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EAP Key Management Framework
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Status of this Memo

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Abstract

This document provides a framework for EAP key management, including a statement of applicability and guidelines for generation, transport and usage of EAP keying material. Algorithms for key derivation or mechanisms for key transport are not specified in this document. Rather, this document provides a framework within which algorithms and transport mechanisms can be discussed and evaluated.

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1. Introduction

The Extensible Authentication Protocol (EAP), defined in [I-D.ietf-eap-rfc2284bis], was designed to enable extensible authentication for network access in situations in which the IP protocol is not available. Originally developed for use with PPP [RFC1661], it has subsequently also been applied to IEEE 802 wired networks [IEEE8021X].

This document provides a framework for the generation, transport and usage of keying material generated by EAP authentication algorithms, known as "methods". Since in EAP keying material is generated by EAP methods, transported by AAA protocols, transformed into session keys by secure association protocols and used by lower layer ciphersuites, it is necessary to describe each of these elements and provide a system-level security analysis.

1.1 Requirements Language

In this document, several words are used to signify the requirements of the specification. These words are often capitalized. The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119].

1.2 Terminology

This document frequently uses the following terms:

authenticator
The end of the link initiating EAP authentication. Where no backend authentication server is present, the authenticator acts as the EAP server, terminating the EAP conversation with the peer. Where a backend authentication server is present, the authenticator may act as a pass-through for one or more authentication methods and for non-local users. This terminology is also used in [IEEE8021X], and has the same meaning in this document.

backend authentication server
A backend authentication server is an entity that provides an authentication service to an authenticator. When used, this server typically executes EAP Methods for the authenticator. This terminology is also used in [IEEE8021X].

AAA-Token
The package within which keying material and one or more attributes is transported between the backend authentication

server and the authenticator. The attributes provide the authenticator with usage context and key names suitable to bind the key to the appropriate context. The format and wrapping of the AAA-Token, which is intended to be accessible only to the backend authentication server and authenticator, is defined by the AAA protocol. Examples include RADIUS [RFC2548], and Diameter [I-D.ietf-aaa-eap].

Cryptographic binding
The demonstration of the EAP peer to the EAP server that a single entity has acted as the EAP peer for all methods executed within a sequence or tunnel. Binding MAY also imply that the EAP server demonstrates to the peer that a single entity has acted as the EAP server for all methods executed within a sequence or tunnel. If executed correctly, binding serves to mitigate man-in-the-middle vulnerabilities.

Cryptographic separation
Two keys (x and y) are "cryptographically separate" if an adversary that knows all messages exchanged in the protocol cannot compute x from y or y from x without "breaking" some cryptographic

assumption. In particular, this definition allows that the adversary has the knowledge of all nonces sent in cleartext as well as all predictable counter values used in the protocol. Breaking a cryptographic assumption would typically require inverting a one-way function or predicting the outcome of a cryptographic pseudo-random number generator without knowledge of the secret state. In other words, if the keys are cryptographically separate, there is no shortcut to compute x from y or y from x.

EAP server
The entity which terminates EAP authentication with the peer is known as the EAP server. Where pass-through is supported, the backend authentication server functions as the EAP server; where authentication occurs locally, the EAP server is the authenticator.

AAA-Key
A key derived by the EAP peer and EAP server and transported to the authenticator. In 802.11 terminology, the first 32 octets of the AAA-Key is known as the Pairwise Master Key (PMK).

Key strength
If the effective key strength is N bits, the best currently known methods to recover the key (with non-negligible probability) require an effort comparable to 2^N operations of a typical block cipher.

Mutual authentication
This refers to an EAP method in which, within an interlocked exchange, the authenticator authenticates the peer and the peer authenticates the authenticator. Two one-way conversations, running in opposite directions do not provide mutual authentication as defined here.

peer
The end of the link that responds to the authenticator. In [IEEE8021X], this end is known as the Supplicant.

1.3 Conversation Overview

Where EAP key derivation is supported, EAP authentication is typically a component of a three phase exchange:

Discovery phase (phase 0)
EAP authentication, key derivation and transport (phase 1)
Unicast and multicast secure association establishment (phase 2)

In the discovery phase (phase 0), the EAP peers locate each other and discover their capabilities. This can include an EAP peer locating an authenticator suitable for access to a particular network, or it could involve an EAP peer locating an authenticator behind a bridge with which it desires to establish a secure association. Typically the discovery phase takes place between the EAP peer and authenticator.

Once the EAP peer and authenticator discover each other, EAP authentication may begin (phase 1a). EAP enables deployment of new authentication methods without requiring development of new code on the authenticator. While the authenticator may implement some EAP methods locally and use those methods to authenticate local users, it may at the same time act as a pass-through for other users and methods, forwarding EAP packets back and forth between the backend authentication server and the peer.

As described in Section 2, in addition to supporting authentication, EAP methods may also support derivation of keying material for purposes including protection of the EAP conversation and subsequent data exchanges. EAP key derivation takes place between the EAP peer and EAP server, and methods supporting key derivation MUST also support mutual authentication. Where an authenticator server is present, it acts as the EAP server and transports derived keying material (known as the AAA-Key) to the authenticator (phase 1b).

EAP methods may mutually authenticate and derive keys. However a

distinct secure association exchange is required in order to manage the creation and deletion of unicast (phase 2a) and multicast (phase 2b) security associations between the EAP peer and authenticator.

The phases and the relationship between the parties is illustrated below.

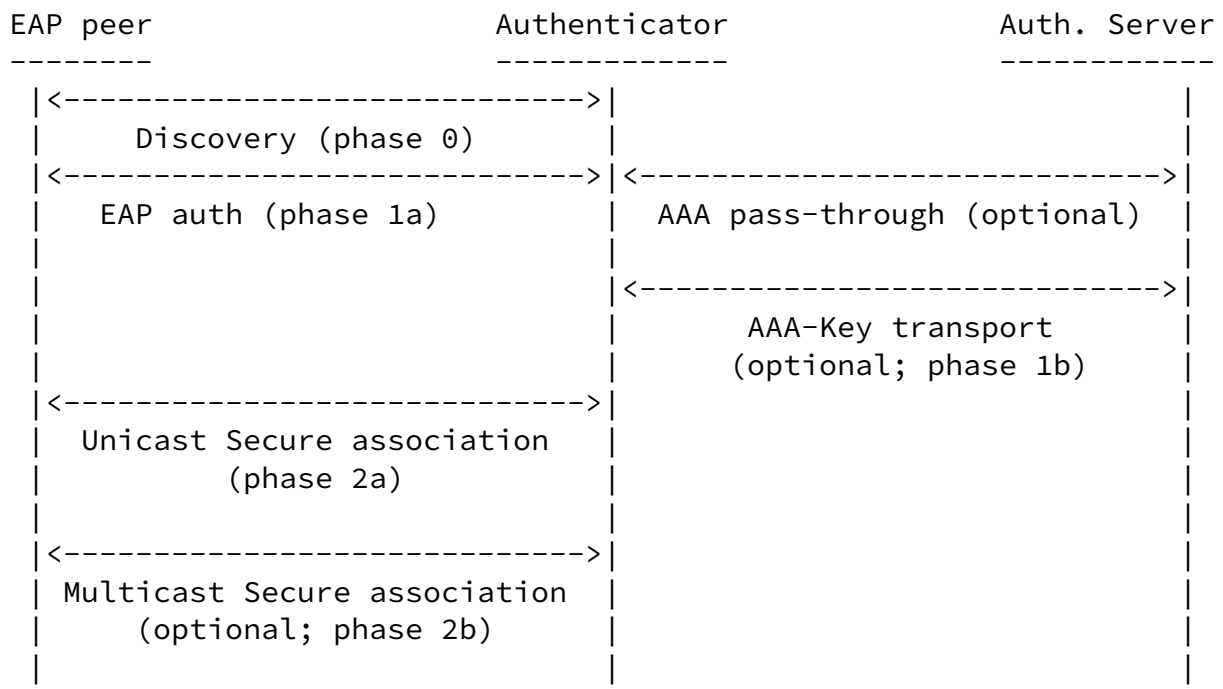


Figure 1: Conversation Overview

1.3.1 Discovery Phase

In the peer discovery exchange (phase 0), the EAP peer and authenticator locate each other and discover each other's capabilities. For example, PPPoE [RFC2516] includes support for a Discovery Stage to allow a peer to identify the Ethernet MAC address of one or more authenticators and establish a PPPoE SESSION_ID. In IEEE 802.11 [IEEE80211], the EAP peer (also known as the Station or STA) discovers the authenticator (Access Point or AP) and determines its capabilities using Beacon or Probe Request/Response frames. Since device discovery is handled outside of EAP, there is no need to provide this functionality within EAP.

Device discovery can occur manually or automatically. In EAP implementations running over PPP, the EAP peer might be configured with a phone book providing phone numbers of authenticators and associated capabilities such as supported rates, authentication protocols or ciphersuites.

Since device discovery can occur prior to authentication and key derivation, it may not be possible for the discovery phase to be protected using keying material derived during an authentication exchange. As a result, device discovery protocols may be insecure, leaving them vulnerable to spoofing unless the discovered parameters can subsequently be securely verified.

1.3.2 Authentication Phase

Once the EAP peer and authenticator discover each other, they exchange EAP packets. Typically, the peer desires access to the network, and the authenticators are Network Access Servers (NASes) providing that access. In such a situation, access to the network can be provided by any authenticator attaching to the desired network, and the EAP peer is typically willing to send data traffic through any authenticator that can demonstrate that it is authorized to provide access to the desired network.

An EAP authenticator may handle the authentication locally, or it may act as a pass-through to a backend authentication server. In the latter case the EAP exchange occurs between the EAP peer and a backend authenticator server, with the authenticator forwarding EAP packets between the two. The entity which terminates EAP authentication with the peer is known as the EAP server. Where pass-through is supported, the backend authentication server functions as the EAP server; where authentication occurs locally, the EAP server is the authenticator. Where a backend authentication server is present, at the successful completion of an authentication exchange, the AAA-Key is transported to the authenticator (phase 1b).

EAP may also be used when it is desired for two network devices (e.g. two switches or routers) to authenticate each other, or where two peers desire to authenticate each other and set up a secure association suitable for protecting data traffic.

Some EAP methods exist which only support one-way authentication; however, EAP methods deriving keys are required to support mutual authentication. In either case, it can be assumed that the parties do not utilize the link to exchange data traffic unless their authentication requirements have been met. For example, a peer completing mutual authentication with an EAP server will not send data traffic over the link until the EAP server has authenticated successfully to the peer, and a secure association has been negotiated.

Since EAP is a peer-to-peer protocol, an independent and simultaneous authentication may take place in the reverse direction. Both peers may act as authenticators and authenticatees at the same time.

Successful completion of EAP authentication and key derivation by an EAP peer and EAP server does not necessarily imply that the peer is committed to joining the network associated with an EAP server. Rather, this commitment is implied by the creation of a security association between the EAP peer and authenticator, as part of the secure association protocol (phase 2). As a result, EAP may be used for "pre-authentication" in situations where it is necessary to pre-establish EAP security associations in order to decrease handoff or roaming latency.

1.3.3 Secure Association Phase

The secure association phase (phase 2) always occurs after the completion of EAP authentication (phase 1a) and key transport (phase 1b), and typically supports the following features:

[1] The secure negotiation of capabilities. This includes usage modes, session parameters and ciphersuites, and required filters, including confirmation of the capabilities discovered during phase 0. By securely negotiating session parameters, the secure association protocol protects against spoofing during the discovery phase and ensures that the peer and authenticator are in agreement about how data is to be secured.

[2] Generation of fresh transient session keys. This is typically accomplished via the exchange of nonces within the secure association protocol, and includes generation of both unicast (phase 2a) and multicast (phase 2b) session keys. By not using the AAA-Key directly to protect data, the secure association protocol protects against compromise of the AAA-Key, and by guaranteeing the freshness of transient session key, assures that session keys are not reused.

[3] Key activation and deletion.

[4] Mutual proof of possession of the AAA-Key. This demonstrates that both the EAP peer and authenticator have been authenticated and authorized by the AAA server. Since mutual proof of possession is not the same as mutual authentication, the EAP peer cannot verify authenticator assertions (including the authenticator identity) as a result of this exchange.

1.4 Authorization issues

In a typical network access scenario (dial-in, wireless LAN, etc.) access control mechanisms are typically applied. These mechanisms include user authentication as well as authorization for the offered

service.

As a part of the authentication process, the AAA network determines the user's authorization profile. The user authorizations are transmitted by the AAA server to the EAP authenticator (also known as the Network Access Server or NAS) included with the AAA-Token, which also contains the AAA-Key, in Phase 1b of the EAP conversation. Typically, the profile is determined based on the user identity, but a certificate presented by the user may also provide authorization information.

The AAA server is responsible for making a user authorization decision, answering the following questions:

- Is this a legitimate user for this particular network?
- Is this user allowed the type of access he or she is requesting?
- Are there any specific parameters (mandatory tunneling, bandwidth, filters, and so on) that the access network should be aware of for this user?
- Is this user within the subscription rules regarding time of day?
- Is this user within his limits for concurrent sessions?
- Are there any fraud, credit limit, or other concerns that indicate that access should be denied?

While the authorization decision is in principle simple, the process is complicated by the distributed nature of AAA decision making. Where brokering entities or proxies are involved, all of the AAA devices in the chain from the NAS to the home AAA server are involved in the decision. For instance, a broker can disallow access even if the home AAA server would allow it, or a proxy can add authorizations (e.g., bandwidth limits).

Decisions can be based on static policy definitions and profiles as well as dynamic state (e.g. time of day or limits on the number of concurrent sessions). In addition to the Accept/Reject decision made by the AAA chain, parameters or constraints can be communicated to the NAS.

The criteria for Accept/Reject decisions or the reasons for choosing particular authorizations are typically not communicated to the NAS, only the final result. As a result, the NAS has no way to know what the decision was based on. Was a set of authorization parameters sent because this service is always provided to the user, or was the

decision based on the time/day and the capabilities of the requesting NAS device?

Within EAP, "fast handoff" is defined as a conversation in which the EAP exchange (phase 1a) and associated AAA passthrough is bypassed, so as to reduce latency. Depending on the fast handoff mechanism, AAA-Key transport (phase 1b) may also be bypassed in favor a context transfer (see [IEEE80211f] and [I-D.aboba-802-context]) or it may be provided in a pre-emptive manner as in [IEEE-03-084] and [I-D.irtf-aaaarch-handoff].

As we will discuss, the introduction of fast handoff creates a new class of security vulnerabilities as well as requirements for the secure handling of authorization context.

1.4.1 Correctness in fast handoff

Bypassing all or portions of the AAA conversation creates challenges in ensuring that authorization is properly handled. These include:

- Consistent application of session time limits. A fast handoff should not automatically increase the available session time, allowing a user to endlessly extend their network access by changing the point of attachment.

- Avoidance of privilege elevation. A fast handoff should not result in a user being granted access to services which they are not entitled to.

- o Consideration of dynamic state. In situations in which dynamic state is involved in the access decision (day/time, simultaneous session limit) it should be possible to take this state into account either before or after access is granted. Note that consideration of network-wide state such as simultaneous session limits can typically only be taken into account by the AAA server.

- o Encoding of restrictions. Since a NAS may not be aware of the criteria considered by a AAA server when allowing access, in order to ensure consistent authorization during a fast handoff it may be necessary to explicitly encode the restrictions within the authorizations provided in the AAA-Token.

- o State validity. The introduction of fast handoff should not render the authentication server incapable of keeping track of network-wide state.

A fast handoff mechanism capable of addressing these concerns is said to be "correct". One condition for correctness is as follows:

For a fast handoff to be "correct" it MUST establish on the new device the same context as would have been created had the new device completed a AAA conversation with the authentication server.

A properly designed fast handoff scheme will only succeed if it is "correct" in this way. If a successful fast handoff would establish "incorrect" state, it is preferable for it to fail, in order to avoid creation of incorrect context.

Some AAA server and NAS configurations are incapable of meeting this definition of "correctness". For example, if the old and new device differ in their capabilities, it may be difficult to meet this definition of correctness in a fast handoff mechanism that bypasses AAA. AAA servers often perform conditional evaluation, in which the authorizations returned in an Access-Accept message are contingent on the NAS or on dynamic state such as the time of day or number of simultaneous sessions. For example, in a heterogeneous deployment, the AAA server might return different authorizations depending on the NAS making the request, in order to make sure that the requested service is consistent with the NAS capabilities.

If differences between the new and old device would result in the AAA

server sending a different set of messages to the new device than were sent to the old device, then if the fast handoff mechanism bypasses AAA, then the fast handoff cannot be carried out correctly.

For example, if some NAS devices within a deployment support dynamic VLANs while others do not, then attributes present in the Access-Request (such as the NAS-IP-Address, NAS-Identifier, Vendor-Identifier, etc.) could be examined to determine when VLAN attributes will be returned, as described in [RFC3580]. VLAN support is defined in [IEEE8021Q]. If a fast handoff bypassing the AAA server were to occur between a NAS supporting dynamic VLANs and another NAS which does not, then a guest user with access restricted to a guest VLAN could be given unrestricted access to the network.

Similarly, in a network where access is restricted based on the day and time, SSID, Calling-Station-Id or other factors, unless the restrictions are encoded within the authorizations, or a partial AAA conversation is included, then a fast handoff could result in the user bypassing the restrictions.

In practice, these considerations limit the situations in which fast handoff mechanisms bypassing AAA can be expected to be successful. Where the deployed devices implement the same set of services, it may be possible to do successful fast handoffs within such mechanisms. However, where the supported services differ between devices, the fast handoff may not succeed. For example, [RFC2865], section 1.1

states:

> "A NAS that does not implement a given service MUST NOT implement the RADIUS attributes for that service. For example, a NAS that is unable to offer ARAP service MUST NOT implement the RADIUS attributes for ARAP. A NAS MUST treat a RADIUS access-accept authorizing an unavailable service as an access-reject instead."

Note that this behavior only applies to attributes that are known, but not implemented. For attributes that are unknown, section of 5 of [RFC2865] states:

> "A RADIUS server MAY ignore Attributes with an unknown Type. A RADIUS client MAY ignore Attributes with an unknown Type."

In order to perform a correct fast handoff, if a new device is provided with RADIUS context for a known but unavailable service, then it MUST process this context the same way it would handle a RADIUS Access-Accept requesting an unavailable service. This MUST cause the fast handoff to fail. However, if a new device is provided with RADIUS context that indicates an unknown attribute, then this attribute MAY be ignored.

Although it may seem somewhat counter-intuitive, failure is indeed the "correct" result where a known but unsupported service is requested. Presumably a correctly configured AAA server would not request that a device carry out a service that it does not implement. This implies that if the new device were to complete a AAA conversation that it would be likely to receive different service instructions. In such a case, failure of the fast handoff is the desired result. This will cause the new device to go back to the AAA server in order to receive the appropriate service definition.

In practice, this implies that fast handoff mechanisms which bypass AAA are most likely to be successful within a homogeneous device deployment within a single administrative domain. For example, it would not be advisable to carry out a fast handoff bypassing AAA between a NAS providing confidentiality and another NAS that does not support this service. The correct result of such a fast handoff would be a failure, since if the handoff were blindly carried out, then the user would be moved from a secure to an insecure channel without permission from the AAA server. Thus the definition of a "known but unsupported service" MUST encompass requests for unavailable security services. This includes vendor-specific attributes related to security, such as those described in [RFC2548]."

2. EAP Key Hierarchy

2.1 EAP Invariants

The EAP key management framework assumes that certain basic characteristics, known as the "EAP Invariants" hold true for all implementations of EAP. These include:

Media independence
Method independence
Ciphersuite independence

2.1.1 Media Independence

As described in [I-D.ietf-eap-rfc2284bis], EAP authentication can run over multiple lower layers, including PPP [RFC1661] and IEEE 802 wired networks [IEEE8021X]. Use with IEEE 802.11 wireless LANs is also contemplated [IEEE80211i]. Since EAP methods cannot be assumed to have knowledge of the lower layer over which they are transported, EAP methods can function on any lower layer meeting the criteria outlined in [I-D.ietf-eap-rfc2284bis], Section 3.1. As a result, EAP methods should not utilize identifiers associated with a particular usage environment (e.g. MAC addresses).

2.1.2 Method Independence

Supporting pass-through of authentication to the backend authentication server enables the authenticator to support any authentication method implemented on the backend authentication server and peer, not just locally implemented methods.

This implies that the authenticator need not implement code for each EAP method required by authenticating peers. In fact, the authenticator is not required to implement any EAP methods at all, nor can it be assumed to implement code specific to any EAP method.

This is useful where there is no single EAP method that is both mandatory-to-implement and offers acceptable security for the media in use. For example, the [I-D.ietf-eap-rfc2284bis] mandatory-to-implement EAP method (MD5-Challenge) does not provide dictionary attack resistance, mutual authentication or key derivation, and as a result is not appropriate for use in wireless authentication.

2.1.3 Ciphersuite Independence

While EAP methods may negotiate the ciphersuite used in protection of

the EAP conversation, the ciphersuite used for the protection of data

is negotiated within the secure association protocol, out-of-band of EAP. The backend authentication server is not a party to this negotiation nor is it an intermediary in the data flow between the EAP peer and authenticator. The backend authentication server may not even have knowledge of the ciphersuites implemented by the peer and authenticator, or be aware of the ciphersuite negotiated between them, and therefore does not implement ciphersuite-specific code.

Since ciphersuite negotiation occurs in the secure association protocol, not in EAP, ciphersuite-specific key generation, if implemented within an EAP method, would potentially conflict with the transient session key derivation occurring in the secure association protocol. As a result, EAP methods generate keying material that is ciphersuite-independent. Additional advantages of ciphersuite-independence include:

Update requirements
: If EAP methods were to specify how to derive transient session keys for each ciphersuite, they would need to be updated each time a new ciphersuite is developed. In addition, backend authentication servers might not be usable with all EAP-capable authenticators, since the backend authentication server would also need to be updated each time support for a new ciphersuite is added to the authenticator.

EAP method complexity
: Requiring each EAP method to include ciphersuite-specific code for transient session key derivation would increase the complexity of each EAP method and would result in duplicated effort.

Knowledge of capabilities
: In practice, an EAP method may not have knowledge of the ciphersuite that has been negotiated between the peer and authenticator. In PPP, ciphersuite negotiation occurs in the Encryption Control Protocol (ECP) [RFC1968]. Since ECP negotiation occurs after authentication, unless an EAP method is utilized that supports ciphersuite negotiation, the peer, authenticator and backend authentication server may not be able to anticipate the negotiated ciphersuite and therefore this information cannot be provided to the EAP method. Since ciphersuite negotiation is assumed to occur out-of-band, there is no need for ciphersuite negotiation within EAP.

2.2 Key Hierarchy

The EAP keying hierarchy, illustrated in Figure 2, makes use of the

following types of keys:

EAP Master key (MK)
A key derived between the EAP client and server during the EAP authentication process, and that is kept local to the EAP method and not exported or made available to a third party.

Master Session Key (MSK)
Keying material (at least 64 octets) that is derived between the EAP client and server and exported by the EAP method.

AAA-Key
Where a backend authentication server is present, acting as an EAP server, keying material known as the AAA-Key is transported from the authentication server to the authenticator wrapped within the AAA-Token. The AAA-Key is used by the EAP peer and authenticator in the derivation of Transient Session Keys (TSKs) for the ciphersuite negotiated between the EAP peer and authenticator. As a result, the AAA-Key is typically known by all parties in the EAP exchange: the peer, authenticator and the authentication server (if present). AAA-Key derivation is discussed in Appendix E.

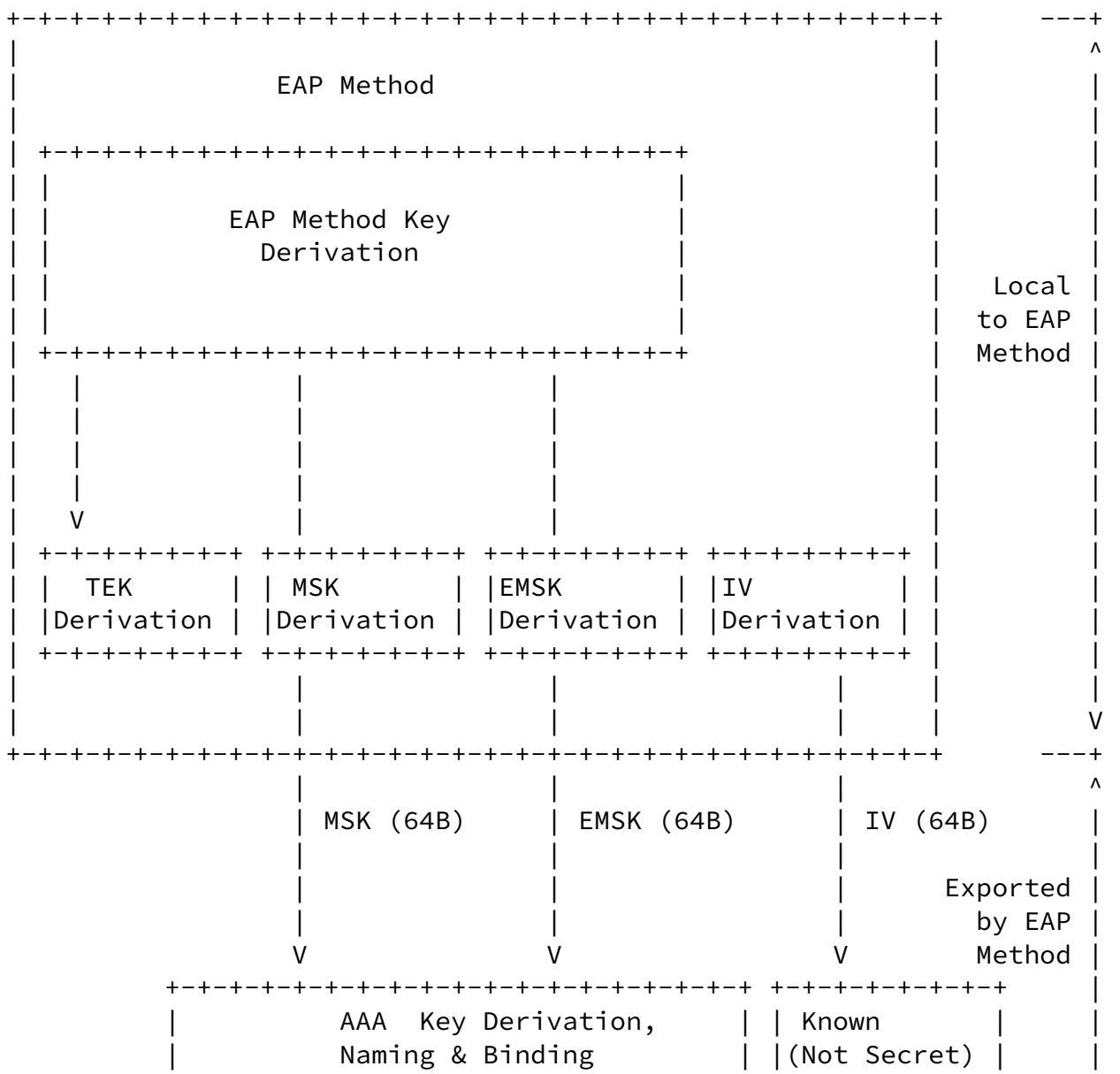
Extended Master Session Key (EMSK)
Additional keying material (64 octets) derived between the EAP client and server that is exported by the EAP method. The EMSK is known only to the EAP peer and server and is not provided to a third party.

Initialization Vector (IV)
A quantity of at least 64 octets, suitable for use in an initialization vector field, that is derived between the EAP client and server. Since the IV is a known value in methods such as EAP-TLS [RFC2716], it cannot be used by itself for computation of any quantity that needs to remain secret. As a result, its use has been deprecated and EAP methods are not required to generate it.

Pairwise Master Key (PMK)
The AAA-Key is divided into two halves, the "Peer to Authenticator Encryption Key" (Enc-RECV-Key) and "Authenticator to Peer Encryption Key" (Enc-SEND-Key) (reception is defined from the point of view of the authenticator). Within [IEEE80211i] Octets 0-31 of the AAA-Key (Enc-RECV-Key) are known as the Pairwise Master Key (PMK). IEEE 802.11i ciphersuites [IEEE80211i] derive their Transient Session Keys (TSKs) solely from the PMK, whereas the WEP ciphersuite, when used with [IEEE8021X], as noted in

[RFC3580], derives its TSKs from both halves of the AAA-Key, the Enc-RECV-Key and the Enc-SEND-Key.

Transient EAP Keys (TEKs)
: Session keys which are used to establish a protected channel between the EAP peer and server during the EAP authentication exchange. The TEKs are appropriate for use with the ciphersuite negotiated between EAP peer and server for use in protecting the EAP conversation. Note that the ciphersuite used to set up the protected channel between the EAP peer and server during EAP authentication is unrelated to the ciphersuite used to subsequently protect data sent between the EAP peer and authenticator. An example TEK key hierarchy is described in Appendix C.


EAP Method
EAP Method Key Derivation
Local to EAP Method
TEK Derivation
MSK Derivation
EMSK Derivation
IV Derivation
MSK (64B)
EMSK (64B)
IV (64B)
Exported by EAP Method
AAA Key Derivation, Naming & Binding
Known (Not Secret)

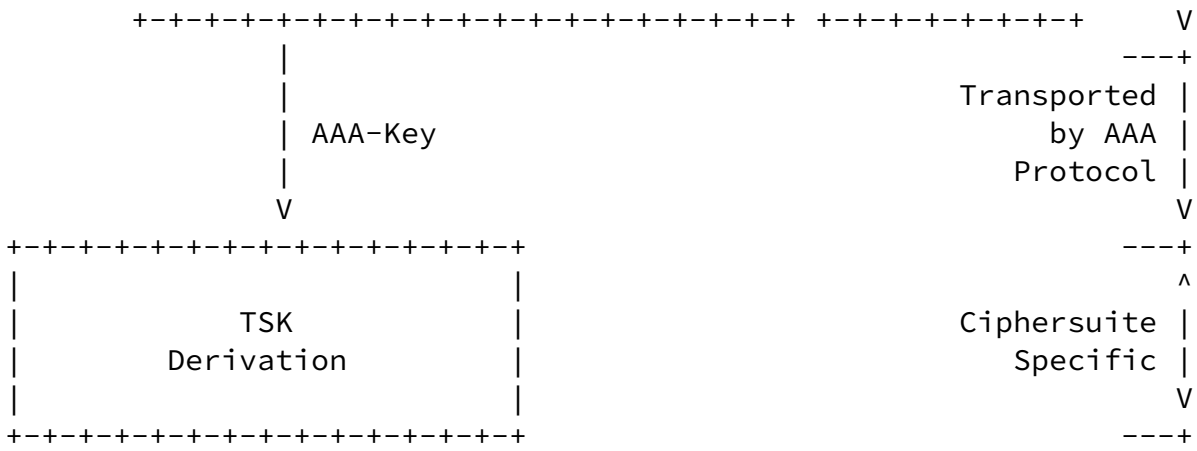


Figure 2: EAP Key Hierarchy

Transient Session Keys (TSKs)
Session keys used to protect data which are appropriate for the ciphersuite negotiated between the EAP peer and authenticator. The TSKs are derived from the keying material included in the AAA-Token via the secure association protocol. In the case of IEEE 802.11, the role of the secure association protocol is handled by the 4-way handshake and group key derivation. An example TSK derivation is provided in Appendix D.

2.3 Exchanges

EAP supports both a two party exchange between an EAP peer and an authenticator, as well as a three party exchange between an EAP peer, an authenticator and an EAP server.

Figure 3 illustrates the two party exchange. Here EAP is spoken between the peer and authenticator, encapsulated within a lower layer protocol, such as PPP, defined in [RFC1661] or IEEE 802, defined in [IEEE802].

Since the authenticator acts as an endpoint of the EAP conversation rather than a pass-through, EAP methods are implemented on the authenticator as well as the peer. If the EAP method negotiated between the EAP peer and authenticator supports mutual authentication

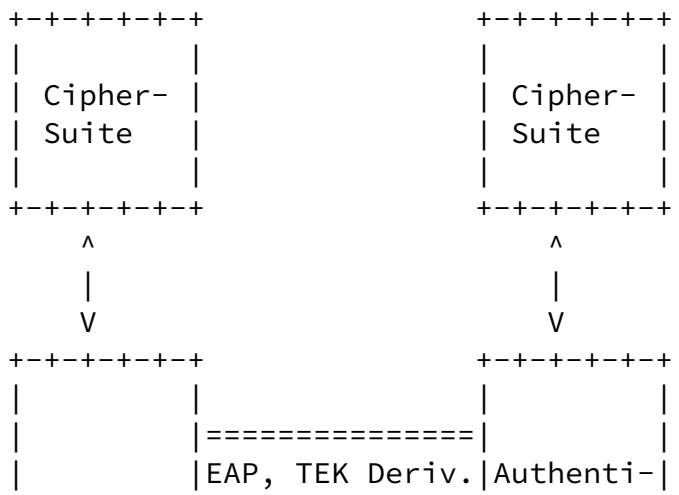
and key derivation, the EAP Master Session Key (MSK) and Extended Master Session Key (EMSK) are derived on the EAP peer and authenticator and exported by the EAP method.

Where no backend authentication server is present, the MSK and EMSK are known only to the peer and authenticator and neither is transported to a third party. As demonstrated in [I-D.ietf-roamops-cert], despite the absence of a backend authentication server, such exchanges can support roaming between providers; it is even possible to support fast handoff without re-authentication. However, this is typically only possible where both the EAP peer and authenticator support certificate-based authentication, or where the user base is sufficiently small that EAP authentication can occur locally.

In order to protect the EAP conversation, the EAP method may negotiate a ciphersuite and derive Transient EAP Keys (TEKs) to provide keys for that ciphersuite in order to protect some or all of the EAP exchange. The TEKs are stored locally within the EAP method and are not exported.

Once EAP mutual authentication completes and is successful, the secure association protocol is run between the peer and

authenticator. This derives fresh transient session keys (TSKs), provides for the secure negotiation of the ciphersuite used to protect data, and supports mutual proof of possession of the AAA-Key.



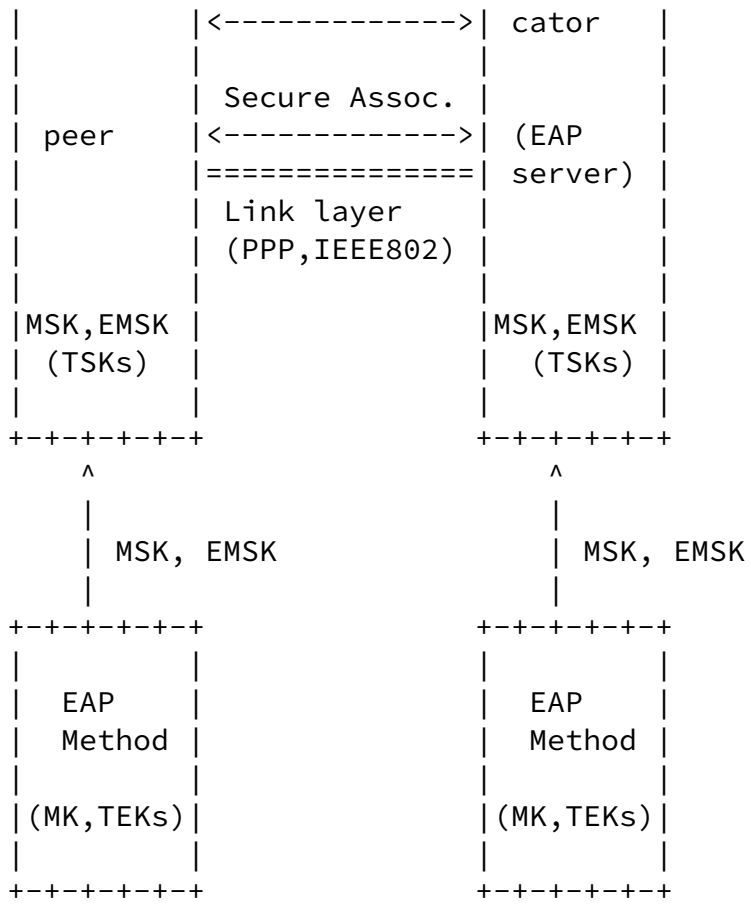
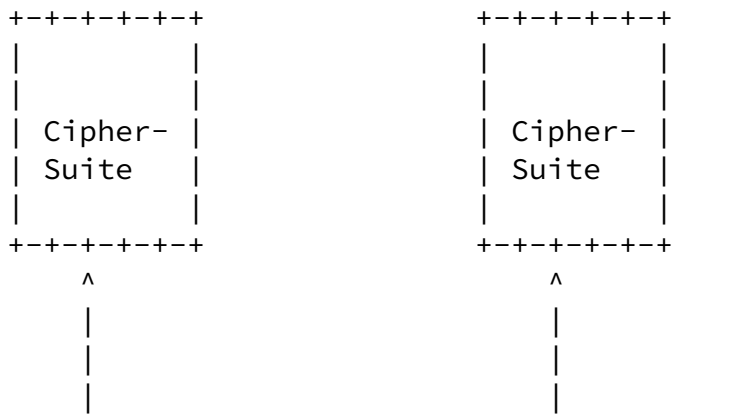


Figure 3: Relationship between EAP peer and authenticator (acting as an EAP server), where no backend authentication server is present.



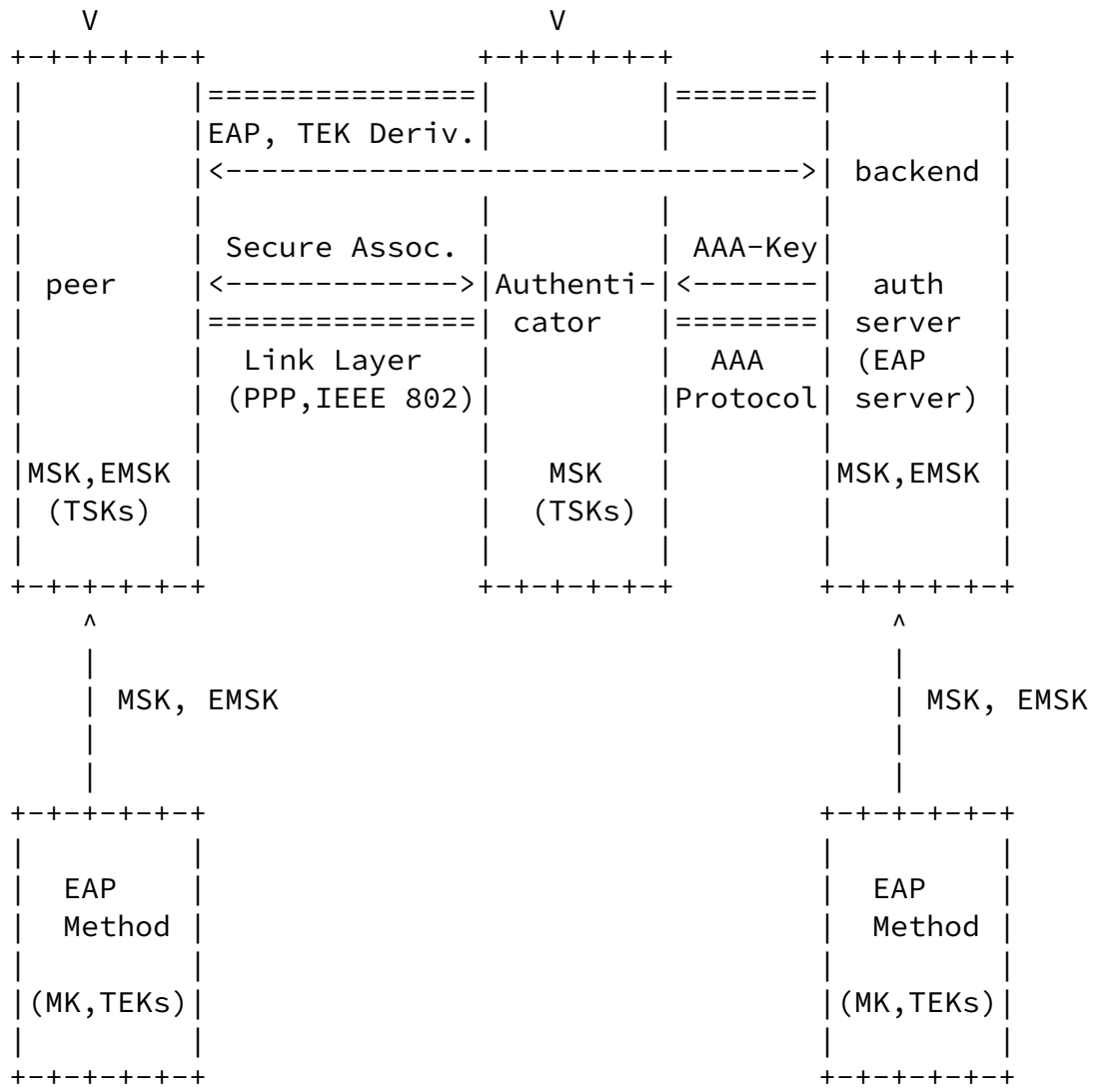


Figure 4: Pass-through relationship between EAP peer, authenticator and backend authentication server.

Where these conditions cannot be met, a backend authentication server is typically required. In this exchange, as described in [RFC3579], the authenticator acts as a pass-through between the EAP peer and a backend authentication server. In this model, the authenticator

delegates the access control decision to the backend authentication server, which acts as a Key Distribution Center (KDC), supplying keying material to both the EAP peer and authenticator.

Figure 4 illustrates the case where the authenticator acts as a pass-through. Here EAP is spoken between the peer and authenticator as before. The authenticator then encapsulates EAP packets within a AAA protocol such as RADIUS [RFC3579] or Diameter [I-D.ietf-aaa-eap], and forwards packets to and from the backend authentication server, which acts as the EAP server. Since the authenticator acts as a pass-through, EAP methods (as well as the derived EAP Master Key, and TEKs) reside only on the peer and backend authentication server.

On completion of a successful authentication, EAP methods on the EAP peer and EAP server export the Master Session Key (MSK) and Extended Master Session Key (EMSK). The backend authentication server then sends a message to the authenticator indicating that authentication has been successful, providing the AAA-Key within a protected package known as the AAA-Token. Along with the keying material, the AAA-Token contains attributes naming the enclosed keys and providing context.

The MSK and EMSK are used to derive the AAA-Key and key name which are enclosed within the AAA-Token, transported to the NAS by the AAA server, and used within the secure association protocol for derivation of Transient Session Keys (TSKs) required for the negotiated ciphersuite. The TSKs are known only to the peer and authenticator.

3. Security Associations

EAP key management involves four types of security associations (SAs):

[1] EAP SA. This is an SA between the peer and EAP server, which allows them to authenticate each other.

[2] EAP method SA. This SA is also between the peer and EAP server. It stores state that can be used for "fast resume" or other functionality in some EAP methods. Not all EAP methods create such an SA.

[3] EAP-Key SA. This is an SA between the peer and EAP server, which is used to store the keying material exported by the EAP method. Current EAP server implementations do not retain this SA after the EAP conversation completes, but future implementations could use this SA for pre-emptive key distribution.

[4] AAA SA(s). These SAs are between the authenticator and the backend authentication server. They permit the parties to mutually authenticate each other and protect the communications between them.

3.1 EAP SA (peer - EAP server)

In order for the peer and EAP server to authenticate each other, they need to store some information.

The authentication can be based on different mechanisms, such as shared secrets or certificates. If the authentication is based on a shared secret key, the parties store the EAP method to be used and the key. The EAP server also stores the peer's identity and/or other information necessary to decide whether access to some service should be granted. The peer stores information necessary to choose which secret to use for which service.

3.2 EAP method SA (peer - EAP server)

An EAP method may store some state on the peer and EAP server even after phase 1a has completed.

Typically, this is used for "fast resume": the peer and EAP server can confirm that they are still talking to the same party, perhaps using fewer roundtrips or less computational power. In this case, the EAP method SA is essentially a cache for performance optimization, and either party may remove the SA from its cache at any point.

An EAP method may also keep state in order to support pseudonym-based identity protection. This is typically a cache as well (the information can be recreated if the original EAP method SA is lost), but may be stored for longer periods of time.

The EAP method SA is not restricted to a particular service or authenticator and is most useful when the peer accesses many different authenticators.

An EAP method is responsible for specifying how the parties select if an existing EAP method SA should be used, and if so, which one. Where multiple backend authentication servers are used, EAP method SAs are not typically synchronized between them.

EAP method implementations should consider the appropriate lifetime for the EAP method SA. "Fast resume" assumes that the information

required (primarily the keys in the EAP method SA) hasn't been

compromised. In case the original authentication was carried out using, for instance, a smart card, it may be easier to compromise the EAP method SA (stored on the PC, for instance), so typically the EAP method SAs have a limited lifetime.

Contents:
- Implicitly, the EAP method this SA refers to
- One or more internal (non-exported) keys
- EAP method SA name
- SA lifetime

3.2.1 Example: EAP-TLS

In EAP-TLS [RFC2716], after the EAP authentication the client (peer) and server can store the following information:

- Implicitly, the EAP method this SA refers to (EAP-TLS)
- Session identifier (a value selected by the server)
- Certificate of the other party (server stores the clients's certificate and vice versa)
- Ciphersuite and compression method
- TLS Master secret (known as the EAP-TLS Master Key or MK)
- SA lifetime (ensuring that the SA is not stored forever)
- If the client has multiple different credentials (certificates and corresponding private keys), a pointer to those credentials

When the server initiates EAP-TLS, the client can look up the EAP-TLS SA based on the credentials it was going to use (certificate and private key), and the expected credentials (certificate or name) of the server. If an EAP-TLS SA exists, and it is not too old, the client informs the server about the existence of this SA by including its Session-Id in the TLS ClientHello message. The server then looks up the correct SA based on the Session-Id (or detects that it doesn't yet have one).

3.2.2 Example: EAP-AKA

In EAP-AKA [I-D.arkko-pppext-eap-aka], after EAP authentication the client and server can store the following information:

- Implicitly, the EAP method this SA refers to (EAP-AKA)
- A re-authentication pseudonym
- The client's permanent identity (IMSI) (server)
- Replay protection counter
- Authentication key (K_aut)
- Encryption key (K_encr)
- Original Master Key (MK)

- SA lifetime (ensuring that the SA is not stored forever)

When the server initiates EAP-AKA, the client can look up the EAP-AKA SA based on the credentials it was going to use (permanent identity). If an EAP-AKA SA exists, and it is not too old, the client informs the server about the existence of this SA by sending its re-authentication pseudonym as its identity in EAP Identity Response message, instead of its permanent identity. The server then looks up the correct SA based on this identity.

3.3 EAP-key SA

This is an SA between the peer and EAP server, which is used to store the keying material exported by the EAP method. Current EAP server implementations do not retain this SA after the EAP conversation completes, but future implementations could use this SA for pre-emptive key distribution.

Contents:
- Name/identifier for this SA
- Identities of the parties
- MSK and EMSK

3.4 AAA SA(s) (authenticator - backend auth. server)

In order for the authenticator and backend authentication server to authenticate each other, they need to store some information.

In case the authenticator and backend authentication server are colocated, and they communicate using local procedure calls or shared memory, this SA need not necessarily contain any information.

3.4.1 Example: RADIUS

In RADIUS, where shared secret authentication is used, the client and server store each other's IP address and the shared secret, which is used to calculate the Response Authenticator [RFC2865] and Message-Authenticator [RFC3579] values, and to encrypt some attributes (such as the AAA-Key [RFC2548]).

Where IPsec is used to protect RADIUS [RFC3579] and IKE is used for key management, the parties store information necessary to authenticate and authorize the other party (e.g. certificates, trust anchors and names). The IKE exchange results in IKE Phase 1 and Phase 2 SAs containing information used to protect the conversation (session keys, selected ciphersuite, etc.)

3.4.2 Example: Diameter with TLS

When using Diameter protected by TLS, the parties store information necessary to authenticate and authorize the other party (e.g. certificates, trust anchors and names). The TLS handshake results in a short-term TLS SA that contains information used to protect the actual communications (session keys, selected TLS ciphersuite, etc.).

3.5 Unicast Secure Association SA

The unicast secure association SA exists between the EAP peer and authenticator. It includes:

- the peer port identifier (Calling-Station-Id)
- the NAS port identifier (Called-Station-Id)
- the unicast Transient Session Keys (TSKs)
- the unicast secure association peer nonce
- the unicast secure association authenticator nonce
- the negotiated unicast capabilities and unicast ciphersuite.

During the phase 2a exchange, the EAP peer and authenticator demonstrate mutual possession of the AAA-Key derived and transported in phase 1; securely negotiate the session capabilities (including unicast ciphersuites), and derive fresh unicast transient session keys. The AAA-Key SA (phase 1b) is therefore used to create the unicast secure association SA (phase 2a), and in the process the

phase 2a unicast secure association SA is bound to ports on the EAP peer and authenticator. However in order for a phase 2a security association to be established, it is not necessary for the phase 1a exchange to be rerun each time. This enables the EAP exchange to be bypassed when fast handoff support is desired.

Since both peer and authenticator nonces are used in the creation of the unicast secure association SA, the transient session keys (TSKs) are guaranteed to be fresh, even if the AAA-Key is not. As a result one or more unicast secure association SAs (phase 2a) may be derived from a single AAA-Key SA (phase 1b). The phase 2a security associations may utilize the same security parameters (e.g. mode, ciphersuite, etc.) or they may utilize different parameters.

A unicast secure association SA (phase 2a) may not persist longer than the maximum lifetime of its parent AAA-Key SA (if known). However, the deletion of a parent EAP or AAA-Key SA does not necessarily imply deletion of the corresponding unicast secure association SA. Similarly, the deletion of a unicast secure association protocol SA does not imply the deletion of the parent AAA-key SA or EAP SA. Failure to mutually prove possession of the AAA-Key during the unicast secure association protocol exchange

(phase 2a) need not be grounds for removal of a AAA-Key SA by both parties; rate-limiting unicast secure association exchanges should suffice to prevent a brute force attack.

An EAP peer may be able to negotiate multiple phase 2a SAs with a single EAP authenticator, or may be able to maintain multiple phase 2a SAs with multiple authenticators, based on a single EAP SA derived in phase 1a. For example, during a re-key of the secure association protocol SA, it is possible for two phase 2a SAs to exist during the period between when the new phase 2a SA parameters (such as the TSKs) are calculated and when they are installed. Except where explicitly specified by the semantics of the unicast secure association protocol, it should not be assumed that the installation of a new phase 2a SA necessarily implies deletion of the old phase 2a SA.

On some media (e.g. 802.11) a port on an EAP peer may only establish phase 2a and 2b SAs with a single port of an authenticator within a given Local Area Network (LAN). This implies that the successful negotiation of phase 2a and/or 2b SAs between an EAP peer port and a

new authentiator port within a given LAN implies the deletion of existing phase 2a and 2b SAs with authenticators offering access to that Local Area Network (LAN). However, since a given IEEE 802.11 SSID may be comprised of multiple LANs, this does not imply an implicit binding of phase 2a and 2b SAs to an SSID.

3.6 Multicast Secure Association SA

The multicast secure association SA includes:

the multicast Transient Session Keys
the direction vector (for a uni-directional SA)
the negotiated multicast capabilities and multicast ciphersuite

It is possible for more than one multicast secure association SA to be derived from a single unicast secure association SA. However, a multicast secure association SA is bound to a single EAP SA and a single AAA-Key SA.

During a re-key of the multicast secure association protocol SA, it is possible for two phase 2b SAs to exist during the period between when the new phase 2b SA parameters (such as the multicast TSKs) are calculated and when they are installed. Except where explicitly specified by the semantics of the multicast secure association protocol, it should not be assumed that the installation of a new phase 2b SA necessarily implies deletion of the old phase 2b SA.

A multicast secure association SA (phase 2b) may not persist longer than the maximum lifetime of its parent AAA-Key or unicast secure

association SA. However, the deletion of a parent EAP, AAA-Key or unicast secure association SA does not necessarily imply deletion of the corresponding multicast secure association SA. For example, a unicast secure association SA may be rekeyed without implying a rekey of the multicast secure association SA.

Similarly, the deletion of a multicast secure association protocol SA does not imply the deletion of the parent EAP, AAA-Key or unicast secure association SA. Failure to mutually prove possession of the AAA-Key during the unicast secure association protocol exchange (phase 2a) need not be grounds for removal of the AAA-Key, unicast secure association and multicast secure association SAs;

rate-limiting unicast secure association exchanges should suffice to prevent a brute force attack.

3.7 Key Naming

In order to support the correct processing of phase 2 security associations, the secure association (phase 2) protocol supports the naming of phase 2 security associations and associated transient session keys, so that the correct set of transient session keys can be identified for processing a given packet. Explicit creation and deletion operations are also typically supported so that establishment and re-establishment of transient session keys can be synchronized between the parties.

In order to securely bind the AAA SA (phase 1b) to its child phase 2 security associations, the phase 2 secure association protocol allows the EAP peer and authenticator to mutually prove possession of the AAA-Key. In order to avoid confusion in the case where an EAP peer has more than one AAA-Key (phase 1b) applicable to establishment of a phase 2 security association, it is necessary for the secure association protocol (phase 2) to support key selection, so that the appropriate phase 1b keying material can be utilized by both parties in the secure association protocol exchange.

For example, a peer might be pre-configured with policy indicating the ciphersuite to be used in communicating with a given authenticator. Within PPP, the ciphersuite is negotiated within the Encryption Control Protocol (ECP), after EAP authentication is completed. Within [IEEE80211i], the AP ciphersuites are advertised in the Beacon and Probe Responses, and are securely verified during a 4-way exchange after EAP authentication has completed.

As part of the secure association protocol (phase 2), it is necessary to bind the Transient Session Keys (TSKs) to the keying material provided in the AAA-Token. This ensures that the EAP peer and authenticator are both clear about what key to use to provide mutual

proof of possession. Keys within the EAP key hierarchy are named as follows:

EAP SA name
The EAP security association is negotiated between the EAP peer

and EAP server, and is uniquely named as follows <EAP peer name, EAP server name, EAP Method Type, EAP peer nonce, EAP server nonce>. Here the EAP peer name and EAP server name are the identifiers securely exchanged within the EAP method. Since multiple EAP SAs may exist between an EAP peer and EAP server, the EAP peer nonce and EAP server nonce allow EAP SAs to be differentiated. The inclusion of the Method Type in the EAP SA name ensures that each EAP method has a distinct EAP SA space.

MK Name
The EAP Master Key, if supported by an EAP method, is named by the concatenation of the EAP SA name and a method-specific session-id.

AAA-Key Name
The AAA-Key is named by the concatenation of the EAP SA name, "AAA-Key" and the authenticator name, since the AAA-Key is bound to a particular authenticator. For the purpose of identification, the NAS-Identifier attribute is recommended. In order to ensure that all parties can agree on the NAS name this requires the NAS to advertise its name (typically using a media-specific mechanism, such as the 802.11 Beacon/Probe Response)."

4. Threat Model

4.1 Security Assumptions

Figure 5 illustrates the relationship between the peer, authenticator and backend authentication server. As noted in the figure, each party in the exchange mutually authenticates with each of the other parties, and derives a unique key. All parties in the diagram have access to the AAA-Key.

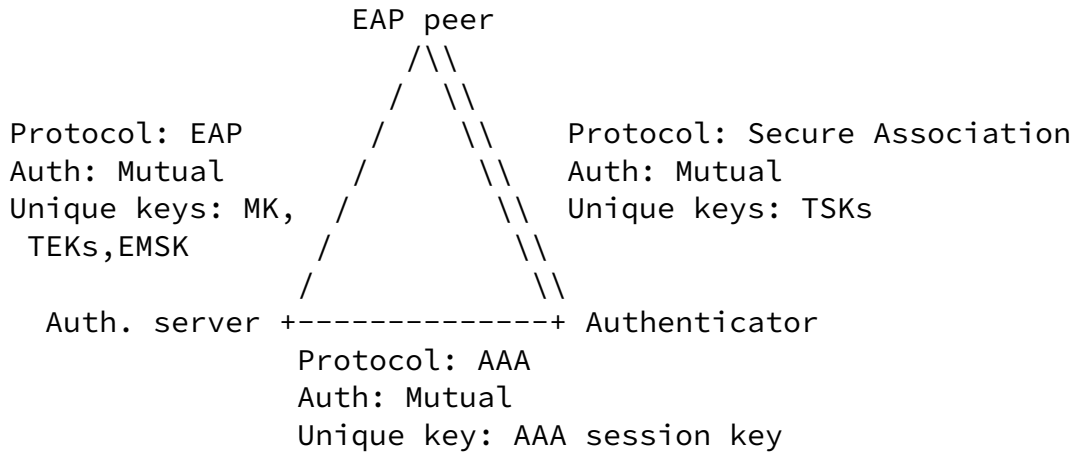


Figure 5: Three-party EAP key distribution

The EAP peer and backend authentication server mutually authenticate via the EAP method, and derive the MK, TEKs and EMSK which are known only to them. The TEKs are used to protect some or all of the EAP conversation between the peer and authenticator, so as to guard against modification or insertion of EAP packets by an attacker. The degree of protection afforded by the TEKs is determined by the EAP method; some methods may protect the entire EAP packet, including the EAP header, while other methods may only protect the contents of the Type-Data field, defined in [I-D.ietf-eap-rfc2284bis].

Since EAP is spoken only between the EAP peer and server, if a backend authentication server is present then the EAP conversation does not provide mutual authentication between the peer and authenticator, only between the EAP peer and EAP server (backend authentication server). As a result, mutual authentication between the peer and authenticator only occurs where a secure association protocol is used, such the unicast and group key derivation handshake supported in [IEEE80211i]. This means that absent use of a secure association protocol, from the point of view of the peer, EAP mutual authentication only proves that the authenticator is trusted by the backend authentication server; the identity of the authenticator is not confirmed.

Utilizing the AAA protocol, the authenticator and backend authentication server mutually authenticate and derive session keys known only to them, used to provide per-packet integrity and replay protection, authentication and confidentiality. The MSK is distributed by the backend authentication server to the authenticator over this channel, bound to attributes constraining its usage, as part of the AAA-Token. The binding of attributes to the MSK within a protected package is important so the authenticator receiving the AAA-Token can determine that it has not been compromised, and that the keying material has not been replayed, or mis-directed in some

way.

The security properties of the EAP exchange are dependent on each leg of the triangle: the selected EAP method, AAA protocol and the secure association protocol.

Assuming that the AAA protocol provides protection against rogue authenticators forging their identity, then the AAA-Token can be assumed to be sent to the correct authenticator, and where it is wrapped appropriately, it can be assumed to be immune to compromise by a snooping attacker.

Where an untrusted AAA intermediary is present, the AAA-Token must not be provided to the intermediary so as to avoid compromise of the AAA-Token. This can be avoided by use of re-direct as defined in [RFC3588].

When EAP is used for authentication on PPP or wired IEEE 802 networks, it is typically assumed that the link is physically secure, so that an attacker cannot gain access to the link, or insert a rogue device. EAP methods defined in [I-D.ietf-eap-rfc2284bis] reflect this usage model. These include EAP MD5, as well as One-Time Password (OTP) and Generic Token Card. These methods support one-way authentication (from EAP peer to authenticator) but not mutual authentication or key derivation. As a result, these methods do not bind the initial authentication and subsequent data traffic, even when the the ciphersuite used to protect data supports per-packet authentication and integrity protection. As a result, EAP methods not supporting mutual authentication are vulnerable to session hijacking as well as attacks by rogue devices.

On wireless networks such as IEEE 802.11 [IEEE80211], these attacks become easy to mount, since any attacker within range can access the wireless medium, or act as an access point. As a result, new ciphersuites have been proposed for use with wireless LANs [IEEE80211i] which provide per-packet authentication, integrity and replay protection. In addition, mutual authentication and key derivation, provided by methods such as EAP-TLS [RFC2716] are required [IEEE80211i], so as to address the threat of rogue devices, and provide keying material to bind the initial authentication to subsequent data traffic.

If the selected EAP method does not support mutual authentication, then the peer will be vulnerable to attack by rogue authenticators and backend authentication servers. If the EAP method does not derive keys, then TSKs will not be available for use with a negotiated ciphersuite, and there will be no binding between the initial EAP authentication and subsequent data traffic, leaving the session

vulnerable to hijack.

If the backend authentication server does not protect against authenticator masquerade, or provide the proper binding of the AAA-Key to the session within the AAA-Token, then one or more AAA-Keys may be sent to an unauthorized party, and an attacker may be able to gain access to the network. If the AAA-Token is provided to an untrusted AAA intermediary, then that intermediary may be able to modify the AAA-Key, or the attributes associated with it, as described in [RFC2607].

If the secure association protocol does not provide mutual proof of possession of the AAA-Key material, then the peer will not have assurance that it is connected to the correct authenticator, only that the authenticator and backend authentication server share a trust relationship (since AAA protocols support mutual authentication). This distinction can become important when multiple authenticators receive AAA-Keys from the backend authentication server, such as where fast handoff is supported. If the TSK derivation does not provide for protected ciphersuite and capabilities negotiation, then downgrade attacks are possible.

4.2 Security Requirements

This section describes the security requirements for EAP methods, AAA protocols, secure association protocols and Ciphersuites. These requirements MUST be met by specifications requesting publication as an RFC. Based on these requirements, the security properties of EAP exchanges are analyzed.

4.2.1 EAP method requirements

It is possible for the peer and EAP server to mutually authenticate and derive keys. In order to provide keying material for use in a subsequently negotiated ciphersuite, an EAP method supporting key

derivation MUST export a Master Session Key (MSK) of at least 64 octets, and an Extended Master Session Key (EMSK) of at least 64 octets. EAP Methods deriving keys MUST provide for mutual authentication between the EAP peer and the EAP Server.

The MSK and EMSK MUST NOT be used directly to protect data; however, they are of sufficient size to enable derivation of a AAA-Key subsequently used to derive Transient Session Keys (TSKs) for use with the selected ciphersuite. Each ciphersuite is responsible for specifying how to derive the TSKs from the AAA-Key.

The AAA-Key is derived from the keying material exported by the EAP method (MSK and EMSK). This derivation occurs on the AAA server. In

many existing protocols that use EAP, the AAA-Key and MSK are equivalent, but more complicated mechanisms are possible (see Appendix E for details).

EAP methods SHOULD ensure the freshness of the MSK and EMSK even in cases where one party may not have a high quality random number generator. A RECOMMENDED method is for each party to provide a nonce of at least 128 bits, used in the derivation of the MSK and EMSK.

EAP methods export the MSK and EMSK and not Transient Session Keys so as to allow EAP methods to be ciphersuite and media independent. Keying material exported by EAP methods MUST be independent of the ciphersuite negotiated to protect data.

Depending on the lower layer, EAP methods may run before or after ciphersuite negotiation, so that the selected ciphersuite may not be known to the EAP method. By providing keying material usable with any ciphersuite, EAP methods can used with a wide range of ciphersuites and media.

It is RECOMMENDED that methods providing integrity protection of EAP packets include coverage of all the EAP header fields, including the Code, Identifier, Length, Type and Type-Data fields.

In order to preserve algorithm independence, EAP methods deriving keys SHOULD support (and document) the protected negotiation of the ciphersuite used to protect the EAP conversation between the peer and server. This is distinct from the ciphersuite negotiated between the

peer and authenticator, used to protect data.

The strength of Transient Session Keys (TSKs) used to protect data is ultimately dependent on the strength of keys generated by the EAP method. If an EAP method cannot produce keying material of sufficient strength, then the TSKs may be subject to brute force attack. In order to enable deployments requiring strong keys, EAP methods supporting key derivation SHOULD be capable of generating an MSK and EMSK, each with an effective key strength of at least 128 bits.

Methods supporting key derivation MUST demonstrate cryptographic separation between the MSK and EMSK branches of the EAP key hierarchy. Without violating a fundamental cryptographic assumption (such as the non-invertibility of a one-way function) an attacker recovering the MSK or EMSK MUST NOT be able to recover the other quantity with a level of effort less than brute force.

Non-overlapping substrings of the MSK MUST be cryptographically separate from each other. That is, knowledge of one substring MUST

NOT help in recovering some other substring without breaking some hard cryptographic assumption. This is required because some existing ciphersuites form TSKs by simply splitting the AAA-Key to pieces of appropriate length. Likewise, non-overlapping substrings of the EMSK MUST be cryptographically separate from each other, and from substrings of the MSK.

The EMSK MUST remain on the EAP peer and EAP server where it is derived; it MUST NOT be transported to, or shared with, additional parties, or used to derive any other keys.

Since EAP does not provide for explicit key lifetime negotiation, EAP peers, authenticators and authentication servers MUST be prepared for situations in which one of the parties discards key state which remains valid on another party.

The development and validation of key derivation algorithms is difficult, and as a result EAP methods SHOULD reuse well established and analyzed mechanisms for key derivation (such as those specified in IKE [RFC2409] or TLS [RFC2246]), rather than inventing new ones. EAP methods SHOULD also utilize well established and analyzed

mechanisms for MSK and EMSK derivation.

4.2.2 AAA Protocol Requirements

AAA protocols suitable for use in transporting EAP MUST provide the following facilities:

Security services
: AAA protocols used for transport of EAP keying material MUST implement and SHOULD use per-packet integrity and authentication, replay protection and confidentiality. These requirements are met by Diameter EAP [I-D.ietf-aaa-eap], as well as RADIUS over IPsec [RFC3579].

Session Keys
: AAA protocols used for transport of EAP keying material MUST implement and SHOULD use dynamic key management in order to derive fresh session keys, as in Diameter EAP [I-D.ietf-aaa-eap] and RADIUS over IPsec [RFC3579], rather than using a static key, as originally defined in RADIUS [RFC2865].

Mutual authentication
: AAA protocols used for transport of EAP keying material MUST provide for mutual authentication between the authenticator and backend authentication server. These requirements are met by Diameter EAP [I-D.ietf-aaa-eap] as well as by RADIUS EAP [RFC3579].

Authorization
: AAA protocols used for transport of EAP keying material SHOULD provide protection against rogue authenticators masquerading as other authenticators. This can be accomplished, for example, by requiring that AAA agents check the source address of packets against the origin attributes (Origin-Host AVP in Diameter, NAS-IP-Address, NAS-IPv6-Address, NAS-Identifier in RADIUS). For details, see Section 4.3.7 of [RFC3579].

Key transport
: Since EAP methods do not export Transient Session Keys (TSKs) in order to maintain media and ciphersuite independence, the AAA server MUST NOT transport TSKs from the backend authentication server to authenticator.

Key transport specification
: In order to enable backend authentication servers to provide keying material to the authenticator in a well defined format, AAA protocols suitable for use with EAP MUST define the format and wrapping of the AAA-Token.

EMSK transport
: Since the EMSK is a secret known only to the backend authentication server and peer, the AAA-Token MUST NOT transport the EMSK from the backend authentication server to the authenticator.

AAA-Token protection
: To ensure against compromise, the AAA-Token MUST be integrity protected, authenticated, replay protected and encrypted in transit, using well-established cryptographic algorithms.

Session Keys
: The AAA-Token SHOULD be protected with session keys as in Diameter [RFC3588] or RADIUS over IPsec [RFC3579] rather than static keys, as in [RFC2548].

Key naming
: In order to ensure against confusion between the appropriate keying material to be used in a given secure association protocol exchange, the AAA-Token SHOULD include explicit key names and context appropriate for informing the authenticator how the keying material is to be used.

Key Compromise
: Where untrusted intermediaries are present, the AAA-Token SHOULD NOT be provided to the intermediaries. In Diameter, handling of keys by intermediaries can be avoided using Redirect functionality

[RFC3588].

4.2.3 Secure Association Protocol Requirements

The Secure Association Protocol supports the following:

Mutual proof of possession
: The peer and authenticator MUST each demonstrate possession of the keying material transported between the AAA server and authenticator (AAA-Key).

Key Naming
: The Secure Association Protocol MUST explicitly name the keys used in the proof of possession exchange, so as to prevent confusion when more than one set of keying material could potentially be used as the basis for the exchange.

Creation and Deletion
: In order to support the correct processing of phase 2 security associations, the secure association (phase 2) protocol MUST support the naming of phase 2 security associations and associated transient session keys, so that the correct set of transient session keys can be identified for processing a given packet. The phase 2 secure association protocol also MUST support transient session key activation and SHOULD support deletion, so that establishment and re-establishment of transient session keys can be synchronized between the parties.

Integrity and Replay Protection
: The Secure Association Protocol MUST support integrity and replay protection of all messages.

Direct operation
: Since the phase 2 secure association protocol is concerned with the establishment of security associations between the EAP peer and authenticator, including the derivation of transient session keys, only those parties have "a need to know" the transient session keys. The secure association protocol MUST operate directly between the peer and authenticator, and MUST NOT be passed-through to the backend authentication server, or include additional parties.

Derivation of transient session keys
: The secure association protocol negotiation MUST support derivation of unicast and multicast transient session keys suitable for use with the negotiated ciphersuite.

TSK freshness
: The secure association (phase 2) protocol MUST support the derivation of fresh unicast and multicast transient session keys, even when the keying material provided by the AAA server is not fresh. This is typically supported by including an exchange of nonces within the secure association protocol.

Bi-directional operation
: While some ciphersuites only require a single set of transient session keys to protect traffic in both directions, other ciphersuites require a unique set of transient session keys in each direction. The phase 2 secure association protocol SHOULD provide for the derivation of unicast and multicast keys in each direction, so as not to require two separate phase 2 exchanges in order to create a bi-directional phase 2 security association.

Secure capabilities negotiation
: The Secure Association Protocol MUST support secure capabilities negotiation. This includes security parameters such as the security association identifier (SAID) and ciphersuites. It also includes confirmation of the capabilities discovered during the discovery phase (phase 0), so as to ensure that the announced capabilities have not been forged.

4.2.4 Ciphersuite Requirements

Ciphersuites suitable for keying by EAP methods MUST provide the following facilities:

TSK derivation
: In order to allow a ciphersuite to be usable within the EAP keying framework, a specification MUST be provided describing how transient session keys suitable for use with the ciphersuite are derived from the AAA-Key.

EAP method independence
: Algorithms for deriving transient session keys from the AAA-Key MUST NOT depend on the EAP method. However, algorithms for deriving TEKs MAY be specific to the EAP method.

Cryptographic separation
: The TSKs derived from the AAA-Key MUST be cryptographically separate from each other. Similarly, TEKs MUST be cryptographically separate from each other. In addition, the TSKs MUST be cryptographically separate from the TEKs.

5. IANA Considerations

This specification does not create any new registries, or define any new EAP codes or types.

6. Security Considerations

6.1 Key Strength

In order to guard against brute force attacks, EAP methods deriving keys need to be capable of generating keys with an appropriate effective symmetric key strength. In order to ensure that key generation is not the weakest link, it is necessary for EAP methods utilizing public key cryptography to choose a public key that has a cryptographic strength meeting the symmetric key strength requirement.

As noted in Section 5 of [I-D.orman-public-key-lengths], this results in the following required RSA or DH module and DSA subgroup size in bits, for a given level of attack resistance in bits:

Attack Resistance (bits)	RSA or DH Modulus size (bits)	DSA subgroup size (bits)
70	947	128
80	1228	145
90	1553	153
100	1926	184
150	4575	279
200	8719	373
250	14596	475

6.2 Key Wrap

As described in [RFC3579], Section 4.3, known problems exist in the key wrap specified in [RFC2548]. Where the same RADIUS shared secret is used by a PAP authenticator and an EAP authenticator, there is a vulnerability to known plaintext attack. Since RADIUS uses the shared secret for multiple purposes, including per-packet authentication, attribute hiding, considerable information is exposed about the shared secret with each packet. This exposes the shared

secret to dictionary attacks. MD5 is used both to compute the RADIUS Response Authenticator and the Message-Authenticator attribute, and some concerns exist relating to the security of this hash [MD5Attack]. As discussed in [RFC3579], Section 4.2, these and other RADIUS vulnerabilities may be addressed by running RADIUS over IPsec.

Where an untrusted AAA intermediary is present (such as a RADIUS proxy or a Diameter agent), and data object security is not used, the AAA-Key may be recovered by an attacker in control of the untrusted intermediary. Possession of the AAA-Key enables decryption of data traffic sent between the peer and a specific authenticator; however where key separation is implemented, compromise of the AAA-Key does not enable an attacker to impersonate the peer to another authenticator, since that requires possession of the MK or EMSK, which are not transported by the AAA protocol. This vulnerability may be mitigated by implementation of redirect functionality, as provided in[RFC3588].

6.3 Man-in-the-middle Attacks

As described in [I-D.puthenkulam-eap-binding], EAP method sequences and compound authentication mechanisms may be subject to man-in-the-middle attacks. When such attacks are successfully carried out, the attacker acts as an intermediary between a victim and a legitimate authenticator. This allows the attacker to authenticate successfully to the authenticator, as well as to obtain access to the network.

In order to prevent these attacks, [I-D.puthenkulam-eap-binding] recommends derivation of a compound key by which the EAP peer and server can prove that they have participated in the entire EAP exchange. Since the compound key must not be known to an attacker posing as an authenticator, and yet must be derived from quantities that are exported by EAP methods, it may be desirable to derive the compound key from a portion of the EMSK. In order to provide proper key hygiene, it is recommended that the compound key used for man-in-the-middle protection be cryptographically separate from other keys derived from the EMSK, such as fast handoff keys, discussed in Appendix E.

6.4 Impersonation

Both the RADIUS and Diameter protocols are potentially vulnerable to impersonation by a rogue authenticator.

When RADIUS requests are forwarded by a proxy, the NAS-IP-Address or NAS-IPv6-Address attributes may not correspond to the source address. Since the NAS-Identifier attribute need not contain an FQDN, it also may not correspond to the source address, even indirectly. [RFC2865] Section 3 states:

> A RADIUS server MUST use the source IP address of the RADIUS UDP packet to decide which shared secret to use, so that RADIUS requests can be proxied.

This implies that it is possible for a rogue authenticator to forge NAS-IP-Address, NAS-IPv6-Address or NAS-Identifier attributes within a RADIUS Access-Request in order to impersonate another authenticator. Among other things, this can result in messages (and MSKs) being sent to the wrong authenticator. Since the rogue authenticator is authenticated by the RADIUS proxy or server purely based on the source address, other mechanisms are required to detect the forgery. In addition, it is possible for attributes such as the Called-Station-Id and Calling-Station-Id to be forged as well.

As recommended in [RFC3579], this vulnerability can be mitigated by having RADIUS proxies check authenticator identification attributes against the source address.

To allow verification of session parameters such as the Called-Station- Id and Calling-Station-Id, these can be sent by the EAP peer to the server, protected by the TEKs. The RADIUS server can then check the parameters sent by the EAP peer against those claimed by the authenticator. If a discrepancy is found, an error can be logged.

While [RFC3588] requires use of the Route-Record AVP, this utilizes FQDNs, so that impersonation detection requires DNS A/AAAA and PTR RRs to be properly configured. As a result, it appears that Diameter is as vulnerable to this attack as RADIUS, if not more so. To address this vulnerability, it is necessary to allow the backend authentication server to communicate with the authenticator directly, such as via the redirect functionality supported in [RFC3588].

6.5 Denial of Service Attacks

The caching of security associations may result in vulnerability to denial of service attacks. Since an EAP peer may derive multiple EAP SAs with a given EAP server, and creation of a new EAP SA does not implicitly delete a previous EAP SA, EAP methods that result in creation of persistant state may be vulnerable to denial of service attacks by a rogue EAP peer.

As a result, EAP methods creating persistent state may wish to limit the number of cached EAP SAs (Phase 1a) corresponding to an EAP peer. For example, an EAP server may choose to only retain a few EAP SAs for each peer. This prevents a rogue peer from denying access to other peers.

Similarly, an authenticator may have multiple AAA-Key SAs corresponding to a given EAP peer; to conserve resources an authenticator may choose to limit the number of cached AAA-Key (Phase 1 b) SAs for each peer.

Depending on the media, creation of a new unicast secure association SA may or may not imply deletion of a previous unicast secure association SA. Where there is no implied deletion, the authenticator may choose to limit Phase 2 (unicast and multicast) secure association SAs for each peer.

7. Acknowledgements

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Appendix A. Ciphersuite Keying Requirements

To date, PPP and IEEE 802.11 ciphersuites are suitable for keying by EAP. This Appendix describes the keying requirements of common PPP and 802.11 ciphersuites.

PPP ciphersuites include DESEbis [RFC2419], 3DES [RFC2420], and MPPE [RFC3078]. The DES algorithm is described in [FIPSDES], and DES modes (such as CBC, used in [RFC2419] and DES-EDE3-CBC, used in [RFC2420]) are described in [DESMODES]. For PPP DESEbis, a single 56-bit

encryption key is required, used in both directions. For PPP 3DES, a 168-bit encryption key is needed, used in both directions. As described in [RFC2419] for DESEbis and [RFC2420] for 3DES, the IV, which is different in each direction, is "deduced from an explicit 64-bit nonce, which is exchanged in the clear during the ECP negotiation phase [RFC1968]." There is therefore no need for the IV to be provided by EAP.

For MPPE, 40-bit, 56-bit or 128-bit encryption keys are required in

each direction, as described in [RFC3078]. No initialization vector is required.

While these PPP ciphersuites provide encryption, they do not provide per-packet authentication or integrity protection, so an authentication key is not required in either direction.

Within [IEEE80211], Transient Session Keys (TSKs) are required both for unicast traffic as well as for multicast traffic, and therefore separate key hierarchies are required for unicast keys and multicast keys. IEEE 802.11 ciphersuites include WEP-40, described in [IEEE80211], which requires a 40-bit encryption key, the same in either direction; and WEP-128, which requires a 104-bit encryption key, the same in either direction. These ciphersuites also do not support per-packet authentication and integrity protection. In addition to these unicast keys, authentication and encryption keys are required to wrap the multicast encryption key.

Recently, new ciphersuites have been proposed for use with IEEE 802.11 that provide per-packet authentication and integrity protection as well as encryption [IEEE80211i]. These include TKIP, which requires a single 128-bit encryption key and a 128-bit authentication key (used in both directions); AES CCMP, which requires a single 128-bit key (used in both directions) in order to authenticate and encrypt data; and WRAP, which requires a single 128-bit key (used in both directions).

As with WEP, authentication and encryption keys are also required to wrap the multicast encryption (and possibly, authentication) keys.

Appendix B. Transient EAP Key (TEK) Hierarchy

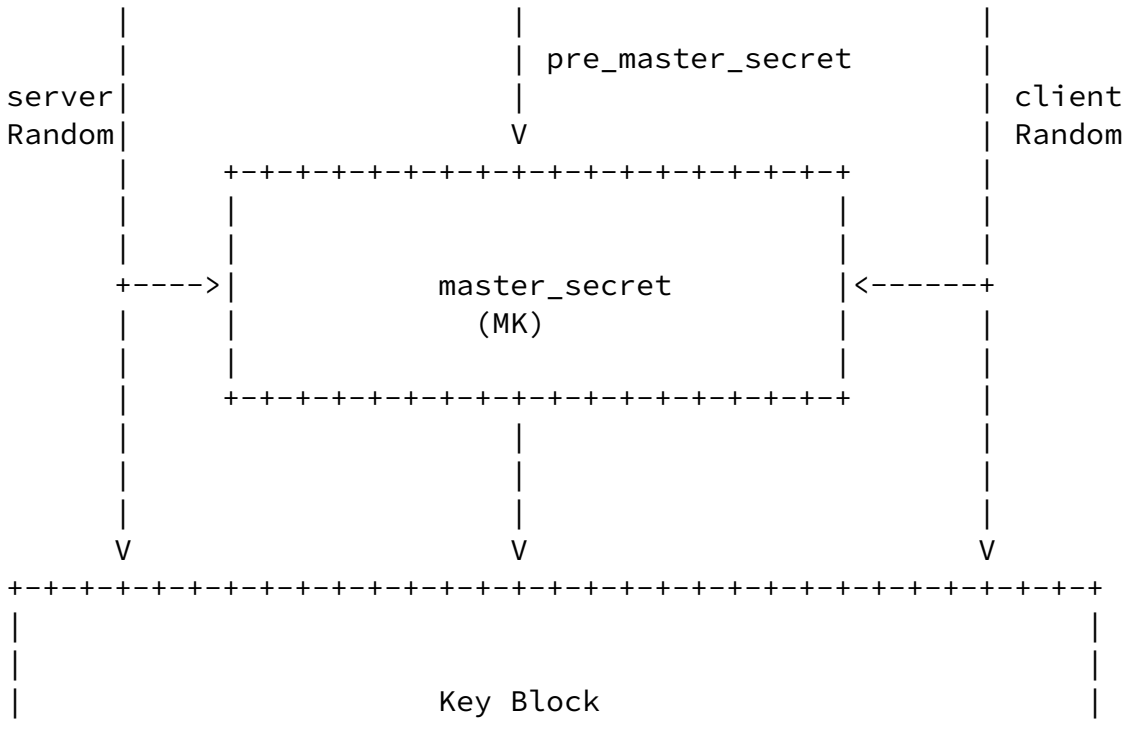
Figure B-1 illustrates the TEK key hierarchy for EAP-TLS [RFC2716], which is based on the TLS key hierarchy [RFC2246]. The TLS-negotiated ciphersuite is used to set up a protected channel for use in protecting the EAP conversation, keyed by the derived TEKs. The TEK derivation proceeds as follows:

```
master_secret   = TLS-PRF-48(pre_master_secret, "master secret",
                  client.random || server.random)

TEK             = TLS-PRF-X(master_secret, "key expansion",
                  server.random || client.random)
```

Where:

TLS-PRF-X = TLS pseudo-random function [RFC2246], computed to X octets.

master_secret = TLS term for the MK.



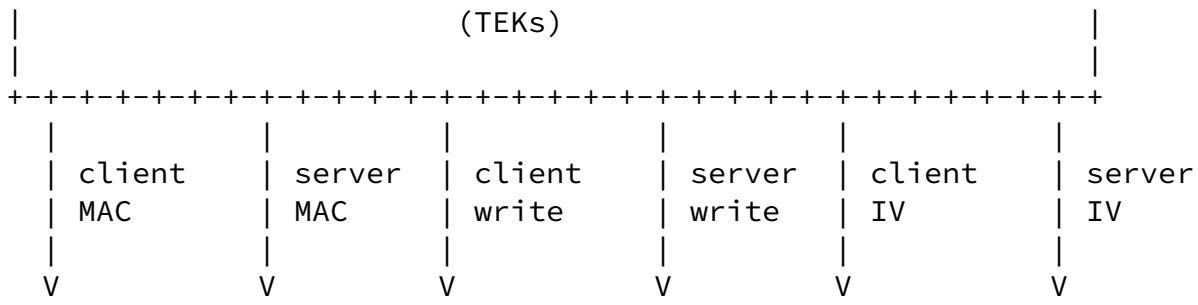


Figure B-1 - TLS [RFC2246] Key Hierarchy

Appendix C. MSK and EMSK Hierarchy

In EAP-TLS [RFC2716], the MSK is divided into two halves, corresponding to the "Peer to Authenticator Encryption Key" (Enc-RECV-Key, 32 octets, also known as the PMK) and "Authenticator to Peer Encryption Key" (Enc-SEND-Key, 32 octets). In [RFC2548], the Enc-RECV-Key (the PMK) is transported in the MS-MPPE-Recv-Key attribute, and the Enc-SEND-Key is transported in the MS-MPPE-Send-Key attribute.

The EMSK is also divided into two halves, corresponding to the "Peer

to Authenticator Authentication Key" (Auth-RECV-Key, 32 octets) and "Authenticator to Peer Authentication Key" (Auth-SEND-Key, 32 octets). The IV is a 64 octet quantity that is a known value; octets 0-31 are known as the "Peer to Authenticator IV" or RECV-IV, and Octets 32-63 are known as the "Authenticator to Peer IV", or SEND-IV.

In EAP-TLS, the MSK, EMSK and IV are derived from the MK via a one-way function. This ensures that the MK cannot be derived from the MSK, EMSK or IV unless the one-way function (TLS PRF) is broken. Since the MSK is derived from the MK, if the MK is compromised then the MSK is also compromised.

As described in [RFC2716], the formula for the derivation of the MSK, EMSK and IV from the MK is as follows:

```
MSK             = TLS-PRF-64(MK, "client EAP encryption",
                  client.random || server.random)
```

```
EMSK           = second 64 octets of:
                 TLS-PRF-128(MK, "client EAP encryption",
                 client.random || server.random)

IV             = TLS-PRF-64("", "client EAP encryption",
                 client.random || server.random)

AAA-Key(0,31)  = Peer to Authenticator Encryption Key (Enc-RECV-Key)
                 (MS-MPPE-Recv-Key in [RFC2548]).  Also known as the
                 PMK.

AAA-Key(32,63) = Authenticator to Peer Encryption Key (Enc-SEND-Key)
                 (MS-MPPE-Send-Key in [RFC2548])

EMSK(0,31)     = Peer to Authenticator Authentication Key
                 (Auth-RECV-Key)

EMSK(32,63)    = Authenticator to Peer Authentication Key
                 (Auth-Send-Key)

IV(0,31)       = Peer to Authenticator Initialization Vector
                 (RECV-IV)

IV(32,63)      = Authenticator to Peer Initialization vector
                 (SEND-IV)
```

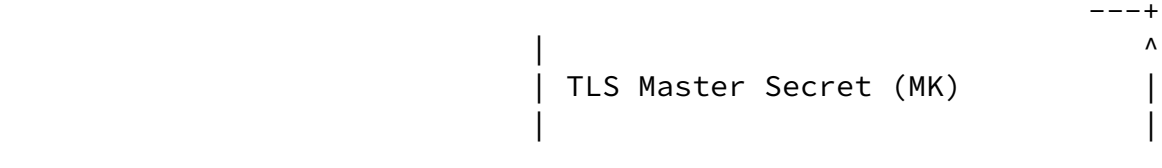
Where:


```
AAA-Key(W,Z)  = Octets W through Z inclusive of the AAA-Key.

IV(W,Z)       = Octets W through Z inclusive of the IV.

MSK(W,Z)      = Octets W through Z inclusive of the MSK.

EMSK(W,Z)     = Octets W through Z inclusive of the EMSK.

MK            = TLS master_secret

TLS-PRF-X     = TLS PRF function [RFC2246], computed to X octets
```

client.random = Nonce generated by the TLS client.

server.random = Nonce generated by the TLS server.

Figure C-1 describes the process by which the MSK,EMSK,IV and ultimately the TSKs, are derived from the MK. Note that in [RFC2716], the MK is referred to as the "TLS Master Secret".



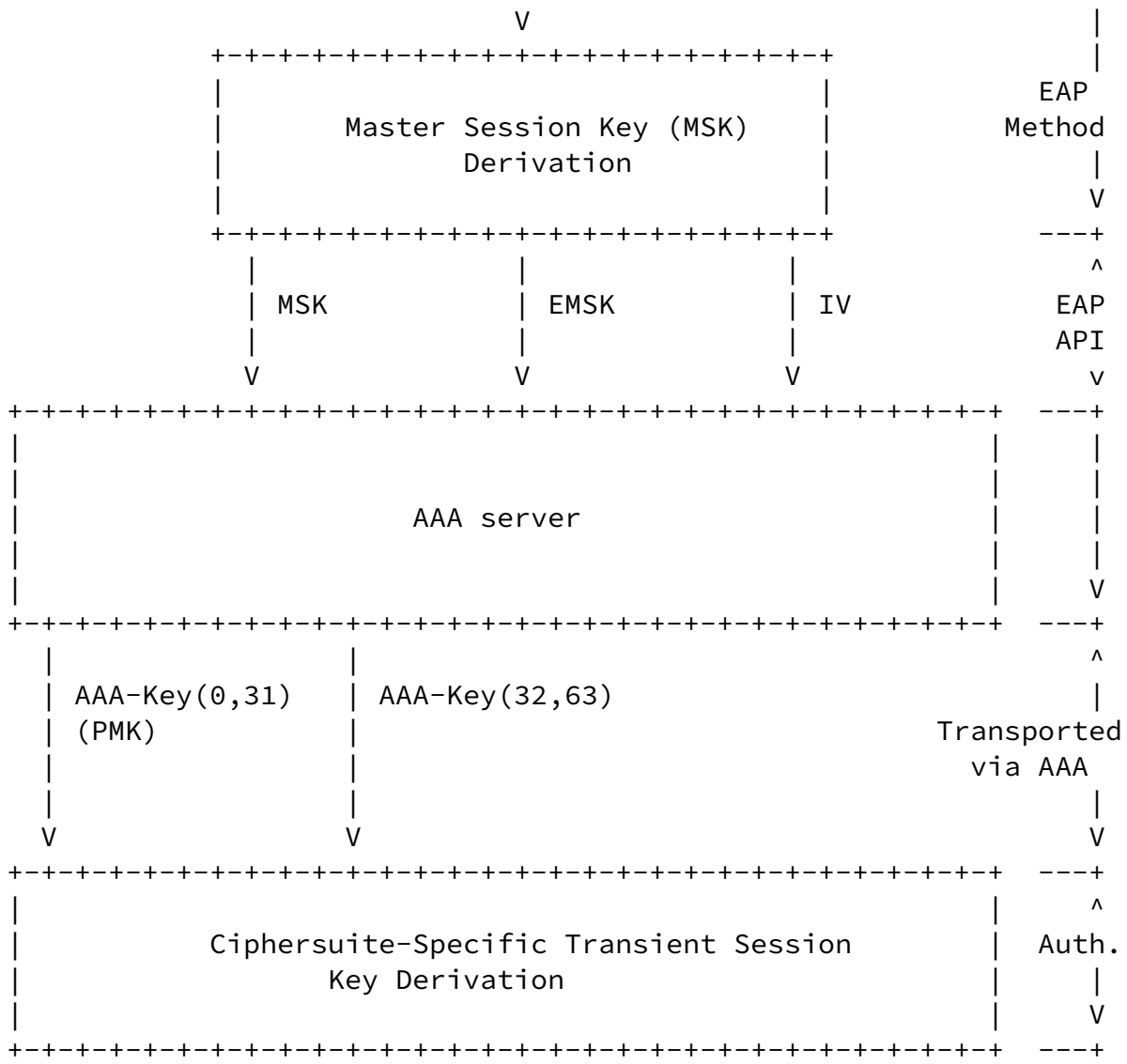


Figure C-1 - EAP TLS [RFC2716] Key hierarchy

Appendix D. Transient Session Key (TSK) Derivation

Within IEEE 802.11 RSN, the Pairwise Transient Key (PTK), a transient session key used to protect unicast traffic, is derived from the PMK (octets 0-31 of the MSK), known in [RFC2716] as the Peer to Authenticator Encryption Key. In [IEEE80211i], the PTK is derived from the PMK via the following formula:

```
PTK             = EAPOL-PRF-X(PMK, "Pairwise key expansion",
                  Min(AA,SA) || Max(AA, SA) || Min(ANonce,SNonce) ||
                  Max(ANonce,SNonce))
```

Where:

```
 PMK            = AAA-Key(0,31)

 SA             = Station MAC address (Calling-Station-Id)

 AA             = Access Point MAC address (Called-Station-Id)

 ANonce         = Access Point Nonce

 SNonce         = Station Nonce

 EAPOL-PRF-X    = Pseudo-Random Function based on HMAC-SHA1,
                  generating a PTK of size X octets.
```

TKIP uses X = 64, while CCMP, WRAP, and WEP use X = 48.

The EAPOL-Key Confirmation Key (KCK) is used to provide data origin authenticity in the TSK derivation. It utilizes the first 128 bits (bits 0-127) of the PTK. The EAPOL-Key Encryption Key (KEK) provides confidentiality in the TSK derivation. It utilizes bits 128-255 of the PTK. Bits 256-383 of the PTK are used by Temporal Key 1, and Bits 384-511 are used by Temporal Key 2. Usage of TK1 and TK2 is ciphersuite specific. Details are available in [IEEE80211i].

Appendix E. AAA-Key Derivation

As discussed in [I-D.irtf-aaaarch-handoff], [IEEE-02-758], [IEEE-03-084], and [8021XHandoff], keying material may be required for use in fast handoff between IEEE 802.11 authenticators. Where the backend authentication server provides keying material to multiple authenticators in order to fascilitate fast handoff, it is highly desirable for the keying material used on different authenticators to be cryptographically separate, so that if one authenticator is compromised, it does not lead to the compromise of other authenticators. Where keying material is provided by the backend authentication server, a key hierarchy derived from the EMSK, as suggested in [IEEE-03-155] can be used to provide cryptographically separate keying material for use in fast handoff:

```
AAA-Key-A       = MSK(0,63)
```

```
AAA-Key-B      = PRF(EMSK(0,63),AAA-Key-A,
                 B-Called-Station-Id,Calling-Station-Id)

AAA-Key-E      = PRF(EMSK(0,63),AAA-Key-A,
                 E-Called-Station-Id,Calling-Station-Id)
```

Where:

```
 Calling-Station-Id  = STA MAC address

 B-Called-Station-Id = AP B MAC address

 E-Called-Station-Id = AP E MAC address
```

Here AAA-Key-A is the AAA-Key derived during the initial EAP authentication between the peer and authenticator A. Based on this initial EAP authentication, the EMSK is also derived, which can be used to derive AAA-Keys for fast authentication between the EAP peer and authenticators B and E. Since the EMSK is cryptographically separate from the MSK, each of these AAA-Keys is cryptographically separate from each other, and are guaranteed to be unique between the EAP peer (also known as the STA) and the authenticator (also known as the AP).

Appendix F. Open issues

(This section should be removed by the RFC editor before publication)

Open issues relating to this specification are tracked on the following web site:

http://www.drizzle.com/~aboba/EAP/eapissues.html

The current working documents for this draft are available at this web site:

http://www.levkowetz.com/pub/ietf/drafts/eap/keying/

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