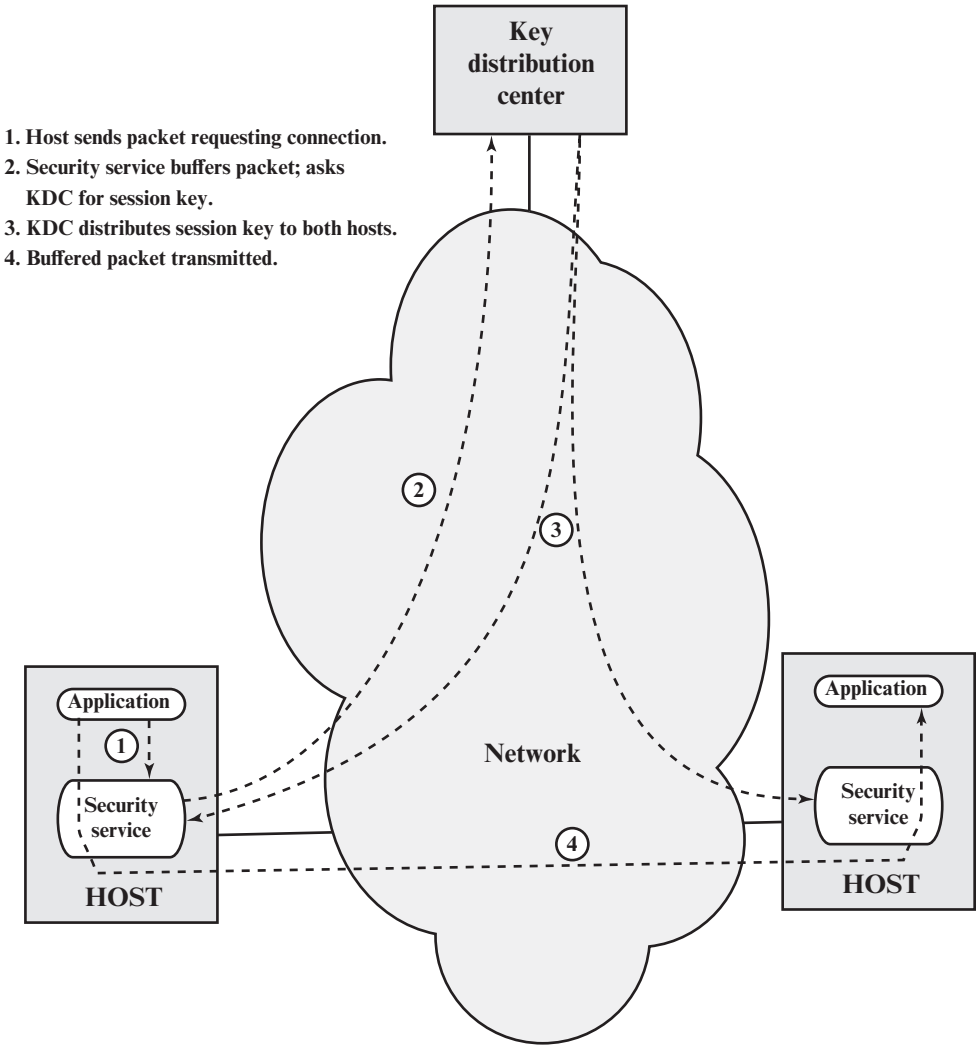


Figure 14.4 Automatic Key Distribution for Connection-Oriented Protocol

at one protocol layer, that performs end-to-end encryption and obtains session keys on behalf of its host or terminal.

The steps involved in establishing a connection are shown in Figure 14.4. When one host wishes to set up a connection to another host, it transmits a connection-request packet (step 1). The SSM saves that packet and applies to the KDC for permission to establish the connection (step 2). The communication between the SSM and the KDC is encrypted using a master key shared only by this SSM and the KDC. If the KDC approves the connection request, it generates the session key and delivers it to the two appropriate SSMs, using a unique permanent key for each SSM (step 3). The requesting SSM can now release the connection request packet, and a connection is set up between the two end systems (step 4). All user data exchanged between the two end systems are encrypted by their respective SSMs using the one-time session key.

The automated key distribution approach provides the flexibility and dynamic characteristics needed to allow a number of terminal users to access a number of hosts and for the hosts to exchange data with each other.

Decentralized Key Control

The use of a key distribution center imposes the requirement that the KDC be trusted and be protected from subversion. This requirement can be avoided if key distribution is fully decentralized. Although full decentralization is not practical for larger networks using symmetric encryption only, it may be useful within a local context.

A decentralized approach requires that each end system be able to communicate in a secure manner with all potential partner end systems for purposes of session key distribution. Thus, there may need to be as many as $[n(n - 1)]/2$ master keys for a configuration with n end systems.

A session key may be established with the following sequence of steps (Figure 14.5).

1. A issues a request to B for a session key and includes a nonce, N_1.
2. B responds with a message that is encrypted using the shared master key. The response includes the session key selected by B, an identifier of B, the value $f(N_1)$, and another nonce, N_2.
3. Using the new session key, A returns $f(N_2)$ to B.

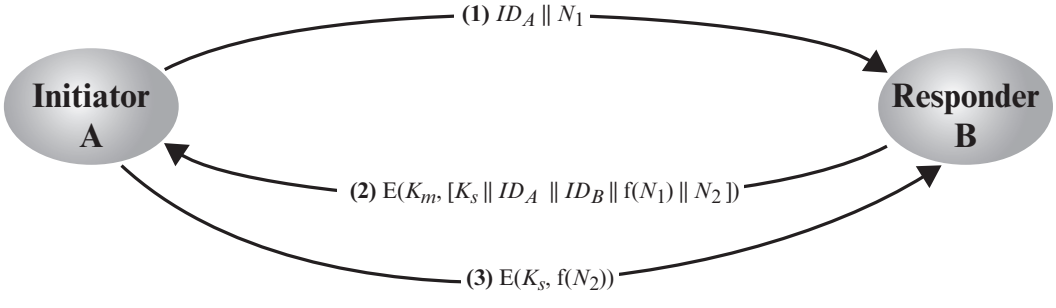


Figure 14.5 Decentralized Key Distribution

Thus, although each node must maintain at most $(n - 1)$ master keys, as many session keys as required may be generated and used. Because the messages transferred using the master key are short, cryptanalysis is difficult. As before, session keys are used for only a limited time to protect them.

Controlling Key Usage

The concept of a key hierarchy and the use of automated key distribution techniques greatly reduce the number of keys that must be manually managed and distributed. It also may be desirable to impose some control on the way in which automatically distributed keys are used. For example, in addition to separating master keys from session keys, we may wish to define different types of session keys on the basis of use, such as

- Data-encrypting key, for general communication across a network
- PIN-encrypting key, for personal identification numbers (PINs) used in electronic funds transfer and point-of-sale applications
- File-encrypting key, for encrypting files stored in publicly accessible locations

To illustrate the value of separating keys by type, consider the risk that a master key is imported as a data-encrypting key into a device. Normally, the master key is physically secured within the cryptographic hardware of the key distribution center and of the end systems. Session keys encrypted with this master key are available to application programs, as are the data encrypted with such session keys. However, if a master key is treated as a session key, it may be possible for an unauthorized application to obtain plaintext of session keys encrypted with that master key.

Thus, it may be desirable to institute controls in systems that limit the ways in which keys are used, based on characteristics associated with those keys. One simple plan is to associate a tag with each key ([JONE82]; see also [DAVI89]). The proposed technique is for use with DES and makes use of the extra 8 bits in each 64-bit DES key. That is, the eight non-key bits ordinarily reserved for parity checking form the key tag. The bits have the following interpretation:

- One bit indicates whether the key is a session key or a master key
- One bit indicates whether the key can be used for encryption
- One bit indicates whether the key can be used for decryption
- The remaining bits are spares for future use.

Because the tag is embedded in the key, it is encrypted along with the key when that key is distributed, thus providing protection. The drawbacks of this scheme are

1. The tag length is limited to 8 bits, limiting its flexibility and functionality.
2. Because the tag is not transmitted in clear form, it can be used only at the point of decryption, limiting the ways in which key use can be controlled.

A more flexible scheme, referred to as the control vector, is described in [MATY91a and b]. In this scheme, each session key has an associated control vector consisting of a number of fields that specify the uses and restrictions for that session key. The length of the control vector may vary.

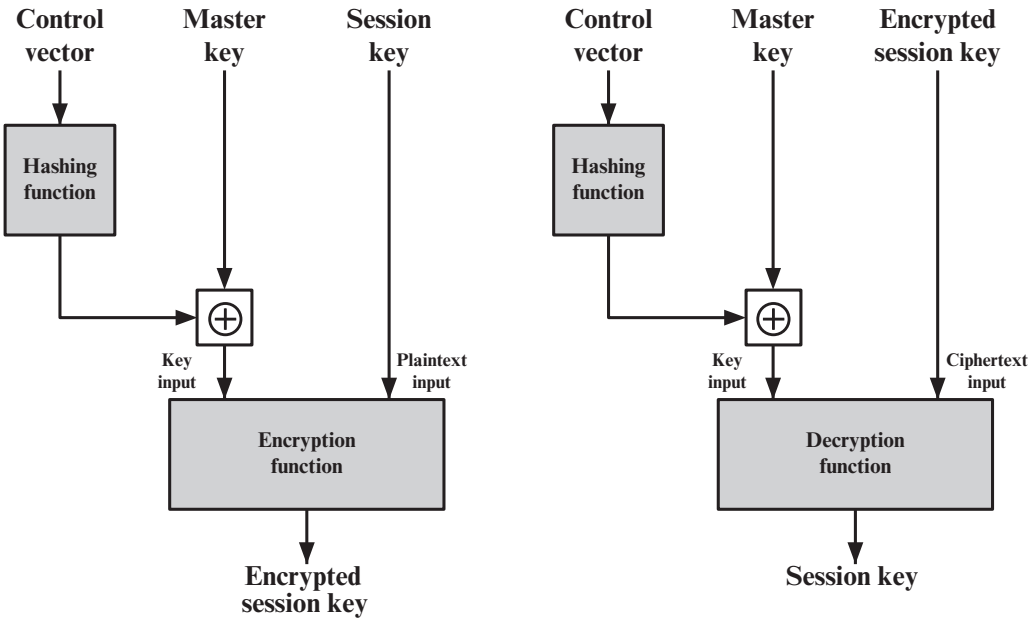


Figure 14.6 Control Vector Encryption and Decryption

The control vector is cryptographically coupled with the key at the time of key generation at the KDC. The coupling and decoupling processes are illustrated in Figure 14.6. As a first step, the control vector is passed through a hash function that produces a value whose length is equal to the encryption key length. Hash functions are discussed in detail in Chapter 11. In essence, a hash function maps values from a larger range into a smaller range with a reasonably uniform spread. Thus, for example, if numbers in the range 1 to 100 are hashed into numbers in the range 1 to 10, approximately 10% of the source values should map into each of the target values.

The hash value is then XORed with the master key to produce an output that is used as the key input for encrypting the session key. Thus,

$$\begin{aligned} \text{Hash value} &= H = \text{h(CV)} \\ \text{Key input} &= K_m \oplus H \\ \text{Ciphertext} &= \text{E}([K_m \oplus H], K_s) \end{aligned}$$

where K_m is the master key and K_s is the session key. The session key is recovered in plaintext by the reverse operation:

$$\text{D}([K_m \oplus H], \text{E}([K_m \oplus H], K_s))$$

When a session key is delivered to a user from the KDC, it is accompanied by the control vector in clear form. The session key can be recovered only by using both the master key that the user shares with the KDC and the control vector. Thus, the linkage between the session key and its control vector is maintained.

Use of the control vector has two advantages over use of an 8-bit tag. First, there is no restriction on length of the control vector, which enables arbitrarily complex controls to be imposed on key use. Second, the control vector is available in clear form at all stages of operation. Thus, control of key use can be exercised in multiple locations.

14.2 SYMMETRIC KEY DISTRIBUTION USING ASYMMETRIC ENCRYPTION

Because of the inefficiency of public-key cryptosystems, they are almost never used for the direct encryption of sizable blocks of data, but are limited to relatively small blocks. One of the most important uses of a public-key cryptosystem is to encrypt secret keys for distribution. We see many specific examples of this in Part Five. Here, we discuss general principles and typical approaches.

Simple Secret Key Distribution

An extremely simple scheme was put forward by Merkle [MERK79], as illustrated in Figure 14.7. If A wishes to communicate with B, the following procedure is employed:

1. A generates a public/private key pair $\{PU_a, PR_a\}$ and transmits a message to B consisting of PU_a and an identifier of A, ID_A.
2. B generates a secret key, K_s, and transmits it to A, which is encrypted with A's public key.
3. A computes $D(PR_a, E(PU_a, K_s))$ to recover the secret key. Because only A can decrypt the message, only A and B will know the identity of K_s.
4. A discards PU_a and PR_a and B discards PU_a.

A and B can now securely communicate using conventional encryption and the session key K_s. At the completion of the exchange, both A and B discard K_s. Despite its simplicity, this is an attractive protocol. No keys exist before the start of the communication and none exist after the completion of communication. Thus, the risk of compromise of the keys is minimal. At the same time, the communication is secure from eavesdropping.

The protocol depicted in Figure 14.7 is insecure against an adversary who can intercept messages and then either relay the intercepted message or substitute another message (see Figure 1.3c). Such an attack is known as a **man-in-the-middle attack** [RIVE84]. We saw this type of attack in Chapter 10 (Figure 10.2). In the present

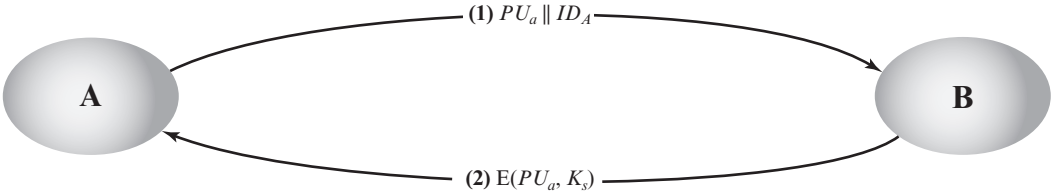


Figure 14.7 Simple Use of Public-Key Encryption to Establish a Session Key

case, if an adversary, D, has control of the intervening communication channel, then D can compromise the communication in the following fashion without being detected (Figure 14.8).

1. A generates a public/private key pair $\{PU_a, PR_a\}$ and transmits a message intended for B consisting of PU_a and an identifier of A, ID_A.
2. D intercepts the message, creates its own public/private key pair $\{PU_d, PR_d\}$ and transmits $PU_d \| ID_A$ to B.
3. B generates a secret key, K_s, and transmits $E(PU_d, K_s)$.
4. D intercepts the message and learns K_s by computing $D(PR_d, E(PU_d, K_s))$.
5. D transmits $E(PU_a, K_s)$ to A.

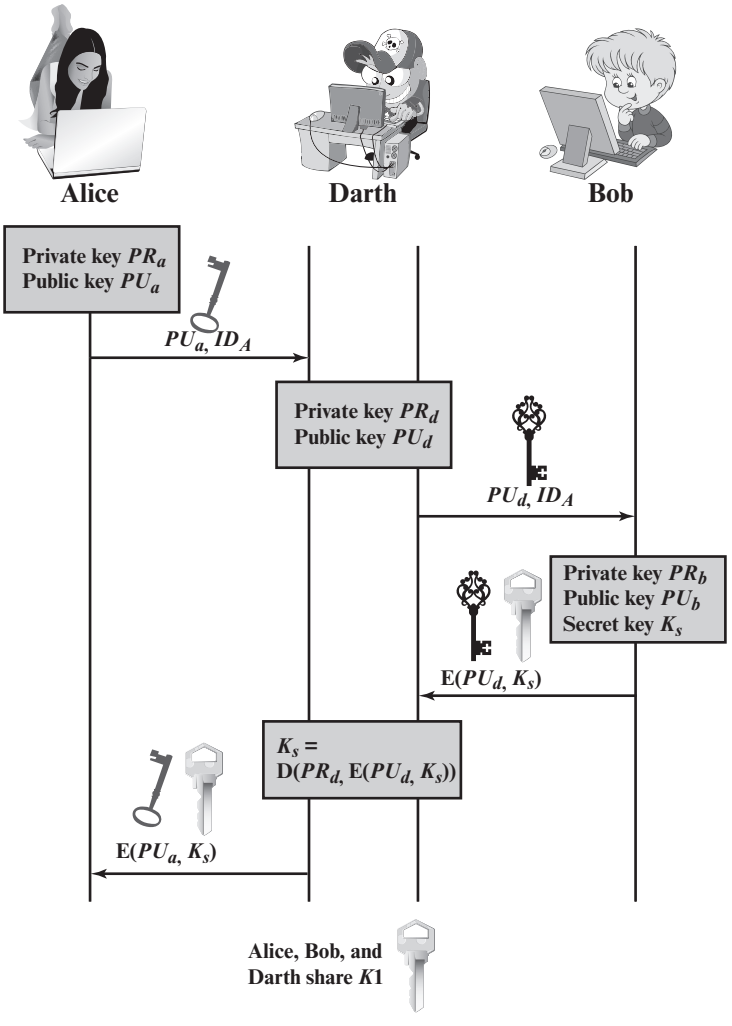


Figure 14.8 Another Man-in-the-Middle Attack

The result is that both A and B know K_s and are unaware that K_s has also been revealed to D. A and B can now exchange messages using K_s. D no longer actively interferes with the communications channel but simply eavesdrops. Knowing K_s, D can decrypt all messages, and both A and B are unaware of the problem. Thus, this simple protocol is only useful in an environment where the only threat is eavesdropping.

Secret Key Distribution with Confidentiality and Authentication

Figure 14.9, based on an approach suggested in [NEED78], provides protection against both active and passive attacks. We begin at a point when it is assumed that A and B have exchanged public keys by one of the schemes described subsequently in this chapter. Then the following steps occur.

1. A uses B's public key to encrypt a message to B containing an identifier of A(ID_A) and a nonce (N_1), which is used to identify this transaction uniquely.
2. B sends a message to A encrypted with PU_a and containing A's nonce (N_1) as well as a new nonce generated by B (N_2). Because only B could have decrypted message (1), the presence of N_1 in message (2) assures A that the correspondent is B.
3. A returns N_2, encrypted using B's public key, to assure B that its correspondent is A.
4. A selects a secret key K_s and sends $M = \mathrm{E}(PU_b, \mathrm{E}(PR_a, K_s))$ to B. Encryption of this message with B's public key ensures that only B can read it; encryption with A's private key ensures that only A could have sent it.
5. B computes $\mathrm{D}(PU_a, \mathrm{D}(PR_b, M))$ to recover the secret key.

The result is that this scheme ensures both confidentiality and authentication in the exchange of a secret key.

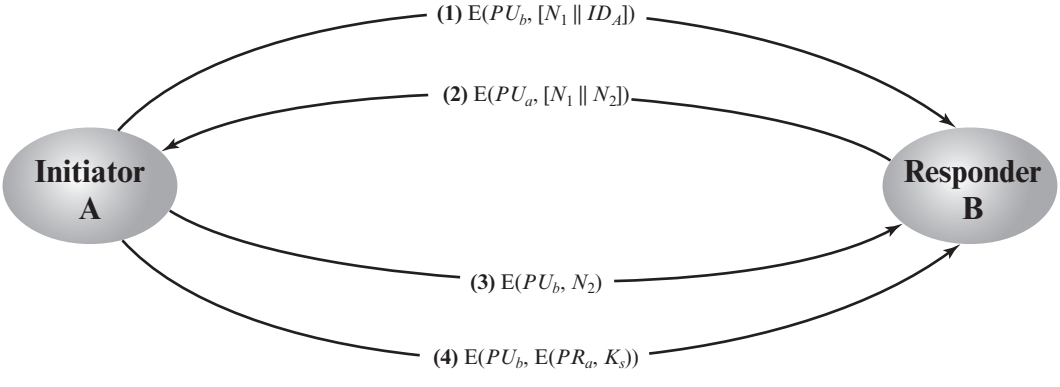


Figure 14.9 Public-Key Distribution of Secret Keys

A Hybrid Scheme

Yet another way to use public-key encryption to distribute secret keys is a hybrid approach in use on IBM mainframes [LE93]. This scheme retains the use of a key distribution center (KDC) that shares a secret master key with each user and distributes secret session keys encrypted with the master key. A public-key scheme is used to distribute the master keys. The following rationale is provided for using this three-level approach:

- **Performance:** There are many applications, especially transaction-oriented applications, in which the session keys change frequently. Distribution of session keys by public-key encryption could degrade overall system performance because of the relatively high computational load of public-key encryption and decryption. With a three-level hierarchy, public-key encryption is used only occasionally to update the master key between a user and the KDC.
- **Backward compatibility:** The hybrid scheme is easily overlaid on an existing KDC scheme with minimal disruption or software changes.

The addition of a public-key layer provides a secure, efficient means of distributing master keys. This is an advantage in a configuration in which a single KDC serves a widely distributed set of users.

14.3 DISTRIBUTION OF PUBLIC KEYS

Several techniques have been proposed for the distribution of public keys. Virtually all these proposals can be grouped into the following general schemes:

- Public announcement
- Publicly available directory
- Public-key authority
- Public-key certificates

Public Announcement of Public Keys

On the face of it, the point of public-key encryption is that the public key is public. Thus, if there is some broadly accepted public-key algorithm, such as RSA, any participant can send his or her public key to any other participant or broadcast the key to the community at large (Figure 14.10). For example, because of the growing popularity of PGP (pretty good privacy, discussed in Chapter 19), which makes use of RSA, many PGP users have adopted the practice of appending their public key to messages that they send to public forums, such as USENET newsgroups and Internet mailing lists.

Although this approach is convenient, it has a major weakness. Anyone can forge such a public announcement. That is, some user could pretend to be user A and send a public key to another participant or broadcast such a public key. Until such time as user A discovers the forgery and alerts other participants, the forger is able to read all encrypted messages intended for A and can use the forged keys for authentication (see Figure 9.3).

Figure 14.10 Uncontrolled Public-Key Distribution

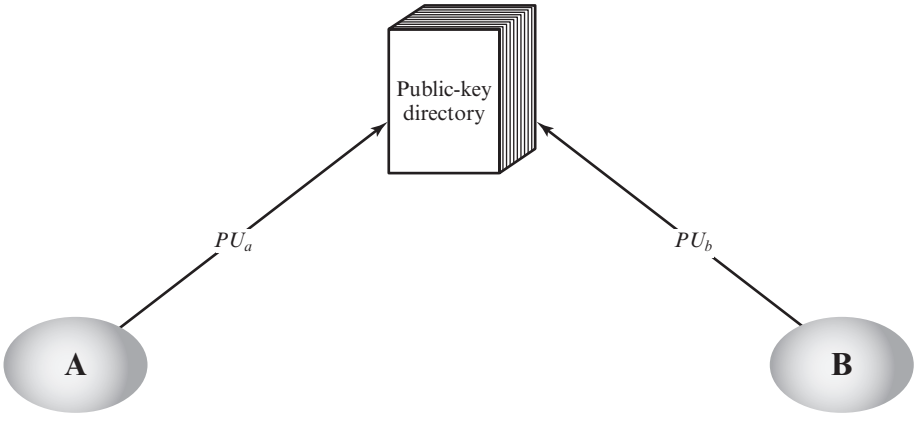


Figure 14.11 Public-Key Publication

Publicly Available Directory

A greater degree of security can be achieved by maintaining a publicly available dynamic directory of public keys. Maintenance and distribution of the public directory would have to be the responsibility of some trusted entity or organization (Figure 14.11). Such a scheme would include the following elements:

1. The authority maintains a directory with a {name, public key} entry for each participant.
2. Each participant registers a public key with the directory authority. Registration would have to be in person or by some form of secure authenticated communication.
3. A participant may replace the existing key with a new one at any time, either because of the desire to replace a public key that has already been used for a large amount of data, or because the corresponding private key has been compromised in some way.
4. Participants could also access the directory electronically. For this purpose, secure, authenticated communication from the authority to the participant is mandatory.

This scheme is clearly more secure than individual public announcements but still has vulnerabilities. If an adversary succeeds in obtaining or computing the private key of the directory authority, the adversary could authoritatively pass out counterfeit public keys and subsequently impersonate any participant and eavesdrop on messages sent to any participant. Another way to achieve the same end is for the adversary to tamper with the records kept by the authority.

Public-Key Authority

Stronger security for public-key distribution can be achieved by providing tighter control over the distribution of public keys from the directory. A typical scenario is illustrated in Figure 14.12, which is based on a figure in [POPE79]. As before, the scenario assumes that a central authority maintains a dynamic directory of public keys of all participants. In addition, each participant reliably knows a public key for the authority, with only the authority knowing the corresponding private key. The following steps (matched by number to Figure 14.12) occur.

1. A sends a timestamped message to the public-key authority containing a request for the current public key of B.
2. The authority responds with a message that is encrypted using the authority's private key, PR_{auth}. Thus, A is able to decrypt the message using the authority's public key. Therefore, A is assured that the message originated with the authority. The message includes the following:
   - B's public key, PU_b, which A can use to encrypt messages destined for B
   - The original request used to enable A to match this response with the corresponding earlier request and to verify that the original request was not altered before reception by the authority
   - The original timestamp given so A can determine that this is not an old message from the authority containing a key other than B's current public key
3. A stores B's public key and also uses it to encrypt a message to B containing an identifier of A (ID_A) and a nonce (N_1), which is used to identify this transaction uniquely.

4, 5. B retrieves A's public key from the authority in the same manner as A retrieved B's public key.

At this point, public keys have been securely delivered to A and B, and they may begin their protected exchange. However, two additional steps are desirable:

6. B sends a message to A encrypted with PU_a and containing A's nonce (N_1) as well as a new nonce generated by B (N_2). Because only B could have decrypted message (3), the presence of N_1 in message (6) assures A that the correspondent is B.
7. A returns N_2, which is encrypted using B's public key, to assure B that its correspondent is A.

Thus, a total of seven messages are required. However, the initial five messages need be used only infrequently because both A and B can save the other's public key for future use—a technique known as caching. Periodically, a user should request fresh copies of the public keys of its correspondents to ensure currency.

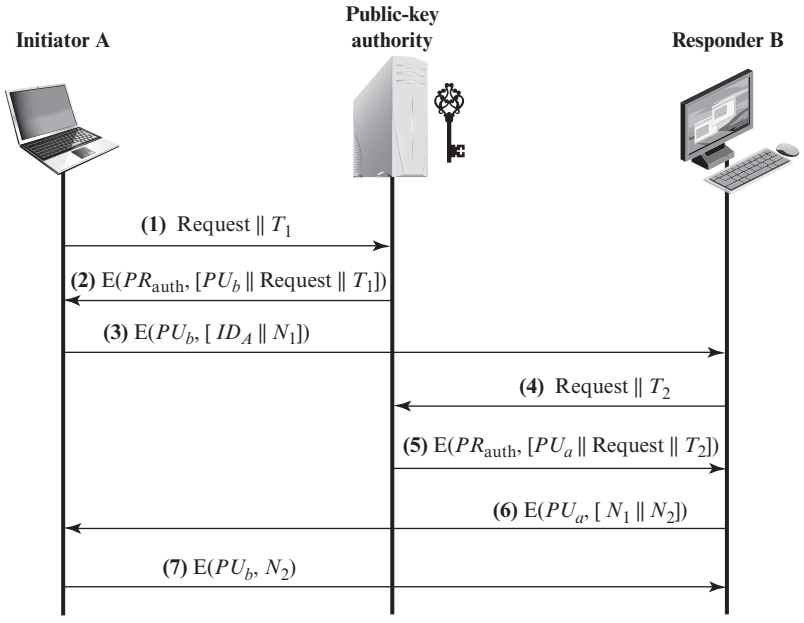


Figure 14.12 Public-Key Distribution Scenario

Public-Key Certificates

The scenario of Figure 14.12 is attractive, yet it has some drawbacks. The public-key authority could be somewhat of a bottleneck in the system, for a user must appeal to the authority for a public key for every other user that it wishes to contact. As before, the directory of names and public keys maintained by the authority is vulnerable to tampering.

An alternative approach, first suggested by Kohnfelder [KOHN78], is to use **certificates** that can be used by participants to exchange keys without contacting a public-key authority, in a way that is as reliable as if the keys were obtained directly from a public-key authority. In essence, a certificate consists of a public key, an identifier of the key owner, and the whole block signed by a trusted third party. Typically, the third party is a certificate authority, such as a government agency or a financial institution, that is trusted by the user community. A user can present his or her public key to the authority in a secure manner and obtain a certificate. The user can then publish the certificate. Anyone needing this user's public key can obtain the certificate and verify that it is valid by way of the attached trusted signature. A participant can also convey its key information to another by transmitting its certificate. Other participants can verify that the certificate was created by the authority. We can place the following requirements on this scheme:

1. Any participant can read a certificate to determine the name and public key of the certificate's owner.
2. Any participant can verify that the certificate originated from the certificate authority and is not counterfeit.
3. Only the certificate authority can create and update certificates.

These requirements are satisfied by the original proposal in [KOHN78]. Denning [DENN83] added the following additional requirement:

4. Any participant can verify the time validity of the certificate.

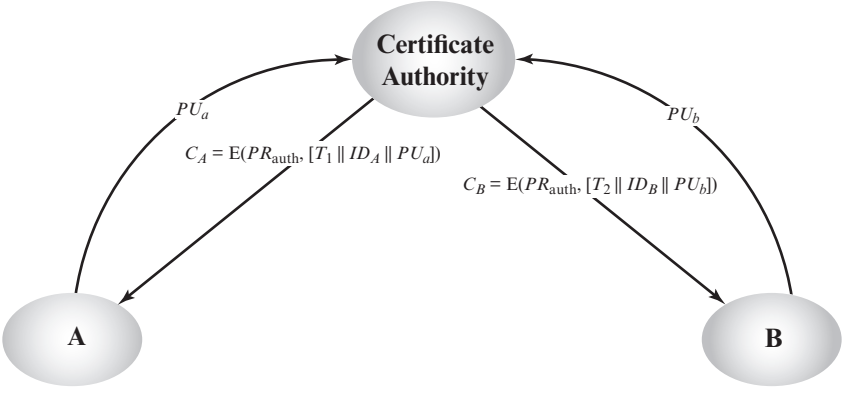
A certificate scheme is illustrated in Figure 14.13. Each participant applies to the certificate authority, supplying a public key and requesting a certificate. Application must be in person or by some form of secure authenticated communication. For participant A, the authority provides a certificate of the form

$$C_A = \mathrm{E}(PR_{\mathrm{auth}}, [T \| ID_A \| PU_a])$$

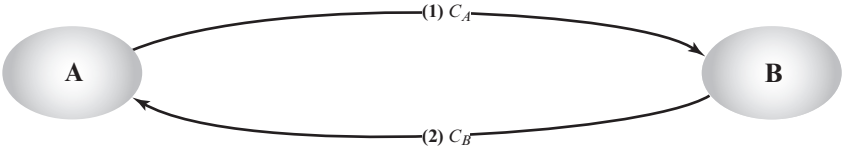
where PR_{auth} is the private key used by the authority and T is a timestamp. A may then pass this certificate on to any other participant, who reads and verifies the certificate as follows:

$$\mathrm{D}(PU_{\mathrm{auth}}, C_A) = \mathrm{D}(PU_{\mathrm{auth}}, \mathrm{E}(PR_{\mathrm{auth}}, [T \| ID_A \| PU_a])) = (T \| ID_A \| PU_a)$$

The recipient uses the authority's public key, PU_{auth}, to decrypt the certificate. Because the certificate is readable only using the authority's public key, this verifies that the certificate came from the certificate authority. The elements ID_A and PU_a provide the recipient with the name and public key of the certificate's holder. The timestamp T validates the currency of the certificate. The timestamp



(a) Obtaining certificates from CA



(b) Exchanging certificates

Figure 14.13 Exchange of Public-Key Certificates

counters the following scenario. A's private key is learned by an adversary. A generates a new private/public key pair and applies to the certificate authority for a new certificate. Meanwhile, the adversary replays the old certificate to B. If B then encrypts messages using the compromised old public key, the adversary can read those messages.

In this context, the compromise of a private key is comparable to the loss of a credit card. The owner cancels the credit card number but is at risk until all possible communicants are aware that the old credit card is obsolete. Thus, the timestamp serves as something like an expiration date. If a certificate is sufficiently old, it is assumed to be expired.

One scheme has become universally accepted for formatting public-key certificates: the X.509 standard. X.509 certificates are used in most network security applications, including IP security, transport layer security (TLS), and S/MIME, all of which are discussed in Part Five. X.509 is examined in detail in the next section.

14.4 X.509 CERTIFICATES

ITU-T recommendation X.509 is part of the X.500 series of recommendations that define a directory service. The directory is, in effect, a server or distributed set of servers that maintains a database of information about users. The information includes a mapping from user name to network address, as well as other attributes and information about the users.

X.509 defines a framework for the provision of authentication services by the X.500 directory to its users. The directory may serve as a repository of public-key certificates of the type discussed in Section 14.3. Each certificate contains the public key of a user and is signed with the private key of a trusted certification authority. In addition, X.509 defines alternative authentication protocols based on the use of public-key certificates.

X.509 is an important standard because the certificate structure and authentication protocols defined in X.509 are used in a variety of contexts. For example, the X.509 certificate format is used in S/MIME (Chapter 19), IP Security (Chapter 20), and SSL/TLS (Chapter 17).

X.509 was initially issued in 1988. The standard was subsequently revised in 1993 to address some of the security concerns documented in [IANS90] and [MITC90]. The standard is currently at version 7, issued in 2012.

X.509 is based on the use of public-key cryptography and digital signatures. The standard does not dictate the use of a specific digital signature algorithm nor a specific hash function. Figure 14.14 illustrates the overall X.509 scheme for generation of a public-key certificate. The certificate for Bob's public key includes unique identifying information for Bob, Bob's public key, and identifying information about the CA, plus other information as explained subsequently. This information is then signed by computing a hash value of the information and generating a digital signature using the hash value and the CA's private key. X.509 indicates that the signature is formed by encrypting the hash value. This suggests the use of one of the RSA schemes discussed in Section 13.6. However, the current version of X.509 does

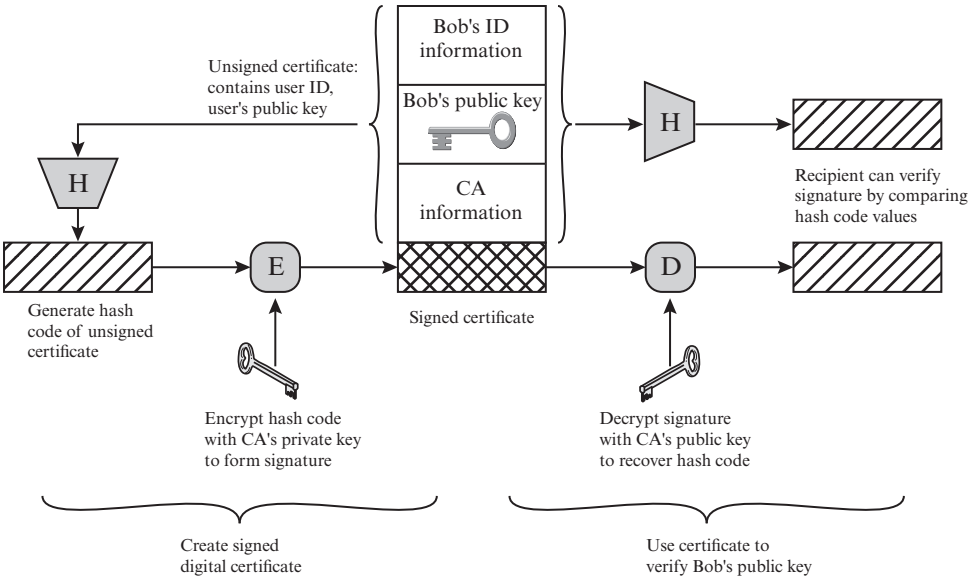


Figure 14.14 X.509 Public-Key Certificate Use

not dictate a specific digital signature algorithm. If the NIST DSA (Section 13.4) or the ECDSA (Section 13.5) scheme is used, then the hash value is not encrypted but serves as input to a digital signature generation algorithm.

Certificates

The heart of the X.509 scheme is the public-key certificate associated with each user. These user certificates are assumed to be created by some trusted certification authority (CA) and placed in the directory by the CA or by the user. The directory server itself is not responsible for the creation of public keys or for the certification function; it merely provides an easily accessible location for users to obtain certificates.

Figure 14.15a shows the general format of a certificate, which includes the following elements.

- **Version:** Differentiates among successive versions of the certificate format; the default is version 1. If the *issuer unique identifier* or *subject unique identifier* are present, the value must be version 2. If one or more extensions are present, the version must be version 3. Although the X.509 specification is currently at version 7, no changes have been made to the fields that make up the certificate since version 3.
- **Serial number:** An integer value unique within the issuing CA that is unambiguously associated with this certificate.
- **Signature algorithm identifier:** The algorithm used to sign the certificate together with any associated parameters. Because this information is repeated in the signature field at the end of the certificate, this field has little, if any, utility.

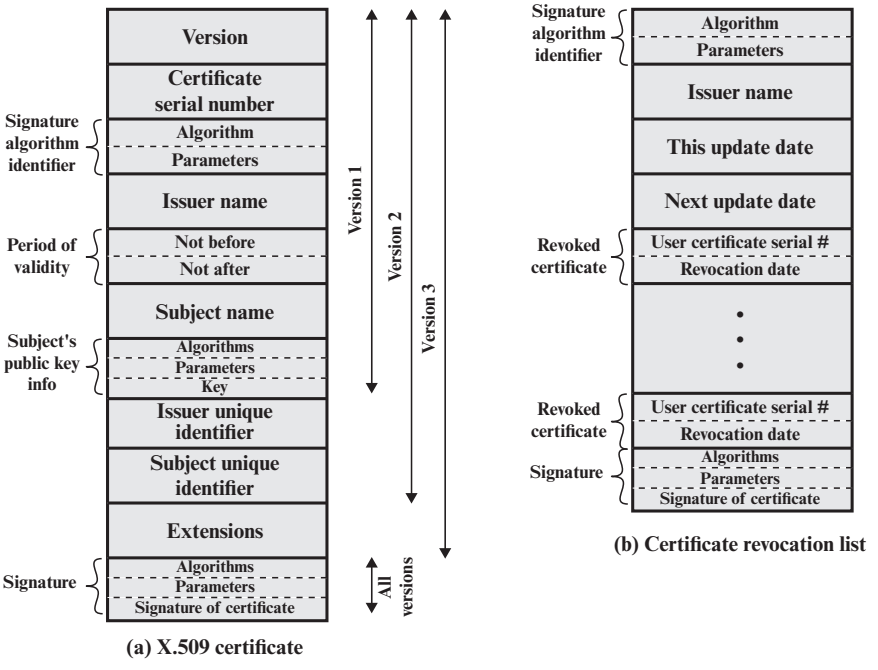


Figure 14.15 X.509 Formats

- **Issuer name:** X.500 name of the CA that created and signed this certificate.
- **Period of validity:** Consists of two dates: the first and last on which the certificate is valid.
- **Subject name:** The name of the user to whom this certificate refers. That is, this certificate certifies the public key of the subject who holds the corresponding private key.
- **Subject's public-key information:** The public key of the subject, plus an identifier of the algorithm for which this key is to be used, together with any associated parameters.
- **Issuer unique identifier:** An optional-bit string field used to identify uniquely the issuing CA in the event the X.500 name has been reused for different entities.
- **Subject unique identifier:** An optional-bit string field used to identify uniquely the subject in the event the X.500 name has been reused for different entities.
- **Extensions:** A set of one or more extension fields. Extensions were added in version 3 and are discussed later in this section.
- **Signature:** Covers all of the other fields of the certificate. One component of this field is the digital signature applied to the other fields of the certificate. This field includes the signature algorithm identifier.

The unique identifier fields were added in version 2 to handle the possible reuse of subject and/or issuer names over time. These fields are rarely used.

The standard uses the following notation to define a certificate:

$$CA \ll A \gg = CA\{V, SN, AI, CA, UCA, A, UA, Ap, T^A\}$$

where

$Y \ll X \gg$ = the certificate of user X issued by certification authority Y
$Y\{I\}$ = the signing of I by Y. It consists of I with an encrypted hash code appended
V = version of the certificate
SN = serial number of the certificate
AI = identifier of the algorithm used to sign the certificate
CA = name of certificate authority
UCA = optional unique identifier of the CA
A = name of user A
UA = optional unique identifier of the user A
Ap = public key of user A
T^A = period of validity of the certificate

The CA signs the certificate with its private key. If the corresponding public key is known to a user, then that user can verify that a certificate signed by the CA is valid. This is the typical digital signature approach illustrated in Figure 13.2.

Obtaining a User's Certificate User certificates generated by a CA have the following characteristics:

- Any user with access to the public key of the CA can verify the user public key that was certified.
- No party other than the certification authority can modify the certificate without this being detected.

Because certificates are unforgeable, they can be placed in a directory without the need for the directory to make special efforts to protect them.

If all users subscribe to the same CA, then there is a common trust of that CA. All user certificates can be placed in the directory for access by all users. In addition, a user can transmit his or her certificate directly to other users. In either case, once B is in possession of A's certificate, B has confidence that messages it encrypts with A's public key will be secure from eavesdropping and that messages signed with A's private key are unforgeable.

If there is a large community of users, it may not be practical for all users to subscribe to the same CA. Because it is the CA that signs certificates, each participating user must have a copy of the CA's own public key to verify signatures. This public key must be provided to each user in an absolutely secure (with respect to integrity and authenticity) way so that the user has confidence in the associated certificates. Thus, with many users, it may be more practical for there to be a number of CAs, each of which securely provides its public key to some fraction of the users.

Now suppose that A has obtained a certificate from certification authority X_1 and B has obtained a certificate from CA X_2. If A does not securely know the public key of X_2, then B's certificate, issued by X_2, is useless to A. A can read B's certificate, but A cannot verify the signature. However, if the two CAs have securely exchanged their own public keys, the following procedure will enable A to obtain B's public key.

Step 1 A obtains from the directory the certificate of X_2 signed by X_1. Because A securely knows X_1's public key, A can obtain X_2's public key from its certificate and verify it by means of X_1's signature on the certificate.

Step 2 A then goes back to the directory and obtains the certificate of B signed by X_2. Because A now has a trusted copy of X_2's public key, A can verify the signature and securely obtain B's public key.

A has used a chain of certificates to obtain B's public key. In the notation of X.509, this chain is expressed as

$$X_1 \ll X_2 \gg X_2 \ll B \gg$$

In the same fashion, B can obtain A's public key with the reverse chain:

$$X_2 \ll X_1 \gg X_1 \ll A \gg$$

This scheme need not be limited to a chain of two certificates. An arbitrarily long path of CAs can be followed to produce a chain. A chain with N elements would be expressed as

$$X_1 \ll X_2 \gg X_2 \ll X_3 \gg \ \ldots \ X_N \ll B \gg$$

In this case, each pair of CAs in the chain (X_i, X_{i+1}) must have created certificates for each other.

All these certificates of CAs by CAs need to appear in the directory, and the user needs to know how they are linked to follow a path to another user's public-key certificate. X.509 suggests that CAs be arranged in a hierarchy so that navigation is straightforward.

Figure 14.16, taken from X.509, is an example of such a hierarchy. The connected circles indicate the hierarchical relationship among the CAs; the associated boxes indicate certificates maintained in the directory for each CA entry. The directory entry for each CA includes two types of certificates:

- **Forward certificates:** Certificates of X generated by other CAs
- **Reverse certificates:** Certificates generated by X that are the certificates of other CAs

In this example, user A can acquire the following certificates from the directory to establish a certification path to B:

$$X \ll W \gg W \ll V \gg V \ll Y \gg Y \ll Z \gg Z \ll B \gg$$

When A has obtained these certificates, it can unwrap the certification path in sequence to recover a trusted copy of B's public key. Using this public key, A can send encrypted messages to B. If A wishes to receive encrypted messages back

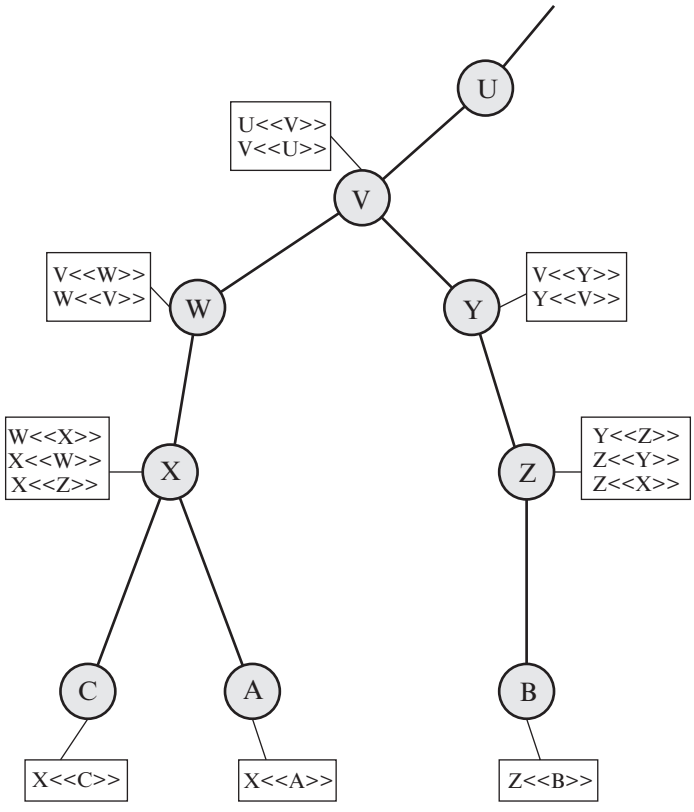


Figure 14.16 X.509 Hierarchy: A Hypothetical Example

from B, or to sign messages sent to B, then B will require A's public key, which can be obtained from the following certification path:

$$Z \ll Y \gg \; Y \ll V \gg \; V \ll W \gg \; W \ll X \gg \; X \ll A \gg$$

B can obtain this set of certificates from the directory, or A can provide them as part of its initial message to B.

Revocation of Certificates Recall from Figure 14.15 that each certificate includes a period of validity, much like a credit card. Typically, a new certificate is issued just before the expiration of the old one. In addition, it may be desirable on occasion to revoke a certificate before it expires, for one of the following reasons.

1. The user's private key is assumed to be compromised.
2. The user is no longer certified by this CA. Reasons for this include that the subject's name has changed, the certificate is superseded, or the certificate was not issued in conformance with the CA's policies.
3. The CA's certificate is assumed to be compromised.

Each CA must maintain a list consisting of all revoked but not expired certificates issued by that CA, including both those issued to users and to other CAs. These lists should also be posted on the directory.

Each certificate revocation list (CRL) posted to the directory is signed by the issuer and includes (Figure 14.15b) the issuer's name, the date the list was created, the date the next CRL is scheduled to be issued, and an entry for each revoked certificate. Each entry consists of the serial number of a certificate and revocation date for that certificate. Because serial numbers are unique within a CA, the serial number is sufficient to identify the certificate.

When a user receives a certificate in a message, the user must determine whether the certificate has been revoked. The user could check the directory each time a certificate is received. To avoid the delays (and possible costs) associated with directory searches, it is likely that the user would maintain a local cache of certificates and lists of revoked certificates.

X.509 Version 3

The X.509 version 2 format does not convey all of the information that recent design and implementation experience has shown to be needed. [FORD95] lists the following requirements not satisfied by version 2.

1. The subject field is inadequate to convey the identity of a key owner to a public-key user. X.509 names may be relatively short and lacking in obvious identification details that may be needed by the user.
2. The subject field is also inadequate for many applications, which typically recognize entities by an Internet email address, a URL, or some other Internet-related identification.
3. There is a need to indicate security policy information. This enables a security application or function, such as IPSec, to relate an X.509 certificate to a given policy.
4. There is a need to limit the damage that can result from a faulty or malicious CA by setting constraints on the applicability of a particular certificate.
5. It is important to be able to identify different keys used by the same owner at different times. This feature supports key lifecycle management: in particular, the ability to update key pairs for users and CAs on a regular basis or under exceptional circumstances.

Rather than continue to add fields to a fixed format, standards developers felt that a more flexible approach was needed. Thus, version 3 includes a number of optional extensions that may be added to the version 2 format. Each extension consists of an extension identifier, a criticality indicator, and an extension value. The criticality indicator indicates whether an extension can be safely ignored. If the indicator has a value of TRUE and an implementation does not recognize the extension, it must treat the certificate as invalid.

The certificate extensions fall into three main categories: key and policy information, subject and issuer attributes, and certification path constraints.

Key and Policy Information These extensions convey additional information about the subject and issuer keys, plus indicators of certificate policy. A certificate policy is a named set of rules that indicates the applicability of a certificate to a particular community and/or class of application with common security requirements. For example, a policy might be applicable to the authentication of

electronic data interchange (EDI) transactions for the trading of goods within a given price range.

This area includes:

- **Authority key identifier:** Identifies the public key to be used to verify the signature on this certificate or CRL. Enables distinct keys of the same CA to be differentiated. One use of this field is to handle CA key pair updating.
- **Subject key identifier:** Identifies the public key being certified. Useful for subject key pair updating. Also, a subject may have multiple key pairs and, correspondingly, different certificates for different purposes (e.g., digital signature and encryption key agreement).
- **Key usage:** Indicates a restriction imposed as to the purposes for which, and the policies under which, the certified public key may be used. May indicate one or more of the following: digital signature, nonrepudiation, key encryption, data encryption, key agreement, CA signature verification on certificates, CA signature verification on CRLs.
- **Private-key usage period:** Indicates the period of use of the private key corresponding to the public key. Typically, the private key is used over a different period from the validity of the public key. For example, with digital signature keys, the usage period for the signing private key is typically shorter than that for the verifying public key.
- **Certificate policies:** Certificates may be used in environments where multiple policies apply. This extension lists policies that the certificate is recognized as supporting, together with optional qualifier information.
- **Policy mappings:** Used only in certificates for CAs issued by other CAs. Policy mappings allow an issuing CA to indicate that one or more of that issuer's policies can be considered equivalent to another policy used in the subject CA's domain.

Certificate Subject and Issuer Attributes These extensions support alternative names, in alternative formats, for a certificate subject or certificate issuer and can convey additional information about the certificate subject to increase a certificate user's confidence that the certificate subject is a particular person or entity. For example, information such as postal address, position within a corporation, or picture image may be required.

The extension fields in this area include:

- **Subject alternative name:** Contains one or more alternative names, using any of a variety of forms. This field is important for supporting certain applications, such as electronic mail, EDI, and IPSec, which may employ their own name forms.
- **Issuer alternative name:** Contains one or more alternative names, using any of a variety of forms.
- **Subject directory attributes:** Conveys any desired X.500 directory attribute values for the subject of this certificate.

Certification Path Constraints These extensions allow constraint specifications to be included in certificates issued for CAs by other CAs. The constraints may restrict the types of certificates that can be issued by the subject CA or that may occur subsequently in a certification chain.

The extension fields in this area include:

- **Basic constraints:** Indicates if the subject may act as a CA. If so, a certification path length constraint may be specified.
- **Name constraints:** Indicates a name space within which all subject names in subsequent certificates in a certification path must be located.
- **Policy constraints:** Specifies constraints that may require explicit certificate policy identification or inhibit policy mapping for the remainder of the certification path.

14.5 PUBLIC-KEY INFRASTRUCTURE

RFC 4949 (*Internet Security Glossary*) defines public-key infrastructure (PKI) as the set of hardware, software, people, policies, and procedures needed to create, manage, store, distribute, and revoke digital certificates based on asymmetric cryptography. The principal objective for developing a PKI is to enable secure, convenient, and efficient acquisition of public keys. The Internet Engineering Task Force (IETF) Public Key Infrastructure X.509 (PKIX) working group has been the driving force behind setting up a formal (and generic) model based on X.509 that is suitable for deploying a certificate-based architecture on the Internet. This section describes the PKIX model.

Figure 14.17 shows the interrelationship among the key elements of the PKIX model. These elements are

- **End entity:** A generic term used to denote end users, devices (e.g., servers, routers), or any other entity that can be identified in the subject field of a public-key certificate. End entities typically consume and/or support PKI-related services.
- **Certification authority (CA):** The issuer of certificates and (usually) certificate revocation lists (CRLs). It may also support a variety of administrative functions, although these are often delegated to one or more Registration Authorities.
- **Registration authority (RA):** An optional component that can assume a number of administrative functions from the CA. The RA is often associated with the end entity registration process but can assist in a number of other areas as well.
- **CRL issuer:** An optional component that a CA can delegate to publish CRLs.
- **Repository:** A generic term used to denote any method for storing certificates and CRLs so that they can be retrieved by end entities.

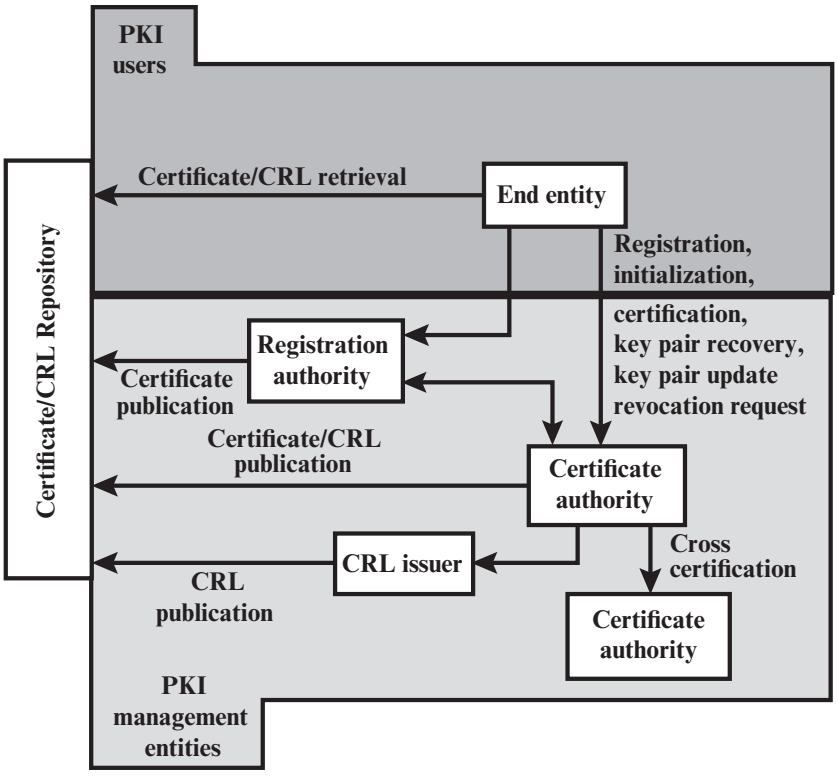


Figure 14.17 PKIX Architectural Model

PKIX Management Functions

PKIX identifies a number of management functions that potentially need to be supported by management protocols. These are indicated in Figure 14.17 and include the following:

- **Registration:** This is the process whereby a user first makes itself known to a CA (directly or through an RA), prior to that CA issuing a certificate or certificates for that user. Registration begins the process of enrolling in a PKI. Registration usually involves some offline or online procedure for mutual authentication. Typically, the end entity is issued one or more shared secret keys used for subsequent authentication.
- **Initialization:** Before a client system can operate securely, it is necessary to install key materials that have the appropriate relationship with keys stored elsewhere in the infrastructure. For example, the client needs to be securely initialized with the public key and other assured information of the trusted CA(s), to be used in validating certificate paths.
- **Certification:** This is the process in which a CA issues a certificate for a user's public key, returns that certificate to the user's client system, and/or posts that certificate in a repository.
- **Key pair recovery:** Key pairs can be used to support digital signature creation and verification, encryption and decryption, or both. When a key pair is used for

encryption/decryption, it is important to provide a mechanism to recover the necessary decryption keys when normal access to the keying material is no longer possible, otherwise it will not be possible to recover the encrypted data. Loss of access to the decryption key can result from forgotten passwords/PINs, corrupted disk drives, damage to hardware tokens, and so on. Key pair recovery allows end entities to restore their encryption/decryption key pair from an authorized key backup facility (typically, the CA that issued the end entity's certificate).

- **Key pair update:** All key pairs need to be updated regularly (i.e., replaced with a new key pair) and new certificates issued. Update is required when the certificate lifetime expires and as a result of certificate revocation.
- **Revocation request:** An authorized person advises a CA of an abnormal situation requiring certificate revocation. Reasons for revocation include private-key compromise, change in affiliation, and name change.
- **Cross certification:** Two CAs exchange information used in establishing a cross-certificate. A cross-certificate is a certificate issued by one CA to another CA that contains a CA signature key used for issuing certificates.

PKIX Management Protocols

The PKIX working group has defines two alternative management protocols between PKIX entities that support the management functions listed in the preceding subsection. RFC 2510 defines the certificate management protocols (CMP). Within CMP, each of the management functions is explicitly identified by specific protocol exchanges. CMP is designed to be a flexible protocol able to accommodate a variety of technical, operational, and business models.

RFC 2797 defines certificate management messages over CMS (CMC), where CMS refers to RFC 2630, cryptographic message syntax. CMC is built on earlier work and is intended to leverage existing implementations. Although all of the PKIX functions are supported, the functions do not all map into specific protocol exchanges.

14.6 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

end-to-end encryption	man-in-the-middle attack	public-key directory
key distribution	master key	X.509 certificate
key distribution center (KDC)	nonce	
key management	public-key certificate	

Review Questions

14.1 Explain why man-in-the-middle attacks are ineffective on the secret key distribution protocol discussed in Figure 14.3.

14.2 What is the major issue in end to end key distribution? How does the key hierarchy concept address that issue?

14.3 What is a nonce?

14.4 What is a key distribution center?

14.5 What are two different uses of public-key cryptography related to key distribution?

14.6 List four general categories of schemes for the distribution of public keys.
14.7 Discuss the potential security issues that arise due to public key directory based system.
14.8 What is a public-key certificate?
14.9 What are the requirements for the use of a public-key certificate scheme?
14.10 What is the purpose of the X.509 standard?
14.11 What is a chain of certificates?
14.12 How is an X.509 certificate revoked?

Problems

14.1 One local area network vendor provides a key distribution facility, as illustrated in Figure 14.18.
a. Describe the scheme.
b. Compare this scheme to that of Figure 14.3. What are the pros and cons?

14.2 "We are under great pressure, Holmes." Detective Lestrade looked nervous. "We have learned that copies of sensitive government documents are stored in computers of one foreign embassy here in London. Normally these documents exist in electronic form only on a selected few government computers that satisfy the most stringent security requirements. However, sometimes they must be sent through the network connecting all government computers. But all messages in this network are encrypted using a top-secret encryption algorithm certified by our best crypto experts. Even the NSA and the KGB are unable to break it. And now these documents have appeared in hands of diplomats of a small, otherwise insignificant, country. And we have no idea how it could happen."

"But you do have some suspicion who did it, do you?" asked Holmes.

"Yes, we did some routine investigation. There is a man who has legal access to one of the government computers and has frequent contacts with diplomats from the embassy. But the computer he has access to is not one of the trusted ones where these documents are normally stored. He is the suspect, but we have no idea how he could obtain copies of the documents. Even if he could obtain a copy of an encrypted document, he couldn't decrypt it."

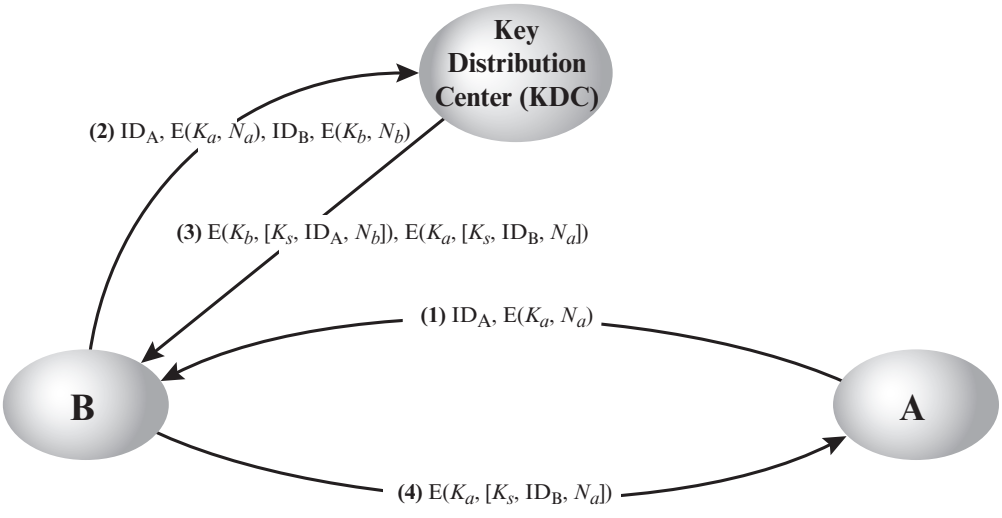


Figure 14.18 Figure for Problem 14.1

"Hmm, please describe the communication protocol used on the network." Holmes opened his eyes, thus proving that he had followed Lestrade's talk with an attention that contrasted with his sleepy look.

"Well, the protocol is as follows. Each node N of the network has been assigned a unique secret key K_n. This key is used to secure communication between the node and a trusted server. That is, all the keys are stored also on the server. User A, wishing to send a secret message M to user B, initiates the following protocol:

1. A generates a random number R and sends to the server his name A, destination B, and $E(K_a, R)$.
2. Server responds by sending $E(K_b, R)$ to A.
3. A sends $E(R, M)$ together with $E(K_b, R)$ to B.
4. B knows K_b, thus decrypts $E(K_b, R)$, to get R and will subsequently use R to decrypt $E(R, M)$ to get M.

You see that a random key is generated every time a message has to be sent. I admit the man could intercept messages sent between the top-secret trusted nodes, but I see no way he could decrypt them."

"Well, I think you have your man, Lestrade. The protocol isn't secure because the server doesn't authenticate users who send him a request. Apparently designers of the protocol have believed that sending $E(K_x, R)$ implicitly authenticates user X as the sender, as only X (and the server) knows K_x. But you know that $E(K_x, R)$ can be intercepted and later replayed. Once you understand where the hole is, you will be able to obtain enough evidence by monitoring the man's use of the computer he has access to. Most likely he works as follows. After intercepting $E(K_a, R)$ and $E(R, M)$ (see steps 1 and 3 of the protocol), the man, let's denote him as Z, will continue by pretending to be A and . . .

Finish the sentence for Holmes.

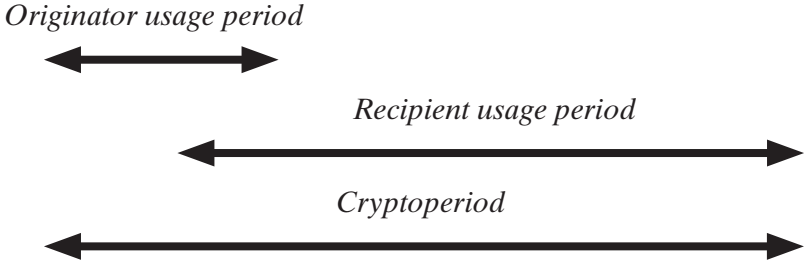
14.3 The 1988 version of X.509 lists properties that RSA keys must satisfy to be secure given current knowledge about the difficulty of factoring large numbers. The discussion concludes with a constraint on the public exponent and the modulus n:

> It must be ensured that $e > \log_2(n)$ to prevent attack by taking the eth root mod n to disclose the plaintext.

Although the constraint is correct, the reason given for requiring it is incorrect. What is wrong with the reason given and what is the correct reason?

14.4 Find at least one intermediate certification authority's certificate and one trusted root certification authority's certificate on your computer (e.g., in the browser). Print screenshots of both the general and details tab for each certificate.

14.5 NIST defines the term cryptoperiod as the time span during which a specific key is authorized for use or in which the keys for a given system or application may remain in effect. One document on key management uses the following time diagram for a shared secret key.



Explain the overlap by giving an example application in which the originator's usage period for the shared secret key begins before the recipient's usage period and also ends before the recipients usage period.

14.6 Consider the following protocol, designed to let A and B decide on a fresh, shared session key K'_{AB}. We assume that they already share a long-term key K_{AB}.

1. $A \rightarrow B$: A, N_A.
2. $B \rightarrow A$: $\mathrm{E}(K_{AB}, [N_A, K'_{AB}])$
3. $A \rightarrow B$: $\mathrm{E}(K'_{AB}, N_A)$

a. We first try to understand the protocol designer's reasoning:

—Why would A and B believe after the protocol ran that they share K'_{AB} with the other party?

—Why would they believe that this shared key is fresh?

In both cases, you should explain both the reasons of both A and B, so your answer should complete the sentences

A believes that she shares K'_{AB} with B since . . .

B believes that he shares K'_{AB} with A since . . .

A believes that K'_{AB} is fresh since . . .

B believes that K'_{AB} is fresh since . . .

b. Assume now that A starts a run of this protocol with B. However, the connection is intercepted by the adversary C. Show how C can start a new run of the protocol using reflection, causing A to believe that she has agreed on a fresh key with B (in spite of the fact that she has only been communicating with C). Thus, in particular, the belief in (a) is false.

c. Propose a modification of the protocol that prevents this attack.

14.7 What are the management functions of a PKI? What is a cross certificate?

14.8 State the significance of key pair recovery. When is the key pair updated?

Note: The remaining problems deal with the a cryptographic product developed by IBM, which is briefly described in a document at box.com/Crypto7e (IBMCrypto.pdf). Try these problems after reviewing the document.

14.9 What is the effect of adding the instruction EMKi

$$\mathrm{EMK}_i\text{: } X \rightarrow \mathrm{E}(KMH_i, X)\ i = 0, 1$$

14.10 Suppose N different systems use the IBM Cryptographic Subsystem with host master keys KMH[i](i = 1, 2, . . . N). Devise a method for communicating between systems without requiring the system to either share a common host master key or to divulge their individual host master keys. *Hint*: Each system needs three variants of its host master key.

14.11 The principal objective of the IBM Cryptographic Subsystem is to protect transmissions between a terminal and the processing system. Devise a procedure, perhaps adding instructions, which will allow the processor to generate a session key KS and distribute it to Terminal i and Terminal j without having to store a key-equivalent variable in the host.

CHAPTER 15

User Authentication

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Understand the distinction between identification and verification.
- Present an overview of techniques for remote user authentication using symmetric encryption.
- Give a presentation on Kerberos.
- Explain the differences between versions 4 and 5 of Kerberos.
- Describe the use of Kerberos in multiple realms.
- Present an overview of techniques for remote user authentication using asymmetric encryption.
- Understand the need for a federated identity management system.
- Explain the use of PIV mechanisms as part of a user authentication system.

This chapter examines some of the authentication functions that have been developed to support network-based user authentication. The chapter begins with an introduction to some of the concepts and key considerations for user authentication over a network or the Internet. The next section examines user-authentication protocols that rely on symmetric encryption. This is followed by a section on one of the earliest and also one of the most widely used authentication services: Kerberos. Next, the chapter looks at user-authentication protocols that rely on asymmetric encryption. This is followed by a discussion of the X.509 user-authentication protocol. Finally, the concept of federated identity is introduced.

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**

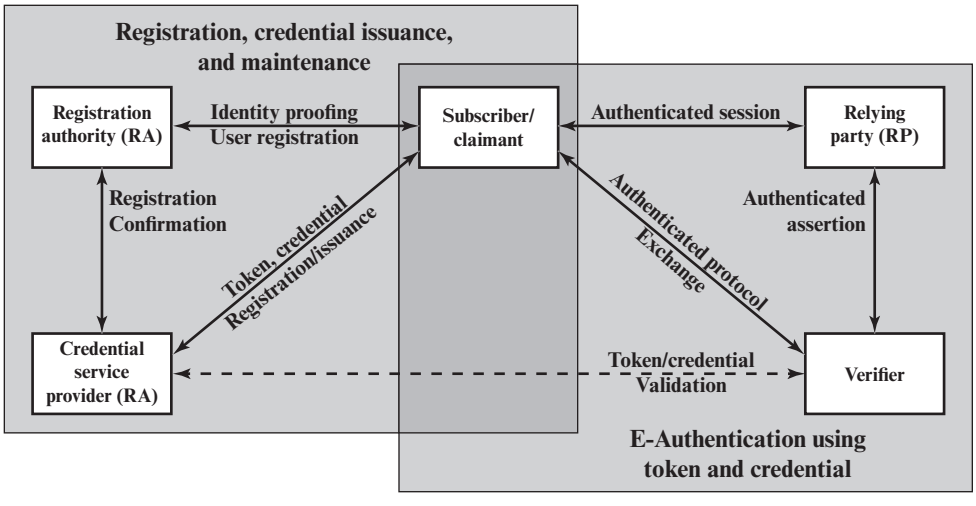


Figure 15.1 The NIST SP 800-63-2 E-Authentication Architectural Model

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.

15.2 REMOTE USER-AUTHENTICATION USING SYMMETRIC ENCRYPTION

Mutual Authentication

As was discussed in Chapter 14, a two-level hierarchy of symmetric encryption keys can be used to provide confidentiality for communication in a distributed environment. In general, this strategy involves the use of a trusted key distribution center

(KDC). Each party in the network shares a secret key, known as a master key, with the KDC. The KDC is responsible for generating keys to be used for a short time over a connection between two parties, known as session keys, and for distributing those keys using the master keys to protect the distribution. This approach is quite common. As an example, we look at the Kerberos system in Section 15.3. The discussion in this subsection is relevant to an understanding of the Kerberos mechanisms.

Figure 14.3 illustrates a proposal initially put forth by Needham and Schroeder [NEED78] for secret key distribution using a KDC that, as was mentioned in Chapter 14, includes authentication features. The protocol can be summarized as follows.[1]

1. A → KDC: $ID_A \| ID_B \| N_1$
2. KDC → A: $E(K_a, [K_s \| ID_B \| N_1 \| E(K_b, [K_s \| ID_A])])$
3. A → B: $E(K_b, [K_s \| ID_A])$
4. B → A: $E(K_s, N_2)$
5. A → B: $E(K_s, f(N_2))$ where f() is a generic function that modifies the value of the nonce.

Secret keys K_a and K_b are shared between A and the KDC and B and the KDC, respectively. The purpose of the protocol is to distribute securely a session key K_s to A and B. Entity A securely acquires a new session key in step 2. The message in step 3 can be decrypted, and hence understood, only by B. Step 4 reflects B's knowledge of K_s, and step 5 assures B of A's knowledge of K_s and assures B that this is a fresh message because of the use of the nonce N_2. Recall from our discussion in Chapter 14 that the purpose of steps 4 and 5 is to prevent a certain type of replay attack. In particular, if an opponent is able to capture the message in step 3 and replay it, this might in some fashion disrupt operations at B.

Despite the handshake of steps 4 and 5, the protocol is still vulnerable to a form of replay attack. Suppose that an opponent, X, has been able to compromise an old session key. Admittedly, this is a much more unlikely occurrence than that an opponent has simply observed and recorded step 3. Nevertheless, it is a potential security risk. X can impersonate A and trick B into using the old key by simply replaying step 3. Unless B remembers indefinitely all previous session keys used with A, B will be unable to determine that this is a replay. If X can intercept the handshake message in step 4, then it can impersonate A's response in step 5. From this point on, X can send bogus messages to B that appear to B to come from A using an authenticated session key.

Denning [DENN81, DENN82] proposes to overcome this weakness by a modification to the Needham/Schroeder protocol that includes the addition of a timestamp to steps 2 and 3. Her proposal assumes that the master keys, K_a and K_b, are secure, and it consists of the following steps.

[1]The portion to the left of the colon indicates the sender and the receiver; the portion to the right indicates the contents of the message; the symbol ‖ indicates concatenation.

1. $A \rightarrow KDC: \quad ID_A \| ID_B$
2. $KDC \rightarrow A: \quad E(K_a, [K_s \| ID_B \| T \| E(K_b, [K_s \| ID_A \| T])])$
3. $A \rightarrow B: \quad E(K_b, [K_s \| ID_A \| T])$
4. $B \rightarrow A: \quad E(K_s, N_1)$
5. $A \rightarrow B: \quad E(K_s, f(N_1))$

T is a timestamp that assures A and B that the session key has only just been generated. Thus, both A and B know that the key distribution is a fresh exchange. A and B can verify timeliness by checking that

$$|\text{Clock} - T| < \Delta t_1 + \Delta t_2$$

where Δt_1 is the estimated normal discrepancy between the KDC's clock and the local clock (at A or B) and Δt_2 is the expected network delay time. Each node can set its clock against some standard reference source. Because the timestamp T is encrypted using the secure master keys, an opponent, even with knowledge of an old session key, cannot succeed because a replay of step 3 will be detected by B as untimely.

A final point: Steps 4 and 5 were not included in the original presentation [DENN81] but were added later [DENN82]. These steps confirm the receipt of the session key at B.

The Denning protocol seems to provide an increased degree of security compared to the Needham/Schroeder protocol. However, a new concern is raised: namely, that this new scheme requires reliance on clocks that are synchronized throughout the network. [GONG92] points out a risk involved. The risk is based on the fact that the distributed clocks can become unsynchronized as a result of sabotage on or faults in the clocks or the synchronization mechanism.[2] The problem occurs when a sender's clock is ahead of the intended recipient's clock. In this case, an opponent can intercept a message from the sender and replay it later when the timestamp in the message becomes current at the recipient's site. This replay could cause unexpected results. Gong refers to such attacks as **suppress-replay attacks**.

One way to counter suppress-replay attacks is to enforce the requirement that parties regularly check their clocks against the KDC's clock. The other alternative, which avoids the need for clock synchronization, is to rely on handshaking protocols using nonces. This latter alternative is not vulnerable to a suppress-replay attack, because the nonces the recipient will choose in the future are unpredictable to the sender. The Needham/Schroeder protocol relies on nonces only but, as we have seen, has other vulnerabilities.

In [KEHN92], an attempt is made to respond to the concerns about suppress-replay attacks and at the same time fix the problems in the Needham/Schroeder protocol. Subsequently, an inconsistency in this latter protocol was noted and an improved strategy was presented in [NEUM93a].[3] The protocol is

[2]Such things can and do happen. In recent years, flawed chips were used in a number of computers and other electronic systems to track the time and date. The chips had a tendency to skip forward one day. [NEUM90]
[3]It really is hard to get these things right.

1. $A \rightarrow B$: $ID_A \| N_a$
2. $B \rightarrow KDC$: $ID_B \| N_b \| E(K_b, [ID_A \| N_a \| T_b])$
3. $KDC \rightarrow A$: $E(K_a, [ID_B \| N_a \| K_s \| T_b]) \| E(K_b, [ID_A \| K_s \| T_b]) \| N_b$
4. $A \rightarrow B$: $E(K_b, [ID_A \| K_s \| T_b]) \| E(K_s, N_b)$

Let us follow this exchange step by step.

1. A initiates the authentication exchange by generating a nonce, N_a, and sending that plus its identifier to B in plaintext. This nonce will be returned to A in an encrypted message that includes the session key, assuring A of its timeliness.
2. B alerts the KDC that a session key is needed. Its message to the KDC includes its identifier and a nonce, N_b. This nonce will be returned to B in an encrypted message that includes the session key, assuring B of its timeliness. B's message to the KDC also includes a block encrypted with the secret key shared by B and the KDC. This block is used to instruct the KDC to issue credentials to A; the block specifies the intended recipient of the credentials, a suggested expiration time for the credentials, and the nonce received from A.
3. The KDC passes on to A B's nonce and a block encrypted with the secret key that B shares with the KDC. The block serves as a "ticket" that can be used by A for subsequent authentications, as will be seen. The KDC also sends to A a block encrypted with the secret key shared by A and the KDC. This block verifies that B has received A's initial message (ID_B) and that this is a timely message and not a replay (N_a), and it provides A with a session key (K_s) and the time limit on its use (T_b).
4. A transmits the ticket to B, together with the B's nonce, the latter encrypted with the session key. The ticket provides B with the secret key that is used to decrypt $E(K_s, N_b)$ to recover the nonce. The fact that B's nonce is encrypted with the session key authenticates that the message came from A and is not a replay.

This protocol provides an effective, secure means for A and B to establish a session with a secure session key. Furthermore, the protocol leaves A in possession of a key that can be used for subsequent authentication to B, avoiding the need to contact the authentication server repeatedly. Suppose that A and B establish a session using the aforementioned protocol and then conclude that session. Subsequently, but within the time limit established by the protocol, A desires a new session with B. The following protocol ensues:

1. $A \rightarrow B$: $E(K_b, [ID_A \| K_s \| T_b]) \| N'_a$
2. $B \rightarrow A$: $N'_b \| E(K_s, N'_a)$
3. $A \rightarrow B$: $E(K_s, N'_b)$

When B receives the message in step 1, it verifies that the ticket has not expired. The newly generated nonces N'_a and N'_b assure each party that there is no replay attack.

In all the foregoing, the time specified in T_b is a time relative to B's clock. Thus, this timestamp does not require synchronized clocks, because B checks only self-generated timestamps.

One-Way Authentication

Using symmetric encryption, the decentralized key distribution scenario illustrated in Figure 14.5 is impractical. This scheme requires the sender to issue a request to the intended recipient, await a response that includes a session key, and only then send the message.

With some refinement, the KDC strategy illustrated in Figure 14.3 is a candidate for encrypted electronic mail. Because we wish to avoid requiring that the recipient (B) be on line at the same time as the sender (A), steps 4 and 5 must be eliminated. For a message with content M, the sequence is as follows:

1. $A \rightarrow KDC: \quad ID_A \| ID_B \| N_1$
2. $KDC \rightarrow A: \quad E(K_a, [K_s \| ID_B \| N_1 \| E(K_b, [K_s \| ID_A])])$
3. $A \rightarrow B: \quad E(K_b, [K_s \| ID_A]) \| E(K_s, M)$

This approach guarantees that only the intended recipient of a message will be able to read it. It also provides a level of authentication that the sender is A. As specified, the protocol does not protect against replays. Some measure of defense could be provided by including a timestamp with the message. However, because of the potential delays in the email process, such timestamps may have limited usefulness.

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.

[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

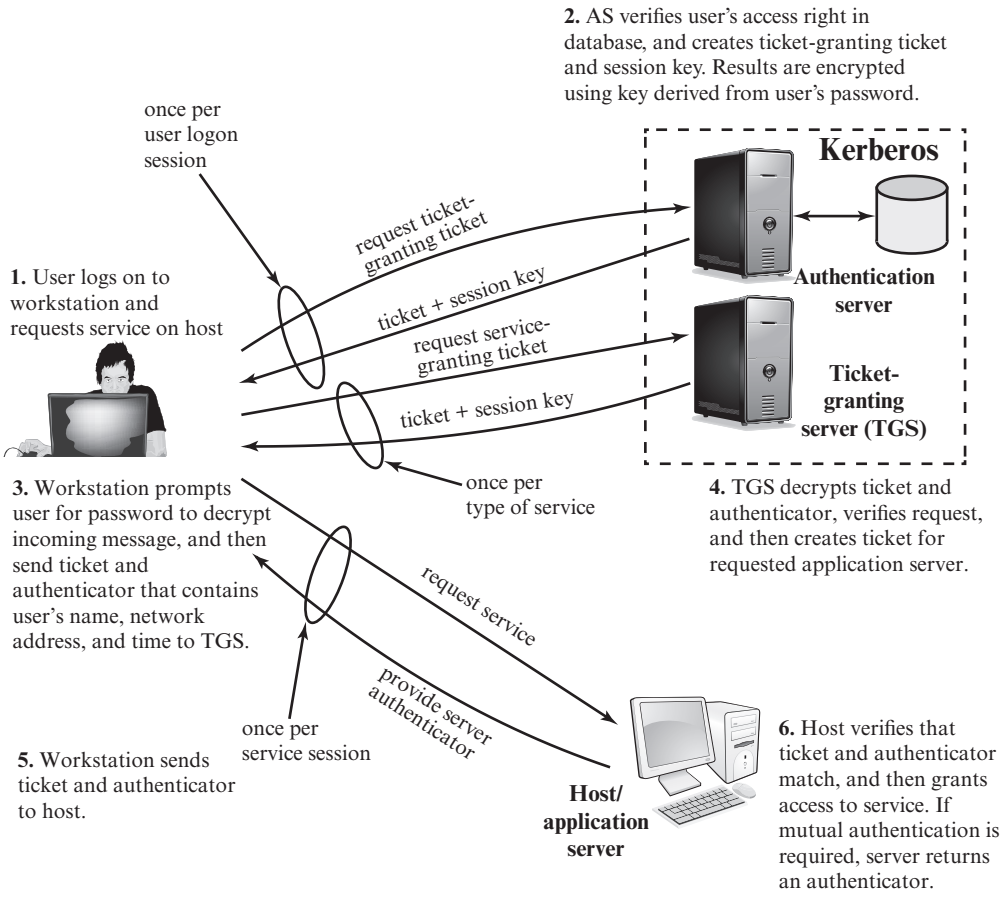


Figure 15.2 Overview of Kerberos

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.

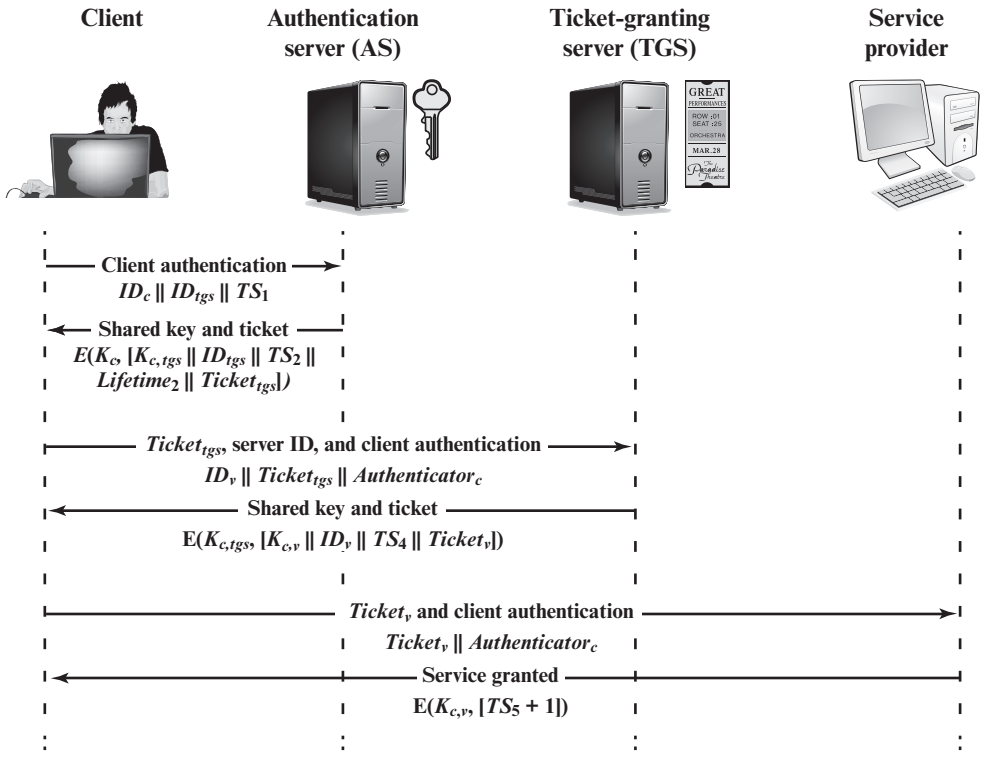


Figure 15.3 Kerberos Exchanges

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}: $Ticket_{\text{vrem}} \| Authenticator_c$

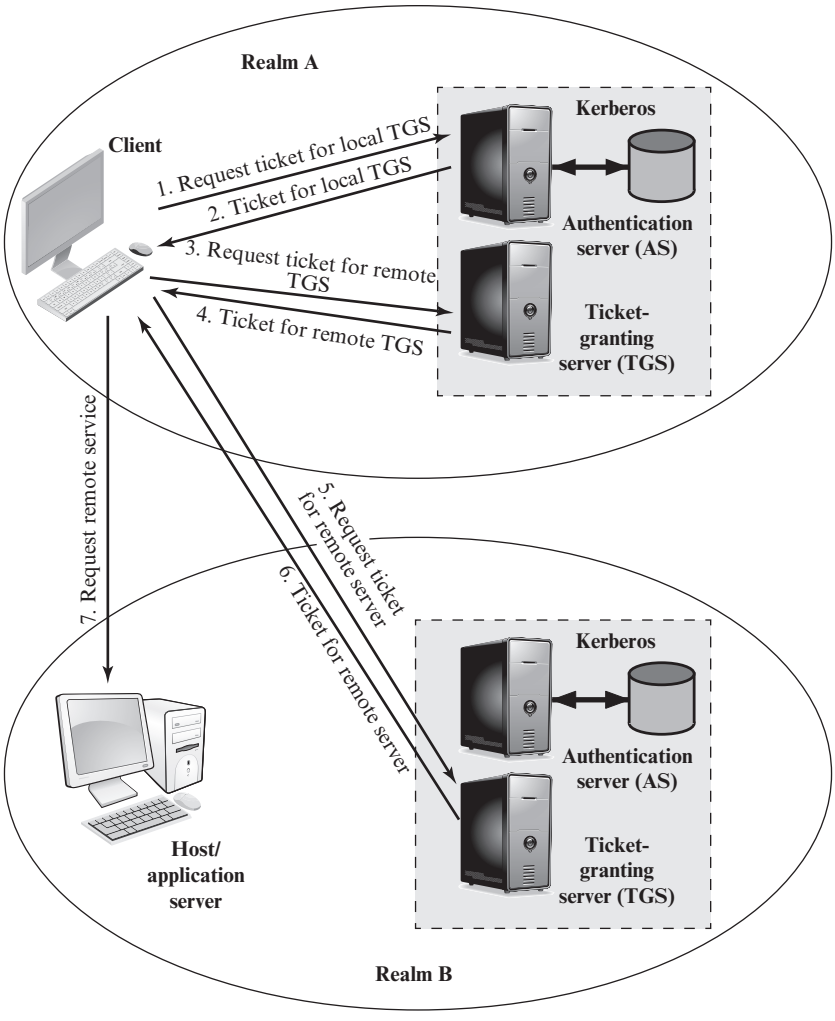


Figure 15.4 Request for Service in Another Realm

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

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. $A \rightarrow KDC$: $ID_A \| ID_B$
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. $KDC \rightarrow B$: $E(PR_{auth}, [ID_A \| PU_a]) \| E(PU_b, E(PR_{auth}, [N_a \| K_s \| ID_B]))$

[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.

15.5 FEDERATED IDENTITY MANAGEMENT

Federated identity management is a relatively new concept dealing with the use of a common identity management scheme across multiple enterprises and numerous applications and supporting many thousands, even millions, of users. We begin our overview with a discussion of the concept of identity management and then examine federated identity management.

Identity Management

Identity management is a centralized, automated approach to provide enterprise-wide access to resources by employees and other authorized individuals. The focus of identity management is defining an identity for each user (human or process), associating attributes with the identity, and enforcing a means by which a user can verify identity. The central concept of an identity management system is the use of single sign-on (SSO).

SSO enables a user to access all network resources after a single authentication.

Typical services provided by a federated identity management system include the following:

- **Point of contact:** Includes authentication that a user corresponds to the user name provided, and management of user/server sessions.
- **SSO protocol services:** Provides a vendor-neutral security token service for supporting a single sign on to federated services.
- **Trust services:** Federation relationships require a trust relationship-based federation between business partners. A trust relationship is represented by the combination of the security tokens used to exchange information about a user, the cryptographic information used to protect these security tokens, and optionally the identity mapping rules applied to the information contained within this token.
- **Key services:** Management of keys and certificates.
- **Identity services:** services that provide the interface to local data stores, including user registries and databases, for identity-related information management.
- **Authorization:** Granting access to specific services and/or resources based on the authentication.
- **Provisioning:** Includes creating an account in each target system for the user, enrollment or registration of user in accounts, establishment of access rights or credentials to ensure the privacy and integrity of account data.
- **Management:** Services related to runtime configuration and deployment.

Note that Kerberos contains a number of the elements of an identity management system.

Figure 15.5 illustrates entities and data flows in a generic identity management architecture. A **principal** is an identity holder. Typically, this is a human user that seeks access to resources and services on the network. User devices, agent processes, and server systems may also function as principals. Principals authenticate themselves to an **identity provider**. The identity provider associates authentication information with a principal, as well as attributes and one or more identifiers.

Increasingly, digital identities incorporate attributes other than simply an identifier and authentication information (such as passwords and biometric information). An **attribute service** manages the creation and maintenance of such attributes. For example, a user needs to provide a shipping address each time an order is placed at a new Web merchant, and this information needs to be revised when the user moves. Identity management enables the user to provide this information once, so that it is maintained in a single place and released to data consumers in accordance with

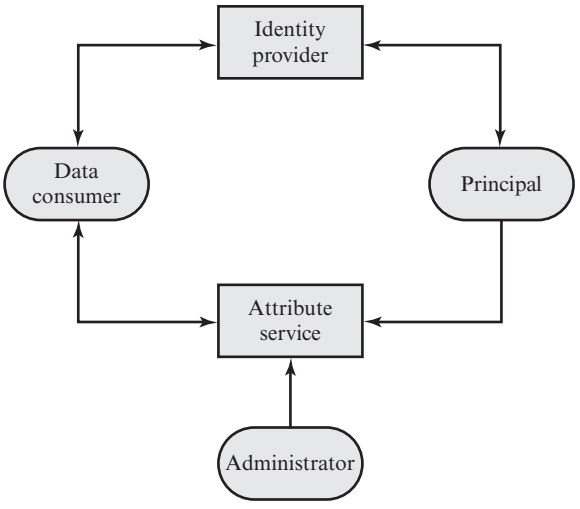


Figure 15.5 Generic Identity Management Architecture

authorization and privacy policies. Users may create some of the attributes to be associated with their digital identity, such as an address. **Administrators** may also assign attributes to users, such as roles, access permissions, and employee information.

Data consumers are entities that obtain and employ data maintained and provided by identity and attribute providers, which are often used to support authorization decisions and to collect audit information. For example, a database server or file server is a data consumer that needs a client's credentials so as to know what access to provide to that client.

Identity Federation

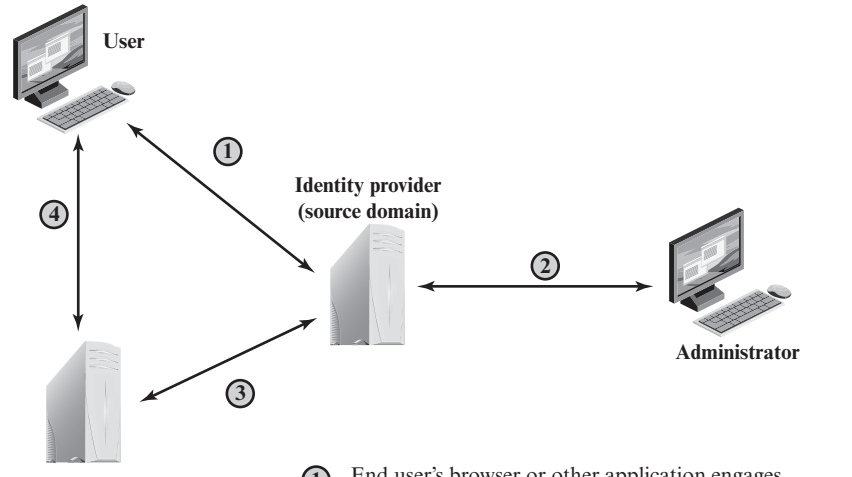
Identity federation is, in essence, an extension of identity management to multiple security domains. Such domains include autonomous internal business units, external business partners, and other third-party applications and services. The goal is to provide the sharing of digital identities so that a user can be authenticated a single time and then access applications and resources across multiple domains. Because these domains are relatively autonomous or independent, no centralized control is possible. Rather, the cooperating organizations must form a federation based on agreed standards and mutual levels of trust to securely share digital identities.

Federated identity management refers to the agreements, standards, and technologies that enable the portability of identities, identity attributes, and entitlements across multiple enterprises and numerous applications and supporting many thousands, even millions, of users. When multiple organizations implement interoperable federated identity schemes, an employee in one organization can use a single sign-on to access services across the federation with trust relationships associated with the identity. For example, an employee may log onto her corporate intranet and be authenticated to perform authorized functions and access authorized services on that intranet. The employee could then access their health benefits from an outside health-care provider without having to reauthenticate.

Beyond SSO, federated identity management provides other capabilities. One is a standardized means of representing attributes. Increasingly, digital identities incorporate attributes other than simply an identifier and authentication information (such as passwords and biometric information). Examples of attributes include account numbers, organizational roles, physical location, and file ownership. A user may have multiple identifiers; for example, each identifier may be associated with a unique role with its own access permissions.

Another key function of federated identity management is identity mapping. Different security domains may represent identities and attributes differently. Further, the amount of information associated with an individual in one domain may be more than is necessary in another domain. The federated identity management protocols map identities and attributes of a user in one domain to the requirements of another domain.

Figure 15.6 illustrates entities and data flows in a generic federated identity management architecture.



1. End user's browser or other application engages in an authentication dialogue with identity provider in the same domain. End user also provides attribute values associated with user's identity.
2. Some attributes associated with an identity, such as allowable roles, may be provided by an administrator in the same domain.
3. A service provider in a remote domain, which the user wishes to access, obtains identity information, authentication information, and associated attributes from the identity provider in the source domain.
4. Service provider opens session with remote user and enforces access control restrictions based on user's identity and attributes.

Figure 15.6 Federated Identity Operation

The identity provider acquires attribute information through dialogue and protocol exchanges with users and administrators. For example, a user needs to provide a shipping address each time an order is placed at a new Web merchant, and this information needs to be revised when the user moves. Identity management enables the user to provide this information once, so that it is maintained in a single place and released to data consumers in accordance with authorization and privacy policies.

Service providers are entities that obtain and employ data maintained and provided by identity providers, often to support authorization decisions and to collect audit information. For example, a database server or file server is a data consumer that needs a client's credentials so as to know what access to provide to that client. A service provider can be in the same domain as the user and the identity provider. The power of this approach is for federated identity management, in which the service provider is in a different domain (e.g., a vendor or supplier network).

Standards Federated identity management uses a number of standards as the building blocks for secure identity exchange across different domains or heterogeneous systems. In essence, organizations issue some form of security tickets for their users that can be processed by cooperating partners. Identity federation standards are thus concerned with defining these tickets, in terms of content and format, providing protocols for exchanging tickets and performing a number of management tasks. These tasks include configuring systems to perform attribute transfers and identity mapping, and performing logging and auditing functions. The key standards are as follows:

- **The Extensible Markup Language (XML):** A markup language that uses sets of embedded tags or labels to characterize text elements within a document so as to indicate their appearance, function, meaning, or context. XML documents appear similar to HTML (Hypertext Markup Language) documents that are visible as Web pages, but provide greater functionality. XML includes strict definitions of the data type of each field, thus supporting database formats and semantics. XML provides encoding rules for commands that are used to transfer and update data objects.
- **The Simple Object Access Protocol (SOAP):** A minimal set of conventions for invoking code using XML over HTTP. It enables applications to request services from one another with XML-based requests and receive responses as data formatted with XML. Thus, XML defines data objects and structures, and SOAP provides a means of exchanging such data objects and performing remote procedure calls related to these objects. See [ROS06] for an informative discussion.
- **WS-Security:** A set of SOAP extensions for implementing message integrity and confidentiality in Web services. To provide for secure exchange of SOAP messages among applications, WS-Security assigns security tokens to each message for use in authentication.
- **Security Assertion Markup Language (SAML):** An XML-based language for the exchange of security information between online business partners. SAML conveys authentication information in the form of assertions about subjects. Assertions are statements about the subject issued by an authoritative entity.

The challenge with federated identity management is to integrate multiple technologies, standards, and services to provide a secure, user-friendly utility. The key, as in most areas of security and networking, is the reliance on a few mature standards widely accepted by industry. Federated identity management seems to have reached this level of maturity.

EXAMPLES To get some feel for the functionality of identity federation, we look at three scenarios, taken from [COMP06].

In the first scenario (Figure 15.7a), Workplace.com contracts with Health.com to provide employee health benefits. An employee uses a Web interface to sign on to Workplace.com and goes through an authentication procedure there. This enables the employee to access authorized services and resources at Workplace.com. When the employee clicks on a link to access health benefits, her browser is redirected to Health.com. At the same time, the Workplace.com software passes the user's identifier to Health.com in a secure manner. The two organizations are part of a federation that cooperatively exchanges user identifiers. Health.com maintains user identities

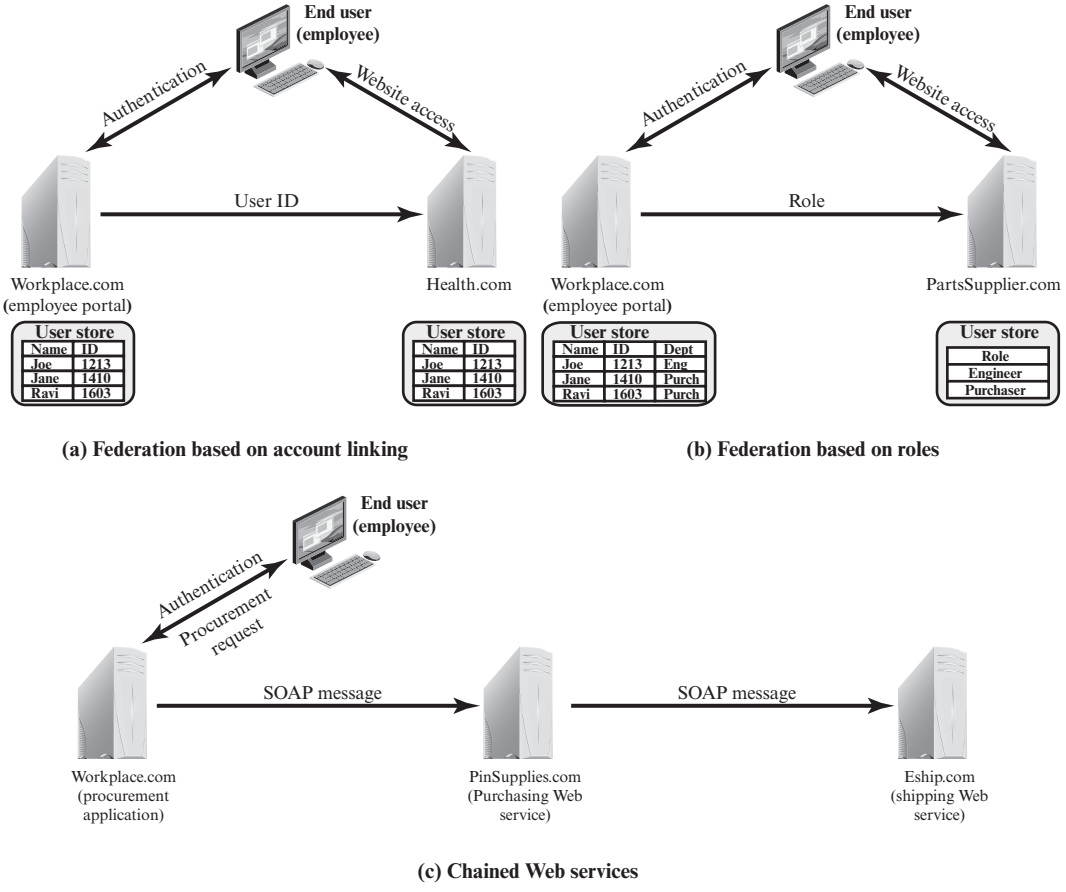


Figure 15.7 Federated Identity Scenarios

for every employee at Workplace.com and associates with each identity health-benefits information and access rights. In this example, the linkage between the two companies is based on account information and user participation is browser based.

Figure 15.7b shows a second type of browser-based scheme. PartsSupplier.com is a regular supplier of parts to Workplace.com. In this case, a role-based access-control (RBAC) scheme is used for access to information. An engineer of Workplace.com authenticates at the employee portal at Workplace.com and clicks on a link to access information at PartsSupplier.com. Because the user is authenticated in the role of an engineer, he is taken to the technical documentation and troubleshooting portion of PartsSupplier.com's Web site without having to sign on. Similarly, an employee in a purchasing role signs on at Workplace.com and is authorized, in that role, to place purchases at PartsSupplier.com without having to authenticate to PartsSupplier.com. For this scenario, PartsSupplier.com does not have identity information for individual employees at Workplace.com. Rather, the linkage between the two federated partners is in terms of roles.

The scenario illustrated in Figure 15.7c can be referred to as document based rather than browser based. In this third example, Workplace.com has a purchasing agreement with PinSupplies.com, and PinSupplies.com has a business relationship with E-Ship.com. An employee of Workplace.com signs on and is authenticated to make purchases. The employee goes to a procurement application that provides a list of Workplace.com's suppliers and the parts that can be ordered. The user clicks on the PinSupplies button and is presented with a purchase order Web page (HTML page). The employee fills out the form and clicks the submit button. The procurement application generates an XML/SOAP document that it inserts into the envelope body of an XML-based message. The procurement application then inserts the user's credentials in the envelope header of the message, together with Workplace.com's organizational identity. The procurement application posts the message to the PinSupplies.com's purchasing Web service. This service authenticates the incoming message and processes the request. The purchasing Web service then sends a SOAP message to its shipping partner to fulfill the order. The message includes a PinSupplies.com security token in the envelope header and the list of items to be shipped as well as the end user's shipping information in the envelope body. The shipping Web service authenticates the request and processes the shipment order.

15.6 PERSONAL IDENTITY VERIFICATION

User authentication based on the possession of a smart card is becoming more widespread. A smart card has the appearance of a credit card, has an electronic interface, and may use a variety of authentication protocols.

A smart card contains within it an entire microprocessor, including processor, memory, and I/O ports. Some versions incorporate a special co-processing circuit for cryptographic operation to speed the task of encoding and decoding messages or generating digital signatures to validate the information transferred. In some cards, the I/O ports are directly accessible by a compatible reader by means of exposed electrical contacts. Other cards rely instead on an embedded antenna for wireless communication with the reader.

A typical smart card includes three types of memory. Read-only memory (ROM) stores data that does not change during the card's life, such as the card number and the cardholder's name. Electrically erasable programmable ROM (EEPROM) holds application data and programs, such as the protocols that the card can execute. It also holds data that may vary with time. For example, in a telephone card, the EEPROM holds the talk time remaining. Random access memory (RAM) holds temporary data generated when applications are executed.

For the practical application of smart card authentication, a wide range of vendors must conform to standards that cover smart card protocols, authentication and access control formats and protocols, database entries, message formats, and so on. An important step in this direction is FIPS 201-2 (*Personal Identity Verification [PIV] of Federal Employees and Contractors*, June 2012). The standard defines a reliable, government-wide PIV system for use in applications such as access to federally controlled facilities and information systems. The standard specifies a PIV system within which common identification credentials can be created and later used to verify a claimed identity. The standard also identifies Federal government-wide requirements for security levels that are dependent on risks to the facility or information being protected. The standard applies to private-sector contractors as well, and serves as a useful guideline for any organization.

PIV System Model

Figure 15.8 illustrates the major components of FIPS 201-2 compliant systems. The PIV front end defines the physical interface to a user who is requesting access to a facility, which could be either physical access to a protected physical area or logical access to an information system. The **PIV front-end subsystem** supports up to three-factor authentication; the number of factors used depends on the level of security required. The front end makes use of a smart card, known as a PIV card, which is a dual-interface contact and contactless card. The card holds a cardholder photograph, X.509 certificates, cryptographic keys, biometric data, and a cardholder unique identifier (CHUID). Certain cardholder information may be read-protected and require a personal identification number (PIN) for read access by the card reader. The biometric reader, in the current version of the standard, is a fingerprint reader or an iris scanner.

The standard defines three assurance levels for verification of the card and the encoded data stored on the card, which in turn leads to verifying the authenticity of the person holding the credential. A level of *some confidence* corresponds to use of the card reader and PIN. A level of *high confidence* adds a biometric comparison of a fingerprint captured and encoded on the card during the card-issuing process and a fingerprint scanned at the physical access point. A *very high confidence* level requires that the process just described is completed at a control point attended by an official observer.

The other major component of the PIV system is the **PIV card issuance and management subsystem**. This subsystem includes the components responsible for identity proofing and registration, card and key issuance and management, and the various repositories and services (e.g., public key infrastructure [PKI] directory, certificate status servers) required as part of the verification infrastructure.

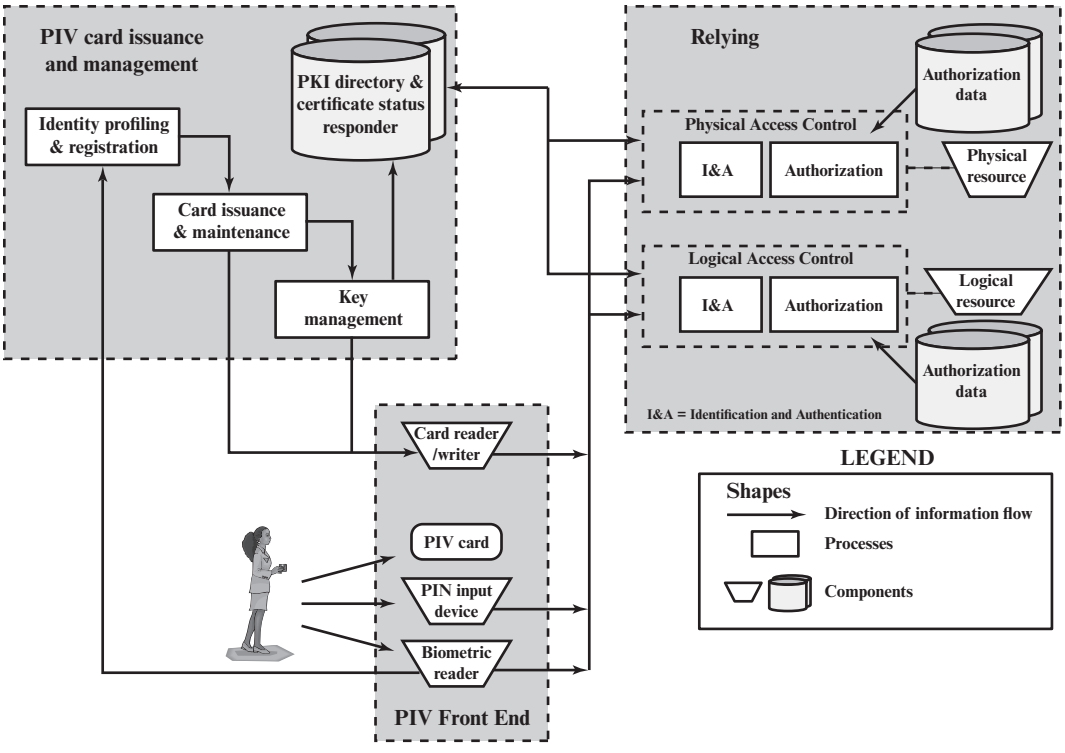


Figure 15.8 FIPS 201 PIV System Model

The PIV system interacts with a **relying subsystem**, which includes components responsible for determining a particular PIV cardholder's access to a physical or logical resource. FIPS 201-2 standardizes data formats and protocols for interaction between the PIV system and the relying system.

Unlike the typical card number/facility code encoded on most access control cards, the FIPS 201 CHUID takes authentication to a new level, through the use of an expiration date (a required CHUID data field) and an optional CHUID digital signature. A digital signature can be checked to ensure that the CHUID recorded on the card was digitally signed by a trusted source and that the CHUID data have not been altered since the card was signed. The CHUID expiration date can be checked to verify that the card has not expired. This is independent from whatever expiration date is associated with cardholder privileges. Reading and verifying the CHUID alone provides only some assurance of identity because it authenticates the card data, not the cardholder. The PIN and biometric factors provide identity verification of the individual.

PIV Documentation

The PIV specification is quite complex, and NIST has issued a number of documents that cover a broad range of PIV topics. These are as follows:

- **FIPS 201-2—Personal Identity Verification (PIV) of Federal Employees and Contractors:** Specifies the physical card characteristics, storage media, and data elements that make up the identity credentials resident on the PIV card.
- **SP 800-73-3—Interfaces for Personal Identity Verification:** Specifies the interfaces and card architecture for storing and retrieving identity credentials from a smart card, and provides guidelines for the use of authentication mechanisms and protocols.
- **SP 800-76-2—Biometric Data Specification for Personal Identity Verification:** Describes technical acquisition and formatting specifications for the biometric credentials of the PIV system.
- **SP 800-78-3—Cryptographic Algorithms and Key Sizes for Personal Identity Verification:** Identifies acceptable symmetric and asymmetric encryption algorithms, digital signature algorithms, and message digest algorithms, and specifies mechanisms to identify the algorithms associated with PIV keys or digital signatures.
- **SP 800-104—A Scheme for PIV Visual Card Topography:** Provides additional recommendations on the PIV card color-coding for designating employee affiliation.
- **SP 800-116—A Recommendation for the Use of PIV Credentials in Physical Access Control Systems (PACS):** Describes a risk-based approach for selecting appropriate PIV authentication mechanisms to manage physical access to Federal government facilities and assets.
- **SP 800-79-1—Guidelines for the Accreditation of Personal Identity Verification Card Issuers:** Provides guidelines for accrediting the reliability of issuers of PIV cards that collect, store, and disseminate personal identity credentials and issue smart cards.
- **SP 800-96—PIV Card to Reader Interoperability Guidelines:** Provides requirements that facilitate interoperability between any card and any reader.

In addition there are other documents that deal with conformance testing and codes for identifiers.

PIV Credentials and Keys

The PIV card contains a number of mandatory and optional data elements that serve as identity credentials with varying levels of strength and assurance. These credentials are used singly or in sets to authenticate the holder of the PIV card to achieve the level of assurance required for a particular activity or transaction. The mandatory data elements are the following:

- **Personal Identification Number (PIN):** Required to activate the card for privileged operation.
- **Cardholder Unique Identifier (CHUID):** Includes the Federal Agency Smart Credential Number (FASC-N) and the Global Unique Identification Number (GUID), which uniquely identify the card and the cardholder.

- **PIV Authentication Key:** Asymmetric key pair and corresponding certificate for user authentication.
- **Two fingerprint templates:** For biometric authentication.
- **Electronic facial image:** For biometric authentication.
- **Asymmetric Card Authentication Key:** Asymmetric key pair and corresponding certificate used for card authentication.

Optional elements include the following:

- **Digital Signature Key:** Asymmetric key pair and corresponding certificate that supports document signing and signing of data elements such as the CHUID.
- **Key Management Key:** Asymmetric key pair and corresponding certificate supporting key establishment and transport.
- **Symmetric Card Authentication Key:** For supporting physical access applications.
- **PIV Card Application Administration Key:** Symmetric key associated with the card management system.
- **One or two iris images:** For biometric authentication.

Table 15.5 lists the algorithm and key size requirements for PIV key types.

Authentication

Using the electronic credentials resident on a PIV card, the card supports the following authentication mechanisms:

- **CHUID:** The cardholder is authenticated using the signed CHUID data element on the card. The PIN is not required. This mechanism is useful in environments where a low level of assurance is acceptable and rapid contactless authentication is necessary.

Table 15.5 PIV Algorithms and Key Sizes

PIV Key Type	Algorithms	Key Sizes (bits)	Application
PIV Authentication Key	RSA	2048	Supports card and cardholder authentication for an interoperable environment
	ECDSA	256	
Card Authentication Key	3TDEA	168	Supports card authentication for physical access
	AES	128, 192, or 256	
	RSA	2048	Supports card authentication for an interoperable environment
	ECDSA	256	
Digital Signature Key	RSA	2048 or 3072	Supports document signing and nonce signing
	ECDSA	256 or 384	
Key Management Key	RSA	2048	Supports key establishment and transport
	ECDH	256 or 384	

- **Card Authentication Key:** The PIV card is authenticated using the Card Authentication Key in a challenge response protocol. The PIN is not required. This mechanism allows contact (via card reader) or contactless (via radio waves) authentication of the PIV card without the holder's active participation, and provides a low level of assurance.
- **BIO:** The cardholder is authenticated by matching his or her fingerprint sample(s) to the signed biometric data element in an environment without a human attendant in view. The PIN is required to activate the card. This mechanism achieves a high level of assurance and requires the cardholder's active participation is submitting the PIN as well as the biometric sample.
- **BIO-A:** The cardholder is authenticated by matching his or her fingerprint sample(s) to the signed biometric data element in an environment with a human attendant in view. The PIN is required to activate the card. This mechanism achieves a very high level of assurance when coupled with full trust validation of the biometric template retrieved from the card, and requires the cardholder's active participation is submitting the PIN as well as the biometric sample.
- **PKI:** The cardholder is authenticated by demonstrating control of the PIV authentication private key in a challenge response protocol that can be validated using the PIV authentication certificate. The PIN is required to activate the card. This mechanism achieves a very high level of identity assurance and requires the cardholder's knowledge of the PIN.

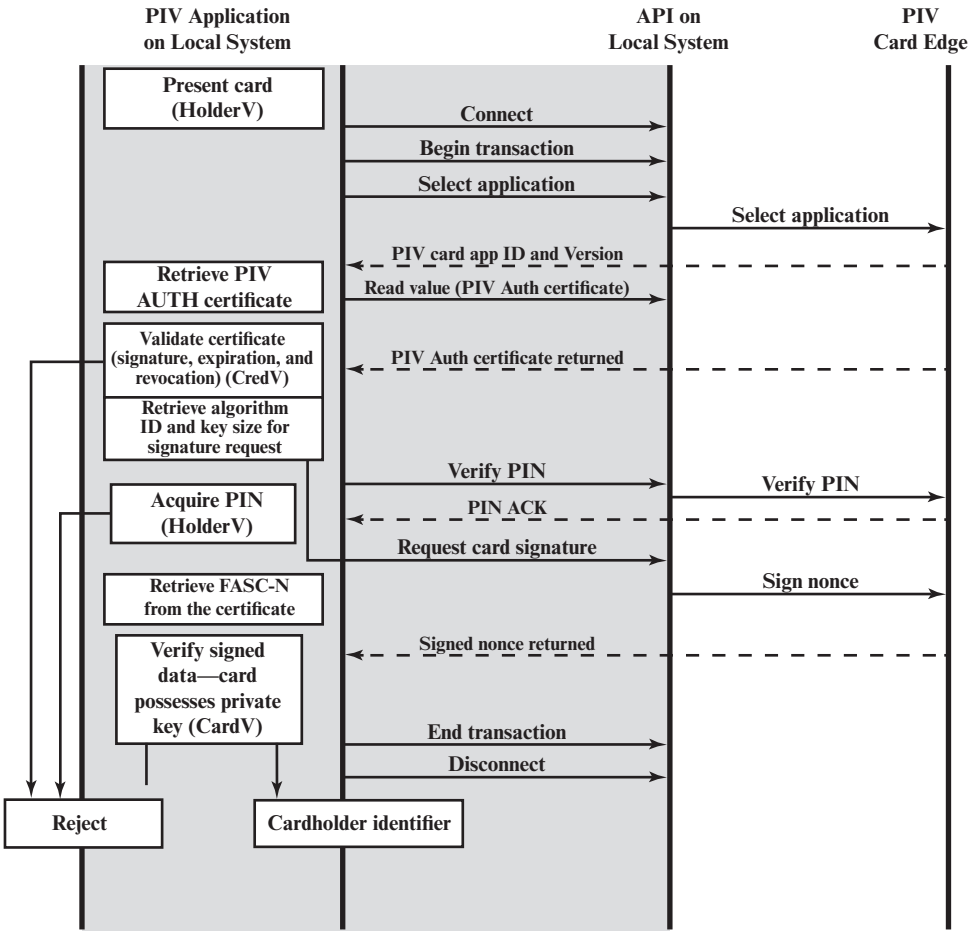
In each of the above use cases, except the symmetric Card Authentication Key use case, the source and the integrity of the corresponding PIV credential are validated by verifying the digital signature on the credential, with the signature being provided by a trusted entity.

A variety of protocols can be constructed for each of these authentication types. SP 800-78-3 gives examples for each type. Figure 15.9 illustrates an authentication scenario that includes the use of the PIV Authentication Key. This scenario provides a high level of assurance. This scenario would be appropriate for authentication of a user who possesses a PIV card and seeks access to a computer resource. The computer, designated *local system* in the figure, includes PIV application software and communicates to the card via an application program interface that enables the use of relatively high-level procedure calls. These high-level commands are converted into PIV commands that are issued to the card through a physical interface via a card reader or via a wireless interface. In either case, SP 800-73 refers to the card command interface as the PIV card edge.

The process begins when the local system detects the card either through an attached card reader or wirelessly. It then selects an application on the card for authentication. The local system then requests the public-key certificate for the card's PIV Authentication Key. If the certificate is valid (i.e., has a valid signature, has not expired or been revoked), authentication continues. Otherwise the card is rejected. The next step is for the local system to request that the cardholder enter the PIN for the card. If the submitted PIN matches the PIN stored on the card, the card returns a positive acknowledgment; otherwise the card returns a failure message.

The local system either continues or rejects the card accordingly. The next phase is a challenge-response protocol. The local system sends a nonce to be signed by the PIV, and the PIV returns the signature. The local system uses the PIV authentication public key to verify the signature. If the signature is valid, the cardholder is accepted as being identified. Otherwise the local system rejects the card.

The scenario of Figure 15.9 accomplishes three types of authentication. The combination of possession of the card and knowledge of the PIN service authenticates the cardholder. The PIV Authentication Key certificate validates the card's credentials. The challenge-response protocol authenticates the card.



CardV = Card validation
CredV = Credential validation
HolderV = Cardholder validation
FASC-N = Federal Agency Smart Credential Number

Figure 15.9 Authentication Using PIV Authentication Key

15.7 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

authentication	Kerberos	relying party (RP)
authentication server	Kerberos realm	replay attack
claimant	mutual authentication	subscriber
credential	nonce	suppress-replay attack
credential service provider (CSP)	one-way authentication	ticket
federated identity management	personal identity verification (PIV)	ticket-granting server (TGS)
identity management	realm	timestamp
	registration authority (RA)	verifier

Review Questions

15.1 What are the steps involved in an authentication process?
15.2 List three general approaches to dealing with replay attacks.
15.3 What is a suppress-replay attack?
15.4 What problem was Kerberos designed to address?
15.5 What are three threats associated with user authentication over a network or Internet?
15.6 List three approaches to secure user authentication in a distributed environment.
15.7 What four requirements were defined for Kerberos?
15.8 What entities constitute a full-service Kerberos environment?
15.9 In the context of Kerberos, what is a realm?
15.10 What are the mandatory elements to authenticate a PIV card holder?

Problems

15.1 In Section 15.4, we outlined the public-key scheme proposed in [WOO92a] for the distribution of secret keys. The revised version includes ID_A in steps 5 and 6. What attack, specifically, is countered by this revision?

15.2 The protocol referred to in Problem 15.1 can be reduced from seven steps to five, having the following sequence:
- **a.** A → B:
- **b.** A → KDC:
- **c.** KDC → B:
- **d.** B → A:
- **e.** A → B:

Show the message transmitted at each step. *Hint:* The final message in this protocol is the same as the final message in the original protocol.

15.3 Reference the suppress-replay attack described in Section 15.2 to answer the following.
- **a.** Give an example of an attack when a party's clock is ahead of that of the KDC.
- **b.** Give an example of an attack when a party's clock is ahead of that of another party.

15.4 There are three typical ways to use nonces as challenges. Suppose N_a is a nonce generated by A, A and B share key K, and f() is a function (such as an increment). The three usages are

Usage 1	Usage 2	Usage 3
(1) A → B: N_a	(1) A → B: E(K, N_a)	(1) A → B: E(K, N_a)
(2) B → A: E(K, N_a)	(2) B → A: N_a	(2) B → A: E(K, f(N_a))

Describe situations for which each usage is appropriate.

15.5 Show that a random error in one block of ciphertext is propagated to all subsequent blocks of plaintext in PCBC mode (See Figure T.2 in Appendix T).

15.6 Suppose that, in PCBC mode, blocks C_i and C_{i+1} are interchanged during transmission. Show that this affects only the decrypted blocks P_i and P_{i+1} but not subsequent blocks.

15.7 In addition to providing a standard for public-key certificate formats, X.509 specifies an authentication protocol. The original version of X.509 contains a security flaw. The essence of the protocol is as follows.

$$\begin{aligned} &\text{A} \rightarrow \text{B:} \quad \text{A}\{t_A, r_A, ID_B\} \\ &\text{B} \rightarrow \text{A:} \quad \text{B}\{t_B, r_B, ID_A, r_A\} \\ &\text{A} \rightarrow \text{B:} \quad \text{A}\{r_B\} \end{aligned}$$

where t_A and t_B are timestamps, r_A and r_B are nonces and the notation X{Y} indicates that the message Y is transmitted, encrypted, and signed by X.

The text of X.509 states that checking timestamps t_A and t_B is optional for three-way authentication. But consider the following example: Suppose A and B have used the preceding protocol on some previous occasion, and that opponent C has intercepted the preceding three messages. In addition, suppose that timestamps are not used and are all set to 0. Finally, suppose C wishes to impersonate A to B. C initially sends the first captured message to B:

$$\text{C} \rightarrow \text{B:} \quad \text{A}\{0, r_A, ID_B\}$$

B responds, thinking it is talking to A but is actually talking to C:

$$\text{B} \rightarrow \text{C:} \quad \text{B}\{0, r'_B, ID_A, r_A\}$$

C meanwhile causes A to initiate authentication with C by some means. As a result, A sends C the following:

$$\text{A} \rightarrow \text{C:} \quad \text{A}\{0, r'_A, ID_C\}$$

C responds to A using the same nonce provided to C by B:

$$\text{C} \rightarrow \text{A:} \quad \text{C}\{0, r'_B, ID_A, r'_A\}$$

A responds with

$$\text{A} \rightarrow \text{C:} \quad \text{A}\{r'_B\}$$

This is exactly what C needs to convince B that it is talking to A, so C now repeats the incoming message back out to B.

$$C \rightarrow B: \quad A \{r'_B\}$$

So B will believe it is talking to A whereas it is actually talking to C. Suggest a simple solution to this problem that does not involve the use of timestamps.

15.8 Consider a one-way authentication technique based on asymmetric encryption:

$$A \rightarrow B: \quad ID_A$$
$$B \rightarrow A: \quad R_1$$
$$A \rightarrow B: \quad E(PR_a, R_1)$$

a. Explain the protocol.
b. What type of attack is this protocol susceptible to?

15.9 Consider a one-way authentication technique based on asymmetric encryption:

$$A \rightarrow B: \ ID_A || E(PU_B, R_A)$$

$$B \rightarrow A: \ R_A$$

a. Explain the protocol.
b. What type of attack is this protocol susceptible to?

15.10 In Kerberos, when Bob receives a Ticket from Alice, how does he know it is not genuine?

15.11 In Kerberos, how does Bob know that the received token is not corresponding to Alice's?

15.12 In Kerberos, how does Alice know that a reply to an earlier message is from Bob?

15.13 In Kerberos, what does the Ticket contain that allows Alice and Bob to talk securely?

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PART SIX: NETWORK AND INTERNET SECURITY

CHAPTER 16

NETWORK ACCESS CONTROL AND CLOUD SECURITY

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Discuss the principal elements of a network access control system.
- Discuss the principal network access enforcement methods.
- Present an overview of the Extensible Authentication Protocol.
- Understand the operation and role of the IEEE 802.1X Port-Based Network Access Control mechanism.
- Present an overview of cloud computing concepts.
- Understand the unique security issues related to cloud computing.

This chapter begins our discussion of network security, focusing on two key topics: network access control and cloud security. We begin with an overview of network access control systems, summarizing the principal elements and techniques involved in such a system. Next, we discuss the Extensible Authentication Protocol and IEEE 802.1X, two widely implemented standards that are the foundation of many network access control systems.

The remainder of the chapter deals with cloud security. We begin with an overview of cloud computing, and follow this with a discussion of cloud security issues.

16.1 NETWORK ACCESS CONTROL

Network access control (NAC) is an umbrella term for managing access to a network. NAC authenticates users logging into the network and determines what data they can access and actions they can perform. NAC also examines the health of the user's computer or mobile device (the endpoints).

Elements of a Network Access Control System

NAC systems deal with three categories of components:

- **Access requestor (AR):** The AR is the node that is attempting to access the network and may be any device that is managed by the NAC system, including workstations, servers, printers, cameras, and other IP-enabled devices. ARs are also referred to as **supplicants**, or simply, clients.
- **Policy server:** Based on the AR's posture and an enterprise's defined policy, the policy server determines what access should be granted. The policy server often relies on backend systems, including antivirus, patch management, or a user directory, to help determine the host's condition.

- **Network access server (NAS):** The NAS functions as an access control point for users in remote locations connecting to an enterprise's internal network. Also called a **media gateway**, a **remote access server (RAS)**, or a **policy server**, an NAS may include its own authentication services or rely on a separate authentication service from the policy server.

Figure 16.1 is a generic network access diagram. A variety of different ARs seek access to an enterprise network by applying to some type of NAS. The first step is generally to authenticate the AR. Authentication typically involves some sort of secure protocol and the use of cryptographic keys. Authentication may be performed by the NAS, or the NAS may mediate the authentication process. In the latter case, authentication takes place between the supplicant and an authentication server that is part of the policy server or that is accessed by the policy server.

The authentication process serves a number of purposes. It verifies a supplicant's claimed identity, which enables the policy server to determine what access privileges, if any, the AR may have. The authentication exchange may result in the

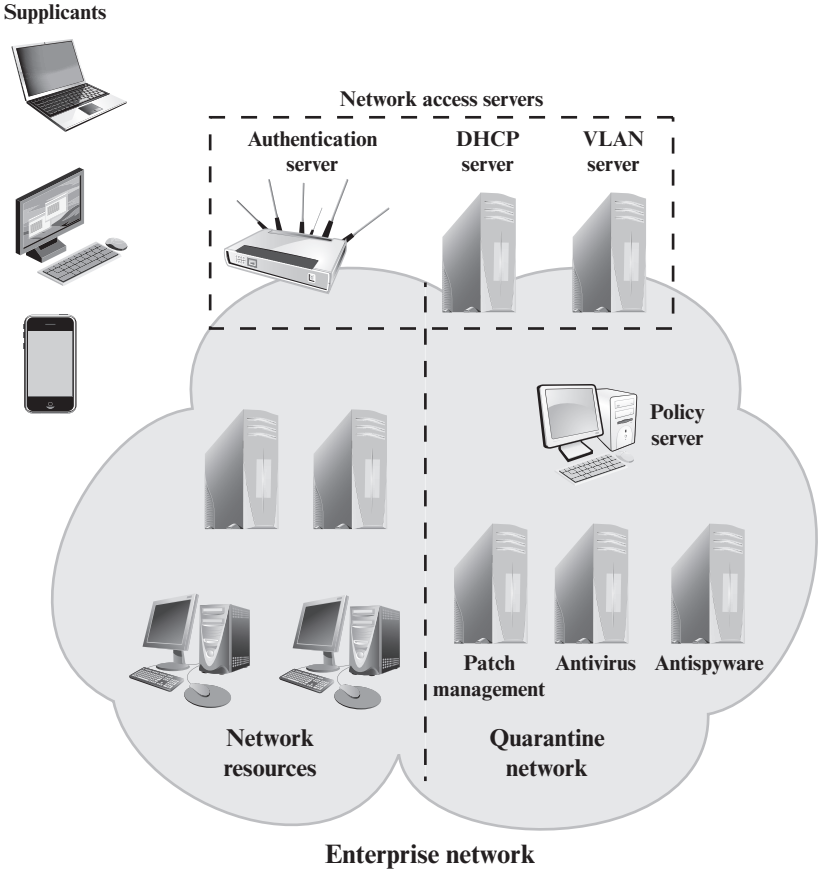


Figure 16.1 Network Access Control Context

establishment of session keys to enable future secure communication between the supplicant and resources on the enterprise network.

Typically, the policy server or a supporting server will perform checks on the AR to determine if it should be permitted interactive remote access connectivity. These checks—sometimes called health, suitability, screening, or assessment checks—require software on the user's system to verify compliance with certain requirements from the organization's secure configuration baseline. For example, the user's antimalware software must be up-to-date, the operating system must be fully patched, and the remote computer must be owned and controlled by the organization. These checks should be performed before granting the AR access to the enterprise network. Based on the results of these checks, the organization can determine whether the remote computer should be permitted to use interactive remote access. If the user has acceptable authorization credentials but the remote computer does not pass the health check, the user and remote computer should be denied network access or have limited access to a quarantine network so that authorized personnel can fix the security deficiencies. Figure 16.1 indicates that the quarantine portion of the enterprise network consists of the policy server and related AR suitability servers. There may also be application servers that do not require the normal security threshold be met.

Once an AR has been authenticated and cleared for a certain level of access to the enterprise network, the NAS can enable the AR to interact with resources in the enterprise network. The NAS may mediate every exchange to enforce a security policy for this AR, or may use other methods to limit the privileges of the AR.

Network Access Enforcement Methods

Enforcement methods are the actions that are applied to ARs to regulate access to the enterprise network. Many vendors support multiple enforcement methods simultaneously, allowing the customer to tailor the configuration by using one or a combination of methods. The following are common NAC enforcement methods.

- **IEEE 802.1X:** This is a link layer protocol that enforces authorization before a port is assigned an IP address. IEEE 802.1X makes use of the Extensible Authentication Protocol for the authentication process. Sections 16.2 and 16.3 cover the Extensible Authentication Protocol and IEEE 802.1X, respectively.
- **Virtual local area networks (VLANs):** In this approach, the enterprise network, consisting of an interconnected set of LANs, is segmented logically into a number of virtual LANs.[1] The NAC system decides to which of the network's VLANs it will direct an AR, based on whether the device needs security remediation, Internet access only, or some level of network access to enterprise resources. VLANs can be created dynamically and VLAN membership, of both enterprise servers and ARs, may overlap. That is, an enterprise server or an AR may belong to more than one VLAN.

[1]A VLAN is a logical subgroup within a LAN that is created via software rather than manually moving cables in the wiring closet. It combines user stations and network devices into a single unit regardless of the physical LAN segment they are attached to and allows traffic to flow more efficiently within populations of mutual interest. VLANs are implemented in port-switching hubs and LAN switches.

- **Firewall:** A firewall provides a form of NAC by allowing or denying network traffic between an enterprise host and an external user. Firewalls are discussed in Chapter 23.
- **DHCP management:** The Dynamic Host Configuration Protocol (DHCP) is an Internet protocol that enables dynamic allocation of IP addresses to hosts. A DHCP server intercepts DHCP requests and assigns IP addresses instead. Thus, NAC enforcement occurs at the IP layer based on subnet and IP assignment. A DCHP server is easy to install and configure, but is subject to various forms of IP spoofing, providing limited security.

There are a number of other enforcement methods available from vendors. The ones in the preceding list are perhaps the most common, and IEEE 802.1X is by far the most commonly implemented solution.

16.2 EXTENSIBLE AUTHENTICATION PROTOCOL

The Extensible Authentication Protocol (EAP), defined in RFC 3748, acts as a framework for network access and authentication protocols. EAP provides a set of protocol messages that can encapsulate various authentication methods to be used between a client and an authentication server. EAP can operate over a variety of network and link level facilities, including point-to-point links, LANs, and other networks, and can accommodate the authentication needs of the various links and networks. Figure 16.2 illustrates the protocol layers that form the context for EAP.

Authentication Methods

EAP supports multiple authentication methods. This is what is meant by referring to EAP as *extensible*. EAP provides a generic transport service for the exchange of authentication information between a client system and an authentication server. The basic EAP transport service is extended by using a specific authentication protocol, or method, that is installed in both the EAP client and the authentication server.

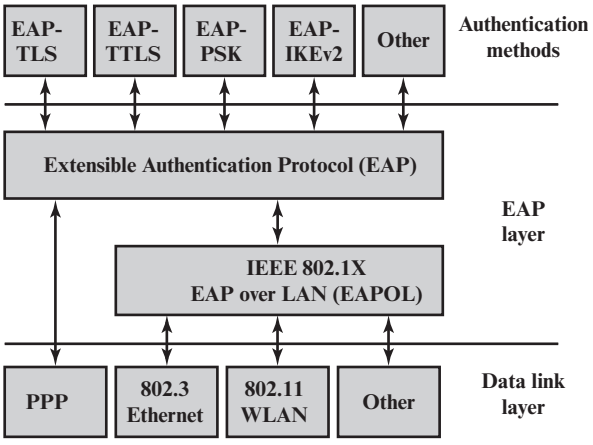


Figure 16.2 EAP Layered Context

Numerous methods have been defined to work over EAP. The following are commonly supported EAP methods:

- **EAP-TLS (EAP Transport Layer Security):** EAP-TLS (RFC 5216) defines how the TLS protocol (described in Chapter 17) can be encapsulated in EAP messages. EAP-TLS uses the handshake protocol in TLS, not its encryption method. Client and server authenticate each other using digital certificates. Client generates a pre-master secret key by encrypting a random number with the server's public key and sends it to the server. Both client and server use the pre-master to generate the same secret key.
- **EAP-TTLS (EAP Tunneled TLS):** EAP-TTLS is like EAP-TLS, except only the server has a certificate to authenticate itself to the client first. As in EAP-TLS, a secure connection (the "tunnel") is established with secret keys, but that connection is used to continue the authentication process by authenticating the client and possibly the server again using any EAP method or legacy method such as PAP (Password Authentication Protocol) and CHAP (Challenge-Handshake Authentication Protocol). EAP-TTLS is defined in RFC 5281.
- **EAP-GPSK (EAP Generalized Pre-Shared Key):** EAP-GPSK, defined in RFC 5433, is an EAP method for mutual authentication and session key derivation using a Pre-Shared Key (PSK). EAP-GPSK specifies an EAP method based on pre-shared keys and employs secret key-based cryptographic algorithms. Hence, this method is efficient in terms of message flows and computational costs, but requires the existence of pre-shared keys between each peer and EAP server. The set up of these pairwise secret keys is part of the peer registration, and thus, must satisfy the system preconditions. It provides a protected communication channel when mutual authentication is successful for both parties to communicate over and is designed for authentication over insecure networks such as IEEE 802.11. EAP-GPSK does not require any public-key cryptography. The EAP method protocol exchange is done in a minimum of four messages.
- **EAP-IKEv2:** It is based on the Internet Key Exchange protocol version 2 (IKEv2), which is described in Chapter 20. It supports mutual authentication and session key establishment using a variety of methods. EAP-TLS is defined in RFC 5106.

EAP Exchanges

Whatever method is used for authentication, the authentication information and authentication protocol information are carried in EAP messages.

RFC 3748 defines the goal of the exchange of EAP messages to be successful authentication. In the context of RFC 3748, *successful authentication* is an exchange of EAP messages, as a result of which the authenticator decides to allow access by the peer, and the peer decides to use this access. The authenticator's decision typically involves both authentication and authorization aspects; the peer may successfully authenticate to the authenticator, but access may be denied by the authenticator due to policy reasons.

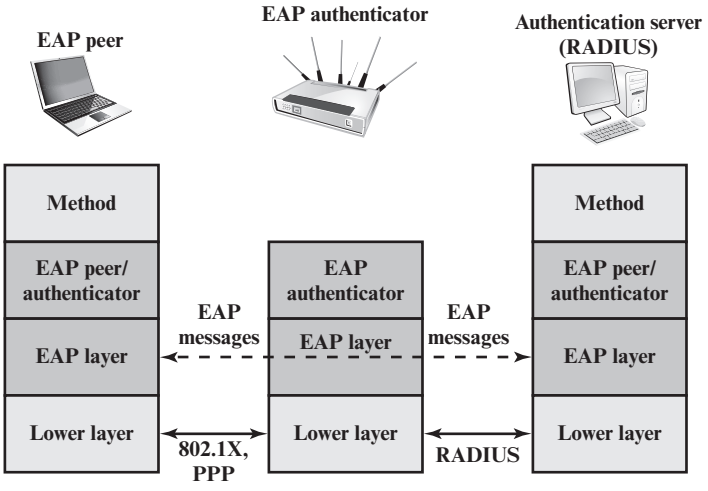


Figure 16.3 EAP Protocol Exchanges

Figure 16.3 indicates a typical arrangement in which EAP is used. The following components are involved:

- **EAP peer:** Client computer that is attempting to access a network.
- **EAP authenticator:** An access point or NAS that requires EAP authentication prior to granting access to a network.
- **Authentication server:** A server computer that negotiates the use of a specific EAP method with an EAP peer, validates the EAP peer's credentials, and authorizes access to the network. Typically, the authentication server is a Remote Authentication Dial-In User Service (RADIUS) server.

The authentication server functions as a backend server that can authenticate peers as a service to a number of EAP authenticators. The EAP authenticator then makes the decision of whether to grant access. This is referred to as the **EAP pass-through mode**. Less commonly, the authenticator takes over the role of the EAP server; that is, only two parties are involved in the EAP execution.

As a first step, a lower-level protocol, such as PPP (point-to-point protocol) or IEEE 802.1X, is used to connect to the EAP authenticator. The software entity in the EAP peer that operates at this level is referred to as the **supplicant**. EAP messages containing the appropriate information for a chosen EAP method are then exchanged between the EAP peer and the authentication server.

EAP messages may include the following fields:

- **Code:** Identifies the Type of EAP message. The codes are Request (1), Response (2), Success (3), and Failure (4).
- **Identifier:** Used to match Responses with Requests.
- **Length:** Indicates the length, in octets, of the EAP message, including the Code, Identifier, Length, and Data fields.

- **Data:** Contains information related to authentication. Typically, the Data field consists of a Type subfield, indicating the type of data carried, and a Type-Data field.

The Success and Failure messages do not include a Data field.

The EAP authentication exchange proceeds as follows. After a lower-level exchange that established the need for an EAP exchange, the authenticator sends a Request to the peer to request an identity, and the peer sends a Response with the identity information. This is followed by a sequence of Requests by the authenticator and Responses by the peer for the exchange of authentication information. The information exchanged and the number of Request–Response exchanges needed depend on the authentication method. The conversation continues until either (1) the authenticator determines that it cannot authenticate the peer and transmits an EAP Failure or (2) the authenticator determines that successful authentication has occurred and transmits an EAP Success.

Figure 16.4 gives an example of an EAP exchange. Not shown in the figure is a message or signal sent from the EAP peer to the authenticator using some protocol other than EAP and requesting an EAP exchange to grant network access. One protocol used for this purpose is IEEE 802.1X, discussed in the next section. The first pair of EAP Request and Response messages is of Type identity, in which the authenticator requests the peer's identity, and the peer returns its claimed identity in the Response message. This Response is passed through the authenticator to the authentication server. Subsequent EAP messages are exchanged between the peer and the authentication server.

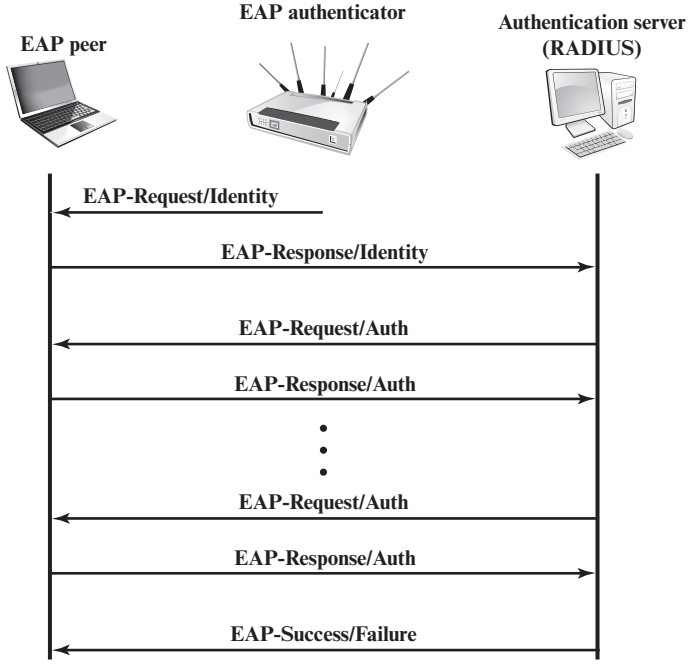


Figure 16.4 EAP Message Flow in Pass-Through Mode

Upon receiving the identity Response message from the peer, the server selects an EAP method and sends the first EAP message with a Type field related to an authentication method. If the peer supports and accepts the selected EAP method, it replies with the corresponding Response message of the same type. Otherwise, the peer sends a NAK, and the EAP server either selects another EAP method or aborts the EAP execution with a failure message. The selected EAP method determines the number of Request/Response pairs. During the exchange the appropriate authentication information, including key material, is exchanged. The exchange ends when the server determines that authentication has succeeded or that no further attempt can be made and authentication has failed.

16.3 IEEE 802.1X PORT-BASED NETWORK ACCESS CONTROL

IEEE 802.1X Port-Based Network Access Control was designed to provide access control functions for LANs. Table 16.1 briefly defines key terms used in the IEEE 802.11 standard. The terms *supplicant*, *network access point*, and *authentication*

Table 16.1 Terminology Related to IEEE 802.1X

Authenticator An entity at one end of a point-to-point LAN segment that facilities authentication of the entity to the other end of the link.
Authentication exchange The two-party conversation between systems performing an authentication process.
Authentication process The cryptographic operations and supporting data frames that perform the actual authentication.
Authentication server (AS) An entity that provides an authentication service to an authenticator. This service determines, from the credentials provided by supplicant, whether the supplicant is authorized to access the services provided by the system in which the authenticator resides.
Authentication transport The datagram session that actively transfers the authentication exchange between two systems.
Bridge port A port of an IEEE 802.1D or 802.1Q bridge.
Edge port A bridge port attached to a LAN that has no other bridges attached to it.
Network access port A point of attachment of a system to a LAN. It can be a physical port, such as a single LAN MAC attached to a physical LAN segment, or a logical port, for example, an IEEE 802.11 association between a station and an access point.
Port access entity (PAE) The protocol entity associated with a port. It can support the protocol functionality associated with the authenticator, the supplicant, or both.
Supplicant An entity at one end of a point-to-point LAN segment that seeks to be authenticated by an authenticator attached to the other end of that link.

server correspond to the EAP terms *peer*, *authenticator*, and *authentication server*, respectively.

Until the AS authenticates a supplicant (using an authentication protocol), the authenticator only passes control and authentication messages between the supplicant and the AS; the 802.1X control channel is unblocked, but the 802.11 data channel is blocked. Once a supplicant is authenticated and keys are provided, the authenticator can forward data from the supplicant, subject to predefined access control limitations for the supplicant to the network. Under these circumstances, the data channel is unblocked.

As indicated in Figure 16.5, 802.1X uses the concepts of controlled and uncontrolled ports. Ports are logical entities defined within the authenticator and refer to physical network connections. Each logical port is mapped to one of these two types of physical ports. An uncontrolled port allows the exchange of protocol data units (PDUs) between the supplicant and the AS, regardless of the authentication state of the supplicant. A controlled port allows the exchange of PDUs between a supplicant and other systems on the network only if the current state of the supplicant authorizes such an exchange.

The essential element defined in 802.1X is a protocol known as EAPOL (EAP over LAN). EAPOL operates at the network layers and makes use of an IEEE 802 LAN, such as Ethernet or Wi-Fi, at the link level. EAPOL enables a supplicant to communicate with an authenticator and supports the exchange of EAP packets for authentication.

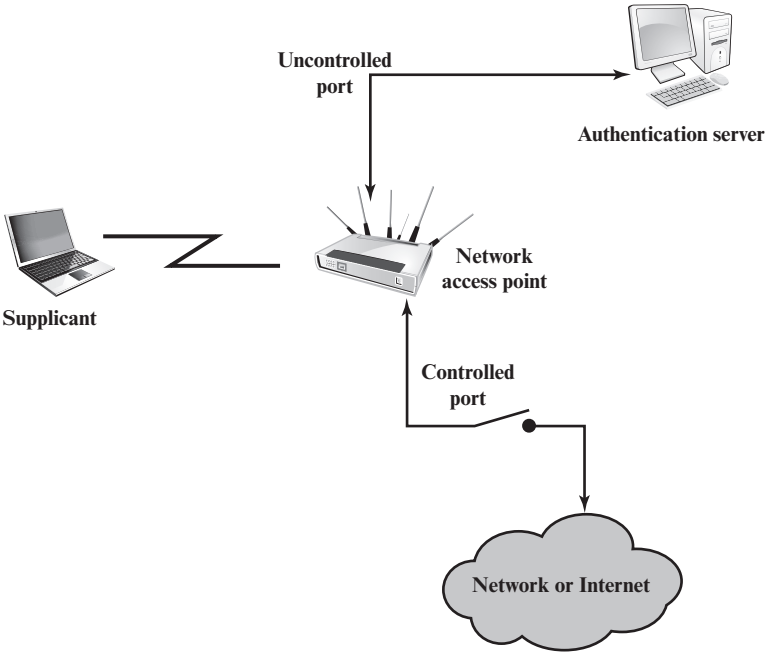


Figure 16.5 802.1X Access Control

Table 16.2 Common EAPOL Frame Types

Frame Type	Definition
EAPOL-EAP	Contains an encapsulated EAP packet.
EAPOL-Start	A supplicant can issue this packet instead of waiting for a challenge from the authenticator.
EAPOL-Logoff	Used to return the state of the port to unauthorized when the supplicant is finished using the network.
EAPOL-Key	Used to exchange cryptographic keying information.

The most common EAPOL packets are listed in Table 16.2. When the supplicant first connects to the LAN, it does not know the MAC address of the authenticator. Actually it doesn't know whether there is an authenticator present at all. By sending an **EAPOL-Start** packet to a special group-multicast address reserved for IEEE 802.1X authenticators, a supplicant can determine whether an authenticator is present and let it know that the supplicant is ready. In many cases, the authenticator will already be notified that a new device has connected from some hardware notification. For example, a hub knows that a cable is plugged in before the device sends any data. In this case the authenticator may preempt the Start message with its own message. In either case the authenticator sends an EAP-Request Identity message encapsulated in an **EAPOL-EAP** packet. The EAPOL-EAP is the EAPOL frame type used for transporting EAP packets.

The authenticator uses the **EAP-Key** packet to send cryptographic keys to the supplicant once it has decided to admit it to the network. The **EAP-Logoff** packet type indicates that the supplicant wishes to be disconnected from the network.

The EAPOL packet format includes the following fields:

- **Protocol version:** version of EAPOL.
- **Packet type:** indicates start, EAP, key, logoff, etc.
- **Packet body length:** If the packet includes a body, this field indicates the body length.
- **Packet body:** The payload for this EAPOL packet. An example is an EAP packet.

Figure 16.6 shows an example of exchange using EAPOL. In Chapter 18, we examine the use of EAP and EAPOL in the context of IEEE 802.11 wireless LAN security.

16.4 CLOUD COMPUTING

There is an increasingly prominent trend in many organizations to move a substantial portion of or even all information technology (IT) operations to an Internet-connected infrastructure known as enterprise cloud computing. This section provides an overview of cloud computing. For a more detailed treatment, see [STAL16].

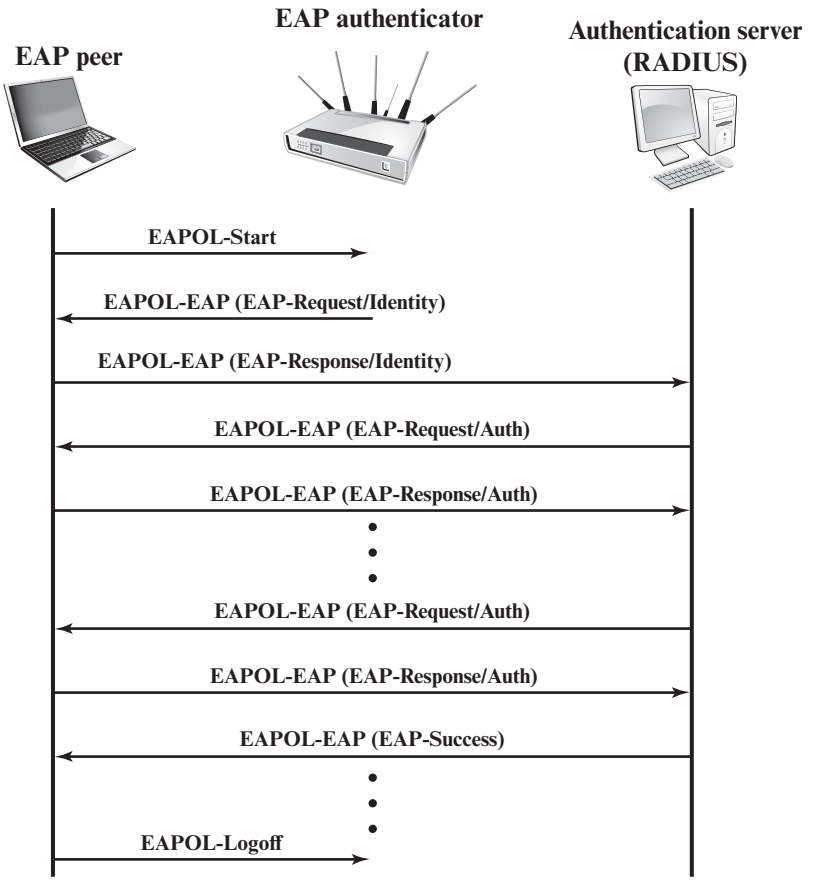


Figure 16.6 Example Timing Diagram for IEEE 802.1X

Cloud Computing Elements

NIST defines cloud computing, in NIST SP-800-145 (*The NIST Definition of Cloud Computing*), as follows:

> **Cloud computing**: A model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. This cloud model promotes availability and is composed of five essential characteristics, three service models, and four deployment models.

The definition refers to various models and characteristics, whose relationship is illustrated in Figure 16.7. The essential characteristics of cloud computing include the following:

- **Broad network access:** Capabilities are available over the network and accessed through standard mechanisms that promote use by heterogeneous thin

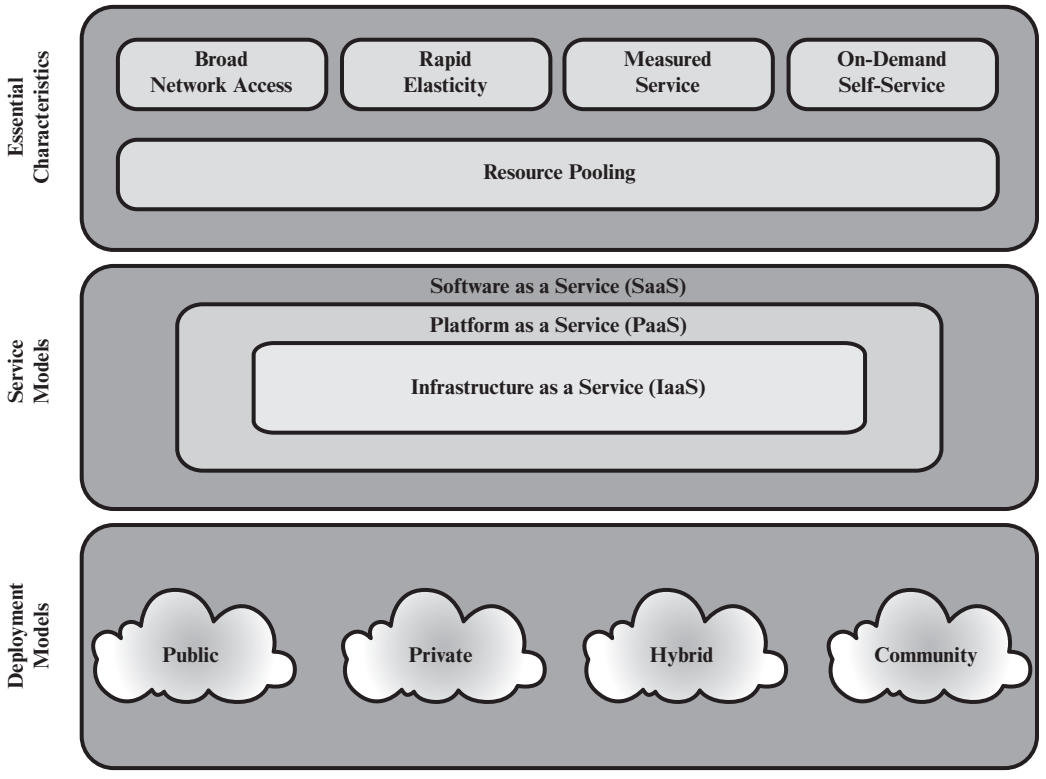


Figure 16.7 Cloud Computing Elements

or thick client platforms (e.g., mobile phones, laptops, and PDAs) as well as other traditional or cloud-based software services.

- **Rapid elasticity:** Cloud computing gives you the ability to expand and reduce resources according to your specific service requirement. For example, you may need a large number of server resources for the duration of a specific task. You can then release these resources upon completion of the task.
- **Measured service:** Cloud systems automatically control and optimize resource use by leveraging a metering capability at some level of abstraction appropriate to the type of service (e.g., storage, processing, bandwidth, and active user accounts). Resource usage can be monitored, controlled, and reported, providing transparency for both the provider and consumer of the utilized service.
- **On-demand self-service:** A consumer can unilaterally provision computing capabilities, such as server time and network storage, as needed automatically without requiring human interaction with each service provider. Because the service is on demand, the resources are not permanent parts of your IT infrastructure.
- **Resource pooling:** The provider's computing resources are pooled to serve multiple consumers using a multi-tenant model, with different physical and virtual resources dynamically assigned and reassigned according to consumer demand. There is a degree of location independence in that the customer

generally has no control or knowledge of the exact location of the provided resources, but may be able to specify location at a higher level of abstraction (e.g., country, state, or data center). Examples of resources include storage, processing, memory, network bandwidth, and virtual machines. Even private clouds tend to pool resources between different parts of the same organization.

NIST defines three **service models**, which can be viewed as nested service alternatives:

- **Software as a service (SaaS):** The capability provided to the consumer is to use the provider's applications running on a cloud infrastructure. The applications are accessible from various client devices through a thin client interface such as a Web browser. Instead of obtaining desktop and server licenses for software products it uses, an enterprise obtains the same functions from the cloud service. SaaS saves the complexity of software installation, maintenance, upgrades, and patches. Examples of services at this level are Gmail, Google's email service, and Salesforce.com, which helps firms keep track of their customers.
- **Platform as a service (PaaS):** The capability provided to the consumer is to deploy onto the cloud infrastructure consumer-created or acquired applications created using programming languages and tools supported by the provider. PaaS often provides middleware-style services such as database and component services for use by applications. In effect, PaaS is an operating system in the cloud.
- **Infrastructure as a service (IaaS):** The capability provided to the consumer is to provision processing, storage, networks, and other fundamental computing resources where the consumer is able to deploy and run arbitrary software, which can include operating systems and applications. IaaS enables customers to combine basic computing services, such as number crunching and data storage, to build highly adaptable computer systems.

NIST defines four **deployment models**:

- **Public cloud:** The cloud infrastructure is made available to the general public or a large industry group and is owned by an organization selling cloud services. The cloud provider is responsible both for the cloud infrastructure and for the control of data and operations within the cloud.
- **Private cloud:** The cloud infrastructure is operated solely for an organization. It may be managed by the organization or a third party and may exist on premise or off premise. The cloud provider (CP) is responsible only for the infrastructure and not for the control.
- **Community cloud:** The cloud infrastructure is shared by several organizations and supports a specific community that has shared concerns (e.g., mission, security requirements, policy, and compliance considerations). It may be managed by the organizations or a third party and may exist on premise or off premise.
- **Hybrid cloud:** The cloud infrastructure is a composition of two or more clouds (private, community, or public) that remain unique entities but are bound together by standardized or proprietary technology that enables data and application portability (e.g., cloud bursting for load balancing between clouds).

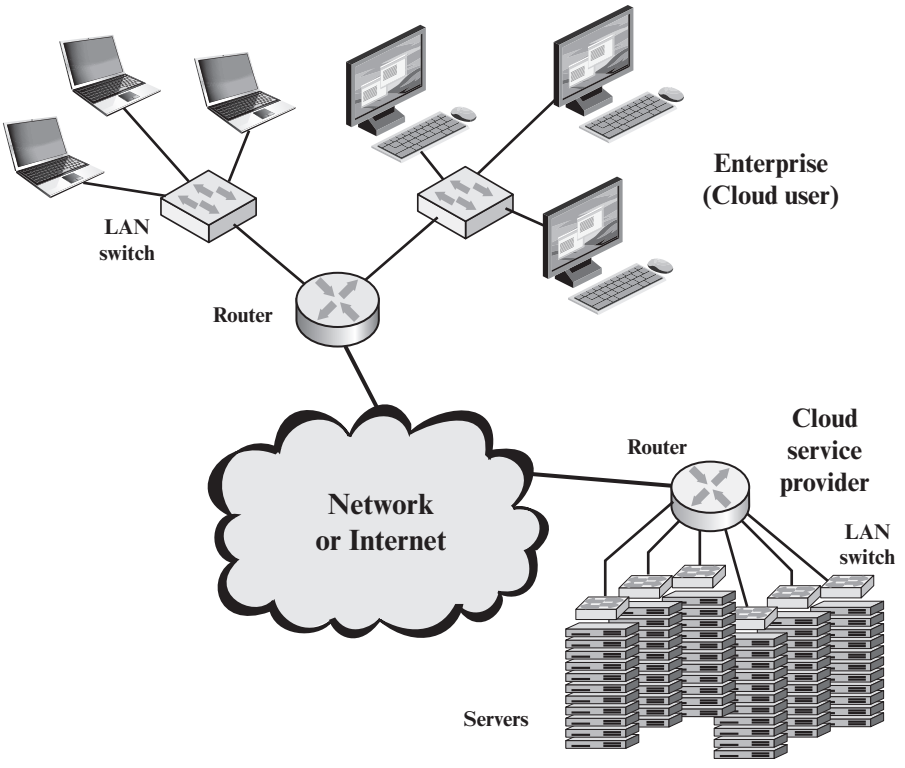


Figure 16.8 Cloud Computing Context

Figure 16.8 illustrates the typical cloud service context. An enterprise maintains workstations within an enterprise LAN or set of LANs, which are connected by a router through a network or the Internet to the cloud service provider. The cloud service provider maintains a massive collection of servers, which it manages with a variety of network management, redundancy, and security tools. In the figure, the cloud infrastructure is shown as a collection of blade servers, which is a common architecture.

Cloud Computing Reference Architecture

NIST SP 500-292 (*NIST Cloud Computing Reference Architecture*) establishes a reference architecture, described as follows:

> The NIST cloud computing reference architecture focuses on the requirements of "what" cloud services provide, not a "how to" design solution and implementation. The reference architecture is intended to facilitate the understanding of the operational intricacies in cloud computing. It does not represent the system architecture of a specific cloud computing system; instead it is a tool for describing, discussing, and developing a system-specific architecture using a common framework of reference.

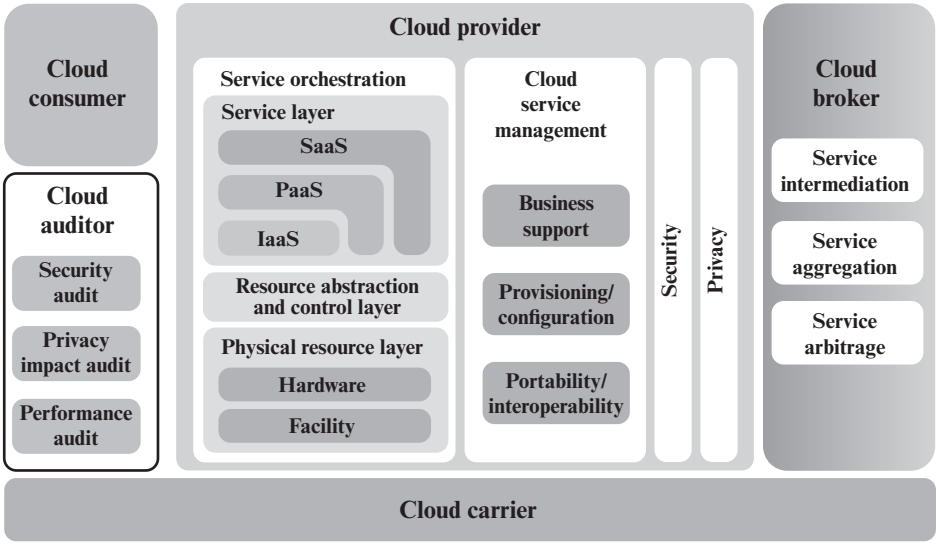


Figure 16.9 NIST Cloud Computing Reference Architecture

NIST developed the reference architecture with the following objectives in mind:

- to illustrate and understand the various cloud services in the context of an overall cloud computing conceptual model
- to provide a technical reference for consumers to understand, discuss, categorize, and compare cloud services
- to facilitate the analysis of candidate standards for security, interoperability, and portability and reference implementations

The reference architecture, depicted in Figure 16.9, defines five major actors in terms of the roles and responsibilities:

- **Cloud consumer:** A person or organization that maintains a business relationship with, and uses service from, cloud providers.
- **Cloud provider:** A person, organization, or entity responsible for making a service available to interested parties.
- **Cloud auditor:** A party that can conduct independent assessment of cloud services, information system operations, performance, and security of the cloud implementation.
- **Cloud broker:** An entity that manages the use, performance, and delivery of cloud services, and negotiates relationships between CPs and cloud consumers.
- **Cloud carrier:** An intermediary that provides connectivity and transport of cloud services from CPs to cloud consumers.

The roles of the cloud consumer and provider have already been discussed. To summarize, a **cloud provider** can provide one or more of the cloud services to meet IT and business requirements of **cloud consumers**. For each of the three service

models (SaaS, PaaS, IaaS), the CP provides the storage and processing facilities needed to support that service model, together with a cloud interface for cloud service consumers. For SaaS, the CP deploys, configures, maintains, and updates the operation of the software applications on a cloud infrastructure so that the services are provisioned at the expected service levels to cloud consumers. The consumers of SaaS can be organizations that provide their members with access to software applications, end users who directly use software applications, or software application administrators who configure applications for end users.

For PaaS, the CP manages the computing infrastructure for the platform and runs the cloud software that provides the components of the platform, such as runtime software execution stack, databases, and other middleware components. Cloud consumers of PaaS can employ the tools and execution resources provided by CPs to develop, test, deploy, and manage the applications hosted in a cloud environment.

For IaaS, the CP acquires the physical computing resources underlying the service, including the servers, networks, storage, and hosting infrastructure. The IaaS cloud consumer in turn uses these computing resources, such as a virtual computer, for their fundamental computing needs.

The **cloud carrier** is a networking facility that provides connectivity and transport of cloud services between cloud consumers and CPs. Typically, a CP will set up service level agreements (SLAs) with a cloud carrier to provide services consistent with the level of SLAs offered to cloud consumers, and may require the cloud carrier to provide dedicated and secure connections between cloud consumers and CPs.

A **cloud broker** is useful when cloud services are too complex for a cloud consumer to easily manage. Three areas of support can be offered by a cloud broker:

- **Service intermediation:** These are value-added services, such as identity management, performance reporting, and enhanced security.
- **Service aggregation:** The broker combines multiple cloud services to meet consumer needs not specifically addressed by a single CP, or to optimize performance or minimize cost.
- **Service arbitrage:** This is similar to service aggregation except that the services being aggregated are not fixed. Service arbitrage means a broker has the flexibility to choose services from multiple agencies. The cloud broker, for example, can use a credit-scoring service to measure and select an agency with the best score.

A **cloud auditor** can evaluate the services provided by a CP in terms of security controls, privacy impact, performance, and so on. The auditor is an independent entity that can assure that the CP conforms to a set of standards.

16.5 CLOUD SECURITY RISKS AND COUNTERMEASURES

In general terms, security controls in cloud computing are similar to the security controls in any IT environment. However, because of the operational models and technologies used to enable cloud service, cloud computing may present risks that are specific to the cloud environment. The essential concept in this regard is that the enterprise loses a substantial amount of control over resources, services, and applications but must maintain accountability for security and privacy policies.

The Cloud Security Alliance [CSA10] lists the following as the top cloud-specific security threats, together with suggested countermeasures:

- **Abuse and nefarious use of cloud computing:** For many CPs, it is relatively easy to register and begin using cloud services, some even offering free limited trial periods. This enables attackers to get inside the cloud to conduct various attacks, such as spamming, malicious code attacks, and denial of service. PaaS providers have traditionally suffered most from this kind of attacks; however, recent evidence shows that hackers have begun to target IaaS vendors as well. The burden is on the CP to protect against such attacks, but cloud service clients must monitor activity with respect to their data and resources to detect any malicious behavior.

  Countermeasures include (1) stricter initial registration and validation processes; (2) enhanced credit card fraud monitoring and coordination; (3) comprehensive introspection of customer network traffic; and (4) monitoring public blacklists for one's own network blocks.

- **Insecure interfaces and APIs:** CPs expose a set of software interfaces or APIs that customers use to manage and interact with cloud services. The security and availability of general cloud services are dependent upon the security of these basic APIs. From authentication and access control to encryption and activity monitoring, these interfaces must be designed to protect against both accidental and malicious attempts to circumvent policy.

  Countermeasures include (1) analyzing the security model of CP interfaces; (2) ensuring that strong authentication and access controls are implemented in concert with encrypted transmission; and (3) understanding the dependency chain associated with the API.

- **Malicious insiders:** Under the cloud computing paradigm, an organization relinquishes direct control over many aspects of security and, in doing so, confers an unprecedented level of trust onto the CP. One grave concern is the risk of malicious insider activity. Cloud architectures necessitate certain roles that are extremely high risk. Examples include CP system administrators and managed security service providers.

  Countermeasures include the following: (1) enforce strict supply chain management and conduct a comprehensive supplier assessment; (2) specify human resource requirements as part of legal contract; (3) require transparency into overall information security and management practices, as well as compliance reporting; and (4) determine security breach notification processes.

- **Shared technology issues:** IaaS vendors deliver their services in a scalable way by sharing infrastructure. Often, the underlying components that make up this infrastructure (CPU caches, GPUs, etc.) were not designed to offer strong isolation properties for a multi-tenant architecture. CPs typically approach this risk by the use of isolated virtual machines for individual clients. This approach is still vulnerable to attack, by both insiders and outsiders, and so can only be a part of an overall security strategy.

  Countermeasures include the following: (1) implement security best practices for installation/configuration; (2) monitor environment for unauthorized changes/activity; (3) promote strong authentication and access control

for administrative access and operations; (4) enforce SLAs for patching and vulnerability remediation; and (5) conduct vulnerability scanning and configuration audits.

- **Data loss or leakage:** For many clients, the most devastating impact from a security breach is the loss or leakage of data. We address this issue in the next subsection.

  Countermeasures include the following: (1) implement strong API access control; (2) encrypt and protect integrity of data in transit; (3) analyze data protection at both design and run time; and (4) implement strong key generation, storage and management, and destruction practices.

- **Account or service hijacking:** Account or service hijacking, usually with stolen credentials, remains a top threat. With stolen credentials, attackers can often access critical areas of deployed cloud computing services, allowing them to compromise the confidentiality, integrity, and availability of those services.

  Countermeasures include the following: (1) prohibit the sharing of account credentials between users and services; (2) leverage strong two-factor authentication techniques where possible; (3) employ proactive monitoring to detect unauthorized activity; and (4) understand CP security policies and SLAs.

- **Unknown risk profile:** In using cloud infrastructures, the client necessarily cedes control to the CP on a number of issues that may affect security. Thus the client must pay attention to and clearly define the roles and responsibilities involved for managing risks. For example, employees may deploy applications and data resources at the CP without observing the normal policies and procedures for privacy, security, and oversight.

  Countermeasures include (1) disclosure of applicable logs and data; (2) partial/full disclosure of infrastructure details (e.g., patch levels and firewalls); and (3) monitoring and alerting on necessary information.

Similar lists have been developed by the European Network and Information Security Agency [ENIS09] and NIST [JANS11].

16.6 DATA PROTECTION IN THE CLOUD

As can be seen from the previous section, there are numerous aspects to cloud security and numerous approaches to providing cloud security measures. A further example is seen in the NIST guidelines for cloud security, specified in SP-800-14 and listed in Table 16.3. Thus, the topic of cloud security is well beyond the scope of this chapter. In this section, we focus on one specific element of cloud security.

There are many ways to compromise data. Deletion or alteration of records without a backup of the original content is an obvious example. Unlinking a record from a larger context may render it unrecoverable, as can storage on unreliable media. Loss of an encoding key may result in effective destruction. Finally, unauthorized parties must be prevented from gaining access to sensitive data.

Table 16.3 NIST Guidelines on Security and Privacy Issues and Recommendations

Governance
Extend organizational practices pertaining to the policies, procedures, and standards used for application development and service provisioning in the cloud, as well as the design, implementation, testing, use, and monitoring of deployed or engaged services. Put in place audit mechanisms and tools to ensure organizational practices are followed throughout the system life cycle.
Compliance
Understand the various types of laws and regulations that impose security and privacy obligations on the organization and potentially impact cloud computing initiatives, particularly those involving data location, privacy and security controls, records management, and electronic discovery requirements. Review and assess the cloud provider's offerings with respect to the organizational requirements to be met and ensure that the contract terms adequately meet the requirements. Ensure that the cloud provider's electronic discovery capabilities and processes do not compromise the privacy or security of data and applications.
Trust
Ensure that service arrangements have sufficient means to allow visibility into the security and privacy controls and processes employed by the cloud provider, and their performance over time. Establish clear, exclusive ownership rights over data. Institute a risk management program that is flexible enough to adapt to the constantly evolving and shifting risk landscape for the life cycle of the system. Continuously monitor the security state of the information system to support ongoing risk management decisions.
Architecture
Understand the underlying technologies that the cloud provider uses to provision services, including the implications that the technical controls involved have on the security and privacy of the system, over the full system life cycle and across all system components.
Identity and access management
Ensure that adequate safeguards are in place to secure authentication, authorization, and other identity and access management functions, and are suitable for the organization.
Software isolation
Understand virtualization and other logical isolation techniques that the cloud provider employs in its multi-tenant software architecture, and assess the risks involved for the organization.
Data protection
Evaluate the suitability of the cloud provider's data management solutions for the organizational data concerned and the ability to control access to data, to secure data while at rest, in transit, and in use, and to sanitize data. Take into consideration the risk of collating organizational data with those of other organizations whose threat profiles are high or whose data collectively represent significant concentrated value. Fully understand and weigh the risks involved in cryptographic key management with the facilities available in the cloud environment and the processes established by the cloud provider.
Availability
Understand the contract provisions and procedures for availability, data backup and recovery, and disaster recovery, and ensure that they meet the organization's continuity and contingency planning requirements. Ensure that during an intermediate or prolonged disruption or a serious disaster, critical operations can be immediately resumed, and that all operations can be eventually reinstituted in a timely and organized manner.
Incident response
Understand the contract provisions and procedures for incident response and ensure that they meet the requirements of the organization.

Table 16.3 Continued

Ensure that the cloud provider has a transparent response process in place and sufficient mechanisms to share information during and after an incident. Ensure that the organization can respond to incidents in a coordinated fashion with the cloud provider in accordance with their respective roles and responsibilities for the computing environment.

The threat of data compromise increases in the cloud, due to the number of and interactions between risks and challenges that are either unique to the cloud or more dangerous because of the architectural or operational characteristics of the cloud environment.

Database environments used in cloud computing can vary significantly. Some providers support a **multi-instance model**, which provides a unique DBMS running on a virtual machine instance for each cloud subscriber. This gives the subscriber complete control over role definition, user authorization, and other administrative tasks related to security. Other providers support a **multi-tenant model**, which provides a predefined environment for the cloud subscriber that is shared with other tenants, typically through tagging data with a subscriber identifier. Tagging gives the appearance of exclusive use of the instance, but relies on the CP to establish and maintain a sound secure database environment.

Data must be secured while at rest, in transit, and in use, and access to the data must be controlled. The client can employ encryption to protect data in transit, though this involves key management responsibilities for the CP. The client can enforce access control techniques but, again, the CP is involved to some extent depending on the service model used.

For data at rest, the ideal security measure is for the client to encrypt the database and only store encrypted data in the cloud, with the CP having no access to the encryption key. So long as the key remains secure, the CP has no ability to read the data, although corruption and other denial-of-service attacks remain a risk.

A straightforward solution to the security problem in this context is to encrypt the entire database and not provide the encryption/decryption keys to the service provider. This solution by itself is inflexible. The user has little ability to access individual data items based on searches or indexing on key parameters, but rather would have to download entire tables from the database, decrypt the tables, and work with the results. To provide more flexibility, it must be possible to work with the database in its encrypted form.

An example of such an approach, depicted in Figure 16.10, is reported in [DAMI05] and [DAMI03]. A similar approach is described in [HACI02]. Four entities are involved:

- **Data owner:** An organization that produces data to be made available for controlled release, either within the organization or to external users.
- **User:** Human entity that presents requests (queries) to the system. The user could be an employee of the organization who is granted access to the database via the server, or a user external to the organization who, after authentication, is granted access.
- **Client:** Frontend that transforms user queries into queries on the encrypted data stored on the server.

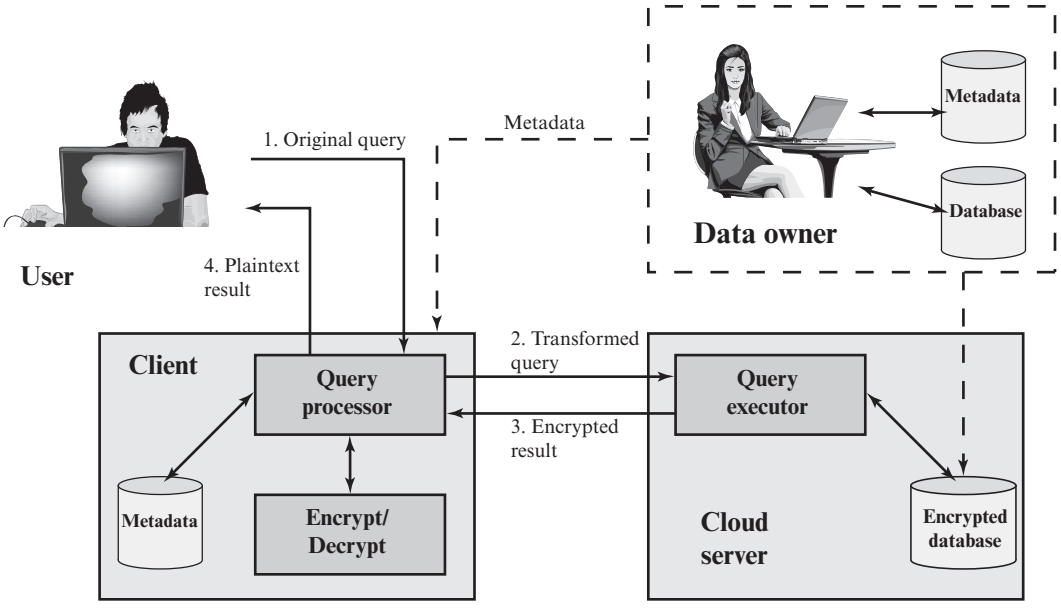


Figure 16.10 An Encryption Scheme for a Cloud-Based Database

- **Server:** An organization that receives the encrypted data from a data owner and makes them available for distribution to clients. The server could in fact be owned by the data owner but, more typically, is a facility owned and maintained by an external provider. For our discussion, the server is a cloud server.

Before continuing this discussion, we need to define some database terms. In relational database parlance, the basic building block is a **relation**, which is a flat table. Rows are referred to as **tuples**, and columns are referred to as **attributes**. A **primary key** is defined to be a portion of a row used to uniquely identify a row in a table; the primary key consists of one or more column names.[2] For example, in an employee table, the employee ID is sufficient to uniquely identify a row in a particular table.

Let us first examine the simplest possible arrangement based on this scenario. Suppose that each individual item in the database is encrypted separately, all using the same encryption key. The encrypted database is stored at the server, but the server does not have the encryption key. Thus, the data are secure at the server. Even if someone were able to hack into the server's system, all he or she would have access to is encrypted data. The client system does have a copy of the encryption key. A user at the client can retrieve a record from the database with the following sequence:

1. The user issues a query for fields from one or more records with a specific value of the primary key.

[2]Note that a primary key has nothing to do with cryptographic keys. A primary key in a database is a means of indexing into the database.

2. The query processor at the client encrypts the primary key, modifies the query accordingly, and transmits the query to the server.
3. The server processes the query using the encrypted value of the primary key and returns the appropriate record or records.
4. The query processor decrypts the data and returns the results.

This method is certainly straightforward but is quite limited. For example, suppose the Employee table contains a salary attribute and the user wishes to retrieve all records for salaries less than $70K. There is no obvious way to do this, because the attribute value for salary in each record is encrypted. The set of encrypted values does not preserve the ordering of values in the original attribute.

There are a number of ways to extend the functionality of this approach. For example, an unencrypted index value can be associated with a given attribute and the table can be partitioned based on these index values, enabling a user to retrieve a certain portion of the table. The details of such schemes are beyond our scope. See [STAL15] for more detail.

16.7 CLOUD SECURITY AS A SERVICE

The term **Security as a Service (SecaaS)** has generally meant a package of security services offered by a service provider that offloads much of the security responsibility from an enterprise to the security service provider. Among the services typically provided are authentication, antivirus, antimalware/-spyware, intrusion detection, and security event management. In the context of cloud computing, cloud security as a service, designated SecaaS, is a segment of the SaaS offering of a CP.

The Cloud Security Alliance defines SecaaS as the provision of security applications and services via the cloud either to cloud-based infrastructure and software or from the cloud to the customers' on-premise systems [CSA11b]. The Cloud Security Alliance has identified the following SecaaS categories of service:

- Identity and access management
- Data loss prevention
- Web security
- Email security
- Security assessments
- Intrusion management
- Security information and event management
- Encryption
- Business continuity and disaster recovery
- Network security

In this section, we examine these categories with a focus on security of the cloud-based infrastructure and services (Figure 16.11).

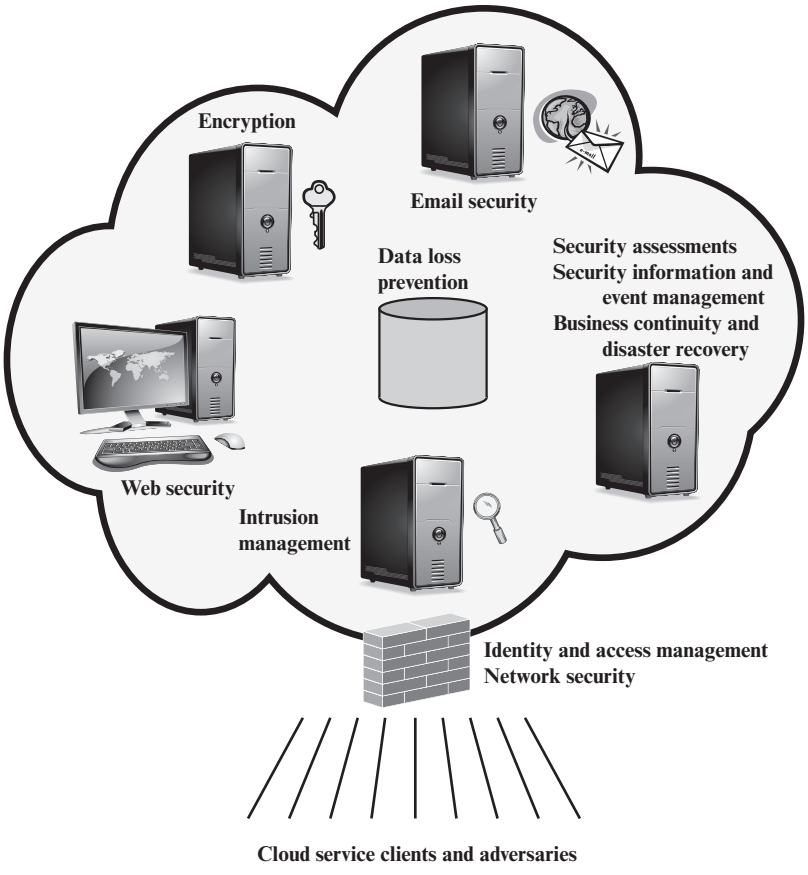


Figure 16.11 Elements of Cloud Security as a Service

Identity and access management (IAM) includes people, processes, and systems that are used to manage access to enterprise resources by assuring that the identity of an entity is verified, and then granting the correct level of access based on this assured identity. One aspect of identity management is identity provisioning, which has to do with providing access to identified users and subsequently deprovisioning, or deny access, to users when the client enterprise designates such users as no longer having access to enterprise resources in the cloud. Another aspect of identity management is for the cloud to participate in the federated identity management scheme (see Chapter 15) scheme used by the client enterprise. Among other requirements, the cloud service provider (CSP) must be able to exchange identity attributes with the enterprise's chosen identity provider.

The access management portion of IAM involves authentication and access control services. For example, the CSP must be able to authenticate users in a trustworthy manner. The access control requirements in SPI environments include establishing trusted user profile and policy information, using it to control access within the cloud service, and doing this in an auditable way.

Data loss prevention (DLP) is the monitoring, protecting, and verifying the security of data at rest, in motion, and in use. Much of DLP can be implemented by

the cloud client, such as discussed in Section 16.6. The CSP can also provide DLP services, such as implementing rules about what functions can be performed on data in various contexts.

Web security is real-time protection offered either on premise through software/appliance installation or via the cloud by proxying or redirecting Web traffic to the CP. This provides an added layer of protection on top of things like antiviruses to prevent malware from entering the enterprise via activities such as Web browsing. In addition to protecting against malware, a cloud-based Web security service might include usage policy enforcement, data backup, traffic control, and Web access control.

A CSP may provide a Web-based email service, for which security measures are needed. **Email security** provides control over inbound and outbound email, protecting the organization from phishing, malicious attachments, enforcing corporate polices such as acceptable use and spam prevention. The CSP may also incorporate digital signatures on all email clients and provide optional email encryption.

Security assessments are third-part audits of cloud services. While this service is outside the province of the CSP, the CSP can provide tools and access points to facilitate various assessment activities.

Intrusion management encompasses intrusion detection, prevention, and response. The core of this service is the implementation of intrusion detection systems (IDSs) and intrusion prevention systems (IPSs) at entry points to the cloud and on servers in the cloud. An IDS is a set of automated tools designed to detect unauthorized access to a host system. We discuss this in Chapter 21. An IPS incorporates IDS functionality but also includes mechanisms designed to block traffic from intruders.

Security information and event management (SIEM) aggregates (via push or pull mechanisms) log and event data from virtual and real networks, applications, and systems. This information is then correlated and analyzed to provide real-time reporting and alerting on information/events that may require intervention or other type of response. The CSP typically provides an integrated service that can put together information from a variety of sources both within the cloud and within the client enterprise network.

Encryption is a pervasive service that can be provided for data at rest in the cloud, email traffic, client-specific network management information, and identity information. Encryption services provided by the CSP involve a range of complex issues, including key management, how to implement virtual private network (VPN) services in the cloud, application encryption, and data content access.

Business continuity and disaster recovery comprise measures and mechanisms to ensure operational resiliency in the event of any service interruptions. This is an area where the CSP, because of economies of scale, can offer obvious benefits to a cloud service client [WOOD10]. The CSP can provide backup at multiple locations, with reliable failover and disaster recovery facilities. This service must include a flexible infrastructure, redundancy of functions and hardware, monitored operations, geographically distributed data centers, and network survivability.

Network security consists of security services that allocate access, distribute, monitor, and protect the underlying resource services. Services include perimeter and server firewalls and denial-of-service protection. Many of the other services

listed in this section, including intrusion management, identity and access management, data loss protection, and Web security, also contribute to the network security service.

16.8 ADDRESSING CLOUD COMPUTING SECURITY CONCERNS

Numerous documents have been developed to guide businesses thinking about the security issues associated with cloud computing. In addition to SP 800-144, which provides overall guidance, NIST has issued SP 800-146 (*Cloud Computing Synopsis and Recommendations,* May 2012). NIST's recommendations systematically consider each of the major types of cloud services consumed by businesses including Software as a Service (SaaS), Infrastructure as a Service (IaaS), and Platform as a Service (PaaS). While security issues vary somewhat depending on the type of cloud service, there are multiple NIST recommendations that are independent of service type. Not surprisingly, NIST recommends selecting cloud providers that support strong encryption, have appropriate redundancy mechanisms in place, employ authentication mechanisms, and offer subscribers sufficient visibility about mechanisms used to protect subscribers from other subscribers and the provider. SP 800-146 also lists the overall security controls that are relevant in a cloud computing environment and that must be assigned to the different cloud actors. These are shown in Table 16.4.

As more businesses incorporate cloud services into their enterprise network infrastructures, cloud computing security will persist as an important issue. Examples of cloud computing security failures have the potential to have a chilling effect on business interest in cloud services and this is inspiring service providers to be serious about incorporating security mechanisms that will allay concerns of potential subscribers. Some service providers have moved their operations to Tier 4 data centers to address user concerns about availability and redundancy. Because so many businesses remain reluctant to embrace cloud computing in a big way, cloud service providers will have to continue to work hard to convince potential customers that computing support for core business processes and mission critical applications can be moved safely and securely to the cloud.

Table 16.4 Control Functions and Classes

Technical	Operational	Management
Access Control Audit and Accountability Identification and Authentication System and Communication Protection	Awareness and Training Configuration and Management Contingency Planning Incident Response Maintenance Media Protection Physical and Environmental Protection Personnel Security System and Information Integrity	Certification, Accreditation, and Security Assessment Planning Risk Assessment System and Services Acquisition

16.9 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

access requestor (AR)	EAP-IKEv2	Network Access Server (NAS)
authentication server	EAP over LAN (EAPOL)	Platform as a Service (PaaS)
cloud	EAP method	policy server
cloud auditor	EAP pass-through mode	private cloud
cloud broker	EAP peer	public cloud
cloud carrier	EAP-TLS	Remote Access Server (RAS)
cloud computing	EAP-TTLS	Security as a Service (SecaaS)
cloud consumer	Extensible Authentication Protocol (EAP)	Software as a Service (SaaS)
cloud provider	firewall	supplicant
community cloud	IEEE 802.1X	Virtual Local Area Network (VLAN)
Dynamic Host Configuration Protocol (DHCP)	media gateway	
EAP authenticator	Network Access Control (NAC)	
EAP-GPSK		

Review Questions

16.1 Provide a brief definition of network access control.

16.2 What is an EAP?

16.3 List and briefly define four EAP authentication methods.

16.4 What is DHCP? How useful is it to help achieve security of IP addresses?

16.5 Why is EAPOL an essential element of IEEE 802.1X?

16.6 What are the essential characteristics of cloud computing?

16.7 List and briefly define the deployment models of cloud computing.

16.8 What is the cloud computing reference architecture?

16.9 Describe some of the main cloud-specific security threats.

Problems

16.1 Investigate the network access control scheme used at your school or place of employment. Draw a diagram and describe the principal components.

16.2 Figure 16.3 suggests that EAP can be described in the context of a four-layer model. Indicate the functions and formats of each of the four layers. You may need to refer to RFC 3748.

16.3 List some commonly used cloud-based data services. Explore and compare these services based on their use of encryption, flexibility, efficiency, speed, and ease of use. Study security breaches on these services in recent past. What changes were made by the services after these attacks?

CHAPTER 17

Transport-Level Security

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Summarize Web security threats and Web traffic security approaches.
- Present an overview of Transport Layer Security (TLS).
- Understand the differences between Secure Sockets Layer and Transport Layer Security.
- Compare the pseudorandom function used in Transport Layer Security with those discussed earlier in the book.
- Present an overview of HTTPS (HTTP over SSL).
- Present an overview of Secure Shell (SSH).

Virtually all businesses, most government agencies, and many individuals now have Web sites. The number of individuals and companies with Internet access is expanding rapidly and all of these have graphical Web browsers. As a result, businesses are enthusiastic about setting up facilities on the Web for electronic commerce. But the reality is that the Internet and the Web are extremely vulnerable to compromises of various sorts. As businesses wake up to this reality, the demand for secure Web services grows.

The topic of Web security is a broad one and can easily fill a book. In this chapter, we begin with a discussion of the general requirements for Web security and then focus on three standardized schemes that are becoming increasingly important as part of Web commerce and that focus on security at the transport layer: SSL/TLS, HTTPS, and SSH.

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

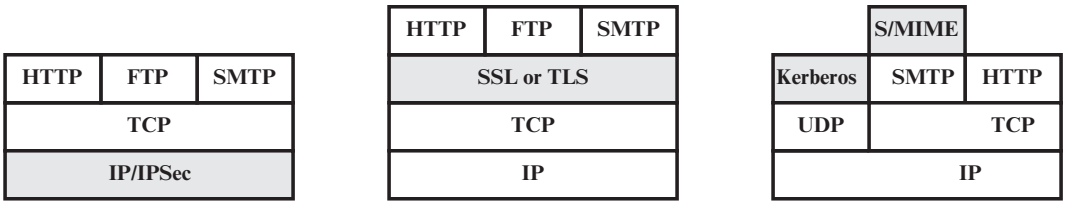


Figure 17.1 Relative Location of Security Facilities in the TCP/IP Protocol Stack

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.

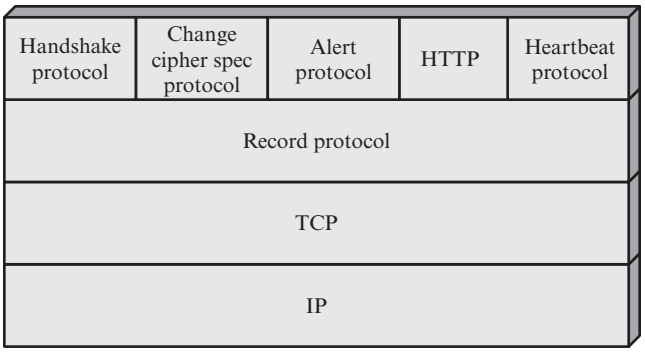


Figure 17.2 TLS Protocol Stack

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

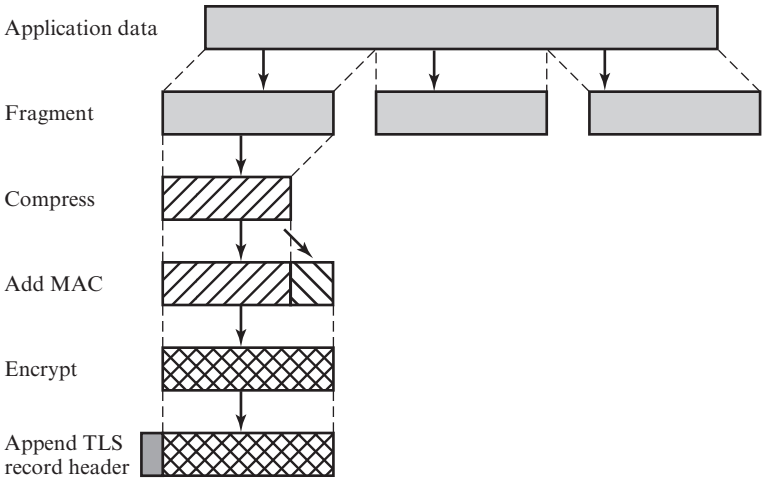


Figure 17.3 TLS Record Protocol Operation

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.

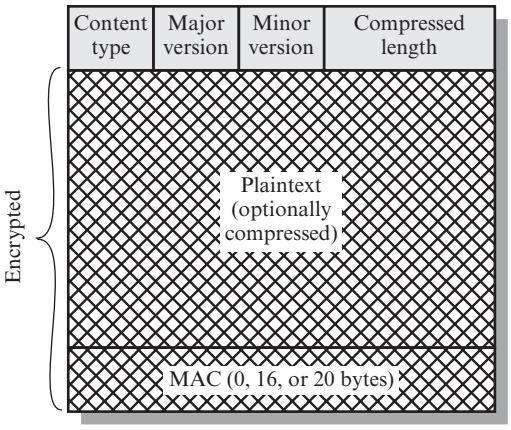


Figure 17.4 TLS Record Format

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.

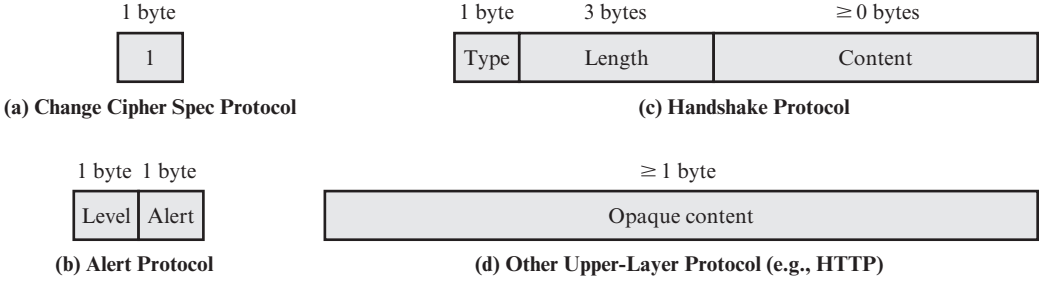


Figure 17.5 TLS Record Protocol Payload

- **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

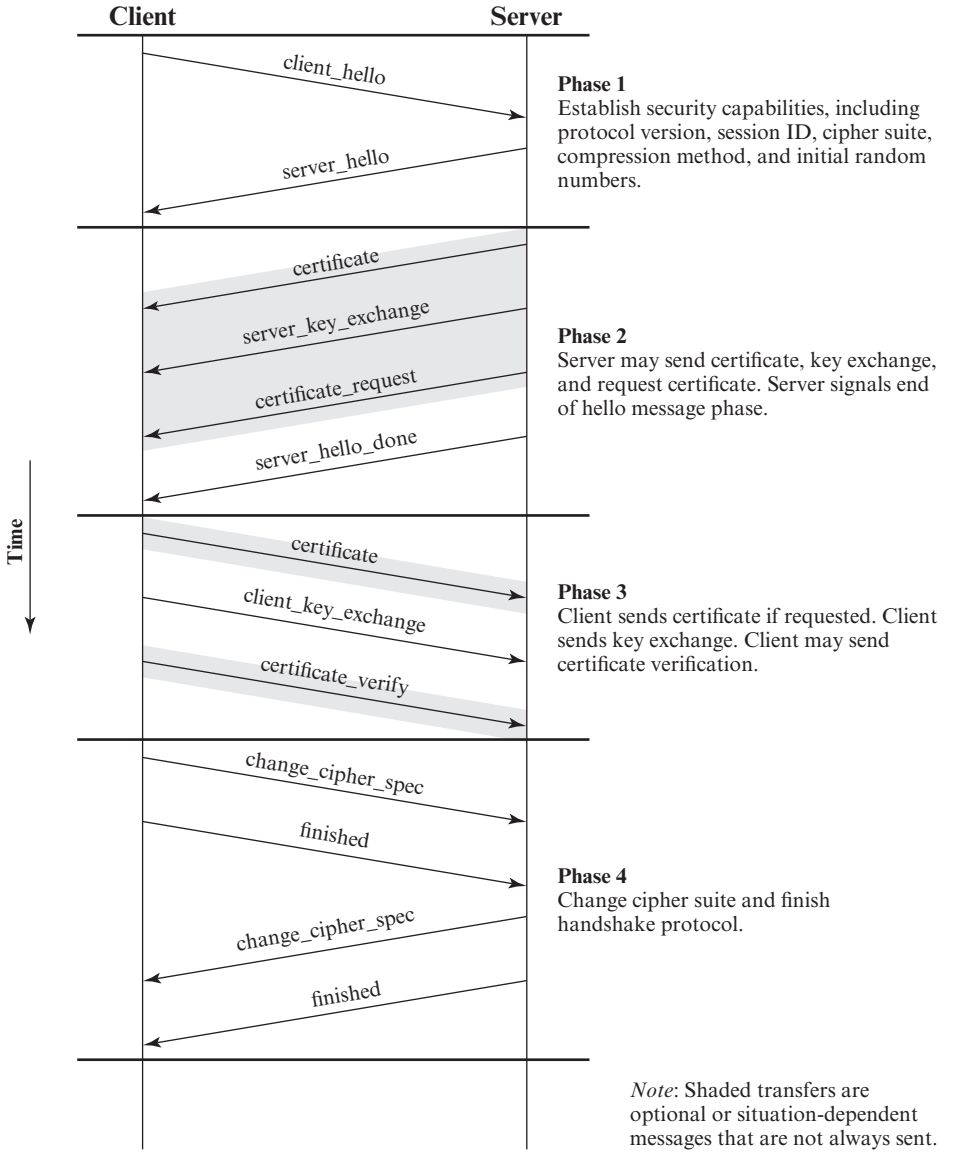


Figure 17.6 Handshake Protocol Action

- **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.

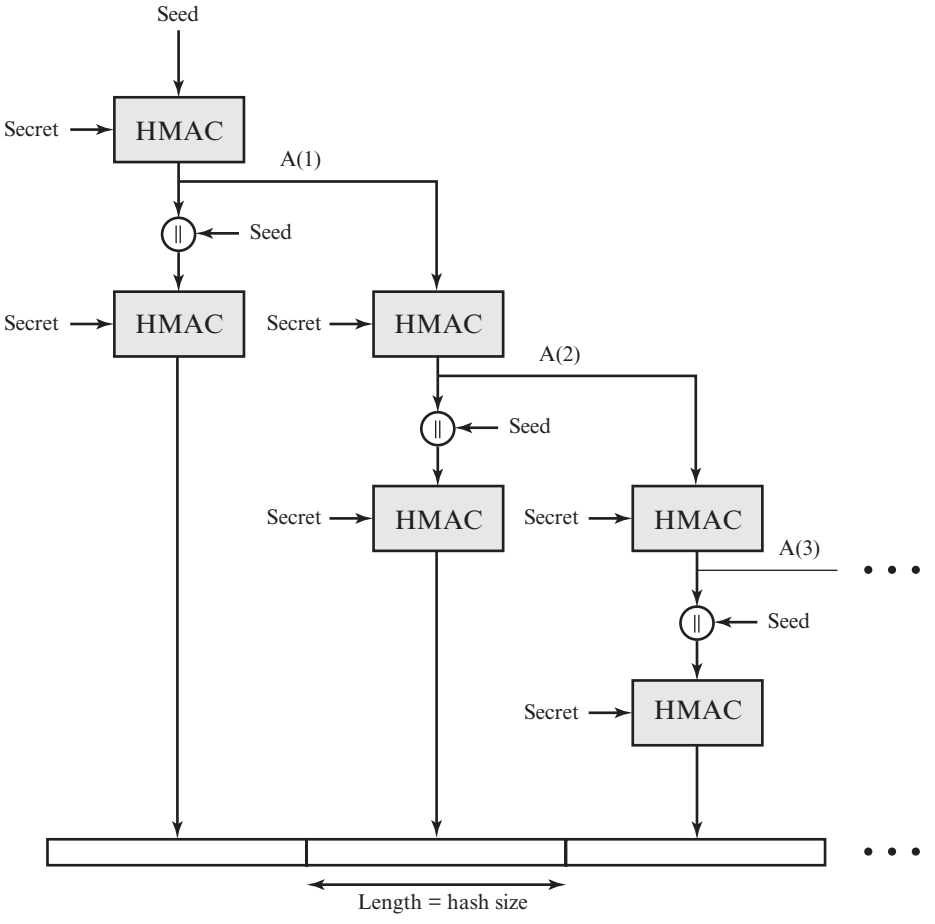


Figure 17.7 TLS Function `P_hash(secret, seed)`

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

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

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.

17.3 HTTPS

HTTPS (HTTP over SSL) refers to the combination of HTTP and SSL to implement secure communication between a Web browser and a Web server. The HTTPS capability is built into all modern Web browsers. Its use depends on the Web server supporting HTTPS communication. For example, some search engines do not support HTTPS.

The principal difference seen by a user of a Web browser is that URL (uniform resource locator) addresses begin with https:// rather than http://. A normal HTTP connection uses port 80. If HTTPS is specified, port 443 is used, which invokes SSL.

When HTTPS is used, the following elements of the communication are encrypted:

- URL of the requested document
- Contents of the document
- Contents of browser forms (filled in by browser user)
- Cookies sent from browser to server and from server to browser
- Contents of HTTP header

HTTPS is documented in RFC 2818, *HTTP Over TLS*. There is no fundamental change in using HTTP over either SSL or TLS, and both implementations are referred to as HTTPS.

Connection Initiation

For HTTPS, the agent acting as the HTTP client also acts as the TLS client. The client initiates a connection to the server on the appropriate port and then sends the TLS ClientHello to begin the TLS handshake. When the TLS handshake has

finished, the client may then initiate the first HTTP request. All HTTP data is to be sent as TLS application data. Normal HTTP behavior, including retained connections, should be followed.

There are three levels of awareness of a connection in HTTPS. At the HTTP level, an HTTP client requests a connection to an HTTP server by sending a connection request to the next lowest layer. Typically, the next lowest layer is TCP, but it also may be TLS/SSL. At the level of TLS, a session is established between a TLS client and a TLS server. This session can support one or more connections at any time. As we have seen, a TLS request to establish a connection begins with the establishment of a TCP connection between the TCP entity on the client side and the TCP entity on the server side.

Connection Closure

An HTTP client or server can indicate the closing of a connection by including the following line in an HTTP record: `Connection: close`. This indicates that the connection will be closed after this record is delivered.

The closure of an HTTPS connection requires that TLS close the connection with the peer TLS entity on the remote side, which will involve closing the underlying TCP connection. At the TLS level, the proper way to close a connection is for each side to use the TLS alert protocol to send a `close_notify` alert. TLS implementations must initiate an exchange of closure alerts before closing a connection. A TLS implementation may, after sending a closure alert, close the connection without waiting for the peer to send its closure alert, generating an "incomplete close". Note that an implementation that does this may choose to reuse the session. This should only be done when the application knows (typically through detecting HTTP message boundaries) that it has received all the message data that it cares about.

HTTP clients also must be able to cope with a situation in which the underlying TCP connection is terminated without a prior `close_notify` alert and without a `Connection: close` indicator. Such a situation could be due to a programming error on the server or a communication error that causes the TCP connection to drop. However, the unannounced TCP closure could be evidence of some sort of attack. So the HTTPS client should issue some sort of security warning when this occurs.

17.4 SECURE SHELL (SSH)

Secure Shell (SSH) is a protocol for secure network communications designed to be relatively simple and inexpensive to implement. The initial version, SSH1 was focused on providing a secure remote logon facility to replace TELNET and other remote logon schemes that provided no security. SSH also provides a more general client/server capability and can be used for such network functions as file transfer and email. A new version, SSH2, fixes a number of security flaws in the original scheme. SSH2 is documented as a proposed standard in IETF RFCs 4250 through 4256.

SSH client and server applications are widely available for most operating systems. It has become the method of choice for remote login and X tunneling and

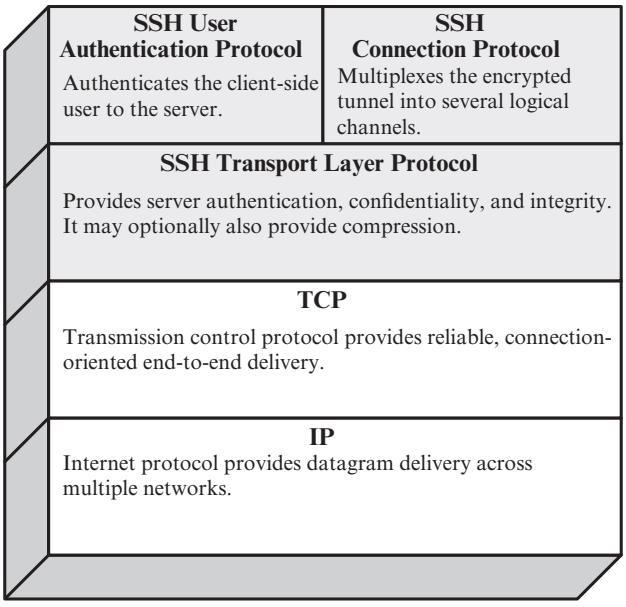


Figure 17.8 SSH Protocol Stack

is rapidly becoming one of the most pervasive applications for encryption technology outside of embedded systems.

SSH is organized as three protocols that typically run on top of TCP (Figure 17.8):

- **Transport Layer Protocol:** Provides server authentication, data confidentiality, and data integrity with forward secrecy (i.e., if a key is compromised during one session, the knowledge does not affect the security of earlier sessions). The transport layer may optionally provide compression.
- **User Authentication Protocol:** Authenticates the user to the server.
- **Connection Protocol:** Multiplexes multiple logical communications channels over a single, underlying SSH connection.

Transport Layer Protocol

Host Keys Server authentication occurs at the transport layer, based on the server possessing a public/private key pair. A server may have multiple host keys using multiple different asymmetric encryption algorithms. Multiple hosts may share the same host key. In any case, the server host key is used during key exchange to authenticate the identity of the host. For this to be possible, the client must have a priori knowledge of the server's public host key. RFC 4251 dictates two alternative trust models that can be used:

1. The client has a local database that associates each host name (as typed by the user) with the corresponding public host key. This method requires no centrally administered infrastructure and no third-party coordination. The downside is that the database of name-to-key associations may become burdensome to maintain.

2. The host name-to-key association is certified by a trusted certification authority (CA). The client only knows the CA root key and can verify the validity of all host keys certified by accepted CAs. This alternative eases the maintenance problem, since ideally, only a single CA key needs to be securely stored on the client. On the other hand, each host key must be appropriately certified by a central authority before authorization is possible.

Packet Exchange Figure 17.9 illustrates the sequence of events in the SSH Transport Layer Protocol. First, the client establishes a TCP connection to the server. This is done via the TCP protocol and is not part of the Transport Layer Protocol. Once the connection is established, the client and server exchange data, referred to as packets, in the data field of a TCP segment. Each packet is in the following format (Figure 17.10).

- **Packet length:** Length of the packet in bytes, not including the packet length and MAC fields.
- **Padding length:** Length of the random padding field.
- **Payload:** Useful contents of the packet. Prior to algorithm negotiation, this field is uncompressed. If compression is negotiated, then in subsequent packets, this field is compressed.

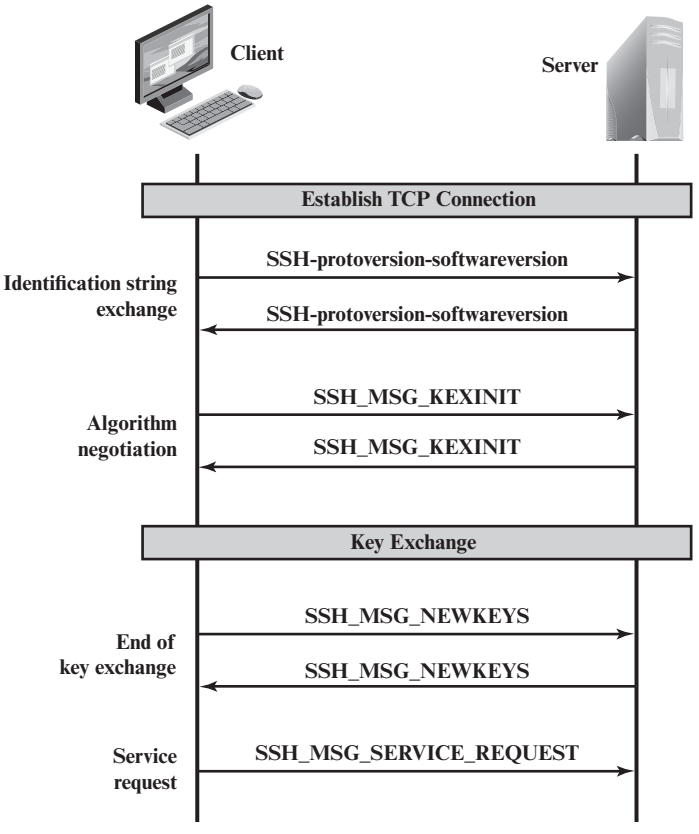


Figure 17.9 SSH Transport Layer Protocol Packet Exchanges

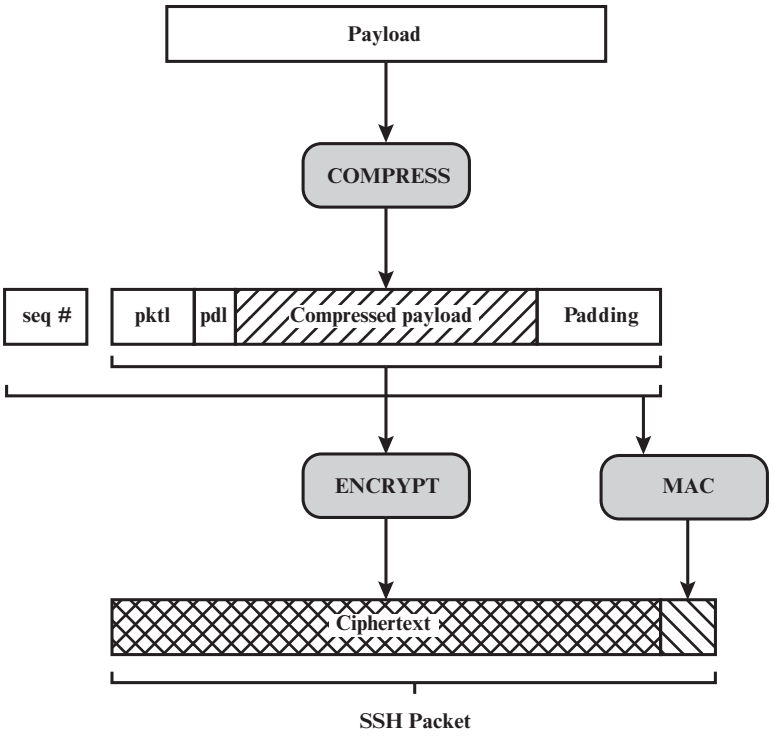


Figure 17.10 SSH Transport Layer Protocol Packet Formation

- **Random padding:** Once an encryption algorithm has been negotiated, this field is added. It contains random bytes of padding so that the total length of the packet (excluding the MAC field) is a multiple of the cipher block size, or 8 bytes for a stream cipher.
- **Message authentication code (MAC):** If message authentication has been negotiated, this field contains the MAC value. The MAC value is computed over the entire packet plus a sequence number, excluding the MAC field. The sequence number is an implicit 32-bit packet sequence that is initialized to zero for the first packet and incremented for every packet. The sequence number is not included in the packet sent over the TCP connection.

Once an encryption algorithm has been negotiated, the entire packet (excluding the MAC field) is encrypted after the MAC value is calculated.

The SSH Transport Layer packet exchange consists of a sequence of steps (Figure 17.9). The first step, the **identification string exchange**, begins with the client sending a packet with an identification string of the form:

```
SSH-protoversion-softwareversion SP comments CR LF
```

where SP, CR, and LF are space character, carriage return, and line feed, respectively. An example of a valid string is SSH-2.0-billsSSH_3.6.3q3<CR><LF>. The server responds with its own identification string. These strings are used in the Diffie–Hellman key exchange.

Next comes **algorithm negotiation**. Each side sends an SSH_MSG_KEXINIT containing lists of supported algorithms in the order of preference to the sender. There is one list for each type of cryptographic algorithm. The algorithms include key exchange, encryption, MAC algorithm, and compression algorithm. Table 17.3 shows the allowable options for encryption, MAC, and compression. For each category, the algorithm chosen is the first algorithm on the client's list that is also supported by the server.

The next step is **key exchange**. The specification allows for alternative methods of key exchange, but at present, only two versions of Diffie–Hellman key exchange are specified. Both versions are defined in RFC 2409 and require only one packet in each direction. The following steps are involved in the exchange. In this, C is the client; S is the server; p is a large safe prime; g is a generator for a subgroup of GF(p); q is the order of the subgroup; V_S is S's identification string; V_C is

Table 17.3 SSH Transport Layer Cryptographic Algorithms

Cipher	
3des-cbc*	Three-key 3DES in CBC mode
blowfish-cbc	Blowfish in CBC mode
twofish256-cbc	Twofish in CBC mode with a 256-bit key
twofish192-cbc	Twofish with a 192-bit key
twofish128-cbc	Twofish with a 128-bit key
aes256-cbc	AES in CBC mode with a 256-bit key
aes192-cbc	AES with a 192-bit key
aes128-cbc**	AES with a 128-bit key
Serpent256-cbc	Serpent in CBC mode with a 256-bit key
Serpent192-cbc	Serpent with a 192-bit key
Serpent128-cbc	Serpent with a 128-bit key
arcfour	RC4 with a 128-bit key
cast128-cbc	CAST-128 in CBC mode

MAC algorithm	
hmac-sha1*	HMAC-SHA1; digest length = key length = 20
hmac-sha1-96**	First 96 bits of HMAC-SHA1; digest length = 12; key length = 20
hmac-md5	HMAC-MD5; digest length = key length = 16
hmac-md5-96	First 96 bits of HMAC-MD5; digest length = 12; key length = 16

Compression algorithm	
none*	No compression
zlib	Defined in RFC 1950 and RFC 1951

* = Required
** = Recommended

C's identification string; K_S is S's public host key; I_C is C's SSH_MSG_KEXINIT message and I_S is S's SSH_MSG_KEXINIT message that have been exchanged before this part begins. The values of p, g, and q are known to both client and server as a result of the algorithm selection negotiation. The hash function hash() is also decided during algorithm negotiation.

1. C generates a random number $x(1 < x < q)$ and computes $e = g^x \bmod p$. C sends e to S.
2. S generates a random number $y(0 < y < q)$ and computes $f = g^y \bmod p$. S receives e. It computes $K = e^y \bmod p, H = \text{hash}(\text{V\_C} \| \text{V\_S} \| \text{I\_C} \| \text{I\_S} \| \text{K\_S} \| e \| f \| \text{K})$, and signature s on H with its private host key. S sends $(\text{K\_S} \| f \| s)$ to C. The signing operation may involve a second hashing operation.
3. C verifies that K_S really is the host key for S (e.g., using certificates or a local database). C is also allowed to accept the key without verification; however, doing so will render the protocol insecure against active attacks (but may be desirable for practical reasons in the short term in many environments). C then computes $K = f^x \bmod p, H = \text{hash}(\text{V\_C} \| \text{V\_S} \| \text{I\_C} \| \text{I\_S} \| \text{K\_S} \| e \| f \| K)$, and verifies the signature s on H.

As a result of these steps, the two sides now share a master key K. In addition, the server has been authenticated to the client, because the server has used its private key to sign its half of the Diffie-Hellman exchange. Finally, the hash value H serves as a session identifier for this connection. Once computed, the session identifier is not changed, even if the key exchange is performed again for this connection to obtain fresh keys.

The **end of key exchange** is signaled by the exchange of SSH_MSG_NEWKEYS packets. At this point, both sides may start using the keys generated from K, as discussed subsequently.

The final step is **service request**. The client sends an SSH_MSG_SERVICE_REQUEST packet to request either the User Authentication or the Connection Protocol. Subsequent to this, all data is exchanged as the payload of an SSH Transport Layer packet, protected by encryption and MAC.

Key Generation The keys used for encryption and MAC (and any needed IVs) are generated from the shared secret key K, the hash value from the key exchange H, and the session identifier, which is equal to H unless there has been a subsequent key exchange after the initial key exchange. The values are computed as follows.

- Initial IV client to server: $\text{HASH}(K \| H \| \text{"A"} \| \text{session\_id})$
- Initial IV server to client: $\text{HASH}(K \| H \| \text{"B"} \| \text{session\_id})$
- Encryption key client to server: $\text{HASH}(K \| H \| \text{"C"} \| \text{session\_id})$
- Encryption key server to client: $\text{HASH}(K \| H \| \text{"}D\text{"} \| \text{session\_id})$
- Integrity key client to server: $\text{HASH}(K \| H \| \text{"}E\text{"} \| \text{session\_id})$
- Integrity key server to client: $\text{HASH}(K \| H \| \text{"}F\text{"} \| \text{session\_id})$

where HASH() is the hash function determined during algorithm negotiation.

User Authentication Protocol

The User Authentication Protocol provides the means by which the client is authenticated to the server.

Message Types and Formats Three types of messages are always used in the User Authentication Protocol. Authentication requests from the client have the format:

byte	`SSH_MSG_USERAUTH_REQUEST (50)`
string	user name
string	service name
string	method name
. . .	method specific fields

where user name is the authorization identity the client is claiming, service name is the facility to which the client is requesting access (typically the SSH Connection Protocol), and method name is the authentication method being used in this request. The first byte has decimal value 50, which is interpreted as `SSH_MSG_USERAUTH_REQUEST`.

If the server either (1) rejects the authentication request or (2) accepts the request but requires one or more additional authentication methods, the server sends a message with the format:

byte	`SSH_MSG_USERAUTH_FAILURE (51)`
name-list	authentications that can continue
boolean	partial success

where the name-list is a list of methods that may productively continue the dialog. If the server accepts authentication, it sends a single byte message: `SSH_MSG_USERAUTH_SUCCESS (52)`.

Message Exchange The message exchange involves the following steps.

1. The client sends a `SSH_MSG_USERAUTH_REQUEST` with a requested method of none.
2. The server checks to determine if the user name is valid. If not, the server returns `SSH_MSG_USERAUTH_FAILURE` with the partial success value of false. If the user name is valid, the server proceeds to step 3.
3. The server returns `SSH_MSG_USERAUTH_FAILURE` with a list of one or more authentication methods to be used.
4. The client selects one of the acceptable authentication methods and sends a `SSH_MSG_USERAUTH_REQUEST` with that method name and the required method-specific fields. At this point, there may be a sequence of exchanges to perform the method.

5. If the authentication succeeds and more authentication methods are required, the server proceeds to step 3, using a partial success value of true. If the authentication fails, the server proceeds to step 3, using a partial success value of false.
6. When all required authentication methods succeed, the server sends a `SSH_MSG_USERAUTH_SUCCESS` message, and the Authentication Protocol is over.

Authentication Methods The server may require one or more of the following authentication methods.

- **`publickey`:** The details of this method depend on the public-key algorithm chosen. In essence, the client sends a message to the server that contains the client's public key, with the message signed by the client's private key. When the server receives this message, it checks whether the supplied key is acceptable for authentication and, if so, it checks whether the signature is correct.
- **`password`:** The client sends a message containing a plaintext password, which is protected by encryption by the Transport Layer Protocol.
- **`hostbased`:** Authentication is performed on the client's host rather than the client itself. Thus, a host that supports multiple clients would provide authentication for all its clients. This method works by having the client send a signature created with the private key of the client host. Thus, rather than directly verifying the user's identity, the SSH server verifies the identity of the client host—and then believes the host when it says the user has already authenticated on the client side.

Connection Protocol

The SSH Connection Protocol runs on top of the SSH Transport Layer Protocol and assumes that a secure authentication connection is in use.[2] That secure authentication connection, referred to as a **tunnel,** is used by the Connection Protocol to multiplex a number of logical channels.

Channel Mechanism All types of communication using SSH, such as a terminal session, are supported using separate channels. Either side may open a channel. For each channel, each side associates a unique channel number, which need not be the same on both ends. Channels are flow controlled using a window mechanism. No data may be sent to a channel until a message is received to indicate that window space is available.

[2]RFC 4254, *The Secure Shell (SSH) Connection Protocol*, states that the Connection Protocol runs on top of the Transport Layer Protocol and the User Authentication Protocol. RFC 4251, *SSH Protocol Architecture*, states that the Connection Protocol runs over the User Authentication Protocol. In fact, the Connection Protocol runs over the Transport Layer Protocol, but assumes that the User Authentication Protocol has been previously invoked.

The life of a channel progresses through three stages: opening a channel, data transfer, and closing a channel.

When either side wishes to **open a new channel,** it allocates a local number for the channel and then sends a message of the form:

byte	SSH_MSG_CHANNEL_OPEN
string	channel type
uint32	sender channel
uint32	initial window size
uint32	maximum packet size
....	channel type specific data follows

where uint32 means unsigned 32-bit integer. The channel type identifies the application for this channel, as described subsequently. The sender channel is the local channel number. The initial window size specifies how many bytes of channel data can be sent to the sender of this message without adjusting the window. The maximum packet size specifies the maximum size of an individual data packet that can be sent to the sender. For example, one might want to use smaller packets for interactive connections to get better interactive response on slow links.

If the remote side is able to open the channel, it returns a SSH_MSG_CHANNEL_OPEN_CONFIRMATION message, which includes the sender channel number, the recipient channel number, and window and packet size values for incoming traffic. Otherwise, the remote side returns a SSH_MSG_CHANNEL_OPEN_FAILURE message with a reason code indicating the reason for failure.

Once a channel is open, **data transfer** is performed using a SSH_MSG_CHANNEL_DATA message, which includes the recipient channel number and a block of data. These messages, in both directions, may continue as long as the channel is open.

When either side wishes to **close a channel,** it sends a SSH_MSG_CHANNEL_CLOSE message, which includes the recipient channel number.

Figure 17.11 provides an example of Connection Protocol Message Exchange.

Channel Types Four channel types are recognized in the SSH Connection Protocol specification.

- **session:** The remote execution of a program. The program may be a shell, an application such as file transfer or email, a system command, or some built-in subsystem. Once a session channel is opened, subsequent requests are used to start the remote program.
- **x11:** This refers to the X Window System, a computer software system and network protocol that provides a graphical user interface (GUI) for networked computers. X allows applications to run on a network server but to be displayed on a desktop machine.

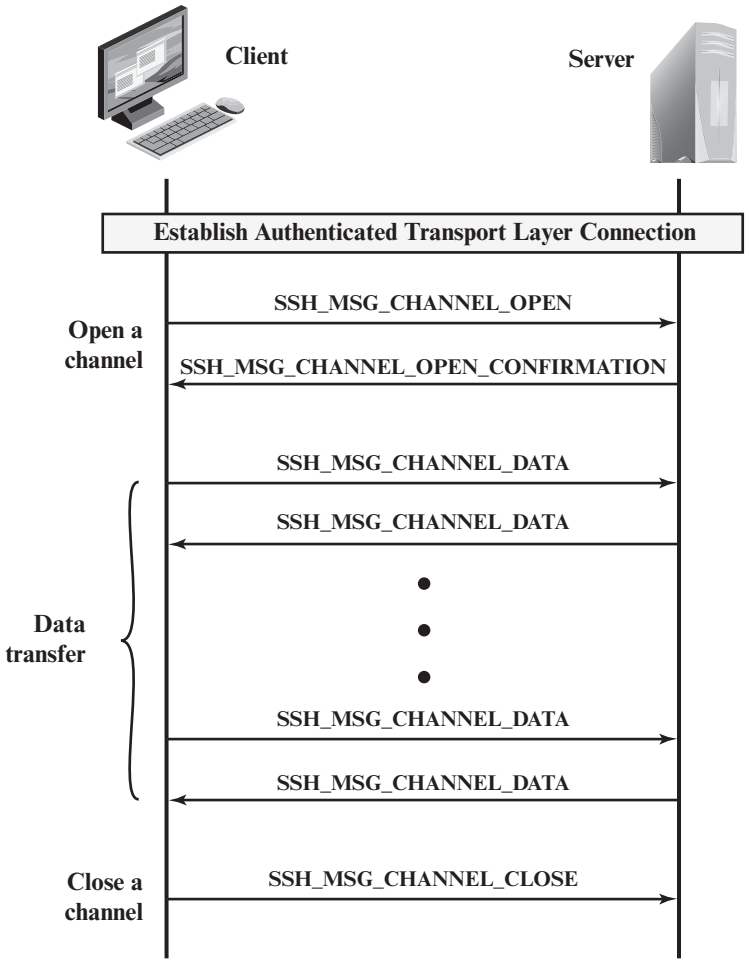


Figure 17.11 Example of SSH Connection Protocol Message Exchange

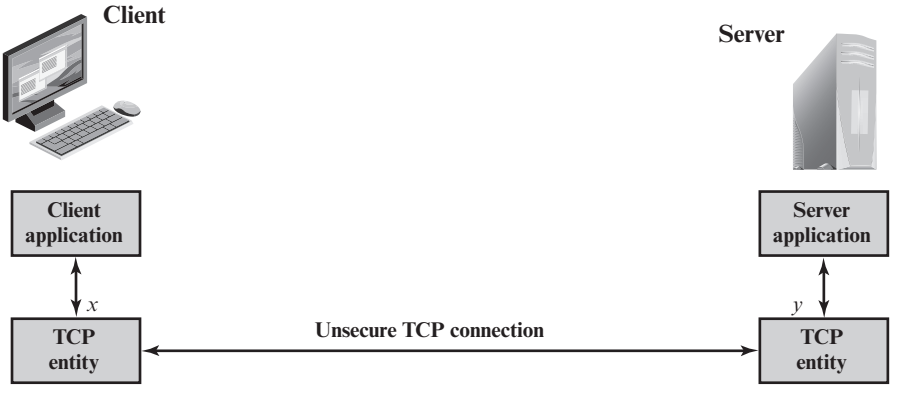
- **forwarded-tcpip:** This is remote port forwarding, as explained in the next subsection.
- **direct-tcpip:** This is local port forwarding, as explained in the next subsection.

Port Forwarding One of the most useful features of SSH is port forwarding. In essence, port forwarding provides the ability to convert any insecure TCP connection into a secure SSH connection. This is also referred to as SSH tunneling. We need to know what a port is in this context. A **port** is an identifier of a user of TCP. So, any application that runs on top of TCP has a port number. Incoming TCP traffic is delivered to the appropriate application on the basis of the port number. An application may employ multiple port numbers. For example, for the Simple Mail Transfer Protocol (SMTP), the server side generally listens on port 25, so an

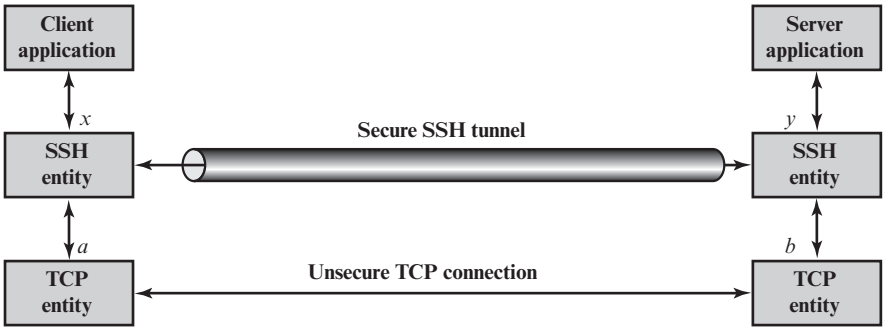
incoming SMTP request uses TCP and addresses the data to destination port 25. TCP recognizes that this is the SMTP server address and routes the data to the SMTP server application.

Figure 17.12 illustrates the basic concept behind port forwarding. We have a client application that is identified by port number x and a server application identified by port number y. At some point, the client application invokes the local TCP entity and requests a connection to the remote server on port y. The local TCP entity negotiates a TCP connection with the remote TCP entity, such that the connection links local port x to remote port y.

To secure this connection, SSH is configured so that the SSH Transport Layer Protocol establishes a TCP connection between the SSH client and server entities, with TCP port numbers a and b, respectively. A secure SSH tunnel is established



(a) Connection via TCP



(b) Connection via SSH tunnel

Figure 17.12 SSH Transport Layer Packet Exchanges

over this TCP connection. Traffic from the client at port *x* is redirected to the local SSH entity and travels through the tunnel where the remote SSH entity delivers the data to the server application on port *y*. Traffic in the other direction is similarly redirected.

SSH supports two types of port forwarding: local forwarding and remote forwarding. **Local forwarding** allows the client to set up a "hijacker" process. This will intercept selected application-level traffic and redirect it from an unsecured TCP connection to a secure SSH tunnel. SSH is configured to listen on selected ports. SSH grabs all traffic using a selected port and sends it through an SSH tunnel. On the other end, the SSH server sends the incoming traffic to the destination port dictated by the client application.

The following example should help clarify local forwarding. Suppose you have an email client on your desktop and use it to get email from your mail server via the Post Office Protocol (POP). The assigned port number for POP3 is port 110. We can secure this traffic in the following way:

1. The SSH client sets up a connection to the remote server.
2. Select an unused local port number, say 9999, and configure SSH to accept traffic from this port destined for port 110 on the server.
3. The SSH client informs the SSH server to create a connection to the destination, in this case mailserver port 110.
4. The client takes any bits sent to local port 9999 and sends them to the server inside the encrypted SSH session. The SSH server decrypts the incoming bits and sends the plaintext to port 110.
5. In the other direction, the SSH server takes any bits received on port 110 and sends them inside the SSH session back to the client, who decrypts and sends them to the process connected to port 9999.

With **remote forwarding**, the user's SSH client acts on the server's behalf. The client receives traffic with a given destination port number, places the traffic on the correct port and sends it to the destination the user chooses. A typical example of remote forwarding is the following. You wish to access a server at work from your home computer. Because the work server is behind a firewall, it will not accept an SSH request from your home computer. However, from work you can set up an SSH tunnel using remote forwarding. This involves the following steps.

1. From the work computer, set up an SSH connection to your home computer. The firewall will allow this, because it is a protected outgoing connection.
2. Configure the SSH server to listen on a local port, say 22, and to deliver data across the SSH connection addressed to remote port, say 2222.
3. You can now go to your home computer, and configure SSH to accept traffic on port 2222.
4. You now have an SSH tunnel that can be used for remote logon to the work server.

17.5 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

Alert protocol	HTTPS (HTTP over SSL)	Secure Socket Layer (SSL)
Change Cipher Spec protocol	Master Secret	Transport Layer Security (TLS)
Handshake protocol	Secure Shell (SSH)	

Review Questions

17.1 What are the advantages of each of the three approaches shown in Figure 17.1?
17.2 What protocols comprise TLS?
17.3 What is the difference between a TLS connection and a TLS session?
17.4 List and briefly define the parameters that define a TLS session state.
17.5 List and briefly define the parameters that define a TLS session connection.
17.6 What services are provided by the TLS Record Protocol?
17.7 What steps are involved in the TLS Record Protocol transmission?
17.8 Give brief details about different level of awareness of a connection in HTTPS.
17.9 Which protocol was replaced by SSH and why? Which version is currently in the process of being standardized?
17.10 List and briefly define the SSH protocols.

Problems

17.1 In SSL and TLS, why is there a separate Change Cipher Spec Protocol rather than including a `change_cipher_spec` message in the Handshake Protocol?
17.2 What purpose does the MAC serve during the change cipher spec TLS exchange?
17.3 Consider the following threats to Web security and describe how each is countered by a particular feature of TLS.
- **a.** Brute-Force Cryptanalytic Attack: An exhaustive search of the key space for a conventional encryption algorithm.
- **b.** Known Plaintext Dictionary Attack: Many messages will contain predictable plaintext, such as the HTTP GET command. An attacker constructs a dictionary containing every possible encryption of the known-plaintext message. When an encrypted message is intercepted, the attacker takes the portion containing the encrypted known plaintext and looks up the ciphertext in the dictionary. The ciphertext should match against an entry that was encrypted with the same secret key. If there are several matches, each of these can be tried against the full ciphertext to determine the right one. This attack is especially effective against small key sizes (e.g., 40-bit keys).
- **c.** Replay Attack: Earlier TLS handshake messages are replayed.
- **d.** Man-in-the-Middle Attack: An attacker interposes during key exchange, acting as the client to the server and as the server to the client.
- **e.** Password Sniffing: Passwords in HTTP or other application traffic are eavesdropped.
- **f.** IP Spoofing: Uses forged IP addresses to fool a host into accepting bogus data.

g. IP Hijacking: An active, authenticated connection between two hosts is disrupted and the attacker takes the place of one of the hosts.
h. SYN Flooding: An attacker sends TCP SYN messages to request a connection but does not respond to the final message to establish the connection fully. The attacked TCP module typically leaves the "half-open connection" around for a few minutes. Repeated SYN messages can clog the TCP module.

17.4 Based on what you have learned in this chapter, is it possible in TLS for the receiver to reorder TLS record blocks that arrive out of order? If so, explain how it can be done. If not, why not?

17.5 For SSH packets, what is the advantage, if any, of not including the MAC in the scope of the packet encryption?

CHAPTER 18

Wireless Network Security

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Present an overview of security threats and countermeasures for wireless networks.
- Understand the unique security threats posed by the use of mobile devices with enterprise networks.
- Describe the principal elements in a mobile device security strategy.
- Understand the essential elements of the IEEE 802.11 wireless LAN standard.
- Summarize the various components of the IEEE 802.11i wireless LAN security architecture.

This chapter begins with a general overview of wireless security issues. We then focus on the relatively new area of mobile device security, examining threats and countermeasures for mobile devices used in the enterprise. Then, we look at the IEEE 802.11i standard for wireless LAN security. This standard is part of IEEE 802.11, also referred to as Wi-Fi. We begin the discussion with an overview of IEEE 802.11, and then we look in some detail at IEEE 802.11i.

18.1 WIRELESS SECURITY

Wireless networks, and the wireless devices that use them, introduce a host of security problems over and above those found in wired networks. Some of the key factors contributing to the higher security risk of wireless networks compared to wired networks include the following [MA10]:

- **Channel:** Wireless networking typically involves broadcast communications, which is far more susceptible to eavesdropping and jamming than wired networks. Wireless networks are also more vulnerable to active attacks that exploit vulnerabilities in communications protocols.
- **Mobility:** Wireless devices are, in principal and usually in practice, far more portable and mobile than wired devices. This mobility results in a number of risks, described subsequently.
- **Resources:** Some wireless devices, such as smartphones and tablets, have sophisticated operating systems but limited memory and processing resources with which to counter threats, including denial of service and malware.
- **Accessibility:** Some wireless devices, such as sensors and robots, may be left unattended in remote and/or hostile locations. This greatly increases their vulnerability to physical attacks.

Figure 18.1 Wireless Networking Components

In simple terms, the wireless environment consists of three components that provide point of attack (Figure 18.1). The wireless client can be a cell phone, a Wi-Fi–enabled laptop or tablet, a wireless sensor, a Bluetooth device, and so on. The wireless access point provides a connection to the network or service. Examples of access points are cell towers, Wi-Fi hotspots, and wireless access points to wired local or wide area networks. The transmission medium, which carries the radio waves for data transfer, is also a source of vulnerability.

Wireless Network Threats

[CHOI08] lists the following security threats to wireless networks:

- **Accidental association:** Company wireless LANs or wireless access points to wired LANs in close proximity (e.g., in the same or neighboring buildings) may create overlapping transmission ranges. A user intending to connect to one LAN may unintentionally lock on to a wireless access point from a neighboring network. Although the security breach is accidental, it nevertheless exposes resources of one LAN to the accidental user.
- **Malicious association:** In this situation, a wireless device is configured to appear to be a legitimate access point, enabling the operator to steal passwords from legitimate users and then penetrate a wired network through a legitimate wireless access point.
- **Ad hoc networks:** These are peer-to-peer networks between wireless computers with no access point between them. Such networks can pose a security threat due to a lack of a central point of control.
- **Nontraditional networks:** Nontraditional networks and links, such as personal network Bluetooth devices, barcode readers, and handheld PDAs, pose a security risk in terms of both eavesdropping and spoofing.
- **Identity theft (MAC spoofing):** This occurs when an attacker is able to eavesdrop on network traffic and identify the MAC address of a computer with network privileges.
- **Man-in-the middle attacks:** This type of attack is described in Chapter 10 in the context of the Diffie–Hellman key exchange protocol. In a broader sense, this attack involves persuading a user and an access point to believe that they are talking to each other when in fact the communication is going through an intermediate attacking device. Wireless networks are particularly vulnerable to such attacks.

- **Denial of service (DoS):** This type of attack is discussed in detail in Chapter 21. In the context of a wireless network, a DoS attack occurs when an attacker continually bombards a wireless access point or some other accessible wireless port with various protocol messages designed to consume system resources. The wireless environment lends itself to this type of attack, because it is so easy for the attacker to direct multiple wireless messages at the target.
- **Network injection:** A network injection attack targets wireless access points that are exposed to nonfiltered network traffic, such as routing protocol messages or network management messages. An example of such an attack is one in which bogus reconfiguration commands are used to affect routers and switches to degrade network performance.

Wireless Security Measures

Following [CHOI08], we can group wireless security measures into those dealing with wireless transmissions, wireless access points, and wireless networks (consisting of wireless routers and endpoints).

Securing Wireless Transmissions The principal threats to wireless transmission are eavesdropping, altering or inserting messages, and disruption. To deal with eavesdropping, two types of countermeasures are appropriate:

- **Signal-hiding techniques:** Organizations can take a number of measures to make it more difficult for an attacker to locate their wireless access points, including turning off service set identifier (SSID) broadcasting by wireless access points; assigning cryptic names to SSIDs; reducing signal strength to the lowest level that still provides requisite coverage; and locating wireless access points in the interior of the building, away from windows and exterior walls. Greater security can be achieved by the use of directional antennas and of signal-shielding techniques.
- **Encryption:** Encryption of all wireless transmission is effective against eavesdropping to the extent that the encryption keys are secured.

The use of encryption and authentication protocols is the standard method of countering attempts to alter or insert transmissions.

The methods discussed in Chapter 21 for dealing with DoS apply to wireless transmissions. Organizations can also reduce the risk of unintentional DoS attacks. Site surveys can detect the existence of other devices using the same frequency range, to help determine where to locate wireless access points. Signal strengths can be adjusted and shielding used in an attempt to isolate a wireless environment from competing nearby transmissions.

Securing Wireless Access Points The main threat involving wireless access points is unauthorized access to the network. The principal approach for preventing such access is the IEEE 802.1X standard for port-based network access control. The standard provides an authentication mechanism for devices wishing to attach to a LAN or wireless network. The use of 802.1X can prevent rogue access points and other unauthorized devices from becoming insecure backdoors.

Section 16.3 provides an introduction to 802.1X.

Securing Wireless Networks [CHOI08] recommends the following techniques for wireless network security:

1. Use encryption. Wireless routers are typically equipped with built-in encryption mechanisms for router-to-router traffic.
2. Use antivirus and antispyware software, and a firewall. These facilities should be enabled on all wireless network endpoints.
3. Turn off identifier broadcasting. Wireless routers are typically configured to broadcast an identifying signal so that any device within range can learn of the router's existence. If a network is configured so that authorized devices know the identity of routers, this capability can be disabled, so as to thwart attackers.
4. Change the identifier on your router from the default. Again, this measure thwarts attackers who will attempt to gain access to a wireless network using default router identifiers.
5. Change your router's pre-set password for administration. This is another prudent step.
6. Allow only specific computers to access your wireless network. A router can be configured to only communicate with approved MAC addresses. Of course, MAC addresses can be spoofed, so this is just one element of a security strategy.

18.2 MOBILE DEVICE SECURITY

Prior to the widespread use of smartphones, the dominant paradigm for computer and network security in organizations was as follows. Corporate IT was tightly controlled. User devices were typically limited to Windows PCs. Business applications were controlled by IT and either run locally on endpoints or on physical servers in data centers. Network security was based upon clearly defined perimeters that separated trusted internal networks from the untrusted Internet. Today, there have been massive changes in each of these assumptions. An organization's networks must accommodate the following:

- **Growing use of new devices:** Organizations are experiencing significant growth in employee use of mobile devices. In many cases, employees are allowed to use a combination of endpoint devices as part of their day-to-day activities.
- **Cloud-based applications:** Applications no longer run solely on physical servers in corporate data centers. Quite the opposite, applications can run anywhere—on traditional physical servers, on mobile virtual servers, or in the cloud. Additionally, end users can now take advantage of a wide variety of cloud-based applications and IT services for personal and professional use. Facebook can be used for an employee's personal profiles or as a component of a corporate marketing campaign. Employees depend upon Skype to speak with friends abroad or for legitimate business video conferencing. Dropbox and Box can be used to distribute documents between corporate and personal devices for mobility and user productivity.

- **De-perimeterization:** Given new device proliferation, application mobility, and cloud-based consumer and corporate services, the notion of a static network perimeter is all but gone. Now there are a multitude of network perimeters around devices, applications, users, and data. These perimeters have also become quite dynamic as they must adapt to various environmental conditions such as user role, device type, server virtualization mobility, network location, and time-of-day.
- **External business requirements:** The enterprise must also provide guests, third-party contractors, and business partners network access using various devices from a multitude of locations.

The central element in all of these changes is the mobile computing device. Mobile devices have become an essential element for organizations as part of the overall network infrastructure. Mobile devices such as smartphones, tablets, and memory sticks provide increased convenience for individuals as well as the potential for increased productivity in the workplace. Because of their widespread use and unique characteristics, security for mobile devices is a pressing and complex issue. In essence, an organization needs to implement a security policy through a combination of security features built into the mobile devices and additional security controls provided by network components that regulate the use of the mobile devices.

Security Threats

Mobile devices need additional, specialized protection measures beyond those implemented for other client devices, such as desktop and laptop devices that are used only within the organization's facilities and on the organization's networks. SP 800-14 (*Guidelines for Managing and Securing Mobile Devices in the Enterprise*, July 2012) lists seven major security concerns for mobile devices. We examine each of these in turn.

Lack of Physical Security Controls Mobile devices are typically under the complete control of the user, and are used and kept in a variety of locations outside the organization's control, including off premises. Even if a device is required to remain on premises, the user may move the device within the organization between secure and nonsecured locations. Thus, theft and tampering are realistic threats.

The security policy for mobile devices must be based on the assumption that any mobile device may be stolen or at least accessed by a malicious party. The threat is twofold: A malicious party may attempt to recover sensitive data from the device itself, or may use the device to gain access to the organization's resources.

Use of Untrusted Mobile Devices In addition to company-issued and company-controlled mobile devices, virtually all employees will have personal smartphones and/or tablets. The organization must assume that these devices are not trustworthy. That is, the devices may not employ encryption and either the user or a third party may have installed a bypass to the built-in restrictions on security, operating system use, and so on.

Use of Untrusted Networks If a mobile device is used on premises, it can connect to organization resources over the organization's own in-house wireless networks. However, for off-premises use, the user will typically access organizational resources via Wi-Fi or cellular access to the Internet and from the Internet to the organization. Thus, traffic that includes an off-premises segment is potentially susceptible to eavesdropping or man-in-the-middle types of attacks. Thus, the security policy must be based on the assumption that the networks between the mobile device and the organization are not trustworthy.

Use of Applications Created by Unknown Parties By design, it is easy to find and install third-party applications on mobile devices. This poses the obvious risk of installing malicious software. An organization has several options for dealing with this threat, as described subsequently.

Interaction with Other Systems A common feature found on smartphones and tablets is the ability to automatically synchronize data, apps, contacts, photos, and so on with other computing devices and with cloud-based storage. Unless an organization has control of all the devices involved in synchronization, there is considerable risk of the organization's data being stored in an unsecured location, plus the risk of the introduction of malware.

Use of Untrusted Content Mobile devices may access and use content that other computing devices do not encounter. An example is the Quick Response (QR) code, which is a two-dimensional barcode. QR codes are designed to be captured by a mobile device camera and used by the mobile device. The QR code translates to a URL, so that a malicious QR code could direct the mobile device to malicious Web sites.

Use of Location Services The GPS capability on mobile devices can be used to maintain a knowledge of the physical location of the device. While this feature might be useful to an organization as part of a presence service, it creates security risks. An attacker can use the location information to determine where the device and user are located, which may be of use to the attacker.

Mobile Device Security Strategy

With the threats listed in the preceding discussion in mind, we outline the principal elements of a mobile device security strategy. They fall into three categories: device security, client/server traffic security, and barrier security (Figure 18.2).

Device Security A number of organizations will supply mobile devices for employee use and preconfigure those devices to conform to the enterprise security policy. However, many organizations will find it convenient or even necessary to adopt a bring-your-own-device (BYOD) policy that allows the personal mobile devices of employees to have access to corporate resources. IT managers should be able to inspect each device before allowing network access. IT will want to establish configuration guidelines for operating systems and applications. For example, "rooted" or "jail-broken" devices are not permitted on the network, and mobile

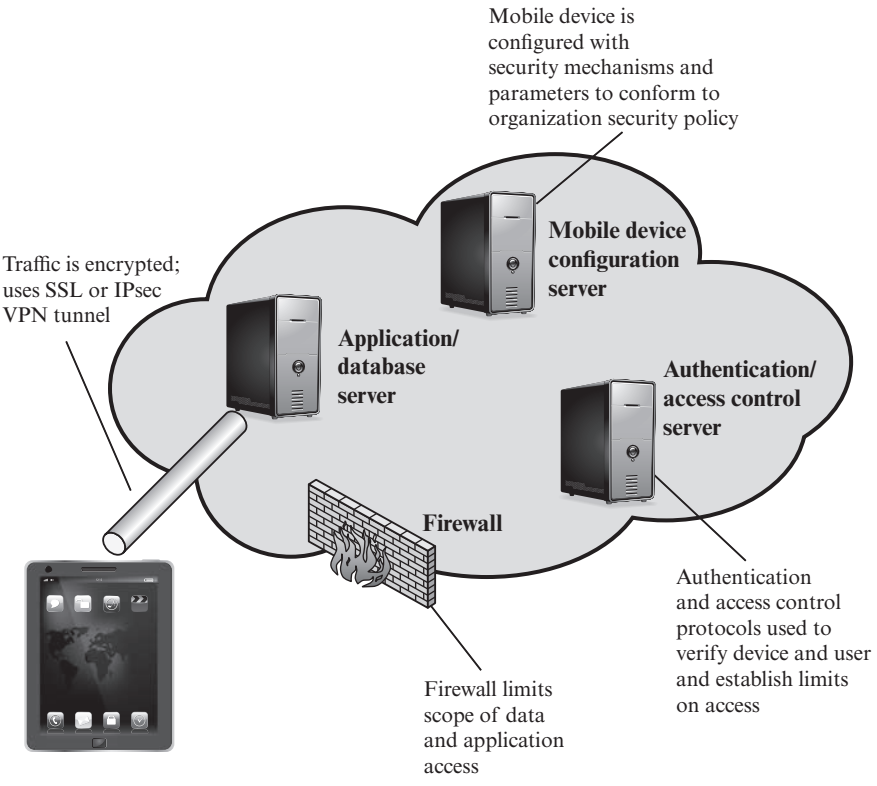


Figure 18.2 Mobile Device Security Elements

devices cannot store corporate contacts on local storage. Whether a device is owned by the organization or BYOD, the organization should configure the device with security controls, including the following:

- Enable auto-lock, which causes the device to lock if it has not been used for a given amount of time, requiring the user to re-enter a four-digit PIN or a password to re-activate the device.
- Enable password or PIN protection. The PIN or password is needed to unlock the device. In addition, it can be configured so that email and other data on the device are encrypted using the PIN or password and can only be retrieved with the PIN or password.
- Avoid using auto-complete features that remember user names or passwords.
- Enable remote wipe.
- Ensure that SSL protection is enabled, if available.
- Make sure that software, including operating systems and applications, is up to date.
- Install antivirus software as it becomes available.

- Either sensitive data should be prohibited from storage on the mobile device or it should be encrypted.
- IT staff should also have the ability to remotely access devices, wipe the device of all data, and then disable the device in the event of loss or theft.
- The organization may prohibit all installation of third-party applications, implement whitelisting to prohibit installation of all unapproved applications, or implement a secure sandbox that isolates the organization's data and applications from all other data and applications on the mobile device. Any application that is on an approved list should be accompanied by a digital signature and a public-key certificate from an approved authority.
- The organization can implement and enforce restrictions on what devices can synchronize and on the use of cloud-based storage.
- To deal with the threat of untrusted content, security responses can include training of personnel on the risks inherent in untrusted content and disabling camera use on corporate mobile devices.
- To counter the threat of malicious use of location services, the security policy can dictate that such service is disabled on all mobile devices.

Traffic Security Traffic security is based on the usual mechanisms for encryption and authentication. All traffic should be encrypted and travel by secure means, such as SSL or IPv6. Virtual private networks (VPNs) can be configured so that all traffic between the mobile device and the organization's network is via a VPN.

A strong authentication protocol should be used to limit the access from the device to the resources of the organization. Often, a mobile device has a single device-specific authenticator, because it is assumed that the device has only one user. A preferable strategy is to have a two-layer authentication mechanism, which involves authenticating the device and then authenticating the user of the device.

Barrier Security The organization should have security mechanisms to protect the network from unauthorized access. The security strategy can also include firewall policies specific to mobile device traffic. Firewall policies can limit the scope of data and application access for all mobile devices. Similarly, intrusion detection and intrusion prevention systems can be configured to have tighter rules for mobile device traffic.

18.3 IEEE 802.11 WIRELESS LAN OVERVIEW

IEEE 802 is a committee that has developed standards for a wide range of local area networks (LANs). In 1990, the IEEE 802 Committee formed a new working group, IEEE 802.11, with a charter to develop a protocol and transmission specifications for wireless LANs (WLANs). Since that time, the demand for WLANs at different frequencies and data rates has exploded. Keeping pace with this demand, the IEEE 802.11 working group has issued an ever-expanding list of standards. Table 18.1 briefly defines key terms used in the IEEE 802.11 standard.

Table 18.1 IEEE 802.11 Terminology

Access point (AP)	Any entity that has station functionality and provides access to the distribution system via the wireless medium for associated stations.
Basic service set (BSS)	A set of stations controlled by a single coordination function.
Coordination function	The logical function that determines when a station operating within a BSS is permitted to transmit and may be able to receive PDUs.
Distribution system (DS)	A system used to interconnect a set of BSSs and integrated LANs to create an ESS.
Extended service set (ESS)	A set of one or more interconnected BSSs and integrated LANs that appear as a single BSS to the LLC layer at any station associated with one of these BSSs.
MAC protocol data unit (MPDU)	The unit of data exchanged between two peer MAC entities using the services of the physical layer.
MAC service data unit (MSDU)	Information that is delivered as a unit between MAC users.
Station	Any device that contains an IEEE 802.11 conformant MAC and physical layer.

The Wi-Fi Alliance

The first 802.11 standard to gain broad industry acceptance was 802.11b. Although 802.11b products are all based on the same standard, there is always a concern whether products from different vendors will successfully interoperate. To meet this concern, the Wireless Ethernet Compatibility Alliance (WECA), an industry consortium, was formed in 1999. This organization, subsequently renamed the Wi-Fi (Wireless Fidelity) Alliance, created a test suite to certify interoperability for 802.11b products. The term used for certified 802.11b products is *Wi-Fi*. Wi-Fi certification has been extended to 802.11g products. The Wi-Fi Alliance has also developed a certification process for 802.11a products, called *Wi-Fi5*. The Wi-Fi Alliance is concerned with a range of market areas for WLANs, including enterprise, home, and hot spots.

More recently, the Wi-Fi Alliance has developed certification procedures for IEEE 802.11 security standards, referred to as Wi-Fi Protected Access (WPA). The most recent version of WPA, known as WPA2, incorporates all of the features of the IEEE 802.11i WLAN security specification.

IEEE 802 Protocol Architecture

Before proceeding, we need to briefly preview the IEEE 802 protocol architecture. IEEE 802.11 standards are defined within the structure of a layered set of protocols. This structure, used for all IEEE 802 standards, is illustrated in Figure 18.3.

Physical Layer The lowest layer of the IEEE 802 reference model is the **physical layer**, which includes such functions as encoding/decoding of signals and bit transmission/reception. In addition, the physical layer includes a specification of the transmission medium. In the case of IEEE 802.11, the physical layer also defines frequency bands and antenna characteristics.

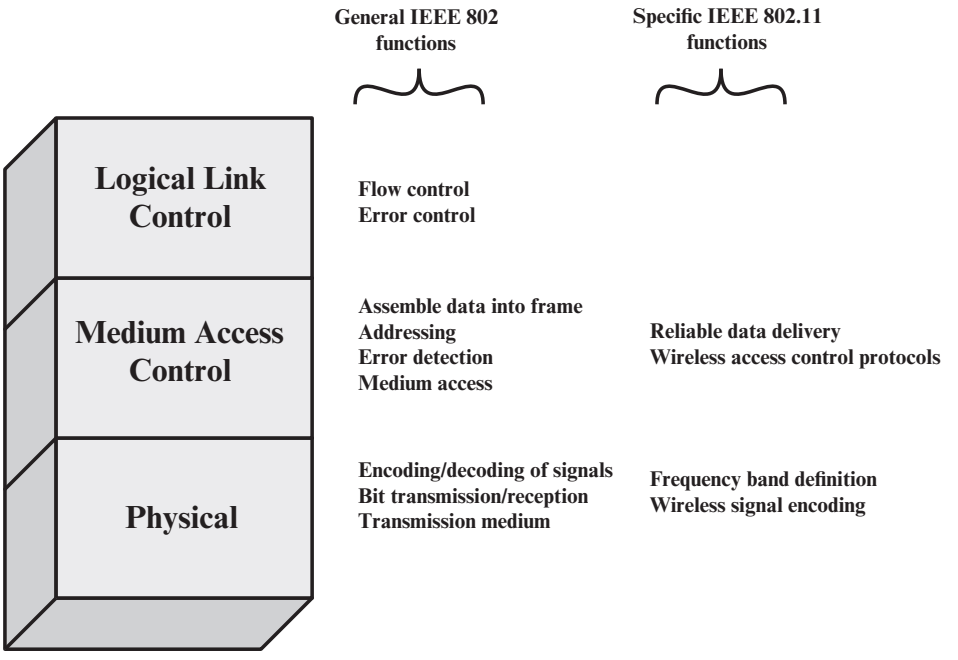


Figure 18.3 IEEE 802.11 Protocol Stack

Media Access Control All LANs consist of collections of devices that share the network's transmission capacity. Some means of controlling access to the transmission medium is needed to provide an orderly and efficient use of that capacity. This is the function of a **media access control (MAC)** layer. The MAC layer receives data from a higher-layer protocol, typically the Logical Link Control (LLC) layer, in the form of a block of data known as the **MAC service data unit (MSDU)**. In general, the MAC layer performs the following functions:

- On transmission, assemble data into a frame, known as a **MAC protocol data unit (MPDU)** with address and error-detection fields.
- On reception, disassemble frame, and perform address recognition and error detection.
- Govern access to the LAN transmission medium.

The exact format of the MPDU differs somewhat for the various MAC protocols in use. In general, all of the MPDUs have a format similar to that of Figure 18.4. The fields of this frame are as follows.

- **MAC Control:** This field contains any protocol control information needed for the functioning of the MAC protocol. For example, a priority level could be indicated here.
- **Destination MAC Address:** The destination physical address on the LAN for this MPDU.
- **Source MAC Address:** The source physical address on the LAN for this MPDU.

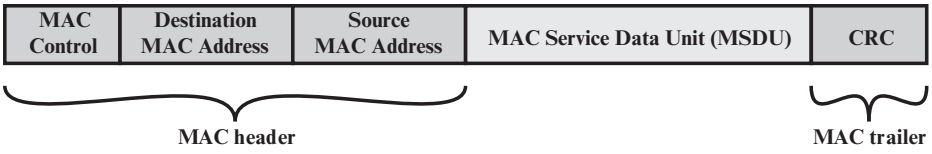


Figure 18.4 General IEEE 802 MPDU Format

- **MAC Service Data Unit:** The data from the next higher layer.
- **CRC:** The cyclic redundancy check field; also known as the Frame Check Sequence (FCS) field. This is an error-detecting code, such as that which is used in other data-link control protocols. The CRC is calculated based on the bits in the entire MPDU. The sender calculates the CRC and adds it to the frame. The receiver performs the same calculation on the incoming MPDU and compares that calculation to the CRC field in that incoming MPDU. If the two values don't match, then one or more bits have been altered in transit.

The fields preceding the MSDU field are referred to as the **MAC header**, and the field following the MSDU field is referred to as the **MAC trailer**. The header and trailer contain control information that accompany the data field and that are used by the MAC protocol.

Logical Link Control In most data-link control protocols, the data-link protocol entity is responsible not only for detecting errors using the CRC, but for recovering from those errors by retransmitting damaged frames. In the LAN protocol architecture, these two functions are split between the MAC and LLC layers. The MAC layer is responsible for detecting errors and discarding any frames that contain errors. The LLC layer optionally keeps track of which frames have been successfully received and retransmits unsuccessful frames.

IEEE 802.11 Network Components and Architectural Model

Figure 18.5 illustrates the model developed by the 802.11 working group. The smallest building block of a wireless LAN is a **basic service set (BSS)**, which consists of wireless stations executing the same MAC protocol and competing for access to the same shared wireless medium. A BSS may be isolated, or it may connect to a backbone **distribution system (DS)** through an **access point (AP)**. The AP functions as a bridge and a relay point. In a BSS, client stations do not communicate directly with one another. Rather, if one station in the BSS wants to communicate with another station in the same BSS, the MAC frame is first sent from the originating station to the AP and then from the AP to the destination station. Similarly, a MAC frame from a station in the BSS to a remote station is sent from the local station to the AP and then relayed by the AP over the DS on its way to the destination station. The BSS generally corresponds to what is referred to as a cell in the literature. The DS can be a switch, a wired network, or a wireless network.

When all the stations in the BSS are mobile stations that communicate directly with one another (not using an AP), the BSS is called an **independent BSS (IBSS)**. An IBSS is typically an ad hoc network. In an IBSS, the stations all communicate directly, and no AP is involved.

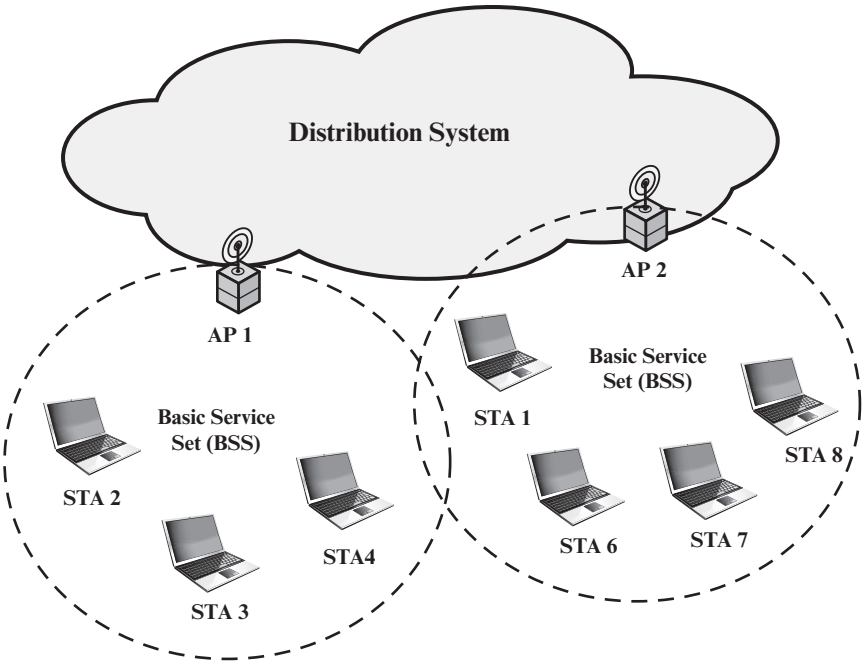


Figure 18.5 IEEE 802.11 Extended Service Set

A simple configuration is shown in Figure 18.5, in which each station belongs to a single BSS; that is, each station is within wireless range only of other stations within the same BSS. It is also possible for two BSSs to overlap geographically, so that a single station could participate in more than one BSS. Furthermore, the association between a station and a BSS is dynamic. Stations may turn off, come within range, and go out of range.

An **extended service set (ESS)** consists of two or more basic service sets interconnected by a distribution system. The extended service set appears as a single logical LAN to the logical link control (LLC) level.

IEEE 802.11 Services

IEEE 802.11 defines nine services that need to be provided by the wireless LAN to achieve functionality equivalent to that which is inherent to wired LANs. Table 18.2 lists the services and indicates two ways of categorizing them.

1. The service provider can be either the station or the DS. Station services are implemented in every 802.11 station, including AP stations. Distribution services are provided between BSSs; these services may be implemented in an AP or in another special-purpose device attached to the distribution system.
2. Three of the services are used to control IEEE 802.11 LAN access and confidentiality. Six of the services are used to support delivery of MSDUs between stations. If the MSDU is too large to be transmitted in a single MPDU, it may be fragmented and transmitted in a series of MPDUs.

Table 18.2 IEEE 802.11 Services

Service	Provider	Used to support
Association	Distribution system	MSDU delivery
Authentication	Station	LAN access and security
Deauthentication	Station	LAN access and security
Disassociation	Distribution system	MSDU delivery
Distribution	Distribution system	MSDU delivery
Integration	Distribution system	MSDU delivery
MSDU delivery	Station	MSDU delivery
Privacy	Station	LAN access and security
Reassociation	Distribution system	MSDU delivery

Following the IEEE 802.11 document, we next discuss the services in an order designed to clarify the operation of an IEEE 802.11 ESS network. **MSDU delivery**, which is the basic service, already has been mentioned. Services related to security are introduced in Section 18.4.

Distribution of Messages Within a DS The two services involved with the distribution of messages within a DS are distribution and integration. **Distribution** is the primary service used by stations to exchange MPDUs when the MPDUs must traverse the DS to get from a station in one BSS to a station in another BSS. For example, suppose a frame is to be sent from station 2 (STA 2) to station 7 (STA 7) in Figure 18.5. The frame is sent from STA 2 to AP 1, which is the AP for this BSS. The AP gives the frame to the DS, which has the job of directing the frame to the AP associated with STA 7 in the target BSS. AP 2 receives the frame and forwards it to STA 7. How the message is transported through the DS is beyond the scope of the IEEE 802.11 standard.

If the two stations that are communicating are within the same BSS, then the distribution service logically goes through the single AP of that BSS.

The **integration** service enables transfer of data between a station on an IEEE 802.11 LAN and a station on an integrated IEEE 802.x LAN. The term *integrated* refers to a wired LAN that is physically connected to the DS and whose stations may be logically connected to an IEEE 802.11 LAN via the integration service. The integration service takes care of any address translation and media conversion logic required for the exchange of data.

Association-Related Services The primary purpose of the MAC layer is to transfer MSDUs between MAC entities; this purpose is fulfilled by the distribution service. For that service to function, it requires information about stations within the ESS that is provided by the association-related services. Before the distribution service can deliver data to or accept data from a station, that station must be *associated*. Before looking at the concept of association, we need

to describe the concept of mobility. The standard defines three transition types, based on mobility:

- **No transition:** A station of this type is either stationary or moves only within the direct communication range of the communicating stations of a single BSS.
- **BSS transition:** This is defined as a station movement from one BSS to another BSS within the same ESS. In this case, delivery of data to the station requires that the addressing capability be able to recognize the new location of the station.
- **ESS transition:** This is defined as a station movement from a BSS in one ESS to a BSS within another ESS. This case is supported only in the sense that the station can move. Maintenance of upper-layer connections supported by 802.11 cannot be guaranteed. In fact, disruption of service is likely to occur.

To deliver a message within a DS, the distribution service needs to know where the destination station is located. Specifically, the DS needs to know the identity of the AP to which the message should be delivered in order for that message to reach the destination station. To meet this requirement, a station must maintain an association with the AP within its current BSS. Three services relate to this requirement:

- **Association:** Establishes an initial association between a station and an AP. Before a station can transmit or receive frames on a wireless LAN, its identity and address must be known. For this purpose, a station must establish an association with an AP within a particular BSS. The AP can then communicate this information to other APs within the ESS to facilitate routing and delivery of addressed frames.
- **Reassociation:** Enables an established association to be transferred from one AP to another, allowing a mobile station to move from one BSS to another.
- **Disassociation:** A notification from either a station or an AP that an existing association is terminated. A station should give this notification before leaving an ESS or shutting down. However, the MAC management facility protects itself against stations that disappear without notification.

18.4 IEEE 802.11i WIRELESS LAN SECURITY

There are two characteristics of a wired LAN that are not inherent in a wireless LAN.

1. In order to transmit over a wired LAN, a station must be physically connected to the LAN. On the other hand, with a wireless LAN, any station within radio range of the other devices on the LAN can transmit. In a sense, there is a form of authentication with a wired LAN in that it requires some positive and presumably observable action to connect a station to a wired LAN.
2. Similarly, in order to receive a transmission from a station that is part of a wired LAN, the receiving station also must be attached to the wired LAN. On the other hand, with a wireless LAN, any station within radio range can receive. Thus, a wired LAN provides a degree of privacy, limiting reception of data to stations connected to the LAN.

These differences between wired and wireless LANs suggest the increased need for robust security services and mechanisms for wireless LANs. The original 802.11 specification included a set of security features for privacy and authentication that were quite weak. For privacy, 802.11 defined the **Wired Equivalent Privacy (WEP)** algorithm. The privacy portion of the 802.11 standard contained major weaknesses. Subsequent to the development of WEP, the 802.11i task group has developed a set of capabilities to address the WLAN security issues. In order to accelerate the introduction of strong security into WLANs, the Wi-Fi Alliance promulgated **Wi-Fi Protected Access (WPA)** as a Wi-Fi standard. WPA is a set of security mechanisms that eliminates most 802.11 security issues and was based on the current state of the 802.11i standard. The final form of the 802.11i standard is referred to as **Robust Security Network (RSN)**. The Wi-Fi Alliance certifies vendors in compliance with the full 802.11i specification under the WPA2 program.

The RSN specification is quite complex, and occupies 145 pages of the 2012 IEEE 802.11 standard. In this section, we provide an overview.

IEEE 802.11i Services

The 802.11i RSN security specification defines the following services.

- **Authentication:** A protocol is used to define an exchange between a user and an AS that provides mutual authentication and generates temporary keys to be used between the client and the AP over the wireless link.
- **Access control:**[1] This function enforces the use of the authentication function, routes the messages properly, and facilitates key exchange. It can work with a variety of authentication protocols.
- **Privacy with message integrity:** MAC-level data (e.g., an LLC PDU) are encrypted along with a message integrity code that ensures that the data have not been altered.

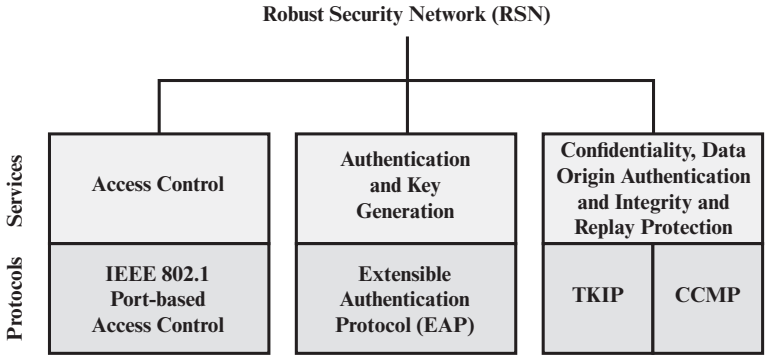
Figure 18.6a indicates the security protocols used to support these services, while Figure 18.6b lists the cryptographic algorithms used for these services.

IEEE 802.11i Phases of Operation

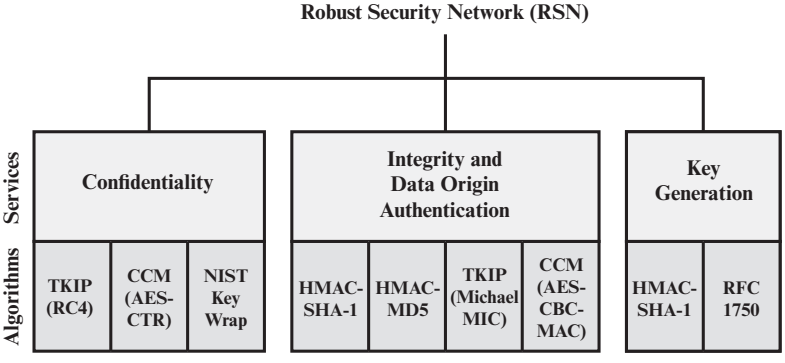
The operation of an IEEE 802.11i RSN can be broken down into five distinct phases of operation. The exact nature of the phases will depend on the configuration and the end points of the communication. Possibilities include (see Figure 18.5):

1. Two wireless stations in the same BSS communicating via the access point (AP) for that BSS.
2. Two wireless stations (STAs) in the same ad hoc IBSS communicating directly with each other.

[1]In this context, we are discussing access control as a security function. This is a different function than media access control (MAC) as described in Section 18.3. Unfortunately, the literature and the standards use the term *access control* in both contexts.



(a) Services and protocols



(b) Cryptographic algorithms

CBC-MAC = Cipher Block Chaining Message Authentication Code (MAC)
CCM = Counter Mode with Cipher Block Chaining Message Authentication Code
CCMP = Counter Mode with Cipher Block Chaining MAC Protocol
TKIP = Temporal Key Integrity Protocol

Figure 18.6 Elements of IEEE 802.11i

3. Two wireless stations in different BSSs communicating via their respective APs across a distribution system.
4. A wireless station communicating with an end station on a wired network via its AP and the distribution system.

IEEE 802.11i security is concerned only with secure communication between the STA and its AP. In case 1 in the preceding list, secure communication is assured if each STA establishes secure communications with the AP. Case 2 is similar, with the AP functionality residing in the STA. For case 3, security is not provided across the distribution system at the level of IEEE 802.11, but only within each BSS. End-to-end security (if required) must be provided at a higher layer. Similarly, in case 4, security is only provided between the STA and its AP.

With these considerations in mind, Figure 18.7 depicts the five phases of operation for an RSN and maps them to the network components involved. One new component is the authentication server (AS). The rectangles indicate the exchange of sequences of MPDUs. The five phases are defined as follows.

- **Discovery:** An AP uses messages called Beacons and Probe Responses to advertise its IEEE 802.11i security policy. The STA uses these to identify an AP for a WLAN with which it wishes to communicate. The STA associates with the AP, which it uses to select the cipher suite and authentication mechanism when the Beacons and Probe Responses present a choice.
- **Authentication:** During this phase, the STA and AS prove their identities to each other. The AP blocks non-authentication traffic between the STA and AS until the authentication transaction is successful. The AP does not participate in the authentication transaction other than forwarding traffic between the STA and AS.
- **Key generation and distribution:** The AP and the STA perform several operations that cause cryptographic keys to be generated and placed on the AP and the STA. Frames are exchanged between the AP and STA only.
- **Protected data transfer:** Frames are exchanged between the STA and the end station through the AP. As denoted by the shading and the encryption module icon, secure data transfer occurs between the STA and the AP only; security is not provided end-to-end.

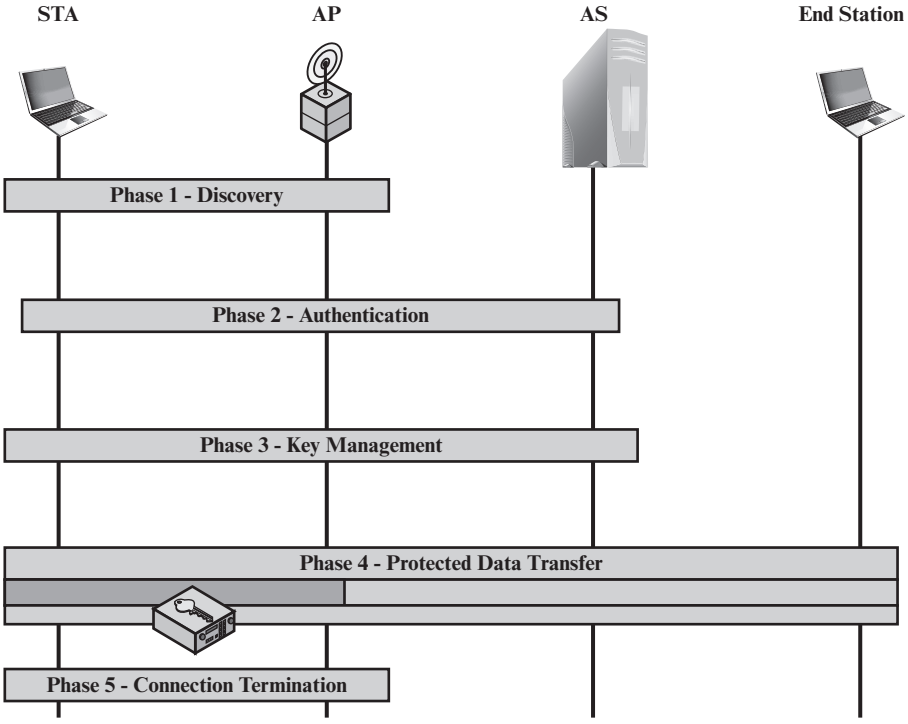


Figure 18.7 IEEE 802.11i Phases of Operation

- **Connection termination:** The AP and STA exchange frames. During this phase, the secure connection is torn down and the connection is restored to the original state.

Discovery Phase

We now look in more detail at the RSN phases of operation, beginning with the discovery phase, which is illustrated in the upper portion of Figure 18.8. The purpose of this phase is for an STA and an AP to recognize each other, agree on a set of security capabilities, and establish an association for future communication using those security capabilities.

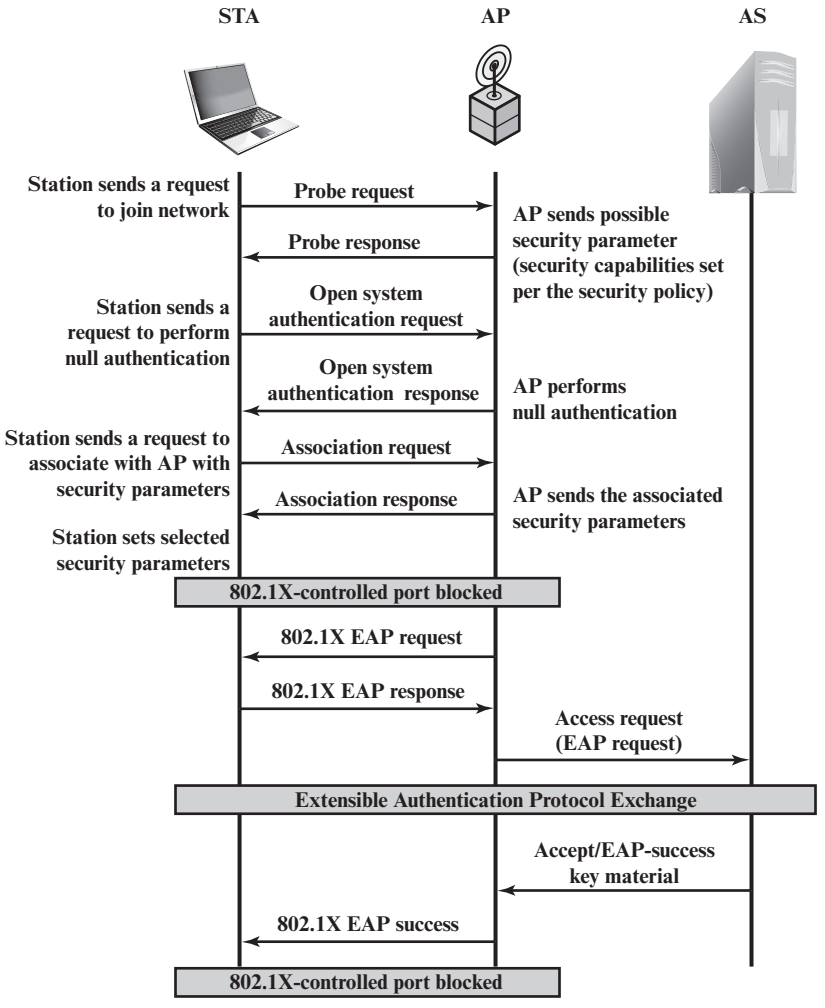


Figure 18.8 IEEE 802.11i Phases of Operation: Capability Discovery, Authentication, and Association

Security Capabilities During this phase, the STA and AP decide on specific techniques in the following areas:

- Confidentiality and MPDU integrity protocols for protecting unicast traffic (traffic only between this STA and AP)
- Authentication method
- Cryptography key management approach

Confidentiality and integrity protocols for protecting multicast/broadcast traffic are dictated by the AP, since all STAs in a multicast group must use the same protocols and ciphers. The specification of a protocol, along with the chosen key length (if variable) is known as a *cipher suite*. The options for the confidentiality and integrity cipher suite are

- WEP, with either a 40-bit or 104-bit key, which allows backward compatibility with older IEEE 802.11 implementations
- TKIP
- CCMP
- Vendor-specific methods

The other negotiable suite is the authentication and key management (AKM) suite, which defines (1) the means by which the AP and STA perform mutual authentication and (2) the means for deriving a root key from which other keys may be generated. The possible AKM suites are

- IEEE 802.1X
- Pre-shared key (no explicit authentication takes place and mutual authentication is implied if the STA and AP share a unique secret key)
- Vendor-specific methods

MPDU Exchange The discovery phase consists of three exchanges.

- **Network and security capability discovery:** During this exchange, STAs discover the existence of a network with which to communicate. The AP either periodically broadcasts its security capabilities (not shown in figure), indicated by RSN IE (Robust Security Network Information Element), in a specific channel through the Beacon frame; or responds to a station's Probe Request through a Probe Response frame. A wireless station may discover available access points and corresponding security capabilities by either passively monitoring the Beacon frames or actively probing every channel.
- **Open system authentication:** The purpose of this frame sequence, which provides no security, is simply to maintain backward compatibility with the IEEE 802.11 state machine, as implemented in existing IEEE 802.11 hardware. In essence, the two devices (STA and AP) simply exchange identifiers.
- **Association:** The purpose of this stage is to agree on a set of security capabilities to be used. The STA then sends an Association Request frame to the AP. In this frame, the STA specifies one set of matching capabilities

(one authentication and key management suite, one pairwise cipher suite, and one group-key cipher suite) from among those advertised by the AP. If there is no match in capabilities between the AP and the STA, the AP refuses the Association Request. The STA blocks it too, in case it has associated with a rogue AP or someone is inserting frames illicitly on its channel. As shown in Figure 18.8, the IEEE 802.1X controlled ports are blocked, and no user traffic goes beyond the AP. The concept of blocked ports is explained subsequently.

Authentication Phase

As was mentioned, the authentication phase enables mutual authentication between an STA and an authentication server (AS) located in the DS. Authentication is designed to allow only authorized stations to use the network and to provide the STA with assurance that it is communicating with a legitimate network.

IEEE 802.1X Access Control Approach IEEE 802.11i makes use of another standard that was designed to provide access control functions for LANs. The standard is IEEE 802.1X, Port-Based Network Access Control. The authentication protocol that is used, the Extensible Authentication Protocol (EAP), is defined in the IEEE 802.1X standard. IEEE 802.1X uses the terms *supplicant*, *authenticator*, and *authentication server* (AS). In the context of an 802.11 WLAN, the first two terms correspond to the wireless station and the AP. The AS is typically a separate device on the wired side of the network (i.e., accessible over the DS) but could also reside directly on the authenticator.

Before a supplicant is authenticated by the AS using an authentication protocol, the authenticator only passes control or authentication messages between the supplicant and the AS; the 802.1X control channel is unblocked, but the 802.11 data channel is blocked. Once a supplicant is authenticated and keys are provided, the authenticator can forward data from the supplicant, subject to predefined access control limitations for the supplicant to the network. Under these circumstances, the data channel is unblocked.

As indicated in Figure 16.5, 802.1X uses the concepts of controlled and uncontrolled ports. Ports are logical entities defined within the authenticator and refer to physical network connections. For a WLAN, the authenticator (the AP) may have only two physical ports: one connecting to the DS and one for wireless communication within its BSS. Each logical port is mapped to one of these two physical ports. An uncontrolled port allows the exchange of PDUs between the supplicant and the other AS, regardless of the authentication state of the supplicant. A controlled port allows the exchange of PDUs between a supplicant and other systems on the LAN only if the current state of the supplicant authorizes such an exchange. IEEE 802.1X is covered in more detail in Chapter 16.

The 802.1X framework, with an upper-layer authentication protocol, fits nicely with a BSS architecture that includes a number of wireless stations and an AP. However, for an IBSS, there is no AP. For an IBSS, 802.11i provides a more complex solution that, in essence, involves pairwise authentication between stations on the IBSS.

MPDU Exchange The lower part of Figure 18.8 shows the MPDU exchange dictated by IEEE 802.11 for the authentication phase. We can think of authentication phase as consisting of the following three phases.

- **Connect to AS:** The STA sends a request to its AP (the one with which it has an association) for connection to the AS. The AP acknowledges this request and sends an access request to the AS.
- **EAP exchange:** This exchange authenticates the STA and AS to each other. A number of alternative exchanges are possible, as explained subsequently.
- **Secure key delivery:** Once authentication is established, the AS generates a master session key (MSK), also known as the Authentication, Authorization, and Accounting (AAA) key and sends it to the STA. As explained subsequently, all the cryptographic keys needed by the STA for secure communication with its AP are generated from this MSK. IEEE 802.11i does not prescribe a method for secure delivery of the MSK but relies on EAP for this. Whatever method is used, it involves the transmission of an MPDU containing an encrypted MSK from the AS, via the AP, to the AS.

EAP Exchange As mentioned, there are a number of possible EAP exchanges that can be used during the authentication phase. Typically, the message flow between STA and AP employs the EAP over LAN (EAPOL) protocol, and the message flow between the AP and AS uses the Remote Authentication Dial In User Service (RADIUS) protocol, although other options are available for both STA-to-AP and AP-to-AS exchanges. [FRAN07] provides the following summary of the authentication exchange using EAPOL and RADIUS.

1. The EAP exchange begins with the AP issuing an EAP-Request/Identity frame to the STA.
2. The STA replies with an EAP-Response/Identity frame, which the AP receives over the uncontrolled port. The packet is then encapsulated in RADIUS over EAP and passed on to the RADIUS server as a RADIUS-Access-Request packet.
3. The AAA server replies with a RADIUS-Access-Challenge packet, which is passed on to the STA as an EAP-Request. This request is of the appropriate authentication type and contains relevant challenge information.
4. The STA formulates an EAP-Response message and sends it to the AS. The response is translated by the AP into a Radius-Access-Request with the response to the challenge as a data field. Steps 3 and 4 may be repeated multiple times, depending on the EAP method in use. For TLS tunneling methods, it is common for authentication to require 10 to 20 round trips.
5. The AAA server grants access with a Radius-Access-Accept packet. The AP issues an EAP-Success frame. (Some protocols require confirmation of the EAP success inside the TLS tunnel for authenticity validation.) The controlled port is authorized, and the user may begin to access the network.

Note from Figure 18.8 that the AP controlled port is still blocked to general user traffic. Although the authentication is successful, the ports remain blocked

until the temporal keys are installed in the STA and AP, which occurs during the 4-Way Handshake.

Key Management Phase

During the key management phase, a variety of cryptographic keys are generated and distributed to STAs. There are two types of keys: pairwise keys used for communication between an STA and an AP and group keys used for multicast communication. Figure 18.9, based on [FRAN07], shows the two key hierarchies, and Table 18.3 defines the individual keys.

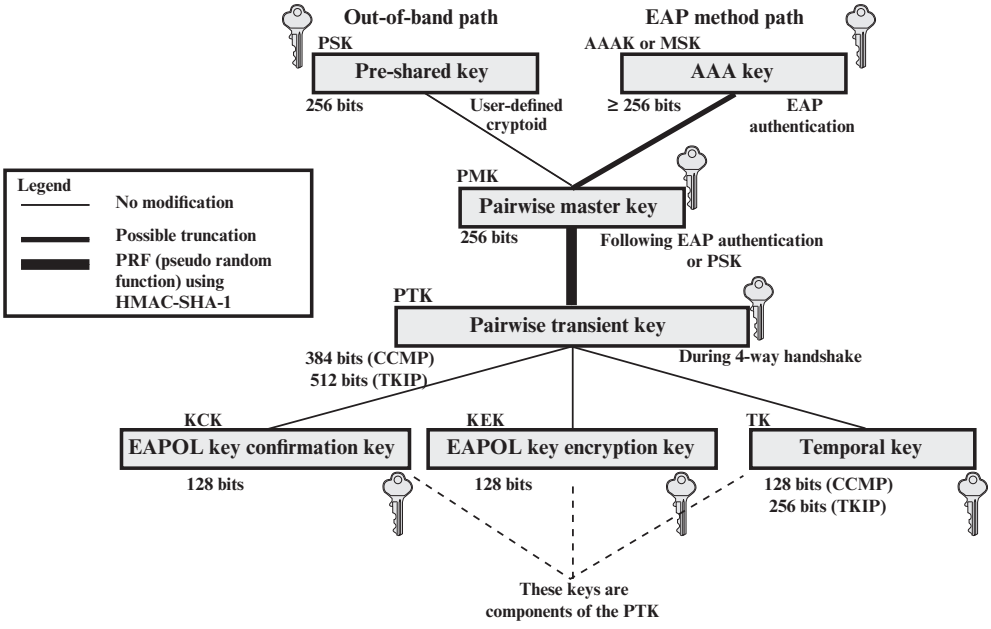


Figure 18.9 IEEE 802.11i Key Hierarchies

Table 18.3 IEEE 802.11i Keys for Data Confidentiality and Integrity Protocols

Abbreviation	Name	Description / Purpose	Size (bits)	Type
AAA Key	Authentication, Accounting, and Authorization Key	Used to derive the PMK. Used with the IEEE 802.1X authentication and key management approach. Same as MMSK.	≥ 256	Key generation key, root key
PSK	Pre-shared Key	Becomes the PMK in pre-shared key environments.	256	Key generation key, root key
PMK	Pairwise Master Key	Used with other inputs to derive the PTK.	256	Key generation key
GMK	Group Master Key	Used with other inputs to derive the GTK.	128	Key generation key
PTK	Pair-wise Transient Key	Derived from the PMK. Comprises the EAPOL-KCK, EAPOL-KEK, and TK and (for TKIP) the MIC key.	512 (TKIP) 384 (CCMP)	Composite key
TK	Temporal Key	Used with TKIP or CCMP to provide confidentiality and integrity protection for unicast user traffic.	256 (TKIP) 128 (CCMP)	Traffic key
GTK	Group Temporal Key	Derived from the GMK. Used to provide confidentiality and integrity protection for multicast/broadcast user traffic.	256 (TKIP) 128 (CCMP) 40,104 (WEP)	Traffic key
MIC Key	Message Integrity Code Key	Used by TKIP's Michael MIC to provide integrity protection of messages.	64	Message integrity key
EAPOL-KCK	EAPOL-Key Confirmation Key	Used to provide integrity protection for key material distributed during the 4-Way Handshake.	128	Message integrity key
EAPOL-KEK	EAPOL-Key Encryption Key	Used to ensure the confidentiality of the GTK and other key material in the 4-Way Handshake.	128	Traffic key / key encryption key
WEP Key	Wired Equivalent Privacy Key	Used with WEP.	40,104	Traffic key

Pairwise Keys Pairwise keys are used for communication between a pair of devices, typically between an STA and an AP. These keys form a hierarchy beginning with a master key from which other keys are derived dynamically and used for a limited period of time.

At the top level of the hierarchy are two possibilities. A **pre-shared key (PSK)** is a secret key shared by the AP and a STA and installed in some fashion outside the scope of IEEE 802.11i. The other alternative is the **master session key (MSK)**, also known as the AAAK, which is generated using the IEEE 802.1X protocol during the authentication phase, as described previously. The actual method of key generation depends on the details of the authentication protocol used. In either case (PSK or MSK), there is a unique key shared by the AP with each STA with which it communicates. All the other keys derived from this master key are also unique between an AP and an STA. Thus, each STA, at any time, has one set of keys, as depicted in the hierarchy of Figure 18.9a, while the AP has one set of such keys for each of its STAs.

The **pairwise master key (PMK)** is derived from the master key. If a PSK is used, then the PSK is used as the PMK; if a MSK is used, then the PMK is derived from the MSK by truncation (if necessary). By the end of the authentication phase, marked by the 802.1X EAP Success message (Figure 18.8), both the AP and the STA have a copy of their shared PMK.

The PMK is used to generate the **pairwise transient key (PTK)**, which in fact consists of three keys to be used for communication between an STA and AP after they have been mutually authenticated. To derive the PTK, the HMAC-SHA-1 function is applied to the PMK, the MAC addresses of the STA and AP, and nonces generated when needed. Using the STA and AP addresses in the generation of the PTK provides protection against session hijacking and impersonation; using nonces provides additional random keying material.

The three parts of the PTK are as follows.

- **EAP Over LAN (EAPOL) Key Confirmation Key (EAPOL-KCK):** Supports the integrity and data origin authenticity of STA-to-AP control frames during operational setup of an RSN. It also performs an access control function: proof-of-possession of the PMK. An entity that possesses the PMK is authorized to use the link.
- **EAPOL Key Encryption Key (EAPOL-KEK):** Protects the confidentiality of keys and other data during some RSN association procedures.
- **Temporal Key (TK):** Provides the actual protection for user traffic.

Group Keys Group keys are used for multicast communication in which one STA sends MPDU's to multiple STAs. At the top level of the group key hierarchy is the **group master key (GMK)**. The GMK is a key-generating key used with other inputs to derive the **group temporal key (GTK)**. Unlike the PTK, which is generated using material from both AP and STA, the GTK is generated by the AP and transmitted

to its associated STAs. Exactly how this GTK is generated is undefined. IEEE 802.11i, however, requires that its value is computationally indistinguishable from random. The GTK is distributed securely using the pairwise keys that are already established. The GTK is changed every time a device leaves the network.

Pairwise Key Distribution The upper part of Figure 18.10 shows the MPDU exchange for distributing pairwise keys. This exchange is known as the **4-way handshake**. The STA and AP use this handshake to confirm the existence of the

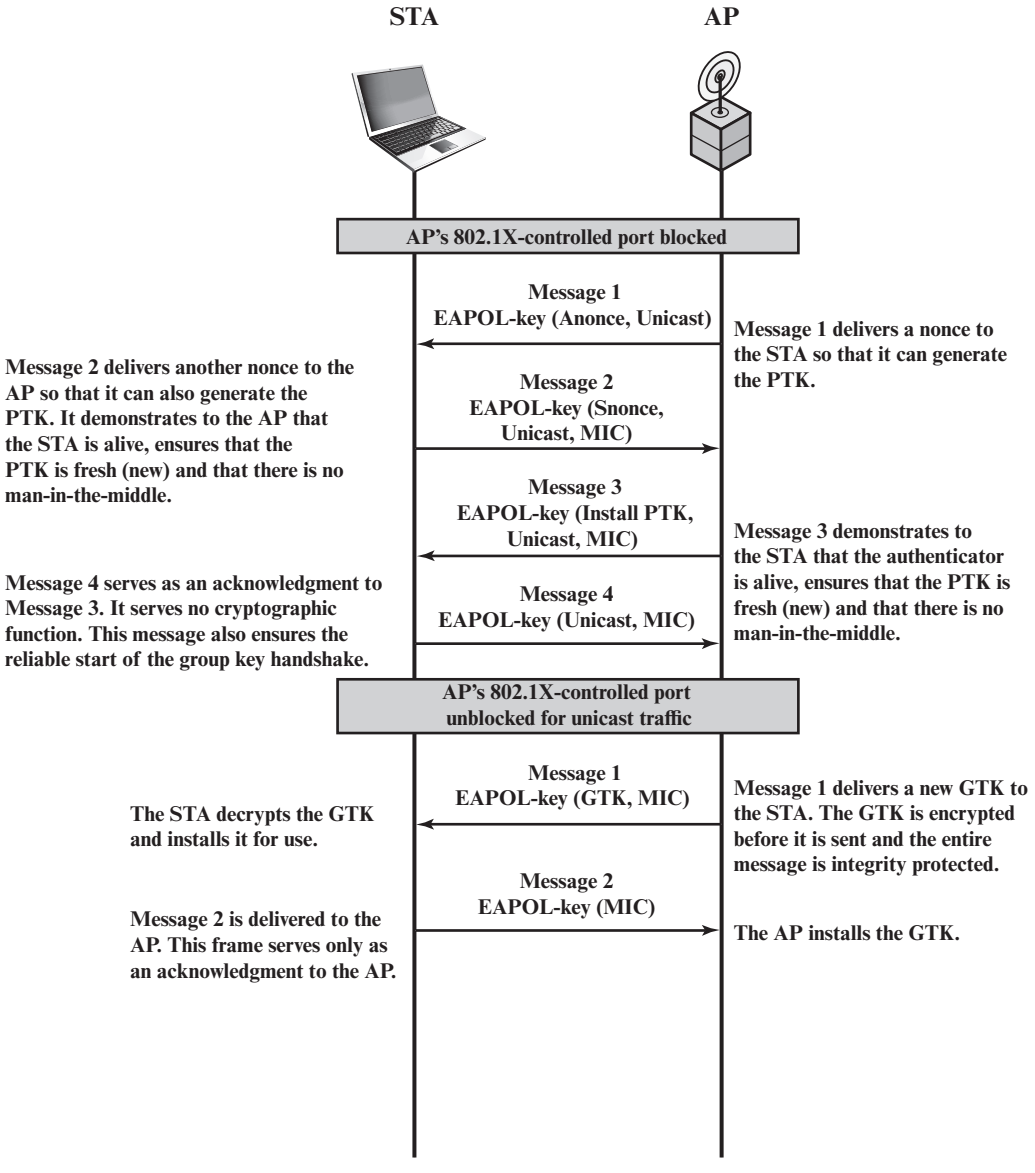


Figure 18.10 IEEE 802.11i Phases of Operation: Four-Way Handshake and Group Key Handshake

PMK, verify the selection of the cipher suite, and derive a fresh PTK for the following data session. The four parts of the exchange are as follows.

- **AP → STA:** Message includes the MAC address of the AP and a nonce (Anonce)
- **STA → AP:** The STA generates its own nonce (Snonce) and uses both nonces and both MAC addresses, plus the PMK, to generate a PTK. The STA then sends a message containing its MAC address and Snonce, enabling the AP to generate the same PTK. This message includes a message integrity code (MIC)[2] using HMAC-MD5 or HMAC-SHA-1-128. The key used with the MIC is KCK.
- **AP → STA:** The AP is now able to generate the PTK. The AP then sends a message to the STA, containing the same information as in the first message, but this time including a MIC.
- **STA → AP:** This is merely an acknowledgment message, again protected by a MIC.

Group Key Distribution For group key distribution, the AP generates a GTK and distributes it to each STA in a multicast group. The two-message exchange with each STA consists of the following:

- **AP → STA:** This message includes the GTK, encrypted either with RC4 or with AES. The key used for encryption is KEK, using a key wrapping algorithm (as discussed in Chapter 12). A MIC value is appended.
- **STA → AP:** The STA acknowledges receipt of the GTK. This message includes a MIC value.

Protected Data Transfer Phase

IEEE 802.11i defines two schemes for protecting data transmitted in 802.11 MPDUs: the Temporal Key Integrity Protocol (TKIP), and the Counter Mode-CBC MAC Protocol (CCMP).

TKIP TKIP is designed to require only software changes to devices that are implemented with the older wireless LAN security approach called Wired Equivalent Privacy (WEP). TKIP provides two services:

- **Message integrity:** TKIP adds a message integrity code (MIC) to the 802.11 MAC frame after the data field. The MIC is generated by an algorithm, called Michael, that computes a 64-bit value using as input the source and destination MAC address values and the Data field, plus key material.
- **Data confidentiality:** Data confidentiality is provided by encrypting the MPDU plus MIC value using RC4.

[2] While *MAC* is commonly used in cryptography to refer to a Message Authentication Code, the term *MIC* is used instead in connection with 802.11i because *MAC* has another standard meaning, Media Access Control, in networking.

The 256-bit TK (Figure 18.9) is employed as follows. Two 64-bit keys are used with the Michael message digest algorithm to produce a message integrity code. One key is used to protect STA-to-AP messages, and the other key is used to protect AP-to-STA messages. The remaining 128 bits are truncated to generate the RC4 key used to encrypt the transmitted data.

For additional protection, a monotonically increasing TKIP sequence counter (TSC) is assigned to each frame. The TSC serves two purposes. First, the TSC is included with each MPDU and is protected by the MIC to protect against replay attacks. Second, the TSC is combined with the session TK to produce a dynamic encryption key that changes with each transmitted MPDU, thus making cryptanalysis more difficult.

CCMP CCMP is intended for newer IEEE 802.11 devices that are equipped with the hardware to support this scheme. As with TKIP, CCMP provides two services:

- **Message integrity:** CCMP uses the cipher block chaining message authentication code (CBC-MAC), described in Chapter 12.
- **Data confidentiality:** CCMP uses the CTR block cipher mode of operation with AES for encryption. CTR is described in Chapter 7.

The same 128-bit AES key is used for both integrity and confidentiality. The scheme uses a 48-bit packet number to construct a nonce to prevent replay attacks.

The IEEE 802.11i Pseudorandom Function

At a number of places in the IEEE 802.11i scheme, a pseudorandom function (PRF) is used. For example, it is used to generate nonces, to expand pairwise keys, and to generate the GTK. Best security practice dictates that different pseudorandom number streams be used for these different purposes. However, for implementation efficiency, we would like to rely on a single pseudorandom number generator function.

The PRF is built on the use of HMAC-SHA-1 to generate a pseudorandom bit stream. Recall that HMAC-SHA-1 takes a message (block of data) and a key of length at least 160 bits and produces a 160-bit hash value. SHA-1 has the property that the change of a single bit of the input produces a new hash value with no apparent connection to the preceding hash value. This property is the basis for pseudorandom number generation.

The IEEE 802.11i PRF takes four parameters as input and produces the desired number of random bits. The function is of the form PRF(*K, A, B, Len*), where

K = a secret key

A = a text string specific to the application (e.g., nonce generation or pairwise key expansion)

B = some data specific to each case

Len = desired number of pseudorandom bits

For example, for the pairwise transient key for CCMP:

```
PTK = PRF (PMK, "Pairwise key expansion", min (AP-
      Addr, STA-Addr) || max (AP-Addr, STA-Addr) || min
      (Anonce, Snonce) || max (Anonce, Snonce), 384)
```

So, in this case, the parameters are

K = PMK

A = the text string "Pairwise key expansion"

B = a sequence of bytes formed by concatenating the two MAC addresses and the two nonces

Len = 384 bits

Similarly, a nonce is generated by

```
Nonce = PRF (Random Number, "InitCounter", MAC || Time, 256)
```

where **Time** is a measure of the network time known to the nonce generator.

The group temporal key is generated by

```
GTK = PRF (GMK, "Group key expansion", MAC || Gnonce, 256)
```

Figure 18.11 illustrates the function PRF(*K, A, B, Len*). The parameter *K* serves as the key input to HMAC. The message input consists of four items concatenated together: the parameter *A*, a byte with value 0, the parameter *B*, and a counter *i*. The counter is initialized to 0. The HMAC algorithm is run once, producing a 160-bit hash value. If more bits are required, HMAC is run again with the same inputs, except that *i* is incremented each time until the necessary number of bits is generated. We can express the logic as

```
PRF (K, A, B, Len)
     R ← null string
     for i ← 0 to ((Len + 159)/160 – 1) do
     R ← R || HMAC-SHA-1 (K, A || 0 || B || i)
     Return Truncate-to-Len (R, Len)
```

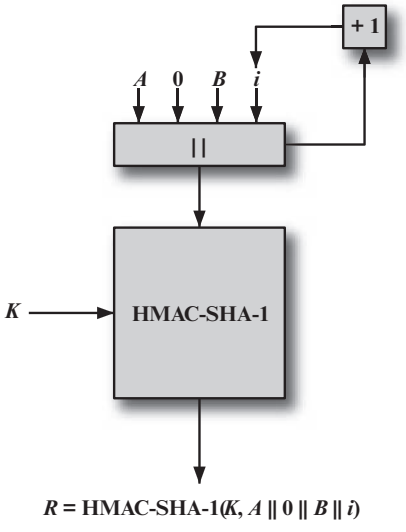


Figure 18.11 IEEE 802.11i Pseudorandom Function

18.5 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

4-way handshake	independent BSS (IBSS)	pseudorandom function
access point (AP)	logical link control (LLC)	Robust Security Network (RSN)
basic service set (BSS)	media access control (MAC)	Temporal Key Integrity Protocol (TKIP)
Counter Mode-CBC MAC Protocol (CCMP)	MAC protocol data unit (MPDU)	Wi-Fi
distribution system (DS)	MAC service data unit (MSDU)	Wi-Fi Protected Access (WPA)
extended service set (ESS)	message integrity code (MIC)	Wired Equivalent Privacy (WEP)
group keys	Michael	Wireless LAN (WLAN)
IEEE 802.1X	pairwise keys	
IEEE 802.11		
IEEE 802.11i		

Review Questions

18.1 What is the basic building block of an 802.11 WLAN?
18.2 List and briefly define threats to a wireless network.
18.3 List and briefly define IEEE 802.11 services.
18.4 List some security threats related to mobile devices.
18.5 How is the concept of an association related to that of mobility?
18.6 What security areas are addressed by IEEE 802.11i?
18.7 Briefly describe the five IEEE 802.11i phases of operation.
18.8 What is the difference between TKIP and CCMP?

Problems

18.1 In IEEE 802.11, open system authentication simply consists of two communications. An authentication is requested by the client, which contains the station ID (typically the MAC address). This is followed by an authentication response from the AP/router containing a success or failure message. An example of when a failure may occur is if the client's MAC address is explicitly excluded in the AP/router configuration.
- **a.** What are the benefits of this authentication scheme?
- **b.** What are the security vulnerabilities of this authentication scheme?

18.2 Prior to the introduction of IEEE 802.11i, the security scheme for IEEE 802.11 was Wired Equivalent Privacy (WEP). WEP assumed all devices in the network share a secret key. The purpose of the authentication scenario is for the STA to prove that it possesses the secret key. Authentication proceeds as shown in Figure 18.12. The STA sends a message to the AP requesting authentication. The AP issues a challenge, which is a sequence of 128 random bytes sent as plaintext. The STA encrypts the challenge with the shared key and returns it to the AP. The AP decrypts the incoming value and compares it to the challenge that it sent. If there is a match, the AP confirms that authentication has succeeded.
- **a.** What are the benefits of this authentication scheme?
- **b.** This authentication scheme is incomplete. What is missing and why is this important? *Hint:* The addition of one or two messages would fix the problem.
- **c.** What is a cryptographic weakness of this scheme?

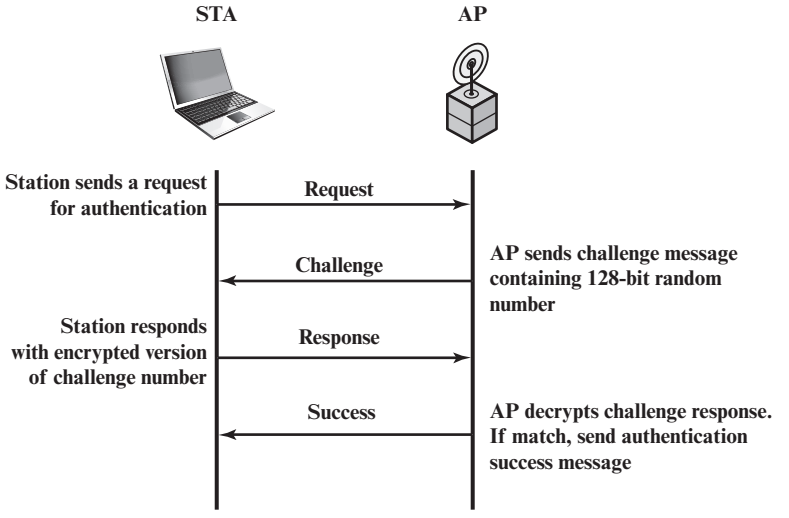


Figure 18.12 WEP Authentication; refer to Problem 18.2

18.3 For WEP, data integrity and data confidentiality are achieved using the RC4 stream encryption algorithm. The transmitter of an MPDU performs the following steps, referred to as encapsulation:

1. The transmitter selects an initial vector (IV) value.
2. The IV value is concatenated with the WEP key shared by transmitter and receiver to form the seed, or key input, to RC4.
3. A 32-bit cyclic redundancy check (CRC) is computed over all the bits of the MAC data field and appended to the data field. The CRC is a common error-detection code used in data link control protocols. In this case, the CRC serves as a integrity check value (ICV).
4. The result of step 3 is encrypted using RC4 to form the ciphertext block.
5. The plaintext IV is prepended to the ciphertext block to form the encapsulated MPDU for transmission.
   a. Draw a block diagram that illustrates the encapsulation process.
   b. Describe the steps at the receiver end to recover the plaintext and perform the integrity check.
   c. Draw a block diagram that illustrates part b.

18.4 A potential weakness of the CRC as an integrity check is that it is a linear function. This means that you can predict which bits of the CRC are changed if a single bit of the message is changed. Furthermore, it is possible to determine which combination of bits could be flipped in the message so that the net result is no change in the CRC. Thus, there are a number of combinations of bit flippings of the plaintext message that leave the CRC unchanged, so message integrity is defeated. However, in WEP, if an attacker does not know the encryption key, the attacker does not have access to the plaintext, only to the ciphertext block. Does this mean that the ICV is protected from the bit flipping attack? Explain.

CHAPTER 19

Electronic Mail Security

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Summarize the key functional components of the Internet mail architecture.
- Explain the basic functionality of SMTP, POP3, and IMAP.
- Explain the need for MIME as an enhancement to ordinary email.
- Describe the key elements of MIME.
- Understand the functionality of S/MIME and the security threats it addresses.
- Understand the basic mechanisms of STARTTLS and its role in email security.
- Understand the basic mechanisms of DANE and its role in email security.
- Understand the basic mechanisms of SPF and its role in email security.
- Understand the basic mechanisms of DKIM and its role in email security.
- Understand the basic mechanisms of DMARC and its role in email security.

In virtually all distributed environments, electronic mail is the most heavily used network-based application. Users expect to be able to, and do, send email to others who are connected directly or indirectly to the Internet, regardless of host operating system or communications suite. With the explosively growing reliance on email, there grows a demand for authentication and confidentiality services. Two schemes stand out as approaches that enjoy widespread use: Pretty Good Privacy (PGP) and S/MIME. Both are examined in this chapter. This chapter concludes with a discussion of DomainKeys Identified Mail.

19.1 INTERNET MAIL ARCHITECTURE

For an understanding of the topics in this chapter, it is useful to have a basic grasp of the Internet mail architecture, which is currently defined in RFC 5598 (*Internet Mail Architecture*, July 2009). This section provides an overview of the basic concepts.

Email Components

At its most fundamental level, the Internet mail architecture consists of a user world in the form of Message User Agents (MUA), and the transfer world, in the form of the **Message Handling Service (MHS)**, which is composed of Message Transfer Agents (MTA). The MHS accepts a message from one user and delivers it to one or more other users, creating a virtual MUA-to-MUA exchange environment. This architecture involves three types of interoperability. One is directly between users: messages must be formatted by the MUA on behalf of the message author so that the message can be displayed to the message recipient by the destination MUA. There are also interoperability requirements between the MUA and the MHS—first when a message is posted from an MUA to the MHS and later when it is delivered from the MHS to the destination MUA. Interoperability is required among the MTA components along the transfer path through the MHS.

Figure 19.1 illustrates the key components of the Internet mail architecture, which include the following.

- **Message User Agent (MUA):** Operates on behalf of user actors and user applications. It is their representative within the email service. Typically, this function is housed in the user's computer and is referred to as a client email

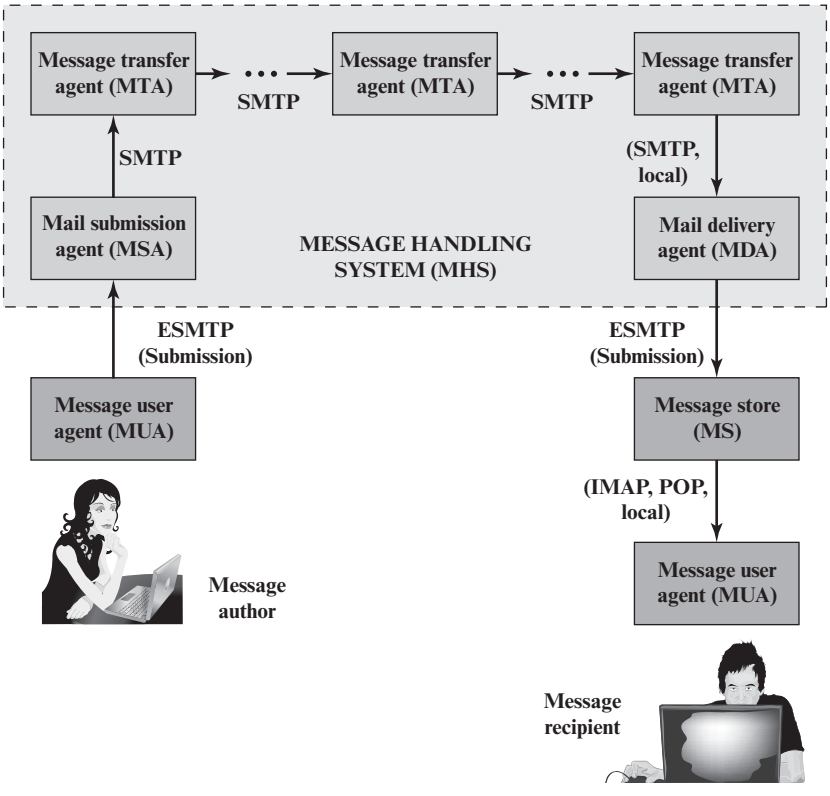


Figure 19.1 Function Modules and Standardized Protocols Used between them in the Internet Mail Architecture

program or a local network email server. The author MUA formats a message and performs initial submission into the MHS via a MSA. The recipient MUA processes received mail for storage and/or display to the recipient user.

- **Mail Submission Agent (MSA):** Accepts the message submitted by an MUA and enforces the policies of the hosting domain and the requirements of Internet standards. This function may be located together with the MUA or as a separate functional model. In the latter case, the Simple Mail Transfer Protocol (SMTP) is used between the MUA and the MSA.
- **Message Transfer Agent (MTA):** Relays mail for one application-level hop. It is like a packet switch or IP router in that its job is to make routing assessments and to move the message closer to the recipients. Relaying is performed by a sequence of MTAs until the message reaches a destination MDA. An MTA also adds trace information to the message header. SMTP is used between MTAs and between an MTA and an MSA or MDA.
- **Mail Delivery Agent (MDA):** Responsible for transferring the message from the MHS to the MS.
- **Message Store (MS):** An MUA can employ a long-term MS. An MS can be located on a remote server or on the same machine as the MUA. Typically, an MUA retrieves messages from a remote server using POP (Post Office Protocol) or IMAP (Internet Message Access Protocol).

Two other concepts need to be defined. An **administrative management domain (ADMD)** is an Internet email provider. Examples include a department that operates a local mail relay (MTA), an IT department that operates an enterprise mail relay, and an ISP that operates a public shared email service. Each ADMD can have different operating policies and trust-based decision making. One obvious example is the distinction between mail that is exchanged within an organization and mail that is exchanged between independent organizations. The rules for handling the two types of traffic tend to be quite different.

The **Domain Name System (DNS)** is a directory lookup service that provides a mapping between the name of a host on the Internet and its numerical address. DNS is discussed subsequently in this chapter.

Email Protocols

Two types of protocols are used for transferring email. The first type is used to move messages through the Internet from source to destination. The protocol used for this purpose is SMTP, with various extensions and in some cases restrictions. The second type consists of protocols used to transfer messages between mail servers, of which IMAP and POP are the most commonly used.

Simple Mail Transfer Protocol SMTP encapsulates an email message in an envelope and is used to relay the encapsulated messages from source to destination through multiple MTAs. SMTP was originally specified in 1982 as RFC 821 and has undergone several revisions, the most current being RFC 5321 (October 2008). These revisions have added additional commands and introduced extensions. The term Extended SMTP (ESMTP) is often used to refer to these later versions of SMTP.

SMTP is a text-based client-server protocol where the client (email sender) contacts the server (next-hop recipient) and issues a set of commands to tell the server about the message to be sent, then sending the message itself. The majority of these commands are ASCII text messages sent by the client and a resulting return code (and additional ASCII text) returned by the server.

The transfer of a message from a source to its ultimate destination can occur over a single SMTP client/server conversation over a single TCP connection. Alternatively, an SMTP server may be an intermediate relay that assumes the role of an SMTP client after receiving a message and then forwards that message to an SMTP server along a route to the ultimate destination.

The operation of SMTP consists of a series of commands and responses exchanged between the SMTP sender and receiver. The initiative is with the SMTP sender, who establishes the TCP connection. Once the connection is established, the SMTP sender sends commands over the connection to the receiver. Each command consists of a single line of text, beginning with a four-letter command code followed in some cases by an argument field. Each command generates exactly one reply from the SMTP receiver. Most replies are a single-line, although multiple-line replies are possible. Each reply begins with a three-digit code and may be followed by additional information.

Figure 19.2 illustrates the SMTP exchange between a client (C) and server (S). The interchange begins with the client establishing a TCP connection to TCP port 25 on the server (not shown in figure). This causes the server to activate SMTP

```
S: 220 foo.com Simple Mail Transfer Service Ready
C: HELO bar.com
S: 250 OK
C: MAIL FROM:<Smith@bar.com>
S: 250 OK
C: RCPT TO:<Jones@foo.com>
S: 250 OK
C: RCPT TO:<Green@foo.com>
S: 550 No such user here
C: RCPT TO:<Brown@foo.com>
S: 250 OK
C: DATA
S: 354 Start mail input; end with <crlf>.<crlf>
C: Blah blah blah . . .
C: . . . etc. etc. etc.
C: <crlf><crlf>
S: 250 OK
C: QUIT
S: 221 foo.com Service closing transmission channel
```

Figure 19.2 Example SMTP Transaction Scenario

and send a 220 reply to the client. The HELO command identifies the sending domain, which the server acknowledges and accepts with a 250 reply. The SMTP sender is transmitting mail that originates with the user Smith@bar.com. The MAIL command identifies the originator of the message. The message is addressed to three users on machine foo.com, namely, Jones, Green, and Brown. The client identifies each of these in a separate RCPT command. The SMTP receiver indicates that it has mailboxes for Jones and Brown but does not have information on Green. Because at least one of the intended recipients has been verified, the client proceeds to send the text message, by first sending a DATA command to ensure the server is ready for the data. After the server acknowledges receipt of all the data, it issues a 250 OK message. Then the client issues a QUIT command and the server closes the connection.

A significant security-related extension for SMTP, called STARTTLS, is defined in RFC 3207 (*SMTP Service Extension for Secure SMTP over Transport Layer Security*, February 2002). STARTTLS enables the addition of confidentiality and authentication in the exchange between SMTP agents. This gives SMTP agents the ability to protect some or all of their communications from eavesdroppers and attackers. If the client does initiate the connection over a TLS-enabled port (e.g., port 465 was previously used for SMTP over SSL), the server may prompt with a message indicating that the STARTTLS option is available. The client can then issue the STARTTLS command in the SMTP command stream, and the two parties proceed to establish a secure TLS connection. An advantage of using STARTTLS is that the server can offer SMTP service on a single port, rather than requiring separate port numbers for secure and cleartext operations. Similar mechanisms are available for running TLS over IMAP and POP protocols.

Historically, MUA/MSA message transfers have used SMTP. The standard currently preferred is SUBMISSION, defined in RFC 6409 (*Message Submission for Mail*, November 2011). Although SUBMISSION derives from SMTP, it uses a separate TCP port and imposes distinct requirements, such as access authorization.

Mail Access Protocols (POP3, IMAP) Post Office Protocol (POP3) allows an email client (user agent) to download an email from an email server (MTA). POP3 user agents connect via TCP to the server (typically port 110). The user agent enters a username and password (either stored internally for convenience or entered each time by the user for stronger security). After authorization, the UA can issue POP3 commands to retrieve and delete mail.

As with POP3, Internet Mail Access Protocol (IMAP) also enables an email client to access mail on an email server. IMAP also uses TCP, with server TCP port 143. IMAP is more complex than POP3. IMAP provides stronger authentication than POP3 and provides other functions not supported by POP3.

19.2 EMAIL FORMATS

To understand S/MIME, we need first to have a general understanding of the underlying email format that it uses, namely, MIME. But to understand the significance of MIME, we need to go back to the traditional email format standard,

RFC 822, which is still in common use. The most recent version of this format specification is RFC 5322 (*Internet Message Format*, October 2008). Accordingly, this section first provides an introduction to these two earlier standards and then moves on to a discussion of S/MIME.

RFC 5322

RFC 5322 defines a format for text messages that are sent using electronic mail. It has been the standard for Internet-based text mail messages and remains in common use. In the RFC 5322 context, messages are viewed as having an envelope and contents. The envelope contains whatever information is needed to accomplish transmission and delivery. The contents compose the object to be delivered to the recipient. The RFC 5322 standard applies only to the contents. However, the content standard includes a set of header fields that may be used by the mail system to create the envelope, and the standard is intended to facilitate the acquisition of such information by programs.

The overall structure of a message that conforms to RFC 5322 is very simple. A message consists of some number of header lines (*the header*) followed by unrestricted text (*the body*). The header is separated from the body by a blank line. Put differently, a message is ASCII text, and all lines up to the first blank line are assumed to be header lines used by the user agent part of the mail system.

A header line usually consists of a keyword, followed by a colon, followed by the keyword's arguments; the format allows a long line to be broken up into several lines. The most frequently used keywords are *From*, *To*, *Subject*, and *Date*. Here is an example message:

```
Date: October 8, 2009 2:15:49 PM EDT
From: "William Stallings" <ws@shore.net>
Subject: The Syntax in RFC 5322
To: Smith@Other-host.com
Cc: Jones@Yet-Another-Host.com

Hello. This section begins the actual
message body, which is delimited from the
message heading by a blank line.
```

Another field that is commonly found in RFC 5322 headers is *Message-ID*. This field contains a unique identifier associated with this message.

Multipurpose Internet Mail Extensions

Multipurpose Internet Mail Extension (MIME) is an extension to the RFC 5322 framework that is intended to address some of the problems and limitations of the use of Simple Mail Transfer Protocol (SMTP) or some other mail transfer protocol and RFC 5322 for electronic mail. RFCs 2045 through 2049 define MIME, and there have been a number of updating documents since then.

As justification for the use of MIME, [PARZ06] lists the following limitations of the SMTP/5322 scheme.

1. SMTP cannot transmit executable files or other binary objects. A number of schemes are in use for converting binary files into a text form that can be used by SMTP mail systems, including the popular UNIX UUencode/UUdecode scheme. However, none of these is a standard or even a *de facto* standard.
2. SMTP cannot transmit text data that includes national language characters, because these are represented by 8-bit codes with values of 128 decimal or higher, and SMTP is limited to 7-bit ASCII.
3. SMTP servers may reject mail message over a certain size.
4. SMTP gateways that translate between ASCII and the character code EBCDIC do not use a consistent set of mappings, resulting in translation problems.
5. SMTP gateways to X.400 electronic mail networks cannot handle nontextual data included in X.400 messages.
6. Some SMTP implementations do not adhere completely to the SMTP standards defined in RFC 821. Common problems include:
   - —Deletion, addition, or reordering of carriage return and linefeed
   - —Truncating or wrapping lines longer than 76 characters
   - —Removal of trailing white space (tab and space characters)
   - —Padding of lines in a message to the same length
   - —Conversion of tab characters into multiple space characters

MIME is intended to resolve these problems in a manner that is compatible with existing RFC 5322 implementations.

Overview The MIME specification includes the following elements.

1. Five new message header fields are defined, which may be included in an RFC 5322 header. These fields provide information about the body of the message.
2. A number of content formats are defined, thus standardizing representations that support multimedia electronic mail.
3. Transfer encodings are defined that enable the conversion of any content format into a form that is protected from alteration by the mail system.

In this subsection, we introduce the five message header fields. The next two subsections deal with content formats and transfer encodings.

The five header fields defined in MIME are as follows:

- **MIME-Version:** Must have the parameter value 1.0. This field indicates that the message conforms to RFCs 2045 and 2046.
- **Content-Type:** Describes the data contained in the body with sufficient detail that the receiving user agent can pick an appropriate agent or mechanism to represent the data to the user or otherwise deal with the data in an appropriate manner.

- **Content-Transfer-Encoding:** Indicates the type of transformation that has been used to represent the body of the message in a way that is acceptable for mail transport.
- **Content-ID:** Used to identify MIME entities uniquely in multiple contexts.
- **Content-Description:** A text description of the object with the body; this is useful when the object is not readable (e.g., audio data).

Any or all of these fields may appear in a normal RFC 5322 header. A compliant implementation must support the MIME-Version, Content-Type, and Content-Transfer-Encoding fields; the Content-ID and Content-Description fields are optional and may be ignored by the recipient implementation.

MIME Content Types The bulk of the MIME specification is concerned with the definition of a variety of content types. This reflects the need to provide standardized ways of dealing with a wide variety of information representations in a multimedia environment.

Table 19.1 lists the content types specified in RFC 2046. There are seven different major types of content and a total of 15 subtypes. In general, a content type declares the general type of data, and the subtype specifies a particular format for that type of data.

Table 19.1 MIME Content Types

Type	Subtype	Description
Text	Plain	Unformatted text; may be ASCII or ISO 8859.
	Enriched	Provides greater format flexibility.
Multipart	Mixed	The different parts are independent but are to be transmitted together. They should be presented to the receiver in the order that they appear in the mail message.
	Parallel	Differs from Mixed only in that no order is defined for delivering the parts to the receiver.
	Alternative	The different parts are alternative versions of the same information. They are ordered in increasing faithfulness to the original, and the recipient's mail system should display the "best" version to the user.
	Digest	Similar to Mixed, but the default type/subtype of each part is message/rfc822.
Message	rfc822	The body is itself an encapsulated message that conforms to RFC 822.
	Partial	Used to allow fragmentation of large mail items, in a way that is transparent to the recipient.
	External-body	Contains a pointer to an object that exists elsewhere.
Image	jpeg	The image is in JPEG format, JFIF encoding.
	gif	The image is in GIF format.
Video	mpeg	MPEG format.
Audio	Basic	Single-channel 8-bit ISDN μ-law encoding at a sample rate of 8 kHz.
Application	PostScript	Adobe Postscript format.
	octet-stream	General binary data consisting of 8-bit bytes.

For the **text type** of body, no special software is required to get the full meaning of the text aside from support of the indicated character set. The primary subtype is *plain text*, which is simply a string of ASCII characters or ISO 8859 characters. The *enriched* subtype allows greater formatting flexibility.

The **multipart type** indicates that the body contains multiple, independent parts. The Content-Type header field includes a parameter (called boundary) that defines the delimiter between body parts. This boundary should not appear in any parts of the message. Each boundary starts on a new line and consists of two hyphens followed by the boundary value. The final boundary, which indicates the end of the last part, also has a suffix of two hyphens. Within each part, there may be an optional ordinary MIME header.

Here is a simple example of a multipart message containing two parts—both consisting of simple text (taken from RFC 2046):

```
From: Nathaniel Borenstein <nsb@bellcore.com>
To: Ned Freed <ned@innosoft.com>
Subject: Sample message
MIME-Version: 1.0
Content-type: multipart/mixed; boundary="simple boundary"

This is the preamble. It is to be ignored, though it is a
handy place for mail composers to include an explanatory
note to non-MIME conformant readers.
—simple boundary

This is implicitly typed plain ASCII text. It does NOT end
with a linebreak.
—simple boundary
Content-type: text/plain; charset=us-ascii

This is explicitly typed plain ASCII text. It DOES end
with a linebreak.

—simple boundary—
This is the epilogue. It is also to be ignored.
```

There are four subtypes of the multipart type, all of which have the same overall syntax. The **multipart/mixed subtype** is used when there are multiple independent body parts that need to be bundled in a particular order. For the **multipart/parallel subtype**, the order of the parts is not significant. If the recipient's system is appropriate, the multiple parts can be presented in parallel. For example, a picture or text part could be accompanied by a voice commentary that is played while the picture or text is displayed.

For the **multipart/alternative subtype**, the various parts are different representations of the same information. The following is an example:

```
From: Nathaniel Borenstein <nsb@bellcore.com>
To: Ned Freed <ned@innosoft.com>
Subject: Formatted text mail
```

```
MIME-Version: 1.0
Content-Type: multipart/alternative;
boundary=boundary42

—boundary42

Content-Type: text/plain; charset=us-ascii

   . . . plain text version of message goes here. . . .

—boundary42
Content-Type: text/enriched

   . . . RFC 1896 text/enriched version of same message
goes here . . .

—boundary42—
```

In this subtype, the body parts are ordered in terms of increasing preference. For this example, if the recipient system is capable of displaying the message in the text/enriched format, this is done; otherwise, the plain text format is used.

The **multipart/digest subtype** is used when each of the body parts is interpreted as an RFC 5322 message with headers. This subtype enables the construction of a message whose parts are individual messages. For example, the moderator of a group might collect email messages from participants, bundle these messages, and send them out in one encapsulating MIME message.

The **message type** provides a number of important capabilities in MIME. The **message/rfc822 subtype** indicates that the body is an entire message, including header and body. Despite the name of this subtype, the encapsulated message may be not only a simple RFC 5322 message, but also any MIME message.

The **message/partial subtype** enables fragmentation of a large message into a number of parts, which must be reassembled at the destination. For this subtype, three parameters are specified in the Content-Type: Message/Partial field: an *id* common to all fragments of the same message, a *sequence number* unique to each fragment, and the *total* number of fragments.

The **message/external-body subtype** indicates that the actual data to be conveyed in this message are not contained in the body. Instead, the body contains the information needed to access the data. As with the other message types, the message/external-body subtype has an outer header and an encapsulated message with its own header. The only necessary field in the outer header is the Content-Type field, which identifies this as a message/external-body subtype. The inner header is the message header for the encapsulated message. The Content-Type field in the outer header must include an access-type parameter, which indicates the method of access, such as FTP (file transfer protocol).

The **application type** refers to other kinds of data, typically either uninterpreted binary data or information to be processed by a mail-based application.

MIME Transfer Encodings The other major component of the MIME specification, in addition to content type specification, is a definition of transfer encodings for message bodies. The objective is to provide reliable delivery across the largest range of environments.

The MIME standard defines two methods of encoding data. The Content-Transfer-Encoding field can actually take on six values, as listed in Table 19.2. However, three of these values (7-bit, 8-bit, and binary) indicate that no encoding has been done but provide some information about the nature of the data. For SMTP transfer, it is safe to use the 7-bit form. The 8-bit and binary forms may be usable in other mail transport contexts. Another Content-Transfer-Encoding value is x-token, which indicates that some other encoding scheme is used for which a name is to be supplied. This could be a vendor-specific or application-specific scheme. The two actual encoding schemes defined are quoted-printable and base64. Two schemes are defined to provide a choice between a transfer technique that is essentially human readable and one that is safe for all types of data in a way that is reasonably compact.

The **quoted-printable** transfer encoding is useful when the data consists largely of octets that correspond to printable ASCII characters. In essence, it represents nonsafe characters by the hexadecimal representation of their code and introduces reversible (soft) line breaks to limit message lines to 76 characters.

The **base64 transfer encoding**, also known as radix-64 encoding, is a common one for encoding arbitrary binary data in such a way as to be invulnerable to the processing by mail-transport programs. It is also used in PGP and is described in Appendix X.

A Multipart Example Figure 19.3, taken from RFC 2045, is the outline of a complex multipart message. The message has five parts to be displayed serially: two introductory plain text parts, an embedded multipart message, a richtext part, and a closing encapsulated text message in a non-ASCII character set. The embedded multipart message has two parts to be displayed in parallel: a picture and an audio fragment.

Canonical Form An important concept in MIME and S/MIME is that of canonical form. Canonical form is a format, appropriate to the content type, that is standardized for use between systems. This is in contrast to native form, which is a format that may be peculiar to a particular system. RFC 2049 defines these two forms as follows:

- **Native form:** The body to be transmitted is created in the system's native format. The native character set is used and, where appropriate, local end-of-line conventions are used as well. The body may be any format that corresponds to

Table 19.2 MIME Transfer Encodings

7 bit	The data are all represented by short lines of ASCII characters.
8 bit	The lines are short, but there may be non-ASCII characters (octets with the high-order bit set).
binary	Not only may non-ASCII characters be present but the lines are not necessarily short enough for SMTP transport.
quoted-printable	Encodes the data in such a way that if the data being encoded are mostly ASCII text, the encoded form of the data remains largely recognizable by humans.
base64	Encodes data by mapping 6-bit blocks of input to 8-bit blocks of output, all of which are printable ASCII characters.
x-token	A named nonstandard encoding.

```
MIME-Version: 1.0
     From: Nathaniel Borenstein <nsb@bellcore.com>
     To: Ned Freed <ned@innosoft.com>
     Subject: A multipart example
     Content-Type: multipart/mixed;
       boundary=unique-boundary-1
     This is the preamble area of a multipart message. Mail readers that
     understand multipart format should ignore this preamble. If you are reading
     this text, you might want to consider changing to a mail reader that
     understands how to properly display multipart messages.

     —unique-boundary-1
      . . . Some text appears here . . .
     [Note that the preceding blank line means no header fields were given and
     this is text, with charset US ASCII. It could have been done with explicit
     typing as in the next part.]

     —unique-boundary-1
     Content-type: text/plain; charset=US-ASCII
     This could have been part of the previous part, but illustrates explicit
     versus implicit typing of body parts.

     —unique-boundary-1
     Content-Type: multipart/parallel; boundary=unique-boundary-2

     —unique-boundary-2
     Content-Type: audio/basic
     Content-Transfer-Encoding: base64
      . . . base64-encoded 8000 Hz single-channel mu-law-format audio data goes
     here . . . .

     —unique-boundary-2
     Content-Type: image/jpeg
     Content-Transfer-Encoding: base64
      . . . base64-encoded image data goes here . . . .

     —unique-boundary-2—
     —unique-boundary-1
     Content-type: text/enriched

     This is richtext. as defined in RFC 1896

       Isn't it cool?

     —unique-boundary-1
     Content-Type: message/rfc822

     From: (mailbox in US-ASCII)
     To: (address in US-ASCII)
     Subject: (subject in US-ASCII)
     Content-Type: Text/plain; charset=ISO-8859-1
     Content-Transfer-Encoding: Quoted-printable

      . . . Additional text in ISO-8859-1 goes here . . .

     —unique-boundary-1—
```

Figure 19.3 Example MIME Message Structure

the local model for the representation of some form of information. Examples include a UNIX-style text file, or a Sun raster image, or a VMS indexed file, and audio data in a system-dependent format stored only in memory. In essence, the data are created in the native form that corresponds to the type specified by the media type.

- **Canonical form:** The entire body, including out-of-band information such as record lengths and possibly file attribute information, is converted to a universal canonical form. The specific media type of the body as well as its associated attributes dictates the nature of the canonical form that is used. Conversion to the proper canonical form may involve character set conversion, transformation of audio data, compression, or various other operations specific to the various media types.

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:

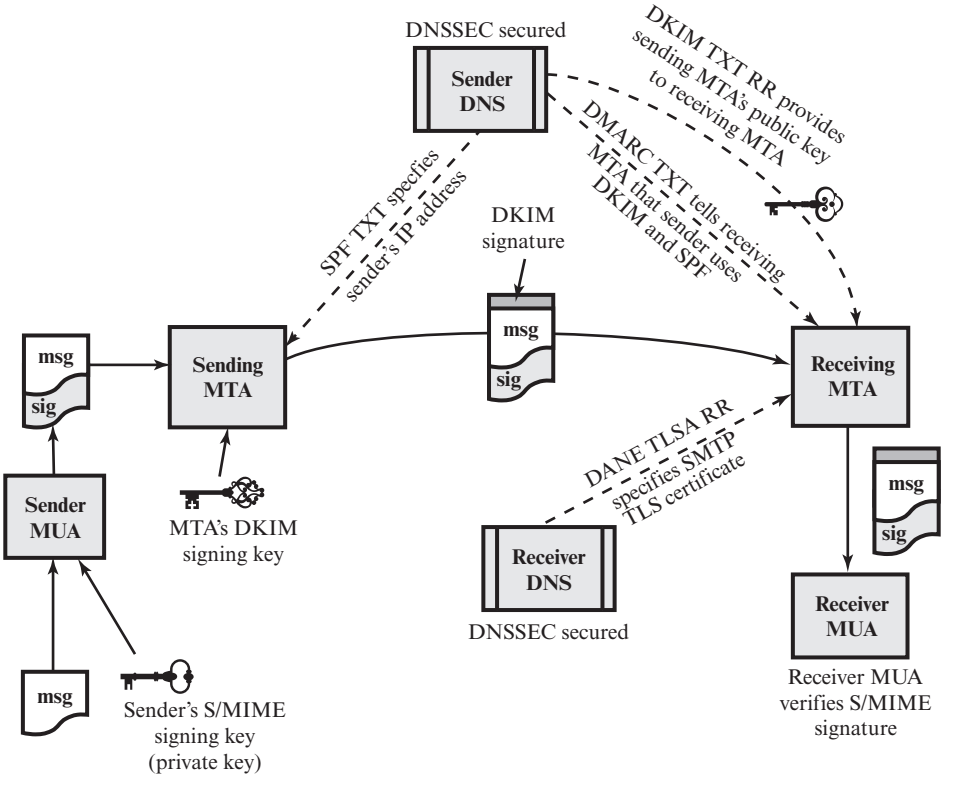
- **STARTTLS:** An SMTP security extension that provides authentication, integrity, non-repudiation (via digital signatures) and confidentiality (via encryption) for the entire SMTP message by running SMTP over TLS.
- **S/MIME:** Provides authentication, integrity, non-repudiation (via digital signatures) 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.

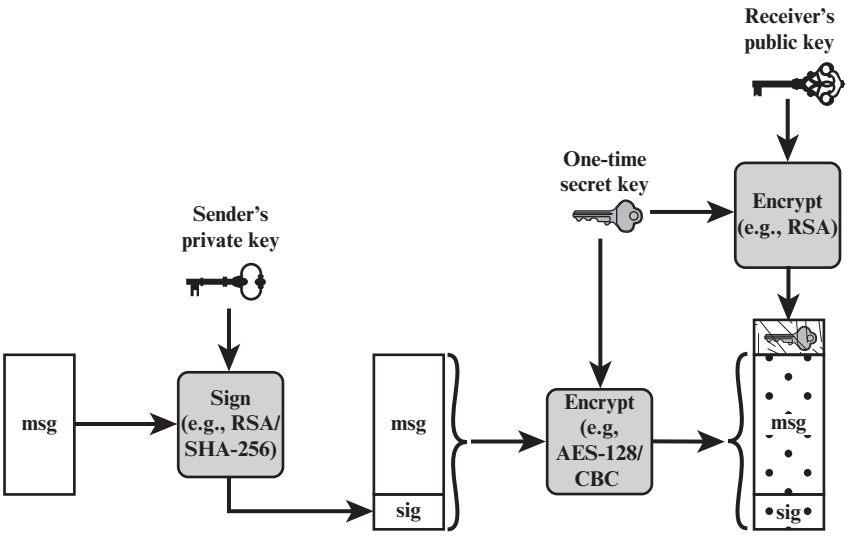
S/MIME allows the signing and message encryption operations to be performed in either order. If signing is done first, the identity of the signer is hidden by the encryption. Plus, it is generally more convenient to store a signature with a plaintext version of a message. Furthermore, for purposes of 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.

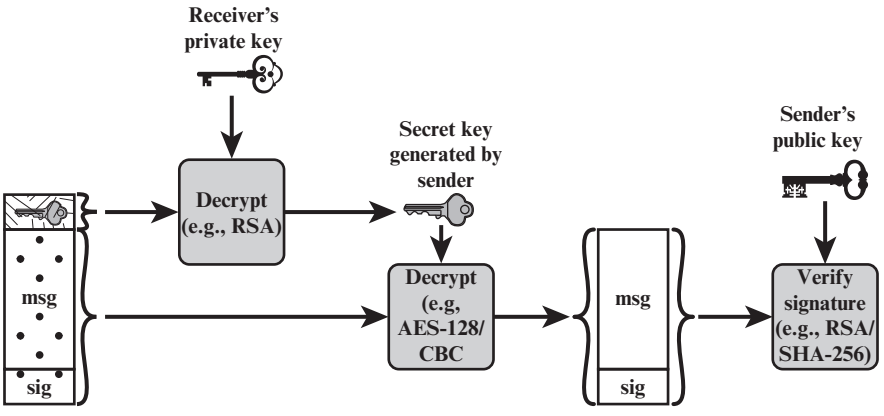
Email Compatibility When S/MIME is used, at least part of the block to be transmitted is encrypted. If only the signature service is used, then the message digest is encrypted (with the sender's private key). If the confidentiality service is used, the message plus signature (if present) are encrypted (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.



(a) Sender signs, then encrypts message



(b) Receiver decrypts message, then verifies sender's signature

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.

19.6 DNSSEC

DNS Security Extensions (DNSSEC) are used by several protocols that provide email security. This section provides a brief overview of the Domain Name System (DNS) and then looks at DNSSEC.

Domain Name System

DNS is a directory lookup service that provides a mapping between the name of a host on the Internet and its numeric IP address. DNS is essential to the functioning of the Internet. The DNS is used by MUAs and MTAs to find the address of the next hop server for mail delivery. Sending MTAs query DNS for the Mail Exchange Resource Record (MX RR) of the recipient's domain (the right hand side of the "@" symbol) in order to find the receiving MTA to contact.

Four elements comprise the DNS:

- **Domain name space:** DNS uses a tree-structured name space to identify resources on the Internet.
- **DNS database:** Conceptually, each node and leaf in the name space tree structure names a set of information (e.g., IP address, name server for this domain name) that is contained in resource record. The collection of all RRs is organized into a distributed database.
- **Name servers:** These are server programs that hold information about a portion of the domain name tree structure and the associated RRs.
- **Resolvers:** These are programs that extract information from name servers in response to client requests. A typical client request is for an IP address corresponding to a given domain name.

The DNS Database DNS is based on a hierarchical database containing **resource records (RRs)** that include the name, IP address, and other information about hosts. The key features of the database are as follows:

- **Variable-depth hierarchy for names:** DNS allows essentially unlimited levels and uses the period (.) as the level delimiter in printed names, as described earlier.

Table 19.6 Resource Record Types

Type	Description
A	A host address. This RR type maps the name of a system to its IPv4 address. Some systems (e.g., routers) have multiple addresses, and there is a separate RR for each.
AAAA	Similar to A type, but for IPv6 addresses.
CNAME	Canonical name. Specifies an alias name for a host and maps this to the canonical (true) name.
HINFO	Host information. Designates the processor and operating system used by the host.
MINFO	Mailbox or mail list information. Maps a mailbox or mail list name to a host name.
MX	Mail exchange. Identifies the system(s) via which mail to the queried domain name should be relayed.
NS	Authoritative name server for this domain.
PTR	Domain name pointer. Points to another part of the domain name space.
SOA	Start of a zone of authority (which part of naming hierarchy is implemented). Includes parameters related to this zone.
SRV	For a given service provides name of server or servers in domain that provide that service.
TXT	Arbitrary text. Provides a way to add text comments to the database.
WKS	Well-known services. May list the application services available at this host.

- **Distributed database:** The database resides in DNS servers scattered throughout the Internet.
- **Distribution controlled by the database:** The DNS database is divided into thousands of separately managed zones, which are managed by separate administrators. Distribution and update of records is controlled by the database software.

Using this database, DNS servers provide a name-to-address directory service for network applications that need to locate specific servers. For example, every time an email message is sent or a Web page is accessed, there must be a DNS name lookup to determine the IP address of the email server or Web server.

Table 19.6 lists the various types of resource records.

DNS Operation DNS operation typically includes the following steps (Figure 19.6):

1. A user program requests an IP address for a domain name.
2. A resolver module in the local host or local ISP queries a local name server in the same domain as the resolver.
3. The local name server checks to see if the name is in its local database or cache, and, if so, returns the IP address to the requestor. Otherwise, the name server queries other available name servers, if necessary going to the root server, as explained subsequently.
4. When a response is received at the local name server, it stores the name/address mapping in its local cache and may maintain this entry for the amount of time specified in the time-to-live field of the retrieved RR.
5. The user program is given the IP address or an error message.

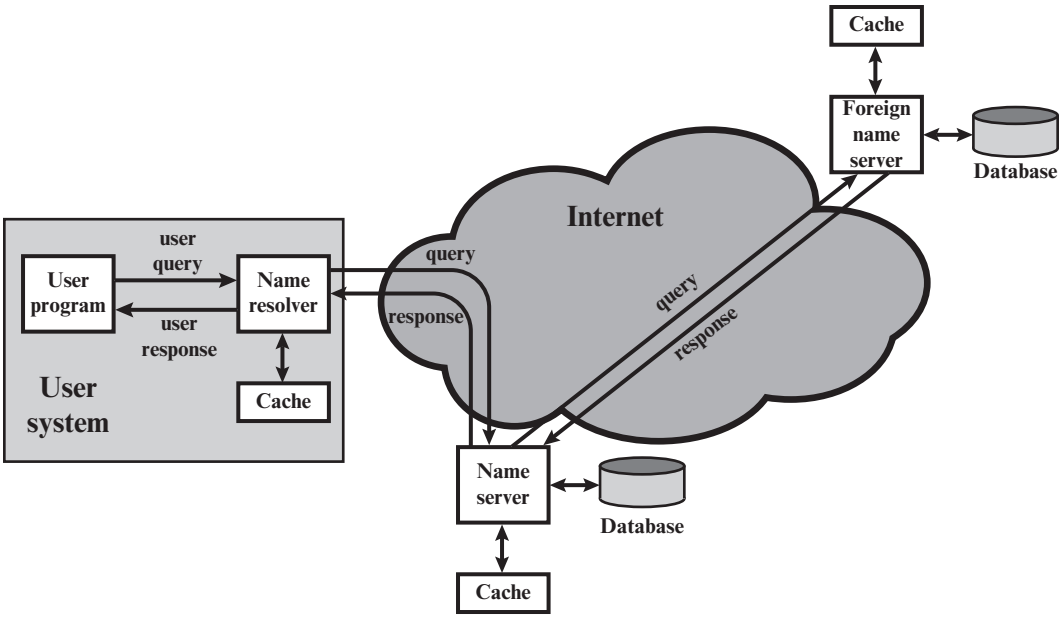


Figure 19.6 DNS Name Resolution

The distributed DNS database that supports the DNS functionality must be updated frequently because of the rapid and continued growth of the Internet. Further, the DNS must cope with dynamic assignment of IP addresses, such as is done for home DSL users by their ISP. Accordingly, dynamic updating functions for DNS have been defined. In essence, DNS name servers automatically send out updates to other relevant name servers as conditions warrant.

DNS Security Extensions

DNSSEC provides end-to-end protection through the use of digital signatures that are created by responding zone administrators and verified by a recipient's resolver software. In particular, DNSSEC avoids the need to trust intermediate name servers and resolvers that cache or route the DNS records originating from the responding zone administrator before they reach the source of the query. DNSSEC consists of a set of new resource record types and modifications to the existing DNS protocol, and is defined in the following documents:

- **RFC 4033, DNS Security Introduction and Requirements:** Introduces the DNS security extensions and describes their capabilities and limitations. The document also discusses the services that the DNS security extensions do and do not provide.
- **RFC 4034, Resource Records for the DNS Security Extensions:** Defines four new resource records that provide security for DNS.

- **RFC 4035, Protocol Modifications for the DNS Security Extensions:** Defines the concept of a signed zone, along with the requirements for serving and resolving by using DNSSEC. These techniques allow a security-aware resolver to authenticate both DNS resource records and authoritative DNS error indications.

DNSSEC Operation In essence, DNSSEC is designed to protect DNS clients from accepting forged or altered DNS resource records. It does this by using digital signatures to provide:

- **Data origin authentication:** Ensures that data has originated from the correct source.
- **Data integrity verification:** Ensures that the content of a RR has not been modified.

The DNS zone administrator digitally signs every Resource Record set (RRset) in the zone, and publishes this collection of digital signatures, along with the zone administrator's public key, in the DNS itself. In DNSSEC, trust in the public key (for signature verification) of the source is established not by going to a third party or a chain of third parties (as in public key infrastructure [PKI] chaining), but by starting from a trusted zone (such as the root zone) and establishing the chain of trust down to the current source of response through successive verifications of signature of the public key of a child by its parent. The public key of the trusted zone is called the *trust anchor*.

Resource Records for DNSSEC RFC 4034 defines four new DNS resource records:

- **DNSKEY:** Contains a public key.
- **RRSIG:** A resource record digital signature.
- **NSEC:** Authenticated denial of existence record.
- **DS:** Delegation signer.

An RRSIG is associated with each RRset, where an RRset is the set of resource records that have the same label, class, and type. When a client requests data, an RRset is returned, together with the associated digital signature in an RRSIG record. The client obtains the relevant DNSKEY public key and verifies the signature for this RRset.

DNSSEC depends on establishing the authenticity of the DNS hierarchy leading to the domain name in question, and thus its operation depends on beginning the use of cryptographic digital signatures in the root zone. The DS resource record facilitates key signing and authentication between DNS zones to create an authentication chain, or trusted sequence of signed data, from the root of the DNS tree down to a specific domain name. To secure all DNS lookups, including those for non-existent domain names and record types, DNSSEC uses the NSEC resource record to authenticate negative responses to queries. NSEC is used to identify the

range of DNS names or resource record types that do not exist among the sequence of domain names in a zone.

19.7 DNS-BASED AUTHENTICATION OF NAMED ENTITIES

DANE is a protocol to allow X.509 certificates, commonly used for Transport Layer Security (TLS), to be bound to DNS names using DNSSEC. It is proposed in RFC 6698 as a way to authenticate TLS client and server entities without a certificate authority (CA).

The rationale for DANE is the vulnerability of the use of CAs in a global PKI system. Every browser developer and operating system supplier maintains a list of CA root certificates as trust anchors. These are called the software's root certificates and are stored in its root certificate store. The PKIX procedure allows a certificate recipient to trace a certificate back to the root. So long as the root certificate remains trustworthy, and the authentication concludes successfully, the client can proceed with the connection.

However, if any of the hundreds of CAs operating on the Internet is compromised, the effects can be widespread. The attacker can obtain the CA's private key, get issued certificates under a false name, or introduce new bogus root certificates into a root certificate store. There is no limitation of scope for the global PKI and a compromise of a single CA damages the integrity of the entire PKI system. In addition, some CAs have engaged in poor security practices. For example, some CAs have issued wildcard certificates that allow the holder to issue sub-certificates for any domain or entity, anywhere in the world.

The purpose of DANE is to replace reliance on the security of the CA system with reliance on the security provided by DNSSEC. Given that the DNS administrator for a domain name is authorized to give identifying information about the zone, it makes sense to allow that administrator to also make an authoritative binding between the domain name and a certificate that might be used by a host at that domain name.

TLSA Record

DANE defines a new DNS record type, TLSA, that can be used for a secure method of authenticating SSL/TLS certificates. The TLSA provides for:

- Specifying constraints on which CA can vouch for a certificate, or which specific PKIX end-entity certificate is valid.
- Specifying that a service certificate or a CA can be directly authenticated in the DNS itself.

The TLSA RR enables certificate issue and delivery to be tied to a given domain. A server domain owner creates a TLSA resource record that identifies the certificate and its public key. When a client receives an X.509 certificate in the TLS negotiation, it looks up the TLSA RR for that domain and matches the TLSA data against the certificate as part of the client's certificate validation procedure.

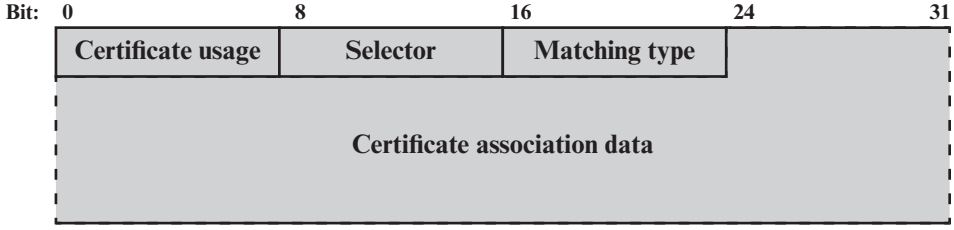


Figure 19.7 TLSA RR Transmission Format

Figure 19.7 shows the format of a TLSA RR as it is transmitted to a requesting entity. It contains four fields. The **Certificate Usage** field defines four different usage models, to accommodate users who require different forms of authentication. The usage models are:

- **PKIX-TA (CA constraint):** Specifies which CA should be trusted to authenticate the certificate for the service. This usage model limits which CA can be used to issue certificates for a given service on a host. The server certificate chain must pass PKIX validation that terminates with a trusted root certificate stored in the client.
- **PKIX-EE (service certificate constraint):** Defines which specific end entity service certificate should be trusted for the service. This usage model limits which end entity certificate can be used by a given service on a host. The server certificate chain must pass PKIX validation that terminates with a trusted root certificate stored in the client.
- **DANE-TA (trust anchor assertion):** Specifies a domain-operated CA to be used as a trust anchor. This usage model allows a domain name administrator to specify a new trust anchor—for example, if the domain issues its own certificates under its own CA that is not expected to be in the end users' collection of trust anchors. The server certificate chain is self-issued and does not need to verify against a trusted root stored in the client.
- **DANE-EE (domain-issued certificate):** Specifies a domain-operated CA to be used as a trust anchor. This certificate usage allows a domain name administrator to issue certificates for a domain without involving a third-party CA. The server certificate chain is self-issued and does not need to verify against a trusted root stored in the client.

The first two usage models are designed to co-exist with and strengthen the public CA system. The final two usage models operate without the use of public CAs.

The **Selector** field indicates whether the full certificate will be matched or just the value of the public key. The match is made between the certificate presented in TLS negotiation and the certificate in the TLSA RR. The **Matching Type** field indicates how the match of the certificate is made. The options are exact match, SHA-256 hash match, or SHA-512 hash match. The **Certificate Association Data** is the raw certificate data in hex format.

Use of DANE for SMTP

DANE can be used in conjunction with SMTP over TLS, as provided by STARTTLS, to more fully secure email delivery. DANE can authenticate the certificate of the SMTP submission server that the user's mail client (MUA) communicates with. It can also authenticate the TLS connections between SMTP servers (MTAs). The use of DANE with SMTP is documented in an Internet Draft (*SMTP Security via Opportunistic DANE TLS*, draft-ietf-dane-smtp-with-dane-19, May 29, 2015).

As discussed in Section 19.1, SMTP can use the STARTTLS extension to run SMTP over TLS, so that the entire email message plus SMTP envelope are encrypted. This is done opportunistically, that is, if both sides support STARTTLS. Even when TLS is used to provide confidentiality, it is vulnerable to attack in the following ways:

- Attackers can strip away the TLS capability advertisement and downgrade the connection to not use TLS.
- TLS connections are often unauthenticated (e.g., the use of self-signed certificates as well as mismatched certificates is common).

DANE can address both these vulnerabilities. A domain can use the presence of the TLSA RR as an indicator that encryption must be performed, thus preventing malicious downgrade. A domain can authenticate the certificate used in the TLS connection setup using a DNSSEC-signed TLSA RR.

Use of DNSSEC for S/MIME

DNSSEC can be used in conjunction with S/MIME to more fully secure email delivery, in a manner similar to the DANE functionality. This use is documented in an Internet Draft (*Using Secure DNS to Associate Certificates with Domain Names for S/MIME*, draft-ietf-dane-smime-09, August 27, 2015), which proposes a new SMIMEA DNS RR. The purpose of the SMIMEA RR is to associate certificates with DNS domain names.

As discussed in Section 19.4, S/MIME messages often contain certificates that can assist in authenticating the message sender and can be used in encrypting messages sent in reply. This feature requires that the receiving MUA validate the certificate associated with the purported sender. SMIMEA RRs can provide a secure means of doing this validation.

In essence, the SMIMEA RR will have the same format and content as the TLSA RR, with the same functionality. The difference is that it is geared to the needs of MUAs in dealing with domain names as specified in email addresses in the message body, rather than domain names specified in the outer SMTP envelope.

19.8 SENDER POLICY FRAMEWORK

SPF is the standardized way for a sending domain to identify and assert the mail senders for a given domain. The problem that SPF addresses is the following: With the current email infrastructure, any host can use any domain name for each of the

various identifiers in the mail header, not just the domain name where the host is located. Two major drawbacks of this freedom are:

- It is a major obstacle to reducing unsolicited bulk email (UBE), also known as spam. It makes it difficult for mail handlers to filter out emails on the basis of known UBE sources.
- ADMDs (see Section 19.1) are understandably concerned about the ease with which other entities can make use of their domain names, often with malicious intent.

RFC 7208 defines the SPF. It provides a protocol by which ADMDs can authorize hosts to use their domain names in the "MAIL FROM" or "HELO" identities. Compliant ADMDs publish Sender Policy Framework (SPF) records in the DNS specifying which hosts are permitted to use their names, and compliant mail receivers use the published SPF records to test the authorization of sending Mail Transfer Agents (MTAs) using a given "HELO" or "MAIL FROM" identity during a mail transaction.

SPF works by checking a sender's IP address against the policy encoded in any SPF record found at the sending domain. The sending domain is the domain used in the SMTP connection, not the domain indicated in the message header as displayed in the MUA. This means that SPF checks can be applied before the message content is received from the sender.

Figure 19.8 is an example in which SPF would come into play. Assume that the sender's IP address is 192.168.0.1. The message arrives from the MTA with domain mta.example.net. The sender uses the MAIL FROM tag of alice@example.org, indicating that the message originates in the example.org domain. But the message header specifies alice.sender@example.net. The receiver uses SPF to query for the SPF RR that corresponds to example.com to check if the IP address 192.168.0.1 is

```
S: 220 foo.com Simple Mail Transfer Service Ready
C: HELO mta.example.net
S: 250 OK
C: MAIL FROM:<alice@example.org>
S: 250 OK
C: RCPT TO:<Jones@foo.com>
S: 250 OK
C: DATA
S: 354 Start mail input; end with <crlf>.<crlf>
C: To: bob@foo.com
C: From: alice.sender@example.net
C: Date: Today
C: Subject: Meeting Today
 . . .
```

Figure 19.8 Example in which SMTP Envelope Header Does Not Match Message Header

listed as a valid sender, and then takes appropriate action based on the results of checking the RR.

SPF on the Sender Side

A sending domain needs to identify all the senders for a given domain and add that information into the DNS as a separate resource record. Next, the sending domain encodes the appropriate policy for each sender using the SPF syntax. The encoding is done in a TXT DNS resource record as a list of mechanisms and modifiers. Mechanisms are used to define an IP address or range of addresses to be matched, and modifiers indicate the policy for a given match. Table 19.7 lists the most important mechanisms and modifiers used in SPF.

The SPF syntax is fairly complex and can express complex relationships between senders. For more detail, see RFC 7208.

SPF on the Receiver Side

If SPF is implemented at a receiver, the SPF entity uses the SMTP envelope MAIL FROM: address domain and the IP address of the sender to query an SPF TXT RR. The SPF checks can be started before the body of the email message is received,

Table 19.7 Common SPF Mechanisms and Modifiers

Tag	Description
ip4	Specifies an IPv4 address or range of addresses that are authorized senders for a domain.
ip6	Specifies an IPv6 address or range of addresses that are authorized senders for a domain.
mx	Asserts that the listed hosts for the Mail Exchange RRs are also valid senders for the domain.
include	Lists another domain where the receiver should look for an SPF RR for further senders. This can be useful for large organizations with many domains or sub-domains that have a single set of shared senders. The include mechanism is recursive, in that the SPF check in the record found is tested in its entirety before proceeding. It is not simply a concatenation of the checks.
all	Matches every IP address that has not otherwise been matched.

(a) SPF Mechanisms

Modifier	Description
+	The given mechanism check must pass. This is the default mechanism and does not need to be explicitly listed.
−	The given mechanism is not allowed to send email on behalf of the domain.
~	The given mechanism is in transition and if an email is seen from the listed host/IP address, then it should be accepted but marked for closer inspection.
?	The SPF RR explicitly states nothing about the mechanism. In this case, the default behavior is to accept the email. (This makes it equivalent to '+' unless some sort of discrete or aggregate message review is conducted.)

(b) SPF Mechanism Modifiers

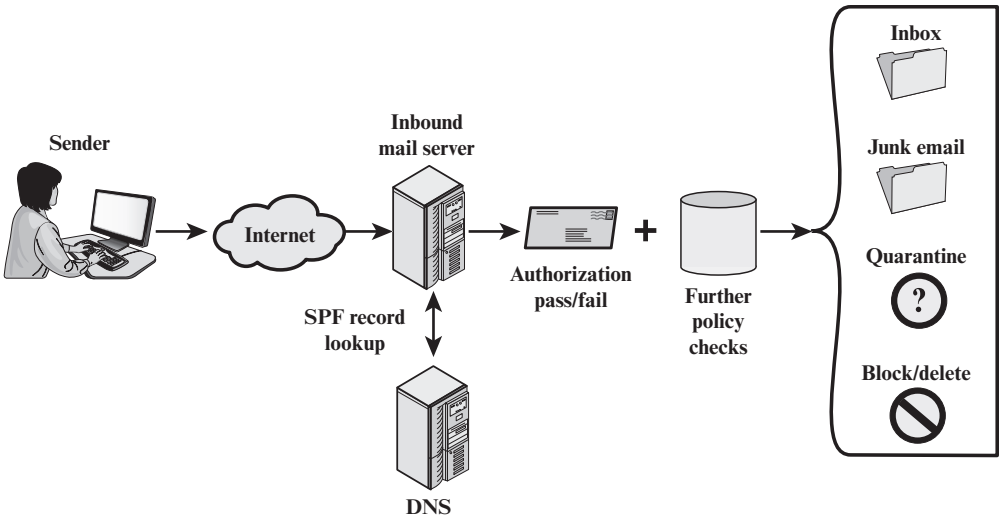


Figure 19.9 Sender Policy Framework Operation

which may result in blocking the transmission of the email content. Alternatively, the entire message can be absorbed and buffered until all the checks are finished. In either case, checks must be completed before the mail message is sent to the end user's inbox.

The checking involves the following rules:

1. If no SPF TXT RR is returned, the default behavior is to accept the message.
2. If the SPF TXT RR has formatting errors, the default behavior is to accept the message.
3. Otherwise the mechanisms and modifiers in the RR are used to determine disposition of the email message.

Figure 19.9 illustrates SPF operation.

19.9 DOMAINKEYS IDENTIFIED MAIL

DomainKeys Identified Mail (DKIM) is a specification for cryptographically signing email messages, permitting a signing domain to claim responsibility for a message in the mail stream. Message recipients (or agents acting in their behalf) can verify the signature by querying the signer's domain directly to retrieve the appropriate public key and thereby can confirm that the message was attested to by a party in possession of the private key for the signing domain. DKIM is an Internet Standard (RFC 6376: *DomainKeys Identified Mail (DKIM) Signatures*). DKIM has been widely adopted by a range of email providers, including corporations, government agencies, gmail, Yahoo!, and many Internet Service Providers (ISPs).

Email Threats

RFC 4686 (*Analysis of Threats Motivating DomainKeys Identified Mail*) describes the threats being addressed by DKIM in terms of the characteristics, capabilities, and location of potential attackers.

Characteristics RFC 4686 characterizes the range of attackers on a spectrum of three levels of threat.

1. At the low end are attackers who simply want to send email that a recipient does not want to receive. The attacker can use one of a number of commercially available tools that allow the sender to falsify the origin address of messages. This makes it difficult for the receiver to filter spam on the basis of originating address or domain.
2. At the next level are professional senders of bulk spam mail. These attackers often operate as commercial enterprises and send messages on behalf of third parties. They employ more comprehensive tools for attack, including Mail Transfer Agents (MTAs) and registered domains and networks of compromised computers (zombies), to send messages and (in some cases) to harvest addresses to which to send.
3. The most sophisticated and financially motivated senders of messages are those who stand to receive substantial financial benefit, such as from an email-based fraud scheme. These attackers can be expected to employ all of the above mechanisms and additionally may attack the Internet infrastructure itself, including DNS cache-poisoning attacks and IP routing attacks.

Capabilities RFC 4686 lists the following as capabilities that an attacker might have.

1. Submit messages to MTAs and Message Submission Agents (MSAs) at multiple locations in the Internet.
2. Construct arbitrary Message Header fields, including those claiming to be mailing lists, resenders, and other mail agents.
3. Sign messages on behalf of domains under their control.
4. Generate substantial numbers of either unsigned or apparently signed messages that might be used to attempt a denial-of-service attack.
5. Resend messages that may have been previously signed by the domain.
6. Transmit messages using any envelope information desired.
7. Act as an authorized submitter for messages from a compromised computer.
8. Manipulation of IP routing. This could be used to submit messages from specific IP addresses or difficult-to-trace addresses, or to cause diversion of messages to a specific domain.
9. Limited influence over portions of DNS using mechanisms such as cache poisoning. This might be used to influence message routing or to falsify advertisements of DNS-based keys or signing practices.

10. Access to significant computing resources, for example, through the conscription of worm-infected "zombie" computers. This could allow the "bad actor" to perform various types of brute-force attacks.
11. Ability to eavesdrop on existing traffic, perhaps from a wireless network.

Location DKIM focuses primarily on attackers located outside of the administrative units of the claimed originator and the recipient. These administrative units frequently correspond to the protected portions of the network adjacent to the originator and recipient. It is in this area that the trust relationships required for authenticated message submission do not exist and do not scale adequately to be practical. Conversely, within these administrative units, there are other mechanisms (such as authenticated message submission) that are easier to deploy and more likely to be used than DKIM. External bad actors are usually attempting to exploit the "any-to-any" nature of email that motivates most recipient MTAs to accept messages from anywhere for delivery to their local domain. They may generate messages without signatures, with incorrect signatures, or with correct signatures from domains with little traceability. They may also pose as mailing lists, greeting cards, or other agents that legitimately send or resend messages on behalf of others.

DKIM Strategy

DKIM is designed to provide an email authentication technique that is transparent to the end user. In essence, a user's email message is signed by a private key of the administrative domain from which the email originates. The signature covers all of the content of the message and some of the RFC 5322 message headers. At the receiving end, the MDA can access the corresponding public key via a DNS and verify the signature, thus authenticating that the message comes from the claimed administrative domain. Thus, mail that originates from somewhere else but claims to come from a given domain will not pass the authentication test and can be rejected. This approach differs from that of S/MIME and PGP, which use the originator's private key to sign the content of the message. The motivation for DKIM is based on the following reasoning:[2]

1. S/MIME depends on both the sending and receiving users employing S/MIME. For almost all users, the bulk of incoming mail does not use S/MIME, and the bulk of the mail the user wants to send is to recipients not using S/MIME.
2. S/MIME signs only the message content. Thus, RFC 5322 header information concerning origin can be compromised.
3. DKIM is not implemented in client programs (MUAs) and is therefore transparent to the user; the user need not take any action.
4. DKIM applies to all mail from cooperating domains.
5. DKIM allows good senders to prove that they did send a particular message and to prevent forgers from masquerading as good senders.

[2] The reasoning is expressed in terms of the use of S/MIME. The same argument applies to PGP.

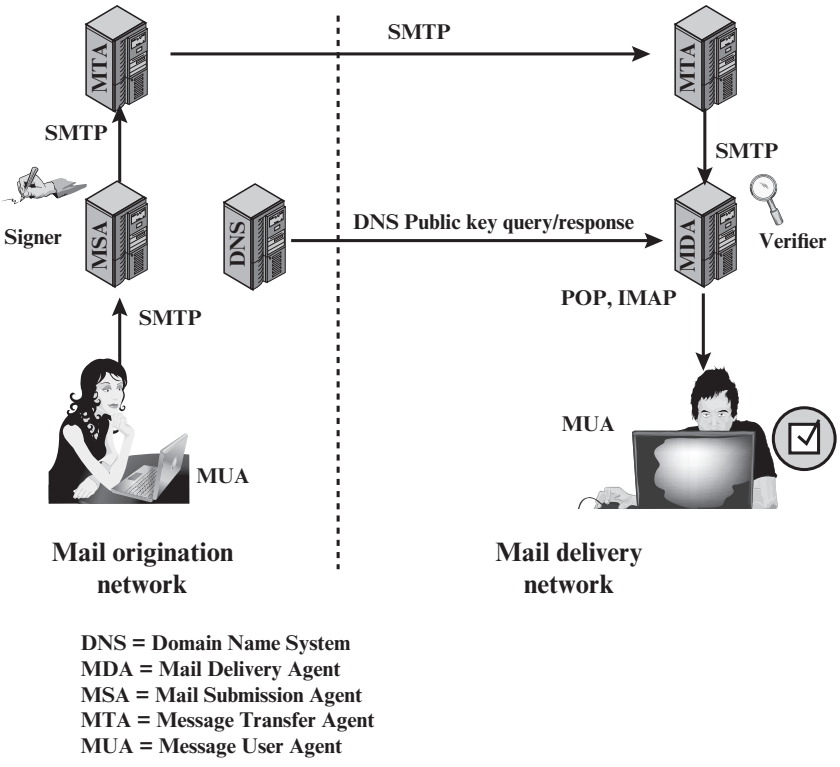


Figure 19.10 Simple Example of DKIM Deployment

Figure 19.10 is a simple example of the operation of DKIM. We begin with a message generated by a user and transmitted into the MHS to an MSA that is within the user's administrative domain. An email message is generated by an email client program. The content of the message, plus selected RFC 5322 headers, is signed by the email provider using the provider's private key. The signer is associated with a domain, which could be a corporate local network, an ISP, or a public email facility such as gmail. The signed message then passes through the Internet via a sequence of MTAs. At the destination, the MDA retrieves the public key for the incoming signature and verifies the signature before passing the message on to the destination email client. The default signing algorithm is RSA with SHA-256. RSA with SHA-1 also may be used.

DKIM Functional Flow

Figure 19.11 provides a more detailed look at the elements of DKIM operation. Basic message processing is divided between a signing Administrative Management Domain (ADMD) and a verifying ADMD. At its simplest, this is between the originating ADMD and the delivering ADMD, but it can involve other ADMDs in the handling path.

Signing is performed by an authorized module within the signing ADMD and uses private information from a Key Store. Within the originating ADMD,

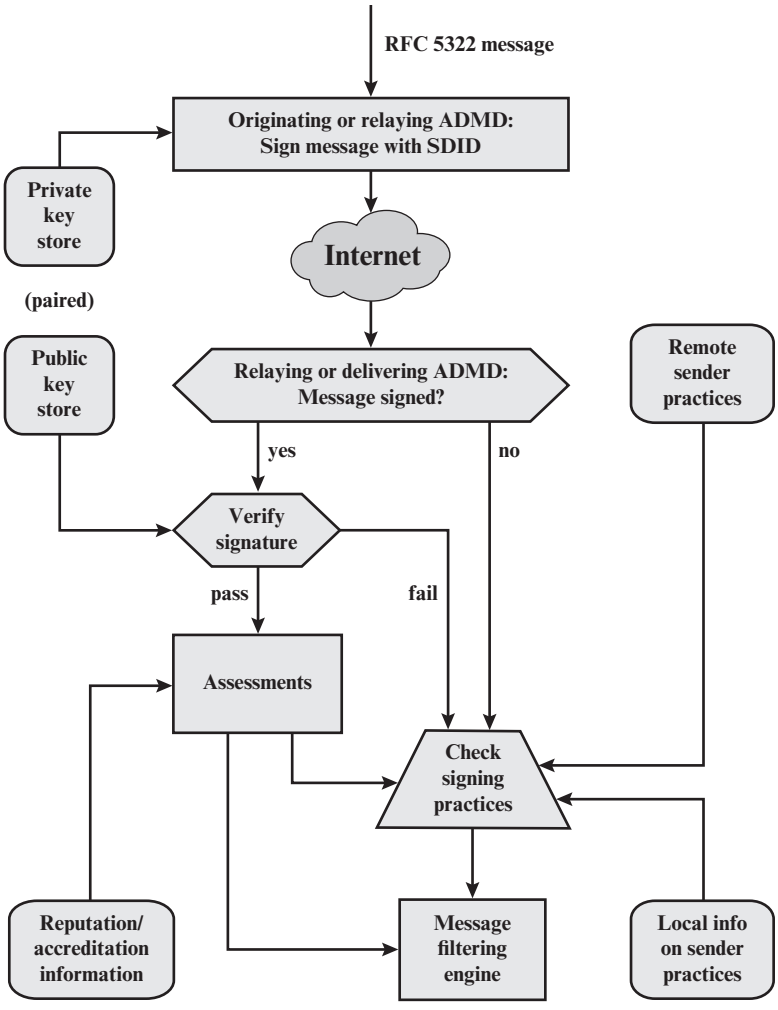


Figure 19.11 DKIM Functional Flow

this might be performed by the MUA, MSA, or an MTA. Verifying is performed by an authorized module within the verifying ADMD. Within a delivering ADMD, verifying might be performed by an MTA, MDA or MUA. The module verifies the signature or determines whether a particular signature was required. Verifying the signature uses public information from the Key Store. If the signature passes, reputation information is used to assess the signer and that information is passed to the message filtering system. If the signature fails or there is no signature using the author's domain, information about signing practices related to the author can be retrieved remotely and/or locally, and that information is passed to the message filtering system. For example, if the sender (e.g., gmail) uses DKIM but no DKIM signature is present, then the message may be considered fraudulent.

The signature is inserted into the RFC 5322 message as an additional header entry, starting with the keyword Dkim-Signature. You can view examples from your own incoming mail by using the View Long Headers (or similar wording) option for an incoming message. Here is an example:

```
Dkim-Signature:      v=1; a=rsa-sha256; c=relaxed/relaxed;
                     d=gmail.com; s=gamma; h=domainkey-
                     signature:mime-version:received:date:
                     message-id:subject :from:to:content-type:
                     content-transfer-encoding;
                     bh=5mZvQDyCRuyLb1Y28K4zgS2MPOemFToDBgvbJ
                     7GO90s=;
                     b=PcUvPSDygb4ya5Dyj1rbZGp/VyRiScuaz7TTG
                     J5qW5slM+klzv6kcfYdGDHzEVJW+Z
                     FetuPfF1ETOVhELtwH0zjSccOyPkEiblOf6gILO
                     bm3DDRm3Ys1/FVrbhVOlA+/jH9Aei
                     uIIw/5iFnRbSH6qPDVv/beDQqAWQfA/wF7O5k=
```

Before a message is signed, a process known as canonicalization is performed on both the header and body of the RFC 5322 message. Canonicalization is necessary to deal with the possibility of minor changes in the message made en route, including character encoding, treatment of trailing white space in message lines, and the "folding" and "unfolding" of header lines. The intent of canonicalization is to make a minimal transformation of the message (for the purpose of signing; the message itself is not changed, so the canonicalization must be performed again by the verifier) that will give it its best chance of producing the same canonical value at the receiving end. DKIM defines two header canonicalization algorithms ("simple" and "relaxed") and two for the body (with the same names). The simple algorithm tolerates almost no modification, while the relaxed algorithm tolerates common modifications.

The signature includes a number of fields. Each field begins with a tag consisting of a tag code followed by an equals sign and ends with a semicolon. The fields include the following:

- **v=** DKIM version/
- **a=** Algorithm used to generate the signature; must be either `rsa-sha1` or `rsa-sha256`
- **c=** Canonicalization method used on the header and the body.
- **d=** A domain name used as an identifier to refer to the identity of a responsible person or organization. In DKIM, this identifier is called the Signing Domain IDentifier (SDID). In our example, this field indicates that the sender is using a gmail address.
- **s=** In order that different keys may be used in different circumstances for the same signing domain (allowing expiration of old keys, separate departmental signing, or the like), DKIM defines a selector (a name associated with a key) that is used by the verifier to retrieve the proper key during signature verification.

- **h=** Signed Header fields. A colon-separated list of header field names that identify the header fields presented to the signing algorithm. Note that in our example above, the signature covers the domainkey-signature field. This refers to an older algorithm (since replaced by DKIM) that is still in use.
- **bh=** The hash of the canonicalized body part of the message. This provides additional information for diagnosing signature verification failures.
- **b=** The signature data in base64 format; this is the encrypted hash code.

19.10 DOMAIN-BASED MESSAGE AUTHENTICATION, REPORTING, AND CONFORMANCE

Domain-Based Message Authentication, Reporting, and Conformance (DMARC) allows email senders to specify policy on how their mail should be handled, the types of reports that receivers can send back, and the frequency those reports should be sent. It is defined in RFC 7489 (*Domain-based Message Authentication, Reporting, and Conformance*, March 2015).

DMARC works with SPF and DKIM. SPF and DKM enable senders to advise receivers, via DNS, whether mail purporting to come from the sender is valid, and whether it should be delivered, flagged, or discarded. However, neither SPF nor DKIM include a mechanism to tell receivers if SPF or DKIM are in use, nor do they have feedback mechanism to inform senders of the effectiveness of the anti-spam techniques. For example, if a message arrives at a receiver without a DKIM signature, DKIM provides no mechanism to allow the receiver to learn if the message is authentic but was sent from a sender that did not implement DKIM, or if the message is a spoof. DMARC addresses these issues essentially by standardizing how email receivers perform email authentication using SPF and DKIM mechanisms.

Identifier Alignment

DKIM, SPF, and DMARC authenticate various aspects of an individual message. DKIM authenticates the domain that affixed a signature to the message. SPF focuses on the SMTP envelope, defined in RFC 5321. It can authenticate either the domain that appears in the MAIL FROM portion of the SMTP envelope or the HELO domain, or both. These may be different domains, and they are typically not visible to the end user.

DMARC authentication deals with the From domain in the message header, as defined in RFC 5322. This field is used as the central identity of the DMARC mechanism because it is a required message header field and therefore guaranteed to be present in compliant messages, and most MUAs represent the RFC 5322 From field as the originator of the message and render some or all of this header field's content to end users. The email address in this field is the one used by end users to identify the source of the message and therefore is a prime target for abuse.

DMARC requires that From address match (be aligned with) an Authenticated Identifier from DKIM or SPF. In the case of DKIM, the match is made between the DKIM signing domain and the From domain. In the case of SPF, the match is between the SPF-authenticated domain and the From domain.

DMARC on the Sender Side

A mail sender that uses DMARC must also use SPF or DKIM, or both. The sender posts a DMARC policy in the DNS that advises receivers on how to treat messages that purport to originate from the sender's domain. The policy is in the form of a DNS TXT resource record. The sender also needs to establish email addresses to receive aggregate and forensic reports. As these email addresses are published unencrypted in the DNS TXT RR, they are easily discovered, leaving the poster subject to unsolicited bulk email. Thus, the poster of the DNS TXT RR needs to employ some kind of abuse countermeasures.

Similar to SPF and DKIM, the DMARC policy in the TXT RR is encoded in a series of `tag=value` pairs separated by semicolons. Table 19.8 describes the common tags.

Once the DMARC RR is posted, messages from the sender are typically processed as follows:

1. The domain owner constructs an SPF policy and publishes it in its DNS database. The domain owner also configures its system for DKIM signing. Finally, the domain owner publishes via the DNS a DMARC message-handling policy.
2. The author generates a message and hands the message to the domain owner's designated mail submission service.
3. The submission service passes relevant details to the DKIM signing module in order to generate a DKIM signature to be applied to the message.
4. The submission service relays the now-signed message to its designated transport service for routing to its intended recipient(s).

DMARC on the Receiver Side

A message generated on the sender side may pass through other relays but eventually arrives at a receiver's transport service. The typical processing order for DMARC on the receiving side is the following:

1. The receiver performs standard validation tests, such as checking against IP blocklists and domain reputation lists, as well as enforcing rate limits from a particular source.
2. The receiver extracts the RFC 5322 From address from the message. This must contain a single, valid address or else the mail is refused as an error.
3. The receiver queries for the DMARC DNS record based on the sending domain. If none exists, terminate DMARC processing.
4. The receiver performs DKIM signature checks. If more than one DKIM signature exists in the message, one must verify.
5. The receiver queries for the sending domain's SPF record and performs SPF validation checks.
6. The receiver conducts Identifier Alignment checks between the RFC 5321 From and the results of the SPF and DKIM records (if present).

Table 19.8 DMARC Tag and Value Descriptions

Tag (Name)	Description
v= (Version)	Version field that must be present as the first element. By default the value is always **DMARC1**.
p= (Policy)	Mandatory policy field. May take values **none** or **quarantine** or **reject**. This allows for a gradually tightening policy where the sender domain recommends no specific action on mail that fails DMARC checks **(p= none),** through treating failed mail as suspicious **(p= quarantine),** to rejecting all failed mail **(p= reject),** preferably at the SMTP transaction stage.
aspf= (SPF Policy)	Values are **r** (default) for relaxed and **s** for strict SPF domain enforcement. Strict alignment requires an exact match between the From address domain and the (passing) SPF check must exactly match the MailFrom address (HELO address). Relaxed requires that only the From and MailFrom address domains be in alignment. For example, the MailFrom address domain **smtp.example.org** and the From address **announce@example.org** are in alignment, but not a strict match.
adkim= (DKIM Policy)	Optional. Values are **r** (default) for relaxed and **s** for strict DKIM domain enforcement. Strict alignment requires an exact match between the From domain in the message header and the DKIM domain presented in the **(d=** DKIM), tag. Relaxed requires only that the domain part is in alignment (as in **aspf**).
fo= (Failure reporting options)	Optional. Ignore if a **ruf** argument is not also present. Value **0** indicates the receiver should generate a DMARC failure report if all underlying mechanisms fail to produce an aligned pass result. Value **1** means generate a DMARC failure report if any underlying mechanism produces something other than an aligned pass result. Other possible values are **d** (generate a DKIM failure report if a signature failed evaluation), and **s** (generate an SPF failure report if the message failed SPF evaluation). These values are not exclusive and may be combined.
ruf=	Optional, but requires the **fo** argument to be present. Lists a series of URIs (currently just **mailto:**<emailaddress>) that list where to send forensic feedback reports. This is for reports on message-specific failures.
rua=	Optional list of URIs (like in **ruf=** , using the **mailto:** URI) listing where to send aggregate feedback back to the sender. These reports are sent based on the interval requested using the **ri=** option with a default of 86400 seconds if not listed.
ri= (Reporting interval)	Optional with the default value of 86400 seconds. The value listed is the reporting interval desired by the sender.
pct= (Percent)	Optional with the default value of **100**. Expresses the percentage of a sender's mail that should be subject to the given DMARC policy. This allows senders to ramp up their policy enforcement gradually and prevent having to commit to a rigorous policy before getting feedback on their existing policy.
sp= (Receiver Policy)	Optional with a default value of **none**. Other values include the same range of values as the **p=** argument. This is the policy to be applied to mail from all identified subdomains of the given DMARC RR.

7. The results of these steps are passed to the DMARC module along with the Author's domain. The DMARC module attempts to retrieve a policy from the DNS for that domain. If none is found, the DMARC module determines the organizational domain and repeats the attempt to retrieve a policy from the DNS.
8. If a policy is found, it is combined with the Author's domain and the SPF and DKIM results to produce a DMARC policy result (a "pass" or "fail") and can optionally cause one of two kinds of reports to be generated.

9. Recipient transport service either delivers the message to the recipient inbox or takes other local policy action based on the DMARC result.
10. When requested, Recipient transport service collects data from the message delivery session to be used in providing feedback.

Figure 19.12, based on one at DMARC.org, summarizes the sending and receiving functional flow.

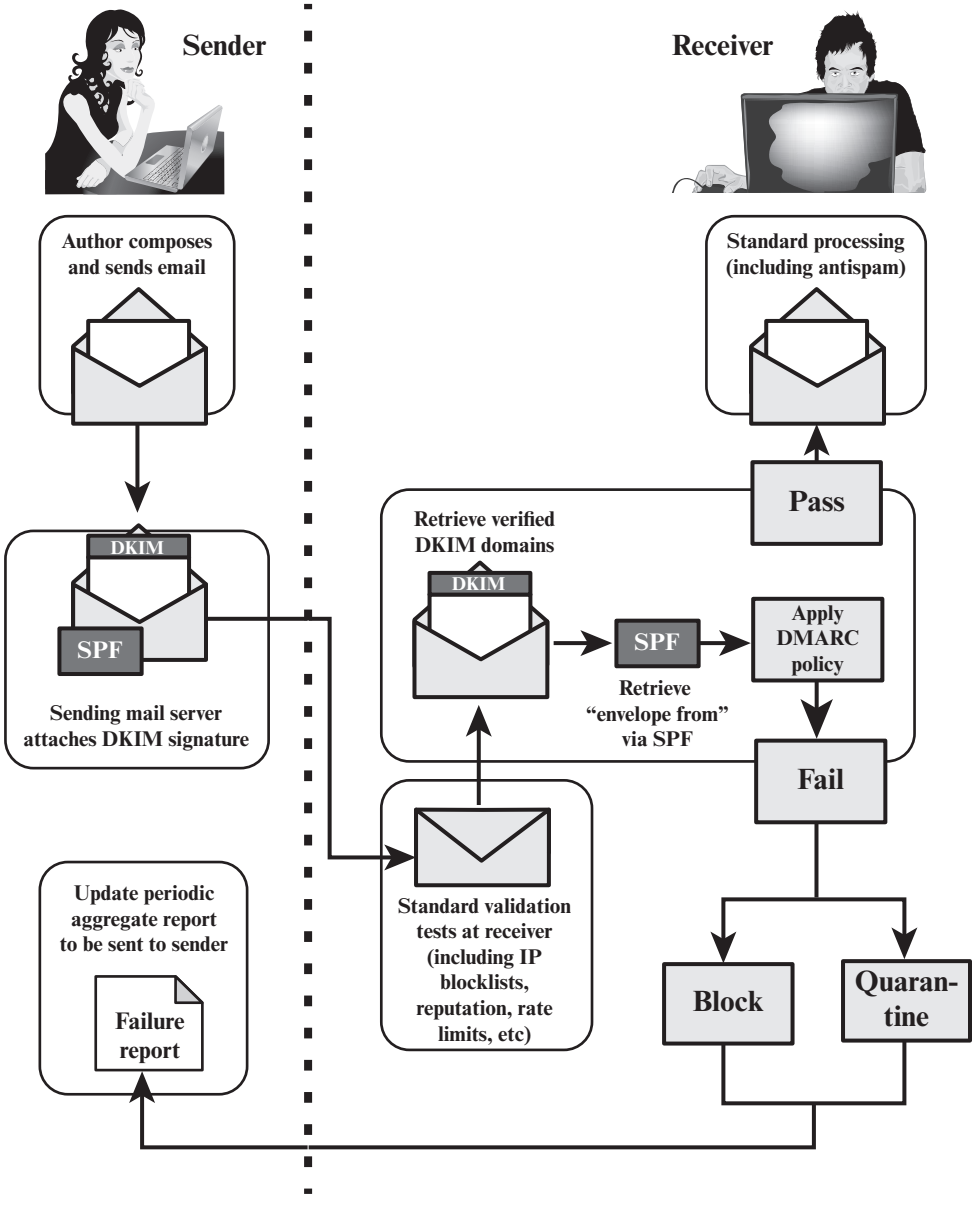


Figure 19.12 DMARC Functional Flow

DMARC Reports

DMARC reporting provides the sender's feedback on their SPF, DKIM, Identifier Alignment, and message disposition policies, which enable the sender to make these policies more effective. Two types of reports are sent: aggregate reports and forensic reports.

Aggregate reports are sent by receivers periodically and include aggregate figures for successful and unsuccessful message authentications, including:

- The sender's DMARC policy for that interval.
- The message disposition by the receiver (i.e., delivered, quarantined, rejected).
- SPF result for a given SPF identifier.
- DKIM result for a given DKIM identifier.
- Whether identifiers are in alignment or not.
- Results classified by sender subdomain.
- The sending and receiving domain pair.
- The policy applied, and whether this is different from the policy requested.
- The number of successful authentications.
- Totals for all messages received.

This information enables the sender to identify gaps in email infrastructure and policy. SP 800-177 recommends that a sending domain begin by setting a DMARC policy of **p= none**, so that the ultimate disposition of a message that fails some check is determined by the receiver's local policy. As DMARC aggregate reports are collected, the sender will have a quantitatively better assessment of the extent to which the sender's email is authenticated by outside receivers, and will be able to set a policy of **p = reject**, indicating that any message that fails the SPF, DKIM, and alignment checks really should be rejected. From their own traffic analysis, receivers can develop a determination of whether a sender's **p = reject** policy is sufficiently trustworthy to act on.

A forensic report helps the sender refine the component SPF and DKIM mechanisms as well as alerting the sender that their domain is being used as part of a phishing/spam campaign. Forensic reports are similar in format to aggregation reports, with these changes:

- Receivers include as much of the message and message header as is reasonable to allow the domain to investigate the failure. Add an Identity-Alignment field, with DKIM and SPF DMARC-method fields as appropriate.
- Optionally add a Delivery-Result field.
- Add DKIM Domain, DKIM Identity, and DKIM selector fields, if the message was DKIM signed. Optionally also add DKIM Canonical header and body fields.
- Add an additional DMARC authentication failure type, for use when some authentication mechanisms fail to produce aligned identifiers.

19.11 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

administrative management domain (ADMD)	Domain Name System (DNS)	Message User Agent (MUA)
base64	DomainKeys Identified Mail (DKIM)	Multipurpose Internet Mail Extensions (MIME)
Cryptographic Message Syntax (CMS)	electronic mail	Post Office Protocol (POP3)
detached signature	Internet Mail Access Protocol (IMAP)	Pretty Good Privacy (PGP)
DNS-based Authentication of Named Entities (DANE)	Mail Delivery Agent (MDA)	Sender Policy Framework (SPF)
DNS Security Extensions (DNSSEC)	Mail Submission Agent (MSA)	session key
Domain-based Message Authentication, Reporting, and Conformance (DMARC)	Message Handling Service (MHS)	Simple Mail Transfer Protocol (SMTP)
	Message Store	STARTTLS
	Message Transfer Agents (MTA)	SUBMISSION
		S/MIME
		trust

Review Questions

19.1 What types of interoperability issues are involved in internet mail architecture and how are they handled?

19.2 What are the SMTP and MIME standards?

19.3 What is the difference between a MIME content type and a MIME transfer encoding?

19.4 Briefly explain base64 encoding.

19.5 Why is base64 conversion useful for an email application?

19.6 What is S/MIME?

19.7 What are the four principal services provided by S/MIME?

19.8 What is the utility of a detached signature?

19.9 What is DKIM?

Problems

19.1 The character sequence "<CR><LF>.<CR><LF>" indicates the end of mail data to a SMTP-server. What happens if the mail data itself contains that character sequence?

19.2 What are POP3 and IMAP?

19.3 If a lossless compression algorithm, such as ZIP, is used with S/MIME, why is it preferable to generate a signature before applying compression?

19.4 Before the deployment of the Domain Name System, a simple text file (HOSTS.TXT) centrally maintained at the SRI Network Information Center was used to enable mapping between host names and addresses. Each host connected to the Internet had to have an updated local copy of it to be able to use host names instead of having to cope directly with their IP addresses. Discuss the main advantages of the DNS over the old centralized HOSTS.TXT system.

19.5 For this problem and the next few, consult Appendix P. In Figure P.2, each entry in the public-key ring contains an Owner Trust field that indicates the degree of trust associated with this public-key owner. Why is that not enough? That is, if this owner is trusted and this is supposed to be the owner's public key, why is that trust not enough to permit PGP to use this public key?

19.6 What is the basic difference between X.509 and PGP in terms of key hierarchies and key trust?

19.7 In PGP, what is the expected number of session keys generated before a previously created key is produced?

19.8 A PGP user may have multiple public keys. So that a recipient knows which public key is being used by a sender, a key ID, consisting of the least significant 64 bits of the public key, is sent with the message. What is the probability that a user with N public keys will have at least one duplicate key ID?

19.9 The first 16 bits of the message digest in a PGP signature are translated in the clear. This enables the recipient to determine if the correct public key was used to decrypt the message digest by comparing this plaintext copy of the first two octets with the first two octets of the decrypted digest.

a. To what extent does this compromise the security of the hash algorithm?

b. To what extent does it in fact perform its intended function, namely, to help determine if the correct RSA key was used to decrypt the digest?

19.10 Consider base64 conversion as a form of encryption. In this case, there is no key. But suppose that an opponent knew only that some form of substitution algorithm was being used to encrypt English text and did not guess that it was base64. How effective would this algorithm be against cryptanalysis?

19.11 Encode the text "ciphertext" using the following techniques. Assume characters are stored in 8-bit ASCII with zero parity.

a. base64

b. Quoted-printable

19.12 Use a 2×2 matrix to categorize the properties of the four certificate usage models in DANE.

CHAPTER 20

IP Security

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Present an overview of IP security (IPsec).
- Explain the difference between transport mode and tunnel mode.
- Understand the concept of security association.
- Explain the difference between the security association database and the security policy database.
- Summarize the traffic processing functions performed by IPsec for outbound packets and for inbound packets.
- Present an overview of Encapsulating Security Payload.
- Discuss the alternatives for combining security associations.
- Present an overview of Internet Key Exchange.
- Summarize the alternative cryptographic suites approved for use with IPsec.

There are application-specific security mechanisms for a number of application areas, including electronic mail (S/MIME, PGP), client/server (Kerberos), Web access (Secure Sockets Layer), and others. However, users have security concerns that cut across protocol layers. For example, an enterprise can run a secure, private IP network by disallowing links to untrusted sites, encrypting packets that leave the premises, and authenticating packets that enter the premises. By implementing security at the IP level, an organization can ensure secure networking not only for applications that have security mechanisms but also for the many security-ignorant applications.

IP-level security encompasses three functional areas: authentication, confidentiality, and key management. The authentication mechanism assures that a received packet was, in fact, transmitted by the party identified as the source in the packet header. In addition, this mechanism assures that the packet has not been altered in transit. The confidentiality facility enables communicating nodes to encrypt messages to prevent eavesdropping by third parties. The key management facility is concerned with the secure exchange of keys.

We begin this chapter with an overview of IP security (IPsec) and an introduction to the IPsec architecture. We then look at each of the three functional areas in detail. Appendix L reviews Internet protocols.

20.1 IP SECURITY OVERVIEW

In 1994, the Internet Architecture Board (IAB) issued a report titled "Security in the Internet Architecture" (RFC 1636). The report identified key areas for security mechanisms. Among these were the need to secure the network infrastructure from

unauthorized monitoring and control of network traffic and the need to secure end-user-to-end-user traffic using authentication and encryption mechanisms.

To provide security, the IAB included authentication and encryption as necessary security features in the next-generation IP, which has been issued as IPv6. Fortunately, these security capabilities were designed to be usable both with the current IPv4 and the future IPv6. This means that vendors can begin offering these features now, and many vendors now do have some IPsec capability in their products. The IPsec specification now exists as a set of Internet standards.

Applications of IPsec

IPsec provides the capability to secure communications across a LAN, across private and public WANs, and across the Internet. Examples of its use include:

- **Secure branch office connectivity over the Internet:** A company can build a secure virtual private network over the Internet or over a public WAN. This enables a business to rely heavily on the Internet and reduce its need for private networks, saving costs and network management overhead.
- **Secure remote access over the Internet:** An end user whose system is equipped with IP security protocols can make a local call to an Internet Service Provider (ISP) and gain secure access to a company network. This reduces the cost of toll charges for traveling employees and telecommuters.
- **Establishing extranet and intranet connectivity with partners:** IPsec can be used to secure communication with other organizations, ensuring authentication and confidentiality and providing a key exchange mechanism.
- **Enhancing electronic commerce security:** Even though some Web and electronic commerce applications have built-in security protocols, the use of IPsec enhances that security. IPsec guarantees that all traffic designated by the network administrator is both encrypted and authenticated, adding an additional layer of security to whatever is provided at the application layer.

The principal feature of IPsec that enables it to support these varied applications is that it can encrypt and/or authenticate *all* traffic at the IP level. Thus, all distributed applications (including remote logon, client/server, email, file transfer, Web access, and so on) can be secured. Figure 20.1a shows a simplified packet format for an IPsec option known as tunnel mode, described subsequently. Tunnel mode makes use of an IPsec function, a combined authentication/encryption function called Encapsulating Security Payload (ESP), and a key exchange function. For VPNs, both authentication and encryption are generally desired, because it is important both to (1) assure that unauthorized users do not penetrate the VPN, and (2) assure that eavesdroppers on the Internet cannot read messages sent over the VPN.

Figure 20.1b is a typical scenario of IPsec usage. An organization maintains LANs at dispersed locations. Nonsecure IP traffic is conducted on each LAN. For traffic offsite, through some sort of private or public WAN, IPsec protocols are used. These protocols operate in networking devices, such as a router or firewall, that connect each LAN to the outside world. The IPsec networking device will typically encrypt all traffic going into the WAN and decrypt traffic coming from the WAN; these operations are transparent to workstations and servers on the LAN. Secure

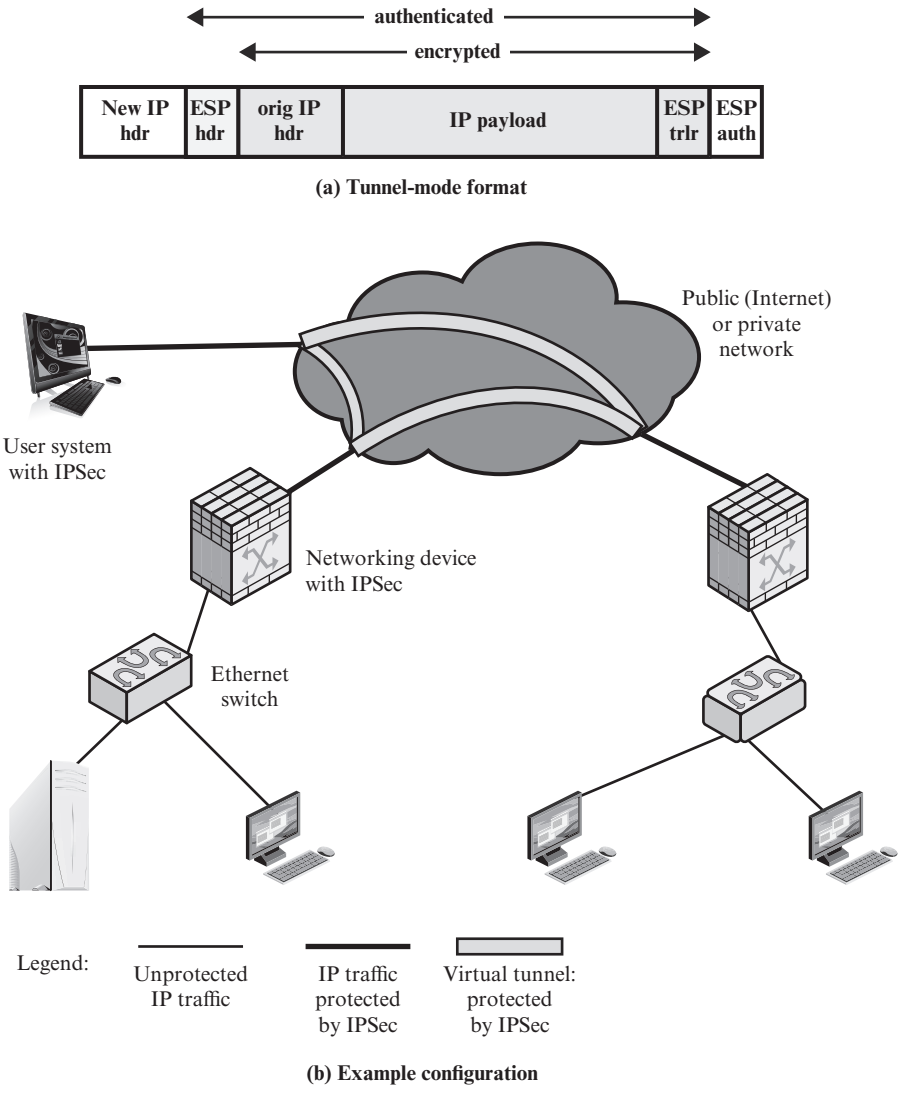


Figure 20.1 An IPSec VPN Scenario

transmission is also possible with individual users who dial into the WAN. Such user workstations must implement the IPsec protocols to provide security.

Benefits of IPsec

Some of the benefits of IPsec:

- When IPsec is implemented in a firewall or router, it provides strong security that can be applied to all traffic crossing the perimeter. Traffic within a company or workgroup does not incur the overhead of security-related processing.

- IPsec in a firewall is resistant to bypass if all traffic from the outside must use IP and the firewall is the only means of entrance from the Internet into the organization.
- IPsec is below the transport layer (TCP, UDP) and so is transparent to applications. There is no need to change software on a user or server system when IPsec is implemented in the firewall or router. Even if IPsec is implemented in end systems, upper-layer software, including applications, is not affected.
- IPsec can be transparent to end users. There is no need to train users on security mechanisms, issue keying material on a per-user basis, or revoke keying material when users leave the organization.
- IPsec can provide security for individual users if needed. This is useful for offsite workers and for setting up a secure virtual subnetwork within an organization for sensitive applications.

Routing Applications

In addition to supporting end users and protecting premises systems and networks, IPsec can play a vital role in the routing architecture required for internetworking. [HUIT98] lists the following examples of the use of IPsec. IPsec can assure that

- A router advertisement (a new router advertises its presence) comes from an authorized router.
- A neighbor advertisement (a router seeks to establish or maintain a neighbor relationship with a router in another routing domain) comes from an authorized router.
- A redirect message comes from the router to which the initial IP packet was sent.
- A routing update is not forged.

Without such security measures, an opponent can disrupt communications or divert some traffic. Routing protocols such as Open Shortest Path First (OSPF) should be run on top of security associations between routers that are defined by IPsec.

IPsec Documents

IPsec encompasses three functional areas: authentication, confidentiality, and key management. The totality of the IPsec specification is scattered across dozens of RFCs and draft IETF documents, making this the most complex and difficult to grasp of all IETF specifications. The best way to grasp the scope of IPsec is to consult the latest version of the IPsec document roadmap, which as of this writing is RFC 6071 [*IP Security (IPsec) and Internet Key Exchange (IKE) Document Roadmap*, February 2011]. The documents can be categorized into the following groups.

- **Architecture:** Covers the general concepts, security requirements, definitions, and mechanisms defining IPsec technology. The current specification is RFC 4301, *Security Architecture for the Internet Protocol*.

- **Authentication Header (AH):** AH is an extension header to provide message authentication. The current specification is RFC 4302, *IP Authentication Header*. Because message authentication is provided by ESP, the use of AH is deprecated. It is included in IPsecv3 for backward compatibility but should not be used in new applications. We do not discuss AH in this chapter.
- **Encapsulating Security Payload (ESP):** ESP consists of an encapsulating header and trailer used to provide encryption or combined encryption/authentication. The current specification is RFC 4303, *IP Encapsulating Security Payload (ESP)*.
- **Internet Key Exchange (IKE):** This is a collection of documents describing the key management schemes for use with IPsec. The main specification is RFC 7296, *Internet Key Exchange (IKEv2) Protocol*, but there are a number of related RFCs.
- **Cryptographic algorithms:** This category encompasses a large set of documents that define and describe cryptographic algorithms for encryption, message authentication, pseudorandom functions (PRFs), and cryptographic key exchange.
- **Other:** There are a variety of other IPsec-related RFCs, including those dealing with security policy and management information base (MIB) content.

IPsec Services

IPsec provides security services at the IP layer by enabling a system to select required security protocols, determine the algorithm(s) to use for the service(s), and put in place any cryptographic keys required to provide the requested services. Two protocols are used to provide security: an authentication protocol designated by the header of the protocol, Authentication Header (AH); and a combined encryption/authentication protocol designated by the format of the packet for that protocol, Encapsulating Security Payload (ESP). RFC 4301 lists the following services:

- Access control
- Connectionless integrity
- Data origin authentication
- Rejection of replayed packets (a form of partial sequence integrity)
- Confidentiality (encryption)
- Limited traffic flow confidentiality

Transport and Tunnel Modes

Both AH and ESP support two modes of use: transport and tunnel mode. The operation of these two modes is best understood in the context of a description of ESP, which is covered in Section 20.3. Here we provide a brief overview.

Transport Mode Transport mode provides protection primarily for upper-layer protocols. That is, transport mode protection extends to the payload of an IP packet.[1] Examples include a TCP or UDP segment or an ICMP packet, all of which operate directly above IP in a host protocol stack. Typically, transport mode is used for end-to-end communication between two hosts (e.g., a client and a server, or two workstations). When a host runs AH or ESP over IPv4, the payload is the data that normally follow the IP header. For IPv6, the payload is the data that normally follow both the IP header and any IPv6 extensions headers that are present, with the possible exception of the destination options header, which may be included in the protection.

ESP in transport mode encrypts and optionally authenticates the IP payload but not the IP header. AH in transport mode authenticates the IP payload and selected portions of the IP header.

Tunnel Mode Tunnel mode provides protection to the entire IP packet. To achieve this, after the AH or ESP fields are added to the IP packet, the entire packet plus security fields is treated as the payload of new outer IP packet with a new outer IP header. The entire original, inner, packet travels through a tunnel from one point of an IP network to another; no routers along the way are able to examine the inner IP header. Because the original packet is encapsulated, the new, larger packet may have totally different source and destination addresses, adding to the security. Tunnel mode is used when one or both ends of a security association (SA) are a security gateway, such as a firewall or router that implements IPsec. With tunnel mode, a number of hosts on networks behind firewalls may engage in secure communications without implementing IPsec. The unprotected packets generated by such hosts are tunneled through external networks by tunnel mode SAs set up by the IPsec software in the firewall or secure router at the boundary of the local network.

Here is an example of how tunnel mode IPsec operates. Host A on a network generates an IP packet with the destination address of host B on another network. This packet is routed from the originating host to a firewall or secure router at the boundary of A's network. The firewall filters all outgoing packets to determine the need for IPsec processing. If this packet from A to B requires IPsec, the firewall performs IPsec processing and encapsulates the packet with an outer IP header. The source IP address of this outer IP packet is this firewall, and the destination address may be a firewall that forms the boundary to B's local network. This packet is now routed to B's firewall, with intermediate routers examining only the outer IP header. At B's firewall, the outer IP header is stripped off, and the inner packet is delivered to B.

ESP in tunnel mode encrypts and optionally authenticates the entire inner IP packet, including the inner IP header. AH in tunnel mode authenticates the entire inner IP packet and selected portions of the outer IP header.

Table 20.1 summarizes transport and tunnel mode functionality.

[1]In this chapter, the term *IP packet* refers to either an IPv4 datagram or an IPv6 packet.

Table 20.1 Tunnel Mode and Transport Mode Functionality

	Transport Mode SA	Tunnel Mode SA
AH	Authenticates IP payload and selected portions of IP header and IPv6 extension headers.	Authenticates entire inner IP packet (inner header plus IP payload) plus selected portions of outer IP header and outer IPv6 extension headers.
ESP	Encrypts IP payload and any IPv6 extension headers following the ESP header.	Encrypts entire inner IP packet.
ESP with Authentication	Encrypts IP payload and any IPv6 extension headers following the ESP header. Authenticates IP payload but not IP header.	Encrypts entire inner IP packet. Authenticates inner IP packet.

20.2 IP SECURITY POLICY

Fundamental to the operation of IPsec is the concept of a security policy applied to each IP packet that transits from a source to a destination. IPsec policy is determined primarily by the interaction of two databases, the **security association database (SAD)** and the **security policy database (SPD)**. This section provides an overview of these two databases and then summarizes their use during IPsec operation. Figure 20.2 illustrates the relevant relationships.

Security Associations

A key concept that appears in both the authentication and confidentiality mechanisms for IP is the security association (SA). An association is a one-way logical connection between a sender and a receiver that affords security services to the traffic carried on it. If a peer relationship is needed for two-way secure exchange, then two security associations are required.

A security association is uniquely identified by three parameters.

- **Security Parameters Index (SPI):** A 32-bit unsigned integer assigned to this SA and having local significance only. The SPI is carried in AH and ESP headers to enable the receiving system to select the SA under which a received packet will be processed.
- **IP Destination Address:** This is the address of the destination endpoint of the SA, which may be an end-user system or a network system such as a firewall or router.
- **Security Protocol Identifier:** This field from the outer IP header indicates whether the association is an AH or ESP security association.

Hence, in any IP packet, the security association is uniquely identified by the Destination Address in the IPv4 or IPv6 header and the SPI in the enclosed extension header (AH or ESP).

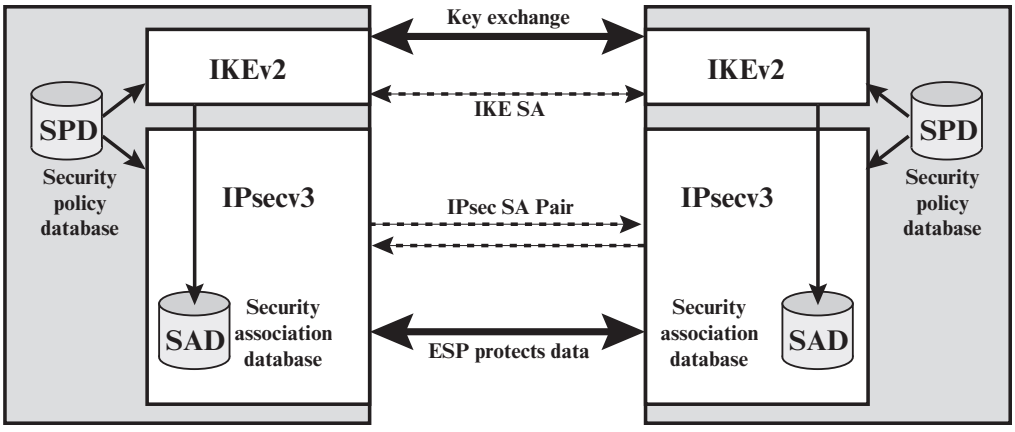


Figure 20.2 IPsec Architecture

Security Association Database

In each IPsec implementation, there is a nominal[2] Security Association Database that defines the parameters associated with each SA. A security association is normally defined by the following parameters in an SAD entry.

- **Security Parameter Index:** A 32-bit value selected by the receiving end of an SA to uniquely identify the SA. In an SAD entry for an outbound SA, the SPI is used to construct the packet's AH or ESP header. In an SAD entry for an inbound SA, the SPI is used to map traffic to the appropriate SA.
- **Sequence Number Counter:** A 32-bit value used to generate the Sequence Number field in AH or ESP headers, described in Section 20.3 (required for all implementations).
- **Sequence Counter Overflow:** A flag indicating whether overflow of the Sequence Number Counter should generate an auditable event and prevent further transmission of packets on this SA (required for all implementations).
- **Anti-Replay Window:** Used to determine whether an inbound AH or ESP packet is a replay, described in Section 20.3 (required for all implementations).
- **AH Information:** Authentication algorithm, keys, key lifetimes, and related parameters being used with AH (required for AH implementations).
- **ESP Information:** Encryption and authentication algorithm, keys, initialization values, key lifetimes, and related parameters being used with ESP (required for ESP implementations).
- **Lifetime of this Security Association:** A time interval or byte count after which an SA must be replaced with a new SA (and new SPI) or terminated, plus an indication of which of these actions should occur (required for all implementations).

[2]Nominal in the sense that the functionality provided by a Security Association Database must be present in any IPsec implementation, but the way in which that functionality is provided is up to the implementer.

- **IPsec Protocol Mode:** Tunnel, transport, or wildcard.
- **Path MTU:** Any observed path maximum transmission unit (maximum size of a packet that can be transmitted without fragmentation) and aging variables (required for all implementations).

The key management mechanism that is used to distribute keys is coupled to the authentication and privacy mechanisms only by way of the Security Parameters Index (SPI). Hence, authentication and privacy have been specified independent of any specific key management mechanism.

IPsec provides the user with considerable flexibility in the way in which IPsec services are applied to IP traffic. As we will see later, SAs can be combined in a number of ways to yield the desired user configuration. Furthermore, IPsec provides a high degree of granularity in discriminating between traffic that is afforded IPsec protection and traffic that is allowed to bypass IPsec, as in the former case relating IP traffic to specific SAs.

Security Policy Database

The means by which IP traffic is related to specific SAs (or no SA in the case of traffic allowed to bypass IPsec) is the nominal Security Policy Database (SPD). In its simplest form, an SPD contains entries, each of which defines a subset of IP traffic and points to an SA for that traffic. In more complex environments, there may be multiple entries that potentially relate to a single SA or multiple SAs associated with a single SPD entry. The reader is referred to the relevant IPsec documents for a full discussion.

Each SPD entry is defined by a set of IP and upper-layer protocol field values, called *selectors*. In effect, these selectors are used to filter outgoing traffic in order to map it into a particular SA. Outbound processing obeys the following general sequence for each IP packet.

1. Compare the values of the appropriate fields in the packet (the selector fields) against the SPD to find a matching SPD entry, which will point to zero or more SAs.
2. Determine the SA if any for this packet and its associated SPI.
3. Do the required IPsec processing (i.e., AH or ESP processing).

The following selectors determine an SPD entry:

- **Remote IP Address:** This may be a single IP address, an enumerated list or range of addresses, or a wildcard (mask) address. The latter two are required to support more than one destination system sharing the same SA (e.g., behind a firewall).
- **Local IP Address:** This may be a single IP address, an enumerated list or range of addresses, or a wildcard (mask) address. The latter two are required to support more than one source system sharing the same SA (e.g., behind a firewall).
- **Next Layer Protocol:** The IP protocol header (IPv4, IPv6, or IPv6 Extension) includes a field (Protocol for IPv4, Next Header for IPv6 or IPv6 Extension) that designates the protocol operating over IP. This is an individual protocol number, ANY, or for IPv6 only, OPAQUE. If AH or ESP is used, then this IP protocol header immediately precedes the AH or ESP header in the packet.

Table 20.2 Host SPD Example

Protocol	Local IP	Port	Remote IP	Port	Action	Comment
UDP	1.2.3.101	500	*	500	BYPASS	IKE
ICMP	1.2.3.101	*	*	*	BYPASS	Error messages
*	1.2.3.101	*	1.2.3.0/24	*	PROTECT: ESP intransport-mode	Encrypt intranet traffic
TCP	1.2.3.101	*	1.2.4.10	80	PROTECT: ESP intransport-mode	Encrypt to server
TCP	1.2.3.101	*	1.2.4.10	443	BYPASS	TLS: avoid double encryption
*	1.2.3.101	*	1.2.4.0/24	*	DISCARD	Others in DMZ
*	1.2.3.101	*	*	*	BYPASS	Internet

- **Name:** A user identifier from the operating system. This is not a field in the IP or upper-layer headers but is available if IPsec is running on the same operating system as the user.
- **Local and Remote Ports:** These may be individual TCP or UDP port values, an enumerated list of ports, or a wildcard port.

Table 20.2 provides an example of an SPD on a host system (as opposed to a network system such as a firewall or router). This table reflects the following configuration: A local network configuration consists of two networks. The basic corporate network configuration has the IP network number 1.2.3.0/24. The local configuration also includes a secure LAN, often known as a DMZ, that is identified as 1.2.4.0/24. The DMZ is protected from both the outside world and the rest of the corporate LAN by firewalls. The host in this example has the IP address 1.2.3.10, and it is authorized to connect to the server 1.2.4.10 in the DMZ.

The entries in the SPD should be self-explanatory. For example, UDP port 500 is the designated port for IKE. Any traffic from the local host to a remote host for purposes of an IKE exchange bypasses the IPsec processing.

IP Traffic Processing

IPsec is executed on a packet-by-packet basis. When IPsec is implemented, each outbound IP packet is processed by the IPsec logic before transmission, and each inbound packet is processed by the IPsec logic after reception and before passing the packet contents on to the next higher layer (e.g., TCP or UDP). We look at the logic of these two situations in turn.

Outbound Packets Figure 20.3 highlights the main elements of IPsec processing for outbound traffic. A block of data from a higher layer, such as TCP, is passed down to the IP layer and an IP packet is formed, consisting of an IP header and an IP body. Then the following steps occur:

1. IPsec searches the SPD for a match to this packet.
2. If no match is found, then the packet is discarded and an error message is generated.

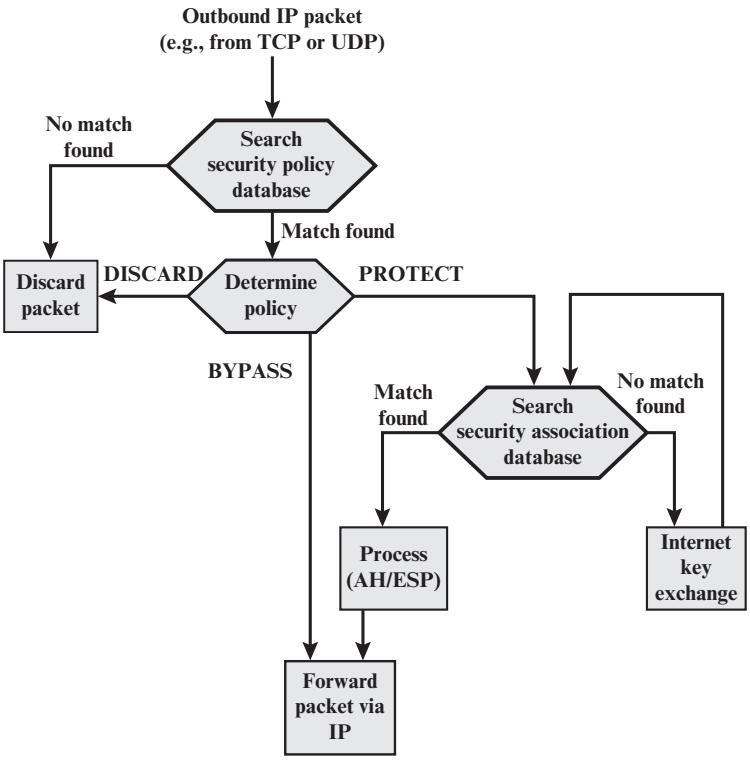


Figure 20.3 Processing Model for Outbound Packets

3. If a match is found, further processing is determined by the first matching entry in the SPD. If the policy for this packet is DISCARD, then the packet is discarded. If the policy is BYPASS, then there is no further IPsec processing; the packet is forwarded to the network for transmission.
4. If the policy is PROTECT, then a search is made of the SAD for a matching entry. If no entry is found, then IKE is invoked to create an SA with the appropriate keys and an entry is made in the SA.
5. The matching entry in the SAD determines the processing for this packet. Either encryption, authentication, or both can be performed, and either transport or tunnel mode can be used. The packet is then forwarded to the network for transmission.

Inbound Packets Figure 20.4 highlights the main elements of IPsec processing for inbound traffic. An incoming IP packet triggers the IPsec processing. The following steps occur:

1. IPsec determines whether this is an unsecured IP packet or one that has ESP or AH headers/trailers, by examining the IP Protocol field (IPv4) or Next Header field (IPv6).

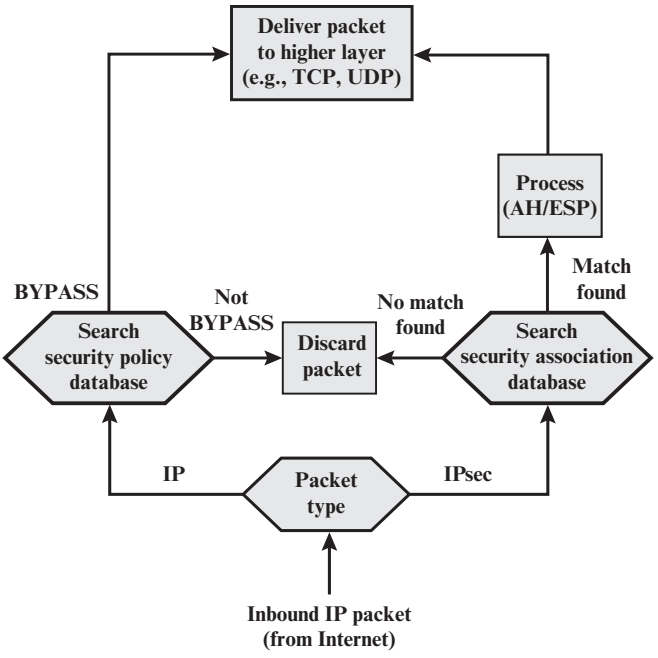


Figure 20.4 Processing Model for Inbound Packets

2. If the packet is unsecured, IPsec searches the SPD for a match to this packet. If the first matching entry has a policy of BYPASS, the IP header is processed and stripped off and the packet body is delivered to the next higher layer, such as TCP. If the first matching entry has a policy of PROTECT or DISCARD, or if there is no matching entry, the packet is discarded.
3. For a secured packet, IPsec searches the SAD. If no match is found, the packet is discarded. Otherwise, IPsec applies the appropriate ESP or AH processing. Then, the IP header is processed and stripped off and the packet body is delivered to the next higher layer, such as TCP.

20.3 ENCAPSULATING SECURITY PAYLOAD

ESP can be used to provide confidentiality, data origin authentication, connectionless integrity, an anti-replay service (a form of partial sequence integrity), and (limited) traffic flow confidentiality. The set of services provided depends on options selected at the time of Security Association (SA) establishment and on the location of the implementation in a network topology.

ESP can work with a variety of encryption and authentication algorithms, including authenticated encryption algorithms such as GCM.

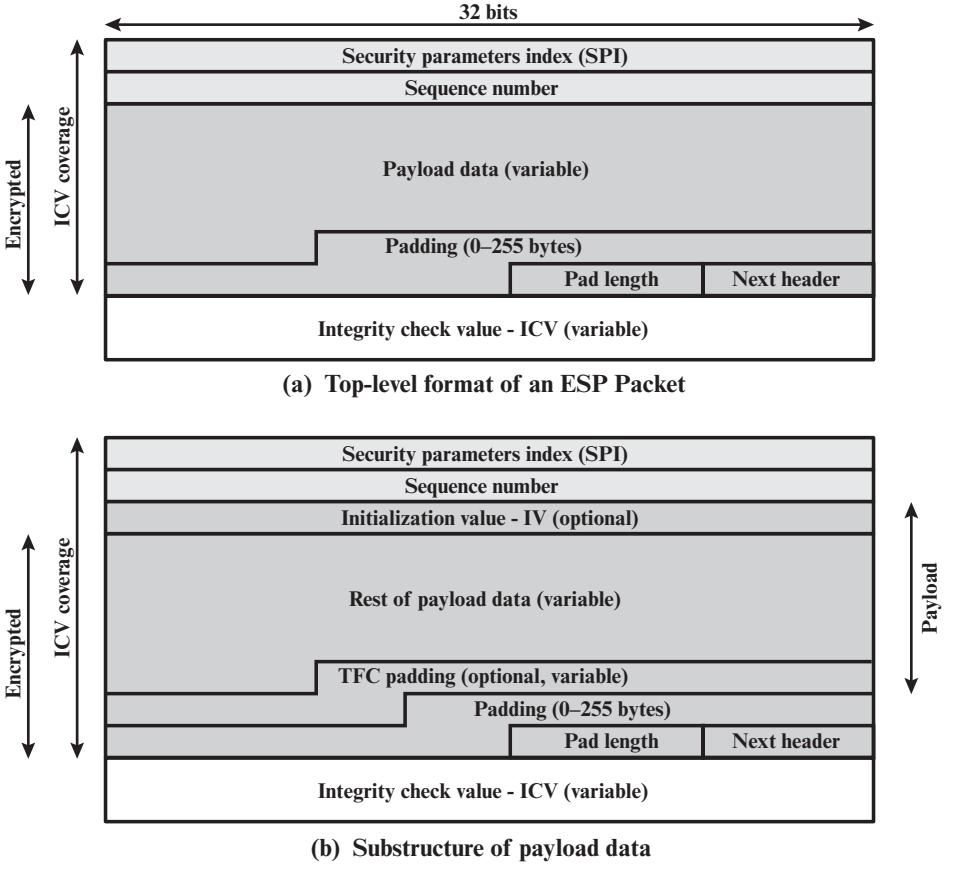


Figure 20.5 ESP Packet Format

ESP Format

Figure 20.5a shows the top-level format of an ESP packet. It contains the following fields.

- **Security Parameters Index (32 bits):** Identifies a security association.
- **Sequence Number (32 bits):** A monotonically increasing counter value; this provides an anti-replay function, as discussed for AH.
- **Payload Data (variable):** This is a transport-level segment (transport mode) or IP packet (tunnel mode) that is protected by encryption.
- **Padding (0–255 bytes):** The purpose of this field is discussed later.
- **Pad Length (8 bits):** Indicates the number of pad bytes immediately preceding this field.
- **Next Header (8 bits):** Identifies the type of data contained in the payload data field by identifying the first header in that payload (e.g., an extension header in IPv6, or an upper-layer protocol such as TCP).
- **Integrity Check Value (variable):** A variable-length field (must be an integral number of 32-bit words) that contains the Integrity Check Value computed over the ESP packet minus the Authentication Data field.

When any combined mode algorithm is employed, the algorithm itself is expected to return both decrypted plaintext and a pass/fail indication for the integrity check. For combined mode algorithms, the ICV that would normally appear at the end of the ESP packet (when integrity is selected) may be omitted. When the ICV is omitted and integrity is selected, it is the responsibility of the combined mode algorithm to encode within the Payload Data an ICV-equivalent means of verifying the integrity of the packet.

Two additional fields may be present in the payload (Figure 20.5b). An **initialization value (IV)**, or nonce, is present if this is required by the encryption or authenticated encryption algorithm used for ESP. If tunnel mode is being used, then the IPsec implementation may add **traffic flow confidentiality (TFC)** padding after the Payload Data and before the Padding field, as explained subsequently.

Encryption and Authentication Algorithms

The Payload Data, Padding, Pad Length, and Next Header fields are encrypted by the ESP service. If the algorithm used to encrypt the payload requires cryptographic synchronization data, such as an initialization vector (IV), then these data may be carried explicitly at the beginning of the Payload Data field. If included, an IV is usually not encrypted, although it is often referred to as being part of the ciphertext.

The ICV field is optional. It is present only if the integrity service is selected and is provided by either a separate integrity algorithm or a combined mode algorithm that uses an ICV. The ICV is computed after the encryption is performed. This order of processing facilitates rapid detection and rejection of replayed or bogus packets by the receiver prior to decrypting the packet, hence potentially reducing the impact of denial of service (DoS) attacks. It also allows for the possibility of parallel processing of packets at the receiver that is decryption can take place in parallel with integrity checking. Note that because the ICV is not protected by encryption, a keyed integrity algorithm must be employed to compute the ICV.

Padding

The Padding field serves several purposes:

- If an encryption algorithm requires the plaintext to be a multiple of some number of bytes (e.g., the multiple of a single block for a block cipher), the Padding field is used to expand the plaintext (consisting of the Payload Data, Padding, Pad Length, and Next Header fields) to the required length.
- The ESP format requires that the Pad Length and Next Header fields be right aligned within a 32-bit word. Equivalently, the ciphertext must be an integer multiple of 32 bits. The Padding field is used to assure this alignment.
- Additional padding may be added to provide partial traffic-flow confidentiality by concealing the actual length of the payload.

Anti-Replay Service

A **replay attack** is one in which an attacker obtains a copy of an authenticated packet and later transmits it to the intended destination. The receipt of duplicate, authenticated IP packets may disrupt service in some way or may have some other

undesired consequence. The Sequence Number field is designed to thwart such attacks. First, we discuss sequence number generation by the sender, and then we look at how it is processed by the recipient.

When a new SA is established, the **sender** initializes a sequence number counter to 0. Each time that a packet is sent on this SA, the sender increments the counter and places the value in the Sequence Number field. Thus, the first value to be used is 1. If anti-replay is enabled (the default), the sender must not allow the sequence number to cycle past $2^{32} - 1$ back to zero. Otherwise, there would be multiple valid packets with the same sequence number. If the limit of $2^{32} - 1$ is reached, the sender should terminate this SA and negotiate a new SA with a new key.

Because IP is a connectionless, unreliable service, the protocol does not guarantee that packets will be delivered in order and does not guarantee that all packets will be delivered. Therefore, the IPsec authentication document dictates that the **receiver** should implement a window of size W, with a default of $W = 64$. The right edge of the window represents the highest sequence number, N, so far received for a valid packet. For any packet with a sequence number in the range from $N - W + 1$ to N that has been correctly received (i.e., properly authenticated), the corresponding slot in the window is marked (Figure 20.6). Inbound processing proceeds as follows when a packet is received:

1. If the received packet falls within the window and is new, the MAC is checked. If the packet is authenticated, the corresponding slot in the window is marked.
2. If the received packet is to the right of the window and is new, the MAC is checked. If the packet is authenticated, the window is advanced so that this sequence number is the right edge of the window, and the corresponding slot in the window is marked.
3. If the received packet is to the left of the window or if authentication fails, the packet is discarded; this is an auditable event.

Transport and Tunnel Modes

Figure 20.7 shows two ways in which the IPsec ESP service can be used. In the upper part of the figure, encryption (and optionally authentication) is provided directly between two hosts. Figure 20.7b shows how tunnel mode operation can be used to set up

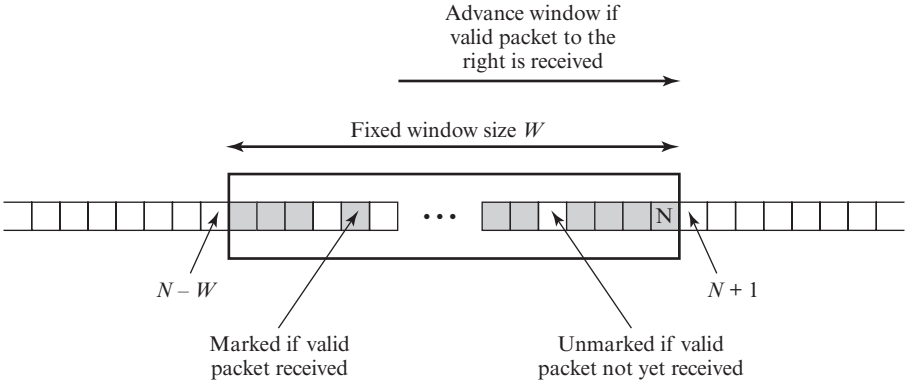


Figure 20.6 Anti-replay Mechanism

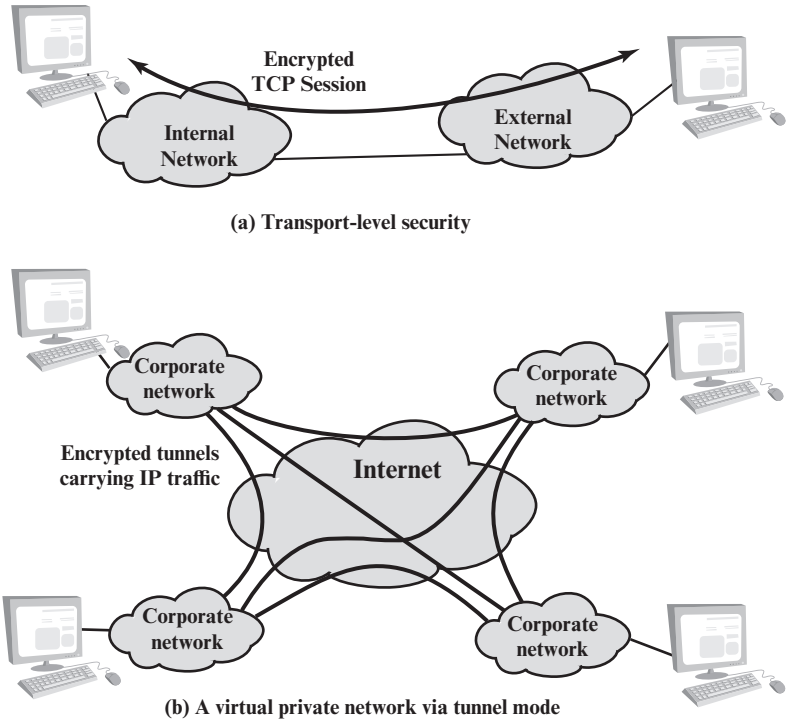


Figure 20.7 Transport-Mode versus Tunnel-Mode Encryptionx

a **virtual private network**. In this example, an organization has four private networks interconnected across the Internet. Hosts on the internal networks use the Internet for transport of data but do not interact with other Internet-based hosts. By terminating the tunnels at the security gateway to each internal network, the configuration allows the hosts to avoid implementing the security capability. The former technique is supported by a transport mode SA, while the latter technique uses a tunnel mode SA.

In this section, we look at the scope of ESP for the two modes. The considerations are somewhat different for IPv4 and IPv6. We use the packet formats of Figure 20.8a as a starting point.

Transport Mode ESP Transport mode ESP is used to encrypt and optionally authenticate the data carried by IP (e.g., a TCP segment), as shown in Figure 20.8b. For this mode using IPv4, the ESP header is inserted into the IP packet immediately prior to the transport-layer header (e.g., TCP, UDP, ICMP), and an ESP trailer (Padding, Pad Length, and Next Header fields) is placed after the IP packet. If authentication is selected, the ESP Authentication Data field is added after the ESP trailer. The entire transport-level segment plus the ESP trailer are encrypted. Authentication covers all of the ciphertext plus the ESP header.

In the context of IPv6, ESP is viewed as an end-to-end payload; that is, it is not examined or processed by intermediate routers. Therefore, the ESP header appears after the IPv6 base header and the hop-by-hop, routing, and fragment extension headers. The destination options extension header could appear before or after the ESP header, depending on the semantics desired. For IPv6, encryption covers

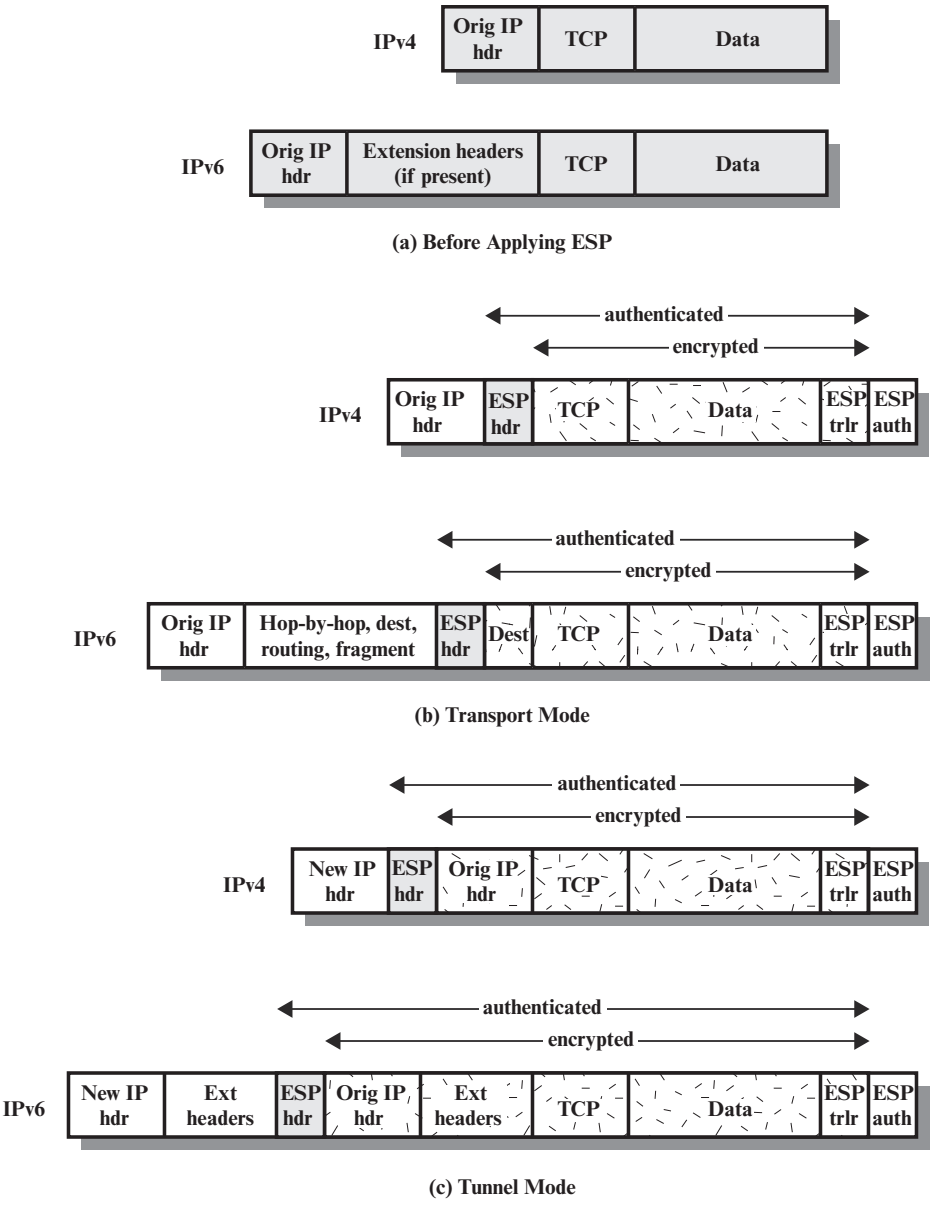


Figure 20.8 Scope of ESP Encryption and Authentication

the entire transport-level segment plus the ESP trailer plus the destination options extension header if it occurs after the ESP header. Again, authentication covers the ciphertext plus the ESP header.

Transport mode operation may be summarized as follows.

1. At the source, the block of data consisting of the ESP trailer plus the entire transport-layer segment is encrypted and the plaintext of this block is replaced

with its ciphertext to form the IP packet for transmission. Authentication is added if this option is selected.

2. The packet is then routed to the destination. Each intermediate router needs to examine and process the IP header plus any plaintext IP extension headers but does not need to examine the ciphertext.
3. The destination node examines and processes the IP header plus any plaintext IP extension headers. Then, on the basis of the SPI in the ESP header, the destination node decrypts the remainder of the packet to recover the plaintext transport-layer segment.

Transport mode operation provides confidentiality for any application that uses it, thus avoiding the need to implement confidentiality in every individual application. One drawback to this mode is that it is possible to do traffic analysis on the transmitted packets.

Tunnel Mode ESP Tunnel mode ESP is used to encrypt an entire IP packet (Figure 20.8c). For this mode, the ESP header is prefixed to the packet and then the packet plus the ESP trailer is encrypted. This method can be used to counter traffic analysis.

Because the IP header contains the destination address and possibly source routing directives and hop-by-hop option information, it is not possible simply to transmit the encrypted IP packet prefixed by the ESP header. Intermediate routers would be unable to process such a packet. Therefore, it is necessary to encapsulate the entire block (ESP header plus ciphertext plus Authentication Data, if present) with a new IP header that will contain sufficient information for routing but not for traffic analysis.

Whereas the transport mode is suitable for protecting connections between hosts that support the ESP feature, the tunnel mode is useful in a configuration that includes a firewall or other sort of security gateway that protects a trusted network from external networks. In this latter case, encryption occurs only between an external host and the security gateway or between two security gateways. This relieves hosts on the internal network of the processing burden of encryption and simplifies the key distribution task by reducing the number of needed keys. Further, it thwarts traffic analysis based on ultimate destination.

Consider a case in which an external host wishes to communicate with a host on an internal network protected by a firewall, and in which ESP is implemented in the external host and the firewalls. The following steps occur for transfer of a transport-layer segment from the external host to the internal host.

1. The source prepares an inner IP packet with a destination address of the target internal host. This packet is prefixed by an ESP header; then the packet and ESP trailer are encrypted and Authentication Data may be added. The resulting block is encapsulated with a new IP header (base header plus optional extensions such as routing and hop-by-hop options for IPv6) whose destination address is the firewall; this forms the outer IP packet.
2. The outer packet is routed to the destination firewall. Each intermediate router needs to examine and process the outer IP header plus any outer IP extension headers but does not need to examine the ciphertext.

3. The destination firewall examines and processes the outer IP header plus any outer IP extension headers. Then, on the basis of the SPI in the ESP header, the destination node decrypts the remainder of the packet to recover the plaintext inner IP packet. This packet is then transmitted in the internal network.
4. The inner packet is routed through zero or more routers in the internal network to the destination host.

Figure 20.9 shows the protocol architecture for the two modes.

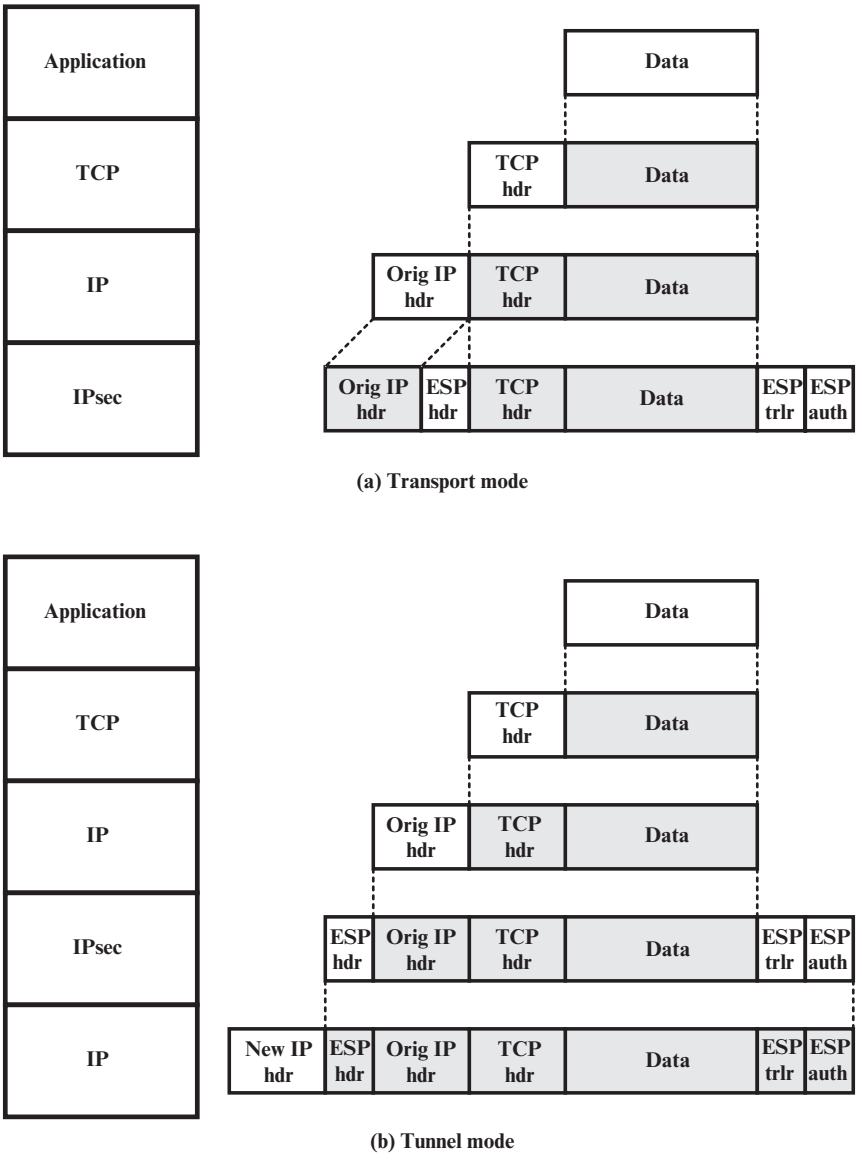


Figure 20.9 Protocol Operation for ESP

20.4 COMBINING SECURITY ASSOCIATIONS

An individual SA can implement either the AH or ESP protocol but not both. Sometimes a particular traffic flow will call for the services provided by both AH and ESP. Further, a particular traffic flow may require IPsec services between hosts and, for that same flow, separate services between security gateways, such as firewalls. In all of these cases, multiple SAs must be employed for the same traffic flow to achieve the desired IPsec services. The term *security association bundle* refers to a sequence of SAs through which traffic must be processed to provide a desired set of IPsec services. The SAs in a bundle may terminate at different endpoints or at the same endpoints.

Security associations may be combined into bundles in two ways:

- **Transport adjacency:** Refers to applying more than one security protocol to the same IP packet without invoking tunneling. This approach to combining AH and ESP allows for only one level of combination; further nesting yields no added benefit since the processing is performed at one IPsec instance: the (ultimate) destination.
- **Iterated tunneling:** Refers to the application of multiple layers of security protocols effected through IP tunneling. This approach allows for multiple levels of nesting, since each tunnel can originate or terminate at a different IPsec site along the path.

The two approaches can be combined, for example, by having a transport SA between hosts travel part of the way through a tunnel SA between security gateways.

One interesting issue that arises when considering SA bundles is the order in which authentication and encryption may be applied between a given pair of endpoints and the ways of doing so. We examine that issue next. Then we look at combinations of SAs that involve at least one tunnel.

Authentication Plus Confidentiality

Encryption and authentication can be combined in order to transmit an IP packet that has both confidentiality and authentication between hosts. We look at several approaches.

ESP with Authentication Option This approach is illustrated in Figure 20.8. In this approach, the user first applies ESP to the data to be protected and then appends the authentication data field. There are actually two subcases:

- **Transport mode ESP:** Authentication and encryption apply to the IP payload delivered to the host, but the IP header is not protected.
- **Tunnel mode ESP:** Authentication applies to the entire IP packet delivered to the outer IP destination address (e.g., a firewall), and authentication is performed at that destination. The entire inner IP packet is protected by the privacy mechanism for delivery to the inner IP destination.

For both cases, authentication applies to the ciphertext rather than the plaintext.

Transport Adjacency Another way to apply authentication after encryption is to use two bundled transport SAs, with the inner being an ESP SA and the outer being an AH SA. In this case, ESP is used without its authentication option. Because the inner SA is a transport SA, encryption is applied to the IP payload. The resulting packet consists of an IP header (and possibly IPv6 header extensions) followed by an ESP. AH is then applied in transport mode, so that authentication covers the ESP plus the original IP header (and extensions) except for mutable fields. The advantage of this approach over simply using a single ESP SA with the ESP authentication option is that the authentication covers more fields, including the source and destination IP addresses. The disadvantage is the overhead of two SAs versus one SA.

Transport-Tunnel Bundle The use of authentication prior to encryption might be preferable for several reasons. First, because the authentication data are protected by encryption, it is impossible for anyone to intercept the message and alter the authentication data without detection. Second, it may be desirable to store the authentication information with the message at the destination for later reference. It is more convenient to do this if the authentication information applies to the unencrypted message; otherwise the message would have to be reencrypted to verify the authentication information.

One approach to applying authentication before encryption between two hosts is to use a bundle consisting of an inner AH transport SA and an outer ESP tunnel SA. In this case, authentication is applied to the IP payload plus the IP header (and extensions) except for mutable fields. The resulting IP packet is then processed in tunnel mode by ESP; the result is that the entire, authenticated inner packet is encrypted and a new outer IP header (and extensions) is added.

Basic Combinations of Security Associations

The IPsec Architecture document lists four examples of combinations of SAs that must be supported by compliant IPsec hosts (e.g., workstation, server) or security gateways (e.g., firewall, router). These are illustrated in Figure 20.10. The lower part of each case in the figure represents the physical connectivity of the elements; the upper part represents logical connectivity via one or more nested SAs. Each SA can be either AH or ESP. For host-to-host SAs, the mode may be either transport or tunnel; otherwise it must be tunnel mode.

Case 1. All security is provided between end systems that implement IPsec. For any two end systems to communicate via an SA, they must share the appropriate secret keys. Among the possible combinations are

a. AH in transport mode
b. ESP in transport mode
c. ESP followed by AH in transport mode (an ESP SA inside an AH SA)
d. Any one of a, b, or c inside an AH or ESP in tunnel mode

We have already discussed how these various combinations can be used to support authentication, encryption, authentication before encryption, and authentication after encryption.

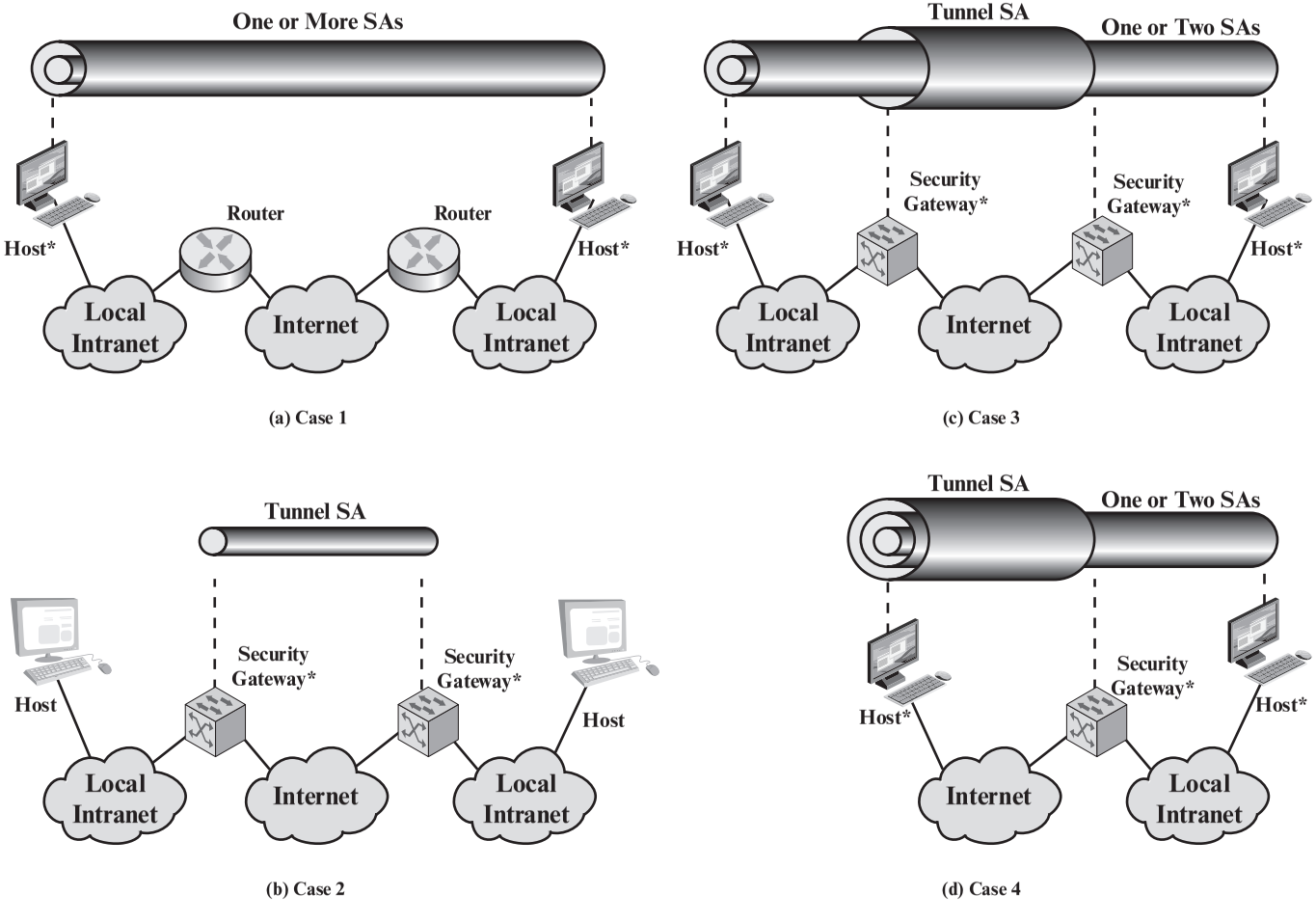


Figure 20.10 Basic Combinations of Security Associations

Case 2. Security is provided only between gateways (routers, firewalls, etc.) and no hosts implement IPsec. This case illustrates simple virtual private network support. The security architecture document specifies that only a single tunnel SA is needed for this case. The tunnel could support AH, ESP, or ESP with the authentication option. Nested tunnels are not required, because the IPsec services apply to the entire inner packet.

Case 3. This builds on case 2 by adding end-to-end security. The same combinations discussed for cases 1 and 2 are allowed here. The gateway-to-gateway tunnel provides either authentication, confidentiality, or both for all traffic between end systems. When the gateway-to-gateway tunnel is ESP, it also provides a limited form of traffic confidentiality. Individual hosts can implement any additional IPsec services required for given applications or given users by means of end-to-end SAs.

Case 4. This provides support for a remote host that uses the Internet to reach an organization's firewall and then to gain access to some server or workstation behind the firewall. Only tunnel mode is required between the remote host and the firewall. As in case 1, one or two SAs may be used between the remote host and the local host.

20.5 INTERNET KEY EXCHANGE

The key management portion of IPsec involves the determination and distribution of secret keys. A typical requirement is four keys for communication between two applications: transmit and receive pairs for both integrity and confidentiality. The IPsec Architecture document mandates support for two types of key management:

- **Manual:** A system administrator manually configures each system with its own keys and with the keys of other communicating systems. This is practical for small, relatively static environments.
- **Automated:** An automated system enables the on-demand creation of keys for SAs and facilitates the use of keys in a large distributed system with an evolving configuration.

The default automated key management protocol for IPsec is referred to as ISAKMP/Oakley and consists of the following elements:

- **Oakley Key Determination Protocol:** Oakley is a key exchange protocol based on the Diffie–Hellman algorithm but providing added security. Oakley is generic in that it does not dictate specific formats.
- **Internet Security Association and Key Management Protocol (ISAKMP):** ISAKMP provides a framework for Internet key management and provides the specific protocol support, including formats, for negotiation of security attributes.

ISAKMP by itself does not dictate a specific key exchange algorithm; rather, ISAKMP consists of a set of message types that enable the use of a variety of key exchange algorithms. Oakley is the specific key exchange algorithm mandated for use with the initial version of ISAKMP.

In IKEv2, the terms Oakley and ISAKMP are no longer used, and there are significant differences from the use of Oakley and ISAKMP in IKEv1. Nevertheless, the basic functionality is the same. In this section, we describe the IKEv2 specification.

Key Determination Protocol

IKE key determination is a refinement of the Diffie–Hellman key exchange algorithm. Recall that Diffie–Hellman involves the following interaction between users A and B. There is prior agreement on two global parameters: q, a large prime number; and α, a primitive root of q. A selects a random integer X_A as its private key and transmits to B its public key $Y_A = \alpha^{X_A} \bmod q$. Similarly, B selects a random integer X_B as its private key and transmits to A its public key $Y_B = \alpha^{X_B} \bmod q$. Each side can now compute the secret session key:

$$K = (Y_B)^{X_A} \bmod q = (Y_A)^{X_B} \bmod q = \alpha^{X_A X_B} \bmod q$$

The Diffie–Hellman algorithm has two attractive features:

- Secret keys are created only when needed. There is no need to store secret keys for a long period of time, exposing them to increased vulnerability.
- The exchange requires no pre-existing infrastructure other than an agreement on the global parameters.

However, there are a number of weaknesses to Diffie–Hellman, as pointed out in [HUIT98].

- It does not provide any information about the identities of the parties.
- It is subject to a man-in-the-middle attack, in which a third party C impersonates B while communicating with A and impersonates A while communicating with B. Both A and B end up negotiating a key with C, which can then listen to and pass on traffic. The man-in-the-middle attack proceeds as
  1. B sends his public key Y_B in a message addressed to A (see Figure 10.2).
  2. The enemy (E) intercepts this message. E saves B's public key and sends a message to A that has B's User ID but E's public key Y_E. This message is sent in such a way that it appears as though it was sent from B's host system. A receives E's message and stores E's public key with B's User ID. Similarly, E sends a message to B with E's public key, purporting to come from A.
  3. B computes a secret key K_1 based on B's private key and Y_E. A computes a secret key K_2 based on A's private key and Y_E. E computes K_1 using E's secret key X_E and Y_B and computers K_2 using X_E and Y_A.
  4. From now on, E is able to relay messages from A to B and from B to A, appropriately changing their encipherment en route in such a way that neither A nor B will know that they share their communication with E.
- It is computationally intensive. As a result, it is vulnerable to a clogging attack, in which an opponent requests a high number of keys. The victim spends considerable computing resources doing useless modular exponentiation rather than real work.

IKE key determination is designed to retain the advantages of Diffie–Hellman, while countering its weaknesses.

Features of IKE key determination The IKE key determination algorithm is characterized by five important features:

1. It employs a mechanism known as cookies to thwart clogging attacks.
2. It enables the two parties to negotiate a *group*; this, in essence, specifies the global parameters of the Diffie–Hellman key exchange.
3. It uses nonces to ensure against replay attacks.
4. It enables the exchange of Diffie–Hellman public key values.
5. It authenticates the Diffie–Hellman exchange to thwart man-in-the-middle attacks.

We have already discussed Diffie–Hellman. Let us look at the remainder of these elements in turn. First, consider the problem of clogging attacks. In this attack, an opponent forges the source address of a legitimate user and sends a public Diffie–Hellman key to the victim. The victim then performs a modular exponentiation to compute the secret key. Repeated messages of this type can *clog* the victim's system with useless work. The **cookie exchange** requires that each side send a pseudorandom number, the cookie, in the initial message, which the other side acknowledges. This acknowledgment must be repeated in the first message of the Diffie–Hellman key exchange. If the source address was forged, the opponent gets no answer. Thus, an opponent can only force a user to generate acknowledgments and not to perform the Diffie–Hellman calculation.

IKE mandates that cookie generation satisfy three basic requirements:

1. The cookie must depend on the specific parties. This prevents an attacker from obtaining a cookie using a real IP address and UDP port and then using it to swamp the victim with requests from randomly chosen IP addresses or ports.
2. It must not be possible for anyone other than the issuing entity to generate cookies that will be accepted by that entity. This implies that the issuing entity will use local secret information in the generation and subsequent verification of a cookie. It must not be possible to deduce this secret information from any particular cookie. The point of this requirement is that the issuing entity need not save copies of its cookies, which are then more vulnerable to discovery, but can verify an incoming cookie acknowledgment when it needs to.
3. The cookie generation and verification methods must be fast to thwart attacks intended to sabotage processor resources.

The recommended method for creating the cookie is to perform a fast hash (e.g., MD5) over the IP Source and Destination addresses, the UDP Source and Destination ports, and a locally generated secret value.

IKE key determination supports the use of different groups for the Diffie–Hellman key exchange. Each group includes the definition of the two global parameters and the identity of the algorithm. The current specification includes the following groups.

- Modular exponentiation with a 768-bit modulus

$$q = 2^{768} - 2^{704} - 1 + 2^{64} \times (\lfloor 2^{638} \times \pi \rfloor + 149686)$$
$$\alpha = 2$$

- Modular exponentiation with a 1024-bit modulus

$$q = 2^{1024} - 2^{960} - 1 + 2^{64} \times (\lfloor 2^{894} \times \pi \rfloor + 129093)$$
$$\alpha = 2$$

- Modular exponentiation with a 1536-bit modulus
  - Parameters to be determined
- Elliptic curve group over 2^{155}
  - Generator (hexadecimal): X = 7B, Y = 1C8
  - Elliptic curve parameters (hexadecimal): A = 0, Y = 7338F
- Elliptic curve group over 2^{185}
  - Generator (hexadecimal): X = 18, Y = D
  - Elliptic curve parameters (hexadecimal): A = 0, Y = 1EE9

The first three groups are the classic Diffie–Hellman algorithm using modular exponentiation. The last two groups use the elliptic curve analog to Diffie–Hellman, which was described in Chapter 10.

IKE key determination employs **nonces** to ensure against replay attacks. Each nonce is a locally generated pseudorandom number. Nonces appear in responses and are encrypted during certain portions of the exchange to secure their use.

Three different **authentication** methods can be used with IKE key determination:

- **Digital signatures:** The exchange is authenticated by signing a mutually obtainable hash; each party encrypts the hash with its private key. The hash is generated over important parameters, such as user IDs and nonces.
- **Public-key encryption:** The exchange is authenticated by encrypting parameters such as IDs and nonces with the sender's private key.
- **Symmetric-key encryption:** A key derived by some out-of-band mechanism can be used to authenticate the exchange by symmetric encryption of exchange parameters.

IKEv2 Exchanges The IKEv2 protocol involves the exchange of messages in pairs. The first two pairs of exchanges are referred to as the **initial exchanges** (Figure 20.11a). In the first exchange, the two peers exchange information concerning cryptographic algorithms and other security parameters they are willing to use along with nonces and Diffie–Hellman (DH) values. The result of this exchange is to set up a special SA called the IKE SA (see Figure 20.2). This SA defines parameters for a secure channel between the peers over which subsequent message exchanges take place. Thus, all subsequent IKE message exchanges are protected by encryption and message authentication. In the second exchange, the two parties authenticate one another and set up a first IPsec SA to be placed in the SADB and used for

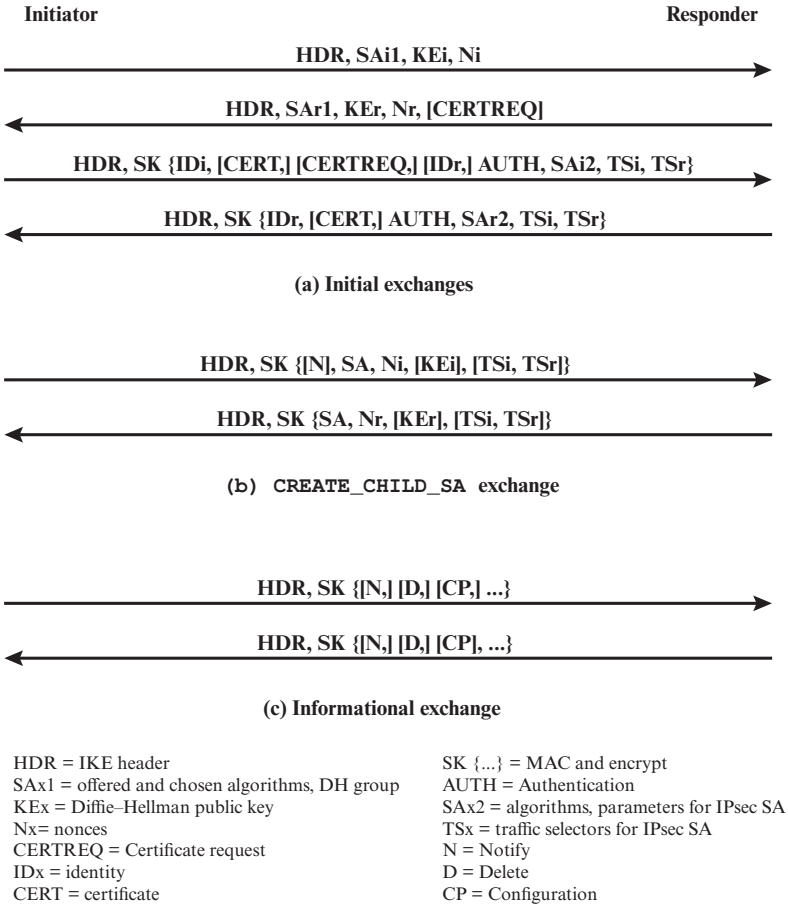


Figure 20.11 IKEv2 Exchanges

protecting ordinary (i.e. non-IKE) communications between the peers. Thus, four messages are needed to establish the first SA for general use.

The **CREATE_CHILD_SA exchange** can be used to establish further SAs for protecting traffic. The **informational exchange** is used to exchange management information, IKEv2 error messages, and other notifications.

Header and Payload Formats

IKE defines procedures and packet formats to establish, negotiate, modify, and delete security associations. As part of SA establishment, IKE defines payloads for exchanging key generation and authentication data. These payload formats provide a consistent framework independent of the specific key exchange protocol, encryption algorithm, and authentication mechanism.

IKE Header Format An IKE message consists of an IKE header followed by one or more payloads. All of this is carried in a transport protocol. The specification dictates that implementations must support the use of UDP for the transport protocol.

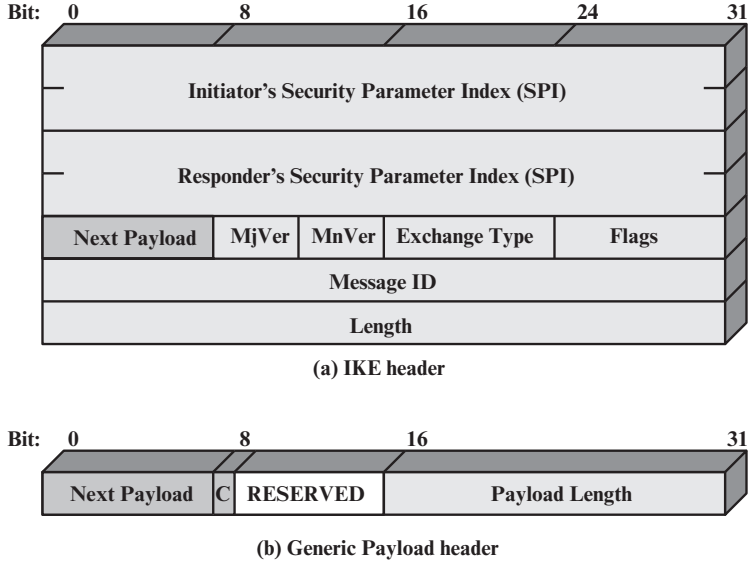


Figure 20.12 IKE Formats

Figure 20.12a shows the header format for an IKE message. It consists of the following fields.

- **Initiator SPI (64 bits):** A value chosen by the initiator to identify a unique IKE security association (SA).
- **Responder SPI (64 bits):** A value chosen by the responder to identify a unique IKE SA.
- **Next Payload (8 bits):** Indicates the type of the first payload in the message; payloads are discussed in the next subsection.
- **Major Version (4 bits):** Indicates major version of IKE in use.
- **Minor Version (4 bits):** Indicates minor version in use.
- **Exchange Type (8 bits):** Indicates the type of exchange; these are discussed later in this section.
- **Flags (8 bits):** Indicates specific options set for this IKE exchange. Three bits are defined so far. The initiator bit indicates whether this packet is sent by the SA initiator. The version bit indicates whether the transmitter is capable of using a higher major version number than the one currently indicated. The response bit indicates whether this is a response to a message containing the same message ID.
- **Message ID (32 bits):** Used to control retransmission of lost packets and matching of requests and responses.
- **Length (32 bits):** Length of total message (header plus all payloads) in octets.

IKE Payload Types All IKE payloads begin with the same generic payload header shown in Figure 20.12b. The Next Payload field has a value of 0 if this is the last

payload in the message; otherwise its value is the type of the next payload. The Payload Length field indicates the length in octets of this payload, including the generic payload header.

The critical bit is 0 if the sender wants the recipient to skip this payload if it does not understand the payload type code in the Next Payload field of the previous payload. It is set to 1 if the sender wants the recipient to reject this entire message if it does not understand the payload type.

Table 20.3 summarizes the payload types defined for IKE and lists the fields, or parameters, that are part of each payload. The **SA payload** is used to begin the establishment of an SA. The payload has a complex, hierarchical structure. The payload may contain multiple proposals. Each proposal may contain multiple protocols. Each protocol may contain multiple transforms. And each transform may contain multiple attributes. These elements are formatted as substructures within the payload as follows.

- **Proposal:** This substructure includes a proposal number, a protocol ID (AH, ESP, or IKE), an indicator of the number of transforms, and then a transform substructure. If more than one protocol is to be included in a proposal, then there is a subsequent proposal substructure with the same proposal number.
- **Transform:** Different protocols support different transform types. The transforms are used primarily to define cryptographic algorithms to be used with a particular protocol.
- **Attribute:** Each transform may include attributes that modify or complete the specification of the transform. An example is key length.

Table 20.3 IKE Payload Types

Type	Parameters
Security Association	Proposals
Key Exchange	DH Group #, Key Exchange Data
Identification	ID Type, ID Data
Certificate	Cert Encoding, Certificate Data
Certificate Request	Cert Encoding, Certification Authority
Authentication	Auth Method, Authentication Data
Nonce	Nonce Data
Notify	Protocol-ID, SPI Size, Notify Message Type, SPI, Notification Data
Delete	Protocol-ID, SPI Size, # of SPIs, SPI (one or more)
Vendor ID	Vendor ID
Traffic Selector	Number of TSs, Traffic Selectors
Encrypted	IV, Encrypted IKE payloads, Padding, Pad Length, ICV
Configuration	CFG Type, Configuration Attributes
Extensible Authentication Protocol	EAP Message

The **Key Exchange payload** can be used for a variety of key exchange techniques, including Oakley, Diffie–Hellman, and the RSA-based key exchange used by PGP. The Key Exchange data field contains the data required to generate a session key and is dependent on the key exchange algorithm used.

The **Identification payload** is used to determine the identity of communicating peers and may be used for determining authenticity of information. Typically the ID Data field will contain an IPv4 or IPv6 address.

The **Certificate payload** transfers a public-key certificate. The Certificate Encoding field indicates the type of certificate or certificate-related information, which may include the following:

- PKCS #7 wrapped X.509 certificate
- PGP certificate
- DNS signed key
- X.509 certificate—signature
- X.509 certificate—key exchange
- Kerberos tokens
- Certificate Revocation List (CRL)
- Authority Revocation List (ARL)
- SPKI certificate

At any point in an IKE exchange, the sender may include a **Certificate Request** payload to request the certificate of the other communicating entity. The payload may list more than one certificate type that is acceptable and more than one certificate authority that is acceptable.

The **Authentication** payload contains data used for message authentication purposes. The authentication method types so far defined are RSA digital signature, shared-key message integrity code, and DSS digital signature.

The **Nonce** payload contains random data used to guarantee liveness during an exchange and to protect against replay attacks.

The **Notify** payload contains either error or status information associated with this SA or this SA negotiation. The following table lists the IKE notify messages.

Error Messages	Status Messages
Unsupported Critical	Initial Contact
Payload	Set Window Size
Invalid IKE SPI	Additional TS Possible
Invalid Major Version	IPCOMP Supported
Invalid Syntax	NAT Detection Source IP
Invalid Payload Type	NAT Detection Destination IP
Invalid Message ID	Cookie
Invalid SPI	Use Transport Mode

Error Messages	Status Messages
No Proposal Chosen	HTTP Cert Lookup Supported
Invalid KE Payload	Rekey SA
Authentication Failed	ESP TFC Padding Not Supported
Single Pair Required	Non First Fragments Also
No Additional SAS	
Internal Address Failure	
Failed CP Required	
TS Unacceptable	
Invalid Selectors	

The **Delete** payload indicates one or more SAs that the sender has deleted from its database and that therefore are no longer valid.

The **Vendor ID** payload contains a vendor-defined constant. The constant is used by vendors to identify and recognize remote instances of their implementations. This mechanism allows a vendor to experiment with new features while maintaining backward compatibility.

The **Traffic Selector** payload allows peers to identify packet flows for processing by IPsec services.

The **Encrypted** payload contains other payloads in encrypted form. The encrypted payload format is similar to that of ESP. It may include an IV if the encryption algorithm requires it and an ICV if authentication is selected.

The **Configuration** payload is used to exchange configuration information between IKE peers.

The **Extensible Authentication Protocol (EAP)** payload allows IKE SAs to be authenticated using EAP, which was discussed in Chapter 16.

20.6 CRYPTOGRAPHIC SUITES

The IPsecv3 and IKEv3 protocols rely on a variety of types of cryptographic algorithms. As we have seen in this book, there are many cryptographic algorithms of each type, each with a variety of parameters, such as key size. To promote interoperability, two RFCs define recommended suites of cryptographic algorithms and parameters for various applications.

RFC 4308 defines two cryptographic suites for establishing virtual private networks. Suite VPN-A matches the commonly used corporate VPN security used in older IKEv1 implementations at the time of the issuance of IKEv2 in 2005. Suite VPN-B provides stronger security and is recommended for new VPNs that implement IPsecv3 and IKEv2.

Table 20.4a lists the algorithms and parameters for the two suites. There are several points to note about these two suites. Note that for symmetric cryptography,

Table 20.4 Cryptographic Suites for IPsec

	VPN-A	VPN-B
ESP encryption	3DES-CBC	AES-CBC (128-bit key)
ESP integrity	HMAC-SHA1-96	AES-XCBC-MAC-96
IKE encryption	3DES-CBC	AES-CBC (128-bit key)
IKE PRF	HMAC-SHA1	AES-XCBC-PRF-128
IKE Integrity	HMAC-SHA1-96	AES-XCBC-MAC-96
IKE DH group	1024-bit MODP	2048-bit MODP

(a) Virtual private networks (RFC 4308)

	GCM-128	GCM-256	GMAC-128	GMAC-256
ESP encryption/ Integrity	AES-GCM (128-bit key)	AES-GCM (256-bit key)	Null	Null
ESP integrity	Null	Null	AES-GMAC (128-bit key)	AES-GMAC (256-bit key)
IKE encryption	AES-CBC (128-bit key)	AES-CBC (256-bit key)	AES-CBC (128-bit key)	AES-CBC (256-bit key)
IKE PRF	HMAC-SHA-256	HMAC-SHA-384	HMAC-SHA-256	HMAC-SHA-384
IKE Integrity	HMAC-SHA-256-128	HMAC-SHA-384-192	HMAC-SHA-256-128	HMAC-SHA-384-192
IKE DH group	256-bit random ECP	384-bit random ECP	256-bit random ECP	384-bit random ECP

(b) NSA Suite B (RFC 6379)

VPN-A relies on 3DES and HMAC, while VPN-B relies exclusively on AES. Three types of secret-key algorithms are used:

- **Encryption:** For encryption, the cipher block chaining (CBC) mode is used.
- **Message authentication:** For message authentication, VPN-A relies on HMAC with SHA-1 with the output truncated to 96 bits. VPN-B relies on a variant of CMAC with the output truncated to 96 bits.
- **Pseudorandom function:** IKEv2 generates pseudorandom bits by repeated use of the MAC used for message authentication.

RFC 6379 defines four optional cryptographic suites that are compatible with the United States National Security Agency's Suite B specifications. In 2005, the NSA issued Suite B, which defined the algorithms and strengths needed to protect both sensitive but unclassified (SBU) and classified information for use in its Cryptographic Modernization program [LATT09]. The four suites defined in RFC 6379 provide choices for ESP and IKE. The four suites are differentiated by the choice of cryptographic algorithm strengths and a choice of whether ESP is to provide both confidentiality and integrity or integrity only. All of the suites offer greater protection than the two VPN suites defined in RFC 4308.

Table 20.4b lists the algorithms and parameters for the two suites. As with RFC 4308, three categories of secret key algorithms are listed:

- **Encryption:** For ESP, authenticated encryption is provided using the GCM mode with either 128-bit or 256-bit AES keys. For IKE encryption, CBC is used, as it was for the VPN suites.
- **Message authentication:** For ESP, if only authentication is required, then GMAC is used. As discussed in Chapter 12, GMAC is simply the authentication portion of GMC. For IKE, message authentication is provided using HMAC with one of the SHA-3 hash functions.
- **Pseudorandom function:** As with the VPN suites, IKEv2 in these suites generates pseudorandom bits by repeated use of the MAC used for message authentication.

For the Diffie–Hellman algorithm, the use of elliptic curve groups modulo a prime is specified. For authentication, elliptic curve digital signatures are listed. The original IKEv2 documents used RSA-based digital signatures. Equivalent or greater strength can be achieved using ECC with fewer key bits.

20.7 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

anti-replay service	Internet Security Association and Key Management Protocol (ISAKMP)	Oakley key determination protocol
Authentication Header (AH)	IP Security (IPsec)	replay attack
Encapsulating Security Payload (ESP)	IPv4	security association (SA)
Internet Key Exchange (IKE)	IPv6	transport mode
		tunnel mode

Review Questions

20.1 List and briefly describe some benefits of IPsec.
20.2 List and briefly define different categories of IPsec documents.
20.3 What parameters identify an SA and what parameters characterize the nature of a particular SA?
20.4 What is the difference between transport mode and tunnel mode?
20.5 What are the types of secret key algorithm used in IPsec?
20.6 Why does ESP include a padding field?
20.7 What are the basic approaches to bundling SAs?
20.8 What are the roles of the Oakley key determination protocol and ISAKMP in IPsec?

Problems

20.1 Describe and explain each of the entries in Table 20.2.

20.2 Draw a figure similar to Figure 20.8 for AH.

20.3 List the major security services provided by AH and ESP, respectively.

20.4 In discussing AH processing, it was mentioned that not all of the fields in an IP header are included in MAC calculation.

- **a.** For each of the fields in the IPv4 header, indicate whether the field is immutable, mutable but predictable, or mutable (zeroed prior to ICV calculation).
- **b.** Do the same for the IPv6 header.
- **c.** Do the same for the IPv6 extension headers.

In each case, justify your decision for each field.

20.5 Suppose that the current replay window spans from 120 to 530.

- **a.** If the next incoming authenticated packet has sequence number 340, what will the receiver do with the packet, and what will be the parameters of the window after that?
- **b.** If instead the next incoming authenticated packet has sequence number 598, what will the receiver do with the packet, and what will be the parameters of the window after that?
- **c.** If instead the next incoming authenticated packet has sequence number 110, what will the receiver do with the packet, and what will be the parameters of the window after that?

20.6 When tunnel mode is used, a new outer IP header is constructed. For both IPv4 and IPv6, indicate the relationship of each outer IP header field and each extension header in the outer packet to the corresponding field or extension header of the inner IP packet. That is, indicate which outer values are derived from inner values and which are constructed independently of the inner values.

20.7 End-to-end authentication and encryption are desired between two hosts. Draw figures similar to Figure 20.8 that show each of the following.

- **a.** Transport adjacency with encryption applied before authentication.
- **b.** A transport SA bundled inside a tunnel SA with encryption applied before authentication.
- **c.** A transport SA bundled inside a tunnel SA with authentication applied before encryption.

20.8 The IPsec architecture document states that when two transport mode SAs are bundled to allow both AH and ESP protocols on the same end-to-end flow, only one ordering of security protocols seems appropriate: performing the ESP protocol before performing the AH protocol. Why is this approach recommended rather than authentication before encryption?

20.9 For the IKE key exchange, indicate which parameters in each message go in which ISAKMP payload types.

20.10 Where does IPsec reside in a protocol stack?