Ascertain Methods for 802.11 WLAN and Fast-Secure Roaming on CUWN

Contents

Introduction

This document describes wireless and fast-secure roaming types available for IEEE 802.11 Wireless LANs

(WLANs) on Unified Wireless Network (CUWN).

Prerequisites

Requirements

Cisco recommends that you have knowledge of these topics:

- IEEE 802.11 WLAN Fundamentals
- IEEE 802.11 WLAN Security
- IEEE 802.1X/EAP Basics

Components Used

The information in this document is based on Cisco WLAN Controller Software Version 7.4.

The information in this document was created from the devices in a specific lab environment. All of the devices used in this document started with a cleared (default) configuration. If your network is live, ensure that you understand the potential impact of any command.

Background Information

The information in this document is based on Cisco WLAN Controller Software Version 7.4, but most of the debug outputs and behaviors described can apply to any software version that supports the methods discussed. Specifics of all the methods explained here remain the same on later Cisco WLAN Controller codes (up to version 8.3 by the time this article was updated).

This document describes the different types of wireless roaming and fast-secure roaming methods available for IEEE 802.11 Wireless LANs (WLANs) supported on the Cisco Unified Wireless Network (CUWN).

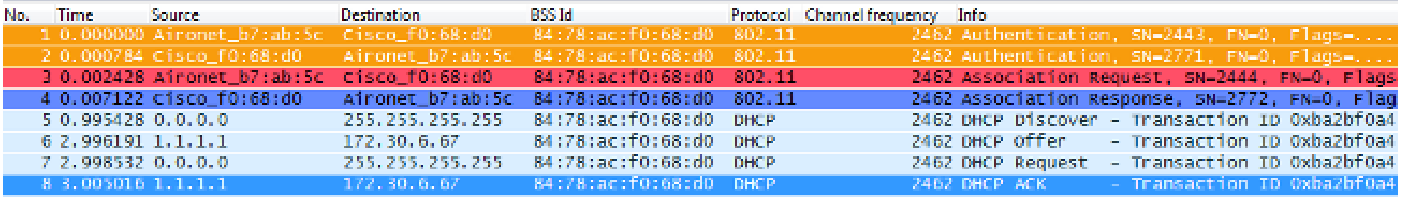
The document does not provide all of the specifics about how each method works or how they are configured. The main purpose of this document is to describe the differences between the various techniques available, their advantages and limitations, and the frames-exchange on each method. Examples of WLAN Controller (WLC) debugs are provided, and wireless packet images are used in order to analyze and explain the events that occur for each roaming method described.

Before a description of the different fast-secure roaming methods available for WLANs is given, it is important to understand how the WLAN association process works, and how a regular roaming event occurs when there is no security configured on the Service Set Identifier (SSID).

When an 802.11 wireless client connects to an Access Point (AP), before it begins to pass traffic (wireless data frames), it first must pass the basic 802.11 Open System authentication process. Then, the association process must be completed. The Open System authentication process is like a cable connection on the AP that the client selects. This is a very important point, because it is always the wireless client that selects which AP is preferred, and bases the decision on multiple factors that vary between vendors. This is why the client begins this process by sending the Authentication frame to the selected AP, as shown later in this document. The AP cannot request that you establish a connection.

Once the Open System authentication process is completed successfully with a response from the AP ("cable connected"), the association process essentially finishes the 802.11 Layer 2 (L2) negotiation that establishes the link between the client and the AP. The AP assigns an association ID to the client if the connection is successful, and prepares it in order to pass traffic or perform a higher-level security method if configured on the SSID. The Open System authentication process consists of two management frames as well as the association process. Authentication and Association frames are wireless **management frames**, not data frames, which are basically the ones used for the connection process with the AP.

Here is a image of the wireless frames over-the-air for this process:



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Aironet_b7:ab:5c	Cisco_f0:68:d0	84:78:ac:f0:68:d0	802.11	2462	Authentication, SN=2443, FN=0, Flags=....
2	0.000784	Cisco_f0:68:d0	Aironet_b7:ab:5c	84:78:ac:f0:68:d0	802.11	2462	Authentication, SN=2771, FN=0, Flags=....
3	0.002428	Aironet_b7:ab:5c	Cisco_f0:68:d0	84:78:ac:f0:68:d0	802.11	2462	Association Request, SN=2444, FN=0, Flags
4	0.007122	Cisco_f0:68:d0	Aironet_b7:ab:5c	84:78:ac:f0:68:d0	802.11	2462	Association Response, SN=2772, FN=0, Flag
5	0.995428	0.0.0.0	255.255.255.255	84:78:ac:f0:68:d0	DHCP	2462	DHCP Discover - Transaction ID 0xba2bf0a4
6	2.996191	1.1.1.1	172.30.6.67	84:78:ac:f0:68:d0	DHCP	2462	DHCP Offer - Transaction ID 0xba2bf0a4
7	2.998532	0.0.0.0	255.255.255.255	84:78:ac:f0:68:d0	DHCP	2462	DHCP Request - Transaction ID 0xba2bf0a4
8	3.005016	1.1.1.1	172.30.6.67	84:78:ac:f0:68:d0	DHCP	2462	DHCP ACK - Transaction ID 0xba2bf0a4

Note: If you want to learn about 802.11 wireless sniffing, and about the filters/colors used on Wireshark for the images that appear in this document, visit the Cisco Support Community post called 802.11 Sniffer image Analysis.

The wireless client begins with the Authentication frame, and the AP replies with another Authentication frame. The client then sends the Association Request frame, and the AP finishes in a reply with the Association Response frame. As shown from the DHCP packets, once the 802.11 Open System authentication and association processes are passed, the client begins to pass data frames. In this case, there is no security method configured on the SSID, so the client immediately begins to send data frames (in this case DHCP) that are not encrypted.

As shown later in this document, if security is enabled on the SSID, there are higher-level authentication and encryption handshake frames for the specific security method, just after the Association Response and prior to any client traffic data frames are sent, such as DHCP, Address Resolution Protocol (ARP), and applications packets, which are encrypted. Data frames can only be sent until the client is fully authenticated, and the encryption keys are negotiated, based on the security method configured.

Based on the previous image, here are the messages that you see in the outputs of the WLC **debug client** command when the wireless client begins a new association to the WLAN:

<#root>

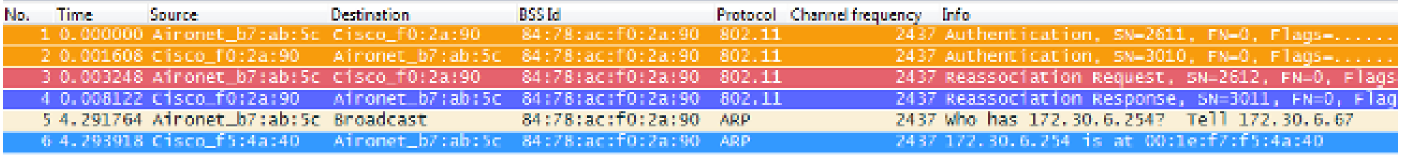
```
*apfMsConnTask_0: Jun 21 18:55:14.221: 00:40:96:b7:ab:5c
  Association received from mobile on BSSID 84:78:ac:f0:68:d0

!--- This is the Association Request from the wireless client
     to the selected AP

.

*apfMsConnTask_0: Jun 21 18:55:14.222: 00:40:96:b7:ab:5c
  Sending Assoc Response to station on BSSID 84:78:ac:f0:68:d0
  (status 0) ApVapId 1 Slot 0

!--- This is the Association Response from the AP to the client

.
```

Note: The WLC debug used for the outputs shown in this document is the **debug client** command, and the examples only show some relevant messages, not the entire output. For more details about this debug command, reference the document called Understand the Debug Client on Wireless LAN Controllers (WLCs).

These messages show the Association Request and Response frames; the initial Authentication frames are not logged at the WLC because this handshake happens quickly at the AP-level on the CUWN.

What information appears when the client roams? The client always exchanges four management frames upon establishment of a connection to an AP, which is due to either client establishment of association, or a roaming event. The client has only one connection established to only one AP at a time. The only difference in the frame exchange between a new connection to the WLAN infrastructure and a roaming event is that the Association frames of a roaming event are called **Reassociation** frames, which indicate that the client is actually roaming from another AP with no attempts to establish a new association to the WLAN. These frames can contain different elements that are used in order to negotiate the roaming event; this depends on the setup, but those details are out of the scope of this document.

Here is an example of the frame exchange:



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Aironet_b7:ab:5c	Cisco_f0:2a:90	84:78:ac:f0:2a:90	802.11	2437	Authentication, SN=2611, FN=0, Flags=......
2	0.001608	Cisco_f0:2a:90	Aironet_b7:ab:5c	84:78:ac:f0:2a:90	802.11	2437	Authentication, SN=3010, FN=0, Flags=......
3	0.003248	Aironet_b7:ab:5c	Cisco_f0:2a:90	84:78:ac:f0:2a:90	802.11	2437	Reassociation Request, SN=2612, FN=0, Flags
4	0.008122	Cisco_f0:2a:90	Aironet_b7:ab:5c	84:78:ac:f0:2a:90	802.11	2437	Reassociation Response, SN=3011, FN=0, Flag
5	4.291764	Aironet_b7:ab:5c	Broadcast	84:78:ac:f0:2a:90	ARP	2437	Who has 172.30.6.254? Tell 172.30.6.67
6	4.293918	Cisco_f5:4a:40	Aironet_b7:ab:5c	84:78:ac:f0:2a:90	ARP	2437	172.30.6.254 is at 00:1e:f7:f5:4a:40

These messages appear in the debug output:

<#root>

```
*apfMsConnTask_2: Jun 21 19:02:19.709: 00:40:96:b7:ab:5c
  Reassociation received from mobile on BSSID 84:78:ac:f0:2a:90

!--- This is the Reassociation Request from the wireless client
     to the selected AP

.

*apfMsConnTask_2: Jun 21 19:02:19.710: 00:40:96:b7:ab:5c
  Sending Assoc Response to station on BSSID 84:78:ac:f0:2a:90
  (status 0) ApVapId 1 Slot 0

!--- This is the Reassociation Response from the AP to the client

.
```

As shown, the client successfully performs a roaming event after the Reassociation Request to the new AP is sent, and receives the Reassociation Response from the AP. Since the client already has an IP address, the first data frames are for ARP packets.

If you expect a roaming event, but the client sends an Association Request instead of a Reassociation Request (which you can confirm from some images and debugs similar to those explained earlier in this document), then the client is not really roaming. The client begins a new association to the WLAN as if a disconnection took place, and tries to reconnect from scratch. This can happen for multiple reasons, such as when a client moves away from the coverage areas and then finds an AP with enough signal quality to start an association, but it normally indicates a client issue where the client does not initiate a roaming event due to drivers, firmware, or software issues.

Note: You can check with the wireless client vendor in order to determine the cause of the issue.

Roaming with Higher-Level Security

When the SSID is configured with L2 higher-level security on top of basic 802.11 Open System authentication, then more frames are required for the initial association and when roaming. The two most-common security methods standardized and implemented for 802.11 WLANs are described in this document:

- **WPA/WPA2-PSK (Pre-Shared Key)** - authentication of clients with a Preshared-Key.
- **WPA/WPA2-EAP (Extensible Authentication Protocol)** - authentication of clients with an 802.1X/EAP method in order to validate more secure credentials through the use of an Authentication Server, such as certificates, username and password, and tokens.

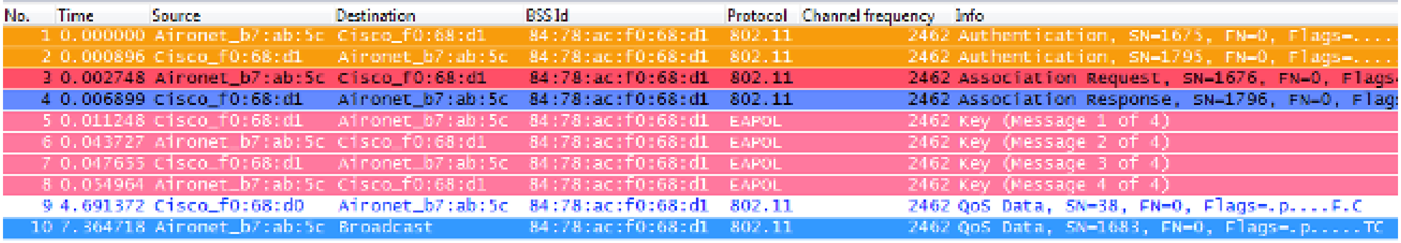
It is important to know that, even though these two methods (PSK and EAP) authenticate/validate the clients in different ways, both use basically the same WPA/WPA2 rules for the key management process. Whether the security is WPA/WPA2-PSK or WPA/WPA2-EAP, the process known as the WPA/WPA2 4-Way handshake begins the key negotiation between the WLC/AP and the client with a Master Session Key (MSK) as the original key material once the client is validated with the specific authentication method used.

Here is a summary of the process:

1. An MSK is derived from the EAP authentication phase when 802.1X/EAP security is used, or from the PSK when WPA/WPA2-PSK is used as the security method.
2. From this MSK, the client and WLC/AP derive the Pairwise Master Key (PMK), and the WLC/AP generates a Group Master Key (GMK).
3. Once these two Master Keys are ready, the client and the WLC/AP initiate the WPA/WPA2 4-Way handshake (which is illustrated later in this document with some screen images and debugs) with the Master Keys as the seeds for negotiation of the actual encryption keys.
4. Those final encryption keys are known as the Pairwise Transient Key (PTK) and the Group Transient Key (GTK). The PTK is derived from the PMK and used in order to encrypt unicast frames with the client. The Group Transient Key (GTK) is derived from the GMK, and is used in order to encrypt multicast/broadcast on this specific SSID/AP.

WPA/WPA2-PSK

When WPA-PSK or WPA2-PSK is performed via Temporal Key Integrity Protocol (TKIP) or Advanced Encryption Standard (AES) for the encryption, the client must go through the process known as the WPA 4-Way handshake for both the initial association and also when roaming. As previously explained, this is basically the key management process used in order for WPA/WPA2 to derive the encryption keys. However, when PSK is performed, it is also used in order to verify that the client has a valid Pre-Shared Key to join the WLAN. This image shows the initial association process when WPA or WPA2 with PSK is performed:



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Aironet_b7:ab:5c	Cisco_f0:68:d1	84:78:ac:f0:68:d1	802.11	2462	Authentication, SN=1675, FN=0, Flags=....
2	0.000896	Cisco_f0:68:d1	Aironet_b7:ab:5c	84:78:ac:f0:68:d1	802.11	2462	Authentication, SN=1795, FN=0, Flags=....
3	0.002748	Aironet_b7:ab:5c	Cisco_f0:68:d1	84:78:ac:f0:68:d1	802.11	2462	Association Request, SN=1676, FN=0, Flags
4	0.006899	Cisco_f0:68:d1	Aironet_b7:ab:5c	84:78:ac:f0:68:d1	802.11	2462	Association Response, SN=1796, FN=0, Flag
5	0.011248	Cisco_f0:68:d1	Aironet_b7:ab:5c	84:78:ac:f0:68:d1	EAPOL	2462	Key (Message 1 of 4)
6	0.043727	Aironet_b7:ab:5c	Cisco_f0:68:d1	84:78:ac:f0:68:d1	EAPOL	2462	Key (Message 2 of 4)
7	0.047655	Cisco_f0:68:d1	Aironet_b7:ab:5c	84:78:ac:f0:68:d1	EAPOL	2462	Key (Message 3 of 4)
8	0.054964	Aironet_b7:ab:5c	Cisco_f0:68:d1	84:78:ac:f0:68:d1	EAPOL	2462	Key (Message 4 of 4)
9	4.691372	Cisco_f0:68:d0	Aironet_b7:ab:5c	84:78:ac:f0:68:d1	802.11	2462	QoS Data, SN=38, FN=0, Flags=.p....F.C
10	7.364718	Aironet_b7:ab:5c	Broadcast	84:78:ac:f0:68:d1	802.11	2462	QoS Data, SN=1683, FN=0, Flags=.p.....TC

As shown, after the 802.11 Open System authentication and association process, there are four EAPOL frames from the WPA 4-Way handshake, which are initiated by the AP with **message-1**, and finished by the client with **message-4**. After a successful handshake, the client begins to pass data frames (such as DHCP), which in this case are encrypted with the keys derived from the 4-Way handshake (this is why you cannot see the actual content and type of traffic from the wireless images).

Note: EAPOL frames are used in order to transport all of the key management frames and 802.1X/EAP Authentication frames over-the-air between the AP and the client; they are transmitted as wireless data frames.

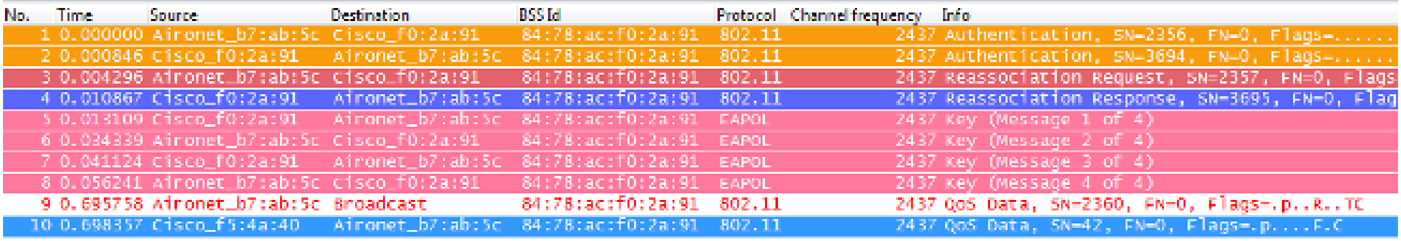
These messages appear in the debug outputs:

<#root>

```
*apfMsConnTask_0: Jun 21 19:30:05.172: 00:40:96:b7:ab:5c
  Association received from mobile on BSSID 84:78:ac:f0:68:d1
*apfMsConnTask_0: Jun 21 19:30:05.173: 00:40:96:b7:ab:5c
  Sending Assoc Response to station on BSSID 84:78:ac:f0:68:d1
  (status 0) ApVapId 2 Slot 0

!--- The Association handshake is finished.



*dot1xMsgTask: Jun 21 19:30:05.178: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c
  state INITPMK (message 1), replay counter
  00.00.00.00.00.00.00.00

!--- Message-1 of the WPA/WPA2 4-Way handshake is sent
     from the WLC/AP to the client.



*Dot1x_NW_MsgTask_4: Jun 21 19:30:05.289: 00:40:96:b7:ab:5c
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c
*Dot1x_NW_MsgTask_4: Jun 21 19:30:05.289: 00:40:96:b7:ab:5c
  Received EAPOL-key in PTK_START state (message 2)
  from mobile 00:40:96:b7:ab:5c

!--- Message-2 of the WPA/WPA2 4-Way handshake is successfully
     received from the client.



*Dot1x_NW_MsgTask_4: Jun 21 19:30:05.290: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c
  state PTKINITNEGOTIATING (message 3), replay counter
  00.00.00.00.00.00.00.01

!--- Message-3 of the WPA/WPA2 4-Way handshake is sent
     from the WLC/AP to the client.



*Dot1x_NW_MsgTask_4: Jun 21 19:30:05.309: 00:40:96:b7:ab:5c
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c
*Dot1x_NW_MsgTask_4: Jun 21 19:30:05.310: 00:40:96:b7:ab:5c
  Received EAPOL-key in PTKINITNEGOTIATING state (message 4)
  from mobile 00:40:96:b7:ab:5c
```

```
!--- Message-4 (final message) of the WPA/WPA2 4-Way handshake
     is successfully received from the client, which confirms
     the installation of the derived keys. They can now be used in
     order to encrypt data frames with current AP.
```

When roaming, the client basically tracks the same frame exchange, where the WPA 4-Way handshake is required in order to derive new encryption keys with the new AP. This is due to security reasons established by the standard, and the fact that the new AP does not know the original keys. The only difference is that there are Reassociation frames instead of Association frames, as shown in this image:



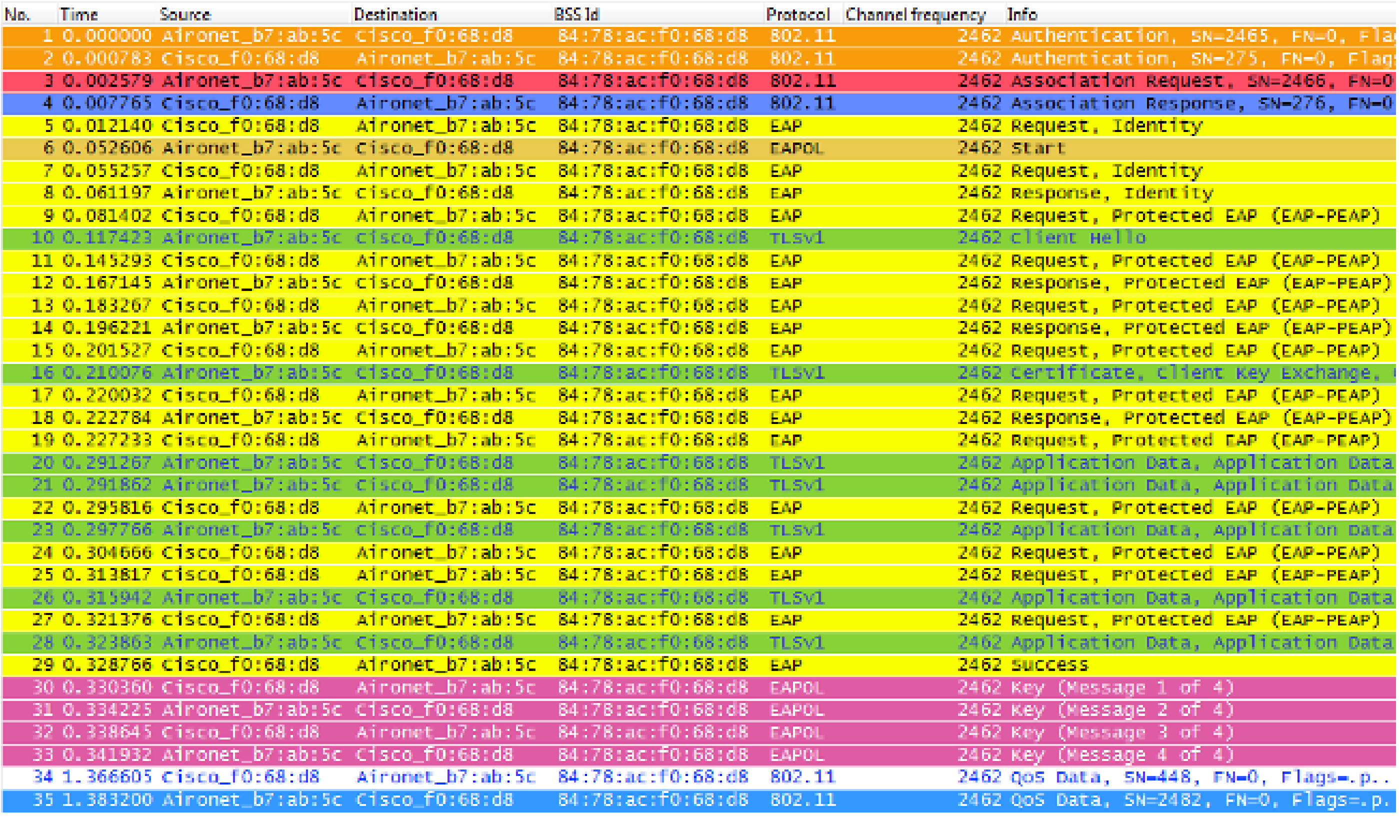
No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Aironet_b7:ab:5c	Cisco_f0:2a:91	84:78:ac:f0:2a:91	802.11	2437	Authentication, SN=2356, FN=0, Flags=......
2	0.000846	Cisco_f0:2a:91	Aironet_b7:ab:5c	84:78:ac:f0:2a:91	802.11	2437	Authentication, SN=3694, FN=0, Flags=......
3	0.004296	Aironet_b7:ab:5c	Cisco_f0:2a:91	84:78:ac:f0:2a:91	802.11	2437	Reassociation Request, SN=2357, FN=0, Flags
4	0.010867	Cisco_f0:2a:91	Aironet_b7:ab:5c	84:78:ac:f0:2a:91	802.11	2437	Reassociation Response, SN=3695, FN=0, Flag
5	0.013109	Cisco_f0:2a:91	Aironet_b7:ab:5c	84:78:ac:f0:2a:91	EAPOL	2437	Key (Message 1 of 4)
6	0.034339	Aironet_b7:ab:5c	Cisco_f0:2a:91	84:78:ac:f0:2a:91	EAPOL	2437	Key (Message 2 of 4)
7	0.041124	Cisco_f0:2a:91	Aironet_b7:ab:5c	84:78:ac:f0:2a:91	EAPOL	2437	Key (Message 3 of 4)
8	0.056241	Aironet_b7:ab:5c	Cisco_f0:2a:91	84:78:ac:f0:2a:91	EAPOL	2437	Key (Message 4 of 4)
9	0.695758	Aironet_b7:ab:5c	Broadcast	84:78:ac:f0:2a:91	802.11	2437	QoS Data, SN=2360, FN=0, Flags=.p..R..TC
10	0.698357	Cisco_f5:4a:40	Aironet_b7:ab:5c	84:78:ac:f0:2a:91	802.11	2437	QoS Data, SN=42, FN=0, Flags=.p....F.C

You see the same messages in the debug outputs, but the first packet from the client is a Reassociation instead of an Association, as shown and explained previously.

WPA/WPA2-EAP

When an 802.1X/EAP method is used in order to authenticate the clients on a secure SSID, there are even more frames required before the client begins to pass traffic. These extra frames are used in order to authenticate the client credentials, and dependent upon the EAP method, there can be between four and twenty frames. These come after the Association/Reassociation, but before the WPA/WPA2 4-Way handshake, because the authentication phase derives the MSK used as the seed for the final encryption key generation in the key management process (4-Way handshake).

This image shows an example of the frames exchanged over the air between the AP and the wireless client on initial association when WPA with PEAPv0/EAP-MSCHAPv2 is performed:



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	802.11	2462	Authentication, SN=2465, FN=0, Fla
2	0.000783	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	802.11	2462	Authentication, SN=275, FN=0, Flag
3	0.002579	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	802.11	2462	Association Request, SN=2466, FN=0
4	0.007765	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	802.11	2462	Association Response, SN=276, FN=0
5	0.012140	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Identity
6	0.052606	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	EAPOL	2462	Start
7	0.055257	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Identity
8	0.061197	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	EAP	2462	Response, Identity
9	0.081402	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Protected EAP (EAP-PEAP)
10	0.117423	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	TLSv1	2462	Client Hello
11	0.145293	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Protected EAP (EAP-PEAP)
12	0.167145	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	EAP	2462	Response, Protected EAP (EAP-PEAP)
13	0.183267	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Protected EAP (EAP-PEAP)
14	0.196221	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	EAP	2462	Response, Protected EAP (EAP-PEAP)
15	0.201527	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Protected EAP (EAP-PEAP)
16	0.210076	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	TLSv1	2462	Certificate, Client Key Exchange,
17	0.220032	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Protected EAP (EAP-PEAP)
18	0.222784	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	EAP	2462	Response, Protected EAP (EAP-PEAP)
19	0.227233	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Protected EAP (EAP-PEAP)
20	0.291267	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	TLSv1	2462	Application Data, Application Data
21	0.291862	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	TLSv1	2462	Application Data, Application Data
22	0.295816	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Protected EAP (EAP-PEAP)
23	0.297766	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	TLSv1	2462	Application Data, Application Data
24	0.304666	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Protected EAP (EAP-PEAP)
25	0.313817	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Protected EAP (EAP-PEAP)
26	0.315942	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	TLSv1	2462	Application Data, Application Data
27	0.321376	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Request, Protected EAP (EAP-PEAP)
28	0.323863	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	TLSv1	2462	Application Data, Application Data
29	0.328766	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAP	2462	Success
30	0.330360	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAPOL	2462	Key (Message 1 of 4)
31	0.334225	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	EAPOL	2462	Key (Message 2 of 4)
32	0.338645	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	EAPOL	2462	Key (Message 3 of 4)
33	0.341932	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	EAPOL	2462	Key (Message 4 of 4)
34	1.366605	Cisco_f0:68:d8	Aironet_b7:ab:5c	84:78:ac:f0:68:d8	802.11	2462	QoS Data, SN=448, FN=0, Flags=.p..
35	1.383200	Aironet_b7:ab:5c	Cisco_f0:68:d8	84:78:ac:f0:68:d8	802.11	2462	QoS Data, SN=2482, FN=0, Flags=.p.

Sometimes this exchange shows more or less frames, which depends on multiple factors, such as the EAP method, retransmissions due to problems, client behavior (such as the two Identity Requests in this example, because the client sends an **EAPOL START** after the AP sends the first Identity Request), or if the client already exchanged the certificate with the server. Whenever the SSID is configured for an 802.1X/EAP method, there are more frames (for the authentication), and hence, it requires more time before the client begins to send data frames.

Here is a summary of the debug messages:

<#root>

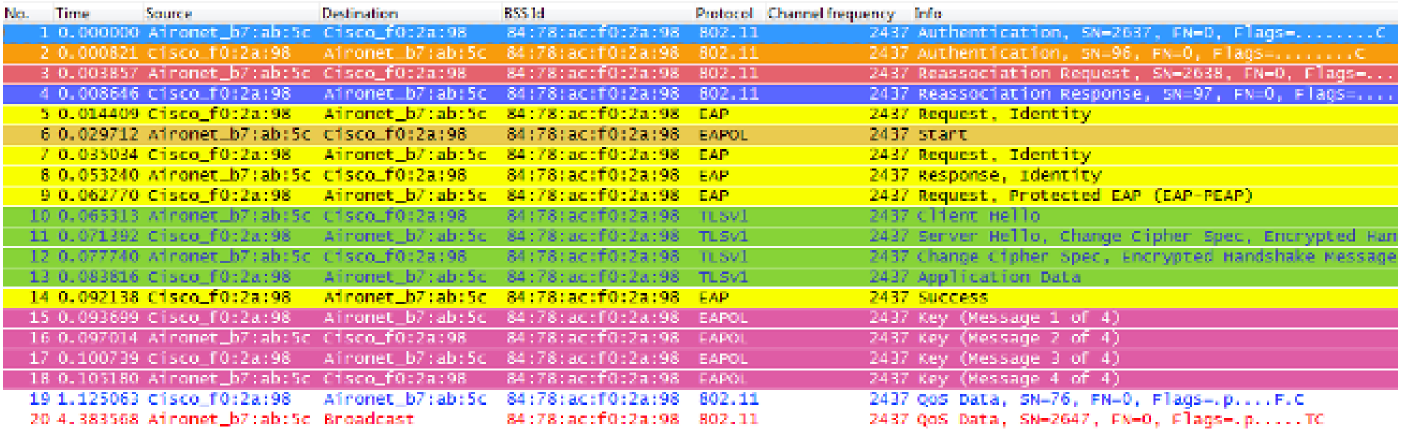
```
*apfMsConnTask_0: Jun 21 23:41:19.092: 00:40:96:b7:ab:5c
  Association received from mobile on BSSID 84:78:ac:f0:68:d8
*apfMsConnTask_0: Jun 21 23:41:19.094: 00:40:96:b7:ab:5c
  Sending Assoc Response to station on BSSID 84:78:ac:f0:68:d8
  (status 0) ApVapId 9 Slot 0

!--- The Association handshake is finished.



*dot1xMsgTask: Jun 21 23:41:19.098: 00:40:96:b7:ab:5c
  Sending EAP-Request/Identity to mobile 00:40:96:b7:ab:5c
  (EAP Id 1)

!--- The EAP Identity Request is sent to the client once it is
     associated in order to begin the higher-level authentication
     process. This informs the client that an identity to start
     this type of 802.1X/EAP authentication must be provided.



*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.226: 00:40:96:b7:ab:5c
  Received EAPOL START from mobile 00:40:96:b7:ab:5c
```

```
!--- The wireless client decides to start the EAP authentication
     process, and informs the AP with an EAPOL START data frame.



*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.227: 00:40:96:b7:ab:5c
  Sending EAP-Request/Identity to mobile 00:40:96:b7:ab:5c
  (EAP Id 2)

!--- WLC/AP sends another EAP Identity Request to the client.



*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.235: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c
*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.235: 00:40:96:b7:ab:5c
  Received Identity Response (count=2) from mobile 00:40:96:b7:ab:5c

!--- The client responds with an EAP Identity Response on an EAPOL
     frame.



*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.301: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c
*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.301: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 3)

!--- Once the WLC/AP sends the client response to the Authentication
     Server on a RADIUS Access-Request packet, the server responds
     with a RADIUS Access-Challenge in order to officially start the
     EAP negotiation, handshake, and authentication with the client
     (sometimes with mutual authentication, dependent upon the EAP
     method). This response received by the WLC/AP is sent to the client.



*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.344: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c
*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.344: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 3, EAP Type 25)

!--- The client responds with an EAP Response on an EAPOL frame, which
     is sent to the Authentication Server on a RADIUS Access-Request
     packet. The server responds with another RADIUS Access-Challenge.
     This process continues, dependent upon the EAP method (the exchange
     of certificates when used, the building of TLS tunnels, validation
     of client credentials, client validation of server identity when
     applicable). Hence, the next few messages are basically the same on
     the WLC/AP side, as this acts as a "proxy" between the client and
     the Authentication Server exchanges.



*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.347: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.347: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 4)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.375: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c
```

```
*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.375: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 4, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.377: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.377: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 5)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.403: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.403: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 5, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.404: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.404: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 6)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.414: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.414: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 6, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.421: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.421: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 7)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.425: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.425: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 7, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.427: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.427: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 8)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.434: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.434: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 8, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.436: 00:40:96:b7:ab:5c
```

```
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.436: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 9)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.440: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.440: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 9, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.442: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.442: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 10)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.449: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.449: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 10, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.452: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.452: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 11)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.457: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.457: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 11, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.459: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.459: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 13)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.469: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.469: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 13, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.472: 00:40:96:b7:ab:5c
  Processing Access-Accept for mobile 00:40:96:b7:ab:5c

!--- The authentication finishes and is successful for this client,
     so the RADIUS Server sends a RADIUS Access-Accept to the WLC/AP.
     This RADIUS Access-Accept comes with the special attributes
     that are assigned to this client (if any are configured on the
     Authentication Server for this client). This Access-Accept also
     comes with the MSK derived with the client in the EAP
     authentication process, so the WLC/AP installs it in order to
     initiate the WPA/WPA2 4-Way handshake with the wireless client.



*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.473: 00:40:96:b7:ab:5c
  Sending EAP-Success to mobile 00:40:96:b7:ab:5c
  (EAP Id 13)

!--- The accept/pass of the authentication is sent to the client as
     an EAP-Success message.



*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.473: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c
  state INITPMK (message 1), replay counter
  00.00.00.00.00.00.00.00

!--- Message-1 of the WPA/WPA2 4-Way handshake is sent from the
     WLC/AP to the client.



*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.481: 00:40:96:b7:ab:5c
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c
*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.481: 00:40:96:b7:ab:5c
  Received EAPOL-key in PTK_START state (message 2)
  from mobile 00:40:96:b7:ab:5c

!--- Message-2 of the WPA/WPA-2 4-Way handshake is successfully
     received from the client.



*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.481: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c
  state PTKINITNEGOTIATING (message 3), replay counter
  00.00.00.00.00.00.00.01

!--- Message-3 of the WPA/WPA2 4-Way handshake is sent from the
     WLC/AP to the client.



*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.487: 00:40:96:b7:ab:5c
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c
*Dot1x_NW_MsgTask_4: Jun 21 23:41:19.487: 00:40:96:b7:ab:5c
  Received EAPOL-key in PTKINITNEGOTIATING state (message 4)
  from mobile 00:40:96:b7:ab:5c

!--- Message-4 (final message) of the WPA/WPA2 4-Way handshake
     is successfully received from the client, which confirms the
     installation of the derived keys. They can now be used in
     order to encrypt data frames with the current AP.
```

When the wireless client performs a regular roaming here (the normal behavior, without implementation of a fast-secure roaming method), the client must go through the exact same process and perform a full authentication against the Authentication Server, as shown in the images. The only difference is that the client uses a Reassociation Request in order to inform the new AP that it is actually roaming from another AP, but the client still has to go through full validation and new key generation:



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Aironet_b7:ab:5c	Cisco_f0:2a:98	84:78:ac:f0:2a:98	802.11	2437	Authentication, SN=2637, FN=0, Flags=........C
2	0.000821	Cisco_f0:2a:98	Aironet_b7:ab:5c	84:78:ac:f0:2a:98	802.11	2437	Authentication, SN=96, FN=0, Flags=........C
3	0.003857	Aironet_b7:ab:5c	Cisco_f0:2a:98	84:78:ac:f0:2a:98	802.11	2437	Reassociation Request, SN=2638, FN=0, Flags=...
4	0.008646	Cisco_f0:2a:98	Aironet_b7:ab:5c	84:78:ac:f0:2a:98	802.11	2437	Reassociation Response, SN=97, FN=0, Flags=....
5	0.014409	Cisco_f0:2a:98	Aironet_b7:ab:5c	84:78:ac:f0:2a:98	EAP	2437	Request, Identity
6	0.029712	Aironet_b7:ab:5c	Cisco_f0:2a:98	84:78:ac:f0:2a:98	EAPOL	2437	Start
7	0.035034	Cisco_f0:2a:98	Aironet_b7:ab:5c	84:78:ac:f0:2a:98	EAP	2437	Request, Identity
8	0.053240	Aironet_b7:ab:5c	Cisco_f0:2a:98	84:78:ac:f0:2a:98	EAP	2437	Response, Identity
9	0.062770	Cisco_f0:2a:98	Aironet_b7:ab:5c	84:78:ac:f0:2a:98	EAP	2437	Request, Protected EAP (EAP-PEAP)
10	0.065313	Aironet_b7:ab:5c	Cisco_f0:2a:98	84:78:ac:f0:2a:98	TLSv1	2437	Client Hello
11	0.071392	Cisco_f0:2a:98	Aironet_b7:ab:5c	84:78:ac:f0:2a:98	TLSv1	2437	Server Hello, Change Cipher Spec, Encrypted Han
12	0.077740	Aironet_b7:ab:5c	Cisco_f0:2a:98	84:78:ac:f0:2a:98	TLSv1	2437	Change Cipher Spec, Encrypted Handshake Message
13	0.083816	Cisco_f0:2a:98	Aironet_b7:ab:5c	84:78:ac:f0:2a:98	TLSv1	2437	Application Data
14	0.092138	Cisco_f0:2a:98	Aironet_b7:ab:5c	84:78:ac:f0:2a:98	EAP	2437	Success
15	0.093699	Cisco_f0:2a:98	Aironet_b7:ab:5c	84:78:ac:f0:2a:98	EAPOL	2437	Key (Message 1 of 4)
16	0.097014	Aironet_b7:ab:5c	Cisco_f0:2a:98	84:78:ac:f0:2a:98	EAPOL	2437	Key (Message 2 of 4)
17	0.100739	Cisco_f0:2a:98	Aironet_b7:ab:5c	84:78:ac:f0:2a:98	EAPOL	2437	Key (Message 3 of 4)
18	0.105180	Aironet_b7:ab:5c	Cisco_f0:2a:98	84:78:ac:f0:2a:98	EAPOL	2437	Key (Message 4 of 4)
19	1.125063	Cisco_f0:2a:98	Aironet_b7:ab:5c	84:78:ac:f0:2a:98	802.11	2437	QoS Data, SN=76, FN=0, Flags=.p....F.C
20	4.383568	Aironet_b7:ab:5c	Broadcast	84:78:ac:f0:2a:98	802.11	2437	QoS Data, SN=2647, FN=0, Flags=.p.....TC

As shown, even when there are less frames than in the initial authentication (which is caused by multiple factors, as mentioned before), when the client roams to a new AP, the EAP authentication and the WPA key management processes must still be completed in order to continue to pass data frames (even if traffic was actively sent before roaming). Therefore, if the client has an active application that is sensitive to delays (such as voice-traffic applications, or applications that are sensitive to timeouts), then the user can perceive problems when roaming, such as audio gaps or application disconnects. This depends on how long the process takes in order for the client to continue to send/receive data frames. This delay can be longer, dependent upon: the RF environment, the amount of clients, the round-trip time between the WLC and LAPs and with the Authentication Server, and other reasons.

Here is a summary of the debug messages for this roaming event (basically the same as the previous ones, so these messages are not described further):

```
*apfMsConnTask_2: Jun 21 23:47:54.872: 00:40:96:b7:ab:5c
  Reassociation received from mobile on BSSID 84:78:ac:f0:2a:98

*apfMsConnTask_2: Jun 21 23:47:54.874: 00:40:96:b7:ab:5c
  Sending Assoc Response to station on BSSID 84:78:ac:f0:2a:98
  (status 0) ApVapId 9 Slot 0

*dot1xMsgTask: Jun 21 23:47:54.879: 00:40:96:b7:ab:5c
  Sending EAP-Request/Identity to mobile 00:40:96:b7:ab:5c
  (EAP Id 1)

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.895: 00:40:96:b7:ab:5c
  Received EAPOL START from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.895: 00:40:96:b7:ab:5c
  dot1x - moving mobile 00:40:96:b7:ab:5c into Connecting state

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.895: 00:40:96:b7:ab:5c
  Sending EAP-Request/Identity to mobile 00:40:96:b7:ab:5c
  (EAP Id 2)

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.922: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.922: 00:40:96:b7:ab:5c
  Received Identity Response (count=2) from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.929: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.929: 00:40:96:b7:ab:5c
```

```
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 3)

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.941: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.941: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 3, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.943: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.943: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 4)

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.954: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.954: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 4, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.956: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.957: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 7)

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.976: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.976: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 7, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.978: 00:40:96:b7:ab:5c
  Processing Access-Accept for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.978: 00:40:96:b7:ab:5c
  Sending EAP-Success to mobile 00:40:96:b7:ab:5c
  (EAP Id 7)

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.978: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c
  state INITPMK (message 1), replay counter
  00.00.00.00.00.00.00.00

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.995: 00:40:96:b7:ab:5c
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.995: 00:40:96:b7:ab:5c
  Received EAPOL-key in PTK_START state (message 2)
  from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:54.995: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c
  state PTKINITNEGOTIATING (message 3), replay counter
  00.00.00.00.00.00.00.01
```

```
*Dot1x_NW_MsgTask_4: Jun 21 23:47:55.005: 00:40:96:b7:ab:5c
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 23:47:55.005: 00:40:96:b7:ab:5c
  Received EAPOL-key in PTKINITNEGOTIATING state (message 4)
  from mobile 00:40:96:b7:ab:5c
```

This is the way that 802.1X/EAP and the WPA/WPA2 security framework work. In order to prevent the application/service impact on delays from a regular roaming event, multiple fast-secure roaming methods are developed and implemented by the WiFi industry in order to accelerate the roaming process when security is used on the WLAN/SSID. The clients face some latency when they continue to pass traffic while roaming around between APs via deployment of high-level security on the WLAN. This is due to the EAP authentication and key-management frame exchanges required by the security setup, as previously explained.

It is important to understand that fast-secure roaming is just the term used by the industry in reference to the implementation of a method/scheme that accelerates the roaming process when security is configured on the WLAN. The different fast-secure roaming methods/schemes that are available for WLANs, and are supported by the CUWN, are explained in the next section.

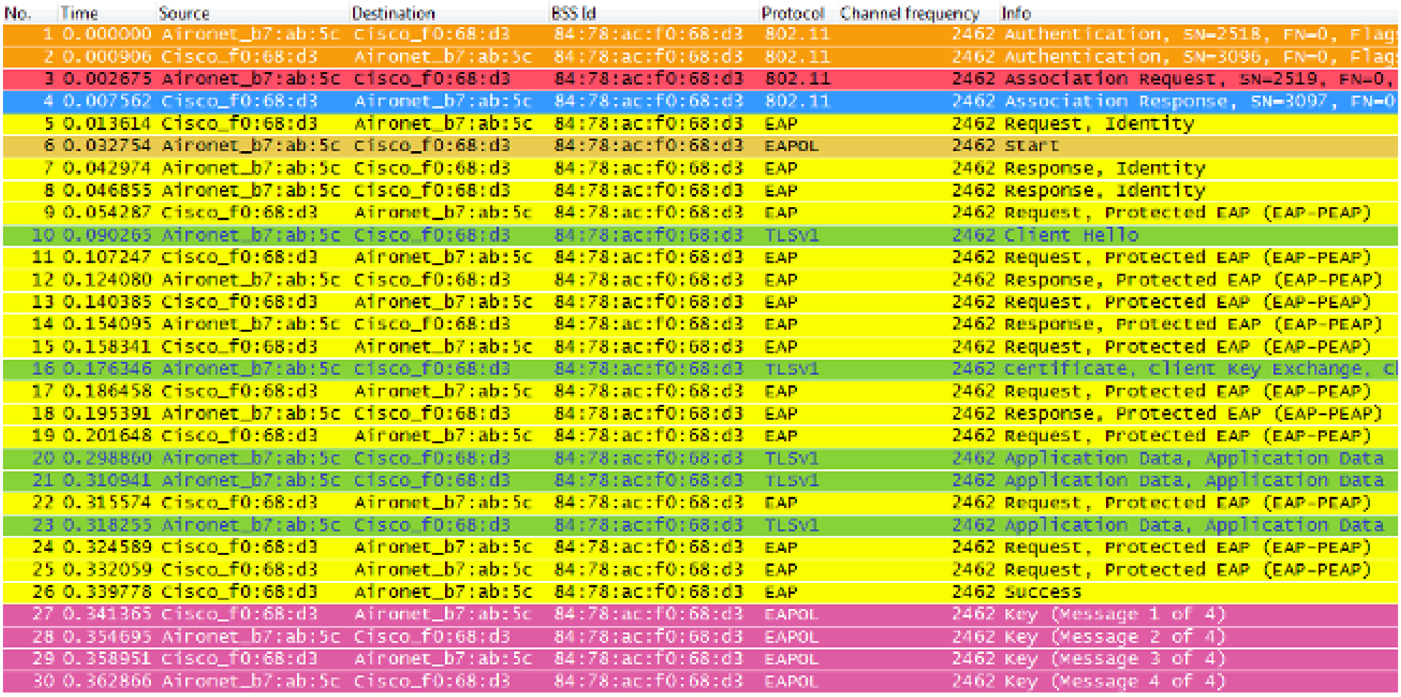
Fast-Secure Roaming with CCKM

Cisco Centralized Key Management (CCKM) is the first fast-secure roaming method developed and implemented on enterprise WLANs, created by Cisco as the solution used in order to mitigate the delays explained thus far, when 802.1X/EAP security is used on the WLAN. As this is a Cisco proprietary protocol, it is only supported by Cisco WLAN infrastructure devices and wireless clients (from multiple vendors) that are Cisco Compatible Extension (CCX)-compatible for CCKM.

CCKM can be implemented with all of the different encryption methods available for WLANs, to include: WEP, TKIP, and AES. It is also supported with most of the 802.1X/EAP authentication methods used for WLANs, dependent upon the CCX version supported by the devices.

Note: For an overview on the feature content supported by the different versions of the CCX specification (that includes EAP methods supported), reference the CCX Versions and Features document, and verify the exact CCX version that is supported by your wireless clients (if they are CCX-compatible), so that you can confirm if the security method you desire to use with CCKM can be implemented.

This wireless image provides an example of the frames exchanged upon initial association when you perform CCKM with TKIP as the encryption, and PEAPv0/EAP-MSCHAPv2 as the 802.1X/EAP method. This is basically the same exchange as if WPA/TKIP with PEAPv0/EAP-MSCHAPv2 is performed, but this time CCKM between the client and the infrastructure is negotiated so that they use different key hierarchy and cache methods in order to perform Fast Secure Roaming when the client must roam:



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	802.11	2462	Authentication, SN=2518, FN=0, Flag
2	0.000906	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	802.11	2462	Authentication, SN=3096, FN=0, Flag
3	0.002675	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	802.11	2462	Association Request, SN=2519, FN=0,
4	0.007562	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	802.11	2462	Association Response, SN=3097, FN=0
5	0.013614	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAP	2462	Request, Identity
6	0.032754	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	EAPOL	2462	Start
7	0.042974	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	EAP	2462	Response, Identity
8	0.046855	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	EAP	2462	Response, Identity
9	0.054287	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAP	2462	Request, Protected EAP (EAP-PEAP)
10	0.090265	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	TLSv1	2462	Client Hello
11	0.107247	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAP	2462	Request, Protected EAP (EAP-PEAP)
12	0.124080	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	EAP	2462	Response, Protected EAP (EAP-PEAP)
13	0.140385	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAP	2462	Request, Protected EAP (EAP-PEAP)
14	0.154095	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	EAP	2462	Response, Protected EAP (EAP-PEAP)
15	0.158341	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAP	2462	Request, Protected EAP (EAP-PEAP)
16	0.176346	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	TLSv1	2462	Certificate, Client Key Exchange, Cl
17	0.186458	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAP	2462	Request, Protected EAP (EAP-PEAP)
18	0.195391	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	EAP	2462	Response, Protected EAP (EAP-PEAP)
19	0.201648	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAP	2462	Request, Protected EAP (EAP-PEAP)
20	0.298860	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	TLSv1	2462	Application Data, Application Data
21	0.310941	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	TLSv1	2462	Application Data, Application Data
22	0.315574	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAP	2462	Request, Protected EAP (EAP-PEAP)
23	0.318255	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	TLSv1	2462	Application Data, Application Data
24	0.324589	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAP	2462	Request, Protected EAP (EAP-PEAP)
25	0.332059	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAP	2462	Request, Protected EAP (EAP-PEAP)
26	0.339778	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAP	2462	Success
27	0.341365	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAPOL	2462	Key (Message 1 of 4)
28	0.354695	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	EAPOL	2462	Key (Message 2 of 4)
29	0.358951	Cisco_f0:68:d3	Aironet_b7:ab:5c	84:78:ac:f0:68:d3	EAPOL	2462	Key (Message 3 of 4)
30	0.362866	Aironet_b7:ab:5c	Cisco_f0:68:d3	84:78:ac:f0:68:d3	EAPOL	2462	Key (Message 4 of 4)

Here is a summary of the debug messages (with some EAP exchanges removed in order to reduce the output):

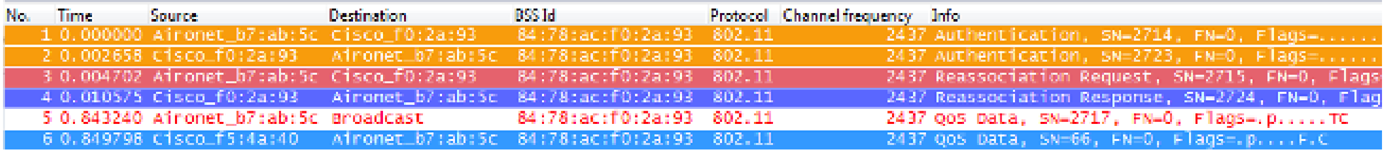
<#root>

```
*apfMsConnTask_0: Jun 25 15:41:41.507: 00:40:96:b7:ab:5c
  Association received from mobile on BSSID 84:78:ac:f0:68:d3

!--- This is the Association Request from the client.



*apfMsConnTask_0: Jun 25 15:41:41.507: 00:40:96:b7:ab:5c
  Processing WPA IE type 221, length 22 for mobile
  00:40:96:b7:ab:5c
*apfMsConnTask_0: Jun 25 15:41:41.507: 00:40:96:b7:ab:5c
  CCKM: Mobile is using CCKM

!--- The WLC/AP finds an Information Element that claims CCKM
      support on the Association request that is sent from the client.



*apfMsConnTask_0: Jun 25 15:41:41.507: 00:40:96:b7:ab:5c
  Setting active key cache index 8 ---> 8

!--- This is the key cache index for this client, which is set temporally.



*apfMsConnTask_0: Jun 25 15:41:41.508: 00:40:96:b7:ab:5c
  Sending Assoc Response to station on BSSID 84:78:ac:f0:68:d3
  (status 0) ApVapId 4 Slot 0

!--- The Association Response is sent to the client.



*dot1xMsgTask: Jun 25 15:41:41.513: 00:40:96:b7:ab:5c
  Sending EAP-Request/Identity to mobile 00:40:96:b7:ab:5c
  (EAP Id 1)

!--- An EAP Identity Request is sent to the client once it is
     associated in order to begin the higher-level authentication
     process. This informs the client that an identity to start
     this type of 802.1X/EAP authentication must be provided.
     Further EAP messages are not described, as they are basically
     the same as the ones previously-explained.



*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.536: 00:40:96:b7:ab:5c
  Received EAPOL START from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.536: 00:40:96:b7:ab:5c
  Sending EAP-Request/Identity to mobile 00:40:96:b7:ab:5c
  (EAP Id 2)

*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.546: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.546: 00:40:96:b7:ab:5c
  Received EAP Response packet with mismatching id
  (currentid=2, eapid=1) from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.550: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.550: 00:40:96:b7:ab:5c
  Received Identity Response (count=2) from mobile
  00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.555: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.555: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 3)

*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.594: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.594: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 3, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.840: 00:40:96:b7:ab:5c
  Processing Access-Accept for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.841: 00:40:96:b7:ab:5c
  Creating a PKC PMKID Cache entry for station 00:40:96:b7:ab:5c
  (RSN 0)<br/ >
*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.841: 00:40:96:b7:ab:5c
  Setting active key cache index 8 ---> 8
*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.841: 00:40:96:b7:ab:5c
  Setting active key cache index 8 ---> 0
*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.841: 00:40:96:b7:ab:5c
  CCKM: Create a global PMK cache entry

!--- WLC creates a global PMK cache entry for this client,
     which is for CCKM in this case.
```

```
*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.841: 00:40:96:b7:ab:5c
  Sending EAP-Success to mobile 00:40:96:b7:ab:5c
  (EAP Id 13)

!--- The client is informed of the successful EAP authentication.



*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.841: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c state
  INITPMK(message 1),replay counter 00.00.00.00.00.00.00.00

!--- Message-1 of the initial 4-Way handshake is sent from the
     WLC/AP to the client.



*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.858: 00:40:96:b7:ab:5c
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c
*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.858: 00:40:96:b7:ab:5c
  Received EAPOL-key in PTK_START state (message 2) from mobile
  00:40:96:b7:ab:5c

!--- Message-2 of the initial 4-Way handshake is received
     successfully from the client.



*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.858: 00:40:96:b7:ab:5c
  CCKM: Sending cache add
*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.858: CCKM: Sending CCKM PMK
  (Version_1) information to mobility group
*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.858: CCKM: Sending CCKM PMK
  (Version_2) information to mobility group

!--- The CCKM PMK cache entry for this client is shared with
     the WLCs on the mobility group.



*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.858: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c
  state PTKINITNEGOTIATING (message 3), replay counter
  00.00.00.00.00.00.00.01

!--- Message-3 of the initial 4-Way handshake is sent from the
     WLC/AP to the client.



*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.866: 00:40:96:b7:ab:5c
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c
*Dot1x_NW_MsgTask_4: Jun 25 15:41:41.866: 00:40:96:b7:ab:5c Received
  EAPOL-key in PTKINITNEGOTIATING state (message 4) from mobile
  00:40:96:b7:ab:5c

!--- Message-4 (final message) of this initial 4-Way handshake
     is received successfully from the client, which confirms the
     installation of the derived keys. They can now be used in order
     to encrypt data frames with the current AP.
```

With CCKM, the initial association to the WLAN is similar to the regular WPA/WPA2, where an MSK (also known here as the Network Session Key (NSK)) is mutually derived with the client and the RADIUS Server. This primary key is sent from the server to the WLC after a successful authentication, and is cached as the basis for derivation of all subsequent keys for the lifetime of the client association with this WLAN. From here, the WLC and the client derive the seed information that is used for fast-secure roaming based on CCKM, this goes through a 4-Way handshake similar to that of WPA/WPA2, in order to derive the unicast (PTK) and multicast/broadcast (GTK) encryption keys with the first AP.

The big difference is noticed when roaming. In this case, the CCKM client sends a single Reassociation Request frame to the AP/WLC (that includes an MIC and a sequentially incrementing Random Number), and provides enough information (that includes the new AP MAC address **-BSSID-**) in order to derive the new PTK. With this Reassociation Request, the WLC and new AP also have enough information in order to derive the new PTK, so they simply respond with a Reassociation Response. The client can now continue to pass traffic, as shown in this image:



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Aironet_b7:ab:5c	Cisco_f0:2a:93	84:78:ac:f0:2a:93	802.11	2437	Authentication, SN=2714, FN=0, Flags=......
2	0.002658	Cisco_f0:2a:93	Aironet_b7:ab:5c	84:78:ac:f0:2a:93	802.11	2437	Authentication, SN=2723, FN=0, Flags=......
3	0.004702	Aironet_b7:ab:5c	Cisco_f0:2a:93	84:78:ac:f0:2a:93	802.11	2437	Reassociation Request, SN=2715, FN=0, Flags
4	0.010575	Cisco_f0:2a:93	Aironet_b7:ab:5c	84:78:ac:f0:2a:93	802.11	2437	Reassociation Response, SN=2724, FN=0, Flag
5	0.843240	Aironet_b7:ab:5c	Broadcast	84:78:ac:f0:2a:93	802.11	2437	QoS Data, SN=2717, FN=0, Flags=.p.....TC
6	0.849798	Cisco_f5:4a:40	Aironet_b7:ab:5c	84:78:ac:f0:2a:93	802.11	2437	QoS Data, SN=66, FN=0, Flags=.p....F.C

Here is a summary of the WLC debugs for this roaming event:

<#root>

```
*apfMsConnTask_2: Jun 25 15:43:33.749: 00:40:96:b7:ab:5c
  CCKM: Received REASSOC REQ IE
*apfMsConnTask_2: Jun 25 15:43:33.749: 00:40:96:b7:ab:5c
  Reassociation received from mobile on BSSID
  84:78:ac:f0:2a:93
*apfMsConnTask_2: Jun 25 15:43:33.750: 00:40:96:b7:ab:5c
  Processing WPA IE type 221, length 22 for mobile
  00:40:96:b7:ab:5c
*apfMsConnTask_2: Jun 25 15:43:33.750: 00:40:96:b7:ab:5c
  CCKM: Mobile is using CCKM

!--- The Reassociation Request is received from the client,
     which provides the CCKM information needed in order to
     derive the new keys with a fast-secure roam.



*apfMsConnTask_2: Jun 25 15:43:33.750: 00:40:96:b7:ab:5c
  Setting active key cache index 0 ---> 8

*apfMsConnTask_2: Jun 25 15:43:33.750: 00:40:96:b7:ab:5c
  CCKM: Processing REASSOC REQ IE

*apfMsConnTask_2: Jun 25 15:43:33.750: 00:40:96:b7:ab:5c
  CCKM: using HMAC MD5 to compute MIC

!--- WLC computes the MIC used for this CCKM fast-roaming
     exchange.



*apfMsConnTask_2: Jun 25 15:43:33.750: 00:40:96:b7:ab:5c
  CCKM: Received a valid REASSOC REQ IE

*apfMsConnTask_2: Jun 25 15:43:33.751: 00:40:96:b7:ab:5c
  CCKM: Initializing PMK cache entry with a new PTK
```

```
!--- The new PTK is derived.



*apfMsConnTask_2: Jun 25 15:43:33.751: 00:40:96:b7:ab:5c
  Setting active key cache index 8 ---> 8

*apfMsConnTask_2: Jun 25 15:43:33.751: 00:40:96:b7:ab:5c
  Setting active key cache index 8 ---> 8

*apfMsConnTask_2: Jun 25 15:43:33.751: 00:40:96:b7:ab:5c
  Setting active key cache index 8 ---> 0

*apfMsConnTask_2: Jun 25 15:43:33.751: 00:40:96:b7:ab:5c
  Creating a PKC PMKID Cache entry for station
  00:40:96:b7:ab:5c (RSN 0) on BSSID 84:78:ac:f0:2a:93

!--- The new PMKID cache entry is created for this new
     AP-to-client association.



*apfMsConnTask_2: Jun 25 15:43:33.751: 00:40:96:b7:ab:5c
  CCKM: using HMAC MD5 to compute MIC
*apfMsConnTask_2: Jun 25 15:43:33.751: 00:40:96:b7:ab:5c
  Including CCKM Response IE (length 62) in Assoc Resp to mobile
*apfMsConnTask_2: Jun 25 15:43:33.751: 00:40:96:b7:ab:5c
  Sending Assoc Response to station on BSSID 84:78:ac:f0:2a:93
  (status 0) ApVapId 4 Slot 0

!--- The Reassociation Response is sent from the WLC/AP to
     the client, which includes the CCKM information required
     in order to confirm the new fast-roam and key derivation.



*dot1xMsgTask: Jun 25 15:43:33.757: 00:40:96:b7:ab:5c
  Skipping EAP-Success to mobile 00:40:96:b7:ab:5c

!--- EAP is skipped due to the fast roaming, and CCKM does not
     require further key handshakes. The client is now ready to
     pass encrypted data frames on the new AP.
```

As shown, fast-secure roaming is performed while the EAP authentication frames are avoided and even more 4-Way handshakes, because the new encryption keys are still derived, but based on the CCKM negotiation scheme. This is completed with the roaming Reassociation frames and the information previously-cached by the client and the WLC.

FlexConnect with CCKM

- Central Authentication is supported. This includes Local and Central data swtiching. The APs must be part of the same FlexConnect Group.
- Flex Local Authentication is supported. In connected mode, the cache can be distributed from the AP to the controller and then to the rest of the APs in the FlexConnect Group.
- Standalone mode is supported. If the cache is already present on the AP (due to previous distribution), fast roam shall work. New authentication in standalone mode does not support fast-secure roaming.

Pros with CCKM

- CCKM is the fastest fast-secure roaming method mostly deployed on enterprise WLANs. Clients do not need to go over a key management handshake in order to derive new keys when a move between APs takes place, and are never again required to perform a full 802.1X/EAP authentication with new APs during the client lifetime on this WLAN.
- CCKM supports all of the encryption methods available within the 802.11 standard (WEP, TKIP, and AES), in addition to some legacy Cisco proprietary methods still used on legacy clients.

Cons with CCKM

- CCKM is a Cisco proprietary method, which limits the implementation and support to Cisco WLAN infrastructure and CCX wireless clients.
- CCX Version 5 is not widely adopted, so CCKM with WPA2/AES is not supported by many CCX wireless clients (mainly because most of them already support CCKM with WPA/TKIP, which is still very secure).

Fast-Secure Roaming with PMKID Caching / Sticky Key Caching

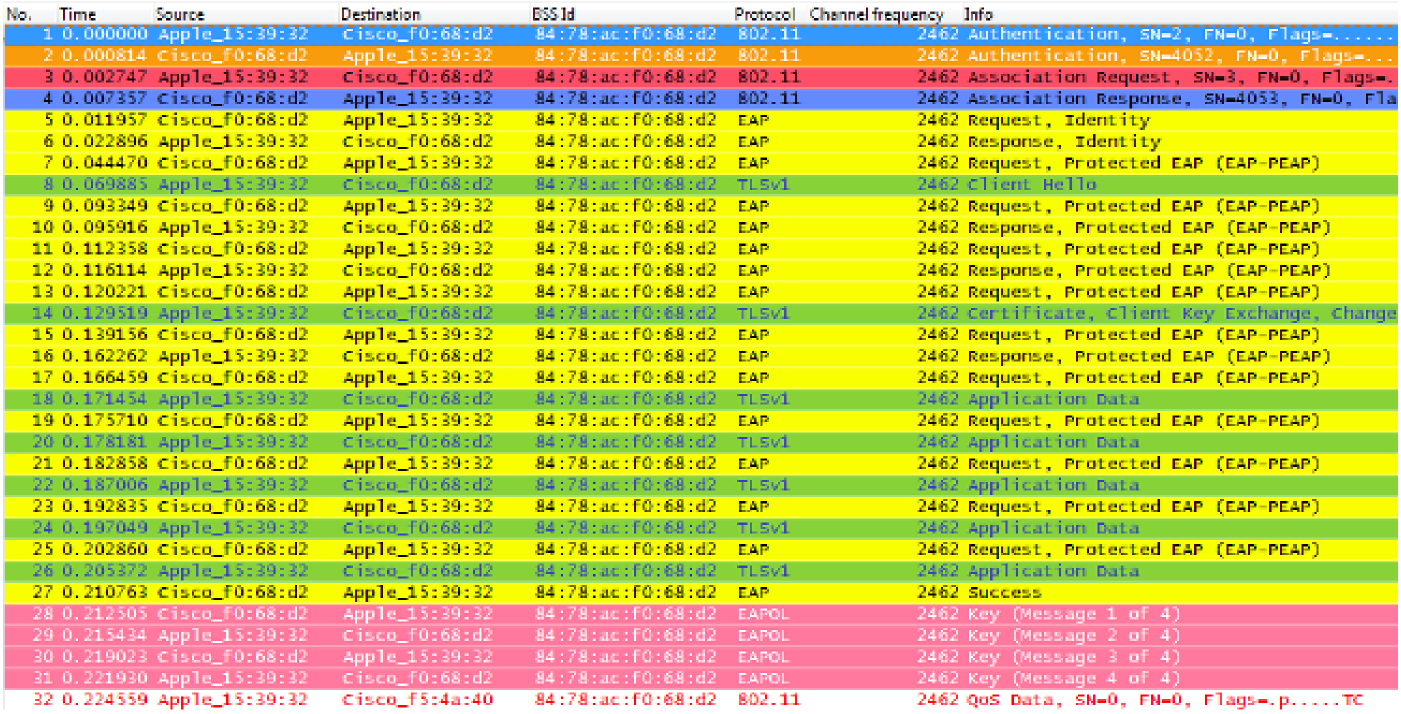
Pairwise think Key ID (PMKID) caching, or **Sticky Key Caching (SKC)**, is the first fast-secure roaming method suggested by the IEEE 802.11 standard within the 802.11i security amendment, where the main purpose is to standardize a high level of security for WLANs. This fast-secure roaming technique was added as an optional method for WPA2 devices in order to improve roaming when this security was implemented.

This is possible because, every time a client is fully EAP-authenticated, the client and Authentication Server derive an MSK, which is used in order to derive the PMK. This is used as the seed for the WPA2 4-Way handshake in order to derive the final unicast encryption key (PTK) that is used for the session (until the client roams to another AP or the session expires); hence, this method prevents the EAP authentication phase when roaming because it reutilizes the original PMK cached by the client and the AP. The client only has to go through the WPA2 4-Way handshake in order to derive new encryption keys.

This method is not widely deployed as the recommended 802.11 standard fast-secure roaming method mainly due to these reasons:

- This method is optional and is not supported by all WPA2 devices, because the purpose of the 802.11i amendment does not concern fast-secure roaming, and the IEEE already worked on another amendment to standardize fast-secure roaming for WLANs (802.11r, which is covered later in this document).
- This method has a big limitation on its implementation: Wireless clients can only perform fast-secure roaming when roaming back to an AP where they had previously authenticated/connected.

With this method, the initial association to any AP is just like a regular first-time authentication to the WLAN, where the entire 802.1X/EAP authentication against the Authentication Server and the 4-Way handshake for key generation must happen before the client is able to send data frames, as shown in this screen image:



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	802.11	2462	Authentication, SN=2, FN=0, Flags=......
2	0.000814	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	802.11	2462	Authentication, SN=4052, FN=0, Flags=...
3	0.002747	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	802.11	2462	Association Request, SN=3, FN=0, Flags=.
4	0.007357	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	802.11	2462	Association Response, SN=4053, FN=0, Fla
5	0.011957	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Request, Identity
6	0.022896	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAP	2462	Response, Identity
7	0.044470	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
8	0.069885	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Client Hello
9	0.093349	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
10	0.095916	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAP	2462	Response, Protected EAP (EAP-PEAP)
11	0.112358	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
12	0.116114	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAP	2462	Response, Protected EAP (EAP-PEAP)
13	0.120221	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
14	0.129519	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Certificate, Client Key Exchange, Change
15	0.139156	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
16	0.162262	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAP	2462	Response, Protected EAP (EAP-PEAP)
17	0.166459	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
18	0.171454	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Application Data
19	0.175710	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
20	0.178181	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Application Data
21	0.182858	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
22	0.187006	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Application Data
23	0.192835	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
24	0.197049	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Application Data
25	0.202860	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
26	0.205372	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Application Data
27	0.210763	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAP	2462	Success
28	0.212505	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 1 of 4)
29	0.215434	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 2 of 4)
30	0.219023	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 3 of 4)
31	0.221930	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 4 of 4)
32	0.224559	Apple_15:39:32	Cisco_f5:4a:40	84:78:ac:f0:68:d2	802.11	2462	QoS Data, SN=0, FN=0, Flags=.p.....TC

The debugs reveal the same EAP authentication frame exchange as the rest of the methods upon initial authentication to the WLAN, with some outputs added in regards to the key caching techniques used here. These debug outputs are cut in order to show mainly the new information, not the entire EAP frame exchange, because basically the same information is exchanged every time for authentication of the client against the Authentication Server. This is demonstrated thus far, and correlated with the EAP authentication frames shown in the packet images, so most of the EAP messages are removed from the debug outputs for simplicity:

<#root>

```
*apfMsConnTask_0: Jun 22 00:23:15.097: ec:85:2f:15:39:32
  Association received from mobile on BSSID 84:78:ac:f0:68:d2

!--- This is the Association Request from the client.



*apfMsConnTask_0: Jun 22 00:23:15.098: ec:85:2f:15:39:32
  Processing RSN IE type 48, length 20 for mobile ec:85:2f:15:39:32

!--- The WLC/AP finds an Information Element that claims PMKID
     Caching support on the Association request that is sent
     from the client.



*apfMsConnTask_0: Jun 22 00:23:15.098: ec:85:2f:15:39:32
  Received RSN IE with 0 PMKIDs from mobile ec:85:2f:15:39:32

!--- Since this is an initial association, the Association
     Request comes without any PMKID.



*apfMsConnTask_0: Jun 22 00:23:15.098: ec:85:2f:15:39:32
  Setting active key cache index 8 ---> 8
```

```
*apfMsConnTask_0: Jun 22 00:23:15.099: ec:85:2f:15:39:32
  Sending Assoc Response to station on BSSID 84:78:ac:f0:68:d2
  (status 0) ApVapId 3 Slot 0
```

!--- The Association Response is sent to the client.

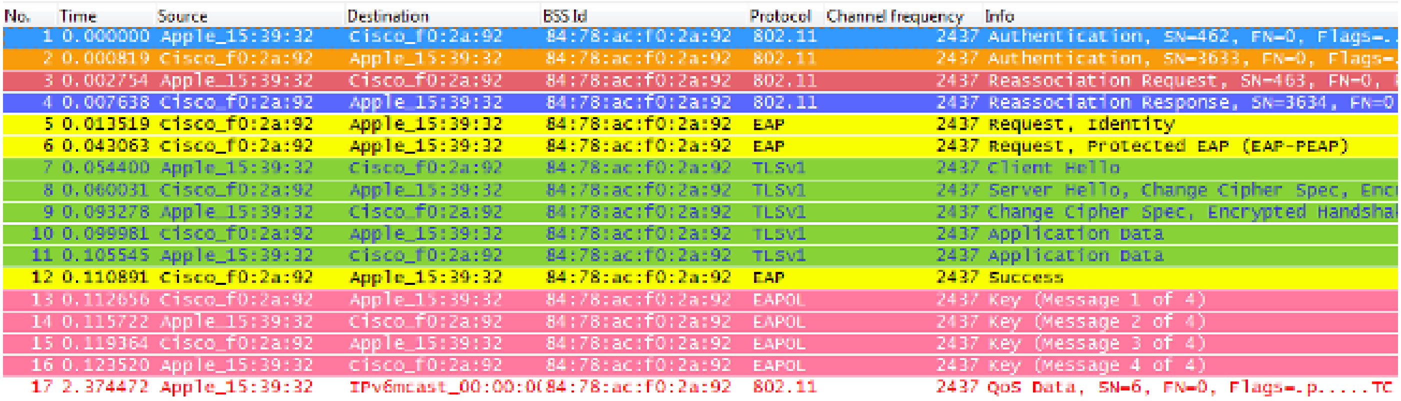
```
*dot1xMsgTask: Jun 22 00:23:15.103: ec:85:2f:15:39:32
  Sending EAP-Request/Identity to mobile ec:85:2f:15:39:32
  (EAP Id 1)

*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.118: ec:85:2f:15:39:32
  Received EAPOL EAPPKT from mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.118: ec:85:2f:15:39:32
  Received Identity Response (count=1) from mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.126: ec:85:2f:15:39:32
  Processing Access-Challenge for mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.126: ec:85:2f:15:39:32
  Sending EAP Request from AAA to mobile ec:85:2f:15:39:32
  (EAP Id 2)

*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.146: ec:85:2f:15:39:32
  Received EAPOL EAPPKT from mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.146: ec:85:2f:15:39:32
  Received EAP Response from mobile ec:85:2f:15:39:32
  (EAP Id 2, EAP Type 25)

*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.274: ec:85:2f:15:39:32
  Processing Access-Accept for mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.274: ec:85:2f:15:39:32
  Creating a PKC PMKID Cache entry for station ec:85:2f:15:39:32
  (RSN 2)
*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.274: ec:85:2f:15:39:32
  Setting active key cache index 8 ---> 8
*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.274: ec:85:2f:15:39:32
  Setting active key cache index 8 ---> 0
*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.274: ec:85:2f:15:39:32
  Adding BSSID 84:78:ac:f0:68:d2 to PMKID cache at index 0
  for station ec:85:2f:15:39:32
*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.274:
  New PMKID: (16)
*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.274:
  [0000] c9 4d 0d 97 03 aa a9 0f 1b c8 33 73 01 f1 18 f5
```

**!--- WLC creates a PMK cache entry for this client, which is
     used for SKC in this case, so the PMKID is computed with
     the AP MAC address (BSSID 84:78:ac:f0:68:d2).**

```
*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.274: ec:85:2f:15:39:32
  Sending EAP-Success to mobile ec:85:2f:15:39:32
  (EAP Id 12)

*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.275:
  Including PMKID in M1  (16)
```

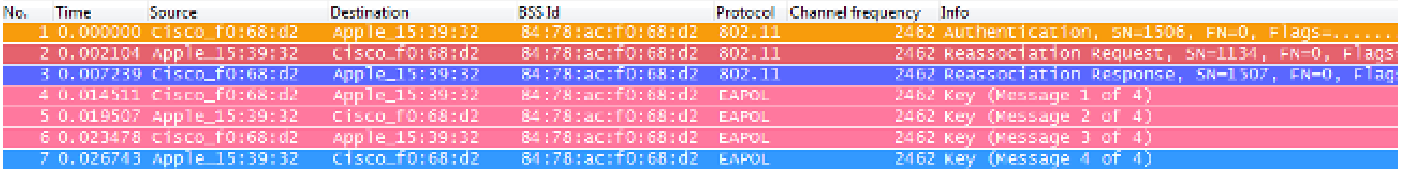
```
!--- The hashed PMKID is included on the Message-1 of the
     WPA/WPA2 4-Way handshake.



*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.275:
  [0000] c9 4d 0d 97 03 aa a9 0f 1b c8 33 73 01 f1 18 f5

!--- This is the hashed PMKID.



*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.275: ec:85:2f:15:39:32
  Sending EAPOL-Key Message to mobile ec:85:2f:15:39:32
  state INITPMK (message 1), replay counter
  00.00.00.00.00.00.00.00

!--- Message-1 of the WPA/WPA2 4-Way handshake is sent from
     the WLC/AP to the client.



*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.284: ec:85:2f:15:39:32
  Received EAPOL-Key from mobile ec:85:2f:15:39:32
*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.284: ec:85:2f:15:39:32
  Received EAPOL-key in PTK_START state (message 2) from mobile
  ec:85:2f:15:39:32

!--- Message-2 of the WPA/WPA-2 4-Way handshake is successfully
     received from the client.



*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.284: ec:85:2f:15:39:32
  PMK: Sending cache add

*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.285: ec:85:2f:15:39:32
  Sending EAPOL-Key Message to mobile ec:85:2f:15:39:32
  state PTKINITNEGOTIATING (message 3), replay counter
  00.00.00.00.00.00.00.01

!--- Message-3 of the WPA/WPA2 4-Way handshake is sent from
     the WLC/AP to the client.



*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.291: ec:85:2f:15:39:32
  Received EAPOL-Key from mobile ec:85:2f:15:39:32
*Dot1x_NW_MsgTask_2: Jun 22 00:23:15.291: ec:85:2f:15:39:32
  Received EAPOL-key in PTKINITNEGOTIATING state (message 4)
  from mobile ec:85:2f:15:39:32

!--- Message-4 (final message) of this initial WPA/WPA2 4-Way
     handshake is successfully received from the client, which
     confirms the installation of the derived keys. They can
     now be used in order to encrypt data frames with the current AP.
```

With this method, the AP and wireless client cache the PMKs of the secure associations already established. Therefore, if the wireless client roams to a new AP where it has never associated, the client must perform a full EAP authentication again, as shown in this image where the client roams to a new AP:



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Apple_15:39:32	Cisco_f0:2a:92	84:78:ac:f0:2a:92	802.11	2437	Authentication, SN=462, FN=0, Flags=..
2	0.000819	Cisco_f0:2a:92	Apple_15:39:32	84:78:ac:f0:2a:92	802.11	2437	Authentication, SN=3633, FN=0, Flags=.
3	0.002754	Apple_15:39:32	Cisco_f0:2a:92	84:78:ac:f0:2a:92	802.11	2437	Reassociation Request, SN=463, FN=0,
4	0.007638	Cisco_f0:2a:92	Apple_15:39:32	84:78:ac:f0:2a:92	802.11	2437	Reassociation Response, SN=3634, FN=0
5	0.013519	Cisco_f0:2a:92	Apple_15:39:32	84:78:ac:f0:2a:92	EAP	2437	Request, Identity
6	0.043063	Cisco_f0:2a:92	Apple_15:39:32	84:78:ac:f0:2a:92	EAP	2437	Request, Protected EAP (EAP-PEAP)
7	0.054400	Apple_15:39:32	Cisco_f0:2a:92	84:78:ac:f0:2a:92	TLSv1	2437	Client Hello
8	0.060031	Cisco_f0:2a:92	Apple_15:39:32	84:78:ac:f0:2a:92	TLSv1	2437	Server Hello, Change Cipher Spec, Enc
9	0.093278	Apple_15:39:32	Cisco_f0:2a:92	84:78:ac:f0:2a:92	TLSv1	2437	Change Cipher Spec, Encrypted Handsha
10	0.099981	Cisco_f0:2a:92	Apple_15:39:32	84:78:ac:f0:2a:92	TLSv1	2437	Application Data
11	0.105545	Apple_15:39:32	Cisco_f0:2a:92	84:78:ac:f0:2a:92	TLSv1	2437	Application Data
12	0.110891	Cisco_f0:2a:92	Apple_15:39:32	84:78:ac:f0:2a:92	EAP	2437	Success
13	0.112656	Cisco_f0:2a:92	Apple_15:39:32	84:78:ac:f0:2a:92	EAPOL	2437	Key (Message 1 of 4)
14	0.115722	Apple_15:39:32	Cisco_f0:2a:92	84:78:ac:f0:2a:92	EAPOL	2437	Key (Message 2 of 4)
15	0.119364	Cisco_f0:2a:92	Apple_15:39:32	84:78:ac:f0:2a:92	EAPOL	2437	Key (Message 3 of 4)
16	0.123520	Apple_15:39:32	Cisco_f0:2a:92	84:78:ac:f0:2a:92	EAPOL	2437	Key (Message 4 of 4)
17	2.374472	Apple_15:39:32	IPv6mcast_00:00:0(	84:78:ac:f0:2a:92	802.11	2437	QoS Data, SN=6, FN=0, Flags=.p.....TC

However, if the wireless client roams back to an AP where a previous association/authentication took place, then the client sends a Reassociation Request frame that lists multiple PMKIDs, which informs the AP of the PMKs cached from all of the APs where the client has previously authenticated. Therefore, since the client is roaming back to an AP that also has a PMK cached for this client, then the client does not need to reauthenticate through EAP in order to derive a new PMK. The client simply goes through the WPA2 4-Way handshake in order to derive the new transient encryption keys:



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	802.11	2462	Authentication, SN=1506, FN=0, Flags=......
2	0.002104	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	802.11	2462	Reassociation Request, SN=1134, FN=0, Flags
3	0.007239	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	802.11	2462	Reassociation Response, SN=1507, FN=0, Flag
4	0.014511	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 1 of 4)
5	0.019507	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 2 of 4)
6	0.023478	Cisco_f0:68:d2	Apple_15:39:32	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 3 of 4)
7	0.026743	Apple_15:39:32	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 4 of 4)

Note: This image does not show the first 802.11 Open System authentication frame from the client, but this is not due to the method implemented, as this frame is always required. The reason is that this specific frame is not imaged by the adapter or wireless packet image software used in order to sniff the over-the-air frames for this example, but it is left like this on the example for educational purposes. Be aware that there is a possibility that this can happen when you perform over-the-air packet images; some frames can be missed by the image, but are actually exchanged between the client and the AP. Otherwise, the roaming never starts on this example.

Here is a summary of the WLC debugs for this fast-secure roaming method:

<#root>

```
*apfMsConnTask_0: Jun 22 00:26:40.787: ec:85:2f:15:39:32
  Reassociation received from mobile on BSSID
  84:78:ac:f0:68:d2

!--- This is the Reassociation Request from the client.



*apfMsConnTask_0: Jun 22 00:26:40.787: ec:85:2f:15:39:32
  Processing RSN IE type 48, length 38 for mobile
  ec:85:2f:15:39:32

!--- The WLC/AP finds an Information Element that claims PMKID
     Caching support on the Association request that is sent
     from the client.
```

```
*apfMsConnTask_0: Jun 22 00:26:40.787: ec:85:2f:15:39:32
  Received RSN IE with 1 PMKIDs from mobile
  ec:85:2f:15:39:32

!--- The Reassociation Request from the client comes with
     one PMKID.



*apfMsConnTask_0: Jun 22 00:26:40.787:
  Received PMKID:  (16)
*apfMsConnTask_0: Jun 22 00:26:40.788:
  [0000] c9 4d 0d 97 03 aa a9 0f 1b c8 33 73 01 f1 18 f5

!--- This is the PMKID that is received.



*apfMsConnTask_0: Jun 22 00:26:40.788: ec:85:2f:15:39:32
  Searching for PMKID in MSCB PMKID cache for mobile
  ec:85:2f:15:39:32

!--- WLC searches for a matching PMKID on the database.



*apfMsConnTask_0: Jun 22 00:26:40.788: ec:85:2f:15:39:32
  Found an cache entry for BSSID 84:78:ac:f0:68:d2 in
  PMKID cache at index 0 of station ec:85:2f:15:39:32

*apfMsConnTask_0: Jun 22 00:26:40.788: ec:85:2f:15:39:32
  Found a valid PMKID in the MSCB PMKID cache for mobile
  ec:85:2f:15:39:32

!--- The WLC validates the PMKID provided by the client,
     and confirms that it has a valid PMK cache for this
     client-and-AP pair.



*apfMsConnTask_0: Jun 22 00:26:40.788: ec:85:2f:15:39:32
  Setting active key cache index 1 ---> 0

*apfMsConnTask_0: Jun 22 00:26:40.788: ec:85:2f:15:39:32
  Sending Assoc Response to station on BSSID
  84:78:ac:f0:68:d2(status 0) ApVapId 3 Slot 0

!--- The Reassociation Response is sent to the client, which
     validates the fast-roam with SKC.



*dot1xMsgTask: Jun 22 00:26:40.795: ec:85:2f:15:39:32
  Initiating RSN with existing PMK to mobile
  ec:85:2f:15:39:32

!--- WLC initiates a Robust Secure Network association with
     this client-and-AP pair based on the cached PMK found.
     Hence, EAP is avoided as per the next message.



*dot1xMsgTask: Jun 22 00:26:40.795: ec:85:2f:15:39:32
```

```
  Skipping EAP-Success to mobile ec:85:2f:15:39:32

*dot1xMsgTask: Jun 22 00:26:40.795: ec:85:2f:15:39:32
  Found an cache entry for BSSID 84:78:ac:f0:68:d2 in
  PMKID cache at index 0 of station ec:85:2f:15:39:32

*dot1xMsgTask: Jun 22 00:26:40.795: Including PMKID in M1(16)

!--- The hashed PMKID is included on the Message-1 of the
     WPA/WPA2 4-Way handshake.



*dot1xMsgTask: Jun 22 00:26:40.795:
  [0000] c9 4d 0d 97 03 aa a9 0f 1b c8 33 73 01 f1 18 f5

!--- The PMKID is hashed. The next messages are the same
     WPA/WPA2 4-Way handshake messages described thus far
     that are used in order to finish the encryption keys
     generation/installation.



*dot1xMsgTask: Jun 22 00:26:40.795: ec:85:2f:15:39:32
  Sending EAPOL-Key Message to mobile ec:85:2f:15:39:32 state
  INITPMK (message 1), replay counter 00.00.00.00.00.00.00.00

*Dot1x_NW_MsgTask_2: Jun 22 00:26:40.811: ec:85:2f:15:39:32
  Received EAPOL-Key from mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 22 00:26:40.812: ec:85:2f:15:39:32
  Received EAPOL-key in PTK_START state (message 2) from mobile
  ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 22 00:26:40.812: ec:85:2f:15:39:32
  PMK: Sending cache add

*Dot1x_NW_MsgTask_2: Jun 22 00:26:40.812: ec:85:2f:15:39:32
  Sending EAPOL-Key Message to mobile ec:85:2f:15:39:32 state
  PTKINITNEGOTIATING (message 3), replay counter
  00.00.00.00.00.00.00.01

*Dot1x_NW_MsgTask_2: Jun 22 00:26:40.820: ec:85:2f:15:39:32
  Received EAPOL-Key from mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 22 00:26:40.820: ec:85:2f:15:39:32
  Received EAPOL-key in PTKINITNEGOTIATING state (message 4)
  from mobile ec:85:2f:15:39:32
```

FlexConnect with PMKID Caching / Sticky Key Caching

- When you use this method on a FlexConnect setup, it could work and the behavior can seem similar to what was previously explained if you use Central Authentication back to the WLC (with either central or local switching); however, this SKC method is not supported on FlexConnect.
- This method is only officially supported on CUWN with Local mode APs, not on FlexConnect or other modes.

Pros with PMKID Caching / Sticky Key Caching

This method can be implemented locally by autonomous-independent APs, without the need of a centralized device to manage the cached keys.

Cons with PMKID Caching / Sticky Key Caching

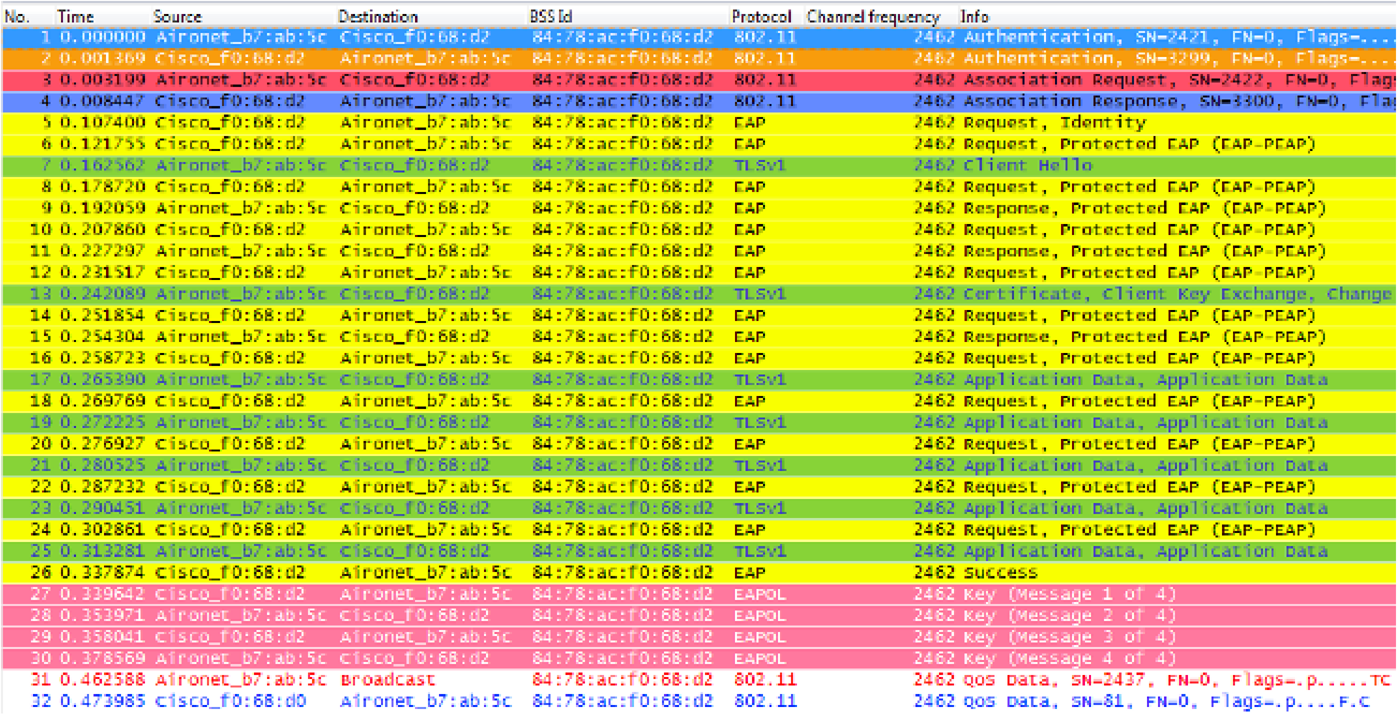
- As mentioned earlier in this document, the main limitation of this method is that the client can only perform fast-secure roaming when roaming back to an AP where it previously associated/authenticated. If roaming to a new AP, the client must complete the full EAP authentication again.
- The wireless client and APs must remember all of the PMKs derived on every new authentication, so this feature is normally limited to a certain amount of PMKs that are cached. Since this limit is not clearly defined by the standard, the vendors can define different limits on their SKC implementations. For example, the Cisco WLAN Controllers can currently cache the PMKs from a client for up to eight APs. If a client roams to more than eight APs per session, the oldest APs are removed from the cache list in order to store the newly-cached entries.
- This method is optional and is still not supported by many WPA2 devices; therefore, this method is not widely adopted and deployed.
- SKC is not supported when you perform intercontroller roaming, which occurs when you move between APs managed by different WLCs, even if they are on the same mobility group.

Fast-Secure Roaming with Opportunistic Key Caching

Opportunistic Key Caching (OKC), also known as Proactive Key Caching (PKC) (this term is explained in greater detail in a note that is next), is basically an enhancement of the WPA2 PMKID caching method described previously, which is why it is also named Proactive/Opportunistic PMKID Caching. Hence, it is important to note that this is not a fast-secure roaming method defined by the 802.11 standard and is not supported by many devices, but just like PMKID caching, it works with WPA2-EAP.

This technique allows the wireless client and the WLAN infrastructure to cache only one PMK for the lifetime of the client association with this WLAN (derived from the MSK after the initial 802.1X/EAP authentication with the Authentication Server), even when roaming between multiple APs, as they all share the original PMK that is used as the seed on all WPA2 4-way handshakes. This is still required, just as it is in SKC, in order to generate new encryption keys every time the client reassociates with the APs. For the APs to share this one original PMK from the client session, they must all be under some sort of administrative control, with a centralized device that caches and distributes the original PMK for all of the APs. This is similar to the CUWN, where the WLC performs this job for all of the LAPs under its control, and uses the mobility groups in order to handle this PMK between multiple WLCs; therefore, this is a limitation on autonomous AP environments.

With this method, just as in PMKID Caching (SKC), the initial association to any AP is a regular first-time authentication to the WLAN, where you must complete the entire 802.1X/EAP authentication against the Authentication Server and the 4-Way handshake for key generation before you can send data frames. Here is a screen image that illustrates this:



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	802.11	2462	Authentication, SN=2421, FN=0, Flags=....
2	0.001369	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	802.11	2462	Authentication, SN=3299, FN=0, Flags=....
3	0.003199	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	802.11	2462	Association Request, SN=2422, FN=0, Flag
4	0.008447	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	802.11	2462	Association Response, SN=3300, FN=0, Fla
5	0.107400	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Request, Identity
6	0.121755	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
7	0.162562	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Client Hello
8	0.178720	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
9	0.192059	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAP	2462	Response, Protected EAP (EAP-PEAP)
10	0.207860	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
11	0.227297	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAP	2462	Response, Protected EAP (EAP-PEAP)
12	0.231517	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
13	0.242089	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Certificate, Client Key Exchange, Change
14	0.251854	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
15	0.254304	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAP	2462	Response, Protected EAP (EAP-PEAP)
16	0.258723	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
17	0.265390	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Application Data, Application Data
18	0.269769	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
19	0.272225	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Application Data, Application Data
20	0.276927	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
21	0.280525	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Application Data, Application Data
22	0.287232	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
23	0.290451	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Application Data, Application Data
24	0.302861	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Request, Protected EAP (EAP-PEAP)
25	0.313281	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	TLSv1	2462	Application Data, Application Data
26	0.337874	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAP	2462	Success
27	0.339642	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 1 of 4)
28	0.353971	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 2 of 4)
29	0.358041	Cisco_f0:68:d2	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 3 of 4)
30	0.378569	Aironet_b7:ab:5c	Cisco_f0:68:d2	84:78:ac:f0:68:d2	EAPOL	2462	Key (Message 4 of 4)
31	0.462588	Aironet_b7:ab:5c	Broadcast	84:78:ac:f0:68:d2	802.11	2462	QoS Data, SN=2437, FN=0, Flags=.p.....TC
32	0.473985	Cisco_f0:68:d0	Aironet_b7:ab:5c	84:78:ac:f0:68:d2	802.11	2462	QoS Data, SN=81, FN=0, Flags=.p....F.C

The debug outputs show basically the same EAP authentication frame exchange as the rest of the methods described in this document upon initial authentication to the WLAN (as shown in the images), along with the addition of some outputs that concern the key caching techniques used by the WLC here. This debug output is also cut in order to show only the relevant information:

<#root>

```
*apfMsConnTask_0: Jun 21 21:46:06.515: 00:40:96:b7:ab:5c
  Association received from mobile on BSSID
  84:78:ac:f0:68:d2

!--- This is the Association Request from the client.



*apfMsConnTask_0: Jun 21 21:46:06.516: 00:40:96:b7:ab:5c
  Processing RSN IE type 48, length 20 for mobile
  00:40:96:b7:ab:5c

!--- The WLC/AP finds an Information Element that claims
     PMKID Caching support on the Association request that
     is sent from the client.



*apfMsConnTask_0: Jun 21 21:46:06.516: 00:40:96:b7:ab:5c
  Received RSN IE with 0 PMKIDs from mobile
  00:40:96:b7:ab:5c

!--- Since this is an initial association, the Association
     Request comes without any PMKID.



*apfMsConnTask_0: Jun 21 21:46:06.516: 00:40:96:b7:ab:5c
  Setting active key cache index 0 ---> 8

*apfMsConnTask_0: Jun 21 21:46:06.516: 00:40:96:b7:ab:5c
```

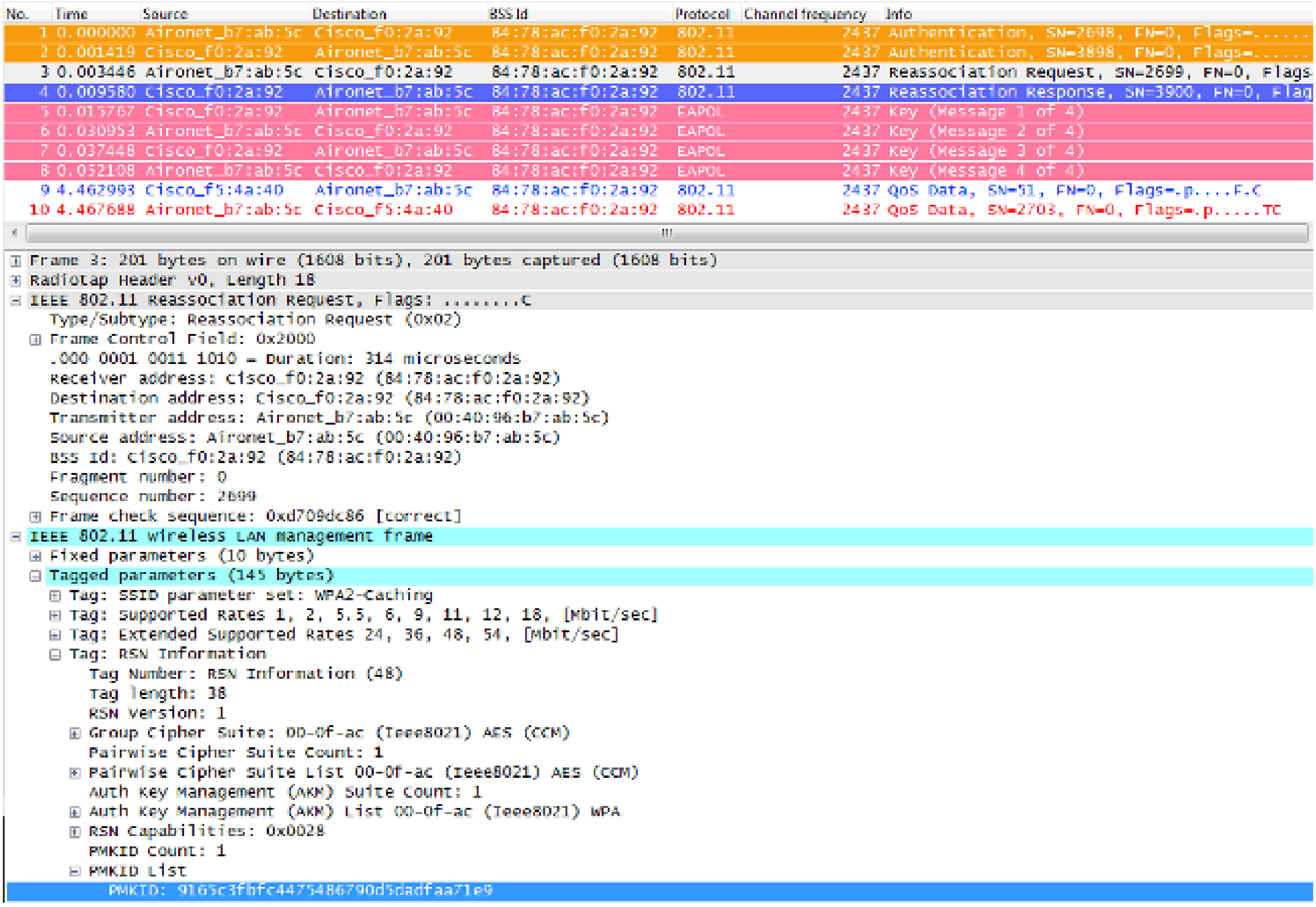
```
  Sending Assoc Response to station on BSSID
  84:78:ac:f0:68:d2 (status 0) ApVapId 3 Slot

!--- The Association Response is sent to the client.



*dot1xMsgTask: Jun 21 21:46:06.522: 00:40:96:b7:ab:5
  Sending EAP-Request/Identity to mobile 00:40:96:b7:ab:5c
  (EAP Id 1)

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.614: 00:40:96:b7:ab:5c
  Received EAPOL START from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.614: 00:40:96:b7:ab:5c
  Sending EAP-Request/Identity to mobile 00:40:96:b7:ab:5c
  (EAP Id 2)

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.623: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.623: 00:40:96:b7:ab:5c
  Received Identity Response (count=2) from mobile
  00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.630: 00:40:96:b7:ab:5c
  Processing Access-Challenge for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.630: 00:40:96:b7:ab:5c
  Sending EAP Request from AAA to mobile 00:40:96:b7:ab:5c
  (EAP Id 3)

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.673: 00:40:96:b7:ab:5c
  Received EAPOL EAPPKT from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.673: 00:40:96:b7:ab:5c
  Received EAP Response from mobile 00:40:96:b7:ab:5c
  (EAP Id 3, EAP Type 25)

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.843: 00:40:96:b7:ab:5c
  Processing Access-Accept for mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844: 00:40:96:b7:ab:5c
  Creating a PKC PMKID Cache entry for station
  00:40:96:b7:ab:5c (RSN 2)
*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844: 00:40:96:b7:ab:5c
  Setting active key cache index 8 ---> 8
*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844: 00:40:96:b7:ab:5c
  Setting active key cache index 8 ---> 0
*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844: 00:40:96:b7:ab:5c
  Adding BSSID 84:78:ac:f0:68:d2 to PMKID cache at index 0
  for station 00:40:96:b7:ab:5
*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844: New PMKID: (16)
*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844:
  [0000] 4e a1 7f 5a 75 48 9c f9 96 e3 a8 71 25 6f 11 d0

!--- WLC creates a PMK cache entry for this client, which is
     used for OKC in this case, so the PMKID is computed
     with the AP MAC address (BSSID 84:78:ac:f0:68:d2).



*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844: 00:40:96:b7:ab:5c
```

```
  PMK sent to mobility group

!--- The PMK cache entry for this client is shared with the
     WLCs on the mobility group.



*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844: 00:40:96:b7:ab:5c
  Sending EAP-Success to mobile 00:40:96:b7:ab:5c (EAP Id 13)

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844: 00:40:96:b7:ab:5c
  Found an cache entry for BSSID 84:78:ac:f0:68:d2 in PMKID
  cache at index 0 of station 00:40:96:b7:ab:5

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844: Including PMKID
  in M1  (16)

!--- The hashed PMKID is included on the Message-1 of the
     WPA/WPA2 4-Way handshake.



*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844:
  [0000] 4e a1 7f 5a 75 48 9c f9 96 e3 a8 71 25 6f 11 d0

!--- This is the hashed PMKID. The next messages are the same
     WPA/WPA2 4-Way handshake messages described thus far that
     are used in order to finish the encryption keys
     generation/installation.



*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.844: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c state
  INITPMK (message 1), replay counter 00.00.00.00.00.00.00.00

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.865: 00:40:96:b7:ab:5c
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.865: 00:40:96:b7:ab:5c
  Received EAPOL-key in PTK_START state (message 2)
  from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.865: 00:40:96:b7:ab:5c
  PMK: Sending cache add

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.865: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c state
  PTKINITNEGOTIATING (message 3), replay counter
  00.00.00.00.00.00.00.01

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.889: 00:40:96:b7:ab:5c
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:46:06.890: 00:40:96:b7:ab:5c
  Received EAPOL-key in PTKINITNEGOTIATING state (message 4)
  from mobile 00:40:96:b7:ab:5c
```

With this method, the wireless client and the WLC (for all the managed APs) cache the one original PMK of the secure association that is initially established. Basically, every time the wireless client connects to a specific AP, a PMKID is hashed based on: the client MAC address, the AP MAC address (BSSID of the

WLAN), and the PMK derived with that AP. Therefore, since OKC caches the same original PMK for all of the APs and the specific client, when this client (re)associates to another AP, the only value that changes in order to hash the new PMKID is the new AP MAC address.

When the client initiates roaming to a new AP and sends the Reassociation Request frame, it adds the PMKID on the WPA2 RSN Information Element if it wants to inform the AP that a cached PMK is used for fast-secure roaming. It already knows the MAC address of the BSSID (AP) for where it roams, then the client simply hashes the new PMKID that is used on this Reassociation Request. When the AP receives this request from the client, it also hashes the PMKID with the values that it already has (the cached PMK, the client MAC address, and its own AP MAC address), and responds with the successful Reassociation Response that confirms the PMKIDs matched. The cached PMK can be used as the seed that starts a WPA2 4-Way handshake in order to derive the new encryption keys (and skip EAP):



No.	Time	Source	Destination	BSS Id	Protocol	Channel frequency	Info
1	0.000000	Aironet_b7:ab:5c	Cisco_f0:2a:92	84:78:ac:f0:2a:92	802.11	2437	Authentication, SN=2698, FN=0, Flags=......
2	0.001419	Cisco_f0:2a:92	Aironet_b7:ab:5c	84:78:ac:f0:2a:92	802.11	2437	Authentication, SN=3898, FN=0, Flags=......
3	0.003446	Aironet_b7:ab:5c	Cisco_f0:2a:92	84:78:ac:f0:2a:92	802.11	2437	Reassociation Request, SN=2699, FN=0, Flags
4	0.009580	Cisco_f0:2a:92	Aironet_b7:ab:5c	84:78:ac:f0:2a:92	802.11	2437	Reassociation Response, SN=3900, FN=0, Flag
5	0.015767	Cisco_f0:2a:92	Aironet_b7:ab:5c	84:78:ac:f0:2a:92	EAPOL	2437	Key (Message 1 of 4)
6	0.030953	Aironet_b7:ab:5c	Cisco_f0:2a:92	84:78:ac:f0:2a:92	EAPOL	2437	Key (Message 2 of 4)
7	0.037448	Cisco_f0:2a:92	Aironet_b7:ab:5c	84:78:ac:f0:2a:92	EAPOL	2437	Key (Message 3 of 4)
8	0.052108	Aironet_b7:ab:5c	Cisco_f0:2a:92	84:78:ac:f0:2a:92	EAPOL	2437	Key (Message 4 of 4)
9	4.462993	Cisco_f5:4a:40	Aironet_b7:ab:5c	84:78:ac:f0:2a:92	802.11	2437	QoS Data, SN=51, FN=0, Flags=.p....F.C
10	4.467688	Aironet_b7:ab:5c	Cisco_f5:4a:40	84:78:ac:f0:2a:92	802.11	2437	QoS Data, SN=2703, FN=0, Flags=.p.....TC

```
⊞ Frame 3: 201 bytes on wire (1608 bits), 201 bytes captured (1608 bits)
⊞ Radiotap Header v0, Length 18
⊟ IEEE 802.11 Reassociation Request, Flags: ........C
    Type/Subtype: Reassociation Request (0x02)
  ⊞ Frame Control Field: 0x2000
    .000 0001 0011 1010 = Duration: 314 microseconds
    Receiver address: Cisco_f0:2a:92 (84:78:ac:f0:2a:92)
    Destination address: Cisco_f0:2a:92 (84:78:ac:f0:2a:92)
    Transmitter address: Aironet_b7:ab:5c (00:40:96:b7:ab:5c)
    Source address: Aironet_b7:ab:5c (00:40:96:b7:ab:5c)
    BSS Id: Cisco_f0:2a:92 (84:78:ac:f0:2a:92)
    Fragment number: 0
    Sequence number: 2699
  ⊞ Frame check sequence: 0xd709dc86 [correct]
⊟ IEEE 802.11 wireless LAN management frame
  ⊞ Fixed parameters (10 bytes)
  ⊟ Tagged parameters (145 bytes)
    ⊞ Tag: SSID parameter set: WPA2-Caching
    ⊞ Tag: Supported Rates 1, 2, 5.5, 6, 9, 11, 12, 18, [Mbit/sec]
    ⊞ Tag: Extended Supported Rates 24, 36, 48, 54, [Mbit/sec]
    ⊟ Tag: RSN Information
        Tag Number: RSN Information (48)
        Tag length: 38
        RSN Version: 1
      ⊞ Group Cipher Suite: 00-0f-ac (Ieee8021) AES (CCM)
        Pairwise Cipher Suite Count: 1
      ⊞ Pairwise Cipher Suite List 00-0f-ac (Ieee8021) AES (CCM)
        Auth Key Management (AKM) Suite Count: 1
      ⊞ Auth Key Management (AKM) List 00-0f-ac (Ieee8021) WPA
      ⊞ RSN Capabilities: 0x0028
        PMKID Count: 1
      ⊟ PMKID List
          PMKID: 9165c3fbfc44754867 90d5dadfaa71e9
```

In this image, the Reassociation Request frame from the client is selected and expanded so that you can see more details of the frame. The MAC address information and also the Robust Security Network (RSN, as per 802.11i – WPA2) Information Element, where information about the WPA2 settings used for this association is shown (highlighted is the PMKID obtained from the hashed formula).

Here is a summary of WLC debugs for this fast-secure roaming method with OKC:

<#root>

```
*apfMsConnTask_2: Jun 21 21:48:50.562: 00:40:96:b7:ab:5c
  Reassociation received from mobile on BSSID
  84:78:ac:f0:2a:92

!--- This is the Reassociation Request from the client.
```

```
*apfMsConnTask_2: Jun 21 21:48:50.563: 00:40:96:b7:ab:5c
  Processing RSN IE type 48, length 38 for mobile
  00:40:96:b7:ab:5c

!--- The WLC/AP finds and Information Element that claims
     PMKID Caching support on the Association request that
     is sent from the client.



*apfMsConnTask_2: Jun 21 21:48:50.563: 00:40:96:b7:ab:5c
  Received RSN IE with 1 PMKIDs from mobile
  00:40:96:b7:ab:5c

!--- The Reassociation Request from the client comes with
     one PMKID.



*apfMsConnTask_2: Jun 21 21:48:50.563:
  Received PMKID:  (16)

*apfMsConnTask_2: Jun 21 21:48:50.563:
  [0000] 91 65 c3 fb fc 44 75 48 67 90 d5 da df aa 71 e9

*apfMsConnTask_2: Jun 21 21:48:50.563: 00:40:96:b7:ab:5c
  Searching for PMKID in MSCB PMKID cache for mobile
  00:40:96:b7:ab:5c
*apfMsConnTask_2: Jun 21 21:48:50.563: 00:40:96:b7:ab:5c
  No valid PMKID found in the MSCB PMKID cache for mobile
  00:40:96:b7:ab:5

!--- As the client has never authenticated with this new AP,
     the WLC cannot find a valid PMKID to match the one provided
     by the client. However, since the client performs OKC
     and not SKC (as per the following messages), the WLC computes
     a new PMKID based on the information gathered (the cached PMK,
     the client MAC address, and the new AP MAC address).



*apfMsConnTask_2: Jun 21 21:48:50.563: 00:40:96:b7:ab:5c
  Trying to compute a PMKID from MSCB PMK cache for mobile
  00:40:96:b7:ab:5c

*apfMsConnTask_2: Jun 21 21:48:50.563:
  CCKM: Find PMK in cache: BSSID =  (6)
*apfMsConnTask_2: Jun 21 21:48:50.563:
  [0000] 84 78 ac f0 2a 90
*apfMsConnTask_2: Jun 21 21:48:50.563:
  CCKM: Find PMK in cache: realAA =  (6)
*apfMsConnTask_2: Jun 21 21:48:50.563:
  [0000] 84 78 ac f0 2a 92
*apfMsConnTask_2: Jun 21 21:48:50.563:
  CCKM: Find PMK in cache: PMKID =  (16)
*apfMsConnTask_2: Jun 21 21:48:50.563:
  [0000] 91 65 c3 fb fc 44 75 48 67 90 d5 da df aa 71 e9
*apfMsConnTask_2: Jun 21 21:48:50.563:
  CCKM: AA (6)
*apfMsConnTask_2: Jun 21 21:48:50.563:
  [0000] 84 78 ac f0 2a 92
*apfMsConnTask_2: Jun 21 21:48:50.563:
  CCKM: SPA (6)
*apfMsConnTask_2: Jun 21 21:48:50.563:
  [0000] 00 40 96 b7 ab 5c
*apfMsConnTask_2: Jun 21 21:48:50.563: 00:40:96:b7:ab:5c
  Adding BSSID 84:78:ac:f0:2a:92 to PMKID cache at
  index 0 for station 00:40:96:b7:ab:5c
*apfMsConnTask_2: Jun 21 21:48:50.563:
  New PMKID: (16)
*apfMsConnTask_2: Jun 21 21:48:50.563:
  [0000] 91 65 c3 fb fc 44 75 48 67 90 d5 da df aa 71 e9
*apfMsConnTask_2: Jun 21 21:48:50.563: 00:40:96:b7:ab:5c
  Computed a valid PMKID from MSCB PMK cache for mobile
  00:40:96:b7:ab:5c

!--- The new PMKID is computed and validated to match the
     one provided by the client, which is also computed with
     the same information. Hence, the fast-secure roam is
     possible.



*apfMsConnTask_2: Jun 21 21:48:50.563: 00:40:96:b7:ab:5c
  Setting active key cache index 0 ---> 0

*apfMsConnTask_2: Jun 21 21:48:50.564: 00:40:96:b7:ab:5c
  Sending Assoc Response to station on BSSID 84:78:ac:f0:2a:92
  (status 0) ApVapId 3 Slot

!--- The Reassociation response is sent to the client, which
     validates the fast-roam with OKC.



*dot1xMsgTask: Jun 21 21:48:50.570: 00:40:96:b7:ab:5c
  Initiating RSN with existing PMK to mobile
  00:40:96:b7:ab:5c

!--- WLC initiates a Robust Secure Network association with
     this client-and AP pair with the cached PMK found.
     Hence, EAP is avoided, as per the the next message.



*dot1xMsgTask: Jun 21 21:48:50.570: 00:40:96:b7:ab:5c
  Skipping EAP-Success to mobile 00:40:96:b7:ab:5c

*dot1xMsgTask: Jun 21 21:48:50.570: 00:40:96:b7:ab:5c
  Found an cache entry for BSSID 84:78:ac:f0:2a:92 in
  PMKID cache at index 0 of station 00:40:96:b7:ab:5c

*dot1xMsgTask: Jun 21 21:48:50.570:
  Including PMKID in M1  (16)

!--- The hashed PMKID is included on the Message-1 of the
     WPA/WPA2 4-Way handshake.



*dot1xMsgTask: Jun 21 21:48:50.570:
  [0000] 91 65 c3 fb fc 44 75 48 67 90 d5 da df aa 71 e9

!--- The PMKID is hashed. The next messages are the same
     WPA/WPA2 4-Way handshake messages described thus far,
     which are used in order to finish the encryption keys
     generation/installation.
```

```
*dot1xMsgTask: Jun 21 21:48:50.570: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c state
  INITPMK (message 1), replay counter 00.00.00.00.00.00.00.00

*Dot1x_NW_MsgTask_4: Jun 21 21:48:50.589: 00:40:96:b7:ab:5
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:48:50.589: 00:40:96:b7:ab:5c
  Received EAPOL-key in PTK_START state (message 2) from mobile
  00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:48:50.589: 00:40:96:b7:ab:5c
  PMK: Sending cache add

*Dot1x_NW_MsgTask_4: Jun 21 21:48:50.590: 00:40:96:b7:ab:5c
  Sending EAPOL-Key Message to mobile 00:40:96:b7:ab:5c state
  PTKINITNEGOTIATING (message 3), replay counter
  00.00.00.00.00.00.00.01

*Dot1x_NW_MsgTask_4: Jun 21 21:48:50.610: 00:40:96:b7:ab:5c
  Received EAPOL-Key from mobile 00:40:96:b7:ab:5c

*Dot1x_NW_MsgTask_4: Jun 21 21:48:50.610: 00:40:96:b7:ab:5c
  Received EAPOL-key in PTKINITNEGOTIATING state (message 4)
  from mobile 00:40:96:b7:ab:5c
```

As shown at the beginning of the debugs, the PMKID must be computed after the Reassociation Request from the client is received. This is needed in order to validate the PMKID and confirm that the cached PMK is used with the WPA2 4-Way handshake to derive the encryption keys and finish the fast-secure roaming. Do not confuse the CCKM entries on the debugs; this is not used in order to perform CCKM, but OKC, as previously explained. CCKM here is simply a name used by the WLC for those outputs, such as the name of a function that handles the values in order to compute the PMKID.

FlexConnect with Opportunistic Key Caching

- Central Authentication is supported. This includes Local and Central data switching. If the AP is part of the same FlexConnect group, fast-secure roam is by the AP, else fast-secure roam is by the controller.

  Note: This setup can work if the APs are not on the same FlexConnect Group, but this is not a recommended or supported setup.

- Flex Local Authentication is supported. In connected mode, the cache can be distributed from the AP to the controller and then to the rest of the APs in the FlexConnect Group.
- Standalone mode is supported. If the cache is already present on the AP (due to previous distribution), fast-secure roam shall work. New authentication in standalone mode does not support fast-secure roaming.

Pros with Opportunistic Key Caching

- The wireless client and the WLAN infrastructure do not need to remember multiple PMKIDs, but simply cache the one original PMK from the initial authentication to the WLAN. Then you must rehash the proper PMKID (used on the Reassociation Request) required with each AP secure

association in order to validate the fast-secure roaming.
- Here, the wireless client performs fast-secure roaming to a new AP on the same WLAN/SSID, even if it never associated with that AP (not the case in SKC). As long as the client performs the initial 802.1X/EAP authentication with one AP managed by the centralized deployment that handles the PMK cache for all of the APs for where the client roams, then no more full authentications are required for the rest of the client lifetime on this WLAN.

Cons with Opportunistic Key Caching

- This method is only deployed on a centralized environment where all of the APs are under some sort of administrative control (such as a WLAN Controller) that is responsible for caching and sharing the one original PMK from the client session. Therefore, this is a limitation on autonomous AP environments.
- The techniques that are applied in this method are not suggested or described on the 802.11 standard, so the support varies widely from one device to another. Nevertheless, this is still the method that was more adopted while waiting for 802.11r.

Note about the Term “Proactive Key Caching”

Proactive Key Caching (or PKC) has been known as OKC (Opportunistic Key Caching), and the two terms are used interchangeably when they describe the same method explained here. However, this was just a term that was used by Airspace in 2001 for an old key caching method, which was then used by the 802.11i standard as the basis for “Preauthentication” (another Fast Secure Roaming method briefly explained below). PKC is not Preauthentication or OKC (Opportunistic Key Caching), but when you hear or read about PKC, the reference is basically to OKC, and not to Preauthentication.

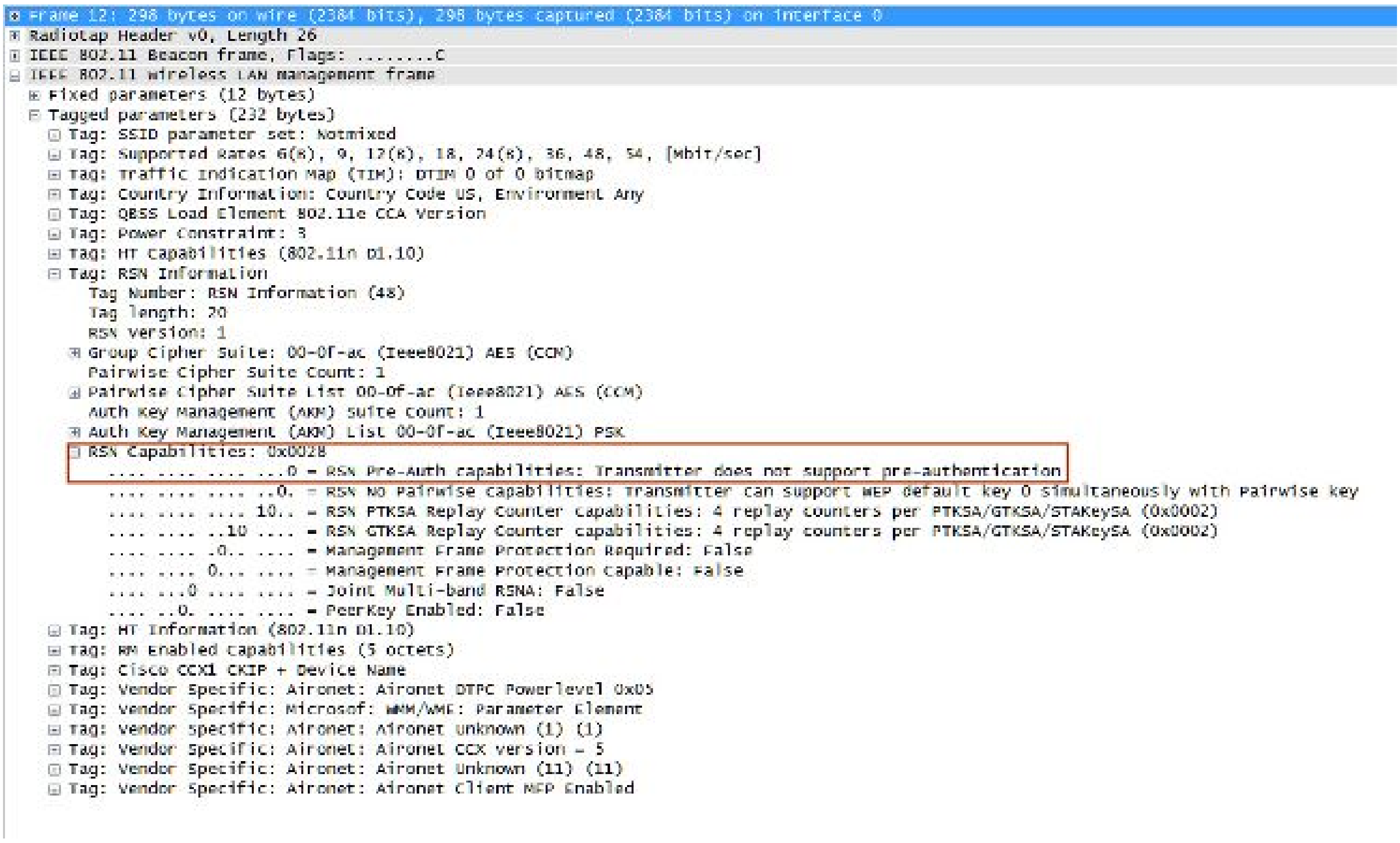
Fast-Secure Roaming with Preauthentication

This method is also suggested by the IEEE 802.11 standard within the 802.11i security amendment, so it also works with WPA2, but it is the only Fast Secure Roaming method that is not supported by Cisco WLAN infrastructures. For this reason, it is explained only briefly here and without outputs.

With Preauthentication, the wireless clients can authenticate with multiple APs at a time while associated with the current AP. When this occurs, the client sends the EAP authentication frames to the current AP where it is connected, but it is destined to the other AP(s) where the client wants to perform Preauthentication (neighbor APs that are possible candidates for roaming). The current AP sends these frames to the target AP(s) over the distribution system. The new AP performs full authentication against the RADIUS server for this client, so an entire new EAP authentication handshake is completed, and this new AP acts as the Authenticator.

The idea is to perform authentication and derive PMK with the neighbor APs before the client actually roams to them, so when it is time to roam, the client is already authenticated and with a PMK already cached for this new AP-to-client secure association, so they only need to perform the 4-Way Handshake and experience a fast roam after the client sends its initial Reassociation request.

Here is a image from an AP beacon that shows the RSN IE field that advertises support for Preauthentication (this one is from a Cisco AP, where it is confirmed that Preauthentication is not supported):



```
⊞ Frame 12: 298 bytes on wire (2384 bits), 298 bytes captured (2384 bits) on interface 0
⊞ Radiotap Header v0, Length 26
⊞ IEEE 802.11 Beacon frame, Flags: ........C
⊟ IEEE 802.11 wireless LAN management frame
  ⊞ Fixed parameters (12 bytes)
  ⊟ Tagged parameters (232 bytes)
    ⊞ Tag: SSID parameter set: Notmixed
    ⊞ Tag: Supported Rates 6(B), 9, 12(B), 18, 24(B), 36, 48, 54, [Mbit/sec]
    ⊞ Tag: Traffic Indication Map (TIM): DTIM 0 of 0 bitmap
    ⊞ Tag: Country Information: Country Code US, Environment Any
    ⊞ Tag: QBSS Load Element 802.11e CCA Version
    ⊞ Tag: Power Constraint: 3
    ⊞ Tag: HT Capabilities (802.11n D1.10)
    ⊟ Tag: RSN Information
        Tag Number: RSN Information (48)
        Tag length: 20
        RSN Version: 1
      ⊞ Group Cipher Suite: 00-0f-ac (Ieee8021) AES (CCM)
        Pairwise Cipher Suite Count: 1
      ⊞ Pairwise Cipher Suite List 00-0f-ac (Ieee8021) AES (CCM)
        Auth Key Management (AKM) Suite Count: 1
      ⊞ Auth Key Management (AKM) List 00-0f-ac (Ieee8021) PSK
      ⊟ RSN Capabilities: 0x0028
          .... .... .... ...0 = RSN Pre-Auth capabilities: Transmitter does not support pre-authentication
          .... .... .... ..0. = RSN No Pairwise capabilities: Transmitter can support WEP default key 0 simultaneously with Pairwise key
          .... .... .... 10.. = RSN PTKSA Replay Counter capabilities: 4 replay counters per PTKSA/GTKSA/STAKeySA (0x0002)
          .... .... ..10 .... = RSN GTKSA Replay Counter capabilities: 4 replay counters per PTKSA/GTKSA/STAKeySA (0x0002)
          .... .... .0.. .... = Management Frame Protection Required: False
          .... .... 0... .... = Management Frame Protection Capable: False
          .... ...0 .... .... = Joint Multi-band RSNA: False
          .... ..0. .... .... = PeerKey Enabled: False
    ⊞ Tag: HT Information (802.11n D1.10)
    ⊞ Tag: RM Enabled Capabilities (5 octets)
    ⊞ Tag: Cisco CCX1 CKIP + Device Name
    ⊞ Tag: Vendor Specific: Aironet: Aironet DTPC Powerlevel 0x05
    ⊞ Tag: Vendor Specific: Microsof: WMM/WME: Parameter Element
    ⊞ Tag: Vendor Specific: Aironet: Aironet Unknown (1) (1)
    ⊞ Tag: Vendor Specific: Aironet: Aironet CCX version = 5
    ⊞ Tag: Vendor Specific: Aironet: Aironet Unknown (11) (11)
    ⊞ Tag: Vendor Specific: Aironet: Aironet Client MFP Enabled
```

Pros with Preauthentication

There is one PMK for each AP-to-client secure association, which could be considered a security advantage in case an AP is compromised and the keys become stolen (cannot be used with other APs). However, this security advantage is handled by the WLAN infrastructure in different ways on other methods.

Cons with Preauthentication

- Because there is one PMK per AP, the clients have a limit on the amount of APs that can be pre-authenticated.
- Every time a client performs preauthentication with a new AP, there is a complete EAP authentication exchange, which means more load on the network and on the Authentication Server.
- Most wireless clients do not support this method, as this was never highly adopted (OKC was more adopted).

Fast-Secure Roaming with 802.11r

The fast-secure roaming technique based on the 802.11r amendment (officially named **Fast BSS Transition** by the 802.11 standard, and known as **FT**) is the first method officially ratified (on 2008) by the IEEE for the 802.11 standard as the solution to perform fast transitions between APs (Basic Service Sets or BSSs), which clearly defines the key hierarchy that is used when you handle and cache keys on a WLAN. However, its adoption has been slow, mainly due to the other solutions already available when fast transitions were actually required, such as with VoWLAN implementations when used with one of the methods previously explained in this document. There are only a few devices that currently support some of the FT options (by 2013).

This technique is more complex to explain than the other methods, as it introduces new concepts and multiple layers of PMKs that are cached on different devices (each device with a different role), and provides even more options for fast-secure roaming. Therefore, a brief summary is provided about this method and the way it is implemented with each option available.

802.11r is different from SKC and OKC, primarily because of these reasons:

- Handshake messaging (PMKID, ANonce, and SNonce exchange, for example) happens in 802.11 Authentication frames or in Action frames instead of Reassociation frames. Unlike PMKID caching methods, the separate 4-Way handshake phase, which is carried after the (re)association message exchange, is avoided. The key handshake with the new AP begins before the client fully roams/reassociates with this new AP.
- It provides two methods for the fast-roaming handshake: over the AIR, and over the Distribution System (DS).
- 802.11r has more layers of key hierarchy.
- As this protocol avoids the 4-Way handshake for the key management when a client roams (generates new encryption keys -PTK and GTK- without the need of this handshake), it can also be applied for WPA2 setups with a PSK, and not only when 802.1X/EAP is used for the authentication. This accelerates the roaming even more for these setups, where no EAP or 4-Way handshake exchanges occur.

With this method, the wireless client performs just one initial authentication against the WLAN infrastructure when a connection is established to the first AP, and performs fast-secure roaming while roaming between APs of the same FT mobility domain.

This is one of the new concepts, which basically refers to the APs that use the same SSID (known as an Extended Service Set or ESS) and handle the same FT keys. This is similar to the other methods explained thus far. The way the APs handle the FT mobility domain keys is normally based on a centralized setup, such as the WLC or mobility groups; however, this method can also be implemented on autonomous AP environments.

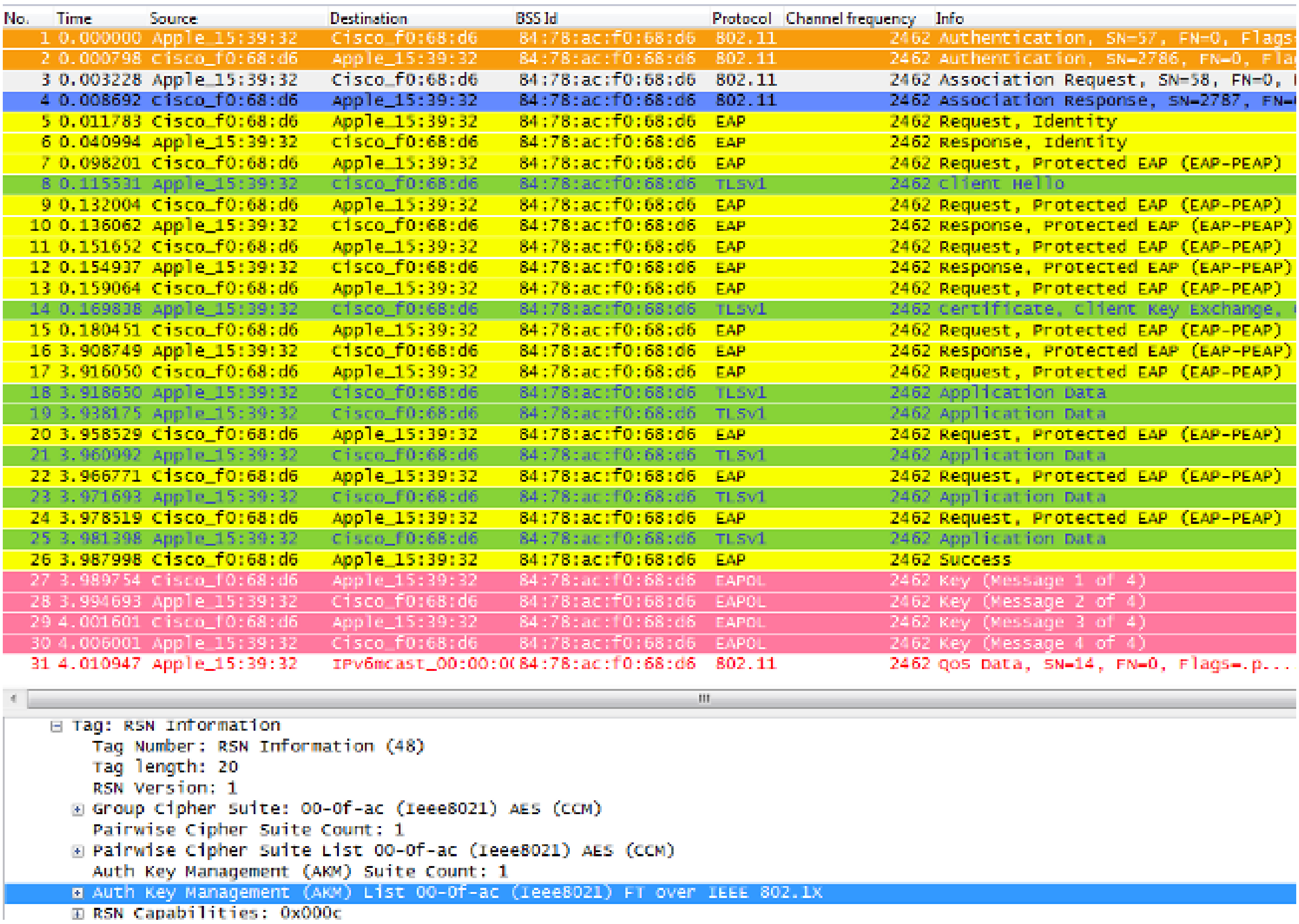
Here is a summary of the key hierarchy:

- An MSK is still derived on the client supplicant and the Authentication Server from the initial 802.1X/EAP authentication phase (transferred from the Authentication Server to the Authenticator (WLC) once the authentication is successful). This MSK, like in the other methods, is used as the seed for the FT key hierarchy. When you use WPA2-PSK instead of an EAP authentication method, the PSK is basically this MSK.
- A Pairwise Master Key R0 (PMK-R0) is derived from the MSK, which is the first-level key of the FT key hierarchy. The key holders for this PMK-R0 are the WLC and the client.
- A second-level key, called a Pairwise Master Key R1 (PMK-R1), is derived from the PMK-R0, and the key holders are the client and the APs managed by the WLC that holds the PMK-R0.
- The third and final level key of the FT key hierarchy is the PTK, which is the final key used in order to encrypt the 802.11 unicast data frames (similar to the other methods that use WPA/TKIP or WPA2/AES). This PTK is derived on FT from the PMK-R1, and the key holders are the client and the APs managed by the WLC.

Note: Dependent upon the WLAN vendor and the implementation setups (such as Autonomous APs, FlexConnect, or Mesh), the WLAN infrastructure can transfer and handle the keys in a different way. It can even change the roles of the key holders, but since that is out of the scope of this document, the examples based on the key hierarchy summary given previously are the next focus. The differences are actually not that relevant to understand the process, unless you actually need to analyze in-depth the infrastructure devices (and their code) in order to discover a software issue.

Fast BSS Transition Over-the-Air

With this method, the first association to any AP is a regular first-time authentication to the WLAN, where the entire 802.1X/EAP authentication against the Authentication Server and the 4-Way handshake for key generation must occur before data frames are sent, as shown in this screen image:



```
No.  Time     Source            Destination        BSS Id             Protocol Channel frequency Info
   1 0.000000 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  802.11            2462 Authentication, SN=57, FN=0, Flags=
   2 0.000798 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  802.11            2462 Authentication, SN=2786, FN=0, Fla
   3 0.003228 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  802.11            2462 Association Request, SN=58, FN=0,
   4 0.008692 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  802.11            2462 Association Response, SN=2787, FN=
   5 0.011783 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAP               2462 Request, Identity
   6 0.040994 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  EAP               2462 Response, Identity
   7 0.098201 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAP               2462 Request, Protected EAP (EAP-PEAP)
   8 0.115531 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  TLSv1             2462 Client Hello
   9 0.132004 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAP               2462 Request, Protected EAP (EAP-PEAP)
  10 0.136062 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  EAP               2462 Response, Protected EAP (EAP-PEAP)
  11 0.151652 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAP               2462 Request, Protected EAP (EAP-PEAP)
  12 0.154937 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  EAP               2462 Response, Protected EAP (EAP-PEAP)
  13 0.159064 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAP               2462 Request, Protected EAP (EAP-PEAP)
  14 0.169838 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  TLSv1             2462 Certificate, Client Key Exchange,
  15 0.180451 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAP               2462 Request, Protected EAP (EAP-PEAP)
  16 3.908749 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  EAP               2462 Response, Protected EAP (EAP-PEAP)
  17 3.916050 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAP               2462 Request, Protected EAP (EAP-PEAP)
  18 3.918650 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  TLSv1             2462 Application Data
  19 3.938175 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  TLSv1             2462 Application Data
  20 3.958529 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAP               2462 Request, Protected EAP (EAP-PEAP)
  21 3.960992 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  TLSv1             2462 Application Data
  22 3.966771 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAP               2462 Request, Protected EAP (EAP-PEAP)
  23 3.971693 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  TLSv1             2462 Application Data
  24 3.978519 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAP               2462 Request, Protected EAP (EAP-PEAP)
  25 3.981398 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  TLSv1             2462 Application Data
  26 3.987998 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAP               2462 Success
  27 3.989754 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAPOL             2462 Key (Message 1 of 4)
  28 3.994693 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  EAPOL             2462 Key (Message 2 of 4)
  29 4.001601 Cisco_f0:68:d6    Apple_15:39:32     84:78:ac:f0:68:d6  EAPOL             2462 Key (Message 3 of 4)
  30 4.006001 Apple_15:39:32    Cisco_f0:68:d6     84:78:ac:f0:68:d6  EAPOL             2462 Key (Message 4 of 4)
  31 4.010947 Apple_15:39:32    IPv6mcast_00:00:0( 84:78:ac:f0:68:d6  802.11            2462 QoS Data, SN=14, FN=0, Flags=.p...
```

```
  ⊟ Tag: RSN Information
      Tag Number: RSN Information (48)
      Tag length: 20
      RSN Version: 1
    ⊞ Group Cipher Suite: 00-0f-ac (Ieee8021) AES (CCM)
      Pairwise Cipher Suite Count: 1
    ⊞ Pairwise Cipher Suite List 00-0f-ac (Ieee8021) AES (CCM)
      Auth Key Management (AKM) Suite Count: 1
    ⊞ Auth Key Management (AKM) List 00-0f-ac (Ieee8021) FT over IEEE 802.1X
    ⊞ RSN Capabilities: 0x000c
```

The main differences are:

- The Authentication Key Management negotiation is slightly different than regular WPA/WPA2, so some extra information is used in order to perform this negotiation when the association to a WLAN infrastructure that supports FT occurs. As shown in the image, the Association Request frame from the client is selected and the AKM field of the RNS Information Element is highlighted in order to show that this client wants to perform FT over 802.1X/EAP.
- Also shown is the Mobility Domain Information Element (part of FT), where the **FT Capability and Policy** field indicates if the Fast BSS Transition is completed Over-the-Air or Over-the-DS when fast roaming (this indicates Over-the-Air in this image).
- Another information element is also added (Fast BSS Transition or FT IE, which is described later in this document) with information that is required in order to perform the FT authentication sequence when FT roaming.
- The key generation is different due to the key hierarchy, so even though the FT 4-Way handshake looks similar to the WPA/WPA2 4-Way handshake, it is actually slightly different in content.

The debugs show basically the same EAP authentication frame exchange as the rest of the methods upon initial authentication to the WLAN (as noticed from the images), but some outputs that concern the key caching techniques used by the WLC are added; thus, this debug output is cut in order to show only the relevant information:

<#root>

```
*apfMsConnTask_0: Jun 27 19:25:23.426: ec:85:2f:15:39:32
  Association received from mobile on BSSID
  84:78:ac:f0:68:d6
```

!--- This is the Association request from the client.

```
*apfMsConnTask_0: Jun 27 19:25:23.427: ec:85:2f:15:39:32
  Marking this mobile as TGr capable.
```

!--- WLC recognizes that the client is 802.11r-capable.

```
*apfMsConnTask_0: Jun 27 19:25:23.427: ec:85:2f:15:39:32
  Processing RSN IE type 48, length 20 for mobile
  ec:85:2f:15:39:32
```

!--- The WLC/AP finds an Information Element that claims FT support on the Association request that is sent from the client.

```
*apfMsConnTask_0: Jun 27 19:25:23.427:
  Sending assoc-resp station:ec:85:2f:15:39:32
  AP:84:78:ac:f0:68:d0-00 thread:144be808
*apfMsConnTask_0: Jun 27 19:25:23.427:
  Adding MDIE, ID is:0xaaf0
*apfMsConnTask_0: Jun 27 19:25:23.427: ec:85:2f:15:39:32
  Including FT Mobility Domain IE (length 5) in Initial
  assoc Resp to mobile
*apfMsConnTask_0: Jun 27 19:25:23.427: ec:85:2f:15:39:32
  Sending R0KH-ID as:-84.30.6.-3
*apfMsConnTask_0: Jun 27 19:25:23.427: ec:85:2f:15:39:32
  Sending R1KH-ID as 3c:ce:73:d8:02:00
*apfMsConnTask_0: Jun 27 19:25:23.427: ec:85:2f:15:39:32
  Including FT IE (length 98) in Initial Assoc Resp to mobile
*apfMsConnTask_0: Jun 27 19:25:23.427: ec:85:2f:15:39:32
  Sending Assoc Response to station on BSSID 84:78:ac:f0:68:d6
  (status 0) ApVapId 7 Slot 0
```

!--- The Association Response is sent to the client once the FT information is computed (as per the previous messages), so this is included in the response.

```
*dot1xMsgTask: Jun 27 19:25:23.432: ec:85:2f:15:39:32
  Sending EAP-Request/Identity to mobile ec:85:2f:15:39:32
  (EAP Id 1)
```

!--- EAP begins, and follows **the same exchange explained so far.**

```
*apfMsConnTask_0: Jun 27 19:25:23.436: ec:85:2f:15:39:32
  Got action frame from this client.

*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.449: ec:85:2f:15:39:32
  Received EAPOL EAPPKT from mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.449: ec:85:2f:15:39:32
  Received Identity Response (count=1) from mobile
  ec:85:2f:15:39:32
```

```
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.456: ec:85:2f:15:39:32
  Processing Access-Challenge for mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.456: ec:85:2f:15:39:32
  Sending EAP Request from AAA to mobile ec:85:2f:15:39:32
  (EAP Id 2)

*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.479: ec:85:2f:15:39:32
  Received EAPOL EAPPKT from mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.479: ec:85:2f:15:39:32
  Received EAP Response from mobile ec:85:2f:15:39:32
  (EAP Id 2, EAP Type 25)

*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.627: ec:85:2f:15:39:32
  Processing Access-Accept for mobile ec:85:2f:15:39:32

!--- The client is validated/authenticated by the RADIUS Server.



*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.627: ec:85:2f:15:39:32
  Creating a PKC PMKID Cache entry for station
  ec:85:2f:15:39:32 (RSN 2)
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.627: ec:85:2f:15:39:32
  Resetting MSCB PMK Cache Entry 0 for station
  ec:85:2f:15:39:32
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.627: ec:85:2f:15:39:32
  Setting active key cache index 8 ---> 8
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.628: ec:85:2f:15:39:32
  Setting active key cache index 8 ---> 0
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.628: ec:85:2f:15:39:32
  Adding BSSID 84:78:ac:f0:68:d6 to PMKID cache at index 0
  for station ec:85:2f:15:39:32
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.628: New PMKID: (16)
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.628:
  [0000] 52 b8 8f cf 50 a7 90 98 2b ba d6 20 79 e4 cd f9
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.629: ec:85:2f:15:39:32
  Created PMK Cache Entry for TGr AKM:802.1x ec:85:2f:15:39:32

!--- WLC creates a PMK cache entry for this client, which is
     used for FT with 802.1X in this case, so the PMKID is
     computed with the AP MAC address (BSSID 84:78:ac:f0:68:d6).



*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.629:
  ec:85:2f:15:39:32   R0KH-ID:172.30.6.253
  R1KH-ID:3c:ce:73:d8:02:00  MSK Len:48 pmkValidTime:1807

!--- The R0KH-ID and R1KH-ID are defined, as well as the PMK
     cache validity period.



*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.630: ec:85:2f:15:39:32
  PMK sent to mobility group

!--- The FT PMK cache entry for this client is shared with the
     WLCs on the mobility group.
```

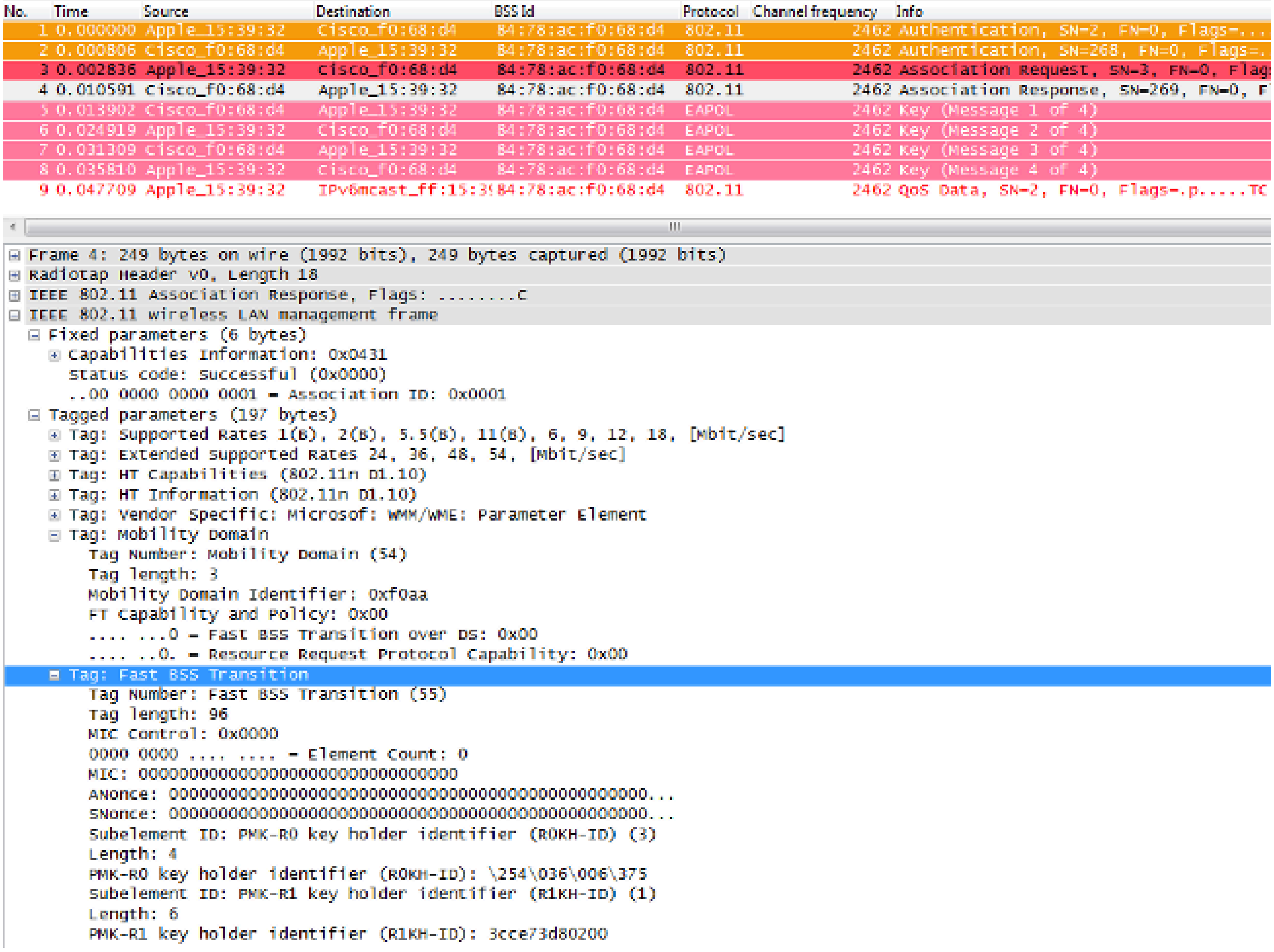
```
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.630: ec:85:2f:15:39:32
  Sending EAP-Success to mobile ec:85:2f:15:39:32 (EAP Id 12)

*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.630: ec:85:2f:15:39:32
  Found an cache entry for BSSID 84:78:ac:f0:68:d6 in PMKID
  cache at index 0 of station ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.630: Including PMKID in
  M1  (16)

!--- The hashed PMKID is included on the Message-1 of the
     initial FT 4-Way handshake.



*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.630:
  [0000] 52 b8 8f cf 50 a7 90 98 2b ba d6 20 79 e4 cd f9

*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.630: ec:85:2f:15:39:32
  Sending EAPOL-Key Message to mobile ec:85:2f:15:39:32 state
  INITPMK (message 1), replay counter 00.00.00.00.00.00.00.0

!--- Message-1 of the FT 4-Way handshake is sent from the
     WLC/AP to the client.



*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.639: ec:85:2f:15:39:32
  Received EAPOL-Key from mobile ec:85:2f:15:39:32
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.639: ec:85:2f:15:39:32
  Received EAPOL-key in PTK_START state (message 2) from
  mobile ec:85:2f:15:39:32

!--- Message-2 of the FT 4-Way handshake is received
     successfully from the client.



*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.639: ec:85:2f:15:39:32
  Calculating PMKR0Name

!--- The PMKR0Name is calculated.



*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.639: ec:85:2f:15:39:32
  DOT11R: Sending cache add

*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.639: Adding MDIE,
  ID is:0xaaf0
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.639: ec:85:2f:15:39:32
  Adding TIE for reassociation deadtime:20000 milliseconds
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.639: ec:85:2f:15:39:32
  Adding TIE for R0Key-Data valid time :1807
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.640: ec:85:2f:15:39:32
  Sending EAPOL-Key Message to mobile ec:85:2f:15:39:32 state
  PTKINITNEGOTIATING (message 3), replay counter
  00.00.00.00.00.00.00.01

!--- After the MDIE, TIE for reassociation deadtime, and TIE
     for R0Key-Data valid time are calculated, the Message-3
     of this FT 4-Way handshake is sent from the WLC/AP to the
     client with this information.
```

```
*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.651: ec:85:2f:15:39:32
  Received EAPOL-Key from mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 27 19:25:23.651: ec:85:2f:15:39:32
  Received EAPOL-key in PTKINITNEGOTIATING state (message 4)
  from mobile ec:85:2f:15:39:32
```

```
!--- Message-4 (final message) of this initial FT 4-Way handshake
     is received successfully from the client, which confirms the
     installation of the derived keys. They can now be used in order
     to encrypt data frames with the current AP.
```

Note: In order to debug this method and reach the extra 802.11r/FT outputs shown here, an additional debug is enabled along with the **debug client**, which is the **debug ft events enable**.

Here are the images and debugs of an initial association to the WLAN when you perform FT with WPA2-PSK (instead of an 802.1X/EAP method), where the Association Response frame from the AP is selected in order to show the Fast BSS Transition Information Element (highlighted). Some of the key information needed in order to perform the FT 4-Way handshake is also shown:



```
No.  Time     Source            Destination         BSS Id             Protocol  Channel frequency  Info
   1 0.000000 Apple_15:39:32    Cisco_f0:68:d4      84:78:ac:f0:68:d4  802.11            2462 Authentication, SN=2, FN=0, Flags=...
   2 0.000806 Cisco_f0:68:d4    Apple_15:39:32      84:78:ac:f0:68:d4  802.11            2462 Authentication, SN=268, FN=0, Flags=.
   3 0.002836 Apple_15:39:32    Cisco_f0:68:d4      84:78:ac:f0:68:d4  802.11            2462 Association Request, SN=3, FN=0, Flag
   4 0.010591 Cisco_f0:68:d4    Apple_15:39:32      84:78:ac:f0:68:d4  802.11            2462 Association Response, SN=269, FN=0, F
   5 0.013902 Cisco_f0:68:d4    Apple_15:39:32      84:78:ac:f0:68:d4  EAPOL             2462 Key (Message 1 of 4)
   6 0.024919 Apple_15:39:32    Cisco_f0:68:d4      84:78:ac:f0:68:d4  EAPOL             2462 Key (Message 2 of 4)
   7 0.031309 Cisco_f0:68:d4    Apple_15:39:32      84:78:ac:f0:68:d4  EAPOL             2462 Key (Message 3 of 4)
   8 0.035810 Apple_15:39:32    Cisco_f0:68:d4      84:78:ac:f0:68:d4  EAPOL             2462 Key (Message 4 of 4)
   9 0.047709 Apple_15:39:32    IPv6mcast_ff:15:3(84:78:ac:f0:68:d4  802.11            2462 QoS Data, SN=2, FN=0, Flags=.p.....TC
```

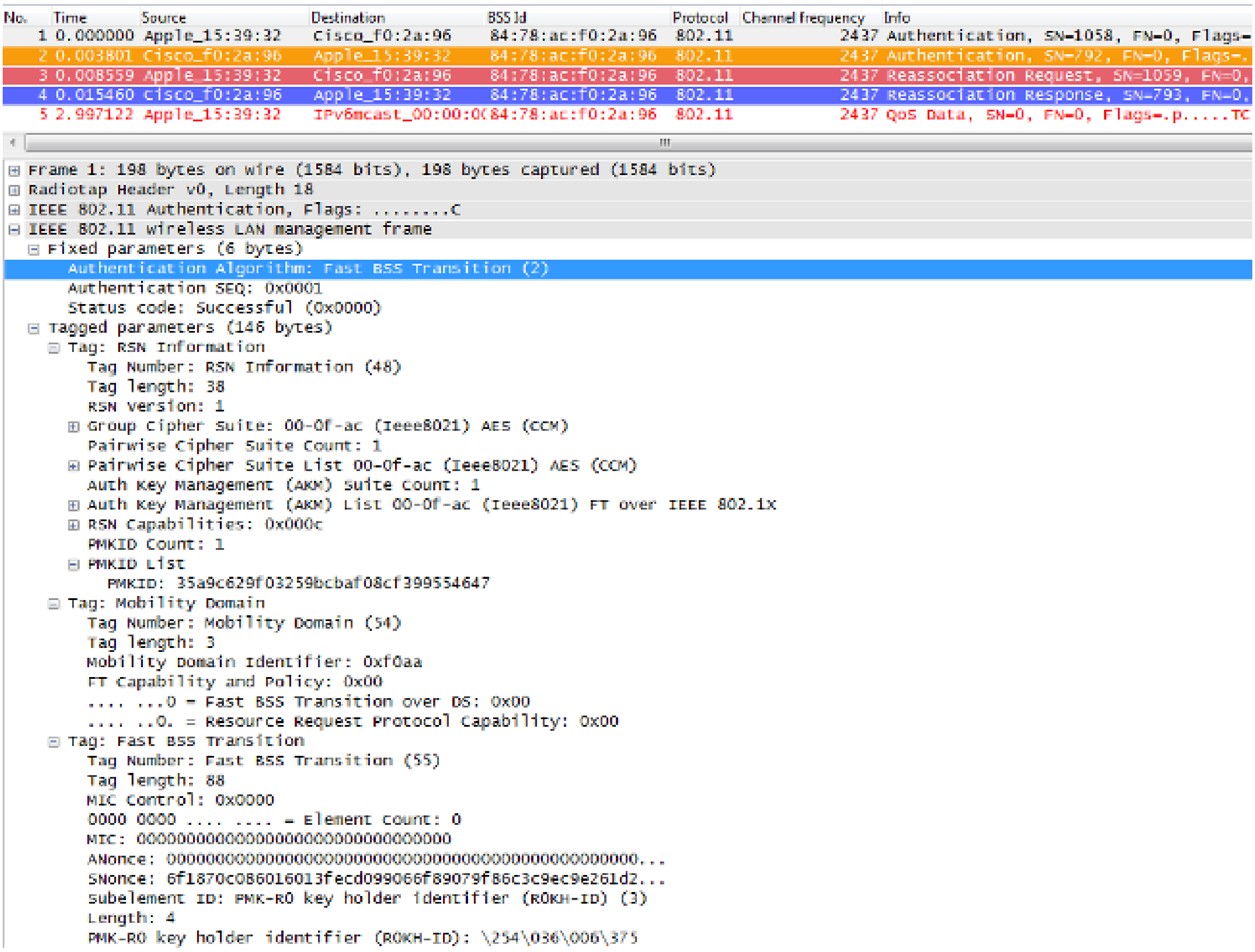
```
⊞ Frame 4: 249 bytes on wire (1992 bits), 249 bytes captured (1992 bits)
⊞ Radiotap Header v0, Length 18
⊞ IEEE 802.11 Association Response, Flags: ........C
⊟ IEEE 802.11 wireless LAN management frame
  ⊟ Fixed parameters (6 bytes)
    ⊞ Capabilities Information: 0x0431
      Status code: Successful (0x0000)
      ..00 0000 0000 0001 = Association ID: 0x0001
  ⊟ Tagged parameters (197 bytes)
    ⊞ Tag: Supported Rates 1(B), 2(B), 5.5(B), 11(B), 6, 9, 12, 18, [Mbit/sec]
    ⊞ Tag: Extended Supported Rates 24, 36, 48, 54, [Mbit/sec]
    ⊞ Tag: HT Capabilities (802.11n D1.10)
    ⊞ Tag: HT Information (802.11n D1.10)
    ⊞ Tag: Vendor Specific: Microsof: WMM/WME: Parameter Element
    ⊟ Tag: Mobility Domain
        Tag Number: Mobility Domain (54)
        Tag length: 3
        Mobility Domain Identifier: 0xf0aa
        FT Capability and Policy: 0x00
        .... ...0 = Fast BSS Transition over DS: 0x00
        .... ..0. = Resource Request Protocol Capability: 0x00
    ⊟ Tag: Fast BSS Transition
        Tag Number: Fast BSS Transition (55)
        Tag length: 96
        MIC Control: 0x0000
        0000 0000 .... .... = Element Count: 0
        MIC: 00000000000000000000000000000000
        ANonce: 000000000000000000000000000000000000000000000000...
        SNonce: 000000000000000000000000000000000000000000000000...
        Subelement ID: PMK-R0 key holder identifier (R0KH-ID) (3)
        Length: 4
        PMK-R0 key holder identifier (R0KH-ID): \254\036\006\375
        Subelement ID: PMK-R1 key holder identifier (R1KH-ID) (1)
        Length: 6
        PMK-R1 key holder identifier (R1KH-ID): 3cce73d80200
```

```
*apfMsConnTask_0: Jun 27 19:29:09.136: ec:85:2f:15:39:32
  Association received from mobile on BSSID
  84:78:ac:f0:68:d4

*apfMsConnTask_0: Jun 27 19:29:09.137: ec:85:2f:15:39:32
  Marking this mobile as TGr capable.

*apfMsConnTask_0: Jun 27 19:29:09.137: ec:85:2f:15:39:32
  Processing RSN IE type 48, length 20 for mobile
  ec:85:2f:15:39:32

*apfMsConnTask_0: Jun 27 19:29:09.137: Sending assoc-resp
  station:ec:85:2f:15:39:32 AP:84:78:ac:f0:68:d0-00
  thread:144be808

*apfMsConnTask_0: Jun 27 19:29:09.137: Adding MDIE,
  ID is:0xaaf0

*apfMsConnTask_0: Jun 27 19:29:09.137: ec:85:2f:15:39:32
  Including FT Mobility Domain IE (length 5) in Initial
  assoc Resp to mobile

*apfMsConnTask_0: Jun 27 19:29:09.137: ec:85:2f:15:39:32
  Sending R0KH-ID as:-84.30.6.-3

*apfMsConnTask_0: Jun 27 19:29:09.137: ec:85:2f:15:39:32
  Sending R1KH-ID as 3c:ce:73:d8:02:00

*apfMsConnTask_0: Jun 27 19:29:09.137: ec:85:2f:15:39:32
  Including FT IE (length 98) in Initial Assoc Resp to mobile

*apfMsConnTask_0: Jun 27 19:29:09.138: ec:85:2f:15:39:32
  Sending Assoc Response to station on BSSID 84:78:ac:f0:68:d4
  (status 0) ApVapId 5 Slot 0

*dot1xMsgTask: Jun 27 19:29:09.141: ec:85:2f:15:39:32
  Creating a PKC PMKID Cache entry for station
  ec:85:2f:15:39:32 (RSN 2)

*dot1xMsgTask: Jun 27 19:29:09.141: ec:85:2f:15:39:32
  Resetting MSCB PMK Cache Entry 0 for station
  ec:85:2f:15:39:32

*dot1xMsgTask: Jun 27 19:29:09.141: ec:85:2f:15:39:32
  Setting active key cache index 8 ---> 8

*dot1xMsgTask: Jun 27 19:29:09.141: ec:85:2f:15:39:32
  Setting active key cache index 8 ---> 0

*dot1xMsgTask: Jun 27 19:29:09.141: ec:85:2f:15:39:32
  Adding BSSID 84:78:ac:f0:68:d4 to PMKID cache at
  index 0 for station ec:85:2f:15:39:32

*dot1xMsgTask: Jun 27 19:29:09.142: New PMKID: (16)

*dot1xMsgTask: Jun 27 19:29:09.142:
  [0000] 17 4b 17 5c ed 5f c7 1d 66 39 e9 5d 3a 63 69 e7

*dot1xMsgTask: Jun 27 19:29:09.142: ec:85:2f:15:39:32
  Creating global PMK cache for this TGr client
```

```
*dot1xMsgTask: Jun 27 19:29:09.142: ec:85:2f:15:39:32
  Created PMK Cache Entry for TGr AKM:PSK
  ec:85:2f:15:39:32

*dot1xMsgTask: Jun 27 19:29:09.142: ec:85:2f:15:39:32
  R0KH-ID:172.30.6.253   R1KH-ID:3c:ce:73:d8:02:00
  MSK Len:48 pmkValidTime:1813

*dot1xMsgTask: Jun 27 19:29:09.142: ec:85:2f:15:39:32
  Initiating RSN PSK to mobile ec:85:2f:15:39:32

*dot1xMsgTask: Jun 27 19:29:09.142: ec:85:2f:15:39:32
  Found an cache entry for BSSID 84:78:ac:f0:68:d4 in
  PMKID cache at index 0 of station ec:85:2f:15:39:32

*dot1xMsgTask: Jun 27 19:29:09.142: Including PMKID
  in M1  (16)

*dot1xMsgTask: Jun 27 19:29:09.142:
  [0000] 17 4b 17 5c ed 5f c7 1d 66 39 e9 5d 3a 63 69 e7

*dot1xMsgTask: Jun 27 19:29:09.143: ec:85:2f:15:39:32
  Sending EAPOL-Key Message to mobile ec:85:2f:15:39:32
  state INITPMK (message 1), replay counter
  00.00.00.00.00.00.00.00

*apfMsConnTask_0: Jun 27 19:29:09.144: ec:85:2f:15:39:32
  Got action frame from this client.

*Dot1x_NW_MsgTask_2: Jun 27 19:29:09.152: ec:85:2f:15:39:32
  Received EAPOL-Key from mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 27 19:29:09.153: ec:85:2f:15:39:32
  Received EAPOL-key in PTK_START state (message 2) from
  mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 27 19:29:09.153: ec:85:2f:15:39:32
  Calculating PMKR0Name

*Dot1x_NW_MsgTask_2: Jun 27 19:29:09.153: Adding MDIE,
  ID is:0xaaf0

*Dot1x_NW_MsgTask_2: Jun 27 19:29:09.153: ec:85:2f:15:39:32
  Adding TIE for reassociation deadtime:20000 milliseconds

*Dot1x_NW_MsgTask_2: Jun 27 19:29:09.153: ec:85:2f:15:39:32
  Adding TIE for R0Key-Data valid time :1813

*Dot1x_NW_MsgTask_2: Jun 27 19:29:09.154: ec:85:2f:15:39:32
  Sending EAPOL-Key Message to mobile ec:85:2f:15:39:32 state
  PTKINITNEGOTIATING (message 3), replay counter
  00.00.00.00.00.00.00.01

*Dot1x_NW_MsgTask_2: Jun 27 19:29:09.163: ec:85:2f:15:39:32
  Received EAPOL-Key from mobile ec:85:2f:15:39:32

*Dot1x_NW_MsgTask_2: Jun 27 19:29:09.163: ec:85:2f:15:39:32
  Received EAPOL-key in PTKINITNEGOTIATING state (message 4)
  from mobile ec:85:2f:15:39:32
```

With 802.11r, the initial association to the WLAN is the basis used in order to derive the base keys used by this technique, just as in the other fast-secure roaming methods. The main differences come when the client begins to roam; FT not only avoids 802.1X/EAP when this is used, but it actually performs a more efficient roaming method that combines the initial 802.11 Open System Authentication and Reassociation frames (which are always used and required when roaming between APs) in order to exchange FT information and derive new dynamic encryption keys in place of the 4-Way handshake.

The next image shows the frames exchanged when a Fast BSS Transition Over-the-Air with 802.1X/EAP security is performed. The Open System Authentication frame from the client to the AP is selected in order to see the FT protocol Information Elements that are required to begin the FT key negotiation. This is used in order to derive the new PTK with the new AP (based on the PMK-R1). The field that shows the authentication algorithm is highlighted in order to show that this client does not perform a simple Open System Authentication, but a Fast BSS Transition:



```
No.  Time     Source            Destination        BSS Id             Protocol  Channel frequency  Info
   1 0.000000 Apple_15:39:32    Cisco_f0:2a:96     84:78:ac:f0:2a:96  802.11            2437 Authentication, SN=1058, FN=0, Flags=
   2 0.003801 Cisco_f0:2a:96    Apple_15:39:32     84:78:ac:f0:2a:96  802.11            2437 Authentication, SN=792, FN=0, Flags=.
   3 0.008559 Apple_15:39:32    Cisco_f0:2a:96     84:78:ac:f0:2a:96  802.11            2437 Reassociation Request, SN=1059, FN=0,
   4 0.015460 Cisco_f0:2a:96    Apple_15:39:32     84:78:ac:f0:2a:96  802.11            2437 Reassociation Response, SN=793, FN=0,
   5 2.997122 Apple_15:39:32    IPv6mcast_00:00:0( 84:78:ac:f0:2a:96  802.11            2437 QoS Data, SN=0, FN=0, Flags=.p.....TC
```

```
⊞ Frame 1: 198 bytes on wire (1584 bits), 198 bytes captured (1584 bits)
⊞ Radiotap Header v0, Length 18
⊞ IEEE 802.11 Authentication, Flags: ........C
⊟ IEEE 802.11 wireless LAN management frame
  ⊟ Fixed parameters (6 bytes)
      Authentication Algorithm: Fast BSS Transition (2)
      Authentication SEQ: 0x0001
      Status code: Successful (0x0000)
  ⊟ Tagged parameters (146 bytes)
    ⊟ Tag: RSN Information
        Tag Number: RSN Information (48)
        Tag length: 38
        RSN Version: 1
      ⊞ Group Cipher Suite: 00-0f-ac (Ieee8021) AES (CCM)
        Pairwise Cipher Suite Count: 1
      ⊞ Pairwise Cipher Suite List 00-0f-ac (Ieee8021) AES (CCM)
        Auth Key Management (AKM) Suite Count: 1
      ⊞ Auth Key Management (AKM) List 00-0f-ac (Ieee8021) FT over IEEE 802.1X
      ⊞ RSN Capabilities: 0x000c
        PMKID Count: 1
      ⊟ PMKID List
          PMKID: 35a9c629f03259bcbaf08cf399554647
    ⊟ Tag: Mobility Domain
        Tag Number: Mobility Domain (54)
        Tag length: 3
        Mobility Domain Identifier: 0xf0aa
        FT Capability and Policy: 0x00
        .... ...0 = Fast BSS Transition over DS: 0x00
        .... ..0. = Resource Request Protocol Capability: 0x00
    ⊟ Tag: Fast BSS Transition
        Tag Number: Fast BSS Transition (55)
        Tag length: 88
        MIC Control: 0x0000
        0000 0000 .... .... = Element count: 0
        MIC: 00000000000000000000000000000000
        ANonce: 0000000000000000000000000000000000000000000000000...
        SNonce: 6f1870c08601601 3fecd099066f89079f86c3c9ec9e261d2...
        Subelement ID: PMK-R0 key holder identifier (R0KH-ID) (3)
        Length: 4
        PMK-R0 key holder identifier (R0KH-ID): \254\036\006\375
```

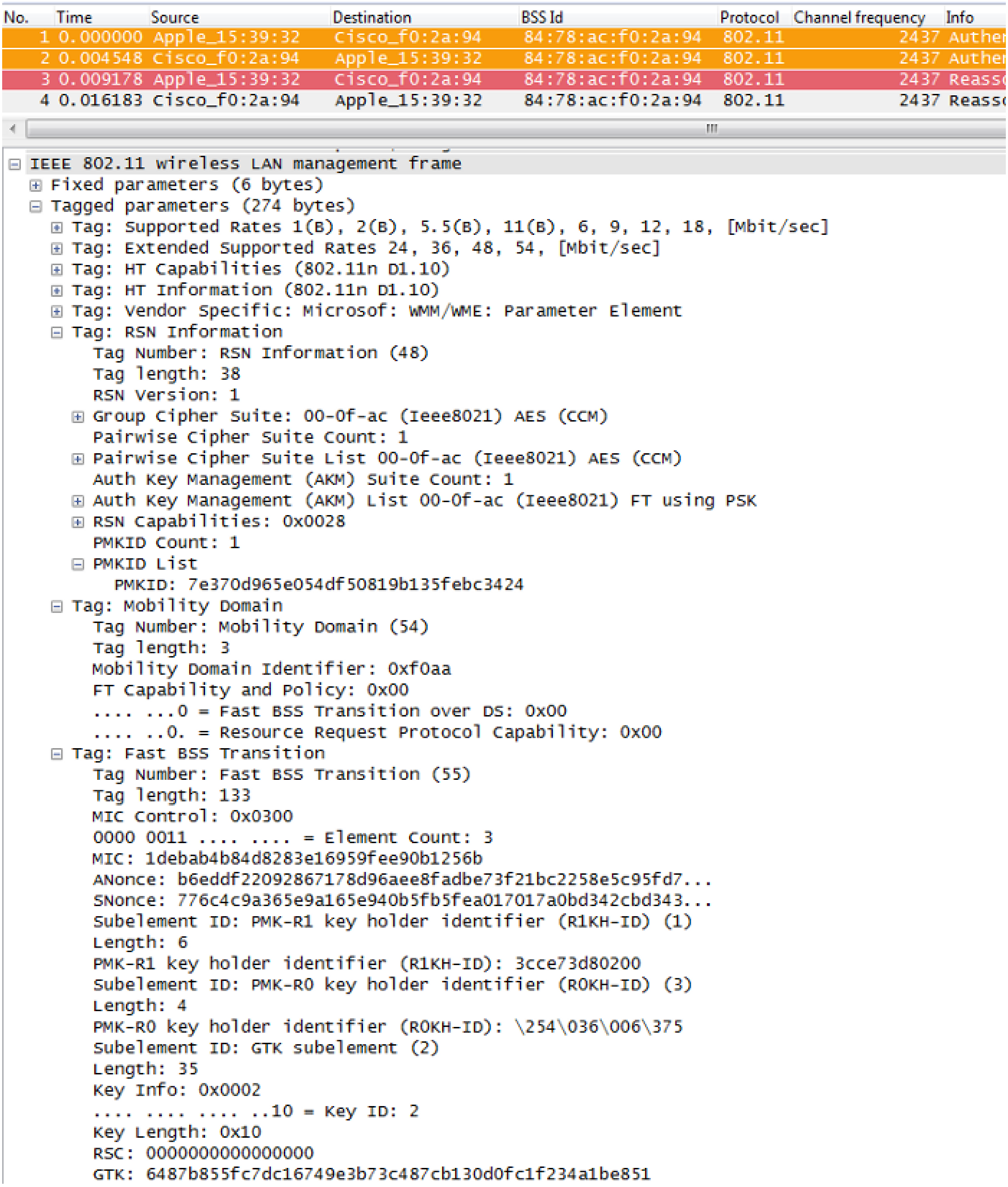
Here are the debug outputs from the WLC when this FT roaming event occurs with 802.1X/EAP:

<#root>

```
*apfMsConnTask_2: Jun 27 19:25:48.751: ec:85:2f:15:39:32
  Doing preauth for this client over the Air
```

```
!--- WLC begins FT fast-secure roaming over-the-Air with
     this client and performs a type of preauthentication,
     because the client asks for this with FT on the Authentication
     frame that is sent to the new AP over-the-Air
     (before the Reassociation Request).



*apfMsConnTask_2: Jun 27 19:25:48.751: ec:85:2f:15:39:32
  Doing local roaming for destination address
  84:78:ac:f0:2a:96

!--- WLC performs the local roaming event with the new AP to
     which the client roams.



*apfMsConnTask_2: Jun 27 19:25:48.751: ec:85:2f:15:39:32
  Got 1 AKMs in RSNIE
*apfMsConnTask_2: Jun 27 19:25:48.751: ec:85:2f:15:39:32
  RSNIE AKM matches with PMK cache entry :0x3

!--- WLC receives one PMK from this client (known as AKM here),
     which matches the PMK cache entry hold for this client.



*apfMsConnTask_2: Jun 27 19:25:48.751: ec:85:2f:15:39:32
  Created a new preauth entry for AP:84:78:ac:f0:2a:96
*apfMsConnTask_2: Jun 27 19:25:48.751: Adding MDIE,
  ID is:0xaaf0

!--- WLC creates a new preauth entry for this AP-and-Client pair,
     and adds the MDIE information.



*apfMsConnTask_2: Jun 27 19:25:48.763: Processing assoc-req
  station:ec:85:2f:15:39:32 AP:84:78:ac:f0:2a:90-00
  thread:144bef38
*apfMsConnTask_2: Jun 27 19:25:48.763: ec:85:2f:15:39:32
  Reassociation received from mobile on BSSID
  84:78:ac:f0:2a:96

!--- Once the client receives the Authentication frame reply from the
     WLC/AP, the Reassociation request is sent, which is received at
     the new AP to which the client roams.



*apfMsConnTask_2: Jun 27 19:25:48.764: ec:85:2f:15:39:32
  Marking this mobile as TGr capable.

*apfMsConnTask_2: Jun 27 19:25:48.764: ec:85:2f:15:39:32
  Processing RSN IE type 48, length 38 for mobile
  ec:85:2f:15:39:32

*apfMsConnTask_2: Jun 27 19:25:48.765: ec:85:2f:15:39:32
  Roaming succeed for this client.

!--- WLC confirms that the FT fast-secure roaming is successful
     for this client.



*apfMsConnTask_2: Jun 27 19:25:48.765: Sending assoc-resp
  station:ec:85:2f:15:39:32 AP:84:78:ac:f0:2a:90-00
  thread:144bef38
*apfMsConnTask_2: Jun 27 19:25:48.766: Adding MDIE,
  ID is:0xaaf0
*apfMsConnTask_2: Jun 27 19:25:48.766: ec:85:2f:15:39:32
  Including FT Mobility Domain IE (length 5) in
  reassociation assoc Resp to mobile
*apfMsConnTask_2: Jun 27 19:25:48.766: ec:85:2f:15:39:32
  Sending Assoc Response to station on BSSID 84:78:ac:f0:2a:96
  (status 0) ApVapId 7 Slot 0

!--- The Reassociation response is sent to the client, which
     includes the FT Mobility Domain IE.



*dot1xMsgTask: Jun 27 19:25:48.769: ec:85:2f:15:39:32
  Finishing FT roaming for mobile ec:85:2f:15:39:32

!--- FT roaming finishes and EAP is skipped (as well as any
     other key management handshake), so the client is ready
     to pass encrypted data frames with the current AP.



*dot1xMsgTask: Jun 27 19:25:48.769: ec:85:2f:15:39:32
  Skipping EAP-Success to mobile ec:85:2f:15:39:32
```

Here is a image that shows a Fast BSS Transition Over-the-Air with WPA2-PSK security, where the final Reassociation Response frame from the AP to the client is selected in order to show more details about this FT exchange:



```
No.  Time      Source            Destination       BSS Id              Protocol  Channel frequency  Info
   1 0.000000  Apple_15:39:32    Cisco_f0:2a:94    84:78:ac:f0:2a:94   802.11                 2437  Authe
   2 0.004548  Cisco_f0:2a:94    Apple_15:39:32    84:78:ac:f0:2a:94   802.11                 2437  Authe
   3 0.009178  Apple_15:39:32    Cisco_f0:2a:94    84:78:ac:f0:2a:94   802.11                 2437  Reass
   4 0.016183  Cisco_f0:2a:94    Apple_15:39:32    84:78:ac:f0:2a:94   802.11                 2437  Reass
```

```
⊟ IEEE 802.11 wireless LAN management frame
  ⊞ Fixed parameters (6 bytes)
  ⊟ Tagged parameters (274 bytes)
    ⊞ Tag: Supported Rates 1(B), 2(B), 5.5(B), 11(B), 6, 9, 12, 18, [Mbit/sec]
    ⊞ Tag: Extended Supported Rates 24, 36, 48, 54, [Mbit/sec]
    ⊞ Tag: HT Capabilities (802.11n D1.10)
    ⊞ Tag: HT Information (802.11n D1.10)
    ⊞ Tag: Vendor Specific: Microsof: WMM/WME: Parameter Element
    ⊟ Tag: RSN Information
        Tag Number: RSN Information (48)
        Tag length: 38
        RSN Version: 1
      ⊞ Group Cipher Suite: 00-0f-ac (Ieee8021) AES (CCM)
        Pairwise Cipher Suite Count: 1
      ⊞ Pairwise Cipher Suite List 00-0f-ac (Ieee8021) AES (CCM)
        Auth Key Management (AKM) Suite Count: 1
      ⊞ Auth Key Management (AKM) List 00-0f-ac (Ieee8021) FT using PSK
      ⊞ RSN Capabilities: 0x0028
        PMKID Count: 1
      ⊟ PMKID List
          PMKID: 7e370d965e054df50819b135febc3424
    ⊟ Tag: Mobility Domain
        Tag Number: Mobility Domain (54)
        Tag length: 3
        Mobility Domain Identifier: 0xf0aa
        FT Capability and Policy: 0x00
        .... ...0 = Fast BSS Transition over DS: 0x00
        .... ..0. = Resource Request Protocol Capability: 0x00
    ⊟ Tag: Fast BSS Transition
        Tag Number: Fast BSS Transition (55)
        Tag length: 133
        MIC Control: 0x0300
        0000 0011 .... .... = Element Count: 3
        MIC: 1debab4b84d8283e16959fee90b1256b
        ANonce: b6eddf22092867178d96aee8fadbe73f21bc2258e5c95fd7...
        SNonce: 776c4c9a365e9a165e940b5fb5fea017017a0bd342cbd343...
        Subelement ID: PMK-R1 key holder identifier (R1KH-ID) (1)
        Length: 6
        PMK-R1 key holder identifier (R1KH-ID): 3cce73d80200
        Subelement ID: PMK-R0 key holder identifier (R0KH-ID) (3)
        Length: 4
        PMK-R0 key holder identifier (R0KH-ID): \254\036\006\375
        Subelement ID: GTK subelement (2)
        Length: 35
        Key Info: 0x0002
        .... .... .... ..10 = Key ID: 2
        Key Length: 0x10
        RSC: 0000000000000000
        GTK: 6487b855fc7dc16749e3b73c487cb130d0fc1f234a1be851
```

Here are the debug outputs when this FT roaming event occurs with PSK, which are similar to the ones when 802.1X/EAP is used:

```
*apfMsConnTask_2: Jun 27 19:29:29.854: ec:85:2f:15:39:32
  Doing preauth for this client over the Air
```

```
*apfMsConnTask_2: Jun 27 19:29:29.854: ec:85:2f:15:39:32
  Doing local roaming for destination address
  84:78:ac:f0:2a:94

*apfMsConnTask_2: Jun 27 19:29:29.854: ec:85:2f:15:39:32
  Got 1 AKMs in RSNIE

*apfMsConnTask_2: Jun 27 19:29:29.854: ec:85:2f:15:39:32
  RSNIE AKM matches with PMK cache entry :0x4

*apfMsConnTask_2: Jun 27 19:29:29.854: ec:85:2f:15:39:32
  Created a new preauth entry for AP:84:78:ac:f0:2a:94

*apfMsConnTask_2: Jun 27 19:29:29.854: Adding MDIE,
  ID is:0xaaf0

*apfMsConnTask_2: Jun 27 19:29:29.867: Processing assoc-req
  station:ec:85:2f:15:39:32 AP:84:78:ac:f0:2a:90-00
  thread:144bef38

*apfMsConnTask_2: Jun 27 19:29:29.867: ec:85:2f:15:39:32
  Reassociation received from mobile on BSSID
  84:78:ac:f0:2a:94

*apfMsConnTask_2: Jun 27 19:29:29.868: ec:85:2f:15:39:32
  Marking this mobile as TGr capable.

*apfMsConnTask_2: Jun 27 19:29:29.868: ec:85:2f:15:39:32
  Processing RSN IE type 48, length 38 for mobile
  ec:85:2f:15:39:32

*apfMsConnTask_2: Jun 27 19:29:29.869: ec:85:2f:15:39:32
  Roaming succeed for this client.

*apfMsConnTask_2: Jun 27 19:29:29.869: Sending assoc-resp
  station:ec:85:2f:15:39:32 AP:84:78:ac:f0:2a:90-00
  thread:144bef38

*apfMsConnTask_2: Jun 27 19:29:29.869: Adding MDIE,
  ID is:0xaaf0

*apfMsConnTask_2: Jun 27 19:29:29.869: ec:85:2f:15:39:32
  Including FT Mobility Domain IE (length 5) in
  reassociation assoc Resp to mobile

*apfMsConnTask_2: Jun 27 19:29:29.870: ec:85:2f:15:39:32
  Sending Assoc Response to station on BSSID
  84:78:ac:f0:2a:94 (status 0) ApVapId 5 Slot 0

*dot1xMsgTask: Jun 27 19:29:29.874: ec:85:2f:15:39:32
  Finishing FT roaming for mobile ec:85:2f:15:39:32
```

As shown in the image, once the Fast BSS Transition is negotiated upon initial association to the WLAN, the four frames that are used and required for roaming (Open System Authentication from the client, Open System Authentication from the AP, Reassociation Request, and Reassociation Response) are basically used as an FT 4-Way handshake in order to derive the new PTK (unicast encryption key) and GTK (multicast/broadcast encryption key).

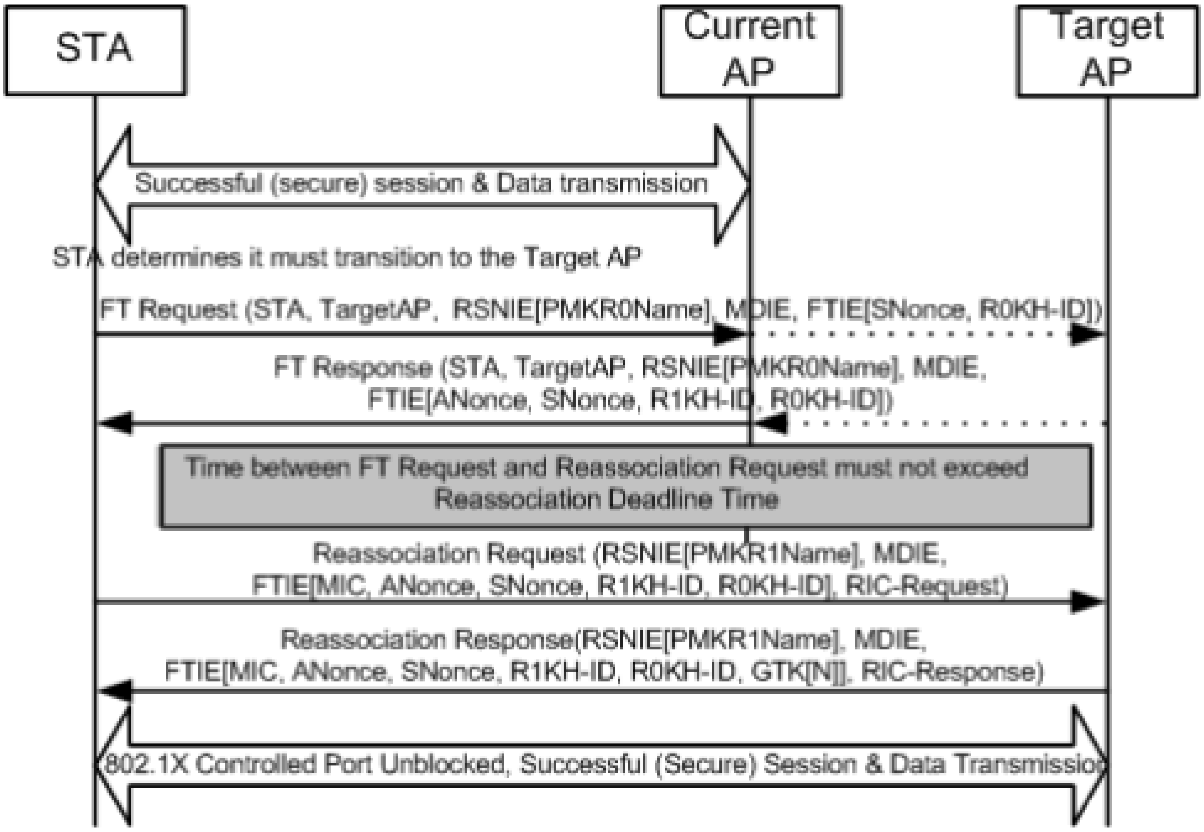
This substitutes for the 4-Way handshake that normally occurs after these frames are exchanged, and the FT content and key negotiation on these frames is basically the same whether you use 802.1X/EAP or PSK as the security method. As shown in the image, the AKM field is the main difference, which confirms if the client performs FT with PSK or 802.1X. Therefore, it is important to note that these four frames normally do not have this type of security information for key negotiation, but only when client FT roams if 802.11r is implemented and negotiated between the client and the WLAN infrastructure upon initial association.

Fast BSS Transition Over-the-DS

802.11r allows another implementation of Fast BSS Transition, where the FT roaming is initiated by the client with the new AP for which the client roams Over-the-DS (Distribution System), and not Over-the-Air. In this case, FT Action frames are used in order to initiate the key negotiation instead of the Open System Authentication frames.

Basically, once the client decides it can roam to a better AP, the client sends an FT Action Request frame to the original AP where it is currently connected before roaming. The client indicates the BSSID (MAC address) of the target AP where it wants to FT roam. The original AP forwards this FT Action Request frame to the target AP over the Distribution System (normally the wired infrastructure), and the target AP responds to the client with an FT Action Response frame (also over the DS, so it can finally send it over-the-air to the client). Once this FT Action frame exchange is successful, the client finishes the FT roaming; the client sends the Reassociation Request to the target AP (this time over-the-air), and receives a Reassociation Response from the new AP in order to confirm the roaming and final keys derivation.

In summary, there are four frames to negotiate Fast BSS Transition and derive new encryption keys, but here the Open System Authentication frames are substituted with the FT Action Request/Response frames, which are exchanged with the target AP over the Distribution System with the current AP. This method is also valid for both security methods 802.1X/EAP and PSK, all supported by the Cisco Wireless LAN Controllers; however, since this Over-the-DS transition is not supported and implemented by most of the wireless clients in the WiFi industry (and since the frame exchange and debug outputs are basically the same), examples are not provided in this document. Instead, this image is used in order to visualize the Fast BSS Transition Over-the-DS:


STA
Current AP
Target AP
Successful (secure) session & Data transmission
STA determines it must transition to the Target AP
FT Request (STA, TargetAP, RSNIE[PMKR0Name], MDIE, FTIE[SNonce, R0KH-ID])
FT Response (STA, TargetAP, RSNIE[PMKR0Name], MDIE, FTIE[ANonce, SNonce, R1KH-ID, R0KH-ID])
Time between FT Request and Reassociation Request must not exceed Reassociation Deadline Time
Reassociation Request (RSNIE[PMKR1Name], MDIE, FTIE[MIC, ANonce, SNonce, R1KH-ID, R0KH-ID], RIC-Request)
Reassociation Response(RSNIE[PMKR1Name], MDIE, FTIE[MIC, ANonce, SNonce, R1KH-ID, R0KH-ID, GTK[N]], RIC-Response)
802.1X Controlled Port Unblocked, Successful (Secure) Session & Data Transmission

FlexConnect with 802.11r

- Central Authentication is supported. This includes Local and Central data switching. The APs must be part of the same FlexConnect Group.
- Local Authentication is not supported.
- Standalone mode is not supported.

Pros with 802.11r

- This method is the first that uses a key hierarchy clearly defined by the IEEE on the 802.11 standard as an amendment (802.11r), so the implementation of these FT techniques are more compatible between vendors and without different interpretations.
- 802.11r allows multiple techniques that are helpful, dependent on your needs (Over-the-Air and Over-the-DS, for 802.1x/EAP security and for PSK security).
- The wireless client performs fast-secure roaming to a new AP on the same WLAN/SSID, even if it never associated with that AP, and without the need to save multiple PMKIDs.
- This is the first fast-secure roaming method that allows faster roaming even with PSK security, and avoids the 4-Way handshake that is required when roaming between APs with WPA/WPA2 PSK. The main purpose of the fast-secure roaming methods is to avoid the 802.1X/EAP handshake when this security method is implemented; however, for PSK security the roaming event is accelerated even more with 802.11r when the 4-Way handshake is avoided.

Cons with 802.11r

- There are a few wireless client devices that actually support Fast BSS Transitions, and in most cases, they do not support all of the techniques available on 802.11r.
- Because of the fact that these implementations are very young, there are not enough test results from

real-production environments or enough debug results in order to address possible caveats that can appear.
- When you configure a WLAN/SSID in order to use any of the FT methods, then only wireless clients that support 802.11r are able to connect to this WLAN/SSID. The FT settings are not optional for the clients, so those wireless clients that do not support 802.11r must connect with a separate WLAN/SSID where FT is not configured at all.

Adaptive 802.11r

- Some legacy clients cannot associate with a WLAN/SSID that has 802.11r enabled even for "mixed mode" (which you hope you can have on the same SSID clients that support and that do not support 802.11r). This is when the driver of the client supplicant that is responsible for parsing the Robust Security Network Information Element (RSN IE) is old and not aware of the additional AKM suites in the IE. Due to this limitation, clients cannot send association requests to WLANs that advertise 802.11r support, and hence, you need to configure one WLAN/SSID for 802.11r clients and a separate WLAN/SSID for clients that do not support 802.11r.

- In order to overcome this, Cisco Wireless LAN infrastructure introduced the Adaptive 802.11r feature. When FT mode is set to Adaptive at the WLAN level, WLAN advertises 802.11r Mobility Domain ID on an 802.11i-enabled WLAN. Some Apple iOS10 client devices identify the presence of MDIE on an 80211i/WPA2 WLAN and do a proprietary handshake in order to establish 802.11r association. Once the client completes successful 802.11r association, it can do FT roaming as in a normal 802.11r enabled WLAN. The FT Adaptive is applicable only to selected Apple iOS10 (and later) devices. All other clients can continue to have 802.11i/WPA2 association on the WLAN, and perform the applicable FSR method as supported.

- More documentation about this new feature introduced for iOS10 devices to perform 802.11r on a WLAN/SSID where 802.11r is not truly enabled (so other non-802.11r clients can successfully connect), can be found in Enterprise Best Practices for Cisco IOS Devices on Cisco Wireless LAN.

Conclusions

- Keep in mind that the client is always the one that decides to roam to a specific AP, and the WLC/AP cannot decide this for the client. The roaming event is initiated by the wireless client once it considers it must roam.
- The WLC supports a combination of most or all of the FSR (Fast-Secure Roaming) methods together on the same WLAN/SSID. However, be aware that this normally does not work, as it depends highly on the client behavior (very different across different mobile devices) in order to support or even understand that which the WLC attempts to advertise as supported. Instead of achieving interoperability in just one SSID, there are normally more issues than the ones that are expected to be fixed, so this is not recommended. Deep testing with all possible clients to be used on this WLAN must be completed if this is really needed.
- It is very important to understand that fast-secure roaming methods are developed in order to accelerate the WLAN roaming process when you move between APs if the WLAN/SSID has security enabled. When no security is in place, there is nothing to accelerate, as the client-AP simply exchanges the wireless management frames that are always required when roaming between APs before data frames are sent (Open System Authentication from the client, Open System Authentication from the AP, Reassociation Request, and Reassociation Response). Therefore, this cannot move any faster. If you encounter roaming issues without security, then there are no fast-roaming methods to improve roaming, only methods in order to confirm if the WLAN/SSID setup and design are appropriate for the wireless client stations to roam accordingly between the AP coverage cells.
- 802.11r/FT is implemented with WPA2-PSK in order to accelerate roaming events with this security

and avoid the 4-Way handshake, as explained within the 802.11r section.

- All of the methods have their advantages and disadvantages, but in the end, you must always verify if the wireless client stations support the specific method that you want to implement, and if the Cisco WLAN infrastructure supports all of the methods available. Thus, you must select the best method that is actually supported by the wireless clients that connect to the specific WLAN/SSID. For example, in some deployments you can create a WLAN/SSID with CCKM for Cisco wireless IP Phones (which support WPA2/AES with CCKM, but not 802.11r), and then another WLAN/SSID with WPA2/AES via 802.11r/FT for wireless clients that support this Fast Secure Roaming method (or use OKC, if this is what is supported).
- If the wireless clients do not support any of the fast-secure roaming methods available, then you can need to accept the fact that those clients can always experiment the delays explained in this document when roaming between APs on a WLAN/SSID with 802.1X/EAP security (which can cause disruptions on the client apps/services).
- All methods, except SKC (WPA2 PMKID Caching), are supported for fast-secure roaming between APs managed by different WLCs (intercontroller roaming), as long as they are on the same mobility group.
- CUWN fully supports all different Fast-Secure Roaming methods covered in this article when 802.1X/EAP authentication is used for WPA/WPA2. CUWN does not support Fast-Secure Roaming on methods that work with WPA2-RSN (CCKM, PMKID Caching/SKC, OKC/PKC) when PSK (WPA2-Personal) is used, where Fast-Roaming methods are mostly not needed. However, CUWN supports Fast-Secure Roaming in the case of WPA2-FT (802.11r) with PSK as also explained in this article.

Related Information

- **802.11r BSS Fast Transition Deployment Guide**
- **Cisco Technical Support & Downloads**