CHAPTER 3

802.11 Security Summary

This chapter discusses 802.11 security for customers currently investigating an enterprise wireless LAN (WLAN) deployment. This chapter focuses on the most current enterprise security features that are available for 802.11 wireless networks. For example, this guide focuses on methods such as Wi-Fi Protected Access (WPA) and WPA2, and spends little time on Wired Equivalent Privacy (WEP).

Regulation, Standards, and Industry Certifications

As with most networking systems, various standards apply, which most often come from one of two different standards bodies: the Institute of Electrical and Electronics Engineers (IEEE) and the Internet Engineering Task Force (IETF). The 802.11 standards defined by the IEEE and the Extensible Authentication Protocol (EAP) methods defined by the IETF are two of the core standards introduced in support of secure WLAN deployments.

IEEE

The IEEE defines the 802.11 group of standards. The original 802.11 standard was published in 1999. Subsequent amendments include adding physical layer implementations and providing greater bit rates (802.11b, 802.11a, and 802.11g), adding QoS enhancements (802.11e), and adding security enhancements (802.11i). This guide focuses on the security enhancements in 802.11i.

The IEEE also defines the 802.1X standard for port security, which is used in 802.11i for authentication of WLAN clients.

IETF

The main IETF RFCs and drafts associated with 802.11 are based on EAP. The advantage of EAP is that it decouples the authentication protocol from its transport. EAP can be carried in 802.1X frames, PPP frames, UDP packets, or RADIUS sessions.

In 802.11 networks, EAP is transported across the WLAN in 802.1X frames and from the Wireless LAN Controller (WLC) to the Authentication, Authorization, and Accounting (AAA) server in the RADIUS protocol, thus providing end-to-end EAP authentication between the WLAN client and the AAA server. This is discussed in more detail later in this guide.

Wi-Fi Alliance

It is typical in core networks to find multiple single-vendor platforms whose integration has largely been achieved as part of product testing by the vendor. However, in cases where various vendor platforms are being integrated, it is usually the responsibility of network engineers/administrators to understand the capabilities of each device with regard to interoperability with other vendor devices.

When systems involve client devices, such as in WLANs, it is common for industry bodies to be formed to certify interoperability because the standards often leave room for interpretation by vendors that might also specify optional features. By certifying basic device behavior, customers are given a reasonable level of assurance that two devices from different vendors are interoperable.

The Wi-Fi Alliance (http://www.wi-fi.org) is an industry body that certifies WLAN device interoperability through its Wi-Fi, Wi-Fi Protected Access (WPA), Wi-Fi Protected Access 2 (WPA2), and Wi-Fi Multimedia (WMM) certification programs.

The WPA standard was developed to address the weakness in the WEP encryption process, which existed before the ratification of the 802.11i workgroup standard. One of the key goals in the development of WPA was to ensure backward compatibility with WEP-based hardware. To that end, the WPA standard still uses the base RC4 encryption method used in WEP, but adds keying enhancements and message integrity check improvements to address the weaknesses in WEP.

WPA2 is based on the ratified 802.11i standard and uses Advanced Encryption Standard-Counter Mode with Cipher Block Chaining Message Authentication Code Protocol (AES CCMP) encryption at its core. WPA2 requires new client and AP hardware. Given current upgrade cycles for laptops and other client devices, it can be expected that a mixture of WPA and WPA2 environments will co-exist for some time. In a green field enterprise deployment, it is expected that customers will deploy WPA2 devices from the start.

Cisco Compatible Extensions

The Cisco Compatible Extensions (CCX) program helps promote the widespread availability of client devices that are interoperable with a Cisco WLAN infrastructure and takes advantage of Cisco-specific innovations for enhanced security, mobility, quality of service (QoS), and network management.

The CCX extensions build on the 802.11 and IETF standards, in addition to Wi-Fi Alliance certifications to create a superset of WLAN features, as shown in Figure 3-1. Even if a customer is not planning to deploy a Cisco Unified Wireless Network, the use of CCX-compatible cards is a wise choice because it offers a simple way of tracking the standards supported and certifications associated with WLAN client devices.

Figure 3-1 CCX Structure

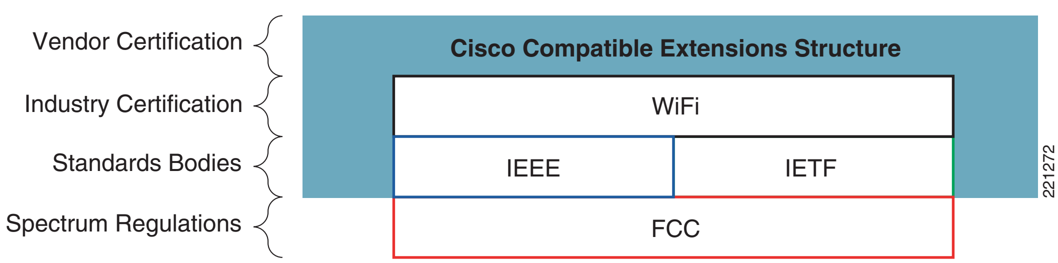


Table 3-1 shows a summary of the security features associated with each CCX certification level. The CCX certification not only specifies which Wi-Fi certifications are applicable, but also which EAP supplicants have been tested as part of the CCX certification.

The complete CCX version table can be found at the following URL:
http://www.cisco.com/web/partners/pr46/pr147/program_additional_information_new_release_features.html

Table 3-1 CCX Security Features Example

Security	v1	v2	v3	v4	ASD
WEP	x	x	x	x	
IEEE 802.1X	x	x	x	x	x
LEAP	x	x	x	x	x
PEAP with EAP-GTC (PEAP-GTC)		x	x	x	optional
EAP-FAST			x	x	x
PEAP with EAP-MSCHAPv2 (PEAP-MSCHAP)				x	
EAP-TLS ASD requires either LEAP, EAP-Fast, or EAP-TLS				x	x
Cisco TKIP (encryption)	x				
WiFi Protected Access (WPA): 802.1X + WPA TKIP		x	x	x	
With LEAP (ASD requires either LEAP, EAP-Fast, or EAP-TLS)		x	x	x	x
With PEAP-GTC		x	x	x	
With EAP-FAST (ASD requires either LEAP, EAP-Fast, or EAP-TLS)			x	x	x
With PEAP-MSCHAP				x	
With EAP-TLS (ASD requires either LEAP, EAP-Fast, or EAP-TLS)				x	x
IEEE 802.11i–WPA2: 802.1X + AES			x	x	
With LEAP			x	x	
With PEAP-GTC			x	x	
With EAP-FAST			x	x	
With PEAP-MSCHAP and EAP-TLS				x	
Network Admission Control (NAC)				x	

221405

CCX v5 provides additional security features such as client-side management frame protection (MFP), which is described in Management Frame Protection, page 4-16.

Federal Wireless Security Policy and FIPS Certification

The mission-critical nature of the United States Department of Defense (DoD) requires it to have exacting standards for wireless security. DoD security policy establishes the overall benchmark for federal and civilian deployments as well as influences the security direction adopted by the commercial enterprise market. These stringent DoD wireless security requirements are outlined in DoD Directive 8100.2: "Use of Commercial WLAN Devices, Systems, and Technologies in the Department of Defense (DoD) Global Information Grid (GIG)", June 2006.

The following is an excerpt of that document:

> (1) WLAN authentication and encryption. Starting in FY 2007 for all new acquisitions, DoD components must implement WLAN solutions that are IEEE 802.11i compliant and are WPA2 Enterprise certified, that implement 802.1X access control with EAP-TLS mutual authentication, and a configuration that ensures the exclusive use of FIPS 140-2 minimum overall Level 1 validated Advanced Encryption Standard-Counter with Cipher Block Chaining-Message Authentication Code Protocol (AES-CCMP) communications. Migration plans for legacy WLAN systems that do not support a Wi-Fi Alliance WPA2 certified 802.11i implementation with a FIPS 140-2 validated cryptographic module must be reported to the DoD CIO within 180 days of this policy memorandum, per paragraph 3.c.(2).

The 8100.2 directive references four key policy areas that are mandatory for all commercial WLAN installations within DoD networks:

- Standards-based IEEE 802.11i security (WPA2)
- Interoperable Wi-Fi certified products
- Wireless intrusion detection with location sensing
- Federal Information Processing Standard (FIPS) 140-2 and Common Criteria certifications

FIPS 140-2 certification is required for all federal (civilian and DoD) WLAN product acquisitions. Cisco Unified Wireless LAN Controllers and Access Points have received National Institute of Standards and Technology (NIST) FIPS 140-2 level 2 certification for compliance with IEEE 802.11i WLAN security standards. FIPS certification ensures that all cryptographic functions and operations within a given crypto-module are implemented correctly. In the case of 802.11i (WPA2) security, this includes the correct implementation and use of AES-CCMP for strong wireless encryption.

The Cisco Unified Wireless Network solution is also in the process of achieving Common Criteria validation as mandated by the DoD wireless policy. Common Criteria validates the information assurance (IA) aspect of an entire end-to-end WLAN system. This includes data protection for all information that passes through and is stored in the system, strong authentication and access control, intrusion detection, and system monitoring. The Cisco Common Criteria solution includes all critical WLAN components, including the following:

- WLAN Controllers
- Aironet Access Points
- Wireless Control System (WCS)
- Access Control Server (ACS)
- Wireless Location Appliance

The DoD policy document also discusses the requirements for strong authentication and wireless intrusion detection with location sensing, which are discussed later in this guide, and subsequent documents discussing threat containment and control.

In summary:

- Cisco Unified Wireless is certified to meet the stringent wireless security requirements of the United States government.
- Cisco Unified Wireless ships with FIPS and Common Criteria integrated into the mainline software and factory hardware.
- Cisco Unified Wireless complies with the DoD end-to-end security requirements (trusted network devices).
- Cisco Unified Wireless meets DoD requirement for “continuous Wireless IDS monitoring with location tracking” for wired and wireless networks.

- Cisco ACS 4.1 is currently undergoing the FIPS certificate process.

Federal Communications Commission

The Federal Communications Commission (FCC) is the regulatory body controlling the radio frequency (RF) spectrum used by WLANs in the United States. The FCC not only sets the rules for radio power and antenna gain in the WLAN spectrum, but is also able to prosecute for breaches of its regulations. For example, an extract of the relevant FCC regulations state the following:

- Section 15.5—General conditions of operation.

  (a) Persons operating intentional or unintentional radiators shall not be deemed to have any vested or recognizable right to continued use of any given frequency by virtue of prior registration or certification of equipment, or, for power line carrier systems, on the basis of prior notification of use pursuant to Section 90.63(g) of this chapter. [Should reference Section 90.35(g).]

  (b) Operation of an intentional, unintentional, or incidental radiator is subject to the conditions that no harmful interference is caused and that interference must be accepted that may be caused by the operation of an authorized radio station, by another intentional or unintentional radiator, by industrial, scientific, and medical (ISM) equipment, or by an incidental radiator.

  (c) The operator of a radio frequency device shall be required to cease operating the device upon notification by a Commission representative that the device is causing harmful interference. Operation shall not resume until the condition causing the harmful interference has been corrected.

- Section 15.9—Prohibition against eavesdropping.

  Except for the operations of law enforcement officers conducted under lawful authority, no person shall use, either directly or indirectly, a device operated pursuant to the provisions of this Part for the purpose of overhearing or recording the private conversations of others unless such use is authorized by all of the parties engaging in the conversation.

Therefore, although the 802.11 radio spectrum is unlicensed, it is regulated, and legal recourse is available in the case of abuse of the spectrum or the unlawful actions.

Base 802.11 Security Features

This section focuses on the enterprise security features that are currently available for 802.11 wireless networks.

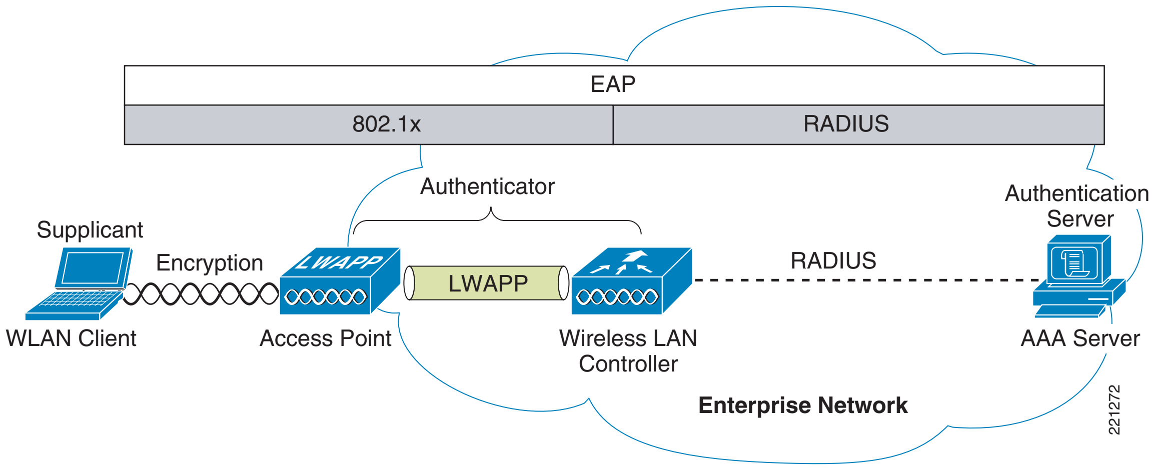
Although there were initially security flaws native to the 802.11 protocol, the introduction of 802.11i has addressed all the known data privacy issues, which are to ensure that the requirements for confidential communications are achieved through the use of strong authentication and encryption methods.

Additional WLAN security issues are discussed later in this guide. Some of these issues are being addressed by standards bodies, while others are being addressed in the Cisco Unified Wireless Network solution.

Terminology

A number of common terms are introduced throughout this guide and are shown in Figure 3-2.

Figure 3-2 Secure Wireless Topology



The basic physical components of the solution are as follows:

- WLAN client
- Access point (AP)
- Wireless LAN Controller (WLC)
- AAA server

Figure 3-2 also shows the basic roles and relationships associated with the 802.1X authentication process:

- An 802.1X supplicant resides on the WLAN client.
- The AP and WLC, using the split-MAC architecture, act together as the 802.1X authenticator.
- The AAA server is the authentication server.

Figure 3-2 also illustrates the role of 802.1X and the RADIUS protocol in carrying EAP packets between the client and the authentication server. Both 802.1X and EAP are discussed in more detail later in this chapter.

802.11 Fundamentals

802.11 WLANs consist of multiple elements and behaviors, which make up the foundation of the 802.11 protocol. A key part of the protocol discovers the appropriate WLAN and establishes a connection with that WLAN. The primary components of this process are as follows:

- Beacons—Used by the WLAN network to advertise its presence
- Probes—Used by WLAN clients to find their networks

- Authentication—An artifact from the original 802.11 standard
- Association—Establishes the data link between an AP and a WLAN client

Although beacons are regularly broadcast by an AP, the probe, authentication, and association frames are generally used only during the association and re-association process.

802.11 Beacons

The following example shows a portion of a WLAN beacon decode for the WLAN network called *wpa1*. In this beacon, you can see the service set identifier (the network name), the supported bit rates, and the security implementation for that WLAN.

The primary purpose of the beacon is to allow WLAN clients to learn which networks and APs are available in a given area, thereby allowing them to choose which network and AP to use.

Note Many WLAN security documents suggest that sending beacons without the service set identifier (SSID) is a security best practice that prevents potential hackers from learning the SSID of a WLAN network. All enterprise WLAN solutions offer this as an option. However, given that the SSID can be easily discovered while sniffing a WLAN client during the association phase, this option has little security value. For operational and client support issues, it is often better to allow the SSID to be broadcast. The SSID chosen should be relatively obscure with regard to the identity of the company or the purpose of the WLAN, while at the same time being as unique as possible; the SSID should not give away the purpose or the owner of the WLAN. Creating long random strings as SSIDs is not recommended because this simply adds to the operations and maintenance overhead without an appreciable security improvement; a simple word is often the best choice. Common WLAN-related words should be avoided because there is no process or standard to prevent accidental or intentional SSID duplication.

The following is an 802.11 beacon example:

```
Type/Subtype: Beacon frame (8)
…
    Destination address: Broadcast (ff:ff:ff:ff:ff:ff)
    …
    Sequence number: 2577IEEE 802.11 wireless LAN management frame
    …
        SSID parameter set: "wpa1"
            Tag Number: 0 (SSID parameter set)
            Tag length: 4
            Tag interpretation: wpa1
        Supported Rates: 1.0 2.0 5.5 11.0(B) 6.0 9.0 12.0 18.0
            Tag Number: 1 (Supported Rates)
            Tag length: 8
            Tag interpretation: Supported rates: 1.0 2.0 5.5 11.0(B) 6.0 9.0 12.0 18.0
[Mbit/sec]
…
        Vendor Specific: WPA
            Tag Number: 221 (Vendor Specific)
            Tag length: 28
            Tag interpretation: WPA IE, type 1, version 1
            Tag interpretation: Multicast cipher suite: TKIP
            Tag interpretation: # of unicast cipher suites: 2
            Tag interpretation: Unicast cipher suite 1: TKIP
            Tag interpretation: # of auth key management suites: 1
            Tag interpretation: auth key management suite 1: WPA
            Tag interpretation: Not interpreted
…
```

802.11 Join Process (Association)

Before an 802.11 client can send data over a WLAN network (Fast Roaming is an exception to this process, but is not discussed in this guide), it goes through the following three-stage process:

- 802.11 probing—802.11 networks make use of a number of options, but for an enterprise deployment, the search for a specific network involves sending a probe request out on multiple channels that specifies the network name (SSID) and bit rates.
- 802.11 authentication—802.11 was originally developed with two authentication mechanisms. The first one, called "open authentication", is fundamentally a NULL authentication where the client says "authenticate me", and the AP responds with "yes". This is the mechanism used in almost all 802.11 deployments.

  A second authentication mechanism is based on a shared WEP key, but the original implementation of this authentication method is flawed. Although it needs to be included for overall standards compliance, it is not used or recommended.

  Open authentication is the only method used in enterprise WLAN deployments, and as previously mentioned, it is fundamentally a NULL authentication, Therefore, "real authentication" is achieved by using 802.1X/EAP authentication mechanisms.
- 802.11 association—This stage finalizes the security and bit rate options and establishes the data link between the WLAN client and the AP.

A typical secure enterprise WLAN AP blocks WLAN client traffic at the AP until a successful 802.1X authentication.

If a client has joined a network and roams from one AP to another within the network, the association is called a re-association. The primary difference between an association and a re-association event is that a re-association frame sends the MAC address (BSSID) of the previous AP in its re-association request to provide roaming information to the extended WLAN network.

Probe Request and Probe Response

A typical WLAN client supplicant is configured with a desired WLAN network, which means that probe requests from the WLAN client contain the SSID of the desired WLAN network. This is sent "in the clear", as are all the association messages, thereby making it relativity easy for a WLAN sniffer to identify which SSIDs are active in an area.

If the WLAN client is simply trying to discover the available WLAN networks, it can send out a probe request with no SSID, and all APs that are configured to respond to this type of query will respond.

Note WLANs without Broadcast SSID enabled do not respond.

The following shows a segment of a sample probe request, where the WLAN client sends out a request for a particular SSID (*wpa1*).

```
IEEE 802.11 wireless LAN management frame
    Tagged parameters (31 bytes)
        SSID parameter set: "wpa1"
            ...
        Supported Rates: 1.0(B) 2.0(B) 5.5 11.0 6.0 9.0 12.0 18.0
           ...
        Extended Supported Rates: 24.0 36.0 48.0 54.0
            ...
```

The following shows a portion of a sample probe response, where an AP using the specified SSID responds with supported rate and security properties for that WLAN SSID.

```
…
IEEE 802.11 wireless LAN management frame
…
            Tag Number: 1 (Supported Rates)
            Tag length: 8
            Tag interpretation: Supported rates: 1.0 2.0 5.5 11.0(B) 6.0 9.0 12.0 18.0
[Mbit/sec]
   …
            Tag interpretation: WPA IE, type 1, version 1
            Tag interpretation: Multicast cipher suite: TKIP
            Tag interpretation: # of unicast cipher suites: 1
            Tag interpretation: Unicast cipher suite 1: TKIP
            Tag interpretation: # of auth key management suites: 1
            Tag interpretation: auth key management suite 1: WPA
            Tag interpretation: Not interpreted
…
```

Authentication

The following samples show an "open" authentication request and response frame, respectively. As can be seen from the decodes, no authentication data is transferred.

- WLAN client authentication request:

```
…
    Type/Subtype: Authentication (11)
…
IEEE 802.11 wireless LAN management frame
    Fixed parameters (6 bytes)
        Authentication Algorithm: Open System (0)
        Authentication SEQ: 0x0001
        Status code: Successful (0x0000)
```

- AP authentication response:

```
…
    Type/Subtype: Authentication (11)
   …
IEEE 802.11 wireless LAN management frame
    Fixed parameters (6 bytes)
        Authentication Algorithm: Open System (0)
        Authentication SEQ: 0x0002
        Status code: Successful (0x0000)
```

Another frame type related to authentication frames is the de-authentication frame, which when sent to a WLAN client causes the client to disconnect from the AP to which the client is currently connected. This may cause a WLAN client to go through the entire probe request process again, or at least make it restart the authentication/association process. De-authentication frames can be sent to the broadcast MAC address and cause the disconnection of every client associated with the AP sending that frame, but many current WLAN clients ignore multicast de-authentication frames, diminishing the potential scale of this type of attack.

Given that a de-authentication frame can be spoofed, it can be used by attackers to create a denial-of-service (DoS) attack on an AP, or to force clients to reassociate, thereby allowing an attack to occur on a client in a known state. This is one of the reasons why Cisco developed management frame protection (MFP) as part of the CCX feature set. MFP is discussed in more detail in Management Frame Protection, page 4-16.

Association

In the following traces, the final bit rates and security parameters are agreed upon at the association request and response frames. After this is successfully completed, 802.11 data frames can be sent between the WLAN client and the WLAN AP. In an enterprise WLAN deployment, these data frames are limited to 802.1X frames between the WLAN client and the AP until 802.1X/EAP authentication is completed and successful.

- WLAN client association request:

```
…
    Type/Subtype: Association Request (0)
    Frame Control: 0x0000 (Normal)
    Duration: 314
    Destination address: Airespac_52:42:d9 (00:0b:85:52:42:d9)
    Source address: IntelCor_7c:a3:47 (00:12:f0:7c:a3:47)
    BSS Id: Airespac_52:42:d9 (00:0b:85:52:42:d9)
    Fragment number: 0
    Sequence number: 90
    Frame check sequence: 0x1f17420d [correct]
IEEE 802.11 wireless LAN management frame
    Fixed parameters (4 bytes)
        Capability Information: 0x0431
        Listen Interval: 0x000a
    Tagged parameters (48 bytes)
        SSID parameter set: "wpa1"
            Tag Number: 0 (SSID parameter set)
            Tag length: 4
            Tag interpretation: wpa1
        Supported Rates: 1.0 2.0 5.5 11.0(B) 6.0 9.0 12.0 18.0
            Tag Number: 1 (Supported Rates)
            Tag length: 8
           Tag interpretation: Supported rates: 1.0 2.0 5.5 11.0(B) 6.0 9.0 12.0 18.0
[Mbit/sec]
        Vendor Specific: WPA
            Tag Number: 221 (Vendor Specific)
            Tag length: 24
            Tag interpretation: WPA IE, type 1, version 1
            Tag interpretation: Multicast cipher suite: TKIP
            Tag interpretation: # of unicast cipher suites: 1
            Tag interpretation: Unicast cipher suite 1: TKIP
            Tag interpretation: # of auth key management suites: 1
            Tag interpretation: auth key management suite 1: WPA
            Tag interpretation: Not interpreted
        Extended Supported Rates: 24.0 36.0 48.0 54.0
            Tag Number: 50 (Extended Supported Rates)
            Tag length: 4
            Tag interpretation: Supported rates: 24.0 36.0 48.0 54.0  [Mbit/sec]
```

- AP association response:

```
…
    Type/Subtype: Association Response (1)
    Frame Control: 0x0010 (Normal)
    Duration: 213
    Destination address: IntelCor_7c:a3:47 (00:12:f0:7c:a3:47)
    Source address: Airespac_52:42:d9 (00:0b:85:52:42:d9)
    BSS Id: Airespac_52:42:d9 (00:0b:85:52:42:d9)
    Fragment number: 0
    Sequence number: 1001
    Frame check sequence: 0x759406b6 [correct]
IEEE 802.11 wireless LAN management frame
```

```
        Fixed parameters (6 bytes)
            Capability Information: 0x0431
            Status code: Successful (0x0000)
            Association ID: 0x0001
        Tagged parameters (47 bytes)
            Supported Rates: 1.0 2.0 5.5 11.0(B) 6.0 9.0 12.0 18.0
                Tag Number: 1 (Supported Rates)
                Tag length: 8
               Tag interpretation: Supported rates: 1.0 2.0 5.5 11.0(B) 6.0 9.0 12.0 18.0
    [Mbit/sec]
            Extended Supported Rates: 24.0 36.0 48.0 54.0
                Tag Number: 50 (Extended Supported Rates)
                Tag length: 4
                Tag interpretation: Supported rates: 24.0 36.0 48.0 54.0  [Mbit/sec]
            Vendor Specific: Aironet Unknown
                Tag Number: 221 (Vendor Specific)
                Tag length: 29
                Aironet IE type: Unknown (12)
                Aironet IE data: 02C1257CF1AA1E0D010000A80200000000494C9788132233...
```

The association process also has a related disassociation frame that can be used to disconnect WLAN clients from their AP. The disassociation frame can be only a unicast frame and is therefore less likely to be used in a DoS attack, but could still be used to cause clients to re-associate, thereby allowing a DoS attack or an attack on the client to begin in a known state.

802.1X

802.1X is an IEEE framework for port-based access control that has been adopted by the 802.11i security workgroup as a means of providing authenticated access to WLAN networks.

- The 802.11 association process creates a "virtual" port for each WLAN client at the AP.
- The AP blocks all data frames apart from 802.1X-based traffic.
- The 802.1X frames carry the EAP authentication packets, which are passed through to the AAA server by the AP.
- If the EAP authentication is successful, the AAA server sends an EAP success message to the AP, where the AP then allows data traffic from the WLAN client to pass through the virtual port.
- Before opening the virtual port, data link encryption between the WLAN client and the AP is established to ensure that no other WLAN client can access the port that has been established for a given authenticated client.

Extensible Authentication Protocol

Extensible Authentication Protocol (EAP) is an IETF RFC that stipulates that an authentication protocol must be decoupled from the transport protocol used to carry it. This allows the EAP protocol to be carried by transport protocols such as 802.1X, UDP, or RADIUS without having to make changes to the authentication protocol itself.

The basic EAP protocol is relatively simple, consisting of the following four packet types:

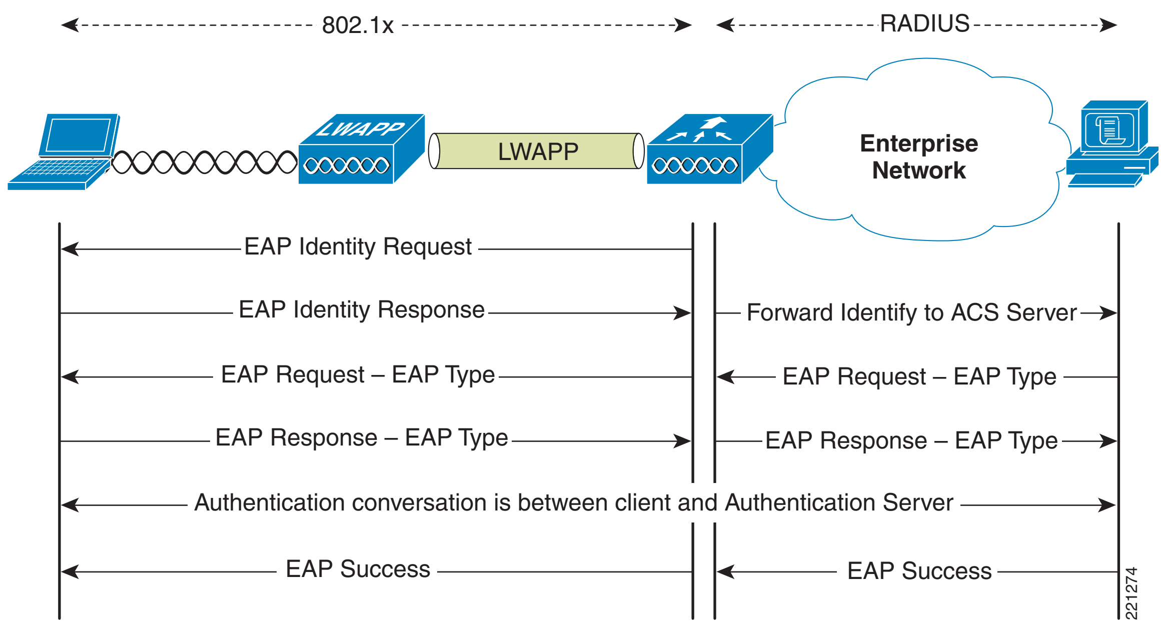
- EAP request—The request packet is sent by the authenticator to the supplicant. Each request has a type field that indicates what is being requested; for example, supplicant identity and EAP type to be used. A sequence number allows the authenticator and the peer to match an EAP response to each EAP request.

- EAP response—The response packet is sent by the supplicant to the authenticator and uses a sequence number to match the initiating EAP request. The type of the EAP response generally matches the EAP request, except if the response is a negative-acknowledgment (NAK).
- EAP success—The success packet is sent when successful authentication has occurred and is sent from the authenticator to the supplicant.
- EAP failure—The failure packet is sent when unsuccessful authentication has occurred and is sent from the authenticator to the supplicant.

When using EAP in an 802.11i compliant system, the AP operates in EAP pass-through mode. In this mode, it checks the code, identifier, and length fields, and then forwards EAP packets received from the client supplicant to the AAA. EAP packets received by the authenticator from the AAA server are forwarded to the supplicant.

Figure 3-3 shows an example of EAP protocol flow.

Figure 3-3 EAP Protocol Flow



Authentication

Depending on the customer requirements, various authentication protocols such as PEAP, EAP-TLS, and EAP-FAST can be used in secure wireless deployments. Regardless of the protocol, they all currently use 802.1X, EAP, and RADIUS as their underlying transport. These protocols allow network access to be controlled based on the successful authentication of the WLAN client, and just as importantly, allow the WLAN network to be authenticated by the user.

This solution also provides authorization through policies communicated through the RADIUS protocol, as well as RADIUS accounting.

EAP types used for performing authentication are described in more detail below. The primary factor affecting the choice of EAP protocol is the authentication system (AAA) currently in use. Ideally, a secure WLAN deployment should not require the introduction of a new authentication system, but rather should leverage the authentication systems that are already in place.

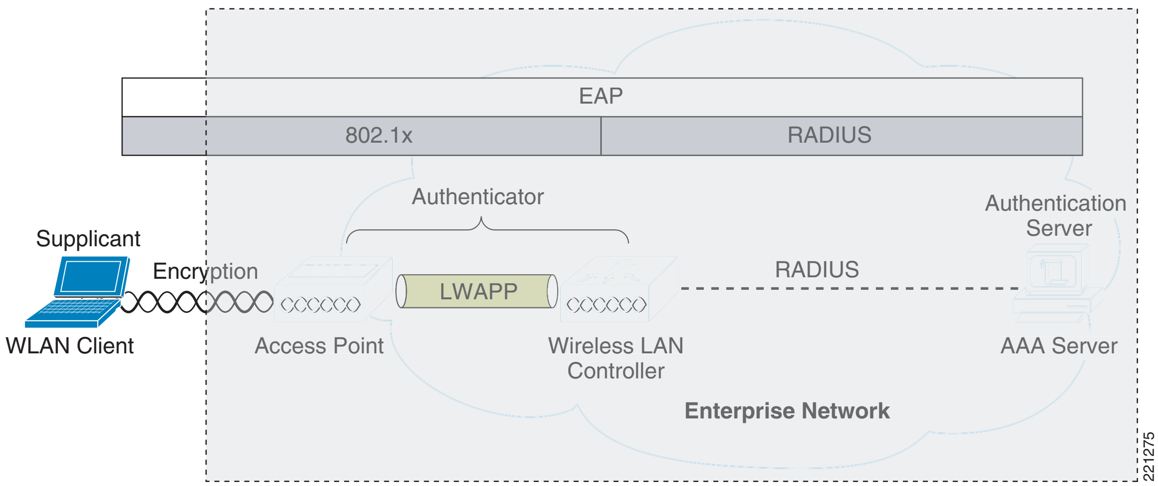
Supplicants

The client software used for WLAN authentication is called a supplicant, based on 802.1X terminology. The Cisco Secure Services Client (CSSC) 5.1 is a supplicant that supports wired and wireless networks, and all the common EAP types. Supplicants may also be provided by the WLAN NIC manufacturer or can come integrated within an operating system; for example, Windows XP supports PEAP MSCHAPV2 and EAP-TLS.

For more information on CSSC, refer to the following URL:
http://www.cisco.com/en/US/prod/collateral/wireless/ps6442/ps7034/product_data_sheet0900aecd805081a7.html

Figure 3-4 shows the logical location of the supplicant relative to the overall authentication architecture. The role of the supplicant is to facilitate end-user authentication using EAP and 802.1X to an upstream authenticator; in this case, the WLC. The authenticator forwards EAP messages received by the supplicant and forwards them to an upstream AAA server using RADIUS.

Figure 3-4 WLAN Client Supplicant



The various EAP supplicants that are available in the marketplace reflect the diversity of authentication solutions and customer priorities.

Table 3-2 shows a summary of common EAP supplicants:

- PEAP MSCHAPv2—Protected EAP MSCHAPv2. Uses a Transport Layer Security (TLS) tunnel, (the IETF standard of an SSL) to protect an encapsulated MSCHAPv2 exchange between the WLAN client and the authentication server.
- PEAP GTC—Protected EAP Generic Token Card (GTC). Uses a TLS tunnel to protect a generic token card exchange; for example, a one-time password or LDAP authentication.
- EAP-FAST—EAP-Flexible Authentication via Secured Tunnel. Uses a tunnel similar to that used in PEAP, but does not require the use of Public Key Infrastructure (PKI).
- EAP-TLS—EAP Transport Layer Security uses PKI to authenticate both the WLAN network and the WLAN client, requiring both a client certificate and an authentication server certificate.

Table 3-2 Comparison of Common Supplicants

	Cisco EAP-FAST	PEAP MS-CHAPv2	PEAP EAP-GTC	EAP-TLS
Single sign-on (MSFT AD only)	Yes	Yes	Yes[1]	Yes
Login scripts (MSFT AD only)	Yes	Yes	Some	Yes[2]
Password change (MSFT AD)	Yes	Yes	Yes	N/A
Microsoft AD database support	Yes	Yes	Yes	Yes
ACS local database support	Yes	Yes	Yes	Yes
LDAP database support	Yes[3]	No	Yes	Yes
OTP authentication support	Yes[4]	No	Yes	No
RADIUS server certificate required?	No[5]	Yes	Yes	Yes
Client certificate required?	No[6]	No	No	Yes
Anonymity	Yes	Yes[7]	Yes[8]	No

1. Supplicant dependent
2. Machine account and machine authentication is required to support the scripts.
3. Automatic provisioning is not supported on with LDAP databases.
4. Supplicant dependent
5. Supported by EAP-FAST and addresses Phase 0 provisioning vulnerability
6. Supported by EAP-FAST and addresses Phase 0 provisioning vulnerability
7. Supplicant dependent
8. Supplicant dependent

Authenticator

The authenticator in the case of the Cisco Secure Wireless Solution is the Wireless LAN Controller (WLC), which acts as a relay for EAP messages being exchanged between the 802.1X-based supplicant and the RADIUS authentication server.

After the completion of a successful authentication, the WLC receives the following:

- A RADIUS packet containing an EAP success message
- An encryption key generated at the authentication server during the EAP authentication
- RADIUS vendor-specific attributes (VSAs) for communicating policy

Figure 3-5 shows the logical location of the “authenticator” within the overall authentication architecture. The authenticator controls network access using the 802.1X protocol and relays EAP messages between the supplicant and the authentication server.

Figure 3-5 Authenticator Location

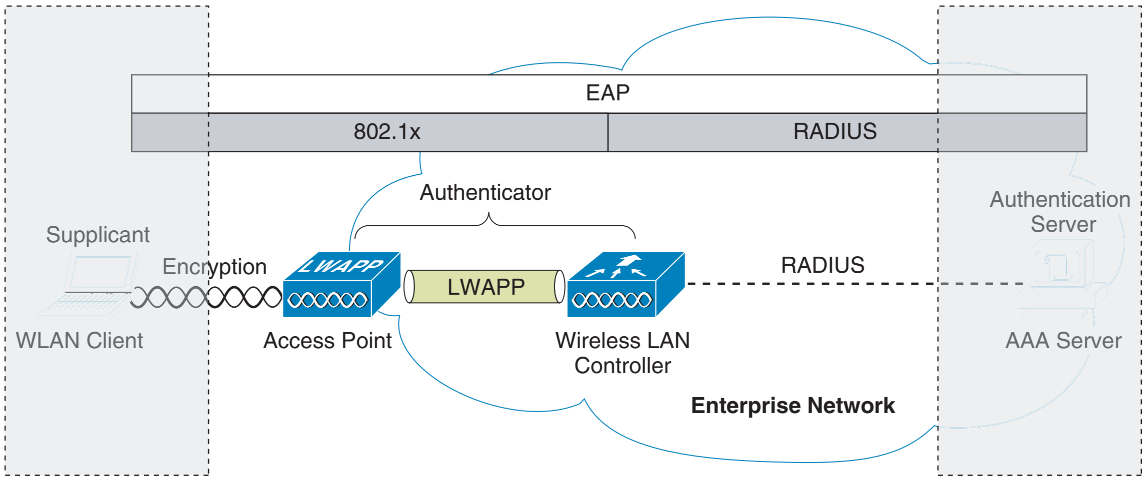


Table 3-3 shows an example decode of an EAP-TLS authentication where the four left-most columns are wireless 802.1X decodes and the three right-most columns are decodes of the respective RADIUS transactions for the same EAP-TLS authentication.

The EAP exchange sequence is as follows:

- Packet #1 is sent by the AP to the client, requesting the client identity. This begins the EAP exchange.
- Packet #2 is the client identity that is forwarded to the RADIUS server. Based on this identity, the RADIUS server can decide whether to continue with the EAP authentication.
- In packet #3, the RADIUS server sends a request to use PEAP as the EAP method for authentication. The actual request depends on the EAP types configured on the RADIUS server. If the client rejects the PEAP request, the RADIUS server may offer other EAP types.
- Packets #4–8 are the TLS tunnel setup for PEAP.
- Packets #9–16 are the authentication exchange within PEAP.
- Packet #17 is the EAP message saying that the authentication was successful.

  In addition to informing the supplicant and authenticator that the authentication was successful, packet #17 also carries encryption keys and authorization information to the authenticator.

Table 3-3 EAP Transaction

#	Source	Dest	Protocol	Info	Source	Dest	RADIUS Info
1	AP	Client	EAP	"Request," Identity			
2	Client	AP	EAP	"Response," Identity	WLC	AAA	"Access-Request(1) (id=114, l=174)"
3	AP	Client	EAP	"Request," PEAP	AAA	WLC	"Access-challenge(11) (id=115, l=76)"
4	Client	AP	TLS[1]	Client Hello	WLC	AAA	"Access-Request(1) (id=116, l=296)"
5	AP	Client	TLS	Server "Hello," "Certificate,"	AAA	WLC	"Access-challenge(11) (id=116, l=968)"

Table 3-3 EAP Transaction (continued)

6	Client	AP	TLS	Client Key "Exchange," Change Cipher "Spec," Encrypted Handshake Message	WLC	AAA	"Access-Request(1) (id=117, l=528)"
7	AP	Client	TLS	Change Cipher "Spec," Encrypted Handshake Message	AAA	WLC	"Access-challenge(11) (id=117, l=145)"
8	Client	AP	EAP	"Response," PEAP	WLC	AAA	"Access-Request(1) (id=118, l=196)"
9	AP	Client	TLS	Application Data	AAA	WLC	"Access-challenge(11) (id=118, l=135)"
10	Client	AP	TLS	Application "Data,"	WLC	AAA	"Access-Request(1) (id=119, l=270)"
11	AP	Client	TLS	Application Data	AAA	WLC	"Access-challenge(11) (id=119, l=151)"
12	Client	AP	TLS	Application "Data,"	WLC	AAA	"Access-Request(1) (id=120, l=334)"
13	AP	Client	TLS	Application Data	AAA	WLC	"Access-challenge(11) (id=120, l=162)"
14	Client	AP	TLS	Application "Data,"	WLC	AAA	"Access-Request(1) (id=121, l=265)"
15	AP	Client	TLS	Application Data	AAA	WLC	"Access-challenge(11) (id=121, l=114)"
16	Client	AP	TLS	Application "Data,"	WLC	AAA	"Access-Request(1) (id=122, l=265)"
17	AP	Client	EAP	Success	AAA	WLC	"Access-Accept(2) (id=122, l=196)"

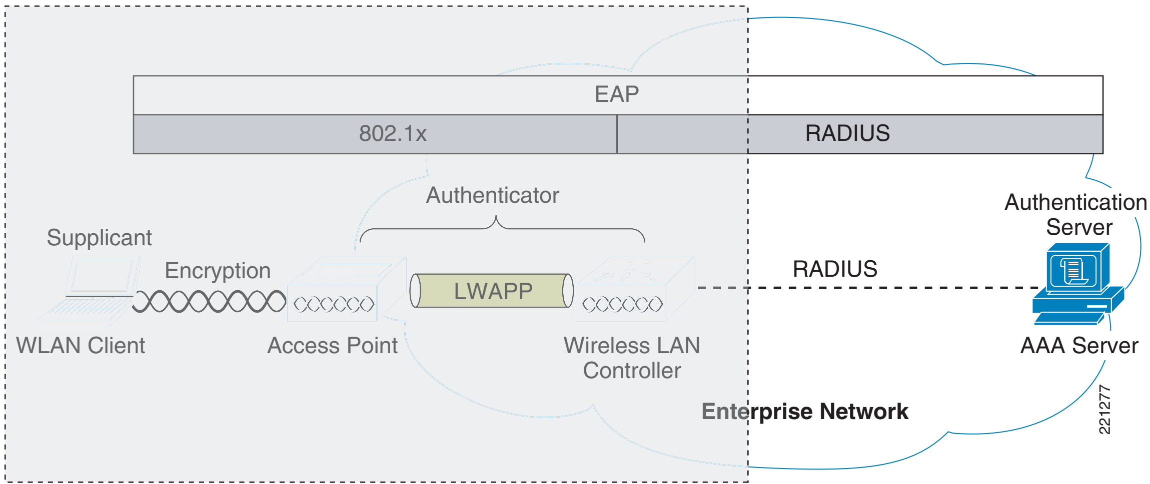
1. The TLS transaction is carried within EAP packets

Authentication Server

The authentication server used in the Cisco Secure Wireless Solution is the Cisco Access Control Server (ACS). Cisco ACS is available as software that is installable on Windows 2000 or 2003 servers or as an appliance. Alternatively, the authentication server function can be implemented within specific WLAN infrastructure devices, such as local authentication services on an IOS AP, local EAP authentication support within the WLC, or any AAA server that supports the required EAP types.

Figure 3-6 shows the logical location of the authentication server within the overall wireless authentication architecture, where it performs the EAP authentication via a RADIUS tunnel.

Figure 3-6 Authentication Server Location



After the completion of a successful EAP authentication, the authentication server sends an EAP success message to the authenticator. This message tells the authenticator that the EAP authentication process was successful and passes the pairwise master key (PMK) to the authenticator that is in turn used as the basis for creating the encrypted stream between the WLAN client and the AP. The following shows an example decode of an EAP success message within RADIUS:

```
Radius Protocol
    Code: Access-Accept (2)
    Packet identifier: 0x7a (122)
    Length: 196
    Authenticator: 1AAAD5ECBC487012B753B2C1627E493A
    Attribute Value Pairs
        AVP: l=6  t=Framed-IP-Address(8): Negotiated
        AVP: l=6  t=EAP-Message(79) Last Segment[1]
            EAP fragment
            Extensible Authentication Protocol
                Code: Success (3)
                Id: 12
                Length: 4
        AVP: l=58  t=Vendor-Specific(26) v=Microsoft(311)
        AVP: l=58  t=Vendor-Specific(26) v=Microsoft(311)
        AVP: l=6  t=User-Name(1): xxxxxxx
        AVP: l=24  t=Class(25): 434143533A302F313938662F63306138336330322F31
        AVP: l=18  t=Message-Authenticator(80): 7C34BA45A95F3E55425FDAC301DA1AD7
```

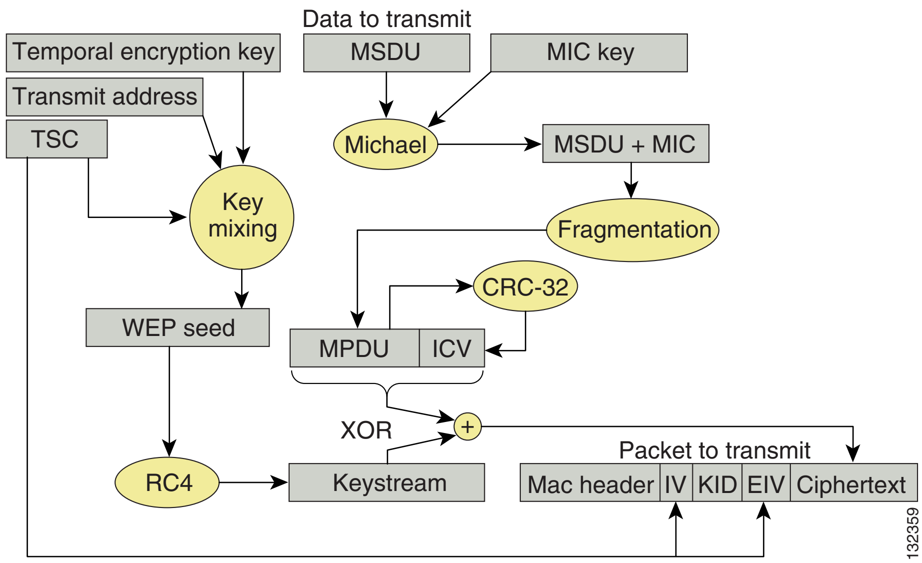
Encryption

Two enterprise-level encryption mechanisms specified by 802.11i are certified as WPA and WPA2 by the Wi-Fi Alliance: Temporal Key Integrity Protocol (TKIP) and Advanced Encryption Standard (AES).

TKIP is the encryption method certified as WPA. It provides support for legacy WLAN equipment by addressing the original flaws associated with the 802.11 WEP encryption method. It does this making use of the original RC4 core encryption algorithm. The hardware refresh cycle of WLAN client devices is such that TKIP (WPA) is likely to be a common encryption option for a number of years. Although TKIP addresses all the known weaknesses of WEP, the AES encryption of WPA2 is the preferred method because it brings the WLAN encryption standards into alignment with broader IT industry standards and best practices.

Figure 3-7 shows a basic TKIP flow chart.

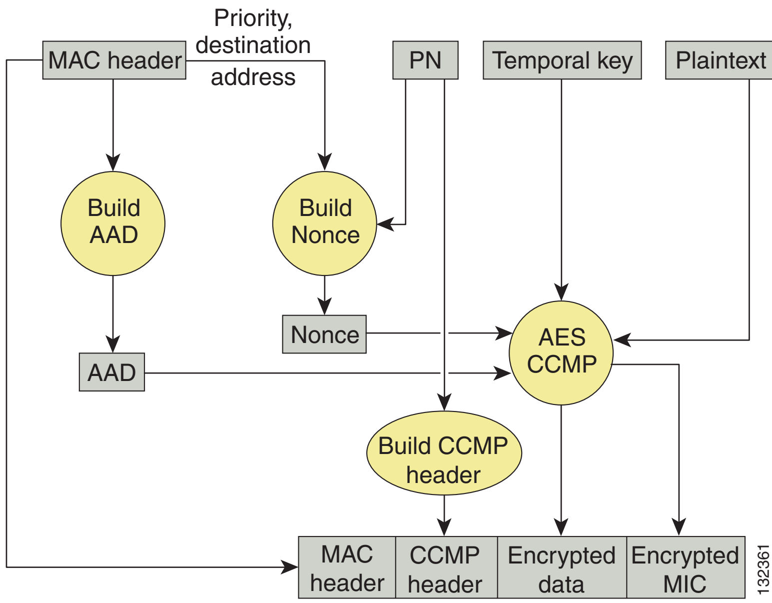
Figure 3-7 WPA TKIP



The two primary functions of TKIP are the generation of a per-packet key using RC4 encryption of the MAC service data unit (MSDU) and a message integrity check (MIC) in the encrypted packet. The per-packet key is a hash of the transmission address, the frame initialization vector (IV), and the encryption key. The IV changes with each frame transmission, so the key used for RC4 encryption is unique for each frame. The MIC is generated using the Michael algorithm to combine a MIC key with user data. The use of the Michael algorithm is a trade-off because although its low computational overhead is good for performance, it can be susceptible to an active attack. To address this, WPA includes countermeasures to safeguard against these attacks that involve temporarily disconnecting the WLAN client and not allowing a new key negotiation for 60 seconds. Unfortunately, this behavior can itself become a type of DoS attack. Many WLAN implementations provide an option to disable this countermeasure feature.

Figure 3-8 shows the basic AES counter mode/CBC MAC Protocol (CCMP) flow chart. CCMP is one of the AES encryption modes, where the counter mode provides confidentiality and CBC MAC provides message integrity.

Figure 3-8 WPA2 AES CCMP



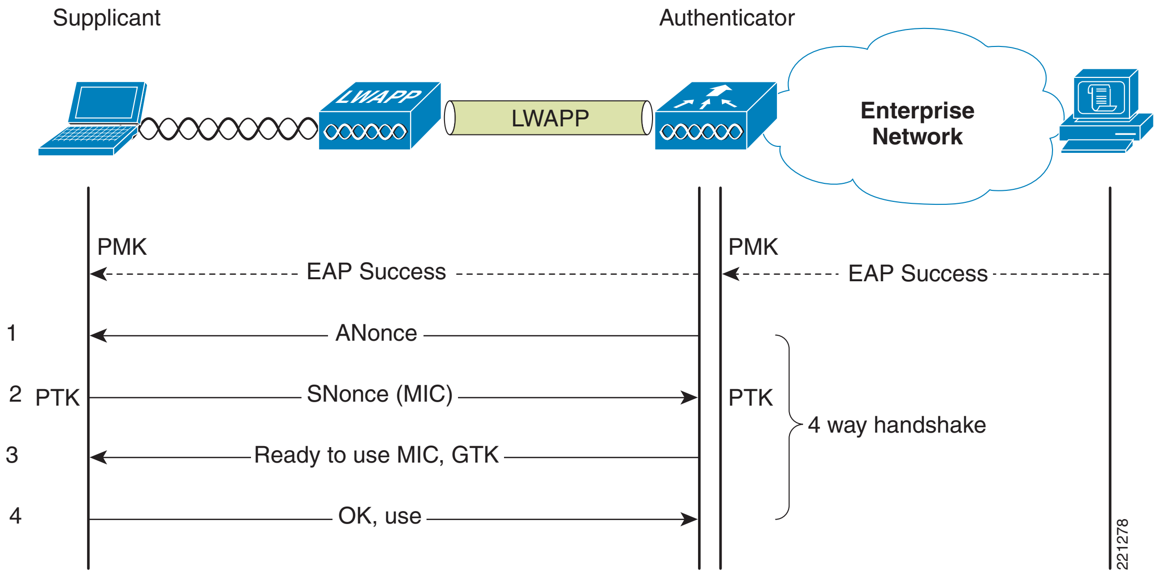
In the CCMP procedure, additional authentication data (AAD) is taken from the MAC header and included in the CCM encryption process. This protects the frame against alteration of the non-encrypted portions of the frame.

To protect against replay attacks, a sequenced packet number (PN) is included in the CCMP header. The PN and portions of the MAC header are used to generate a nonce that is turn used by the CCM encryption process.

4-Way Handshake

The 4-way handshake describes the method used to derive the encryption keys to be used to encrypt wireless data frames. Figure 3-9 shows a diagram of the frame exchanges used to generate the encryption keys. These keys are referred to as temporal keys.

Figure 3-9 4-Way Handshake



The keys used for encryption are derived from the PMK that has been mutually derived during the EAP authentication section. This PMK is sent to the authenticator in the EAP success message, but is not forwarded to the supplicant because the supplicant has derived its own copy of the PMK.

1. The authenticator sends an EAPOL-Key frame containing an ANonce (authenticator nonce, which is a random number generated by the authenticator).
    a. The supplicant derives a pairwise temporal key (PTK) from the ANonce and SNonce (supplicant nonce, which is a random number generated by the client/supplicant).
2. The supplicant sends an EAPOL-Key frame containing an SNonce, the RSN information element from the (re)association request frame, and an MIC.
    a. The authenticator derives a PTK from the ANonce and SNonce and validates the MIC in the EAPOL-Key frame.
3. The authenticator sends an EAPOL-Key frame containing the ANonce, the RSN information element from its beacon or probe response messages; the MIC, determining whether to install the temporal keys; and the encapsulated group temporal key (GTK), the multicast encryption key.
4. The supplicant sends an EAPOL-Key frame to confirm that the temporal keys are installed.