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Lightweight Industrial CMP Profile
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Abstract

The goal of this document is to facilitate interoperability and automation by profiling the Certificate Management Protocol (CMP) [RFC4210] and the related Certificate Request Message Format (CRMF) [RFC4211]. It specifies a subset of CMP and CRMF focusing on typical uses cases relevant for managing certificates of devices in industrial and IoT scenarios. To limit the overhead of certificate management for constrained devices only the most crucial types of transactions are specified as mandatory. To foster interoperability also in more complex scenarios, other types of transactions are specified as recommended or optional.

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1. Introduction

This document specifies certificate management transactions implementing industrial machine-to-machine and IoT use cases. The focus lies on maximum automation and interoperable implementation of all involved components from end entities (EE) through an optional Local Registration Authority (LRA) and the RA up to the CA. The profile makes use of the concepts and syntax specified in CMP [RFC4210], CRMF [RFC4211], and HTTP transfer for CMP [RFC6712]. Especially CMP and CRMF are very feature-rich standards, while only a limited subset of the specified functionality is needed in the target environment of this document. Additionally, both standards are not always precise enough on how to interpret and implement the described concepts. Therefore, we aim at tailoring and specifying in more detail how to use these concepts to implement automated certificate management in industrial target environments.

1.1. Motivation for profiling CMP

CMP was standardized in 1999 and is implemented in several CA products. In 2005 a completely reworked and enhanced version 2 of CMP [RFC4210] and CRMF [RFC4211] has been published followed by a document specifying a transfer mechanism using http [RFC6712] in 2012.

Though CMP is a very solid and capable protocol it could be used more widely. The most important reason for not more intense application of CMP appears to be that the protocol is offering a large set of features and options but being not always precise enough and leaving room for interpretation. On the one hand, this makes CMP applicable to a very wide range of scenarios, but on the other hand a full implementation of all options is unrealistic because this would take enormous effort.

Moreover, many details of the CMP protocol have been left open or have not been specified in full preciseness. The profiles specified in Appendix D and E of [RFC4210] offer some more detailed certificate use cases. But the specific needs of highly automated industrial scenarios are not covered sufficiently.

As also 3GPP, and UNISG already put across, profiling is a way of coping with the challenges mentioned above. To profile means to take advantage of the strengths of the given protocol, while explicitly narrowing down the options it provides to exactly those needed for the purpose(s) at hand and eliminating all identified ambiguities. In this way all the general and applicable aspects of the protocol can be taken over and only the peculiarities of the target scenario need to be dealt with specifically.

Doing such a profiling for a new target environment can be a high effort because the range of available options needs to be well understood and the selected options need to be consistent with each other and with the intended usage scenario. Since industrial use cases typically have much in common it is worth sharing this effort, which is the aim of this document. Other standardization bodies can then reference the profile from this document and do not need to come up with individual profiles.

1.2. Motivation for an industrial profile for CMP

The profiles specified in Appendix D and E of CMP have been developed in particular to manage certificates of human end entities. With the evolution of distributed systems and client-server architectures, certificates for machines and applications on them have become widely used. This trend has strengthened even more in emerging industrial and IoT scenarios. CMP is sufficiently flexible to support these very well.

Today's IT security architectures for industrial solutions typically use certificates for endpoint authentication within protocols like IPSec, TLS or SSH. Therefore, the security of these architectures highly relies upon the security and availability of the implemented certificate management procedures.

Due to increasing security in operational networks as well as availability requirements, especially on critical infrastructures and systems with a high volume of certificates, a state-of-the-art certificate management must be constantly available and cost-efficient, which calls for high automation and reliability. Such PKI operation according to commonly accepted best practices is also required in IEC 62443-3-3 [IEC62443-3-3] for security level 2 up to security level 4.

Further challenges in industrial systems are network segmentation and asynchronous communication, where PKI operation is often not deployed on-site but in a more protected environment of a data center or trust center. Certificate management must be able to cope with such network architectures. CMP offers the required flexibility and functionality, namely self-contained messages, efficient polling, and support for asynchronous message transfer with end-to-end security.

1.3. Existing CMP profiles

As already stated, CMP contains profiles with mandatory and optional transactions in the Appendixes D and E of [RFC4210]. Those profiles focus on management of human user certificates and do not address the specific needs of industrial use cases.

3GPP makes use of CMP [RFC4210] in its Technical Specification 133 310 [ETSI-3GPP] for automatic management of IPsec certificates in UMTS, LTE, and 5G backbone networks. Since 2010 a dedicated CMP profile for initial certificate enrollment and update transactions between end entities and the RA/CA is specified in the document.

UNISIG has included a CMP profile for certificate enrollment in the subset 137 specifying the ETRAM/ECTS on-line key management for train control systems [UNISIG] in 2015.

Both standardization bodies use CMP [RFC4210], CRMF [RFC4211], and HTTP transfer for CMP [RFC6712] to add tailored means for automated certificate management in an industrial setting.

1.4. Compatibility with existing CMP profiles

The profile specified in this document is compatible with CMP [RFC4210] Appendixes D and E (PKI Management Message Profiles), with the following exceptions:

- o signature-based protection is the default protection; initial transactions may also use HMAC,

- o certification of a second key pair within the same transaction is not supported,
- o proof-of-possession (POPO) with self-signature of the certTemplate according to [RFC4211] section 4.1 clause 3 is the only supported POPO method,
- o confirmation of newly enrolled certificates may be omitted, and
- o all transactions consist of request-response message pairs originating at the EE, i.e., announcement messages are omitted.

The profile specified in this document is compatible with the CMP profile for UMTS, LTE, and 5G network domain security and authentication framework [ETSI-3GPP], except that:

- o protection of initial transactions may be HMAC-based,
- o the subject name is mandatory in certificate templates, and
- o confirmation of newly enrolled certificates may be omitted.

The profile specified in this document is compatible with the CMP profile for on-line key management in rail networks as specified in UNISIG subset-137 [UNISIG], except that:

- o the messageTime format is required to be generalizedTime (Note: While requiring UTC, UNISIG is in conflicts with CMP [RFC4210] that requires the messageTime format to be generalizedTime), and
- o in case the request message is MAC protected, also the response, certConf, and PKIconf messages have a MAC-based protection (Note: if changing to signature protection of the response the caPubs field cannot be used securely anymore.).

1.5. Scope of this document

This document specifies requirements on generating messages on the sender side. It does not specify strictness of verification on the receiving side and how in detail to handle error cases.

Especially on the EE side this profile aims at a lightweight protocol that can be implemented on constrained devices. On the side of the central PKI components the profile accepts higher resource needs.

For the sake of robustness and preservation of security properties implementations should, as far as security is not affected, adhere to Postel's law: "Be conservative in what you do, be liberal in what you

accept from others" (often reworded as: "Be conservative in what you send, be liberal in what you accept").

When in chapter 3, 4, and 5 a field of the ASN.1 syntax as defined in RFC 4210 [RFC4210] and RFC 4211 [RFC4211] is not explicitly specified, it SHOULD not be used by the sending entity. The receiving entity MUST NOT require its absence and if present SHOULD ignore it.

1.6. Structure of this document

Chapter 2 introduces the general PKI architecture and approach to certificate management using CMP that is assumed in this document. Then it enlists the industrial certificate management use cases specified in this document and describes them in general words. The list of supported certificate management use cases is divided into mandatory, recommended, and optional ones.

Chapter 3 profiles the CMP message header, protection, and extraCerts section as they are general elements of CMP messages.

Chapter 4 profiles the exchange of CMP messages between an EE and the first PKI component. There are various flavors of certificate enrollment requests optionally with polling, revocation, error handling, and general support transactions.

Chapter 5 profiles the exchange between further PKI components. These are in the first place the forwarding of messages coming from or going to an EE. This includes also initiating delayed delivery of messages, which involves polling. Additionally, it specifies transactions where the PKI component manages certificates on behalf of an EE or for itself.

Chapter 6 outlines different mechanisms for CMP message transfer, namely http-based transfer as already specified in [RFC6712], using an additional TLS layer, offline file-based transport, CoAP [RFC7252], or piggybacking CMP messages on other protocols.

1.7. Convention and Terminology

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 RFC 2119 [RFC2119].

In this document, these words will appear with that interpretation only when in ALL CAPS. Lower case uses of these words are not to be interpreted as carrying significance described in RFC 2119.

Technical terminology is used in conformance with RFC 4210 [RFC4210], RFC 4211 [RFC4211], RFC 5280 [RFC5280], and IEEE 802.1AR [IEEE802.1AR]. The following key words are used:

- CA: Certification authority, which issues certificates.
- RA: Registration authority, an optional system component to which a CA delegates certificate management functions such as authorization checks.
- LRA: Local registration authority, an optional RA system component with proximity to end entities.
- EE: End entity, a user or device or service that holds a PKI certificate. An identifier for the EE is given as the subject of the certificate.

2. Architecture and use cases

2.1. Solution architecture

Typically, an industrial EE will be equipped with a manufacturer certificate during production. A manufacturer certificate is installed during production to identify the device throughout its lifetime. This manufacturer certificate can be used to protect the initial enrollment of operational certificates after installation of the EE in a plant or industrial network. An operational certificate is issued by the owner or operator of the device to identify the device during operation, e.g., within a security protocol like IPSec, TLS, or SSH. In IEEE 802.1AR [IEEE802.1AR] a manufacturer certificate is called IDevID certificate and an operational certificate is called LDevID certificate.

All certificate management transactions are initiated by the EE. The EE creates a CMP request message, protects it using its manufacturer or operational certificate, if available, and sends it to its locally reachable PKI component. This PKI component may be an LRA, RA, or the CA, which checks the request, responds to it itself, or forwards the request upstream to the next PKI component. In case an (L)RA changes the CMP request message header or body or wants to prove a successful verification or authorization, it can apply a protection of its own. Especially the communication between an LRA and RA can be performed synchronously or asynchronously. Synchronous communication describes a timely uninterrupted communication between two communication partners, as asynchronous communication is not performed in a timely consistent manner, e.g., because of a delayed message delivery.

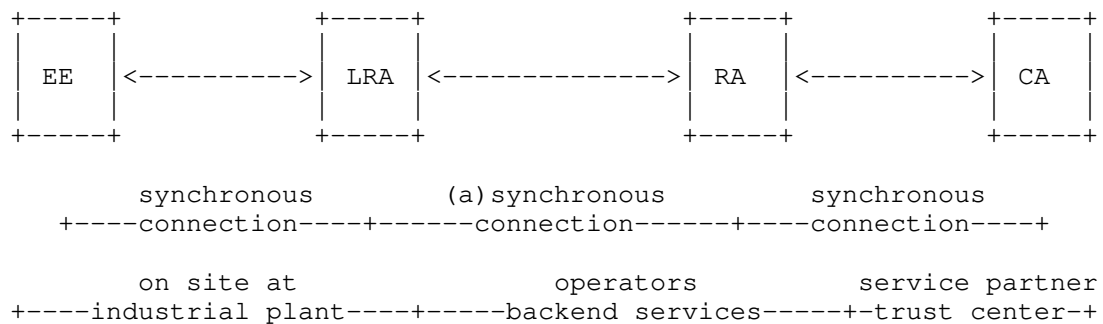


Figure 1: Certificate management on site

In operation environments a layered LRA-RA-CA architecture can be deployed, e.g., with LRAs bundling requests from multiple EEs at dedicated locations and one (or more than one) central RA aggregating the requests from multiple LRAs. Every (L)RA in this scenario will have its own dedicated certificate and private key allowing it to protect CMP messages it processes (CMP signing key/certificate). The figure above shows an architecture using one LRA and one RA. It is also possible to have only an RA or multiple LRAs and/or RAs. Depending on the network infrastructure, the communication between different PKI components may be synchronous online-communication, delayed asynchronous communication, or even offline file transfer.

Third-party CAs typically implement different variants of CMP or even use proprietary interfaces for certificate management. Therefore, the LRA or the RA may need to adapt the exchanged CMP messages to the flavor of communication required by the CA.

2.2. Basic generic CMP message content

Section 3 specifies the generic parts of the CMP messages as used later in Section 4 and Section 5.

- o Header of a CMP message; see Section 3.1.
- o Protection of a CMP message; see Section 3.2.
- o ExtraCerts field of a CMP message; see Section 3.3.

2.3. Supported use cases

Following the outlined scope from Section 1.5, this section gives a brief overview of the certificate management use cases specified in Section 4 and Section 5 and points out, if a implementation by compliant EE or PKI component is mandatory, recommended or optional.

2.3.1. Mandatory use cases

The mandatory uses case in this document shall limit the overhead of certificate management for constrained devices to the most crucial types of transactions.

Section 4 - End Entity focused certificate management use cases

- o Request a certificate from a new PKI with signature protection; see Section 4.1.1.
- o Request to update an existing certificate with signature protection; see Section 4.1.2.
- o Error reporting; see Section 4.3.

Section 5 - LRA and RA focused certificate management use cases

- o Forward messages without changes; see Section 5.1.1.
- o Forward messages with replaced protection and raVerified as proof-of-possession; see Section 5.1.2.2.
- o Error reporting; see Section 5.3.

2.3.2. Recommended Use Cases

Additional recommended use cases shall support some more complex scenarios, that are considered as beneficial for industrial environments.

Section 4 - End Entity focused certificate management use cases

- o Request a certificate from a PKI with MAC protection; see Section 4.1.3.
 - o Handle delayed enrollment due to asynchronous message delivery.
- < Motivation see Section 4.1.6, specification TBD >

Section 5 - LRA and RA focused certificate management use cases

- o Revoke a certificate on LRA or RA side.
- < Motivation see Section 4.2, specification TBD >

2.3.3. Optional use cases

The optional use cases support specific requirements seen only in a subset of industrial environments.

Section 4 – End Entity focused certificate management use cases

- o Request a certificate from a legacy PKI using a PKCS#10 [RFC2986] request.

< Motivation see Section 4.1.4, specification TBD >

- o Add central generation of a key pair to a certificate request.

< Motivation see Section 4.1.5, specification TBD >

- o Request to omit confirmation messages; see Section 4.1.7.

- o Request to revoke a certificate from EE side.

< Motivation see Section 4.2, specification TBD >

- o Additional support messages, e.g., to update a Root CA certificate or to request an RFC 8366 [RFC8366] voucher.

< Motivation see Section 4.4, specification TBD >

Section 5 – LRA and RA focused certificate management use cases

- o Initiate delayed enrollment due to asynchronous message delivery.

< Motivation see Section 5.1.3, specification TBD >

- o Grant an EE's request to omit confirmation messages; see Section 5.1.4.

- o Revoke a certificate of another entity.

< Motivation see Section 5.2, specification TBD >

2.4. CMP message transport

Recommended transport

- o Transfer CMP messages using HTTP; see Section 6.1.

Optional transport

- o Transfer CMP messages using HTTPS with certificate-based authentication; see Section 6.2.
 - o Transfer CMP messages using HTTPS with shared-secret based protection; see Section 6.3.
 - o File-based CMP message transport.
- < Motivation see Section 6.4, specification TBD >
- o Transfer CMP messages using CoAP.
- < Motivation see Section 6.5, specification TBD >
- o Piggyback CMP messages on other reliable transport protocols.
- < Motivation see Section 6.6, specification TBD >

3. Generic parts of the PKI message

To reduce redundancy in the text and to ease implementation, the contents of the header, protection, and extraCerts fields of the CMP messages used in the transactions specified in Section 4 and Section 5 are standardized to the maximum extent possible. Therefore, the generic parts of a CMP message are described centrally in this section.

As described in section 5.1 of [RFC4210], all CMP messages have the following general structure:

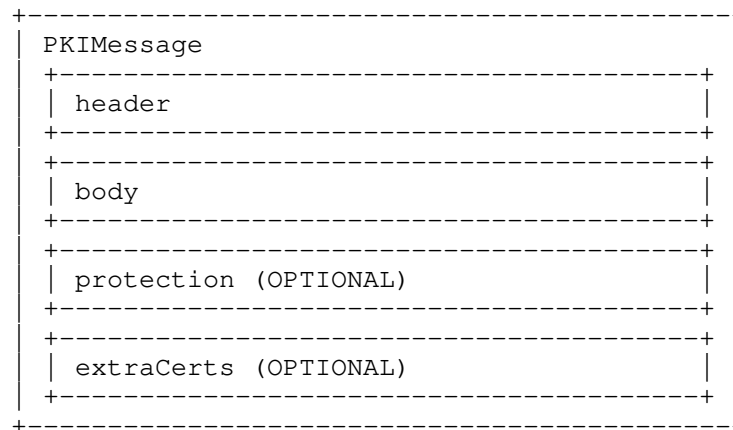


Figure 2: CMP message structure

The general contents of the message header, protection, and extraCerts fields are specified in the Section 3.1 to Section 3.3.

In case a specific CMP message needs different contents in the header, protection, or extraCerts fields, the differences are described in the respective message.

The CMP message body contains the message-specific information. It is described in the context of Section 4 and Section 5.

The behavior in case an error occurs while handling a CMP message is described in Section 5.3.

3.1. General description of the CMP message header

This section describes the generic header field of all CMP messages with signature-based protection. The only variations described here are in the fields recipient, transactionID, and recipNonce of the first message of a transaction.

In case a message has MAC-based protection the changes are described in the respective section. The variations will affect the fields sender, protectionAlg, and senderKID.

For requirements about proper random number generation please refer to [RFC4086]. Any message-specific fields or variations are described in the respective sections of this chapter.

header

- pvno REQUIRED
 - MUST be set to 2 to indicate CMP V2
- sender REQUIRED
 - MUST be the subject of the signing certificate used for protection of this message
- recipient REQUIRED
 - MUST be the name of the intended recipient
 - If this is the first message of a transaction: SHOULD be the subject of the issuing CA certificate
 - In all other messages: SHOULD be the same name as in the sender field of the previous message in this transaction
- messageTime RECOMMENDED
 - MUST be the time at which the message was produced, if present
- protectionAlg REQUIRED
 - MUST be the algorithm identifier of the signature algorithm used for calculation of the protection bits
 - The signature algorithm MUST be consistent with the SubjectPublicKeyInfo field of the signer's certificate
 - The hash algorithm used SHOULD be SHA-256
- algorithm REQUIRED
 - MUST be the OID of the signature algorithm, like sha256WithRSAEncryption or ecdsa-with-SHA256
- parameters PROHIBITED
 - MUST be absent
- senderKID RECOMMENDED
 - MUST be the SubjectKeyIdentifier, if available, of the certificate used for protecting this message
- transactionID REQUIRED
 - If this is the first message of a transaction:
 - MUST be 128 bits of random data for the start of a transaction to reduce the probability of having the transactionID already in use at the server
 - In all other messages:
 - MUST be the value from the previous message in the same transaction
- senderNonce REQUIRED
 - MUST be fresh 128 random bits
- recipNonce RECOMMENDED
 - If this is the first message of a transaction: SHOULD be absent
 - In all other messages: MUST be present and contain the value from senderNonce of the previous message in the same transaction

3.2. General description of the CMP message protection

This section describes the generic protection field of all CMP messages with signature-based protection.

protection REQUIRED
-- MUST contain the signature calculated using the signature
-- algorithm specified in protectionAlg

Only for MAC-based protection major differences apply as described in the respective message.

The CMP message protection provides, if available, message origin authentication and integrity protection for the CMP message header and body. The CMP message extraCerts is not covered by this protection.

NOTE: The requirements for checking certificates given in [RFC5280] MUST be followed for the CMP message protection. OCSP or CRLs SHOULD be used for status checking of the CMP signer certificates of communication partners.

3.3. General description of CMP message extraCerts

This section describes the generic extraCerts field of all CMP messages with signature-based protection.

extraCerts RECOMMENDED
-- SHOULD contain the signing certificate together with its
-- chain, if needed
-- If present, the first certificate in this field MUST
-- be the certificate used for signing this message
-- Self-signed certificates SHOULD NOT be included in
-- extraCerts and MUST NOT be trusted based on the listing in
-- extraCerts in any case

4. End Entity focused certificate management use cases

This chapter focuses on the communication of the EE and the first PKI component it talks to. Depending on the network and PKI solution, this will either be the LRA, the RA or the CA.

Profiles of the Certificate Management Protocol (CMP) [RFC4210] handled in this chapter cover the following certificate management use cases:

- o Requesting a certificate from a PKI with variations like initial requests and updating, central key generation <TBD> and different protection means
- o Revocation of a certificate <TBD>
- o General messages for further support functions <TBD>

The use cases mainly specify the message body of the CMP messages and utilize the specification of the message header, protection and extraCerts as specified in Section 4.

The behavior in case an error occurs is described in Section 4.3.

This chapter is aligned to Appendix D and Appendix E of [RFC4210]. The general rules for interpretation stated in Appendix D.1 in [RFC4210] need to be applied here, too.

This document does not mandate any specific supported algorithms like Appendix D.2 of [RFC4210], [ETSI-3GPP], and [UNISIG] do. Using the message sequences described here require agreement upon the algorithms to support and thus the algorithm identifiers for the specific target environment.

4.1. Requesting a new certificate from a PKI

There are different approaches to request a certificate from a PKI.

These approaches differ on the one hand in the way the EE can authenticate itself to the PKI it wishes to get a new certificate from and on the other hand in its capabilities to generate a proper new key pair. The authentication means may be as follows:

- o Using a certificate from a trusted PKI and the corresponding private key, e.g., a manufacturer certificate
- o Using the certificate to be updated and the corresponding private key
- o Using a shared secret known to the EE and the PKI

Typically, such EE requests a certificate from a CA. When the (L)RA/CA responds with a message containing a certificate, the EE MUST reply with a confirmation message. The (L)RA/CA then MUST send confirmation back, closing the transaction.

The message sequences in this section allow the EE to request certification of a locally generated public-private key pair. (< The

functional extension for central key generation is TBD if needed. >) For requirements about proper random number and key generation please refer to [RFC4086]. The EE MUST provide a signature-based proof-of-possession of the private key associated with the public key contained in the certificate request as defined by [RFC4211] section 4.1 case 3. To this end it is assumed that the private key can technically be used as signing key. The most commonly used algorithms in industrial use cases are RSA and ECDSA, which can technically be used for signature calculation regardless of potentially intended restrictions of the key usage.

The requesting EE provides the binding of the proof-of-possession to its identity by signature-based or MAC-based protection of the CMP request message containing that POPO. The (L)RA/CA needs to verify whether this EE is authorized to obtain a certificate with the requested subject and other attributes and extensions. Especially when removing the protection provided by the EE and applying a new protection the (L)RA MUST verify in particular the included proof-of-possession self-signature of the certTemplate using the public key of the requested certificate and MUST check that the EE, as authenticated by the message protection, is authorized to request a certificate with the subject as specified in the certTemplate (see Section 5.1.2).

There are several ways to install the Root CA certificate of a new PKI on an EE. The installation can be performed in an out-of-band manner, using a voucher [RFC8366] for enrolment, or by the caPubs field in the certificate response message. In case the installation of the new Root CA certificate is performed using the caPubs field, the certificate response message MUST be properly authenticated, and the sender of this message MUST be authorized to install new Root CA certificates on the EE, e.g., by using a specific extendedKeyUsage in the RA certificate.

4.1.1.1. A certificate from a new PKI with signature protection

This message sequence should be used by an EE to request a certificate of a new PKI using an existing certificate from an external PKI, e.g. a manufacturer certificate, to prove its identity to the new PKI. The EE already has established trust in this new PKI it is about to enroll to, e.g., by configuration means. The initialization request message is signature-protected using the existing certificate.

Preconditions:

- 1 The EE MUST have a certificate enrolled by an external PKI in advance to this transaction to authenticate itself to the (L)RA/CA

using signature-based protection, e.g., using a manufacturer certificate.

- 2 The EE SHOULD know the subject name of the new CA it requests a certificate from; this name MAY be established using an enrollment voucher or other configuration means. If the EE does not know the name of the CA, the (L)RA/CA MUST know where to route this request to.
- 3 The EE MUST authenticate responses from the (L)RA/CA; trust MAY be established using an enrollment voucher or other configuration means
- 4 The (L)RA/CA MUST trust the external PKI the EE uses to authenticate itself; trust MAY be established using some configuration means

This message sequence is like that given in [RFC4210] Appendix E.7.

Message flow:

Step#	EE		(L)RA/CA
1	format ir		
2		-> ir	->
3			handle, re-protect or forward ir
4			format or receive ip
5		<- ip	<-
6	handle ip		
7			In case of status "rejection" in the ip message, no certConf and pkiConf are sent
8	format certConf		
9		-> certConf	->
10			handle, re-protect or forward certConf
11			format or receive PKIConf
12		<- pkiConf	<-
13	handle pkiConf		

For this message sequence the EE MUST include exactly one single CertReqMsg in the ir. If more certificates are required, further requests MUST be sent using separate CMP Messages.

If the CA accepts the request it MUST return the new certificate in the certifiedKeyPair field of the ip message. If the EE successfully receives the certificate and accepts it, the EE MUST send a certConf

message, which MUST be answered by the (L)RA/CA with a pkiConf message. If the (L)RA/CA does not receive the expected certConf message in time it MUST handle this like a rejection by the EE.

If the certificate request was refused by the CA, the (L)RA/CA must return an ip message containing the status code "rejection" and no certifiedKeyPair field. Such an ip message MUST NOT be followed by the certConf and pkiConf messages.

Detailed message description:

Certification Request -- ir

Field	Value
header	
--	As described in section 3.1
body	
--	The request of the EE for a new certificate
ir	REQUIRED
--	MUST be exactly one CertReqMsg
--	If more certificates are required, further requests MUST be
--	packaged in separate PKI Messages
certReq	REQUIRED
certReqId	REQUIRED
--	MUST be set to 0
certTemplate	REQUIRED
version	OPTIONAL
--	MUST be 2 if supplied.
subject	REQUIRED
--	MUST contain the suggested subject name of the EE
certificate	
publicKey	REQUIRED
--	MUST include the subject public key algorithm ID and value
extensions	OPTIONAL
--	MAY include end-entity-specific X.509 extensions of the
--	requested certificate like subject alternative name,
--	key usage, and extended key usage
Popo	REQUIRED
POPOSigningKey	REQUIRED
poposkInput	PROHIBITED
--	MUST NOT be used because subject and publicKey are both
--	present in the certTemplate
algorithmIdentifier	REQUIRED
--	The signature algorithm MUST be consistent with the
--	publicKey field of the certTemplate
--	The hash algorithm used SHOULD be SHA-256

```

        signature                REQUIRED
        -- MUST be the signature computed over the DER-encoded
        -- certTemplate

    protection                    REQUIRED
        -- As described in section 3.2

    extraCerts                   REQUIRED
        -- As described in section 3.3

Certification Response -- ip

Field                          Value

header
    -- As described in section 3.1

body
    -- The response of the CA to the request as appropriate
    ip                          REQUIRED
    caPubs                      OPTIONAL
        -- MAY be used
        -- If used it MUST contain only the root certificate of the
        -- certificate contained in certOrEncCert
    response                    REQUIRED
        -- MUST be exactly one CertResponse
    certReqId                   REQUIRED
        -- MUST be set to 0
    status                      REQUIRED
        -- PKIStatusInfo structure MUST be present
    status                     REQUIRED
        -- positive values allowed: "accepted", "grantedWithMods"
        -- negative values allowed: "rejection"
        -- In case of rejection no certConf and pkiConf messages will
        -- be sent
    statusString                OPTIONAL
        -- MAY be any human-readable text for debugging, logging or to
        -- display in a GUI
    failInfo                    OPTIONAL
        -- MUST be present if status is "rejection" and in this case
        -- the transaction MUST be terminated
        -- MUST be absent if the status is "accepted" or
        -- "grantedWithMods"
    certifiedKeyPair            OPTIONAL
        -- MUST be present if status is "accepted" or "grantedWithMods"
        -- MUST be absent if status is "rejection"
    certOrEncCert               REQUIRED

```

```

    -- MUST be present when certifiedKeyPair is present
        certificate REQUIRED
    -- MUST be present when certifiedKeyPair is present
    -- MUST contain the newly enrolled X.509 certificate

protection REQUIRED
    -- As described in section 3.2

extraCerts REQUIRED
    -- As described in section 3.3
    -- MUST contain the chain of the issued certificate
    -- Duplicate certificates MAY be omitted

Certificate Confirmation -- certConf

Field Value

header
    -- As described in section 3.1

body
    -- The message of the EE sends confirmation to the (L)RA/CA
    -- to accept or reject the issued certificates
    certConf REQUIRED
        -- MUST be exactly one CertStatus
        CertStatus REQUIRED
        certHash REQUIRED
        -- MUST be the hash of the certificate, using the same hash
        -- algorithm as used to create the certificate signature
        certReqId REQUIRED
        -- MUST be set to 0
        status RECOMMENDED
        -- PKIStatusInfo structure SHOULD be present
        -- Omission indicates acceptance of the indicated certificate
        status REQUIRED
        -- positive values allowed: "accepted"
        -- negative values allowed: "rejection"
        statusString OPTIONAL
        -- MAY be any human-readable text for debugging or logging
        failInfo OPTIONAL
        -- MUST be present if status is "rejection"
        -- MUST be absent if the status is "accepted"

protection REQUIRED
    -- As described in section 3.2
    -- MUST use the same certificate as for protection of the ir

```

extraCerts RECOMMENDED

- SHOULD contain the protection certificate together with its
- chain
- If present, the first certificate in this field MUST be the
- certificate used for signing this message
- Self-signed certificates SHOULD NOT be included in
- extraCerts and
- MUST NOT be trusted based on the listing in extraCerts in
- any case

PKI Confirmation -- pkiConf

Field	Value
header	-- As described in section 3.1
body	
pkiConf	REQUIRED
	-- The content of this field MUST be NULL
protection	REQUIRED
	-- As described in section 3.2
	-- SHOULD use the same certificate as for protection of the ip
extraCerts	RECOMMENDED
	-- SHOULD contain the protection certificate together with its
	-- chain
	-- If present, the first certificate in this field MUST be the
	-- certificate used for signing this message
	-- Self-signed certificates SHOULD NOT be included in extraCerts
	-- and
	-- MUST NOT be trusted based on the listing in extraCerts in
	-- any case

4.1.2. Update an existing certificate with signature protection

This message sequence should be used by an EE to request an update of one of the certificates it already has and that is still valid. The EE uses the certificate it wishes to update to prove its identity and possession of the private key for the certificate to be updated to the PKI. Therefore, the key update request message is signed using the certificate that is to be updated.

The general message flow for this message sequence is the same as given in Section 4.1.1.

Preconditions:

- 1 The certificate the EE wishes to update MUST NOT be expired or revoked.
- 2 A new public-private key pair SHOULD be used.

The message sequence for this exchange is like that given in [RFC4210] Appendix D.6.

The message sequence for this exchange is identical to that given in Section 4.1.1, with the following changes:

- 1 The body of the first request and response MUST be kur and kup, respectively.
- 2 Protection of the kur MUST be performed using the certificate to be updated.
- 3 The subject field of the CertTemplate MUST contain the subject name of the existing certificate to be updated, without modifications.
- 4 The CertTemplate MUST contain the subject, issuer and publicKey fields only.
- 5 The regCtrl OldCertId SHOULD be used to make clear, even in case an (L)RA changes the message protection, which certificate is to be.
- 6 The caPubs field in the kup message MUST be absent.

As part of the certReq structure of the kur the control is added right after the certTemplate.

```
controls
  type                RECOMMENDED
  -- MUST be the value id-regCtrl-oldCertID, if present
  value
    issuer             REQUIRED
    serialNumber       REQUIRED
  -- MUST contain the issuer and serialNumber of the certificate
  -- to be updated
```

4.1.3. A certificate from a PKI with MAC protection

This message sequence should be used by an EE to request a certificate of a new PKI without having a certificate to prove its identity to the target PKI, but there is a shared secret established between the EE and the PKI. Therefore, the initialization request is MAC-protected using this shared secret. The (L)RA checking the MAC-protection SHOULD replace this protection according to Section 5.1.2 in case the next hop does not know the shared secret too.

For requirements with regard to proper random number and key generation please refer to [RFC4086].

The general message flow for this message sequence is the same as given in Section 4.1.1.

Preconditions:

- 1 The EE and the (L)RA/CA MUST share a symmetric key, this MAY be established by a service technician during initial local configuration.
- 2 The EE SHOULD know the subject name of the new CA it requests a certificate from; this name MAY be established using an enrollment voucher or other configuration means. If the EE does not know the name of the CA, the (L)RA/CA MUST know where to route this request to.
- 3 The EE MUST authenticate responses from the (L)RA/CA; trust MAY be established using the shared symmetric key.

The message sequence for this exchange is like that given in [RFC4210] Appendix D.4.

The message sequence for this exchange is identical to that given in Section 4.1.1, with the following changes:

- 1 The protection of all messages MUST be calculated using Message Authentication Code (MAC); the protectionAlg field MUST be id-PasswordBasedMac as described in section 5.1.3.1 of [RFC4210].
- 2 The sender MUST contain a name representing the originator of the message. The senderKID MUST contain a reference all participating entities can use to identify the symmetric key used for the protection.
- 3 The extraCerts of the ir, certConf, and PKIConf messages MUST be absent.

- 4 The extraCerts of the ip message MUST contain the chain of the issued certificate and root certificates SHOULD not be included and MUST NOT be trusted in any case.

Part of the protectionAlg structure, where the algorithm identifier MUST be id-PasswordBasedMac, is a PBMPParameter sequence. The fields of PBMPParameter SHOULD remain constant throughout this certificate management transaction to reduce the computational overhead.

```

PBMPParameter          REQUIRED
  salt                  REQUIRED
  -- MUST be the random value to salt the secret key
  owf                   REQUIRED
  -- MUST be the algorithm identifier for the one-way function
  -- used
  -- The one-way function SHA-1 MUST be supported due to
  -- [RFC4211] requirements, but SHOULD NOT be used any more
  -- SHA-256 SHOULD be used instead
  iterationCount        REQUIRED,
  -- MUST be a limited number of times the OWF is applied
  -- To prevent brute force and dictionary attacks a reasonable
  -- high number SHOULD be used
  mac                   REQUIRED
  -- MUST be the algorithm identifier of the MAC algorithm used
  -- The MAC function HMAC-SHA1 MUST be supported due to
  -- [RFC4211] requirements, but SHOULD NOT be used any more
  -- HMAC-SHA-256 SHOULD be used instead

```

4.1.4. A certificate from a legacy PKI using PKCS#10 request

This message sequence should be used by an EE to request a certificate of a legacy PKI only capable to process PKCS#10 [RFC2986] certification requests. The EE can prove its identity to the target PKI by using various protection means as described in Section 4.1.1 or Section 4.1.3.

In contrast to the other transactions described in Section 4.1, this transaction uses PKCS#10 [RFC2986] instead of CRMF [RFC4211] for the certificate request for compatibility reasons with legacy CA systems that require a PKCS#10 certificate request and cannot process CMP [RFC4210] or CRMF [RFC4211] messages. In such case the (L)RA can extract the PKCS#10 certificate request from the p10cr and provide it separately to the CA.

< Details need to be defined later >

4.1.5. Generate the key pair centrally at the (L)RA/CA

It is strongly preferable to generate public-private key pairs locally at the EE. Together with proof-of-possession of the private key in the certification request, this is to make sure that only the entity identified in the newly issued certificate has the private key.

There are some rare cases where an EE is not able or not willing to locally generate the new key pair. Reasons for this may be the following:

- o Lack of sufficient initial entropy.

Note: Good random numbers are not only needed for key generation, but also for session keys and nonces in any security protocol. Therefore, we believe that a decent security architecture should anyway support good random number generation on the EE side or provide enough entropy for the RNG seed during manufacturing to guarantee good initial pseudo-random number generation.

- o Due to lack of computational resources, e.g., in case of RSA keys.

Note: As key generation can be performed in advance to the certificate enrollment communication, it is typical not time critical.

Note: Besides the initial enrollment right after the very first bootup of the device, where entropy available on the device may be insufficient, we do not see any good reason for central key generation.

< Details need to be defined later >

4.1.6. Delayed enrollment

This functional extension can be applied in combination with certificate enrollment as described in Section 4.1.1 to Section 4.1.4. The functional extension can be used in case a (L)RA/CA cannot respond to the certificate request in a timely manner, e.g. due to offline upstream communication or registration officer interaction. Depending on the PKI architecture, it is not necessarily the PKI component directly communicating with the EE that initiates the delayed enrollment. In this case this PKI component MUST include the status waiting in the response and this response MUST not contain a newly issued certificate. When receiving a response with status waiting the EE MUST send a poll request to the (L)RA/CA. The (L)RA/CA MUST answer with a poll response containing

a checkAfter time. This value indicates the minimum number of seconds that must elapse before the EE sends another poll request. As soon as the (L)RA/CA can provide the final response message for the initial request of the EE, it MUST provide this in response to a poll request. After receiving this response, the EE can continue the original message sequence as described in the respective section of this document, e.g. send a certConf message.

< Details need to be defined later >

4.1.7. Omitted confirmation

This functional extension can be applied in combination with certificate enrollment as described in sections Section 4.1.1 to Section 4.1.4. The functional extension can be used in case an EE does not want to send certificate confirmation messages to reduce the number of protocol messages exchanged in a transaction, it can indicate this by including the implicitConfirm extension in the header of a certificate request message. Only if the (L)RA/CA confirms this request using the same mechanism, the EE SHOULD omit sending the certificate confirmation message. Depending on the PKI architecture, it is not necessarily that the PKI component directly communicating with the EE replies to the request to omit sending confirmation messages, see also Section 5.1.4.

The EE MUST use the implicitConfirm extension as part of the generalInfo field in the header of the ir/cr/p10cr/kur to indicate its wish to not send a CertConf message. If the (L)RA/CA confirms this request, it MUST include the implicitConfirm extension as part of the generalInfo field in the header of the ip/cp/kup message as well. If the EE does not find the implicitConfirm extension in the response message, it MUST send the certificate confirmation.

The generalInfo field containing the implicitConfirm extension looks like this:

generalInfo	REQUIRED
implicitConfirm	REQUIRED
-- The value MUST be NULL	

4.2. Revoking a certificate

This message sequence should be used by an EE to revoke one of its certificates. The revocation request message MUST be signed using the certificate that is to be revoked to prove the authorization to revoke to the PKI. The certificate request message is signature-protected using this certificate.

< Details need to be defined later >

4.3. Error reporting

This functionality should be used by an EE to report any error conditions upstream to the (L)RA/CA. Error reporting by the (L)RA downstream to the EE is described in Section 5.3.

In case the error condition is related to specific details of an ip, cp, or kup response message and a confirmation is expected the error condition MUST be reported in the respective certConf message with negative contents.

General error conditions, e.g., problems with the message header, protection, or extraCerts, and negative feedback on rp, pollRep, or pkiConf messages MAY be reported in the form of an error message.

In both situations the error is reported in the PKIStatusInfo structure of the respective message.

The (L)RA/CA MUST respond to an error message with a pkiConf message, or with another error message if any part of the header is not valid. Both sides MUST treat this message as the end of the current transaction.

The PKIStatusInfo structure is used to report errors. The PKIStatusInfo structure SHOULD consist of the following fields:

- o status: Here the PKIStatus value rejection is the only one allowed.
- o statusString: Here any human-readable valid value for logging or to display in a GUI SHOULD be added.
- o failInfo: Here the PKIFailureInfo values MAY be used in the following way. For explanation of the reason behind a specific value, please refer to [RFC4210] Appendix F.
 - * transactionIdInUse: This is sent in case the received request contains a transaction ID that is already in use for another transaction. An EE receiving such error message SHOULD resend the request in a new transaction using a different transaction ID.
 - * systemUnavail or systemFailure: This is sent in case a back-end system is not available or currently not functioning correctly. An EE receiving such error message SHOULD resend the request in a new transaction after some time.

Detailed error message description:

Error Message -- error

Field	Value
header	
-- As described in section 3.1	
body	
-- The message sent by the EE or the (L)RA/CA to indicate an	
-- error that occurred	
error	REQUIRED
pKIStatusInfo	REQUIRED
status	REQUIRED
-- MUST have the value "rejection"	
statusString	RECOMMENDED
-- SHOULD be any human-readable text for debugging, logging	
-- or to display in a GUI	
failInfo	OPTIONAL
-- MAY be present	
protection	REQUIRED
-- As described in section 3.2	
extraCerts	OPTIONAL
-- As described in section 3.3	

4.4. Support messages

The following support messages offer on demand in-band transport of content that may be relevant to the EE. The general request messages and general response messages are used for this purpose.

The general message and general response transport InfoTypeAndValue structures. In addition to those infoType values defined in CMP [RFC4210] further OIDs MAY be defined to define new certificate management transactions, or general-purpose messages as needed in a specific environment.

Possible content described here address:

- o Update of Root CA certificates
- o Parameters needed for a planned certificate request message <TBD>
- o Request an enrollment voucher

< Details need to be defined later >

4.4.1. Root CA certificate update

This message sequence can be used by an EE to request an update of a Root CA Certificate by the EE. It utilizes the root CA key update announcement message as described in [RFC4210] Appendix E.4 as response to a respective general request message.

An EE requests a root CA certificate update from the (L)RA/CA by sending a general message with OID id-it-caKeyUpdateInfo. The (L)RA/CA responds with a general response with the same OID that either contains the update of the root CA certificate consisting of three certificates, or with no content in case no update is available. These three certificates are described in more detail in section 4.4.1, section 6.2, and Appendix E.3 of [RFC4210].

< Details need to be defined later >

4.4.2. Get enrollment voucher

This message sequence can be used by an EE to request an enrollment voucher containing the root certificate of a new PKI to establish trust in this PKI, e.g., in case no out-of-band transport is available. Such an enrollment voucher can be used in advance to an enrollment to this new environment. It may contain further information depending on the use case.

An EE requests an enrollment voucher from the (L)RA/CA by sending a general message. The (L)RA/CA responds with a general response with the same OID that contains the voucher.

< Details need to be defined later >

5. LRA and RA focused certificate management use cases

This chapter focuses on the communication of PKI backend components with each other. Depending on the network and PKI solution design, these will either be an LRA, RA or CA.

Typically, an (L)RA forwards messages from downstream, but it may also reply to them itself. Besides forwarding of received messages an (L)RA could also need to revoke certificates of EEs, report errors, or may need to manage its own certificates.

< Like in the CMC Updates [RFC6402] additional Extended Key Usages like id-kp-cmpRA may be defined to indicate that a key pair is

entitled to be used for signature-based protection of a CMP message by an (L)RA/CA. >

5.1. Forwarding of messages

Each CMP request message (i.e., ir, cr, p10cr, kur, pollReq, or certConf) or error message coming from an EE or the previous (downstream) PKI component MUST be sent to the next (upstream) PKI component. This PKI component MUST forward response messages to the next (downstream) PKI component or EE.

The (L)RA SHOULD verify the protection, the syntax, the required message fields, the message type, and if applicable the authorization and the proof-of-possession of the message. Additional checks or actions MAY be applied depending on the PKI solution requirements and concept. If one of these verification procedures fails, the (L)RA SHOULD respond with a negative response message and SHOULD not forward the message further upstream. General error conditions should be handled as described in Section 4.3 and Section 5.3.

An (L)RA SHOULD not change the received message if not necessary. The (L)RA SHOULD only update the message protection if it is technically necessary. Concrete PKI system specifications may define in more detail if and when to do so.

This is particularly relevant in the upstream communication of a request message.

Each hop in a chain of PKI components has one or more functionalities, e.g.:

- o An (L)RA may need to verify the identities of EEs or base authorization decisions for certification request processing on specific knowledge of the local setup, e.g., by consulting an inventory or asset management system.
- o An (L)RA may need to add fields to certificate request messages.
- o An (L)RA may need to store data from a message in a database for later usage or documentation purposes.
- o An (L)RA may provide traversal of a network boundary.
- o An (L)RA may need to double-check if the messages transferred back and forth are properly protected and well formed.
- o An RA can collect messages from different LRAs and forward them to the CA.

- o An (L)RA may provide a proof that it has performed all required checks.
- o An (L)RA may initiate a delayed enrollment due to offline upstream communication or registration officer interaction.
- o An (L)RA may grant the request of an EE to omit sending a confirmation message.

Therefore, the decision if a message should be forwarded

- o unchanged with the original protection,
- o unchanged with a new protection, or
- o changed with a new protection

depends on the PKI solution design and the associated security policy (CP/CPS [RFC3647]).

This section specifies the different options an (L)RA may implement and use.

An (L)RA MAY update the protection of a message

- o if the (L)RA performs changes to the header or the body of the message,
- o if the (L)RA needs to prove checks or validations performed on the message to one of the next (upstream) PKI components,
- o if the (L)RA needs to protect the message using a key and certificate from a different PKI, or
- o if the (L)RA needs to replace a MAC based-protection.

This is particularly relevant in the upstream communication of certificate request messages.

The message protection covers only the header and the body and not the extraCerts. The (L)RA MAY change the extraCerts in any of the following message adaptations, e.g., to sort or add needed or to delete needless certificates to support the next hop. This may be particularly helpful to extend upstream messages with additional certificates or to reduce the number of certificates in downstream messages when forwarding to constrained devices.

5.1.1. Not changing protection

This message adaptation can be used by any (L)RA to forward an original CMP message without changing the header, body or protection. In any of these cases the (L)RA acts more like a proxy, e.g., on a network boundary, implementing no specific RA-like security functionality to the PKI.

This message adaptation **MUST** be used for forwarding kur messages that must not be approved by the respective (L)RA.

5.1.2. Replacing protection

The following two message adaptations can be used by any (L)RA to forward a CMP message with or without changes, but providing its own protection using its CMP signer key providing approval of this message. In this case the (L)RA acts as an actual Registration Authority (RA), which implements important security functionality of the PKI.

Before replacing the existing protection by a new protection, the (L)RA **MUST** verify the protection provided by the EE or by the previous PKI component and approve its content including any own modifications. For certificate requests the (L)RA **MUST** verify in particular the included proof-of-possession self-signature of the certTemplate using the public key of the requested certificate and **MUST** check that the EE, as authenticated by the message protection, is authorized to request a certificate with the subject as specified in the certTemplate.

In case the received message has been protected by a CA or another (L)RA, the current (L)RA **MUST** verify its protection and approve its content including any own modifications. For certificate requests the (L)RA **MUST** check that the other (L)RA, as authenticated by the message protection, is authorized to issue or forward the request.

These message adaptations **MUST NOT** be applied to kur request messages as described in Section 4.1.2 since their original protection using the key and certificate to be updated needs to be preserved, unless the regCtrl OldCertId is used to clearly identify the certificate to be updated.

5.1.2.1. Keeping proof-of-possession

This message adaptation can be used by any (L)RA to forward a CMP message with or without modifying the message header or body while preserving any included proof-of-possession.

By replacing the existing using its own CMP signer key the (L)RA provides a proof of verifying and approving of the message as described above.

In case the (L)RA modifies the certTemplate of an ir or cr message, the message adaptation in Section 5.1.2.2 needs to be applied instead.

5.1.2.2. Breaking proof-of-possession

This message adaptation can be used by any (L)RA to forward an ir or cr message with modifications of the certTemplate i.e., modification, addition, or removal of fields. Such changes will break the proof-of-possession provided by the EE in the original message.

By replacing the existing or applying an initial protection using its own CMP signer key the (L)RA provides a proof of verifying and approving the new message as described above.

In addition to the above the (L)RA MUST verify in particular the proof-of-possession contained in the original message as described above. If these checks were successfully performed the (L)RA MUST change the popo to raVerified.

The popo field MUST contain the raVerified choice in the certReq structure of the modified message as follows:

```
popo
  raVerified          REQUIRED
-- MUST have the value NULL and indicates that the (L)RA
-- verified the popo of the original message.
```

5.1.3. Initiating delayed enrollment

This message adaptation can be used by an (L)RA to initiate delayed enrollment. In this case a (L)RA/CA MUST add the status waiting in the response message. The (L)RA/CA MUST then reply to the pollReq messages as described in Section 4.1.6.

5.1.4. Granting omitted confirmation

This message adaptation can be applied for omitted confirmation in case a (L)RA/CA grants the request to omit sending confirmation messages. This (L)RA/CA includes the implicitConfirm extension in the header of an ip, cp, or kup response message as described in Section 4.1.7.

5.2. Revoking certificates of other entities

This message sequence can be used by an (L)RA to revoke a certificate of any other entity. The revocation request message **MUST** be signed by the (L)RA using its own CMP signer key to prove to the PKI authorization to revoke the certificate on behalf of the EE.

< Details need to be defined later >

5.3. Error reporting

This functionality should be used by the (L)RA to report any error conditions downstream to the EE. Potential error reporting by the EE upstream to the (L)RA/CA is described in Section 4.3.

In case the error condition is related to specific details of an ir, cr, pl0cr, or kur request message it **MUST** be reported in the specific response message, i.e., an ip, cp, or kup with negative contents.

General error conditions, e.g., problems with the message header, protection, or extraCerts, and negative feedback on rr, pollReq, certConf, or error messages **MUST** be reported in the form of an error message.

In both situations the (L)RA reports the errors in the PKIStatusInfo structure of the respective message as described in Section 4.3.

An EE receiving any such negative feedback **SHOULD** log the error appropriately and **MUST** terminate the current transaction.

6. CMP message transport variants

The CMP messages are designed to be self-contained, such that in principle any transport can be used. HTTP **SHOULD** be used for online transport while file-based transport **MAY** be used in case offline transport is required. In case HTTP transport is not desired or possible, CMP messages **MAY** also be piggybacked on any other reliable transport protocol, e.g., CoAP [RFC7252].

Independently of the means of transport it could happen that messages are lost, or a communication partner does not respond. In order to prevent waiting indefinitely, each CMP client component **SHOULD** use a configurable per-request timeout, and each CMP server component **SHOULD** use a configurable per-response timeout in case a further message is to be expected from the client side. In this way a hanging transaction can be closed cleanly with an error and related resources (for instance, any cached extraCerts) can be freed.

6.1. HTTP transport

This transport mechanism can be used by an EE and (L)RA/CA to transfer CMP messages over HTTP. If HTTP transport is used the specifications as described in [RFC6712] MUST be followed.

6.2. HTTPS transport using certificates

This transport mechanism can be used by an EE and (L)RA/CA to further protect the HTTP transport as described in Section 6.1 using TLS 1.2 [RFC5246] or TLS 1.3 [RFC8446] as described in [RFC2818] with certificate-based authentication. Using this transport mechanism, the CMP transport via HTTPS MUST use TLS server authentication and SHOULD use TLS client authentication.

EE:

- o The EE SHOULD use a TLS client certificate as far as available. If no dedicated TLS certificate is available the EE SHOULD use an already existing certificate identifying the EE (e.g., a manufacturer certificate).
- o If no TLS certificate is available at the EE, server-only authenticated TLS SHOULD be used.
- o The EE MUST validate the TLS server certificate of its communication partner.

(L)RA:

- o Each (L)RA SHOULD use a TLS client certificate on its upstream (client) interface.
- o Each (L)RA SHOULD use a TLS server certificate on its downstream (server) interface.
- o Each (L)RA MUST validate the TLS certificate of its communication partner.

NOTE: The requirements for checking certificates given in [RFC5280], [RFC5246] and [RFC8446] MUST be followed for the TLS layer. OCSP or CRLs SHOULD be used for status checking of the TLS certificates of communication partners.

6.3. HTTPS transport using shared secrets

This transport mechanism can be used by an EE and (L)RA/CA to further protect the HTTP transport as described in Section 6.1 using TLS 1.2 [RFC5246] or TLS 1.3 [RFC8446] as described in [RFC2818] with mutual authentication based on shared secrets as described in [RFC5054].

EE:

- o The EE MUST use the shared symmetric key for authentication.

(L)RA:

- o The (L)RA MUST use the shared symmetric key for authentication.

6.4. File-based transport

For offline transfer file-based transport MAY be used. Offline transport is typically used between LRA and RA nodes.

Connection and error handling mechanisms like those specified for HTTP in [RFC6712] need to be implemented.

< Details need to be defined later >

6.5. CoAP transport

In constrained environments where no HTTP transport is desired or possible, CoAP [RFC7252] MAY be used instead.

Connection and error handling mechanisms like those specified for HTTP in [RFC6712] need to be implemented.

< Details need to be defined later >

6.6. Piggybacking on other reliable transport

For online transfer where no HTTP transport is desired or possible CMP messages MAY also be transported on some other reliable protocol.

Connection and error handling mechanisms like those specified for HTTP in [RFC6712] need to be implemented.

< Details need to be defined later >

7. IANA Considerations

<Add any IANA considerations>

8. Security Considerations

<Add any security considerations>

9. Acknowledgements

We would like to thank the various reviewers of this CMP profile.

10. References

10.1. Normative References

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Appendix A. Additional Stuff

This becomes an Appendix.

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Use of the HSS/LMS Hash-based Signature Algorithm
in the Cryptographic Message Syntax (CMS)
<draft-ietf-lamps-cms-hash-sig-10>

Abstract

This document specifies the conventions for using the Hierarchical Signature System (HSS) / Leighton-Micali Signature (LMS) hash-based signature algorithm with the Cryptographic Message Syntax (CMS). In addition, the algorithm identifier and public key syntax are provided. The HSS/LMS algorithm is one form of hash-based digital signature; it is described in RFC 8554.

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1. Introduction

This document specifies the conventions for using the Hierarchical Signature System (HSS) / Leighton-Micali Signature (LMS) hash-based signature algorithm with the Cryptographic Message Syntax (CMS) [CMS] signed-data content type. The LMS system provides a one-time digital signature that is a variant of Merkle Tree Signatures (MTS). The HSS is built on top of the LMS system to efficiently scale for a larger numbers of signatures. The HSS/LMS algorithm is one form of hash-based digital signature, and it is described in [HASHSIG]. The HSS/LMS signature algorithm can only be used for a fixed number of signing operations with a given private key, and the number of signing operations depends upon the size of the tree. The HSS/LMS signature algorithm uses small public keys, and it has low computational cost; however, the signatures are quite large. The HSS/LMS private key can be very small when the signer is willing to perform additional computation at signing time; alternatively, the private key can consume additional memory and provide a faster signing time. The HSS/LMS signatures [HASHSIG] are currently defined to use exclusively SHA-256 [SHS].

1.1. ASN.1

CMS values are generated using ASN.1 [ASN1-B], using the Basic Encoding Rules (BER) and the Distinguished Encoding Rules (DER) [ASN1-E].

1.2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

1.3. Motivation

Recent advances in cryptanalysis [BH2013] and progress in the development of quantum computers [NAS2019] pose a threat to widely deployed digital signature algorithms. As a result, there is a need to prepare for a day that cryptosystems such as RSA and DSA that depend on discrete logarithm and factoring cannot be depended upon.

If large-scale quantum computers are ever built, these computers will be able to break many of the public-key cryptosystems currently in use. A post-quantum cryptosystem [PQC] is a system that is secure against quantum computers that have more than a trivial number of quantum bits (qubits). It is open to conjecture when it will be

feasible to build such computers; however, RSA, DSA, ECDSA, and EdDSA are all vulnerable if large-scale quantum computers come to pass.

Since the HSS/LMS signature algorithm does not depend on the difficulty of discrete logarithm or factoring, the HSS/LMS signature algorithm is considered to be post-quantum secure. One use of post-quantum secure signatures is the protection of software updates, perhaps using the format described in [FWPROT], to enable deployment of software that implements new cryptosystems.

2. HSS/LMS Hash-based Signature Algorithm Overview

Merkle Tree Signatures (MTS) are a method for signing a large but fixed number of messages. An MTS system depends on a one-time signature method and a collision-resistant hash function.

This specification makes use of the hash-based algorithm specified in [HASHSIG], which is the Leighton and Micali adaptation [LM] of the original Lamport-Diffie-Winternitz-Merkle one-time signature system [M1979] [M1987] [M1989a] [M1989b].

As implied by the name, the hash-based signature algorithm depends on a collision-resistant hash function. The hash-based signature algorithm specified in [HASHSIG] uses only the SHA-256 one-way hash function [SHS], but it establishes an IANA registry [IANA-LMS] to permit the registration of additional one-way hash functions in the future.

2.1. Hierarchical Signature System (HSS)

The MTS system specified in [HASHSIG] uses a hierarchy of trees. The Hierarchical N-time Signature System (HSS) allows subordinate trees to be generated when needed by the signer. Otherwise, generation of the entire tree might take weeks or longer.

An HSS signature as specified in [HASHSIG] carries the number of signed public keys (Nspk), followed by that number of signed public keys, followed by the LMS signature as described in Section 2.2. The public key for the top-most LMS tree is the public key of the HSS system. The LMS private key in the parent tree signs the LMS public key in the child tree, and the LMS private key in the bottom-most tree signs the actual message. The signature over the public key and the signature over the actual message are LMS signatures as described in Section 2.2.

The elements of the HSS signature value for a stand-alone tree (a top tree with no children) can be summarized as:

```
u32str(0) ||
lms_signature /* signature of message */
```

where, `u32str()` and `||` are used as defined in [HASHSIG].

The elements of the HSS signature value for a tree with `Nspk` signed public keys can be summarized as:

```
u32str(Nspk) ||
signed_public_key[0] ||
signed_public_key[1] ||
...
signed_public_key[Nspk-2] ||
signed_public_key[Nspk-1] ||
lms_signature /* signature of message */
```

where, as defined in Section 3.3 of [HASHSIG], the `signed_public_key` structure contains the `lms_signature` over the public key followed by the public key itself. Note that `Nspk` is the number of levels in the hierarchy of trees minus 1.

2.2. Leighton-Micali Signature (LMS)

Each tree in the system specified in [HASHSIG] uses the Leighton-Micali Signature (LMS) system. LMS systems have two parameters. The first parameter is the height of the tree, `h`, which is the number of levels in the tree minus one. The [HASHSIG] specification supports five values for this parameter: `h=5`; `h=10`; `h=15`; `h=20`; and `h=25`. Note that there are 2^h leaves in the tree. The second parameter, `m`, is the number of bytes output by the hash function, and it is the amount of data associated with each node in the tree. The [HASHSIG] specification supports only the SHA-256 hash function [SHS], with `m=32`. As a result, the [HASHSIG] specification supports five tree sizes; they are identified as:

```
LMS_SHA256_M32_H5;
LMS_SHA256_M32_H10;
LMS_SHA256_M32_H15;
LMS_SHA256_M32_H20; and
LMS_SHA256_M32_H25.
```

The [HASHSIG] specification establishes an IANA registry [IANA-LMS] to permit the registration of additional hash functions and additional tree sizes in the future.

As specified in [HASHSIG], the LMS public key consists of four elements: the `lms_algorithm_type` from the list above, the `otstype` to identify the LM-OTS type as discussed in Section 2.3, the private key identifier (I) as described in Section 5.3 of [HASHSIG], and the m-byte string associated with the root node of the tree (`T[1]`).

The LMS public key can be summarized as:

```
u32str(lms_algorithm_type) || u32str(otstype) || I || T[1]
```

As specified in [HASHSIG], an LMS signature consists of four elements: the number of the leaf (`q`) associated with the LM-OTS signature, an LM-OTS signature as described in Section 2.3, a typecode indicating the particular LMS algorithm, and an array of values that is associated with the path through the tree from the leaf associated with the LM-OTS signature to the root. The array of values contains the siblings of the nodes on the path from the leaf to the root but does not contain the nodes on the path itself. The array for a tree with height `h` will have `h` values. The first value is the sibling of the leaf, the next value is the sibling of the parent of the leaf, and so on up the path to the root.

The four elements of the LMS signature value can be summarized as:

```
u32str(q) ||
ots_signature ||
u32str(type) ||
path[0] || path[1] || ... || path[h-1]
```

2.3. Leighton-Micali One-time Signature Algorithm (LM-OTS)

Merkle Tree Signatures (MTS) depend on a one-time signature method, and [HASHSIG] specifies the use of the LM-OTS, which has five parameters:

- `n` - The length in bytes of the hash function output. [HASHSIG] supports only SHA-256 [SHS], with `n=32`.
- `H` - A preimage-resistant hash function that accepts byte strings of any length, and returns an `n`-byte string.
- `w` - The width in bits of the Winternitz coefficients. [HASHSIG] supports four values for this parameter: `w=1`; `w=2`; `w=4`; and `w=8`.
- `p` - The number of `n`-byte string elements that make up the LM-OTS signature.

ls - The number of bits that are left-shifted in the final step of the checksum function, which is defined in Section 4.4 of [HASHSIG].

The values of p and ls are dependent on the choices of the parameters n and w, as described in Appendix B of [HASHSIG].

The [HASHSIG] specification supports four LM-OTS variants:

```
LMOTS_SHA256_N32_W1;
LMOTS_SHA256_N32_W2;
LMOTS_SHA256_N32_W4; and
LMOTS_SHA256_N32_W8.
```

The [HASHSIG] specification establishes an IANA registry [IANA-LMS] to permit the registration of additional variants in the future.

Signing involves the generation of C, an n-byte random value.

The LM-OTS signature value can be summarized as the identifier of the LM-OTS variant, the random value, and a sequence of hash values (y[0] through y[p-1]) that correspond to the elements of the public key as described in Section 4.5 of [HASHSIG]:

```
u32str(otstype) || C || y[0] || ... || y[p-1]
```

3. Algorithm Identifiers and Parameters

The algorithm identifier for an HSS/LMS hash-based signatures is:

```
id-alg-hss-lms-hashsig OBJECT IDENTIFIER ::= { iso(1)
  member-body(2) us(840) rsadsi(113549) pkcs(1) pkcs9(9)
  smime(16) alg(3) 17 }
```

When this object identifier is used for an HSS/LMS signature, the AlgorithmIdentifier parameters field MUST be absent (that is, the parameters are not present; the parameters are not set to NULL).

The signature value is a large OCTET STRING as described in Section 2 of this document. The signature format is designed for easy parsing. The HSS, LMS, and LMOTS component of the signature value each format include a counter and a type code that indirectly provide all of the information that is needed to parse the value during signature validation.

The signature value identifies the hash function used in the HSS/LMS tree. In [HASHSIG] uses only the SHA-256 hash function [SHS], but it establishes an IANA registry [IANA-LMS] to permit the registration of

additional hash functions in the future.

4. HSS/LMS Public Key Identifier

The AlgorithmIdentifier for an HSS/LMS public key uses the id-alg-hss-lms-hashsig object identifier, and the parameters field MUST be absent.

When this AlgorithmIdentifier appears in the SubjectPublicKeyInfo field of an X.509 certificate [RFC5280], the certificate key usage extension MAY contain digitalSignature, nonRepudiation, keyCertSign, and cRLSign; however, it MUST NOT contain other values.

```
pk-HSS-LMS-HashSig PUBLIC-KEY ::= {
    IDENTIFIER id-alg-hss-lms-hashsig
    KEY HSS-LMS-HashSig-PublicKey
    PARAMS ARE absent
    CERT-KEY-USAGE
        { digitalSignature, nonRepudiation, keyCertSign, cRLSign } }
```

```
HSS-LMS-HashSig-PublicKey ::= OCTET STRING
```

Note that the id-alg-hss-lms-hashsig algorithm identifier is also referred to as id-alg-mts-hashsig. This synonym is based on the terminology used in an early draft of the document that became [HASHSIG].

The public key value is an OCTET STRING. Like the signature format, it is designed for easy parsing. The value is the number of levels in the public key, L, followed by the LMS public key.

The HSS/LMS public key value can be described as:

```
u32str(L) || lms_public_key
```

Note that the public key for the top-most LMS tree is the public key of the HSS system. When L=1, the HSS system is a single tree.

5. Signed-data Conventions

As specified in [CMS], the digital signature is produced from the message digest and the signer's private key. The signature is computed over different values depending on whether signed attributes are absent or present.

When signed attributes are absent, the HSS/LMS signature is computed over the content. When signed attributes are present, a hash is computed over the content using the same hash function that is used

in the HSS/LMS tree, and then a message-digest attribute is constructed with the hash of the content, and then the HSS/LMS signature is computed over the DER-encoded set of signed attributes (which MUST include a content-type attribute and a message-digest attribute). In summary:

```
IF (signed attributes are absent)
THEN HSS_LMS_Sign(content)
ELSE message-digest attribute = Hash(content);
     HSS_LMS_Sign(DER(SignedAttributes))
```

When using [HASHSIG], the fields in the SignerInfo are used as follows:

digestAlgorithm MUST contain the one-way hash function used in the HSS/LMS tree. In [HASHSIG], SHA-256 is the only supported hash function, but other hash functions might be registered in the future. For convenience, the AlgorithmIdentifier for SHA-256 from [PKIXASN1] is repeated here:

```
mda-sha256 DIGEST-ALGORITHM ::= {
    IDENTIFIER id-sha256
    PARAMS TYPE NULL ARE preferredAbsent }
```

```
id-sha256 OBJECT IDENTIFIER ::= { joint-iso-itu-t(2)
    country(16) us(840) organization(1) gov(101) csor(3)
    nistAlgorithms(4) hashalgs(2) 1 }
```

signatureAlgorithm MUST contain id-alg-hss-lms-hashsig, and the algorithm parameters field MUST be absent.

signature contains the single HSS signature value resulting from the signing operation as specified in [HASHSIG].

6. Security Considerations

Implementations MUST protect the private keys. Compromise of the private keys may result in the ability to forge signatures. Along with the private key, the implementation MUST keep track of which leaf nodes in the tree have been used. Loss of integrity of this tracking data can cause a one-time key to be used more than once. As a result, when a private key and the tracking data are stored on non-volatile media or stored in a virtual machine environment, failed writes, virtual machine snapshotting or cloning, and other operational concerns must be considered to ensure confidentiality and integrity.

When generating an LMS key pair, an implementation MUST generate each

key pair independently of all other key pairs in the HSS tree.

An implementation **MUST** ensure that a LM-OTS private key is used to generate a signature only one time, and ensure that it cannot be used for any other purpose.

The generation of private keys relies on random numbers. The use of inadequate pseudo-random number generators (PRNGs) to generate these values can result in little or no security. An attacker may find it much easier to reproduce the PRNG environment that produced the keys, searching the resulting small set of possibilities, rather than brute force searching the whole key space. The generation of quality random numbers is difficult, and [RFC4086] offers important guidance in this area.

The generation of hash-based signatures also depends on random numbers. While the consequences of an inadequate pseudo-random number generator (PRNG) to generate these values is much less severe than in the generation of private keys, the guidance in [RFC4086] remains important.

When computing signatures, the same hash function **SHOULD** be used to compute the message digest of the content and the signed attributes, if they are present.

7. IANA Considerations

SMI Security for S/MIME Module Identifier (1.2.840.113549.1.9.16.0) registry, change the reference for value 64 to point to this document.

In the SMI Security for S/MIME Algorithms (1.2.840.113549.1.9.16.3) registry, change the description for value 17 to "id-alg-hss-lms-hashsig" and change the reference to point to this document.

Also, add the following note to the registry:

Value 17, "id-alg-hss-lms-hashsig", is also referred to as "id-alg-mts-hashsig".

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Appendix: ASN.1 Module

```
<CODE STARTS>

MTS-HashSig-2013
{ iso(1) member-body(2) us(840) rsadsi(113549) pkcs(1) pkcs9(9)
  id-smime(16) id-mod(0) id-mod-mts-hashsig-2013(64) }

DEFINITIONS IMPLICIT TAGS ::= BEGIN

EXPORTS ALL;

IMPORTS
  PUBLIC-KEY, SIGNATURE-ALGORITHM, SMIME-CAPS
  FROM AlgorithmInformation-2009 -- RFC 5911 [CMSASN1]
  { iso(1) identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) id-mod(0)
    id-mod-algorithmInformation-02(58) } ;

--
-- Object Identifiers
--

id-alg-hss-lms-hashsig OBJECT IDENTIFIER ::= { iso(1)
  member-body(2) us(840) rsadsi(113549) pkcs(1) pkcs9(9)
  smime(16) alg(3) 17 }

id-alg-mts-hashsig OBJECT IDENTIFIER ::= id-alg-hss-lms-hashsig

--
-- Signature Algorithm and Public Key
--

sa-HSS-LMS-HashSig SIGNATURE-ALGORITHM ::= {
  IDENTIFIER id-alg-hss-lms-hashsig
  PARAMS ARE absent
  PUBLIC-KEYS { pk-HSS-LMS-HashSig }
  SMIME-CAPS { IDENTIFIED BY id-alg-hss-lms-hashsig } }
```

```
pk-HSS-LMS-HashSig PUBLIC-KEY ::= {
    IDENTIFIER id-alg-hss-lms-hashsig
    KEY HSS-LMS-HashSig-PublicKey
    PARAMS ARE absent
    CERT-KEY-USAGE
        { digitalSignature, nonRepudiation, keyCertSign, cRLSign } }

HSS-LMS-HashSig-PublicKey ::= OCTET STRING

--
-- Expand the signature algorithm set used by CMS [CMSASN1U]
--

SignatureAlgorithmSet SIGNATURE-ALGORITHM ::=
    { sa-HSS-LMS-HashSig, ... }

--
-- Expand the S/MIME capabilities set used by CMS [CMSASN1]
--

SMimeCaps SMIME-CAPS ::=
    { sa-HSS-LMS-HashSig.&smimeCaps, ... }

END

<CODE ENDS>
```

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Using Pre-Shared Key (PSK) in the Cryptographic Message Syntax (CMS)
<draft-ietf-lamps-cms-mix-with-psk-07.txt>

Abstract

The invention of a large-scale quantum computer would pose a serious challenge for the cryptographic algorithms that are widely deployed today. The Cryptographic Message Syntax (CMS) supports key transport and key agreement algorithms that could be broken by the invention of such a quantum computer. By storing communications that are protected with the CMS today, someone could decrypt them in the future when a large-scale quantum computer becomes available. Once quantum-secure key management algorithms are available, the CMS will be extended to support the new algorithms, if the existing syntax does not accommodate them. In the near-term, this document describes a mechanism to protect today's communication from the future invention of a large-scale quantum computer by mixing the output of key transport and key agreement algorithms with a pre-shared key.

Status of this Memo

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1. Introduction

The invention of a large-scale quantum computer would pose a serious challenge for the cryptographic algorithms that are widely deployed today [S1994]. It is an open question whether or not it is feasible to build a large-scale quantum computer, and if so, when that might happen [NAS2019]. However, if such a quantum computer is invented, many of the cryptographic algorithms and the security protocols that use them would become vulnerable.

The Cryptographic Message Syntax (CMS) [RFC5652][RFC5083] supports key transport and key agreement algorithms that could be broken by the invention of a large-scale quantum computer [C2PQ]. These algorithms include RSA [RFC8017], Diffie-Hellman [RFC2631], and Elliptic Curve Diffie-Hellman [RFC5753]. As a result, an adversary that stores CMS-protected communications today, could decrypt those communications in the future when a large-scale quantum computer becomes available.

Once quantum-secure key management algorithms are available, the CMS will be extended to support them, if the existing syntax does not already accommodate the new algorithms.

In the near-term, this document describes a mechanism to protect today's communication from the future invention of a large-scale quantum computer by mixing the output of existing key transport and key agreement algorithms with a pre-shared key (PSK). Secure communication can be achieved today by mixing a strong PSK with the output of an existing key transport algorithm, like RSA [RFC8017], or an existing key agreement algorithm, like Diffie-Hellman [RFC2631] or Elliptic Curve Diffie-Hellman [RFC5753]. A security solution that is believed to be quantum resistant can be achieved by using a PSK with sufficient entropy along with a quantum resistant key derivation function (KDF), like HKDF [RFC5869], and a quantum resistant encryption algorithm, like 256-bit AES [AES]. In this way, today's CMS-protected communication can be resistant to an attacker with a large-scale quantum computer.

In addition, there may be other reasons for including a strong PSK besides protection against the future invention of a large-scale quantum computer. For example, there is always the possibility of a cryptanalytic breakthrough on one or more of the classic public-key algorithm, and there are longstanding concerns about undisclosed trapdoors in Diffie-Hellman parameters [FGHT2016]. Inclusion of a strong PSK as part of the overall key management offer additional protection against these concerns.

Note that the CMS also supports key management techniques based on symmetric key-encryption keys and passwords, but they are not discussed in this document because they are already quantum resistant. The symmetric key-encryption key technique is quantum resistant when used with an adequate key size. The password technique is quantum resistant when used with a quantum-resistant key derivation function and a sufficiently large password.

1.1. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

1.2. ASN.1

CMS values are generated using ASN.1 [X680], which uses the Basic Encoding Rules (BER) and the Distinguished Encoding Rules (DER) [X690].

1.3. Version Numbers

The major data structures include a version number as the first item in the data structure. The version number is intended to avoid ASN.1 decode errors. Some implementations do not check the version number prior to attempting a decode, and then if a decode error occurs, the version number is checked as part of the error handling routine. This is a reasonable approach; it places error processing outside of the fast path. This approach is also forgiving when an incorrect version number is used by the sender.

Whenever the structure is updated, a higher version number will be assigned. However, to ensure maximum interoperability, the higher version number is only used when the new syntax feature is employed. That is, the lowest version number that supports the generated syntax is used.

2. Overview

The CMS enveloped-data content type [RFC5652] and the CMS authenticated-enveloped-data content type [RFC5083] support both key transport and key agreement public-key algorithms to establish the key used to encrypt the content. No restrictions are imposed on the key transport or key agreement public-key algorithms, which means that any key transport or key agreement algorithm can be used, including algorithms that are specified in the future. In both cases, the sender randomly generates the content-encryption key, and then all recipients obtain that key. All recipients use the sender-generated symmetric content-encryption key for decryption.

This specification defines two quantum-resistant ways to establish a symmetric key-encryption key, which is used to encrypt the sender-generated content-encryption key. In both cases, the PSK is used as one of the inputs to a key-derivation function to create a quantum-

resistant key-encryption key. The PSK MUST be distributed to the sender and all of the recipients by some out-of-band means that does not make it vulnerable to the future invention of a large-scale quantum computer, and an identifier MUST be assigned to the PSK. It is best if each PSK has a unique identifier; however, if a recipient has more than one PSK with the same identifier, the recipient can try each of them in turn. A PSK is expected to be used with many messages, with a lifetime of weeks or months.

The content-encryption key or content-authenticated-encryption key is quantum-resistant, and the sender establishes it using these steps:

When using a key transport algorithm:

1. The content-encryption key or the content-authenticated-encryption key, called CEK, is generated at random.
2. The key-derivation key, called KDK, is generated at random.
3. For each recipient, the KDK is encrypted in the recipient's public key, then the key derivation function (KDF) is used to mix the pre-shared key (PSK) and the KDK to produce the key-encryption key, called KEK.
4. The KEK is used to encrypt the CEK.

When using a key agreement algorithm:

1. The content-encryption key or the content-authenticated-encryption key, called CEK, is generated at random.
2. For each recipient, a pairwise key-encryption key, called KEK1, is established using the recipient's public key and the sender's private key. Note that KEK1 will be used as a key-derivation key.
3. For each recipient, the key derivation function (KDF) is used to mix the pre-shared key (PSK) and the pairwise KEK1, and the result is called KEK2.
4. For each recipient, the pairwise KEK2 is used to encrypt the CEK.

As specified in Section 6.2.5 of [RFC5652], recipient information for additional key management techniques are represented in the OtherRecipientInfo type. Two key management techniques are specified in this document, and they are each identified by a unique ASN.1 object identifier.

The first key management technique, called keyTransPSK, see Section 3, uses a key transport algorithm to transfer the key-derivation key from the sender to the recipient, and then the key-derivation key is mixed with the PSK using a KDF. The output of the KDF is the key-encryption key, which is used for the encryption of the content-encryption key or content-authenticated-encryption key.

The second key management technique, called keyAgreePSK, see Section 4, uses a key agreement algorithm to establish a pairwise key-encryption key, which is then mixed with the PSK using a KDF to produce a second pairwise key-encryption key, which is then used to encrypt the content-encryption key or content-authenticated-encryption key.

3. keyTransPSK

Per-recipient information using keyTransPSK is represented in the KeyTransPSKRecipientInfo type, which is indicated by the id-ori-keyTransPSK object identifier. Each instance of KeyTransPSKRecipientInfo establishes the content-encryption key or content-authenticated-encryption key for one or more recipients that have access to the same PSK.

The id-ori-keyTransPSK object identifier is:

```
id-ori OBJECT IDENTIFIER ::= { iso(1) member-body(2) us(840)
    rsadsi(113549) pkcs(1) pkcs-9(9) smime(16) TBD1 }

id-ori-keyTransPSK OBJECT IDENTIFIER ::= { id-ori 1 }
```

The KeyTransPSKRecipientInfo type is:

```
KeyTransPSKRecipientInfo ::= SEQUENCE {
    version CMSVersion, -- always set to 0
    pskid PreSharedKeyIdentifier,
    kdfAlgorithm KeyDerivationAlgorithmIdentifier,
    keyEncryptionAlgorithm KeyEncryptionAlgorithmIdentifier,
    ktris KeyTransRecipientInfos,
    encryptedKey EncryptedKey }

PreSharedKeyIdentifier ::= OCTET STRING

KeyTransRecipientInfos ::= SEQUENCE OF KeyTransRecipientInfo
```

The fields of the KeyTransPSKRecipientInfo type have the following meanings:

version is the syntax version number. The version MUST be 0. The CMSVersion type is described in Section 10.2.5 of [RFC5652].

pskid is the identifier of the PSK used by the sender. The identifier is an OCTET STRING, and it need not be human readable.

kdfAlgorithm identifies the key-derivation algorithm, and any associated parameters, used by the sender to mix the key-derivation key and the PSK to generate the key-encryption key. The KeyDerivationAlgorithmIdentifier is described in Section 10.1.6 of [RFC5652].

keyEncryptionAlgorithm identifies a key-encryption algorithm used to encrypt the content-encryption key. The KeyEncryptionAlgorithmIdentifier is described in Section 10.1.3 of [RFC5652].

ktris contains one KeyTransRecipientInfo type for each recipient; it uses a key transport algorithm to establish the key-derivation key. That is, the encryptedKey field of KeyTransRecipientInfo contains the key-derivation key instead of the content-encryption key. KeyTransRecipientInfo is described in Section 6.2.1 of [RFC5652].

encryptedKey is the result of encrypting the content-encryption key or the content-authenticated-encryption key with the key-encryption key. EncryptedKey is an OCTET STRING.

4. keyAgreePSK

Per-recipient information using keyAgreePSK is represented in the KeyAgreePSKRecipientInfo type, which is indicated by the id-ori-keyAgreePSK object identifier. Each instance of KeyAgreePSKRecipientInfo establishes the content-encryption key or content-authenticated-encryption key for one or more recipients that have access to the same PSK.

The id-ori-keyAgreePSK object identifier is:

```
id-ori-keyAgreePSK OBJECT IDENTIFIER ::= { id-ori 2 }
```

The KeyAgreePSKRecipientInfo type is:

```
KeyAgreePSKRecipientInfo ::= SEQUENCE {  
    version CMSVersion, -- always set to 0  
    pskid PreSharedKeyIdentifier,  
    originator [0] EXPLICIT OriginatorIdentifierOrKey,  
    ukm [1] EXPLICIT UserKeyingMaterial OPTIONAL,  
    kdfAlgorithm KeyDerivationAlgorithmIdentifier,  
    keyEncryptionAlgorithm KeyEncryptionAlgorithmIdentifier,  
    recipientEncryptedKeys RecipientEncryptedKeys }
```

The fields of the KeyAgreePSKRecipientInfo type have the following meanings:

version is the syntax version number. The version MUST be 0. The CMSVersion type is described in Section 10.2.5 of [RFC5652].

pskid is the identifier of the PSK used by the sender. The identifier is an OCTET STRING, and it need not be human readable.

originator is a CHOICE with three alternatives specifying the sender's key agreement public key. Implementations MUST support all three alternatives for specifying the sender's public key. The sender uses their own private key and the recipient's public key to generate a pairwise key-encryption key. A key derivation function (KDF) is used to mix the PSK and the pairwise key-encryption key to produce a second key-encryption key. The OriginatorIdentifierOrKey type is described in Section 6.2.2 of [RFC5652].

ukm is optional. With some key agreement algorithms, the sender provides a User Keying Material (UKM) to ensure that a different key is generated each time the same two parties generate a pairwise key. Implementations MUST accept a KeyAgreePSKRecipientInfo SEQUENCE that includes a ukm field. Implementations that do not support key agreement algorithms that make use of UKMs MUST gracefully handle the presence of UKMs. The UserKeyingMaterial type is described in Section 10.2.6 of [RFC5652].

kdfAlgorithm identifies the key-derivation algorithm, and any associated parameters, used by the sender to mix the pairwise key-encryption key and the PSK to produce a second key-encryption key of the same length as the first one. The KeyDerivationAlgorithmIdentifier is described in Section 10.1.6 of [RFC5652].

keyEncryptionAlgorithm identifies a key-encryption algorithm used to encrypt the content-encryption key or the content-authenticated-encryption key. The KeyEncryptionAlgorithmIdentifier type is described in Section 10.1.3 of [RFC5652].

recipientEncryptedKeys includes a recipient identifier and encrypted key for one or more recipients. The KeyAgreeRecipientIdentifier is a CHOICE with two alternatives specifying the recipient's certificate, and thereby the recipient's public key, that was used by the sender to generate a pairwise key-encryption key. The encryptedKey is the result of encrypting the content-encryption key or the content-authenticated-encryption key with the second pairwise key-encryption key. EncryptedKey is an OCTET STRING. The RecipientEncryptedKeys type is defined in Section 6.2.2 of [RFC5652].

5. Key Derivation

Many key derivation functions (KDFs) internally employ a one-way hash function. When this is the case, the hash function that is used is indirectly indicated by the KeyDerivationAlgorithmIdentifier. HKDF [RFC5869] is one example of a KDF that makes use of a hash function.

Other KDFs internally employ an encryption algorithm. When this is the case, the encryption that is used is indirectly indicated by the KeyDerivationAlgorithmIdentifier. For example, AES-128-CMAC can be used for randomness extraction in a KDF as described in [NIST2018].

A KDF has several input values. This section describes the conventions for using the KDF to compute the key-encryption key for KeyTransPSKRecipientInfo and KeyAgreePSKRecipientInfo. For simplicity, the terminology used in the HKDF [RFC5869] specification is used here.

The KDF inputs are:

IKM is the input keying material; it is the symmetric secret input to the KDF. For KeyTransPSKRecipientInfo, it is the key-derivation key. For KeyAgreePSKRecipientInfo, it is the pairwise key-encryption key produced by the key agreement algorithm.

salt is an optional non-secret random value. Many KDFs do not require a salt, and the KeyDerivationAlgorithmIdentifier assignments for HKDF [RFC8619] do not offer a parameter for a salt. If a particular KDF requires a salt, then the salt value is provided as a parameter of the KeyDerivationAlgorithmIdentifier.

L is the length of output keying material in octets; the value depends on the key-encryption algorithm that will be used. The algorithm is identified by the KeyEncryptionAlgorithmIdentifier. In addition, the OBJECT IDENTIFIER portion of the KeyEncryptionAlgorithmIdentifier is included in the next input value, called info.

info is optional context and application specific information. The DER-encoding of CMSORIforPSKOtherInfo is used as the info value, and the PSK is included in this structure. Note that EXPLICIT tagging is used in the ASN.1 module that defines this structure. For KeyTransPSKRecipientInfo, the ENUMERATED value of 5 is used. For KeyAgreePSKRecipientInfo, the ENUMERATED value of 10 is used. CMSORIforPSKOtherInfo is defined by the following ASN.1 structure:

```
CMSORIforPSKOtherInfo ::= SEQUENCE {
    psk                OCTET STRING,
    keyMgmtAlgType      ENUMERATED {
        keyTrans        (5),
        keyAgree         (10) },
    keyEncryptionAlgorithm KeyEncryptionAlgorithmIdentifier,
    pskLength           INTEGER (1..MAX),
    kdkLength           INTEGER (1..MAX) }
```

The fields of type CMSORIforPSKOtherInfo have the following meanings:

psk is an OCTET STRING; it contains the PSK.

keyMgmtAlgType is either set to 5 or 10. For KeyTransPSKRecipientInfo, the ENUMERATED value of 5 is used. For KeyAgreePSKRecipientInfo, the ENUMERATED value of 10 is used.

keyEncryptionAlgorithm is the KeyEncryptionAlgorithmIdentifier, which identifies the algorithm and provides algorithm parameters, if any.

pskLength is a positive integer; it contains the length of the PSK in octets.

kdkLength is a positive integer; it contains the length of the key-derivation key in octets. For KeyTransPSKRecipientInfo, the key-derivation key is generated by the sender. For KeyAgreePSKRecipientInfo, the key-derivation key is the pairwise key-encryption key produced by the key agreement algorithm.

The KDF output is:

OKM is the output keying material, which is exactly L octets. The OKM is the key-encryption key that is used to encrypt the content-encryption key or the content-authenticated-encryption key.

An acceptable KDF MUST accept IKM, L, and info inputs; and acceptable KDF MAY also accept salt and other inputs. All of these inputs MUST influence the output of the KDF. If the KDF requires a salt or other inputs, then those inputs MUST be provided as parameters of the KeyDerivationAlgorithmIdentifier.

6. ASN.1 Module

This section contains the ASN.1 module for the two key management techniques defined in this document. This module imports types from other ASN.1 modules that are defined in [RFC5912] and [RFC6268].

<CODE BEGINS>

CMSORIforPSK-2019

```
{ iso(1) member-body(2) us(840) rsadsi(113549) pkcs(1) pkcs-9(9)
  smime(16) modules(0) id-mod-cms-ori-psk-2019(TBD0) }
```

DEFINITIONS EXPLICIT TAGS ::=
BEGIN

-- EXPORTS All

IMPORTS

AlgorithmIdentifier{}, KEY-DERIVATION

```
FROM AlgorithmInformation-2009 -- [RFC5912]
{ iso(1) identified-organization(3) dod(6) internet(1)
  security(5) mechanisms(5) pkix(7) id-mod(0)
  id-mod-algorithmInformation-02(58) }
```

```
OTHER-RECIPIENT, OtherRecipientInfo, CMSVersion,
KeyTransRecipientInfo, OriginatorIdentifierOrKey,
UserKeyingMaterial, RecipientEncryptedKeys, EncryptedKey,
KeyDerivationAlgorithmIdentifier, KeyEncryptionAlgorithmIdentifier
FROM CryptographicMessageSyntax-2010 -- [RFC6268]
{ iso(1) member-body(2) us(840) rsadsi(113549)
  pkcs(1) pkcs-9(9) smime(16) modules(0)
  id-mod-cms-2009(58) } ;
```

```
--
-- OtherRecipientInfo Types (ori-)
--

SupportedOtherRecipInfo OTHER-RECIPIENT ::= {
    ori-keyTransPSK |
    ori-keyAgreePSK,
    ... }

--
-- Key Transport with Pre-Shared Key
--

ori-keyTransPSK OTHER-RECIPIENT ::= {
    KeyTransPSKRecipientInfo IDENTIFIED BY id-ori-keyTransPSK }

id-ori OBJECT IDENTIFIER ::= { iso(1) member-body(2) us(840)
    rsadsi(113549) pkcs(1) pkcs-9(9) smime(16) TBD1 }

id-ori-keyTransPSK OBJECT IDENTIFIER ::= { id-ori 1 }

KeyTransPSKRecipientInfo ::= SEQUENCE {
    version CMSVersion, -- always set to 0
    pskid PreSharedKeyIdentifier,
    kdfAlgorithm KeyDerivationAlgorithmIdentifier,
    keyEncryptionAlgorithm KeyEncryptionAlgorithmIdentifier,
    ktris KeyTransRecipientInfos,
    encryptedKey EncryptedKey }

PreSharedKeyIdentifier ::= OCTET STRING

KeyTransRecipientInfos ::= SEQUENCE OF KeyTransRecipientInfo

--
-- Key Agreement with Pre-Shared Key
--

ori-keyAgreePSK OTHER-RECIPIENT ::= {
    KeyAgreePSKRecipientInfo IDENTIFIED BY id-ori-keyAgreePSK }

id-ori-keyAgreePSK OBJECT IDENTIFIER ::= { id-ori 2 }
```

```

KeyAgreePSKRecipientInfo ::= SEQUENCE {
    version CMSVersion, -- always set to 0
    pskid PreSharedKeyIdentifier,
    originator [0] EXPLICIT OriginatorIdentifierOrKey,
    ukm [1] EXPLICIT UserKeyingMaterial OPTIONAL,
    kdfAlgorithm KeyDerivationAlgorithmIdentifier,
    keyEncryptionAlgorithm KeyEncryptionAlgorithmIdentifier,
    recipientEncryptedKeys RecipientEncryptedKeys }

--
-- Structure to provide 'info' input to the KDF,
-- including the Pre-Shared Key
--

CMSORIforPSKOtherInfo ::= SEQUENCE {
    psk OCTET STRING,
    keyMgmtAlgType ENUMERATED {
        keyTrans (5),
        keyAgree (10) },
    keyEncryptionAlgorithm KeyEncryptionAlgorithmIdentifier,
    pskLength INTEGER (1..MAX),
    kdkLength INTEGER (1..MAX) }

END

<CODE ENDS>

```

7. Security Considerations

The security considerations in related to the CMS enveloped-data content type in [RFC5652] and the security considerations related to the CMS authenticated-enveloped-data content type in [RFC5083] continue to apply.

Implementations of the key derivation function must compute the entire result, which in this specification is a key-encryption key, before outputting any portion of the result. The resulting key-encryption key must be protected. Compromise of the key-encryption key may result in the disclosure of all content-encryption keys or content-authenticated-encryption keys that were protected with that keying material, which in turn may result in the disclosure of the content. Note that there are two key-encryption keys when a PSK with a key agreement algorithm is used, with similar consequence for the compromise of either one of these keys.

Implementations must protect the pre-shared key (PSK), key transport private key, the agreement private key, and the key-derivation key. Compromise of the PSK will make the encrypted content vulnerable to

the future invention of a large-scale quantum computer. Compromise of the PSK and either the key transport private key or the agreement private key may result in the disclosure of all contents protected with that combination of keying material. Compromise of the PSK and the key-derivation key may result in disclosure of all contents protected with that combination of keying material.

A large-scale quantum computer will essentially negate the security provided by the key transport algorithm or the key agreement algorithm, which means that the attacker with a large-scale quantum computer can discover the key-derivation key. In addition a large-scale quantum computer effectively cuts the security provided by a symmetric key algorithm in half. Therefore, the PSK needs at least 256 bits of entropy to provide 128 bits of security. To match that same level of security, the key derivation function needs to be quantum-resistant and produce a key-encryption key that is at least 256 bits in length. Similarly, the content-encryption key or content-authenticated-encryption key needs to be at least 256 bits in length.

When using a PSK with a key transport or a key agreement algorithm, a key-encryption key is produced to encrypt the content-encryption key or content-authenticated-encryption key. If the key-encryption algorithm is different than the algorithm used to protect the content, then the effective security is determined by the weaker of the two algorithms. If, for example, content is encrypted with 256-bit AES, and the key is wrapped with 128-bit AES, then at most 128 bits of protection is provided. Implementers must ensure that the key-encryption algorithm is as strong or stronger than the content-encryption algorithm or content-authenticated-encryption algorithm.

The selection of the key-derivation function imposes an upper bound on the strength of the resulting key-encryption key. The strength of the selected key-derivation function should be at least as strong as the key-encryption algorithm that is selected. NIST SP 800-56C Revision 1 [NIST2018] offers advice on the security strength of several popular key-derivation functions.

Implementers should not mix quantum-resistant key management algorithms with their non-quantum-resistant counterparts. For example, the same content should not be protected with KeyTransRecipientInfo and KeyTransPSKRecipientInfo. Likewise, the same content should not be protected with KeyAgreeRecipientInfo and KeyAgreePSKRecipientInfo. Doing so would make the content vulnerable to the future invention of a large-scale quantum computer.

Implementers should not send the same content in different messages,

one using a quantum-resistant key management algorithm and the other using a non-quantum-resistant key management algorithm, even if the content-encryption key is generated independently. Doing so may allow an eavesdropper to correlate the messages, making the content vulnerable to the future invention of a large-scale quantum computer.

This specification does not require that PSK is known only by the sender and recipients. The PSK may be known to a group. Since confidentiality depends on the key transport or key agreement algorithm, knowledge of the PSK by other parties does not enable inherently eavesdropping. However, group members can record the traffic of other members, and then decrypt it if they ever gain access to a large-scale quantum computer. Also, when many parties know the PSK, there are many opportunities for theft of the PSK by an attacker. Once an attacker has the PSK, they can decrypt stored traffic if they ever gain access to a large-scale quantum computer in the same manner as a legitimate group member.

Sound cryptographic key hygiene is to use a key for one and only one purpose. Use of the recipient's public key for both the traditional CMS and the PSK-mixing variation specified in this document would be a violation of this principle; however, there is no known way for an attacker to take advantage of this situation. That said, an application should enforce separation whenever possible. For example, a purpose identifier for use in the X.509 extended key usage certificate extension [RFC5280] could be identified in the future to indicate that a public key should only be used in conjunction with a PSK, or only without.

Implementations must randomly generate key-derivation keys as well as the content-encryption keys or content-authenticated-encryption keys. Also, the generation of public/private key pairs for the key transport and key agreement algorithms rely on a random numbers. The use of inadequate pseudo-random number generators (PRNGs) to generate cryptographic keys can result in little or no security. An attacker may find it much easier to reproduce the PRNG environment that produced the keys, searching the resulting small set of possibilities, rather than brute force searching the whole key space. The generation of quality random numbers is difficult. [RFC4086] offers important guidance in this area.

Implementers should be aware that cryptographic algorithms become weaker with time. As new cryptanalysis techniques are developed and computing performance improves, the work factor to break a particular cryptographic algorithm will be reduced. Therefore, cryptographic algorithm implementations should be modular, allowing new algorithms to be readily inserted. That is, implementers should be prepared for the set of supported algorithms to change over time.

The security properties provided by the mechanisms specified in this document can be validated using formal methods. A ProVerif proof in [H2019] shows that an attacker with a large-scale quantum computer that is capable of breaking the Diffie-Hellman key agreement algorithm cannot disrupt the delivery of the content-encryption key to the recipient and the attacker cannot learn the content-encryption key from the protocol exchange.

8. Privacy Considerations

An observer can see which parties are using each PSK simply by watching the PSK key identifiers. However, the addition of these key identifiers is not really making privacy worse. When key transport is used, the RecipientIdentifier is always present, and it clearly identifies each recipient to an observer. When key agreement is used, either the IssuerAndSerialNumber or the RecipientKeyIdentifier is always present, and these clearly identify each recipient.

9. IANA Considerations

One object identifier for the ASN.1 module in Section 6 was assigned in the SMI Security for S/MIME Module Identifiers (1.2.840.113549.1.9.16.0) [IANA-MOD] registry:

```
id-mod-cms-ori-psk-2019 OBJECT IDENTIFIER ::= {
    iso(1) member-body(2) us(840) rsadsi(113549) pkcs(1)
    pkcs-9(9) smime(16) mod(0) TBD0 }
```

One new registry was created for Other Recipient Info Identifiers within the SMI Security for S/MIME Mail Security (1.2.840.113549.1.9.16) [IANA-SMIME] registry:

```
id-ori OBJECT IDENTIFIER ::= { iso(1) member-body(2) us(840)
    rsadsi(113549) pkcs(1) pkcs-9(9) smime(16) TBD1 }
```

Updates to the new registry are to be made according to the Specification Required policy as defined in [RFC8126]. The expert is expected to ensure that any new values identify additions RecipientInfo structures for use with the CMS. Object identifiers for other purposes should not be assigned in this arc.

Two assignments were made in the new SMI Security for Other Recipient Info Identifiers (1.2.840.113549.1.9.16.TBD1) [IANA-ORI] registry with references to this document:

```
id-ori-keyTransPSK OBJECT IDENTIFIER ::= {  
    iso(1) member-body(2) us(840) rsadsi(113549) pkcs(1)  
    pkcs-9(9) smime(16) id-ori(TBD1) 1 }
```

```
id-ori-keyAgreePSK OBJECT IDENTIFIER ::= {  
    iso(1) member-body(2) us(840) rsadsi(113549) pkcs(1)  
    pkcs-9(9) smime(16) id-ori(TBD1) 2 }
```

10. References

10.1. Normative References

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Appendix A: Key Transport with PSK Example

This example shows the establishment of an AES-256 content-encryption key using:

- a pre-shared key of 256 bits;
- key transport using RSA PKCS#1 v1.5 with a 3072-bit key;
- key derivation using HKDF with SHA-384; and
- key wrap using AES-256-KEYWRAP.

In real-world use, the originator would encrypt the key-derivation key in their own RSA public key as well as the recipient's public key. This is omitted in an attempt to simplify the example.

A.1. Originator Processing Example

The pre-shared key known to Alice and Bob, in hexadecimal:

c244cdd11a0d1f39d9b61282770244fb0f6befb91ab7f96cb05213365cf95b15

The identifier assigned to the pre-shared key is:
ptf-kmc:13614122112

Alice obtains Bob's public key:

-----BEGIN PUBLIC KEY-----

```
MIIBOjANBgkqhkiG9w0BAQEFAAOCAQY8AMIIBigKCAYEA3ocW14cxncPJ47fnEjBZ
AyfC2lqapL3ET4jvV6C7gGeVrRQxWPDwl+cFYBBR2ej3j3/0ecDmu+XuVi2+s5JH
Keeza+itfuhsz3yifgeEpeK8T+SusHhn20/NBLhYKbh3kiAcCgQ56dpDrDvDcLqq
vS3jg/VO+OPnZbofoHO0evt8Q/roahJe1PlIyQ4udWB8zZezJ4mLLfbOA9YVaYXx
2AHHZJevo3nmRnlGJXo6mE00E/6qkhjDHKSMDl2WG6mO9TCDZc9qY3cAJDU6Ir0v
SH7qU18/vN13y4UOFkn8hM4kmZ6bJqbZt5NbJHtY4uQ0VMW3RyESzhrO02mrp39a
uLNhH3EXdXaVltk75H3qC7zJaeGWMJyQfOE3YfEGRKn8fxubji716D8UecAxAzFy
FL6m1JiOyV5acAiOpXN14qRYZdHnXOM9DqGIGpoeY1UuD4Mo05osOqOUpBJHA9fS
whSZG7VNf+vgNWTLNYSYLI04KiMdulnvU6ds+QPz+KKtAgMBAAE=
```

-----END PUBLIC KEY-----

Bob's RSA public key has the following key identifier:

9eeb67c9b95a74d44d2f16396680e801b5cba49c

Alice randomly generates a content-encryption key:

c8adc30f4a3e20ac420caa76a68f5787c02ab42afea20d19672fd963a5338e83

Alice randomly generates a key-derivation key:

df85af9e3cebffde6e9b9d24263db31114d0a8e33a0d50e05eb64578ccde81eb

Alice encrypts the key-derivation key in Bob's public key:

```
4e6200431ed95e0e28f7288dba56d4b90e75959e068884664c43368f3d978f3d
8179e5837e3c27bf8dc1f6e2827b9ede969be77417516de07d90e37c560add01
48deb0c9178088ccb72c068d8a9076b6a5e7ecc9093e30fdeaec9e138d80626
74fcf685f3082b910839551cd8741beedeee6e87c08ff84f03ba87118730cdf7
667002316f1a29a6cc596c7ddf95a51e398927d1916bf27929945de080fc7c80
6af6281aed6492acffa4ef1b4f53e67fca9a417db2350a2277d586ee3cabefd3
b4a44f04d3c6803d54fe9a7159210dabedda9a94f310d303331da51c0218d92a
2efb003792259195a9fd4cc403af613fdf1a6265ea70bf702fd1c6f734264c9a
59196e8e8fd657fa028e272ef741eb7711fd5b3f4ea7da9c33df66bf487da710
1c9bbfddaf1c073900a3ea99da513d8aa32605db07dc1c47504cab30c9304a85
d87377f603ec3df4056ddcf3d756fb7ed98254421a4ae151f17ad4e28c5ea077
63358dfb1ef5f73435f337b21a38c1a3fa697a530dd97e462f6b5fb2052a2d53
```

Alice produces a 256-bit key-encryption key with HKDF using SHA-384; the secret value is the key-derivation key; the 'info' is the DER-encoded CMSORIforPSKOtherInfo structure with the following values:

```

0   56: SEQUENCE {
2   32:   OCTET STRING
      :   C2 44 CD D1 1A 0D 1F 39 D9 B6 12 82 77 02 44 FB
      :   0F 6B EF B9 1A B7 F9 6C B0 52 13 36 5C F9 5B 15
36  1:   ENUMERATED 5
39  11:  SEQUENCE {
41  9:   OBJECT IDENTIFIER aes256-wrap
      :   { 2 16 840 1 101 3 4 1 45 }
      :   }
52  1:   INTEGER 32
55  1:   INTEGER 32
      :   }

```

The DER encoding of CMSORIforPSKOtherInfo produces 58 octets:

```

30380420c244cdd11a0d1f39d9b61282770244fb0f6befb91ab7f96cb0521336
5cf95b150a0105300b060960864801650304012d020120020120

```

The HKDF output is 256 bits:

```

a14d87451dfd11d83cd54ffe2bd38c49a2adfed3ac49f1d3e62bbdc64ae43b32

```

Alice uses AES-KEY-WRAP to encrypt the 256-bit content-encryption key with the key-encryption key:

```

ae4ea1d99e78fcdceal2d9f10d991ac71502939ee0c30ebdcc97dd1fc5ba3566
c83d0dd5d1b4faa5

```

Alice encrypts the content using AES-256-GCM with the content-encryption key. The 12-octet nonce used is:

```

cafebabefacedbaddecaf888

```

The content plaintext is:

```

48656c6c6f2c20776f726c6421

```

The resulting ciphertext is:

```

9af2d16f21547fcefed9b3ef2d

```

The resulting 12-octet authentication tag is:

```

a0e5925cc184e0172463c44c

```

A.2. ContentInfo and AuthEnvelopedData

Alice encodes the AuthEnvelopedData and the ContentInfo, and sends the result to Bob. The resulting structure is:

```

0 650: SEQUENCE {
4 11: OBJECT IDENTIFIER authEnvelopedData
: { 1 2 840 113549 1 9 16 1 23 }
17 633: [0] {
21 629: SEQUENCE {
25 1: INTEGER 0
28 551: SET {
32 547: [4] {
36 11: OBJECT IDENTIFIER ** Placeholder **
: { 1 2 840 113549 1 9 16 TBD 1 }
49 530: SEQUENCE {
53 1: INTEGER 0
56 19: OCTET STRING 'ptf-kmc:13614122112'
77 13: SEQUENCE {
79 11: OBJECT IDENTIFIER ** Placeholder **
: { 1 2 840 113549 1 9 16 3 TBD }
: }
92 11: SEQUENCE {
94 9: OBJECT IDENTIFIER aes256-wrap
: { 2 16 840 1 101 3 4 1 45 }
: }
105 432: SEQUENCE {
109 428: SEQUENCE {
113 1: INTEGER 2
116 20: [0]
: 9E EB 67 C9 B9 5A 74 D4 4D 2F 16 39 66 80 E8 01
: B5 CB A4 9C
138 13: SEQUENCE {
140 9: OBJECT IDENTIFIER rsaEncryption
: { 1 2 840 113549 1 1 1 }
151 0: NULL
: }
153 384: OCTET STRING
: 18 09 D6 23 17 DF 2D 09 55 57 3B FE 75 95 EB 6A
: 3D 57 84 6C 69 C1 49 0B F1 11 1A BB 40 0C D8 B5
: 26 5F D3 62 4B E2 D8 E4 CA EC 6A 12 36 CA 38 E3
: A0 7D AA E0 5F A1 E3 BC 59 F3 AD A8 8D 95 A1 6B
: 06 85 20 93 C7 C5 C0 05 62 ED DF 02 1D FE 68 7C
: 18 A1 3A AB AA 59 92 30 6A 1B 92 73 D5 01 C6 5B
: FD 1E BB A9 B9 D2 7F 48 49 7F 3C 4F 3C 13 E3 2B
: 2A 19 F1 7A CD BC 56 28 EF 7F CA 4F 69 6B 7E 92
: 66 22 0D 13 B7 23 AD 41 9E 5E 98 2A 80 B7 6C 77
: FF 9B 76 B1 04 BA 30 6D 4B 4D F9 25 57 E0 7F 0E

```

```

:      95 9A 43 6D 14 D5 72 3F AA 8F 66 35 40 D0 E3 71
:      4B 7F 20 9D ED 67 EA 33 79 CD AB 84 16 72 07 D2
:      AC 8D 3A DA 12 43 B7 2F 3A CF 91 3E F1 D9 58 20
:      6D F2 9C 09 E1 EC D2 0B 82 BE 5D 69 77 6F FE F7
:      EB F6 31 C0 D9 B7 15 BF D0 24 F3 05 1F FF 48 76
:      1D 73 17 19 2C 38 C6 D5 86 BD 67 82 2D B2 61 AA
:      08 C7 E4 37 34 D1 2D E0 51 32 15 4A AC 6B 2B 28
:      5B CD FA 7C 65 89 2F A2 63 DB AB 64 88 43 CC 66
:      27 84 29 AC 15 5F 3B 9E 5B DF 99 AE 4F 1B B2 BC
:      19 6C 17 A1 99 A5 CF F7 80 32 11 88 F1 9D B3 6F
:      4B 16 5F 3F 03 F7 D2 04 3D DE 5F 30 CD 8B BB 3A
:      38 DA 9D EC 16 6C 36 4F 8B 7E 99 AA 99 FB 42 D6
:      1A FF 3C 85 D7 A2 30 74 2C D3 AA F7 18 2A 25 3C
:      B5 02 C4 17 62 21 97 F1 E9 81 83 D0 4E BF 5B 5D
:      }
:      }
541 40:      OCTET STRING
:      AE 4E A1 D9 9E 78 FC DC EA 12 D9 F1 0D 99 1A C7
:      15 02 93 9E E0 C3 0E BD CC 97 DD 1F C5 BA 35 66
:      C8 3D 0D D5 D1 B4 FA A5
:      }
:      }
:      }
583 55:      SEQUENCE {
585 9:      OBJECT IDENTIFIER data { 1 2 840 113549 1 7 1 }
596 27:      SEQUENCE {
598 9:      OBJECT IDENTIFIER aes256-GCM
:      { 2 16 840 1 101 3 4 1 46 }
609 14:      SEQUENCE {
611 12:      OCTET STRING CA FE BA BE FA CE DB AD DE CA F8 88
:      }
:      }
625 13:      [0] 9A F2 D1 6F 21 54 7F CE FE D9 B3 EF 2D
:      }
640 12:      OCTET STRING A0 E5 92 5C C1 84 E0 17 24 63 C4 4C
:      }
:      }
:      }

```

A.3. Recipient Processing Example

Bob's private key:

```
-----BEGIN RSA PRIVATE KEY-----
MIIG5AIBAAKAYEA3ocW14cxncPJ47fnEjBZAyfc2lqapL3ET4jvV6C7gGeVrRQx
WPDwl+cFYBBR2ej3j3/0ecDmu+XuVi2+s5JHKEeza+itfuhsz3yifgeEpeK8T+Su
sHhn20/NBLhYKbh3kiAcCgQ56dpDrDvDcLqqvS3jg/VO+OPnZbofoHO0evt8Q/ro
ahJe1PlIyQ4udWB8zZezJ4mLLfbOA9YVaYXx2AAHZJevo3nmRnlgJXo6mE00E/6q
khjDHKSMD12WG6mO9TCDZc9qY3cAJDU6Ir0vSH7qU18/vN13y4UOfkn8m4kmZ6b
JqbZt5NbJhtY4uQ0VMW3RyESzhrO02mrp39auLNNH3EXdXaV1tk75H3qC7zJaeGW
MJyQfOE3YfEGRKn8fxubji716D8UecAxAzFyFL6m1JiOyV5acAiOpxN14qRYZdHn
XOM9DqGIGpoeY1UuD4Mo05osOqOUpBJHA9fSwShSG7VNf+vgNWTNLNYSYLI04KiMd
ulnvU6ds+QPz+KKtAgMBAAECggGATffkSkUjjJCjLvDk4aScpSx6+Rakf2hrdS3x
jwghyUfAXgTTeUQQBs1HVtHCgxQd+qlXyn3/qu8TeZVwG4NPztyi/Z5yB1wOGJEV
3k8N/ytul6pJFFn6p48VM01bUdTrkMJbXERe6g/rr6dBQeeItCaOK7N5SIJH3Oqh
9xYuB5tH4rquCdYLmt17Tx8CaVqU9qPY3vOdQEOWIjjMV8uQUR8rHSO9Kksj8AGs
Lq9kcuPpvgJc2oqMRcNePS2WVh8xPFktRLLRazgLP8STHAtjT6S1J2UzkUqfDHGK
q/BoXxBdu6L1VDwdnIS5HXL54ElcXWsoOyKF8/ilmhRUIUWRZFmlS1ok8IC5IgX
UdL9rJVZFTRLyAwmcCEvRMlasbBrhyEyshSouN5nHJi2WVJ+wShiJeKl1qeLlpMk
HrdIYBq4Nz7/zXmiQphpAy+yQeanhP8O406C8e7RwKdpXe44su4Z8fEgA5yQx0u7
8yR1EhGKydx5bhBLR5CmlVM7rT2BAoHBAP/+e5gZLNf/ECTEBZjeiJ0Vshsz0oUq
haUQPA+9Bx9pytsoKm5oQhB7QDaxAvrn8/FUW2aAkaXsaj9F+/q30AYSQtExai9J
fdKKook3oimN8/yNRsKmhfjGOj8hd4+GjX0qoMSBCEVdT+bAjjry8wgQrqReuZnu
oXU85dmb3jvv0uIczIKvTIEyjXE5afjQIJLmZFXsBm09BG87Ia5EFUKly96BOMJh
/QWEzuYYXDqOFFfzQtKAefXNFW21Kz4Hw2QKBwQDeiGh41xCGTjECvG7fauMGLu+q
DSdYyMHif6t6mx57eS16EjvOrlXKItYhIyZW8Kw0rf/CSB2j8ig1GkMLTogrGIJ1
0322o50F0r5oOmZPueer4pOyAP0fgQ8DD1L3JBpY68/8MhYbsizVrR+Ar4jM0f96
W2bF5Xj3h+fQTDmKx6VrCCQ6miRmBUZH+ZPs5n/lyOzAYrqiKOanaiHy4mjRvlsy
mjZ6z5CG8sISqCLQ/k3Qli5pOY/v0rdBjgwAW/UCgcEAqGVYGjKdXCzuDvf9EpV4
mpTWB6yIV2ckaPon/tZi5BgsmEPwvZYzt0vMbu28Px7sSpkqUuBKbzJ4pcy8uC3I
SuYiTAhMiHS4rxIBX3BYXSudd2RD4vG1+XM0h6jVRHXHh0nOXdvfgnmigPGz3jVJ
B8oph/jD8O2Yck4YCTDOXPEi8Rjusxzro+whvRR+kG0gsGGcKSVNCPj1fNISEte4
gJId701mUAzeDjn/VaS/PXQovEMolssPPKn9NocbKbpAoHBAJnFHJun122W/lrr
ppmPnIzji30YVcYOA5vlqLKyGaAsnfYqP1WUNgfVhq2jRsrHx9cnHQI9Hu442PvI
x+c5H30YFJ4ipE3eRRRmAUi4ghY5WgD+1hw8fqyUW7E715LbSbGEUVXtrkU5G64T
UR91LEyMF8OPATdiV/KD4PWykgaqRm3tVEuCVACDTQkqNsOOi3YPQcm270w6gxfQ
SOEy/kdhCFexJFA8uZvmh6Cp2crczxyBilR/yCxCqKOONqlFdOQKBwFbJk5eHPjJz
AYueKMQESPGYCrwIqxgZGCxqaeVARHvKsEDx5whI6JWoFYVkfA8F0MyhukoEb/2x
2qB5T88Dg3EbqjTiLg3qxrWJ2OxtUo8pBP2I2wbl2N0wzcbrlYhzEZ8bJyxZu5i1
sYILC8PJ4Qzw6js4Qpm4y1WHz8e/ElW6VyfmljZYA7f9WMntdfeQVqCVzNTvKn6f
hg6GSpJTzp4LV3ougi9nQuWXZF2wInsXkLYpsiMbL6Fz34RwohJtYA==
-----END RSA PRIVATE KEY-----
```

Bob decrypts the key-derivation key with his RSA private key:

```
df85af9e3cebffde6e9b9d24263db31114d0a8e33a0d50e05eb64578ccde81eb
```

Bob produces a 256-bit key-encryption key with HKDF using SHA-384; the secret value is the key-derivation key; the 'info' is the DER-encoded CMSORIforPSKOtherInfo structure with the same values as shown in A.1. The HKDF output is 256 bits:

```
a14d87451dfd11d83cd54ffe2bd38c49a2adfed3ac49f1d3e62bbdc64ae43b32
```

Bob uses AES-KEY-WRAP to decrypt the content-encryption key with the key-encryption key; the content-encryption key is:

```
c8adc30f4a3e20ac420caa76a68f5787c02ab42afea20d19672fd963a5338e83
```

Bob decrypts the content using AES-256-GCM with the content-encryption key, and checks the received authentication tag. The 12-octet nonce used is:

```
cafebabefacedbaddecaf888
```

The 12-octet authentication tag is:

```
a0e5925cc184e0172463c44c
```

The received ciphertext content is:

```
9af2d16f21547fcefed9b3ef2d
```

The resulting plaintext content is:

```
48656c6c6f2c20776f726c6421
```

Appendix B: Key Agreement with PSK Example

This example shows the establishment of an AES-256 content-encryption key using:

- a pre-shared key of 256 bits;
- key agreement using ECDH on curve P-384 and X9.63 KDF with SHA-384;
- key derivation using HKDF with SHA-384; and
- key wrap using AES-256-KEYWRAP.

In real-world use, the originator would treat themselves as an additional recipient by performing key agreement with their own static public key and the ephemeral private key generated for this message. This is omitted in an attempt to simplify the example.

B.1. Originator Processing Example

The pre-shared key known to Alice and Bob, in hexadecimal:

```
4aa53cbf500850dd583a5d9821605c6fa228fb5917f87c1c078660214e2d83e4
```

The identifier assigned to the pre-shared key is:

```
ptf-kmc:216840110121
```


Alice randomly generates a content-encryption key:

```
937b1219a64d57ad81c05cc86075e86017848c824d4e85800c731c5b7b091033
```

Alice obtains Bob's static ECDH public key:

```
-----BEGIN PUBLIC KEY-----
```

```
MHYwEAYHKoZIzj0CAQYFK4EEACIDYgAESCgPBO9nmUwGrgbGEOFY9HR/bCo0WyeY
/dePQVrwZmwN2yMJmO2d1kWCvLTz8U7atinxyIRe9CV54yau1KWU/wbkhPDnzuSM
YkcpXMG032z3JetEloW5aFOja13vv/W5
```

```
-----END PUBLIC KEY-----
```

It has a key identifier of:

```
e8218b98b8b7d86b5e9ebdc8aeb8c4ecdc05c529
```

Alice generates an ephemeral ECDH key pair on the same curve:

```
-----BEGIN EC PRIVATE KEY-----
```

```
MIGkAgEBBDCMiWLG44ik+L8cYVvJrQdLcFA+PwlgRF+Wt1Ab25qUh8OB7OePWjxp
/b8P6IOuI6GgBwYFK4EEACKhZANiAAQ5G0EmJk/2ks8sXY1kzbuG3Uu3ttWwQRXA
LFDJICjvYfr+yTpOQVkcHm88FAh9MEkw4NKctokKNgpsiXyrT3DtOg76oIYENpPb
GE5lJdjPx9sBsZQdABwlsU0Zb7P/7i8=
```

```
-----END EC PRIVATE KEY-----
```

Alice computes a shared secret, called Z, using the Bob's static ECDH public key and her ephemeral ECDH private key; Z is:

```
3f015ed0ff4b99523a95157bbe77e9cc0ee52fcffeb7e41eac79d1c11b6cc556
19cf8807e6d800c2de40240fe0e26adc
```

Alice computes the pairwise key-encryption key, called KEK1, from Z using the X9.63 KDF with the ECC-CMS-SharedInfo structure with the following values:

```
0  21: SEQUENCE {
2  11: SEQUENCE {
4   9: OBJECT IDENTIFIER aes256-wrap
      : { 2 16 840 1 101 3 4 1 45 }
      : }
15  6: [2] {
17  4: OCTET STRING 00 00 00 20
      : }
      : }
```

The DER encoding of ECC-CMS-SharedInfo produces 23 octets:

```
3015300b060960864801650304012da206040400000020
```

The X9.63 KDF output is the 256-bit KEK1:

```
27dc25ddb0b425f7a968ceada80a8f73c6ccaab115baafcce4a22a45d6b8f3da
```

Alice produces the 256-bit KEK2 with HKDF using SHA-384; the secret value is KEK1; the 'info' is the DER-encoded CMSORIforPSKOtherInfo structure with the following values:

```
0 56: SEQUENCE {
2 32: OCTET STRING
   : 4A A5 3C BF 50 08 50 DD 58 3A 5D 98 21 60 5C 6F
   : A2 28 FB 59 17 F8 7C 1C 07 86 60 21 4E 2D 83 E4
36 1: ENUMERATED 10
39 11: SEQUENCE {
41 9: OBJECT IDENTIFIER aes256-wrap
   : { 2 16 840 1 101 3 4 1 45 }
   :
52 1: INTEGER 32
55 1: INTEGER 32
   : }
```

The DER encoding of CMSORIforPSKOtherInfo produces 58 octets:
303804204aa53cbf500850dd583a5d9821605c6fa228fb5917f87c1c07866021
4e2d83e40a010a300b060960864801650304012d020120020120

The HKDF output is the 256-bit KEK2:
7de693ee30ae22b5f8f6cd026c2164103f4e1430f1ab135dc1fb98954f9830bb

Alice uses AES-KEY-WRAP to encrypt the content-encryption key with the KEK2; the wrapped key is:
229fe0b45e40003e7d8244ec1b7e7ffb2c8dca16c36f5737222553a71263a92b
de08866a602d63f4

Alice encrypts the content using AES-256-GCM with the content-encryption key. The 12-octet nonce used is:
dbaddecalf888cafebabeface

The plaintext is:
48656c6c6f2c20776f726c6421

The resulting ciphertext is:
fc6d6f823e3ed2d209d0c6ffcf

The resulting 12-octet authentication tag is:
550260c42e5b29719426c1ff

B.2. ContentInfo and AuthEnvelopedData

Alice encodes the AuthEnvelopedData and the ContentInfo, and sends the result to Bob. The resulting structure is:

```

0  327: SEQUENCE {
4   11:  OBJECT IDENTIFIER authEnvelopedData
      :   { 1 2 840 113549 1 9 16 1 23 }
17 310:  [0] {
21 306:  SEQUENCE {
25   1:   INTEGER 0
28 229:  SET {
31 226:  [4] {
34   11:  OBJECT IDENTIFIER ** Placeholder **
      :   { 1 2 840 113549 1 9 16 TBD 2 }
47 210:  SEQUENCE {
50   1:   INTEGER 0
53  20:  OCTET STRING 'ptf-kmc:216840110121'
75  85:  [0] {
77  83:  [1] {
79  19:  SEQUENCE {
81   6:  OBJECT IDENTIFIER
      :   dhSinglePass-stdDH-sha256kdf-scheme
      :   { 1 3 132 1 11 1 }
89   9:  OBJECT IDENTIFIER aes256-wrap
      :   { 2 16 840 1 101 3 4 1 45 }
      :   }
100 60:  BIT STRING, encapsulates {
103 57:  OCTET STRING
      :   1B 41 26 26 4F F6 92 CF 2C 5D 8D 64 CD BB 86 DD
      :   4B B7 B6 D5 B0 41 15 C0 2C 50 C9 20 28 EF 61 FA
      :   FE C9 3A 4E 41 59 1C 86 6F 3C 14 08 7D 30 49 30
      :   E0 D2 9C B6 89 0A 36 0A 6C
      :   }
      :   }
      :   }
162 13:  SEQUENCE {
164 11:  OBJECT IDENTIFIER ** Placeholder **
      :   { 1 2 840 113549 1 9 16 3 TBD }
      :   }
177 11:  SEQUENCE {
179   9:  OBJECT IDENTIFIER aes256-wrap
      :   { 2 16 840 1 101 3 4 1 45 }
      :   }
190 68:  SEQUENCE {
192 66:  SEQUENCE {

```

```

194 22:      [0] {
196 20:      OCTET STRING
      :      E8 21 8B 98 B8 B7 D8 6B 5E 9E BD C8 AE B8 C4 EC
      :      DC 05 C5 29
      :      }
218 40:      OCTET STRING
      :      22 9F E0 B4 5E 40 00 3E 7D 82 44 EC 1B 7E 7F FB
      :      2C 8D CA 16 C3 6F 57 37 22 25 53 A7 12 63 A9 2B
      :      DE 08 86 6A 60 2D 63 F4
      :      }
      :      }
      :      }
      :      }
      :      }
260 55:      SEQUENCE {
262 9:        OBJECT IDENTIFIER data { 1 2 840 113549 1 7 1 }
273 27:      SEQUENCE {
275 9:        OBJECT IDENTIFIER aes256-GCM
      :        { 2 16 840 1 101 3 4 1 46 }
286 14:      SEQUENCE {
288 12:      OCTET STRING DB AD DE CA F8 88 CA FE BA BE FA CE
      :      }
      :      }
302 13:      [0] FC 6D 6F 82 3E 3E D2 D2 09 D0 C6 FF CF
      :      }
317 12:      OCTET STRING 55 02 60 C4 2E 5B 29 71 94 26 C1 FF
      :      }
      :      }
      :      }

```

B.3. Recipient Processing Example

Bob obtains Alice's ephemeral ECDH public key from the message:

```

-----BEGIN PUBLIC KEY-----
MHYwEAYHkoZiZj0CAQYFK4EEACIDYgAEORtBJiZP9pLPLF2NZM27ht1Lt7bVseEV
wCxQySAo72H6/sk6TkFZHIzVpBQIfTBJMODSnLaJCjYKbKl8q09w7ToO+qCGBDaT
2xhOZSXYz8fbAbGUHQAcJbFNGW+z/+4v
-----END PUBLIC KEY-----

```

Bob's static ECDH private key:

```

-----BEGIN EC PRIVATE KEY-----
MIGkAgEBBDAnJ4hB+tTUN9X03/W0RsrYy+qcptlRSYkhaDIIsQYPXfTU0ugjJEmRk
NTPj4y1IRjegBwYFK4EEACKhZANiAARJwY8E72eZTAauBsYSgVj0dH9sKjRbJ5j9
149BWvBmbA3bIwmY7Z3WRYK8tPPxTtq2KfHIhF70JXnjJq7UpZT/BuSE8OfO5Ixi
RynEwajfbPcl60SWhbloU6NrXe+/9bk=
-----END EC PRIVATE KEY-----

```

Bob computes a shared secret, called Z, using the Alice's ephemeral ECDH public key and his static ECDH private key; Z is:

```
3f015ed0ff4b99523a95157bbe77e9cc0ee52fcffeb7e41eac79d1c11b6cc556
19cf8807e6d800c2de40240fe0e26adc
```

Bob computes the pairwise key-encryption key, called KEK1, from Z using the X9.63 KDF with the ECC-CMS-SharedInfo structure with the values shown in B.1. The X9.63 KDF output is the 256-bit KEK1:

```
27dc25ddb0b425f7a968ceada80a8f73c6ccaab115baafcce4a22a45d6b8f3da
```

Bob produces the 256-bit KEK2 with HKDF using SHA-384; the secret value is KEK1; the 'info' is the DER-encoded CMSORIforPSKOtherInfo structure with the values shown in B.1. The HKDF output is the 256-bit KEK2:

```
7de693ee30ae22b5f8f6cd026c2164103f4e1430f1ab135dc1fb98954f9830bb
```

Bob uses AES-KEY-WRAP to decrypt the content-encryption key with the KEK2; the content-encryption key is:

```
937b1219a64d57ad81c05cc86075e86017848c824d4e85800c731c5b7b091033
```

Bob decrypts the content using AES-256-GCM with the content-encryption key, and checks the received authentication tag. The 12-octet nonce used is:

```
dbaddecaf888cafebabeface
```

The 12-octet authentication tag is:

```
550260c42e5b29719426c1ff
```

The received ciphertext content is:

```
fc6d6f823e3ed2d209d0c6ffcf
```

The resulting plaintext content is:

```
48656c6c6f2c20776f726c6421
```

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Use of the SHAKE One-way Hash Functions in the Cryptographic Message
Syntax (CMS)
draft-ietf-lamps-cms-shakes-18

Abstract

This document updates the "Cryptographic Message Syntax Algorithms" (RFC3370) and describes the conventions for using the SHAKE family of hash functions in the Cryptographic Message Syntax as one-way hash functions with the RSA Probabilistic signature and ECDSA signature algorithms. The conventions for the associated signer public keys in CMS are also described.

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1. Change Log

[EDNOTE: Remove this section before publication.]

- o draft-ietf-lamps-cms-shake-18:
 - * Minor ASN.1 changes.
- o draft-ietf-lamps-cms-shake-17:
 - * Minor updates for EDNOTE accuracy.
- o draft-ietf-lamps-cms-shake-16:
 - * Minor nits.
 - * Using bytes instead of bits for consistency.
- o draft-ietf-lamps-cms-shake-15:
 - * Minor editorial nits.

- o draft-ietf-lamps-cms-shake-14:
 - * Fixing error with incorrect preimage resistance bits for SHA128 and SHA256.
- o draft-ietf-lamps-cms-shake-13:
 - * Addressing comments from Dan M.'s secdir review.
 - * Addressing comment from Scott B.'s opsdireview about references in the abstract.
- o draft-ietf-lamps-cms-shake-12:
 - * Nits identified by Roman, Barry L. in ballot position review.
- o draft-ietf-lamps-cms-shake-11:
 - * Minor nits.
 - * Nits identified by Roman in AD Review.
- o draft-ietf-lamps-cms-shake-10:
 - * Updated IANA considerations section to request for OID assignments.
- o draft-ietf-lamps-cms-shake-09:
 - * Fixed minor text nit.
 - * Updates in Sec Considerations section.
- o draft-ietf-lamps-cms-shake-08:
 - * id-shake128-len and id-shake256-len were replaced with id-shal28 with 32 bytes output length and id-shake256 with 64 bytes output length.
 - * Fixed a discrepancy between section 3 and 4.4 about the KMAC OIDs that have parameters as optional.
- o draft-ietf-lamps-cms-shake-07:
 - * Small nit from Russ while in WGLC.
- o draft-ietf-lamps-cms-shake-06:

- * Incorporated Eric's suggestion from WGLC.
- o draft-ietf-lamps-cms-shake-05:
 - * Added informative references.
 - * Updated ASN.1 so it compiles.
 - * Updated IANA considerations.
- o draft-ietf-lamps-cms-shake-04:
 - * Added RFC8174 reference and text.
 - * Explicitly explained why RSASSA-PSS-params are omitted in section 4.2.1.
 - * Simplified Public Keys section by removing redundant info from RFCs.
- o draft-ietf-lamps-cms-shake-03:
 - * Removed paragraph suggesting KMAC to be used in generating k in Deterministic ECDSA. That should be RFC6979-bis.
 - * Removed paragraph from Security Considerations that talks about randomness of k because we are using deterministic ECDSA.
 - * Completed ASN.1 module and fixed KMAC ASN.1 based on Jim's feedback.
 - * Text fixes.
- o draft-ietf-lamps-cms-shake-02:
 - * Updates based on suggestions and clarifications by Jim.
 - * Started ASN.1 module.
- o draft-ietf-lamps-cms-shake-01:
 - * Significant reorganization of the sections to simplify the introduction, the new OIDs and their use in CMS.
 - * Added new OIDs for RSASSA-PSS that hardcodes hash, salt and MGF, according the WG consensus.

- * Updated Public Key section to use the new RSASSA-PSS OIDs and clarify the algorithm identifier usage.
- * Removed the no longer used SHAKE OIDs from section 3.1.
- o draft-ietf-lamps-cms-shake-00:
 - * Various updates to title and section names.
 - * Content changes filling in text and references.
- o draft-dang-lamps-cms-shakes-hash-00:
 - * Initial version

2. Introduction

The "Cryptographic Message Syntax (CMS)" [RFC5652] is used to digitally sign, digest, authenticate, or encrypt arbitrary message contents. "Cryptographic Message Syntax (CMS) Algorithms" [RFC3370] defines the use of common cryptographic algorithms with CMS. This specification updates RFC3370 and describes the use of the SHAKE128 and SHAKE256 specified in [SHA3] as new hash functions in CMS. In addition, it describes the use of these functions with the RSASSA-PSS signature algorithm [RFC8017] and the Elliptic Curve Digital Signature Algorithm (ECDSA) [X9.62] with the CMS signed-data content type.

In the SHA-3 family, two extendable-output functions (SHAKEs), SHAKE128 and SHAKE256, are defined. Four other hash function instances, SHA3-224, SHA3-256, SHA3-384, and SHA3-512, are also defined but are out of scope for this document. A SHAKE is a variable length hash function defined as $\text{SHAKE}(M, d)$ where the output is a d -bits-long digest of message M . The corresponding collision and second-preimage-resistance strengths for SHAKE128 are $\min(d/2, 128)$ and $\min(d, 128)$ bits, respectively (Appendix A.1 [SHA3]). And the corresponding collision and second-preimage-resistance strengths for SHAKE256 are $\min(d/2, 256)$ and $\min(d, 256)$ bits, respectively. In this specification we use $d=256$ (for SHAKE128) and $d=512$ (for SHAKE256).

A SHAKE can be used in CMS as the message digest function (to hash the message to be signed) in RSASSA-PSS and ECDSA, message authentication code and as the mask generation function (MGF) in RSASSA-PSS. This specification describes the identifiers for SHAKEs to be used in CMS and their meaning.

2.1. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

3. Identifiers

This section identifies eight new object identifiers (OIDs) for using SHAKE128 and SHAKE256 in CMS.

Two object identifiers for SHAKE128 and SHAKE256 hash functions are defined in [shake-nist-oids] and we include them here for convenience.

```
id-shake128 OBJECT IDENTIFIER ::= { joint-iso-itu-t(2)
    country(16) us(840) organization(1) gov(101) csor(3)
    nistAlgorithm(4) 2 11 }
```

```
id-shake256 OBJECT IDENTIFIER ::= { joint-iso-itu-t(2)
    country(16) us(840) organization(1) gov(101) csor(3)
    nistAlgorithm(4) 2 12 }
```

In this specification, when using the id-shake128 or id-shake256 algorithm identifiers, the parameters MUST be absent. That is, the identifier SHALL be a SEQUENCE of one component, the OID.

[I-D.ietf-lamps-pkix-shake] [EDNOTE: Update reference with the RFC when it is published.] defines two identifiers for RSASSA-PSS signatures using SHAKES which we include here for convenience.

```
id-RSASSA-PSS-SHAKE128 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6) 30 }
```

```
id-RSASSA-PSS-SHAKE256 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6) 31 }
```

The same RSASSA-PSS algorithm identifiers can be used for identifying public keys and signatures.

[I-D.ietf-lamps-pkix-shake] [EDNOTE: Update reference with the RFC when it is published.] also defines two algorithm identifiers of ECDSA signatures using SHAKES which we include here for convenience.

```
id-ecdsa-with-shake128 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6) 32 }
```

```
id-ecdsa-with-shake256 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6) 33 }
```

The parameters for the four RSASSA-PSS and ECDSA identifiers MUST be absent. That is, each identifier SHALL be a SEQUENCE of one component, the OID.

Two object identifiers for KMACs using SHAKE128 and SHAKE256 as defined in by the National Institute of Standards and Technology (NIST) in [shake-nist-oids] and we include them here for convenience.

```
id-KmacWithSHAKE128 OBJECT IDENTIFIER ::= { joint-iso-itu-t(2)
    country(16) us(840) organization(1) gov(101) csor(3)
    nistAlgorithm(4) 2 19 }
```

```
id-KmacWithSHAKE256 OBJECT IDENTIFIER ::= { joint-iso-itu-t(2)
    country(16) us(840) organization(1) gov(101) csor(3)
    nistAlgorithm(4) 2 20 }
```

The parameters for id-KmacWithSHAKE128 and id-KmacWithSHAKE256 are OPTIONAL.

Section 4.1, Section 4.2.1, Section 4.2.2 and Section 4.4 specify the required output length for each use of SHAKE128 or SHAKE256 in message digests, RSASSA-PSS, ECDSA and KMAC.

4. Use in CMS

4.1. Message Digests

The id-shake128 and id-shake256 OIDs (Section 3) can be used as the digest algorithm identifiers located in the SignedData, SignerInfo, DigestedData, and the AuthenticatedData digestAlgorithm fields in CMS [RFC5652]. The OID encoding MUST omit the parameters field and the output length of SHAKE128 or SHAKE256 as the message digest MUST be 32 or 64 bytes, respectively.

The digest values are located in the DigestedData field and the Message Digest authenticated attribute included in the signedAttributes of the SignedData signerInfo. In addition, digest values are input to signature algorithms. The digest algorithm MUST be the same as the message hash algorithms used in signatures.

4.2. Signatures

In CMS, signature algorithm identifiers are located in the `SignerInfo` `signatureAlgorithm` field of `SignedData` content type and countersignature attribute. Signature values are located in the `SignerInfo` signature field of `SignedData` content type and countersignature attribute.

Conforming implementations that process RSASSA-PSS and ECDSA with SHAKE signatures when processing CMS data MUST recognize the corresponding OIDs specified in Section 3.

When using RSASSA-PSS or ECDSA with SHAKEs, the RSA modulus or ECDSA curve order SHOULD be chosen in line with the SHAKE output length. Refer to Section 6 for more details.

4.2.1. RSASSA-PSS Signatures

The RSASSA-PSS algorithm is defined in [RFC8017]. When `id-RSASSA-PSS-SHAKE128` or `id-RSASSA-PSS-SHAKE256` specified in Section 3 is used, the encoding MUST omit the parameters field. That is, the `AlgorithmIdentifier` SHALL be a SEQUENCE of one component, `id-RSASSA-PSS-SHAKE128` or `id-RSASSA-PSS-SHAKE256`. [RFC4055] defines RSASSA-PSS-params that are used to define the algorithms and inputs to the algorithm. This specification does not use parameters because the hash, mask generation algorithm, trailer and salt are embedded in the OID definition.

The hash algorithm to hash a message being signed and the hash algorithm as the mask generation function used in RSASSA-PSS MUST be the same: both SHAKE128 or both SHAKE256. The output length of the hash algorithm which hashes the message SHALL be 32 (for SHAKE128) or 64 bytes (for SHAKE256).

The mask generation function takes an octet string of variable length and a desired output length as input, and outputs an octet string of the desired length. In RSASSA-PSS with SHAKEs, the SHAKEs MUST be used natively as the MGF function, instead of the MGF1 algorithm that uses the hash function in multiple iterations as specified in Section B.2.1 of [RFC8017]. In other words, the MGF is defined as the SHAKE128 or SHAKE256 with input being the `mgfSeed` for `id-RSASSA-PSS-SHAKE128` and `id-RSASSA-PSS-SHAKE256`, respectively. The `mgfSeed` is the seed from which mask is generated, an octet string [RFC8017]. As explained in Step 9 of section 9.1.1 of [RFC8017], the output length of the MGF is $\text{emLen} - \text{hLen} - 1$ bytes. `emLen` is the maximum message length $\text{ceil}((n-1)/8)$, where `n` is the RSA modulus in bits. `hLen` is 32 and 64-bytes for `id-RSASSA-PSS-SHAKE128` and `id-RSASSA-PSS-SHAKE256`, respectively. Thus when SHAKE is used as the MGF, the

SHAKE output length maskLen is $(8 * \text{emLen} - 264)$ or $(8 * \text{emLen} - 520)$ bits, respectively. For example, when RSA modulus n is 2048, the output length of SHAKE128 or SHAKE256 as the MGF will be 1784 or 1528-bits when id-RSASSA-PSS-SHAKE128 or id-RSASSA-PSS-SHAKE256 is used, respectively.

The RSASSA-PSS saltLength MUST be 32 bytes for id-RSASSA-PSS-SHAKE128 or 64 bytes for id-RSASSA-PSS-SHAKE256. Finally, the trailerField MUST be 1, which represents the trailer field with hexadecimal value 0xBC [RFC8017].

4.2.2. ECDSA Signatures

The Elliptic Curve Digital Signature Algorithm (ECDSA) is defined in [X9.62]. When the id-ecdsa-with-shake128 or id-ecdsa-with-shake256 (specified in Section 3) algorithm identifier appears, the respective SHAKE function is used as the hash. The encoding MUST omit the parameters field. That is, the AlgorithmIdentifier SHALL be a SEQUENCE of one component, the OID id-ecdsa-with-shake128 or id-ecdsa-with-shake256.

For simplicity and compliance with the ECDSA standard specification, the output length of the hash function must be explicitly determined. The output length for SHAKE128 or SHAKE256 used in ECDSA MUST be 32 or 64 bytes, respectively.

Conforming CA implementations that generate ECDSA with SHAKE signatures in certificates or CRLs SHOULD generate such signatures with a deterministically generated, non-random k in accordance with all the requirements specified in [RFC6979]. They MAY also generate such signatures in accordance with all other recommendations in [X9.62] or [SEC1] if they have a stated policy that requires conformance to those standards. Those standards have not specified SHAKE128 and SHAKE256 as hash algorithm options. However, SHAKE128 and SHAKE256 with output length being 32 and 64 octets, respectively can be used instead of 256 and 512-bit output hash algorithms such as SHA256 and SHA512.

4.3. Public Keys

In CMS, the signer's public key algorithm identifiers are located in the OriginatorPublicKey's algorithm attribute. The conventions and encoding for RSASSA-PSS and ECDSA public keys algorithm identifiers are as specified in Section 2.3 of [RFC3279], Section 3.1 of [RFC4055] and Section 2.1 of [RFC5480].

Traditionally, the rsaEncryption object identifier is used to identify RSA public keys. The rsaEncryption object identifier

continues to identify the public key when the RSA private key owner does not wish to limit the use of the public key exclusively to RSASSA-PSS with SHAKEs. When the RSA private key owner wishes to limit the use of the public key exclusively to RSASSA-PSS, the AlgorithmIdentifier for RSASSA-PSS defined in Section 3 SHOULD be used as the algorithm attribute in the OriginatorPublicKey sequence. Conforming client implementations that process RSASSA-PSS with SHAKE public keys in CMS message MUST recognize the corresponding OIDs in Section 3.

Conforming implementations MUST specify and process the algorithms explicitly by using the OIDs specified in Section 3 when encoding ECDSA with SHAKE public keys in CMS messages.

The identifier parameters, as explained in Section 3, MUST be absent.

4.4. Message Authentication Codes

KMAC message authentication code (KMAC) is specified in [SP800-185]. In CMS, KMAC algorithm identifiers are located in the AuthenticatedData macAlgorithm field. The KMAC values are located in the AuthenticatedData mac field.

When the id-KmacWithSHAKE128 or id-KmacWithSHAKE256 OID is used as the MAC algorithm identifier, the parameters field is optional (absent or present). If absent, the SHAKE256 output length used in KMAC is 32 or 64 bytes, respectively, and the customization string is an empty string by default.

Conforming implementations that process KMACs with the SHAKEs when processing CMS data MUST recognize these identifiers.

When calculating the KMAC output, the variable N is 0xD2B282C2, S is an empty string, and L, the integer representing the requested output length in bits, is 256 or 512 for KmacWithSHAKE128 or KmacWithSHAKE256, respectively, in this specification.

5. IANA Considerations

One object identifier for the ASN.1 module in Appendix A was requested for the SMI Security for S/MIME Module Identifiers (1.2.840.113549.1.9.16.0) registry:

Decimal	Description	References
70	CMSAlgsForSHAKE-2019	[EDNOTE: THIS RFC]

6. Security Considerations

This document updates [RFC3370]. The security considerations section of that document applies to this specification as well.

NIST has defined appropriate use of the hash functions in terms of the algorithm strengths and expected time frames for secure use in Special Publications (SPs) [SP800-78-4] and [SP800-107]. These documents can be used as guides to choose appropriate key sizes for various security scenarios.

SHAKE128 with output length of 32 bytes offers 128-bits of collision and preimage resistance. Thus, SHAKE128 OIDs in this specification are RECOMMENDED with 2048 (112-bit security) or 3072-bit (128-bit security) RSA modulus or curves with group order of 256-bits (128-bit security). SHAKE256 with 64 bytes output length offers 256-bits of collision and preimage resistance. Thus, the SHAKE256 OIDs in this specification are RECOMMENDED with 4096-bit RSA modulus or higher or curves with group order of at least 512 bits such as NIST Curve P-521 (256-bit security). Note that we recommended 4096-bit RSA because we would need 15360-bit modulus for 256-bits of security which is impractical for today's technology.

When more than two parties share the same message-authentication key, data origin authentication is not provided. Any party that knows the message-authentication key can compute a valid MAC, therefore the content could originate from any one of the parties.

7. Acknowledgements

This document is based on Russ Housley's draft [I-D.housley-lamps-cms-sha3-hash]. It replaces SHA3 hash functions by SHAKE128 and SHAKE256 as the LAMPS WG agreed.

The authors would like to thank Russ Housley for his guidance and very valuable contributions with the ASN.1 module. Valuable feedback was also provided by Eric Rescorla.

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Appendix A. ASN.1 Module

This appendix includes the ASN.1 modules for SHAKEs in CMS. This module includes some ASN.1 from other standards for reference.

```
CMSAlgsForSHAKE-2019 { iso(1) member-body(2) us(840)
    rsadsi(113549) pkcs(1) pkcs-9(9) smime(16) modules(0)
    id-mod-cms-shakes-2019(70) }

DEFINITIONS EXPLICIT TAGS ::=

BEGIN

-- EXPORTS ALL;

IMPORTS

DIGEST-ALGORITHM, MAC-ALGORITHM, SMIME-CAPS
FROM AlgorithmInformation-2009
    { iso(1) identified-organization(3) dod(6) internet(1) security(5)
      mechanisms(5) pkix(7) id-mod(0)
      id-mod-algorithmInformation-02(58) }

RSAPublicKey, rsaEncryption, id-ecPublicKey
FROM PKIXAlgs-2009 { iso(1) identified-organization(3) dod(6)
    internet(1) security(5) mechanisms(5) pkix(7) id-mod(0)
    id-mod-pkix1-algorithms2008-02(56) }

sa-rsaspssWithSHAKE128, sa-rsaspssWithSHAKE256,
```

```
sa-ecdsaWithSHAKE128, sa-ecdsaWithSHAKE256
FROM PKIXAlgsForSHAKE-2019 {
    iso(1) identified-organization(3) dod(6)
    internet(1) security(5) mechanisms(5) pkix(7) id-mod(0)
    id-mod-pkix1-shakes-2019(94) } ;

-- Message Digest Algorithms (mda-)
-- used in SignedData, SignerInfo, DigestedData,
-- and the AuthenticatedData digestAlgorithm
-- fields in CMS
--
-- This expands MessageAuthAlgs from [RFC5652] and
-- MessageDigestAlgs in [RFC5753]
--
-- MessageDigestAlgs DIGEST-ALGORITHM ::= {
--     mda-shake128      |
--     mda-shake256,
--     ...
-- }

--
-- One-Way Hash Functions
-- SHAKE128
mda-shake128 DIGEST-ALGORITHM ::= {
    IDENTIFIER id-shake128 -- with output length 32 bytes.
}
id-shake128 OBJECT IDENTIFIER ::= { joint-iso-itu-t(2) country(16)
                                     us(840) organization(1) gov(101)
                                     csor(3) nistAlgorithm(4)
                                     hashAlgs(2) 11 }

-- SHAKE256
mda-shake256 DIGEST-ALGORITHM ::= {
    IDENTIFIER id-shake256 -- with output length 64 bytes.
}
id-shake256 OBJECT IDENTIFIER ::= { joint-iso-itu-t(2) country(16)
                                     us(840) organization(1) gov(101)
                                     csor(3) nistAlgorithm(4)
                                     hashAlgs(2) 12 }

--
-- Public key algorithm identifiers located in the
-- OriginatorPublicKey's algorithm attribute in CMS.
-- And Signature identifiers used in SignerInfo
-- signatureAlgorithm field of SignedData content
-- type and countersignature attribute in CMS.
--
-- From RFC5280, for reference.
```

```
-- rsaEncryption OBJECT IDENTIFIER ::= { pkcs-1 1 }
-- When the rsaEncryption algorithm identifier is used
-- for a public key, the AlgorithmIdentifier parameters
-- field MUST contain NULL.
--
id-RSASSA-PSS-SHAKE128 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6) 30 }

id-RSASSA-PSS-SHAKE256 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6) 31 }

-- When the id-RSASSA-PSS-* algorithm identifiers are used
-- for a public key or signature in CMS, the AlgorithmIdentifier
-- parameters field MUST be absent. The message digest algorithm
-- used in RSASSA-PSS MUST be SHAKE128 or SHAKE256 with a 32 or
-- 64 byte outout length, respectively. The mask generation
-- function MUST be SHAKE128 or SHAKE256 with an output length
-- of  $(8 * \text{ceil}((n-1)/8) - 264)$  or  $(8 * \text{ceil}((n-1)/8) - 520)$  bits,
-- respectively, where n is the RSA modulus in bits.
-- The RSASSA-PSS saltLength MUST be 32 or 64 bytes, respectively.
-- The trailerField MUST be 1, which represents the trailer
-- field with hexadecimal value 0xBC. Regardless of
-- id-RSASSA-PSS-* or rsaEncryption being used as the
-- AlgorithmIdentifier of the OriginatorPublicKey, the RSA
-- public key MUST be encoded using the RSAPublicKey type.

-- From RFC4055, for reference.
-- RSAPublicKey ::= SEQUENCE {
--     modulus INTEGER, -- -- n
--     publicExponent INTEGER } -- -- e

id-ecdsa-with-shake128 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6) 32 }

id-ecdsa-with-shake256 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6) 33 }

-- When the id-ecdsa-with-shake* algorithm identifiers are
-- used in CMS, the AlgorithmIdentifier parameters field
-- MUST be absent and the signature algorithm should be
-- deterministic ECDSA [RFC6979]. The message digest MUST
-- be SHAKE128 or SHAKE256 with a 32 or 64 byte outout
-- length, respectively. In both cases, the ECDSA public key,
-- MUST be encoded using the id-ecPublicKey type.
```

```

-- From RFC5480, for reference.
-- id-ecPublicKey OBJECT IDENTIFIER ::= {
--   iso(1) member-body(2) us(840) ansi-X9-62(10045) keyType(2) 1 }
--   -- The id-ecPublicKey parameters must be absent or present
--   -- and are defined as
-- ECPParameters ::= CHOICE {
--   namedCurve          OBJECT IDENTIFIER
--   -- -- implicitCurve   NULL
--   -- -- specifiedCurve  SpecifiedECDomain
-- }

-- This expands SignatureAlgorithms from [RFC5912]
--
-- SignatureAlgs SIGNATURE-ALGORITHM ::= {
--   sa-rsassaPssWithSHAKE128 |
--   sa-rsassaPssWithSHAKE256 |
--   sa-ecdsaWithSHAKE128 |
--   sa-ecdsaWithSHAKE256,
--   ...
-- }

-- This expands MessageAuthAlgs from [RFC5652] and [RFC6268]
--
-- Message Authentication (maca-) Algorithms
-- used in AuthenticatedData macAlgorithm in CMS
--
MessageAuthAlgs MAC-ALGORITHM ::= {
  maca-KMACwithSHAKE128 |
  maca-KMACwithSHAKE256,
  ...
}

-- This expands SMimeCaps from [RFC5911]
--
SMimeCaps SMIME-CAPS ::= {
  -- sa-rsassaPssWithSHAKE128.&smimeCaps |
  -- sa-rsassaPssWithSHAKE256.&smimeCaps |
  -- sa-ecdsaWithSHAKE128.&smimeCaps |
  -- sa-ecdsaWithSHAKE256.&smimeCaps,
  maca-KMACwithSHAKE128.&smimeCaps |
  maca-KMACwithSHAKE256.&smimeCaps,
  ...
}

--
-- KMAC with SHAKE128
maca-KMACwithSHAKE128 MAC-ALGORITHM ::= {
  IDENTIFIER id-KMACWithSHAKE128

```

```

    PARAMS TYPE KMACwithSHAKE128-params ARE optional
    -- If KMACwithSHAKE128-params parameters are absent
    -- the SHAKE128 output length used in KMAC is 256 bits
    -- and the customization string is an empty string.
    IS-KEYED-MAC TRUE
    SMIME-CAPS {IDENTIFIED BY id-KMACWithSHAKE128}
}
id-KMACWithSHAKE128 OBJECT IDENTIFIER ::= { joint-iso-itu-t(2)
    country(16) us(840) organization(1)
    gov(101) csor(3) nistAlgorithm(4)
    hashAlgs(2) 19 }
KMACwithSHAKE128-params ::= SEQUENCE {
    kMACOutputLength    INTEGER DEFAULT 256, -- Output length in bits
    customizationString OCTET STRING DEFAULT ''H
}

-- KMAC with SHAKE256
maca-KMACwithSHAKE256 MAC-ALGORITHM ::= {
    IDENTIFIER id-KMACWithSHAKE256
    PARAMS TYPE KMACwithSHAKE256-params ARE optional
    -- If KMACwithSHAKE256-params parameters are absent
    -- the SHAKE256 output length used in KMAC is 512 bits
    -- and the customization string is an empty string.
    IS-KEYED-MAC TRUE
    SMIME-CAPS {IDENTIFIED BY id-KMACWithSHAKE256}
}
id-KMACWithSHAKE256 OBJECT IDENTIFIER ::= { joint-iso-itu-t(2)
    country(16) us(840) organization(1)
    gov(101) csor(3) nistAlgorithm(4)
    hashAlgs(2) 20 }
KMACwithSHAKE256-params ::= SEQUENCE {
    kMACOutputLength    INTEGER DEFAULT 512, -- Output length in bits
    customizationString OCTET STRING DEFAULT ''H
}

END

```

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Hash Of Root Key Certificate Extension
draft-ietf-lamps-hash-of-root-key-cert-extn-07

Abstract

This document specifies the Hash Of Root Key certificate extension. This certificate extension is carried in the self-signed certificate for a trust anchor, which is often called a Root Certification Authority (CA) certificate. This certificate extension unambiguously identifies the next public key that will be used at some point in the future as the next Root CA certificate, eventually replacing the current one.

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1. Introduction

This document specifies the Hash Of Root Key X.509 version 3 certificate extension. The extension is an optional addition to the Internet X.509 Public Key Infrastructure Certificate and Certificate Revocation List (CRL) Profile [RFC5280]. The certificate extension facilitates the orderly transition from one Root Certification Authority (CA) public key to the next. It does so by publishing the hash value of the next generation public key in the current self-signed certificate. This hash value is a commitment to a particular public key in the next generation self-signed certificate. This commitment allows a relying party to unambiguously recognize the next generation self-signed certificate when it becomes available, install the new self-signed certificate in the trust anchor store, and eventually remove the previous one from the trust anchor store.

A Root CA Certificate MAY include the Hashed Root Key certificate extension to provide the hash value of the next public key that will be used by the Root CA.

1.1. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119][RFC8174] when, and only when, they appear in all capitals, as shown here.

1.2. ASN.1

Certificates [RFC5280] use ASN.1 [X680]; Distinguished Encoding Rules (DER) [X690] are REQUIRED for certificate signing and validation.

2. Overview

Before the initial deployment of the Root CA, the following are generated:

- R1 = The initial Root key pair
- R2 = The second generation Root key pair
- H2 = Thumbprint (hash) of the public key of R2
- C1 = Self-signed certificate for R1, which also contains H2

C1 is a self-signed certificate, and it contains H2 within the HashOfRootKey extension. C1 is distributed as part of the initial the system deployment. The HashOfRootKey certificate extension is described in Section 3.

When the time comes to replace the initial Root CA certificate, R1, the following are generated:

- R3 = The third generation Root key pair
- H3 = Thumbprint (hash) the public key of R3
- C2 = Self-signed certificate for R2, which contains H3

This is an iterative process. That is, R4 and H4 are generated when it is time for C3 to replace C2. And so on.

The successor to the Root CA self-signed certificate can be delivered by any means. Whenever a new Root CA self-signed certificate is received, the recipient is able to verify that the potential Root CA certificate links back to a previously authenticated Root CA certificate with the hashOfRootKey certificate extension. That is, the recipient verifies the signature on the self-signed certificate and verifies that the hash of the DER-encoded SubjectPublicKeyInfo from the potential Root CA certificate matches the value from the HashOfRootKey certificate extension of the current Root CA certificate. Checking the self-signed certificate signature ensures that the certificate contains the subject name, public key algorithm identifier, and public key algorithm parameters intended by the key owner; these are important inputs to certification path validation as defined in Section 6 of [RFC5280]. Checking the hash of the SubjectPublicKeyInfo ensures that the certificate contains the intended public key. If either check fails, then the potential Root CA certificate is not a valid replacement, and the recipient continues to use the current Root CA certificate. If both checks

succeed, then the recipient adds the potential Root CA certificate to the trust anchor store. As discussed in Section 5, the recipient can remove the current Root CA certificate immediately in some situations. In other situations, the recipient waits an appropriate amount of time to ensure that existing certification paths continue to validate.

3. Hash Of Root Key Certificate Extension

The HashOfRootKey certificate extension MUST NOT be critical.

The following ASN.1 [X680][X690] syntax defines the HashOfRootKey certificate extension:

```
ext-HashOfRootKey EXTENSION ::= {      -- Only in Root CA certificates
    SYNTAX          HashedRootKey
    IDENTIFIED BY   id-ce-hashOfRootKey
    CRITICALITY     {FALSE} }

HashedRootKey ::= SEQUENCE {
    hashAlg          HashAlgorithm,      -- Hash algorithm used
    hashValue        OCTET STRING }     -- Hash of DER-encoded
                                         -- SubjectPublicKeyInfo

id-ce-hashOfRootKey ::= OBJECT IDENTIFIER { 1 3 6 1 4 1 51483 2 1 }
```

The definitions of EXTENSION and HashAlgorithm can be found in [RFC5912].

The hashAlg indicates the one-way hash algorithm that was used to compute the hash value.

The hashValue contains the hash value computed from the next generation public key. The public key is DER-encoded SubjectPublicKeyInfo as defined in [RFC5280].

4. IANA Considerations

This document makes no requests of the IANA.

5. Operational Considerations

Guidance on the transition from one trust anchor to another is available in Section 4.4 of [RFC4210]. In particular, the oldWithNew and newWithOld advice ensures that relying parties are able to validate certificates issued under the current Root CA certificate and the next generation Root CA certificate throughout the transition. The notAfter field in the oldWithNew certificate MUST

cover the validity period of all unexpired certificates issued under the old Root CA private key. Further, this advice SHOULD be followed by Root CAs to avoid the need for all relying parties to make the transition at the same time.

After issuing the newWithOld certificate, the Root CA MUST stop using the old private key to sign certificates.

Some enterprise and application-specific environments offer a directory service or certificate repository to make certificate and CRLs available to relying parties. Section 3 in [RFC5280] describes a certificate repository. When a certificate repository is available, the oldWithNew and newWithOld certificates SHOULD be published before the successor to the current Root CA self-signed certificate is released. Recipients that are able to obtain the oldWithNew certificate SHOULD immediately remove the old Root CA self-signed certificate from the trust anchor store.

In environments without such a directory service or repository, like the Web PKI, recipients need a way to obtain the oldWithNew and newWithOld certificates. The Root CA SHOULD include the subject information access extension [RFC5280] with the accessMethod set to id-ad-caRepository and the assessLocation set to the HTTP URL that can be used to fetch a DER-encoded "certs-only" (simple PKI response) message as specified in [RFC5272] in all of their self-signed certificates. The Root CA SHOULD publish the "certs-only" message with the oldWithNew certificate and the newWithOld certificate before the subsequent Root CA self-signed certificate is released. The "certs-only" message format allows certificates to be added and removed from the bag of certificates over time, so the same HTTP URL can be used throughout the lifetime of the Root CA.

In environments without such a directory service or repository, recipients SHOULD keep both the old and replacement Root CA self-signed certificates in the trust anchor store for some amount of time to ensure that all end-entity certificates can be validated until they expire. The recipient MAY keep the old Root CA self-signed certificate until all of the certificates in the local cache that are subordinate to it have expired.

Certification path construction is more complex when the trust anchor store contains multiple self-signed certificates with the same distinguished name. For this reason, the replacement Root CA self-signed certificate SHOULD contain a different distinguished name than the one it is replacing. One approach is to include a number as part of the name that is incremented with each generation, such as "Example CA", "Example CA G2", "Example CA G3", and so on.

Changing names from one generation to another can lead to confusion when reviewing the history of a trust anchor store. To assist with such review, a recipient MAY create an audit entry to capture the old and replacement self-signed certificates.

The Root CA must securely back up the yet-to-be-deployed key pair. If the Root CA stores the key pair in a hardware security module, and that module fails, the Root CA remains committed to the key pair that is no longer available. This leaves the Root CA with no alternative but to deploy a new self-signed certificate that contains a newly-generated key pair in the same manner as the initial self-signed certificate, thus losing the benefits of the Hash Of Root Key certificate extension altogether.

6. Security Considerations

The security considerations from [RFC5280] apply, especially the discussion of self-issued certificates.

The Hash Of Root Key certificate extension facilitates the orderly transition from one Root CA public key to the next by publishing the hash value of the next generation public key in the current certificate. This allows a relying party to unambiguously recognize the next generation public key when it becomes available; however, the full public key is not disclosed until the Root CA releases the next generation certificate. In this way, attackers cannot begin to analyze the public key before the next generation Root CA self-signed certificate is released.

The Root CA needs to ensure that the public key in the next generation certificate is as strong or stronger than the key that it is replacing. Of course, a significant advance in cryptanalytic capability can break the yet-to-be-deployed key pair. Such advances are rare and difficult to predict. If such an advance occurs, the Root CA remains committed to the now broken key. This leaves the Root CA with no alternative but to deploy a new self-signed certificate that contains a newly-generated key pair, most likely using a different signature algorithm, in the same manner as the initial self-signed certificate, thus losing the benefits of the Hash Of Root Key certificate extension altogether.

The Root CA needs to employ a hash function that is resistant to preimage attacks [RFC4270]. A first-preimage attack against the hash function would allow an attacker to find another input that results published hash value. For the attack to be successful, the input would have to be a valid SubjectPublicKeyInfo that contains a public key that corresponds to a private key known to the attacker. A second-preimage attack becomes possible once the Root CA releases the

next generation public key, which makes the input to the hash function available to the attacker and everyone else. Again, the attacker needs to find a valid SubjectPublicKeyInfo that contains the public key that corresponds to a private key known to the attacker. If the employed hash function is broken after the Root CA publishes the self-signed certificate with the HashOfRootKey certificate extension, an attacker would be able to trick the recipient into installing the incorrect next generation certificate in the trust anchor store.

If an early release of the next generation public key occurs and the Root CA is concerned that attackers were given too much lead time to analyze that public key, then the Root CA can transition to a freshly generated key pair by rapidly performing two transitions. The first transition takes the Root CA to the key pair that suffered the early release, and it causes the Root CA to generate the subsequent Root key pair. The second transition occurs when the Root CA is confident that the population of relying parties have completed the first transition, and it takes the Root CA to the freshly generated key pair. Of course, the second transition also causes the Root CA to generate another key pair that is reserved for future use. Queries for the CRLs associated with certificates that are subordinate to the self-signed certificate can give some indication for the number of relying parties that are still actively using the self-signed certificates.

7. Acknowledgements

The Secure Electronic Transaction (SET) [SET] specification published by MasterCard and VISA in 1997 includes a very similar certificate extension. The SET certificate extension has essentially the same semantics, but the syntax fairly different.

CTIA - The Wireless Association - is developing a public key infrastructure that will make use of the certificate extension described in this document, and the object identifiers used in the ASN.1 module were assigned by CTIA.

Many thanks to Stefan Santesson, Jim Schaad, Daniel Kahn Gillmor, Joel Halpern, Paul Hoffman, Rich Salz, and Ben Kaduk. Their review and comments have greatly improved the document, especially the Operational Considerations and Security Considerations sections.

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8.2. Informative References

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Appendix A. ASN.1 Module

The following ASN.1 module provides the complete definition of the HashOfRootKey certificate extension.

```

HashedRootKeyCertExtn { 1 3 6 1 4 1 51483 0 1 }

DEFINITIONS IMPLICIT TAGS ::=
BEGIN

-- EXPORTS All

IMPORTS

HashAlgorithm
  FROM PKIX1-PSS-OAEP-Algorithms-2009 -- [RFC5912]
    { iso(1) identified-organization(3) dod(6) internet(1)
      security(5) mechanisms(5) pkix(7) id-mod(0)
      id-mod-pkix1-rsa-pkalgs-02(54) }

EXTENSION
  FROM PKIX-CommonTypes-2009
    { iso(1) identified-organization(3) dod(6) internet(1)
      security(5) mechanisms(5) pkix(7) id-mod(0)
      id-mod-pkixCommon-02(57) } ;

--
-- Expand the certificate extensions list in [RFC5912]
--

CertExtensions EXTENSION ::= {
  ext-HashOfRootKey, ... }

--
-- HashOfRootKey Certificate Extension
--

ext-HashOfRootKey EXTENSION ::= { -- Only in Root CA certificates
  SYNTAX          HashedRootKey
  IDENTIFIED BY   id-ce-hashOfRootKey
  CRITICALITY     {FALSE} }

HashedRootKey ::= SEQUENCE {
  hashAlg      HashAlgorithm, -- Hash algorithm used
  hashValue    OCTET STRING } -- Hash of DER-encoded
                                -- SubjectPublicKeyInfo

id-ce-hashOfRootKey OBJECT IDENTIFIER ::= { 1 3 6 1 4 1 51483 2 1 }

END

```

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P. Kampanakis
Cisco Systems
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NIST
July 21, 2019

Internet X.509 Public Key Infrastructure: Additional Algorithm
Identifiers for RSASSA-PSS and ECDSA using SHAKEs
draft-ietf-lamps-pkix-shake-15

Abstract

Digital signatures are used to sign messages, X.509 certificates and CRLs. This document updates the "Algorithms and Identifiers for the Internet X.509 Public Key Infrastructure Certificate and Certificate Revocation List Profile" (RFC3279) and describes the conventions for using the SHAKE function family in Internet X.509 certificates and revocation lists as one-way hash functions with the RSA Probabilistic signature and ECDSA signature algorithms. The conventions for the associated subject public keys are also described.

Status of This Memo

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1. Change Log

[EDNOTE: Remove this section before publication.]

- o draft-ietf-lamps-pkix-shake-15:
 - * Minor editorial nits.
- o draft-ietf-lamps-pkix-shake-14:
 - * Fixing error with incorrect preimage resistance bits for SHA128 and SHA256.
- o draft-ietf-lamps-pkix-shake-13:
 - * Addressing one applicable comment from Dan M. about sec levels while in secdir review of draft-ietf-lamps-cms-shakes.
 - * Addressing comment from Scott B.'s opsdirev review about references in the abstract.
- o draft-ietf-lamps-pkix-shake-12:

- * Nits identified by Roman, Eric V. Ben K., Barry L. in ballot position review.
- o draft-ietf-lamps-pkix-shake-11:
 - * Nits identified by Roman in AD Review.
- o draft-ietf-lamps-pkix-shake-10:
 - * Updated IANA considerations section to request for OID assignments.
- o draft-ietf-lamps-pkix-shake-09:
 - * Fixed minor text nits.
 - * Added text name allocation for SHAKEs in IANA considerations.
 - * Updates in Sec Considerations section.
- o draft-ietf-lamps-pkix-shake-08:
 - * Small nits from Russ while in WGLC.
- o draft-ietf-lamps-pkix-shake-07:
 - * Incorporated Eric's suggestion from WGLC.
- o draft-ietf-lamps-pkix-shake-06:
 - * Added informative references.
 - * Updated ASN.1 so it compiles.
 - * Updated IANA considerations.
- o draft-ietf-lamps-pkix-shake-05:
 - * Added RFC8174 reference and text.
 - * Explicitly explained why RSASSA-PSS-params are omitted in section 5.1.1.
 - * Simplified Public Keys section by removing redundant info from RFCs.
- o draft-ietf-lamps-pkix-shake-04:

- * Removed paragraph suggesting KMAC to be used in generating k in Deterministic ECDSA. That should be RFC6979-bis.
- * Removed paragraph from Security Considerations that talks about randomness of k because we are using deterministic ECDSA.
- * Various ASN.1 fixes.
- * Text fixes.
- o draft-ietf-lamps-pkix-shake-03:
 - * Updates based on suggestions and clarifications by Jim.
 - * Added ASN.1.
- o draft-ietf-lamps-pkix-shake-02:
 - * Significant reorganization of the sections to simplify the introduction, the new OIDs and their use in PKIX.
 - * Added new OIDs for RSASSA-PSS that hardcode hash, salt and MGF, according the WG consensus.
 - * Updated Public Key section to use the new RSASSA-PSS OIDs and clarify the algorithm identifier usage.
 - * Removed the no longer used SHAKE OIDs from section 3.1.
 - * Consolidated subsection for message digest algorithms.
 - * Text fixes.
- o draft-ietf-lamps-pkix-shake-01:
 - * Changed titles and section names.
 - * Removed DSA after WG discussions.
 - * Updated shake OID names and parameters, added MGF1 section.
 - * Updated RSASSA-PSS section.
 - * Added Public key algorithm OIDs.
 - * Populated Introduction and IANA sections.
- o draft-ietf-lamps-pkix-shake-00:

* Initial version

2. Introduction

[RFC3279] defines cryptographic algorithm identifiers for the Internet X.509 Certificate and Certificate Revocation Lists (CRL) profile [RFC5280]. This document updates RFC3279 and defines identifiers for several cryptographic algorithms that use variable length output SHAKE functions introduced in [SHA3] which can be used with .

In the SHA-3 family, two extendable-output functions (SHAKEs), SHAKE128 and SHAKE256, are defined. Four other hash function instances, SHA3-224, SHA3-256, SHA3-384, and SHA3-512, are also defined but are out of scope for this document. A SHAKE is a variable length hash function defined as $\text{SHAKE}(M, d)$ where the output is a d -bits-long digest of message M . The corresponding collision and second-preimage-resistance strengths for SHAKE128 are $\min(d/2, 128)$ and $\min(d, 128)$ bits, respectively (Appendix A.1 [SHA3]). And the corresponding collision and second-preimage-resistance strengths for SHAKE256 are $\min(d/2, 256)$ and $\min(d, 256)$ bits, respectively.

A SHAKE can be used as the message digest function (to hash the message to be signed) in RSASSA-PSS [RFC8017] and ECDSA [X9.62] and as the hash in the mask generation function (MGF) in RSASSA-PSS.

3. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

4. Identifiers

This section defines four new object identifiers (OIDs), for RSASSA-PSS and ECDSA with each of SHAKE128 and SHAKE256. The same algorithm identifiers can be used for identifying a public key in RSASSA-PSS.

The new identifiers for RSASSA-PSS signatures using SHAKEs are below.

```
id-RSASSA-PSS-SHAKE128 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6)
    TBD1 }

id-RSASSA-PSS-SHAKE256 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6)
    TBD2 }
```

The new algorithm identifiers of ECDSA signatures using SHAKEs are below.

```
id-ecdsa-with-shake128 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6)
    TBD3 }

id-ecdsa-with-shake256 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6)
    TBD4 }
```

The parameters for the four identifiers above MUST be absent. That is, the identifier SHALL be a SEQUENCE of one component, the OID.

Section 5.1.1 and Section 5.1.2 specify the required output length for each use of SHAKE128 or SHAKE256 in RSASSA-PSS and ECDSA. In summary, when hashing messages to be signed, output lengths of SHAKE128 and SHAKE256 are 256 and 512 bits respectively. When the SHAKEs are used as mask generation functions RSASSA-PSS, their output length is $(8 * \text{ceil}((n-1)/8) - 264)$ or $(8 * \text{ceil}((n-1)/8) - 520)$ bits, respectively, where n is the RSA modulus size in bits.

5. Use in PKIX

5.1. Signatures

Signatures are used in a number of different ASN.1 structures. As shown in the ASN.1 representation from [RFC5280] below, in an X.509 certificate, a signature is encoded with an algorithm identifier in the signatureAlgorithm attribute and a signatureValue attribute that contains the actual signature.

```
Certificate ::= SEQUENCE {  
    tbsCertificate      TBSCertificate,  
    signatureAlgorithm  AlgorithmIdentifier,  
    signatureValue      BIT STRING }
```

The identifiers defined in Section 4 can be used as the AlgorithmIdentifier in the signatureAlgorithm field in the sequence Certificate and the signature field in the sequence TBSCertificate in X.509 [RFC5280]. The parameters of these signature algorithms are absent as explained in Section 4.

Conforming CA implementations MUST specify the algorithms explicitly by using the OIDs specified in Section 4 when encoding RSASSA-PSS or ECDSA with SHAKE signatures in certificates and CRLs. Conforming client implementations that process certificates and CRLs using RSASSA-PSS or ECDSA with SHAKE MUST recognize the corresponding OIDs. Encoding rules for RSASSA-PSS and ECDSA signature values are specified in [RFC4055] and [RFC5480], respectively.

When using RSASSA-PSS or ECDSA with SHAKEs, the RSA modulus and ECDSA curve order SHOULD be chosen in line with the SHAKE output length. Refer to Section 7 for more details.

5.1.1.1. RSASSA-PSS Signatures

The RSASSA-PSS algorithm is defined in [RFC8017]. When id-RSASSA-PSS-SHAKE128 or id-RSASSA-PSS-SHAKE256 specified in Section 4 is used, the encoding MUST omit the parameters field. That is, the AlgorithmIdentifier SHALL be a SEQUENCE of one component, id-RSASSA-PSS-SHAKE128 or id-RSASSA-PSS-SHAKE256. [RFC4055] defines RSASSA-PSS-params that are used to define the algorithms and inputs to the algorithm. This specification does not use parameters because the hash, mask generation algorithm, trailer and salt are embedded in the OID definition.

The hash algorithm to hash a message being signed and the hash algorithm used as the mask generation function in RSASSA-PSS MUST be the same: both SHAKE128 or both SHAKE256. The output length of the hash algorithm which hashes the message SHALL be 32 (for SHAKE128) or 64 bytes (for SHAKE256).

The mask generation function takes an octet string of variable length and a desired output length as input, and outputs an octet string of the desired length. In RSASSA-PSS with SHAKEs, the SHAKEs MUST be used natively as the MGF function, instead of the MGF1 algorithm that uses the hash function in multiple iterations as specified in Section B.2.1 of [RFC8017]. In other words, the MGF is defined as the SHAKE128 or SHAKE256 output of the mgfSeed for id-RSASSA-PSS-

SHAKE128 and id-RSASSA-PSS-SHAKE256, respectively. The mgfSeed is the seed from which mask is generated, an octet string [RFC8017]. As explained in Step 9 of section 9.1.1 of [RFC8017], the output length of the MGF is $\text{emLen} - \text{hLen} - 1$ bytes. emLen is the maximum message length $\text{ceil}((n-1)/8)$, where n is the RSA modulus in bits. hLen is 32 and 64-bytes for id-RSASSA-PSS-SHAKE128 and id-RSASSA-PSS-SHAKE256, respectively. Thus when SHAKE is used as the MGF, the SHAKE output length maskLen is $(8 * \text{emLen} - 264)$ or $(8 * \text{emLen} - 520)$ bits, respectively. For example, when RSA modulus n is 2048, the output length of SHAKE128 or SHAKE256 as the MGF will be 1784 or 1528-bits when id-RSASSA-PSS-SHAKE128 or id-RSASSA-PSS-SHAKE256 is used, respectively.

The RSASSA-PSS saltLength MUST be 32 bytes for id-RSASSA-PSS-SHAKE128 or 64 bytes for id-RSASSA-PSS-SHAKE256. Finally, the trailerField MUST be 1, which represents the trailer field with hexadecimal value 0xBC [RFC8017].

5.1.2. ECDSA Signatures

The Elliptic Curve Digital Signature Algorithm (ECDSA) is defined in [X9.62]. When the id-ecdsa-with-shake128 or id-ecdsa-with-shake256 (specified in Section 4) algorithm identifier appears, the respective SHAKE function (SHAKE128 or SHAKE256) is used as the hash. The encoding MUST omit the parameters field. That is, the AlgorithmIdentifier SHALL be a SEQUENCE of one component, the OID id-ecdsa-with-shake128 or id-ecdsa-with-shake256.

For simplicity and compliance with the ECDSA standard specification, the output length of the hash function must be explicitly determined. The output length, d , for SHAKE128 or SHAKE256 used in ECDSA MUST be 256 or 512 bits, respectively.

Conforming CA implementations that generate ECDSA with SHAKE signatures in certificates or CRLs SHOULD generate such signatures with a deterministically generated, non-random k in accordance with all the requirements specified in [RFC6979]. They MAY also generate such signatures in accordance with all other recommendations in [X9.62] or [SEC1] if they have a stated policy that requires conformance to those standards. Those standards have not specified SHAKE128 and SHAKE256 as hash algorithm options. However, SHAKE128 and SHAKE256 with output length being 32 and 64 octets, respectively, can be used instead of 256 and 512-bit output hash algorithms such as SHA256 and SHA512.

5.2. Public Keys

Certificates conforming to [RFC5280] can convey a public key for any public key algorithm. The certificate indicates the public key algorithm through an algorithm identifier. This algorithm identifier is an OID and optionally associated parameters. The conventions and encoding for RSASSA-PSS and ECDSA public keys algorithm identifiers are as specified in Section 2.3.1 and 2.3.5 of [RFC3279], Section 3.1 of [RFC4055] and Section 2.1 of [RFC5480].

Traditionally, the `rsaEncryption` object identifier is used to identify RSA public keys. The `rsaEncryption` object identifier continues to identify the subject public key when the RSA private key owner does not wish to limit the use of the public key exclusively to RSASSA-PSS with SHAKes. When the RSA private key owner wishes to limit the use of the public key exclusively to RSASSA-PSS with SHAKes, the `AlgorithmIdentifiers` for RSASSA-PSS defined in Section 4 SHOULD be used as the algorithm field in the `SubjectPublicKeyInfo` sequence [RFC5280]. Conforming client implementations that process RSASSA-PSS with SHAKE public keys when processing certificates and CRLs MUST recognize the corresponding OIDs.

Conforming CA implementations MUST specify the X.509 public key algorithm explicitly by using the OIDs specified in Section 4 when encoding ECDSA with SHAKE public keys in certificates and CRLs. Conforming client implementations that process ECDSA with SHAKE public keys when processing certificates and CRLs MUST recognize the corresponding OIDs.

The identifier parameters, as explained in Section 4, MUST be absent.

6. IANA Considerations

One object identifier for the ASN.1 module in Appendix A is requested for the SMI Security for PKIX Module Identifiers (1.3.6.1.5.5.7.0) registry:

Decimal	Description	References
TBD	id-mod-pkix1-shakes-2019	[EDNOTE: THIS RFC]

IANA is requested to update the SMI Security for PKIX Algorithms [SMI-PKIX] (1.3.6.1.5.5.7.6) registry with four additional entries:

Decimal	Description	References
TBD1	id-RSASSA-PSS-SHAKE128	[EDNOTE: THIS RFC]
TBD2	id-RSASSA-PSS-SHAKE256	[EDNOTE: THIS RFC]
TBD3	id-ecdsa-with-shake128	[EDNOTE: THIS RFC]
TBD4	id-ecdsa-with-shake256	[EDNOTE: THIS RFC]

IANA is also requested to update the Hash Function Textual Names Registry [Hash-Texts] with two additional entries for SHAKE128 and SHAKE256:

Hash Function Name	OID	Reference
shake128	2.16.840.1.101.3.4.2.11	[EDNOTE: THIS RFC]
shake256	2.16.840.1.101.3.4.2.12	[EDNOTE: THIS RFC]

7. Security Considerations

This document updates [RFC3279]. The security considerations section of that document applies to this specification as well.

NIST has defined appropriate use of the hash functions in terms of the algorithm strengths and expected time frames for secure use in Special Publications (SPs) [SP800-78-4] and [SP800-107]. These documents can be used as guides to choose appropriate key sizes for various security scenarios.

SHAKE128 with output length of 256-bits offers 128-bits of collision and preimage resistance. Thus, SHAKE128 OIDs in this specification are RECOMMENDED with 2048 (112-bit security) or 3072-bit (128-bit security) RSA modulus or curves with group order of 256-bits (128-bit security). SHAKE256 with 512-bits output length offers 256-bits of collision and preimage resistance. Thus, the SHAKE256 OIDs in this specification are RECOMMENDED with 4096-bit RSA modulus or higher or curves with group order of at least 521-bits (256-bit security). Note that we recommended 4096-bit RSA because we would need 15360-bit modulus for 256-bits of security which is impractical for today's technology.

8. Acknowledgements

We would like to thank Sean Turner, Jim Schaad and Eric Rescorla for their valuable contributions to this document.

The authors would like to thank Russ Housley for his guidance and very valuable contributions with the ASN.1 module.

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Appendix A. ASN.1 module

This appendix includes the ASN.1 module for SHAKEs in X.509. This module does not come from any existing RFC.

```
PKIXAlgsForSHAKE-2019 { iso(1) identified-organization(3) dod(6)
    internet(1) security(5) mechanisms(5) pkix(7) id-mod(0)
    id-mod-pkix1-shakes-2019(TBD) }

DEFINITIONS EXPLICIT TAGS ::=

BEGIN

-- EXPORTS ALL;

IMPORTS

-- FROM [RFC5912]

PUBLIC-KEY, SIGNATURE-ALGORITHM, DIGEST-ALGORITHM, SMIME-CAPS
FROM AlgorithmInformation-2009
    { iso(1) identified-organization(3) dod(6) internet(1) security(5)
      mechanisms(5) pkix(7) id-mod(0)
      id-mod-algorithmInformation-02(58) }

-- FROM [RFC5912]

RSAPublicKey, rsaEncryption, pk-rsa, pk-ec,
CURVE, id-ecPublicKey, ECPoint, ECPParameters, ECDSA-Sig-Value
FROM PKIXAlgs-2009 { iso(1) identified-organization(3) dod(6)
    internet(1) security(5) mechanisms(5) pkix(7) id-mod(0)
    id-mod-pkix1-algorithms2008-02(56) }
;

--
-- Message Digest Algorithms (mda-)
--
DigestAlgorithms DIGEST-ALGORITHM ::= {
    -- This expands DigestAlgorithms from [RFC5912]
    mda-shake128      |
    mda-shake256,
    ...
}
```

```
--
-- One-Way Hash Functions
--

-- SHAKE128
mda-shake128 DIGEST-ALGORITHM ::= {
  IDENTIFIER id-shake128 -- with output length 32 bytes.
}
id-shake128 OBJECT IDENTIFIER ::= { joint-iso-itu-t(2) country(16)
                                     us(840) organization(1) gov(101)
                                     csor(3) nistAlgorithm(4)
                                     hashAlgs(2) 11 }

-- SHAKE256
mda-shake256 DIGEST-ALGORITHM ::= {
  IDENTIFIER id-shake256 -- with output length 64 bytes.
}
id-shake256 OBJECT IDENTIFIER ::= { joint-iso-itu-t(2) country(16)
                                     us(840) organization(1) gov(101)
                                     csor(3) nistAlgorithm(4)
                                     hashAlgs(2) 12 }

--
-- Public Key (pk-) Algorithms
--
PublicKeys PUBLIC-KEY ::= {
  -- This expands PublicKeys from [RFC5912]
  pk-rsaSSA-PSS-SHAKE128 |
  pk-rsaSSA-PSS-SHAKE256,
  ...
}

-- The hashAlgorithm is mda-shake128
-- The maskGenAlgorithm is id-shake128
-- Mask Gen Algorithm is SHAKE128 with output length
--  $(8 * \text{ceil}((n-1)/8) - 264)$  bits, where n is the RSA
-- modulus in bits.
-- The saltLength is 32. The trailerField is 1.
pk-rsaSSA-PSS-SHAKE128 PUBLIC-KEY ::= {
  IDENTIFIER id-RSASSA-PSS-SHAKE128
  KEY RSAPublicKey
  PARAMS ARE absent
  -- Private key format not in this module --
  CERT-KEY-USAGE { nonRepudiation, digitalSignature,
                  keyCertSign, cRLSign }
}

-- The hashAlgorithm is mda-shake256
```

```
-- The maskGenAlgorithm is id-shake256
-- Mask Gen Algorithm is SHAKE256 with output length
-- (8*ceil((n-1)/8) - 520)-bits, where n is the RSA
-- modulus in bits.
-- The saltLength is 64. The trailerField is 1.
pk-rsaSSA-PSS-SHAKE256 PUBLIC-KEY ::= {
  IDENTIFIER id-RSASSA-PSS-SHAKE256
  KEY RSAPublicKey
  PARAMS ARE absent
  -- Private key format not in this module --
  CERT-KEY-USAGE { nonRepudiation, digitalSignature,
                    keyCertSign, cRLSign }
}

--
-- Signature Algorithms (sa-)
--
SignatureAlgs SIGNATURE-ALGORITHM ::= {
  -- This expands SignatureAlgorithms from [RFC5912]
  sa-rsassaPssWithSHAKE128 |
  sa-rsassaPssWithSHAKE256 |
  sa-ecdsaWithSHAKE128 |
  sa-ecdsaWithSHAKE256,
  ...
}

--
-- SMIME Capabilities (sa-)
--
SMimeCaps SMIME-CAPS ::= {
  -- The expands SMimeCaps from [RFC5912]
  sa-rsassaPssWithSHAKE128.&smimeCaps |
  sa-rsassaPssWithSHAKE256.&smimeCaps |
  sa-ecdsaWithSHAKE128.&smimeCaps |
  sa-ecdsaWithSHAKE256.&smimeCaps,
  ...
}

-- RSASSA-PSS with SHAKE128
sa-rsassaPssWithSHAKE128 SIGNATURE-ALGORITHM ::= {
  IDENTIFIER id-RSASSA-PSS-SHAKE128
  PARAMS ARE absent
  -- The hashAlgorithm is mda-shake128
  -- The maskGenAlgorithm is id-shake128
  -- Mask Gen Algorithm is SHAKE128 with output length
  -- (8*ceil((n-1)/8) - 264) bits, where n is the RSA
  -- modulus in bits.
  -- The saltLength is 32. The trailerField is 1
```

```
HASHES { mda-shake128 }
PUBLIC-KEYS { pk-rsa | pk-rsaSSA-PSS-SHAKE128 }
SMIME-CAPS { IDENTIFIED BY id-RSASSA-PSS-SHAKE128 }
}
id-RSASSA-PSS-SHAKE128 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6)
    TBD1 }

-- RSASSA-PSS with SHAKE256
sa-rsassaPssWithSHAKE256 SIGNATURE-ALGORITHM ::= {
    IDENTIFIER id-RSASSA-PSS-SHAKE256
    PARAMS ARE absent
    -- The hashAlgorithm is mda-shake256
    -- The maskGenAlgorithm is id-shake256
    -- Mask Gen Algorithm is SHAKE256 with output length
    -- (8*ceil((n-1)/8) - 520)-bits, where n is the
    -- RSA modulus in bits.
    -- The saltLength is 64. The trailerField is 1.
    HASHES { mda-shake256 }
    PUBLIC-KEYS { pk-rsa | pk-rsaSSA-PSS-SHAKE256 }
    SMIME-CAPS { IDENTIFIED BY id-RSASSA-PSS-SHAKE256 }
}
id-RSASSA-PSS-SHAKE256 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6)
    TBD2 }

-- ECDSA with SHAKE128
sa-ecdsaWithSHAKE128 SIGNATURE-ALGORITHM ::= {
    IDENTIFIER id-ecdsa-with-shake128
    VALUE ECDSA-Sig-Value
    PARAMS ARE absent
    HASHES { mda-shake128 }
    PUBLIC-KEYS { pk-ec }
    SMIME-CAPS { IDENTIFIED BY id-ecdsa-with-shake128 }
}
id-ecdsa-with-shake128 OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) algorithms(6)
    TBD3 }

-- ECDSA with SHAKE256
sa-ecdsaWithSHAKE256 SIGNATURE-ALGORITHM ::= {
    IDENTIFIER id-ecdsa-with-shake256
    VALUE ECDSA-Sig-Value
    PARAMS ARE absent
    HASHES { mda-shake256 }
```

```
PUBLIC-KEYS { pk-ec }
  SMIME-CAPS { IDENTIFIED BY id-ecdsa-with-shake256 }
}
id-ecdsa-with-shake256 OBJECT IDENTIFIER ::= { iso(1)
  identified-organization(3) dod(6) internet(1)
  security(5) mechanisms(5) pkix(7) algorithms(6)
  TBD4 }
```

END

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DNS Certification Authority Authorization (CAA) Resource Record
draft-ietf-lamps-rfc6844bis-07

Abstract

The Certification Authority Authorization (CAA) DNS Resource Record allows a DNS domain name holder to specify one or more Certification Authorities (CAs) authorized to issue certificates for that domain name. CAA Resource Records allow a public Certification Authority to implement additional controls to reduce the risk of unintended certificate mis-issue. This document defines the syntax of the CAA record and rules for processing CAA records by certificate issuers.

This document obsoletes RFC 6844.

Status of This Memo

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1. Introduction

The Certification Authority Authorization (CAA) DNS Resource Record allows a DNS domain name holder to specify the Certification Authorities (CAs) authorized to issue certificates for that domain name. Publication of CAA Resource Records allows a public

Certification Authority to implement additional controls to reduce the risk of unintended certificate mis-issue.

Like the TLSA record defined in DNS-Based Authentication of Named Entities (DANE) [RFC6698], CAA records are used as a part of a mechanism for checking PKIX [RFC6698] certificate data. The distinction between the two specifications is that CAA records specify an authorization control to be performed by a certificate issuer before issue of a certificate and TLSA records specify a verification control to be performed by a relying party after the certificate is issued.

Conformance with a published CAA record is a necessary but not sufficient condition for issuance of a certificate.

Criteria for inclusion of embedded trust anchor certificates in applications are outside the scope of this document. Typically, such criteria require the CA to publish a Certification Practices Statement (CPS) that specifies how the requirements of the Certificate Policy (CP) are achieved. It is also common for a CA to engage an independent third-party auditor to prepare an annual audit statement of its performance against its CPS.

A set of CAA records describes only current grants of authority to issue certificates for the corresponding DNS domain name. Since certificates are valid for a period of time, it is possible that a certificate that is not conformant with the CAA records currently published was conformant with the CAA records published at the time that the certificate was issued. Relying parties **MUST NOT** use CAA records as part of certificate validation.

CAA records **MAY** be used by Certificate Evaluators as a possible indicator of a security policy violation. Such use **SHOULD** take account of the possibility that published CAA records changed between the time a certificate was issued and the time at which the certificate was observed by the Certificate Evaluator.

2. Definitions

2.1. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

2.2. Defined Terms

The following terms are used in this document:

Certificate: An X.509 Certificate, as specified in [RFC5280].

Certificate Evaluator: A party other than a Relying Party that evaluates the trustworthiness of certificates issued by Certification Authorities.

Certification Authority (CA): An Issuer that issues certificates in accordance with a specified Certificate Policy.

Certificate Policy (CP): Specifies the criteria that a Certification Authority undertakes to meet in its issue of certificates. See [RFC3647].

Certification Practices Statement (CPS): Specifies the means by which the criteria of the Certificate Policy are met. In most cases, this will be the document against which the operations of the Certification Authority are audited. See [RFC3647].

Domain Name: The label assigned to a node in the Domain Name System.

Domain Name System (DNS): The Internet naming system specified in [RFC1034] and [RFC1035].

DNS Security (DNSSEC): Extensions to the DNS that provide authentication services as specified in [RFC4033], [RFC4034], [RFC4035], [RFC5155], and revisions.

Fully-Qualified Domain Name (FQDN): A Domain Name that includes the labels of all superior nodes in the Domain Name System.

Issuer: An entity that issues certificates. See [RFC5280].

Property: The tag-value portion of a CAA Resource Record.

Property Tag: The tag portion of a CAA Resource Record.

Property Value: The value portion of a CAA Resource Record.

Resource Record (RR): A particular entry in the DNS including the owner name, class, type, time to live, and data, as defined in [RFC1034] and [RFC2181].

Resource Record Set (RRSet): A set of Resource Records of a particular owner name, class, and type. The time to live on all RRs

within an RRSset is always the same, but the data may be different among RRs in the RRSset.

Relevant Resource Record Set (Relevant RRSset): A set of CAA Resource Records resulting from applying the algorithm in Section 3 to a specific Fully-Qualified Domain Name or Wildcard Domain Name.

Relying Party: A party that makes use of an application whose operation depends on use of a certificate for making a security decision. See [RFC5280].

Wildcard Domain Name: A Domain Name consisting of a single asterisk character followed by a single full stop character ("*.") followed by a Fully-Qualified Domain Name.

3. Relevant Resource Record Set

Before issuing a certificate, a compliant CA MUST check for publication of a Relevant RRSset. If such an RRSset exists, a CA MUST NOT issue a certificate unless the CA determines that either (1) the certificate request is consistent with the applicable CAA Resource Record set or (2) an exception specified in the relevant Certificate Policy or Certification Practices Statement applies. If the Relevant RRSset for a Fully-Qualified Domain Name or Wildcard Domain Name contains no Property Tags that restrict issuance (for instance, if it contains only iodef Property Tags, or only Property Tags unrecognized by the CA), CAA does not restrict issuance.

A certificate request MAY specify more than one Fully-Qualified Domain Name and MAY specify Wildcard Domain Names. Issuers MUST verify authorization for all the Fully-Qualified Domain Names and Wildcard Domain Names specified in the request.

The search for a CAA RRSset climbs the DNS name tree from the specified label up to but not including the DNS root '.' until a CAA RRSset is found.

Given a request for a specific Fully-Qualified Domain Name X, or a request for a Wildcard Domain Name *.X, the Relevant Resource Record Set RelevantCAASet(X) is determined as follows (in pseudocode):

Let CAA(X) be the RRSset returned by performing a CAA record query for the Fully-Qualified Domain Name X, according to the lookup algorithm specified in RFC 1034 section 4.3.2 (in particular chasing aliases). Let Parent(X) be the Fully-Qualified Domain Name produced by removing the leftmost label of X.

```

RelevantCAASet(domain):
  while domain is not ".":
    if CAA(domain) is not Empty:
      return CAA(domain)
    domain = Parent(domain)
  return Empty

```

For example, processing CAA for the Fully-Qualified Domain Name "X.Y.Z" where there are no CAA records at any level in the tree RelevantCAASet would have the following steps:

```

CAA("X.Y.Z.") = Empty; domain = Parent("X.Y.Z.") = "Y.Z."
CAA("Y.Z.")   = Empty; domain = Parent("Y.Z.")   = "Z."
CAA("Z.")     = Empty; domain = Parent("Z.")     = "."
return Empty

```

Processing CAA for the Fully-Qualified Domain Name "A.B.C" where there is a CAA record "issue example.com" at "B.C" would terminate early upon finding the CAA record:

```

CAA("A.B.C.") = Empty; domain = Parent("A.B.C.") = "B.C."
CAA("B.C.")   = "issue example.com"
return "issue example.com"

```

4. Mechanism

4.1. Syntax

A CAA Resource Record contains a single Property consisting of a tag-value pair. A Fully-Qualified Domain Name MAY have multiple CAA RRs associated with it and a given Property Tag MAY be specified more than once across those RRs.

The RDATA section for a CAA Resource Record contains one Property. A Property consists of the following:

+0-1-2-3-4-5-6-7-	0-1-2-3-4-5-6-7-		
Flags	Tag Length = n		
+-----+	+-----+	...+	+-----+
Tag char 0	Tag char 1	...	Tag char n-1
+-----+	+-----+	...+	+-----+
+-----+	+-----++	+-----+
Value byte 0	Value byte 1	Value byte m-1
+-----+	+-----++	+-----+

Where n is the length specified in the Tag length field and m is the remaining octets in the Value field. They are related by ($m = d - n - 2$) where d is the length of the RDATA section.

The fields are defined as follows:

Flags: One octet containing the following field:

Bit 0, Issuer Critical Flag: If the value is set to '1', the Property is critical. A Certification Authority MUST NOT issue certificates for any FQDN the Relevant RRSet for that FQDN contains a CAA critical Property for an unknown or unsupported Property Tag.

Note that according to the conventions set out in [RFC1035], bit 0 is the Most Significant Bit and bit 7 is the Least Significant Bit. Thus, the Flags value 1 means that bit 7 is set while a value of 128 means that bit 0 is set according to this convention.

All other bit positions are reserved for future use.

To ensure compatibility with future extensions to CAA, DNS records compliant with this version of the CAA specification MUST clear (set to "0") all reserved flags bits. Applications that interpret CAA records MUST ignore the value of all reserved flag bits.

Tag Length: A single octet containing an unsigned integer specifying the tag length in octets. The tag length MUST be at least 1.

Tag: The Property identifier, a sequence of US-ASCII characters.

Tags MAY contain US-ASCII characters 'a' through 'z', 'A' through 'Z', and the numbers 0 through 9. Tags MUST NOT contain any other characters. Matching of tags is case insensitive.

Tags submitted for registration by IANA MUST NOT contain any characters other than the (lowercase) US-ASCII characters 'a' through 'z' and the numbers 0 through 9.

Value: A sequence of octets representing the Property Value. Property Values are encoded as binary values and MAY employ sub-formats.

The length of the value field is specified implicitly as the remaining length of the enclosing RDATA section.

4.1.1. Canonical Presentation Format

The canonical presentation format of the CAA record is:

CAA <flags> <tag> <value>

Where:

Flags: Is an unsigned integer between 0 and 255.

Tag: Is a non-zero-length sequence of US-ASCII letters and numbers in lower case.

Value: The value field, expressed as a contiguous set of characters without interior spaces, or as a quoted string. See the <character-string> format specified in [RFC1035], Section 5.1, but note that the value field contains no length byte and is not limited to 255 characters.

4.2. CAA issue Property

If the issue Property Tag is present in the Relevant RRSset for a Fully-Qualified Domain Name, it is a request that Issuers

1. Perform CAA issue restriction processing for the FQDN, and
2. Grant authorization to issue certificates containing that FQDN to the holder of the issuer-domain-name or a party acting under the explicit authority of the holder of the issuer-domain-name.

The CAA issue Property Value has the following sub-syntax (specified in ABNF as per [RFC5234]).

```
issue-value = *WSP [issuer-domain-name *WSP] [";" *WSP [parameters *WSP]]
```

```
issuer-domain-name = label *("." label)
```

```
label = (ALPHA / DIGIT) *( *("-") (ALPHA / DIGIT))
```

```
parameters = (parameter *WSP ";" *WSP parameters) / parameter
```

```
parameter = tag *WSP "=" *WSP value
```

```
tag = (ALPHA / DIGIT) *( *("-") (ALPHA / DIGIT))
```

```
value = *("%x21-3A / %x3C-7E")
```

For consistency with other aspects of DNS administration, FQDN values are specified in letter-digit-hyphen Label (LDH-Label) form.

The following CAA record set requests that no certificates be issued for the FQDN 'certs.example.com' by any Issuer other than cal.example.net or ca2.example.org.

```
certs.example.com      CAA 0 issue "cal.example.net"  
certs.example.com      CAA 0 issue "ca2.example.org"
```

Because the presence of an issue Property Tag in the Relevant RRSset for an FQDN restricts issuance, FQDN owners can use an issue Property Tag with no issuer-domain-name to request no issuance.

For example, the following RRSSet requests that no certificates be issued for the FQDN 'nocerts.example.com' by any Issuer.

```
nocerts.example.com      CAA 0 issue ";"
```

An issue Property Tag where the issue-value does not match the ABNF grammar MUST be treated the same as one specifying an empty issuer-domain-name. For example, the following malformed CAA RRsSet forbids issuance:

```
malformed.example.com    CAA 0 issue "%%%"
```

CAA authorizations are additive; thus, the result of specifying both an empty issuer-domain-name and a non-empty issuer-domain-name is the same as specifying just the non-empty issuer-domain-name.

An Issuer MAY choose to specify parameters that further constrain the issue of certificates by that Issuer, for example, specifying that certificates are to be subject to specific validation policies, billed to certain accounts, or issued under specific trust anchors.

For example, if cal.example.net has requested its customer accountable.example.com to specify their account number "230123" in each of the customer's CAA records using the (CA-defined) "account" parameter, it would look like this:

```
accountable.example.com  CAA 0 issue "cal.example.net; account=230123"
```

The semantics of parameters to the issue Property Tag are determined by the Issuer alone.

4.3. CAA issuewild Property

The issuewild Property Tag has the same syntax and semantics as the issue Property Tag except that it only grants authorization to issue certificates that specify a Wildcard Domain Name and issuewild properties take precedence over issue properties when specified. Specifically:

issuewild properties MUST be ignored when processing a request for a Fully-Qualified Domain Name that is not a Wildcard Domain Name.

If at least one issuewild Property is specified in the Relevant RRsSet for a Wildcard Domain Name, all issue properties MUST be ignored when processing a request for that Wildcard Domain Name.

For example, the following RRsSet requests that only cal.example.net issue certificates for "wild.example.com" or "sub.wild.example.com",

and that `_only_ ca2.example.org` issue certificates for `"*.wild.example.com"` or `"*.sub.wild.example.com"`). Note that this presumes there are no CAA RRs for `sub.wild.example.com`.

```
wild.example.com      CAA 0 issue "ca1.example.net"
wild.example.com      CAA 0 issuewild "ca2.example.org"
```

The following RRSset requests that `_only_ ca1.example.net` issue certificates for `"wild2.example.com"`, `"*.wild2.example.com"` or `"*.sub.wild2.example.com"`.

```
wild2.example.com      CAA 0 issue "ca1.example.net"
```

The following RRSset requests that `_only_ ca2.example.org` issue certificates for `"*.wild3.example.com"` or `"*.sub.wild3.example.com"`. It does not permit any Issuer to issue for `"wild3.example.com"` or `"sub.wild3.example.com"`.

```
wild3.example.com      CAA 0 issuewild "ca2.example.org"
wild3.example.com      CAA 0 issue ";"
```

The following RRSset requests that `_only_ ca2.example.org` issue certificates for `"*.wild3.example.com"` or `"*.sub.wild3.example.com"`. It permits any Issuer to issue for `"wild3.example.com"` or `"sub.wild3.example.com"`.

```
wild3.example.com      CAA 0 issuewild "ca2.example.org"
```

4.4. CAA iodef Property

The iodef Property specifies a means of reporting certificate issue requests or cases of certificate issue for domains for which the Property appears in the Relevant RRSset, when those requests or issuances violate the security policy of the Issuer or the FQDN holder.

The Incident Object Description Exchange Format (IODEF) [RFC7970] is used to present the incident report in machine-readable form.

The iodef Property Tag takes a URL as its Property Value. The URL scheme type determines the method used for reporting:

`mailto:` The IODEF incident report is reported as a MIME email attachment to an SMTP email that is submitted to the mail address specified. The mail message sent SHOULD contain a brief text message to alert the recipient to the nature of the attachment.

http or https: The IODEF report is submitted as a Web service request to the HTTP address specified using the protocol specified in [RFC6546].

These are the only supported URL schemes.

The following RRSset specifies that reports may be made by means of email with the IODEF data as an attachment, a Web service [RFC6546], or both:

report.example.com	CAA 0 issue "cal.example.net"
report.example.com	CAA 0 iodef "mailto:security@example.com"
report.example.com	CAA 0 iodef "http://iodef.example.com/"

4.5. Critical Flag

The critical flag is intended to permit future versions of CAA to introduce new semantics that MUST be understood for correct processing of the record, preventing conforming CAs that do not recognize the new semantics from issuing certificates for the indicated FQDNs.

In the following example, the Property with a Property Tag of 'tbs' is flagged as critical. Neither the cal.example.net CA nor any other Issuer is authorized to issue for "new.example.com" (or any other domains for which this is the Relevant RRSset) unless the Issuer has implemented the processing rules for the 'tbs' Property Tag.

new.example.com	CAA 0 issue "cal.example.net"
new.example.com	CAA 128 tbs "Unknown"

5. Security Considerations

CAA records assert a security policy that the holder of an FQDN wishes to be observed by Issuers. The effectiveness of CAA records as an access control mechanism is thus dependent on observance of CAA constraints by Issuers.

The objective of the CAA record properties described in this document is to reduce the risk of certificate mis-issue rather than avoid reliance on a certificate that has been mis-issued. DANE [RFC6698] describes a mechanism for avoiding reliance on mis-issued certificates.

5.1. Use of DNS Security

Use of DNSSEC to authenticate CAA RRs is strongly RECOMMENDED but not required. An Issuer MUST NOT issue certificates if doing so would conflict with the Relevant RRSets, irrespective of whether the corresponding DNS records are signed.

DNSSEC provides a proof of non-existence for both DNS Fully-Qualified Domain Names and RRSets within FQDNs. DNSSEC verification thus enables an Issuer to determine if the answer to a CAA record query is empty because the RRSSet is empty or if it is non-empty but the response has been suppressed.

Use of DNSSEC allows an Issuer to acquire and archive a proof that they were authorized to issue certificates for the FQDN. Verification of such archives may be an audit requirement to verify CAA record processing compliance. Publication of such archives may be a transparency requirement to verify CAA record processing compliance.

5.2. Non-Compliance by Certification Authority

CAA records offer CAs a cost-effective means of mitigating the risk of certificate mis-issue: the cost of implementing CAA checks is very small and the potential costs of a mis-issue event include the removal of an embedded trust anchor.

5.3. Mis-Issue by Authorized Certification Authority

Use of CAA records does not prevent mis-issue by an authorized Certification Authority, i.e., a CA that is authorized to issue certificates for the FQDN in question by CAA records.

FQDN holders SHOULD verify that the CAs they authorize to issue certificates for their FQDNs employ appropriate controls to ensure that certificates are issued only to authorized parties within their organization.

Such controls are most appropriately determined by the FQDN holder and the authorized CA(s) directly and are thus out of scope of this document.

5.4. Suppression or Spoofing of CAA Records

Suppression of the CAA record or insertion of a bogus CAA record could enable an attacker to obtain a certificate from an Issuer that was not authorized to issue for an affected FQDN.

Where possible, Issuers SHOULD perform DNSSEC validation to detect missing or modified CAA record sets.

In cases where DNSSEC is not deployed for a corresponding FQDN, an Issuer SHOULD attempt to mitigate this risk by employing appropriate DNS security controls. For example, all portions of the DNS lookup process SHOULD be performed against the authoritative name server. Data cached by third parties MUST NOT be relied on as the sole source of DNS CAA information but MAY be used to support additional anti-spoofing or anti-suppression controls.

5.5. Denial of Service

Introduction of a malformed or malicious CAA RR could in theory enable a Denial-of-Service (DoS) attack. This could happen by modification of authoritative DNS records or by spoofing inflight DNS responses.

This specific threat is not considered to add significantly to the risk of running an insecure DNS service.

An attacker could, in principle, perform a DoS attack against an Issuer by requesting a certificate with a maliciously long DNS name. In practice, the DNS protocol imposes a maximum name length and CAA processing does not exacerbate the existing need to mitigate DoS attacks to any meaningful degree.

5.6. Abuse of the Critical Flag

A Certification Authority could make use of the critical flag to trick customers into publishing records that prevent competing Certification Authorities from issuing certificates even though the customer intends to authorize multiple providers. This could happen if the customers were setting CAA records based on data provided by the CA rather than generating those records themselves.

In practice, such an attack would be of minimal effect since any competent competitor that found itself unable to issue certificates due to lack of support for a Property marked critical should investigate the cause and report the reason to the customer. The customer will thus discover that they had been deceived.

6. Deployment Considerations

A CA implementing CAA may find that they receive errors looking up CAA records. The following are some common causes of such errors, so that CAs may provide guidance to their subscribers on fixing the underlying problems.

6.1. Blocked Queries or Responses

Some middleboxes, in particular anti-DDoS appliances, may be configured to drop DNS packets of unknown types, or may start dropping such packets when they consider themselves under attack. This generally manifests as a timed-out DNS query, or a SERVFAIL at a local recursive resolver.

6.2. Rejected Queries and Malformed Responses

Some authoritative nameservers respond with REJECTED or NOTIMP when queried for a Resource Record type they do not recognize. At least one authoritative resolver produces a malformed response (with the QR bit set to 0) when queried for unknown Resource Record types. Per RFC 1034, the correct response for unknown Resource Record types is NOERROR.

6.3. Delegation to Private Nameservers

Some FQDN administrators make the contents of a subdomain unresolvable on the public Internet by delegating that subdomain to a nameserver whose IP address is private. A CA processing CAA records for such subdomains will receive SERVFAIL from its recursive resolver. The CA MAY interpret that as preventing issuance. FQDN administrators wishing to issue certificates for private FQDNs SHOULD use split-horizon DNS with a publicly available nameserver, so that CAs can receive a valid, empty CAA response for those FQDNs.

6.4. Bogus DNSSEC Responses

Queries for CAA Resource Records are different from most DNS RR types, because a signed, empty response to a query for CAA RRs is meaningfully different from a bogus response. A signed, empty response indicates that there is definitely no CAA policy set at a given label. A bogus response may mean either a misconfigured zone, or an attacker tampering with records. DNSSEC implementations may have bugs with signatures on empty responses that go unnoticed, because for more common Resource Record types like A and AAAA, the difference to an end user between empty and bogus is irrelevant; they both mean a site is unavailable.

In particular, at least two authoritative resolvers that implement live signing had bugs when returning empty Resource Record sets for DNSSEC-signed zones, in combination with mixed-case queries. Mixed-case queries, also known as DNS 0x20, are used by some recursive resolvers to increase resilience against DNS poisoning attacks. DNSSEC-signing authoritative resolvers are expected to copy the same capitalization from the query into their ANSWER section, but sign the

response as if they had used all lowercase. In particular, PowerDNS versions prior to 4.0.4 had this bug.

7. Differences versus RFC6844

This document obsoletes RFC6844. The most important change is to the Certification Authority Processing section. RFC6844 specified an algorithm that performed DNS tree-climbing not only on the FQDN being processed, but also on all CNAMEs and DNAMEs encountered along the way. This made the processing algorithm very inefficient when used on FQDNs that utilize many CNAMEs, and would have made it difficult for hosting providers to set CAA policies on their own FQDNs without setting potentially unwanted CAA policies on their customers' FQDNs. This document specifies a simplified processing algorithm that only performs tree climbing on the FQDN being processed, and leaves processing of CNAMEs and DNAMEs up to the CA's recursive resolver.

This document also includes a "Deployment Considerations" section detailing experience gained with practical deployment of CAA enforcement among CAs in the WebPKI.

This document clarifies the ABNF grammar for the issue and issuewild tags and resolves some inconsistencies with the document text. In particular, it specifies that parameters are separated with semicolons. It also allows hyphens in Property Tags.

This document also clarifies processing of a CAA RRset that is not empty, but contains no issue or issuewild tags.

This document removes the section titled "The CAA RR Type," merging it with "Mechanism" because the definitions were mainly duplicates. It moves the "Use of DNS Security" section into Security Considerations. It renames "Certification Authority Processing" to "Relevant Resource Record Set," and emphasizes the use of that term to more clearly define which domains are affected by a given RRset.

8. IANA Considerations

IANA is requested to add [[[RFC Editor: Please replace with this RFC]]] as a reference for the Certification Authority Restriction Flags and Certification Authority Restriction Properties registries, and update references to [RFC6844] within those registries to refer to [[[RFC Editor: Please replace with this RFC]]]. IANA is also requested to update the CAA TYPE in the DNS Parameters registry with a reference to [[[RFC Editor: Please replace with this RFC]]].

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pretty Easy privacy (pEp): Progressive Header Disclosure
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Abstract

Issues with email header protection in S/MIME have been recently raised in the IETF LAMPS Working Group. The need for amendments to the existing specification regarding header protection was expressed.

The pretty Easy privacy (pEp) implementations currently use a mechanism quite similar to the currently standardized message wrapping for S/MIME. The main difference is that pEp is using PGP/MIME instead, and adds space for carrying public keys next to the protected message.

In LAMPS, it has been expressed that whatever mechanism will be chosen, it should not be limited to S/MIME, but also applicable to PGP/MIME.

This document aims to contribute to this discussion and share the pEp implementation experience with email header protection.

Status of This Memo

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1. Introduction

A range of protocols for the protection of electronic mail (email) exist, which allow to assess the authenticity and integrity of the email headers section, or selected header fields, but limited to a domain-level perspective. Specifically these are DomainKeys Identified Mail (DKIM) [RFC6376] and Sender Policy Framework (SPF) [RFC7208] and Domain-based Message Authentication, Reporting, and Conformance (DMARC) [RFC7489]. These protocols, while essential to responding to a range of attacks on email, do not offer full End-to-End protection to the headers section and are not capable of providing privacy regarding the information represented therein.

The need for means of Data Minimization, which includes data sparseness and hiding of all information technically hideable, has grown in importance over the past years.

A standard for End-to-End protection of the email headers section exists for S/MIME since version 3.1. (cf. [RFC8551]):

In order to protect outer, non-content-related message header fields (for instance, the "Subject", "To", "From", and "Cc" fields), the sending client MAY wrap a full MIME message in a message/rfc822 wrapper in order to apply S/MIME security services to these header fields.

No mechanism for header protection has been standardized for [PGPMIME] yet.

End-to-End protection for the email headers section is currently not widely implemented – neither for messages protected by means of S/MIME nor PGP/MIME. At least two variants of header protection are known to be implemented. A recently submitted Internet-Draft [I-D.melnikov-lamps-header-protection] discusses the two variants and the challenges with header protection for S/MIME. The two variants are referred to as:

- o Option 1: Memory Hole
- o Option 2: Wrapping with message/rfc822 or message/global

pEp (pretty Easy privacy) [I-D.birk-pep] for email [I-D.marques-pep-email] already implements an option quite similar to Option 2, adapting the S/MIME standards to PGP/MIME (cf. Section 2, ff.). Existing implementations of pEp have also added inbound support for "Memory Hole" referred to above as Option 1, thus being able to study the differences and the implementator's challenges.

pEp now also supports the "forwarded=no" attribute proposed in [I-D.melnikov-lamps-header-protection], and further described in Section 2.3.

Interoperability and implementation symmetry between PGP/MIME and S/MIME is planned by pEp, but still in an early stage of development.

This document describes Progressive Header Disclosure as implemented in the "pEp message format version 2". This format inherently offers header protection as a side effect, but is only intended for use only with signed-and-encrypted messages. The feature of protecting headers may be used independently by mail user agents otherwise not wanting to conform to pEp standards (Section 2, ff.).

1.1. Requirements Language

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 [RFC2119].

1.2. Terms

The following terms are defined for the scope of this document:

- o Man-in-the-middle attack (MITM): cf. [RFC4949]

2. Message Format for Progressive Header Disclosure

2.1. Compatibility

The pEp message format version 2 is designed such that a receiving Mail User Agent (MUA), which is OpenPGP-compliant but not pEp-compliant, still has built-in capability to properly verify the integrity of the mail, decode it and display all information of the original mail to the user. The recovered protected message is selfsufficiently described, including all protected header fields.

The pEp message format version 2 (as used by all the various pEp implementations, cf. Section 9) is similar to what is standardized for S/MIME in [RFC8551]:

In order to protect outer, non-content-related message header fields (for instance, the "Subject", "To", "From", and "Cc" fields), the sending client MAY wrap a full MIME message in a message/rfc822 wrapper in order to apply S/MIME security services to these header fields. It is up to the receiving client to decide how to present this "inner" header along with the unprotected "outer" header.

When an S/MIME message is received, if the top-level protected MIME entity has a Content-Type of message/rfc822, it can be assumed that the intent was to provide header protection. This entity SHOULD be presented as the top-level message, [...].

2.2. Inner Message

Note: this section is for your information only. It does not add requirements for the header protection feature to work.

The pEp message format requires the innermost protected message to follow a fixed MIME structure and to consist of exactly one human-readable message which is represented in plain or HTML format. Both plain and html entities MUST represent the same message to the user. Any attachment to the message must be laid out in a flat list. No additional multipart entities are allowed in the pEp message.

These restrictions permit to build mail user agents which are immune to the EFAIL attacks.

This message is herein further referred to as the "pEp inner message".

A mail user agent wanting to follow this standard, SHOULD transform any "original message" into a "pEp inner message" for safe representation on the receiving side.

2.3. Content-Type Parameter "forwarded"

One caveat of the design is that the user interaction with message/rfc822 entities varies considerably across different mail user agents. No standard is currently available which enables MUAs to reliably determine whenever a nested message/rfc822 entity is meant to blend the containing message, or if it was effectively intended to be forwarded as a file document. pEp currently implements the proposal described by [I-D.melnikov-lamps-header-protection], 3.2, which defines a new Content-Type header field parameter with name "forwarded", for the MUA to distinguish between a forwarded message and a nested message for the purpose of header protection, i.e., using "forwarded=no".

2.4. Outer Message

With pEp message format version 2, the pEp standardized message is equally wrapped in a message/rfc822 entity, but this time being in turn wrapped in a multipart/mixed entity. The purpose of the additional nesting is to allow for public keys of the sender to be

stored alongside the original message while being protected by the same mechanism.

For the case of PGP/MIME, the currently only implemented MIME encryption protocol implemented in pEp, the top-level entity called the "outer message" MUST contain:

- o exactly one entity of type message/rfc822, and
- o one or more entity of type application/pgp-keys

Notes on the current pEp client implementations:

- o the current pEp implementation also adds a text/plain entity containing "pEp-Wrapped-Message-Info: OUTER" as first element in the MIME tree. This element is not strictly necessary, but is in place for better backwards compatibility when manually navigating the nested message structure. This is part of the study of various solutions to maximize backwards compatibility, and has been omitted from the following examples.
- o the current pEp implementation prepends "pEp-Wrapped-Message-Info: INNER<CR><LF>" to the original message body. This is an implementation detail which should be ignored, and has been omitted in the following examples.
- o the current pEp implementation may render a text/plain directly in place of the multipart/alternate, when no HTML representation was generated by the sending MUA. This is not strict according to pEp's own specification, and is currently being investigated.

This is an example of the top-level MIME entity, before being encrypted and signed:

MIME-Version: 1.0
Content-Type: multipart/mixed;
boundary="6b8b4567327b23c6643c986966334873"

--6b8b4567327b23c6643c986966334873
Content-Type: message/rfc822; forwarded="no"

From: John Doe <jdoe@machine.example>
To: Mary Smith <mary@example.net>
Subject: Example
Date: Fri, 30 Jun 2018 09:55:06 +0200
Message-ID: <05d0526e-41c4-11e9-8828@pretty.Easy.privacy>
X-Pep-Version: 2.0
MIME-Version: 1.0
Content-Type: multipart/alternative;
boundary="29fe9d2b2d7f6a703c1bffc47c162a8c"

--29fe9d2b2d7f6a703c1bffc47c162a8c
Content-Type: text/plain; charset="utf-8"
Content-Transfer-Encoding: quoted-printable
Content-Disposition: inline; filename="msg.txt"

p=E2=89=Alp for Privacy by Default.
-- =20
Sent from my p=E2=89=Alp for Android.

--29fe9d2b2d7f6a703c1bffc47c162a8c
Content-Type: text/html; charset="utf-8"
Content-Transfer-Encoding: quoted-printable

p=E2=89=Alp for Privacy by Default.

--

Sent from my p=E2=89=Alp for Android.

--29fe9d2b2d7f6a703c1bffc47c162a8c--
--6b8b4567327b23c6643c986966334873
Content-Type: application/pgp-keys
Content-Disposition: attachment; filename="pEpkey.asc"

-----BEGIN PGP PUBLIC KEY BLOCK-----

...
-----END PGP PUBLIC KEY BLOCK-----

--6b8b4567327b23c6643c986966334873--

2.5. Transport Message

In pEp message format 2 the "outer message" consists of a full RFC822 message with body and a minimal set of header fields, just those necessary to conform to MIME multipart standards.

The "outer message" should be encrypted and carry a signature according to the MIME encryption standards. The resulting message is the transport message which a root entity of type multipart/encrypted.

A minimal set of header fields should be set on the "transport message", as to permit delivery, without disclosing private information.

The structure of the transport message may be altered in-transit, e.g. through mailing list agents, or inspection gateways.

Signing and encrypting a message with MIME Security with [PGPMIME], yields a message with the following complete MIME structure, seen across the encryption layer:

```
= multipart/encrypted; protocol="application/pgp-encrypted";
+ application/pgp-encrypted [ Version: 1 ]
+ application/octet-stream; name="msg.asc"
{
  Content-Disposition: inline; filename="msg.asc";
}
|
[ opaque encrypted structure ]
|
{ minimal headers }
+ multipart/mixed
+ message/rfc822; forwarded="no";
|
{ protected message headers }
+ multipart/mixed
+ multipart/alternate
+ text/plain
+ text/html
+ application/octet-stream [ attachmet_1 ]
+ application/octet-stream [ attachmet_2 ]
+ application/pgp-keys
```

The header fields of the sub-part of type application/octet-stream SHOULD be modified to ensure that:

- o the Content-Type header field's
 - * "name" parameter is set to the value "msg.asc", and
 - * parameter "forwarded" is set to "no", and
- o the Content-Disposition header field value is set to "inline"
 - * and the "filename" parameter is set to "msg.asc".

2.6. S/MIME Compatibility

Interoperability and implementation symmetry between PGP/MIME and S/MIME is on the roadmap of pEp.

3. Candidate Header Fields for Header Protection

By default, all headers of the original message SHOULD be wrapped with the original message, with one exception:

- o the header field "Bcc" MUST NOT be added to the protected headers.

4. Stub Outside Headers

The outer message requires a minimal set of headers to be in place for being eligible for transport. This includes the "From", "To", "Cc", "Bcc", "Subject" and "Message-ID" header fields. The protocol hereby defined also depends on the "MIME-Version", "Content-Type", "Content-Disposition" and eventually the "Content-Transport-Encoding" header field to be present.

Submission and forwarding based on SMTP carries "from" and "receivers" information out-of-band, so that the "From" and "To" header fields are not strictly necessary. Nevertheless, "From", "Date", and at least one destination header field is mandatory as per [RFC5322]. They SHOULD be conserved for reliability.

The following header fields should contain a verbatim copy of the header fields of the inner message:

- o Date
- o From
- o To
- o Cc (*)

- o Bcc (*)

The entries with an asterisk mark (*) should only be set if also present in the original message.

Clients which follow pEp standards MUST set the header field value for "Subject" to "=?utf-8?Q?p=E2=89=A1p?=" or "pEp". Clients which do not adhere to all pEp standards should set the header field value of "Subject" to a descriptive stub value. An example used in practice is

- o Subject: Encrypted message

The following header fields MUST be initialized with proper values according to the MIME standards:

- o Content-Type
- o Content-Disposition
- o Content-Transport-Encoding (if necessary)

5. Processing Incoming Email under Progressive Header Disclosure

[[TODO]]

5.1. Processing of Signed-only Email

pEp either engages in a signed-and-encrypted communication or in an unsigned plaintext communication. Inbound signatures attached to plaintext messages are duly verified but cannot enhance the perceived quality of the message in the user interface (while an invalid signature degrades the perception) [I-D.birk-peg].

5.2. Incoming Filter Processing

The Mail User Agent may implement outgoing filtering of mails, which may veto, alter, redirect or replicate the messages. The functionality may be implemented on the mailbox server and be configurable through a well-known protocol, e.g., by means of The Sieve Mail-Filtering Language [RFC5490], or be implemented client-side, or in a combination of both.

A mailbox server, which is required to process the full range of possible filters, is requiring plaintext access to the header fields.

In an End-to-End-encryption context, which pEp enforces by default, upon first reception of the message the mailbox server is limited to

see the transport- relevant headers of the outer wrapper message. A pEp client configured to trust the server ("trusted server" setting [I-D.marques-pep-email]) will later download the encrypted message, decrypt it and replace the copy on the server by the decrypted copy.

5.2.1. Staged Filtering of Inbound Messages

Inbound messages are expected to be delivered to the inbox while still being encrypted. At this point in time, server-side filtering can only evaluate the unprotected header fields in the wrapper message.

In an End-to-End-encryption context, which pEp enforces by default, the mailbox server is limited to see the transport-relevant headers of the outer wrapper message only upon first delivery. A pEp client configured to trust the server ("trusted server" setting [I-D.marques-pep-email]) will eventually download the encrypted message, decrypt it locally and replace the copy on the server by the decrypted copy. Server-side message filters SHOULD be able to detect such post-processed messages, and apply the pending filters. The client SHOULD easily reflect the post-filtered messages in the user interface.

5.3. Outgoing Filter Processing

The Mail User Agent may implement outgoing filtering of emails, which may veto, alter or replicate the email. They may also hint the MUA to store a copy in an alternate "Sent" folder.

Filters which veto the sending or do alter the mail or replicate it (e.g., mass-mail generators) SHOULD be completed prior to applying protection, and thus also prior to applying header protection. Redirection to alternate "Sent" folders MUST NOT be decided prior to applying protection, but MUAs MAY abide from this restriction if they implement the "trusted server" option and the option is selected for the specific mailbox server; in this case, MUAs MUST NOT allow to redirect a message to an untrusted server by these rules, to prevent information leakage to the untrusted server.

[[TODO: Mention implicit filter for minimal color-rating for message replication.]]

[[TODO: How to produce key-export-mails manually this way? That is, what about non-pEp-mode?]]

6. Security Considerations

[[TODO]]

7. Privacy Considerations

[[TODO]]

8. IANA Considerations

This document has no actions for IANA.

9. Implementation Status

9.1. Introduction

This section records the status of known implementations of the protocol defined by this specification at the time of posting of this Internet-Draft, and is based on a proposal described in [RFC7942]. The description of implementations in this section is intended to assist the IETF in its decision processes in progressing drafts to RFCs. Please note that the listing of any individual implementation here does not imply endorsement by the IETF. Furthermore, no effort has been spent to verify the information presented here that was supplied by IETF contributors. This is not intended as, and must not be construed to be, a catalog of available implementations or their features. Readers are advised to note that other implementations may exist.

According to [RFC7942], "[...] this will allow reviewers and working groups to assign due consideration to documents that have the benefit of running code, which may serve as evidence of valuable experimentation and feedback that have made the implemented protocols more mature. It is up to the individual working groups to use this information as they see fit."

9.2. Current software implementing pEp

The following software implementing the pEp protocols (to varying degrees) already exists:

- o pEp for Outlook as add-on for Microsoft Outlook, release [SRC.pepforoutlook]
- o pEp for Android (based on a fork of the K9 MUA), release [SRC.pepforandroid]

- o Enigmail/pEp as add-on for Mozilla Thunderbird, release [SRC.enigmailpep]
- o pEp for iOS (implemented in a new MUA), beta [SRC.pepforios]

pEp for Android, iOS and Outlook are provided by pEp Security, a commercial entity specializing in end-user software implementing pEp while Enigmail/pEp is pursued as community project, supported by the pEp Foundation.

All software is available as Free Software and published also in source form.

10. Acknowledgements

The authors would like to thank the following people who have provided significant contributions or feedback for the development of this document: Krista Bennett, Volker Birk, Bernie Hoeneisen and Hernani Marques.

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Appendix A. About pEp Design Principles

pretty Easy privacy (pEp) is working on bringing state-of-the-art automatic cryptography known from areas like TLS to electronic mail (email) communication. pEp is determined to evolve the existing standards as fundamentally and comprehensively as needed to gain easy implementation and integration, and for easy use for regular Internet users. pEp for email wants to attain to good security practice while still retaining backward compatibility for implementations widespread.

To provide the required stability as a foundation for good security practice, pEp for email defines a fixed MIME structure for its innermost message structure, so to remove most attack vectors which have permitted the numerous EFAIL vulnerabilities. (TBD: ref)

Security comes just next after privacy in pEp, for which reason the application of signatures without encryption to messages in transit is not considered purposeful. pEp for email herein referenced, and further described in [I-D.marques-pep-email], either expects to transfer messages in cleartext without signature or encryption, or transfer them encrypted and with enclosed signature and necessary public keys so that replies can be immediately upgraded to encrypted messages.

The pEp message format is equivalent to the S/MIME standard in ensuring header protection, in that the whole message is protected

instead, by wrapping it and providing cryptographic services to the whole original message. The pEp message format is different compared to the S/MIME standard in that the pEp protocols propose opportunistic End-to-End security and signature, by allowing the transport of the necessary public key material along with the original messages.

For the purpose of allowing the insertion of such public keys, the root entity of the protected message is thus nested once more into an additional multipart/mixed MIME entity. The current pEp proposal is for PGP/MIME, while an extension to S/MIME is next.

pEp's proposal is strict in that it requires that the cryptographic services applied to the protected message MUST include encryption. It also mandates a fixed MIME structure for the protected message, which always MUST include a plaintext and optionally an HTML representation (if HTML is used) of the same message, and requires that all other optional elements to be eventually presented as attachments. Alternatively the whole protected message could represent in turn a wrapped pEp wrapper, which makes the message structure fully recursive on purpose (e.g., for the purpose of anonymization through onion routing).

For the purpose of implementing mixnet routing for email, it is foreseen to nest pEp messages recursively. A protected message can in turn contain a protected message due for forwarding. This is for the purpose to increase privacy and counter the necessary leakage of plaintext addressing in the envelope of the email.

The recursive nature of the pEp message format allows for the implementation of progressive disclosure of the necessary transport relevant header fields just as-needed to the next mail transport agents along the transmission path.

Appendix B. Document Changelog

[[RFC Editor: This section is to be removed before publication]]

- o draft-luck-lamps-pep-header-protection-03
 - * Remove Use Cases / Requirements sections (move to new doc)
 - * Adjust title of the document
 - * Added note on implementation done of forwarded=no
- o draft-luck-lamps-pep-header-protection-02

- * Add Privacy and IANA Considerations sections
- * Added / Adjusted requirements
- o draft-luck-lamps-pep-header-protection-01
 - * Major rewrite and update of whole document
- o draft-luck-lamps-pep-header-protection-00
 - * Initial version

Appendix C. Open Issues

- [[RFC Editor: This section should be empty and is to be removed before publication.]]
- o Align with specification for MIME Content-Type message/partial
 - * We probably have issues and overlapping specifications about encoding for nested message/rfc822 entities, specified in [RFC2046]. Further study is needed to find and understand the issues.

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October 18, 2018

Considerations for protecting Email header with S/MIME
draft-melnikov-lamps-header-protection-00

Abstract

This document describes best practices for handling of Email header protected by S/MIME. Procedures described in this document are also applicable to OpenPGP.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

Internet-Drafts are working documents of the Internet Engineering Task Force (IETF). Note that other groups may also distribute working documents as Internet-Drafts. The list of current Internet-Drafts is at <https://datatracker.ietf.org/drafts/current/>.

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This Internet-Draft will expire on April 21, 2019.

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1. Introduction

S/MIME [RFC5751] is typically used to protect (sign and/or encrypt) Email message body parts, but not header of corresponding Email messages. Header fields may contain confidential information or information whose validity need protecting from modification. [RFC5751] describes how to protect the Email message header [RFC5322], by wrapping the message inside a message/rfc822 container [RFC2045]:

In order to protect outer, non-content-related message header fields (for instance, the "Subject", "To", "From", and "Cc" fields), the sending client MAY wrap a full MIME message in a message/rfc822 wrapper in order to apply S/MIME security services to these header fields. It is up to the receiving client to decide how to present this "inner" header along with the unprotected "outer" header.

When an S/MIME message is received, if the top-level protected MIME entity has a Content-Type of message/rfc822, it can be assumed that the intent was to provide header protection. This entity SHOULD be presented as the top-level message, taking into account header merging issues as previously discussed.

While the above advice helps in protecting message header fields, it doesn't provide enough guidance on what information should and should not be included in outer (unprotected) header and how information from outer and inner headers should be presented to users. Additionally, there are very few implementations of the header

protection mechanism specified in [RFC5751]. Email clients that don't support this mechanism display messages with header protection as if they are forwarded email messages. Some of them don't display content of forwarded messages by default (e.g. they display at attachment or an icon), so viewing them requires an extra action by the user.

[[Alexey: Depending on WG consensus, the following text will be updated to either suggest an alternative approach that is friendlier to non compliant email clients or to reinforce use of message/rfc822 for header protection + recommend use of the new "forwarded" parameter to Content-Type.]] This document describes best UI and other practices for handling of message header protection. The goal of this document is to improve interoperability and minimize damage caused by possible differences between inner and outer headers.

2. Conventions Used in This Document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

The terms "header field" and "header section" are defined in [RFC5322].

The following terms are defined in this document:

Signed-only message: a multipart/signed or application/pkcs7-mime containing SignedData message which doesn't contain any encrypted layer. I.e. this is a message which is not encrypted and not encrypted + signed.

3. Recommended algorithms for email header protection

[[LAMPS WG should pick between the following 2 alternatives. They are described in details in subsections of this section.]]

Examples in subsequent sections assume that an email client is trying to protect (sign) the following initial message:

Date: Mon, 25 Sep 2017 17:31:42 +0100 (GMT Daylight Time)
From: "Alexey Melnikov" <alexey.melnikov@example.net>
Message-ID: <e4a483cb-1dfb-481d-903b-298c92c21f5e@mattingly.example.net>
MIME-Version: 1.0
MMHS-Primary-Precedence: 3
Subject: Meeting at my place
To: somebody@example.net
X-Mailer: Isode Harrier Web Server
Content-Type: text/plain; charset=us-ascii

This is an important message that I don't want to be modified.

Without message header protection the corresponding signed message might look like this. (Lines prepended by "O: " are the outer header.)

O: Date: Mon, 25 Sep 2017 17:31:42 +0100 (GMT Daylight Time)
O: Message-ID: <e4a483cb-1dfb-481d-903b-298c92c21f5e@mattingly.example.net>
O: Subject: Meeting at my place
O: From: "Alexey Melnikov" <alexey.melnikov@example.net>
O: MIME-Version: 1.0
O: content-type: multipart/signed; charset=us-ascii; micalg=sha1;
O: protocol="application/pkcs7-signature";
O: boundary=.cbel6d2a-e1a3-4220-b821-38348fc97237

This is a multipart message in MIME format.
--.cbel6d2a-e1a3-4220-b821-38348fc97237
Content-Type: text/plain; charset=us-ascii

This is an important message that I don't want to be modified.

--.cbel6d2a-e1a3-4220-b821-38348fc97237
Content-Transfer-Encoding: base64
content-type: application/pkcs7-signature

[[base-64 encoded signature]]

--.cbel6d2a-e1a3-4220-b821-38348fc97237--

3.1. Option 1: Memory Hole

Memory Hole approach works by copying the normal message header fields into the MIME header section of the top level protected body part. Since the MIME body part header section is itself covered by the protection mechanisms (signing and/or encryption) it shares the protections of the message body.

The following example demonstrates how header section and payload of a protect body part might look like. For example, this will be the first body part of a multipart/signed message or the signed and/or encrypted payload of the application/pkcs7-mime body part. Lines prepended by "O: " are the outer header section. Lines prepended by "I: " are the inner header section.

```
O: Date: Mon, 25 Sep 2017 17:31:42 +0100 (GMT Daylight Time)
O: Message-ID: <e4a483cb-1dfb-481d-903b-298c92c21f5e@mattingly.example.net>
O: Subject: Meeting at my place
O: From: "Alexey Melnikov" <alexey.melnikov@example.net>
O: MIME-Version: 1.0
O: content-type: multipart/signed; charset=us-ascii; micalg=sha1;
O:   protocol="application/pkcs7-signature";
O:   boundary=.cbel6d2a-e1a3-4220-b821-38348fc97237
```

This is a multipart message in MIME format.

```
--.cbel6d2a-e1a3-4220-b821-38348fc97237
I: Date: Mon, 25 Sep 2017 17:31:42 +0100 (GMT Daylight Time)
I: From: "Alexey Melnikov" <alexey.melnikov@example.net>
I: Message-ID: <e4a483cb-1dfb-481d-903b-298c92c21f5e@mattingly.example.net>
I: MIME-Version: 1.0
I: MMHS-Primary-Precedence: 3
I: Subject: Meeting at my place
I: To: somebody@example.net
I: X-Mailer: Isode Harrier Web Server
I: Content-Type: text/plain; charset=us-ascii
```

This is an important message that I don't want to be modified.

```
--.cbel6d2a-e1a3-4220-b821-38348fc97237
Content-Transfer-Encoding: base64
content-type: application/pkcs7-signature
```

[[base-64 encoded signature]]

```
--.cbel6d2a-e1a3-4220-b821-38348fc97237--
```

3.2. Option 2: Wrapping with message/rfc822 or message/global

Wrapping with message/rfc822 (or message/global) works by copying the normal message header fields into the MIME header section of the top level protect body part and then prepending them with "Content-Type: message/rfc822; forwarded=no\r\n" or "Content-Type: message/global; forwarded=no\r\n", where \r\n is US-ASCII CR followed by US-ASCII LF. Since the MIME body part header section is itself covered by the protection mechanisms (signing and/or encryption) it shares the protections of the message body.

The rest of this section formally defines the new "forwarded" Content-Type header field parameter and how header section wrapping works.

This document defines a new Content-Type header field parameter [RFC2045] with name "forwarded". The parameter value is case-insensitive and can be either "yes" or "no". (The default value being "yes"). The parameter is only meaningful with media type "message/rfc822" and "message/global" [RFC6532] when used within S/MIME signed or encrypted body parts. The value "yes" means that the message nested inside "message/rfc822" ("message/global") is a forwarded message and not a construct created solely to protect the inner header section.

Instructions in [RFC5751] describing how to protect the Email message header section [RFC5322], by wrapping the message inside a message/rfc822 container [RFC2045] are thus updated to read:

In order to protect outer, non-content-related message header fields (for instance, the "Subject", "To", "From", and "Cc" fields), the sending client MAY wrap a full MIME message in a message/rfc822 wrapper in order to apply S/MIME security services to these header fields. It is up to the receiving client to decide how to present this "inner" header section along with the unprotected "outer" header section.

When an S/MIME message is received, if the top-level protected MIME entity has a Content-Type of message/rfc822 or message/global without the "forwarded" parameter or with the "forwarded" parameter set to "no", it can be assumed that the intent was to provide header protection. This entity SHOULD be presented as the top-level message, taking into account header section merging issues as previously discussed.

The following example demonstrates how header section and payload of a protect body part might look like. For example, this will be the first body part of a multipart/signed message or the signed and/or encrypted payload of the application/pkcs7-mime body part. Lines prepended by "O: " are the outer header section. Lines prepended by "I: " are the inner header section. Lines prepended by "W: " are the wrapper.

O: Date: Mon, 25 Sep 2017 17:31:42 +0100 (GMT Daylight Time)
O: Message-ID: <e4a483cb-1dfb-481d-903b-298c92c21f5e@mattingly.example.net>
O: Subject: Meeting at my place
O: From: "Alexey Melnikov" <alexey.melnikov@example.net>
O: MIME-Version: 1.0
O: content-type: multipart/signed; charset=us-ascii; micalg=sha1;
O: protocol="application/pkcs7-signature";
O: boundary=.cbel6d2a-ela3-4220-b821-38348fc97237

This is a multipart message in MIME format.

--.cbel6d2a-ela3-4220-b821-38348fc97237

W: Content-Type: message/rfc822; forwarded=no

W:

I: Date: Mon, 25 Sep 2017 17:31:42 +0100 (GMT Daylight Time)
I: From: "Alexey Melnikov" <alexey.melnikov@example.net>
I: Message-ID: <e4a483cb-1dfb-481d-903b-298c92c21f5e@mattingly.example.net>
I: MIME-Version: 1.0
I: MMHS-Primary-Precedence: 3
I: Subject: Meeting at my place
I: To: somebody@example.net
I: X-Mailer: Isode Harrier Web Server
I: Content-Type: text/plain; charset=us-ascii

This is an important message that I don't want to be modified.

--.cbel6d2a-ela3-4220-b821-38348fc97237

Content-Transfer-Encoding: base64

content-type: application/pkcs7-signature

[[base-64 encoded signature]]

--.cbel6d2a-ela3-4220-b821-38348fc97237--

4. Recommendations for handling of S/MIME protected header

[[This section needs more work. Don't treat anything in it as unchangeable.]]

For a signed-only message, it is RECOMMENDED that all "outer" header fields are copied into the "inner" protected body part. This would mean that all header fields are signed. In this case, the "outer" header fields simply match the protected header fields. And in the case that the "outer" header fields differ, they can simply be replaced with their protected versions when displayed to the user.

When generating encrypted or encrypted+signed S/MIME messages which protect header fields:

1. If a header field is being encrypted because it is sensitive, its true value MUST NOT be included in the outer header. If the header field is mandatory according to RFC 5322, a stub value (or a value indicating that the outer value is not to be used) is to be included in the outer header section.
2. The outer header section SHOULD be minimal in order to avoid disclosure of confidential information. It is recommended that the outer header section only contains "Date" (set to the same value as in the inner header field, or, if the Date value is also sensitive, to Monday 9am of the same week), possibly "Subject" and "To"/"Bcc" header fields. In particular, Keywords, In-Reply-To and References header fields SHOULD NOT be included in the outer header; "To" and "Cc" header fields should be omitted and replaced with "Bcc: undisclosed-recipients;".

But note that having key header fields duplicated in the outer header is convenient for many message stores (e.g. IMAP) and clients that can't decode S/MIME encrypted messages. In particular, Subject/To/Cc/Bcc/Date header field values are returned in IMAP ENVELOPE FETCH data item [RFC3501], which is frequently used by IMAP clients in order to avoid parsing message header.

3. The "Subject" header field value of the outer header section SHOULD either be identical to the inner "Subject" header field value, or contain a clear indication that the outer value is not to be used for display (the inner header field value would contain the true value).

Note that recommendations listed above typically only apply to non MIME header fields (header fields with names not starting with "Content-" prefix), but there are exception, e.g. Content-Language.

Note that the above recommendations can also negatively affect antispam processing.

When displaying S/MIME messages which protect header fields (whether they are signed-only, encrypted or encrypted+signed):

1. The outer headers might be tampered with, so a receiving client SHOULD ignore them, unless they are protected in some other way(*). If a header field is present in the inner header, only the inner header field value MUST be displayed (and the corresponding outer value must be ignored). If a particular header field is only present in the outer header, it MAY be ignored (not displayed) or it MAY be displayed with a clear indicator that it is not trustworthy(*).

(*) - this only applies if the header field is not protected is some other way, for example with a DKIM signature that validates and is trusted.

5. Mail User Agent Algorithm for deciding which version of a header field to display

[[TBD: describe how to recurse to find the innermost protected root body part, extract header fields from it and propagate them to the top level. This should also work for triple-wrapped messages.]]

6. Open Issues

[[This list should be empty before publication:]]

7. IANA Considerations

This document requests no action from IANA. RFC Editor can delete this section before publication.

8. Security Considerations

This document talks about UI considerations, including security considerations, when processing messages protecting header fields. One of the goals of this document is to specify UI for displaying such messages which is less confusing/misleading and thus more secure.

The document is not defining new protocol, so it doesn't create any new security concerns not already covered by S/MIME [RFC5751], MIME [RFC2045] and Email [RFC5322] in general.

9. References

- 9.1. Normative References

- [RFC2045] Freed, N. and N. Borenstein, "Multipurpose Internet Mail Extensions (MIME) Part One: Format of Internet Message Bodies", RFC 2045, DOI 10.17487/RFC2045, November 1996, <<https://www.rfc-editor.org/info/rfc2045>>.
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- [RFC5751] Ramsdell, B. and S. Turner, "Secure/Multipurpose Internet Mail Extensions (S/MIME) Version 3.2 Message Specification", RFC 5751, DOI 10.17487/RFC5751, January 2010, <<https://www.rfc-editor.org/info/rfc5751>>.
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- [RFC8174] Leiba, B., "Ambiguity of Uppercase vs Lowercase in RFC 2119 Key Words", BCP 14, RFC 8174, DOI 10.17487/RFC8174, May 2017, <<https://www.rfc-editor.org/info/rfc8174>>.

9.2. Informative References

- [RFC3501] Crispin, M., "INTERNET MESSAGE ACCESS PROTOCOL - VERSION 4rev1", RFC 3501, DOI 10.17487/RFC3501, March 2003, <<https://www.rfc-editor.org/info/rfc3501>>.

Appendix A. Acknowledgements

Thank you to Wei Chuang, Steve Kille, David Wilson and Robert Williams for suggestions, comments and corrections on this document. Text on "Memory Hole" approach was taken from Daniel Kahn Gillmor's emails.

David Wilson came up with the idea of defining a new Content-Type header field parameter to distinguish forwarded messages from inner header field protection constructs.

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Composite Public Keys and Signatures
draft-pala-composite-crypto-03

Abstract

PKIs are used to provide scalability and ease key management. One type of PKIs that is predominant for securing communications and data is based on the X.509 standard. Since the security of PKIs, ultimately, depends on the security of the cryptographic building blocks that are used for authentication and encryption, the standards community made algorithm agility a priority. Algorithm agility, in particular, enables upgrading to newly available algorithms when needed.

The CompositeCrypto (i.e., CompositeKey and CompositeSignature structures) described in this document provides an additional tool that enables the use of multiple algorithms to authenticate data without the need to use multiple certificates and more complex data structures.

This document provide the description of the definition and encoding rules for CompositeKey and CompositeSignature. A description of how to use these structures in main PKIX objects (e.g., X.509 certificates, CRLs, OCSP responses, etc.) is also provided.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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This Internet-Draft will expire on September 26, 2019.

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1. Requirements notation

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 [RFC2119].

2. Introduction and Scope

With the definition of new algorithms (e.g. more efficient factoring techniques) and technologies (e.g., quantum-based computing devices) that might be available in the near future, the need to provide an easy-to-deploy and efficient solution capable of providing multi-algorithms authentication is paramount.

Today there are no complete or general solutions that allow the use of multiple public-key algorithms to authenticate PKIX data without using multiple X.509 certificates or complex data structures. For example, CRLs or OCSP responses can not be protected via multiple algorithms without wrapping the OCSP responses' data via CMS or other signed containers.

We define two new building blocks, i.e. `compositeKey` and `compositeSignature`, that can be used in many environments where Public Key authentication is used - i.e., from the generation of certificates that are authenticated with multiple signatures (i.e., using multiple keys that may or may not use different cryptographic schemes or different number of security bits), to the possibility of specifying a composite key that combines multiple public keys together (instead of one) in a single certificate.

This document describes the encoding of the new building blocks and their application to different X.509 core data structures that are used in PKIs. In particular, this document focuses only on the definition of the composite keys and composite signatures definitions for X.509 based PKIs (PKIX) by providing the encoding rules and their usage in existing X.509 (PKIX) data structures.

3. Composite Cryptography

Composite Cryptography is defined as the possibility to combine different public keys and signatures in PKIX objects. The following OID is defined to identify the algorithm class:

```
id-pk-compositeCrypto OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1) private(4)
    enterprise(1) OpenCA(18227) Algorithms(2) 1 }
```

Composite Cryptography provides three distinct building blocks: the `compositePublicKey`, the `compositePrivateKey` and the `compositeSignature`. The `compositePublicKey` is meant to carry all the public keys associated with an identity. The `compositePrivateKey` is meant to carry all the private keys associated with an identity. The `compositeSignature`, instead, carries a sequence of signatures that

are generated by using the different individual keys from a `compositePrivateKey`.

3.1. Composite Public Keys

This document defines a new Object Identifier and data structure for composite public keys as follows:

```
id-pk-compositePublicKey OBJECT IDENTIFIER ::= { id-kp-compositeCrypto 1 }
```

```
CompositePublicKey ::= SEQUENCE (1..MAX) OF SubjectPublicKeyInfo
```

3.2. Composite Private Keys

This section specifies a syntax and semantics for Composite Keys private key information. Composite private key information is built as a SEQUENCE of BIT STRINGS each of which contains the single private keys and parameters. Additionally, it may include the corresponding public keys.

The structure defined in this document allows for the distribution of the composite keys (public and private) and the associated domain parameters by using a sequence of `OneAsymmetricKey` as defined in [RFC5958].

The Algorithm Identifier and data structure associated for Composite Private Keys is defined as follows:

```
id-pk-compositePrivateKey OBJECT IDENTIFIER ::= { id-kp-compositeCrypto 2 }
```

```
CompositePrivateKey ::= SEQUENCE (1..MAX) OF OneAsymmetricKey
```

3.2.1. Encoding Rules

When encoding Composite Private Keys, generators SHOULD use Distinguished Encoding Rules (DER) [X.690] and receivers SHOULD be prepared to handle Basic Encoding Rules (BER) [X.690] and DER [X.690].

3.2.2. Encrypted and Un-encrypted Local Storage

The `compositePrivateKeys` format as defined in the previous subsection can also be used for local storage of an unencrypted `compositePrivateKeys` binary object. The `compositePrivateKeys` can also be formatted in PEM format that uses the `".pem"` file extension and which is encoded as the Base64 encoding (see Section 4 of [RFC4648]), of the DER-encoded `compositePrivateKeys` object with the following armour:

```
-----BEGIN COMPOSITE PRIVATE KEY-----  
-----END COMPOSITE PRIVATE KEY-----
```

Local storage of an encrypted CompositePrivateKeys object is out of scope of this document. However, CompositePrivateKeys should be the format for the plaintext key being encrypted. DER [X.690] encoding the CompositePrivateKeys will promote interoperability if the key is encrypted for transport to another party. PEM encoding the DER-encoded CompositePrivateKeys is common; "Proc-Type:" and "DEK-INFO:" fields [RFC1421] followed by the DER-encoded CompositePrivateKeys. The following armour used in this case is as follows:

```
-----BEGIN COMPOSITE PRIVATE KEY-----  
-----END COMPOSITE PRIVATE KEY-----
```

3.2.3. Asymmetric Key Packages

The Cryptographic Message Syntax (CMS), as defined in RFC 5652, can be used to digitally sign, digest, authenticate, or encrypt the asymmetric key format content type.

When encoding Composite Private Keys, the privateKeyAlgorithm in the OneAsymmetricKey SHALL be set to id-kp-compositePrivateKey.

The parameters of the privateKeyAlgorithm SHALL be a sequence of AlgorithmIdentifier objects, each of which are encoded according to the rules defined for each of the different keys in the Composite Private Key.

The value of the privateKey field in the OneAsymmetricKey SHALL be set to the DER encoding of the SEQUENCE of private key values that make up the composite key. The number and order of elements in the sequence SHALL be the same as identified in the sequence of parameters in the privateKeyAlgorithm.

The value of the the publicKey (if present) SHALL be set to the DER encoding of the SEQUENCE of publicKey values. If this field is present, the number and order of elements SHALL be the same as identified in the sequence of parameters in the privateKeyAlgorithm.

The value of the attributes is encoded as usual.

3.3. Composite Signatures

The use of composite signatures allows for the use of multiple algorithms for authentication.

id-pk-compositeSignature OBJECT IDENTIFIER ::= { compositeCrypto 3 }

CompositeSignature OBJECT IDENTIFIER ::= SEQUENCE (1..MAX) OF BITSTRING

3.4. Generating Composite Signatures

When generating a CompositeSignature, the signing entity MUST generate one signature per key that is in the corresponding compositePrivateKey set.

The value of the compositeSignature is the DER encoding of the SEQUENCE of BIT STRING where each BIT STRING is the DER representation of the signature generated with one of the private key in the compositePrivateKey set.

When signing, the order of the signature MUST respect the order of keys in the compositePrivateKey and compositePublicKey sets.

3.5. Verifying Composite Signatures

When validating a compositeSignature, the relying party MUST verify at least one of the signatures in the compositeSignature structure and SHOULD verify all of them.

The process of validating composite signatures starts with going through the sequence of the signatures and if the inner signature algorithm is supported, the relying party MUST verify the signature with the corresponding public key in the compositePrivateKey.

The order of the signatures MUST respect the order of keys in the compositePrivateKey and compositePublicKey sets.

4. Use of Composite Crypto in PKIX structures

4.1. Use in X.509 Certificates

4.2. Use in X.509 CRLs

4.3. Use in X.509 OCSP Messages

4.4. Use in PKCS#7

4.5. Use in PKCS#8

4.6. Use in PKCS#12

4.7. Use in CMS

5. Security Considerations

This structures described in this document do not protect the private keys information in any way unless combined with a security protocol or encryption properties of the objects (if any) where the CompositePrivateKey is used (see next Section).

Protection of the private key information is vital to public key cryptography. The consequences of disclosure depend on the purpose of the private key. If a private key is used for signature, then the disclosure allows unauthorized signing. If a private key is used for key management, then disclosure allows unauthorized parties to access the managed keying material. The encryption algorithm used in the encryption process must be as 'strong' as the key it is protecting.

6. IANA considerations

The CMS content type OID is registered in a DoD arc. The ASN.1 module OID is TBD. The id-pk-compositeCrypto, id-pk-compositePrivateKey, id-pk-compositePublicKey, and id-pk-compositeSignature OIDs are to be assigned by IANA. The authors suggest to use the id-pkix arc for this usage.

7. Acknowledgments

The authors would like to thank everybody who provided insightful comments and helped in any form. This document uses a lot of text from similar documents ([RFC3279] and [RFC8410]) as well as [I-D.ietf-lamps-cms-hash-sig]. Thanks go to the authors of those documents. "Copying always makes things easier and less error prone" - [RFC8411].

8. Normative References

- [RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <<https://www.rfc-editor.org/info/rfc2119>>.

Appendix A. ASN.1 Module

```
CompositeCrypto-2009 { iso(1) identified-organization(3) dod(6) internet(1)
    security(5) mechanisms(5) pkix(7) id-mod(0) TBD }
```

```
DEFINITIONS IMPLICIT TAGS ::= BEGIN
```

```
EXPORTS ALL;
```

```
IMPORTS
```

```
    PUBLIC-KEY, SIGNATURE-ALGORITHM
```

```
    FROM AlgorithmInformation-2009 -- RFC 5911 [CMSASN1]
```

```
        { iso(1) identified-organization(3) dod(6) internet(1)
          security(5) mechanisms(5) pkix(7) id-mod(0)
          id-mod-algorithmInformation-02(58) }
```

```
--
```

```
-- Object Identifiers
```

```
--
```

```
id-pk-compositeCrypto OBJECT IDENTIFIER ::= { iso(1)
    identified-organization(3) dod(6) internet(1) private(4)
    enterprise(1) OpenCA(18227) Algorithms(2) 1 }
```

```
id-pk-compositePublicKey OBJECT IDENTIFIER ::= {
    id-kp-compositeCrypto 1 }
```

```
id-pk-compositePrivateKey OBJECT IDENTIFIER ::= {
    id-kp-compositeCrypto 2 }
```

```
id-pk-compositeSignature OBJECT IDENTIFIER ::= {
    id-kp-compositeCrypto 3 }
```

```
END
```

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Algorithm Identifiers for HSS and XMSS for Use in the Internet X.509
Public Key Infrastructure
draft-vangeest-x509-hash-sigs-03

Abstract

This document specifies algorithm identifiers and ASN.1 encoding formats for the Hierarchical Signature System (HSS), eXtended Merkle Signature Scheme (XMSS), and XMSS^{MT}, a multi-tree variant of XMSS. This specification applies to the Internet X.509 Public Key Infrastructure (PKI) when digital signatures are used to sign certificates and certificate revocation lists (CRLs).

Status of This Memo

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1. Introduction

The Hierarchical Signature System (HSS) is described in [I-D.mcgrew-hash-sigs].

The eXtended Merkle Signature Scheme (XMSS), and its multi-tree variant XMSS^{MT}, are described in [RFC8391].

These signature algorithms are based on well-studied Hash Based Signature (HBS) schemes, which can withstand known attacks using quantum computers. They combine Merkle Trees with One Time Signature (OTS) schemes in order to create signature systems which can sign a large but limited number of messages per private key. The private keys are stateful; a key's state must be updated and persisted after signing to prevent reuse of OTS keys. If an OTS key is reused, cryptographic security is not guaranteed for that key.

Due to the statefulness of the private key and the limited number of signatures that can be created, these signature algorithms might not be appropriate for use in interactive protocols. While the right selection of algorithm parameters would allow a private key to sign a

virtually unbounded number of messages (e.g. 2^{60}), this is at the cost of a larger signature size and longer signing time. Since these algorithms are already known to be secure against quantum attacks, and because roots of trust are generally long-lived and can take longer to be deployed than end-entity certificates, these signature algorithms are more appropriate to be used in root and subordinate CA certificates. They are also appropriate in non-interactive contexts such as code signing. In particular, there are multi-party IoT ecosystems where publicly trusted code signing certificates are useful.

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 [RFC2119].

2. Subject Public Key Algorithms

Certificates conforming to [RFC5280] can convey a public key for any public key algorithm. The certificate indicates the algorithm through an algorithm identifier. An algorithm identifier consists of an OID and optional parameters.

In this document, we define new OIDs for identifying the different hash-based signature algorithms. An additional OID is defined in [I-D.ietf-lamps-cms-hash-sig] and repeated here for convenience. For all of the OIDs, the parameters MUST be absent.

2.1. HSS Public Keys

The object identifier and public key algorithm identifier for HSS is defined in [I-D.ietf-lamps-cms-hash-sig]. The definitions are repeated here for reference.

The object identifier for an HSS public key is id-alg-hss-lms-hashsig:

```
id-alg-hss-lms-hashsig OBJECT IDENTIFIER ::= { iso(1)
  member-body(2) us(840) rsadsi(113549) pkcs(1) pkcs9(9)
  smime(16) alg(3) 17 }
```

Note that the id-alg-hss-lms-hashsig algorithm identifier is also referred to as id-alg-mts-hashsig. This synonym is based on the terminology used in an early draft of the document that became [I-D.mcgrewe-hash-sigs].

The HSS public key's properties are defined as follows:

```
pk-HSS-LMS-HashSig PUBLIC-KEY ::= {  
  IDENTIFIER id-alg-hss-lms-hashsig  
  KEY HSS-LMS-HashSig-PublicKey  
  PARAMS ARE absent  
  CERT-KEY-USAGE  
    { digitalSignature, nonRepudiation, keyCertSign, cRLSign } }
```

```
HSS-LMS-HashSig-PublicKey ::= OCTET STRING
```

[I-D.ietf-lamps-cms-hash-sig] contains more information on the contents and format of an HSS public key.

2.2. XMSS Public Keys

The object identifier for an XMSS public key is id-alg-xmss:

```
id-alg-xmss OBJECT IDENTIFIER ::= { itu-t(0)  
  identified-organization(4) etsi(0) reserved(127)  
  etsi-identified-organization(0) isara(15) algorithms(1)  
  asymmetric(1) xmss(13) 0 }
```

The XMSS public key's properties are defined as follows:

```
pk-XMSS PUBLIC-KEY ::= {  
  IDENTIFIER id-alg-xmss  
  KEY XMSS-PublicKey  
  PARAMS ARE absent  
  CERT-KEY-USAGE  
    { digitalSignature, nonRepudiation, keyCertSign, cRLSign } }
```

```
XMSS-PublicKey ::= OCTET STRING
```

The format of an XMSS public key is is formally defined using XDR [RFC4506] and is defined in Appendix B.3 of [RFC8391]. In particular, the first 4 bytes represents the big-ending encoding of the XMSS algorithm type.

2.3. XMSS^{MT} Public Keys

The object identifier for an XMSS^{MT} public key is id-alg-xmssmt:

```
id-alg-xmssmt OBJECT IDENTIFIER ::= { itu-t(0)  
  identified-organization(4) etsi(0) reserved(127)  
  etsi-identified-organization(0) isara(15) algorithms(1)  
  asymmetric(1) xmssmt(14) 0 }
```

The XMSS^{MT} public key's properties are defined as follows:

```
pk-XMSSMT PUBLIC-KEY ::= {  
    IDENTIFIER id-alg-xmssmt  
    KEY XMSSMT-PublicKey  
    PARAMS ARE absent  
    CERT-KEY-USAGE  
        { digitalSignature, nonRepudiation, keyCertSign, cRLSign } }  
  
XMSSMT-PublicKey ::= OCTET STRING
```

The format of an XMSS^{MT} public key is formally defined using XDR [RFC4506] and is defined in Appendix C.3 of [RFC8391]. In particular, the first 4 bytes represents the big-ending encoding of the XMSS^{MT} algorithm type.

3. Key Usage Bits

The intended application for the key is indicated in the keyUsage certificate extension.

If the keyUsage extension is present in an end-entity certificate that indicates id-alg-xmss or id-alg-xmssmt in SubjectPublicKeyInfo, then the keyUsage extension MUST contain one or both of the following values:

```
nonRepudiation; and  
digitalSignature.
```

If the keyUsage extension is present in a certification authority certificate that indicates id-alg-xmss or id-alg-xmssmt, then the keyUsage extension MUST contain one or more of the following values:

```
nonRepudiation;  
digitalSignature;  
keyCertSign; and  
cRLSign.
```

[I-D.ietf-lamps-cms-hash-sig] defines the key usage for id-alg-hss-lms-hashsig, which is the same as for the keys above.

4. Signature Algorithms

This section identifies OIDs for signing using HSS, XMSS, and XMSS^{MT}. When these algorithm identifiers appear in the algorithm field as an AlgorithmIdentifier, the encoding MUST omit the parameters field. That is, the AlgorithmIdentifier SHALL be a SEQUENCE of one component, one of the OIDs defined below.

The data to be signed is prepared for signing. For the algorithms used in this document, the data is signed directly by the signature algorithm, the data is not hashed before processing. Then, a private key operation is performed to generate the signature value. For HSS, the signature value is described in section 3.3 of [I-D.mcgregre-hash-sigs]. For XMSS and XMSS^{MT} the signature values are described in sections B.2 and C.2 of [RFC8391] respectively. The octet string representing the signature is encoded directly in the BIT STRING without adding any additional ASN.1 wrapping. For the Certificate and CertificateList structures, the signature value is wrapped in the "signatureValue" BIT STRING field.

4.1. HSS Signature Algorithm

The HSS public key OID is also used to specify that an HSS signature was generated on the full message, i.e. the message was not hashed before being processed by the HSS signature algorithm.

```
id-alg-hss-lms-hashsig OBJECT IDENTIFIER ::= { iso(1)
  member-body(2) us(840) rsadsi(113549) pkcs(1) pkcs9(9)
  smime(16) alg(3) 17 }
```

[I-D.ietf-lamps-cms-hash-sig] contains more information on the contents and format of an HSS signature.

4.2. XMSS Signature Algorithm

The XMSS public key OID is also used to specify that an XMSS signature was generated on the full message, i.e. the message was not hashed before being processed by the XMSS signature algorithm.

```
id-alg-xmss OBJECT IDENTIFIER ::= { itu-t(0)
  identified-organization(4) etsi(0) reserved(127)
  etsi-identified-organization(0) isara(15) algorithms(1)
  asymmetric(1) xmss(13) 0 }
```

The format of an XMSS signature is formally defined using XDR [RFC4506] and is defined in Appendix B.2 of [RFC8391].

4.3. XMSS^{MT} Signature Algorithm

The XMSS^{MT} public key OID is also used to specify that an XMSS^{MT} signature was generated on the full message, i.e. the message was not hashed before being processed by the XMSS^{MT} signature algorithm.

```
id-alg-xmssmt OBJECT IDENTIFIER ::= { itu-t(0)
    identified-organization(4) etsi(0) reserved(127)
    etsi-identified-organization(0) isara(15) algorithms(1)
    asymmetric(1) xmssmt(14) 0 }
```

The format of an XMSS^{MT} signature is is formally defined using XDR [RFC4506] and is defined in Appendix C.2 of [RFC8391].

5. ASN.1 Module

For reference purposes, the ASN.1 syntax is presented as an ASN.1 module here.

```
-- ASN.1 Module
```

```
Hashsigns-pkix-0 -- TBD - IANA assigned module OID
```

```
DEFINITIONS EXPLICIT TAGS ::=
BEGIN
```

```
IMPORTS
```

```
    PUBLIC-KEY, SIGNATURE-ALGORITHM
```

```
    FROM AlgorithmInformation-2009
```

```
        {iso(1) identified-organization(3) dod(6) internet(1) security(5)
```

```
        mechanisms(5) pkix(7) id-mod(0)
```

```
        id-mod-algorithmInformation-02(58)}
```

```
;
```

```
-- Object Identifiers
```

```
--
```

```
-- id-alg-hss-lms-hashsig is defined in [ietf-lamps-cms-hash-sig]
```

```
--
```

```
-- id-alg-hss-lms-hashsig OBJECT IDENTIFIER ::= { iso(1)
```

```
--     member-body(2) us(840) rsadsi(113549) pkcs(1) pkcs9(9)
```

```
--     smime(16) alg(3) 17 }
```

```
id-alg-xmss OBJECT IDENTIFIER ::= { itu-t(0)
```

```
    identified-organization(4) etsi(0) reserved(127)
```

```
    etsi-identified-organization(0) isara(15) algorithms(1)
```

```
    asymmetric(1) xmss(13) 0 }
```

```
id-alg-xmssmt OBJECT IDENTIFIER ::= { itu-t(0)
```

```
    identified-organization(4) etsi(0) reserved(127)
```

```
    etsi-identified-organization(0) isara(15) algorithms(1)
```

```
    asymmetric(1) xmssmt(14) 0 }
```

```
-- Signature Algorithms and Public Keys

--
-- sa-HSS-LMS-HashSig is defined in [ietf-lamps-cms-hash-sig]
--
-- sa-HSS-LMS-HashSig SIGNATURE-ALGORITHM ::= {
--     IDENTIFIER id-alg-hss-lms-hashsig
--     PARAMS ARE absent
--     PUBLIC-KEYS { pk-HSS-LMS-HashSig }
--     SMIME-CAPS { IDENTIFIED BY id-alg-hss-lms-hashsig } }

--
-- pk-HSS-LMS-HashSig is defined in [ietf-lamps-cms-hash-sig]
--
-- pk-HSS-LMS-HashSig PUBLIC-KEY ::= {
--     IDENTIFIER id-alg-hss-lms-hashsig
--     KEY HSS-LMS-HashSig-PublicKey
--     PARAMS ARE absent
--     CERT-KEY-USAGE
--         { digitalSignature, nonRepudiation, keyCertSign, cRLSign } }
--
-- HSS-LMS-HashSig-PublicKey ::= OCTET STRING

sa-XMSS SIGNATURE-ALGORITHM ::= {
    IDENTIFIER id-alg-xmss
    PARAMS ARE absent
    PUBLIC-KEYS { pk-XMSS }
    SMIME-CAPS { IDENTIFIED BY id-alg-xmss } }

pk-XMSS PUBLIC-KEY ::= {
    IDENTIFIER id-alg-xmss
    KEY XMSS-PublicKey
    PARAMS ARE absent
    CERT-KEY-USAGE
        { digitalSignature, nonRepudiation, keyCertSign, cRLSign } }

XMSS-PublicKey ::= OCTET STRING

sa-XMSSMT SIGNATURE-ALGORITHM ::= {
    IDENTIFIER id-alg-xmssmt
    PARAMS ARE absent
    PUBLIC-KEYS { pk-XMSSMT }
    SMIME-CAPS { IDENTIFIED BY id-alg-xmssmt } }
```

```
pk-XMSSMT PUBLIC-KEY ::= {  
  IDENTIFIER id-alg-xmssmt  
  KEY XMSSMT-PublicKey  
  PARAMS ARE absent  
  CERT-KEY-USAGE  
    { digitalSignature, nonRepudiation, keyCertSign, cRLSign } }  
  
XMSSMT-PublicKey ::= OCTET STRING  
  
END
```

6. Security Considerations

6.1. Algorithm Security Considerations

The cryptographic security of the signatures generated by the algorithms mentioned in this document depends only on the hash algorithms used within the signature algorithms and the pre-hash algorithm used to create an X.509 certificate's message digest. Grover's algorithm [Grover96] is a quantum search algorithm which gives a quadratic improvement in search time to brute-force pre-image attacks. The results of [BBBV97] show that this improvement is optimal, however [Fluhrer17] notes that Grover's algorithm doesn't parallelize well. Thus, given a bounded amount of time to perform the attack and using a conservative estimate of the performance of a real quantum computer, the pre-image quantum security of SHA-256 is closer to 190 bits. All parameter sets for the signature algorithms in this document currently use SHA-256 internally and thus have at least 128 bits of quantum pre-image resistance, or 190 bits using the security assumptions in [Fluhrer17].

[Zhandry15] shows that hash collisions can be found using an algorithm with a lower bound on the number of oracle queries on the order of $2^{(n/3)}$ on the number of bits, however [DJB09] demonstrates that the quantum memory requirements would be much greater. Therefore a parameter set using SHA-256 would have at least 128 bits of quantum collision-resistance as well as the pre-image resistance mentioned in the previous paragraph.

Given the quantum collision and pre-image resistance of SHA-256 estimated above, the current parameter sets used by id-alg-hss-lms-hashsig, id-alg-xmss and id-alg-xmssmt provide 128 bits or more of quantum security. This is believed to be secure enough to protect X.509 certificates for well beyond any reasonable certificate lifetime.

6.2. Implementation Security Considerations

Implementations MUST protect the private keys. Compromise of the private keys may result in the ability to forge signatures. Along with the private key, the implementation MUST keep track of which leaf nodes in the tree have been used. Loss of integrity of this tracking data can cause a one-time key to be used more than once. As a result, when a private key and the tracking data are stored on non-volatile media or stored in a virtual machine environment, care must be taken to preserve confidentiality and integrity.

The generation of private keys relies on random numbers. The use of inadequate pseudo-random number generators (PRNGs) to generate these values can result in little or no security. An attacker may find it much easier to reproduce the PRNG environment that produced the keys, searching the resulting small set of possibilities, rather than brute force searching the whole key space. The generation of quality random numbers is difficult. [RFC4086] offers important guidance in this area.

The generation of hash-based signatures also depends on random numbers. While the consequences of an inadequate pseudo-random number generator (PRNGs) to generate these values is much less severe than the generation of private keys, the guidance in [RFC4086] remains important.

7. Acknowledgements

Thanks for Russ Housley for the helpful suggestions.

This document uses a lot of text from similar documents ([RFC3279] and [RFC8410]) as well as [I-D.ietf-lamps-cms-hash-sig]. Thanks go to the authors of those documents. "Copying always makes things easier and less error prone" - [RFC8411].

8. IANA Considerations

IANA is requested to assign a module OID from the "SMI for PKIX Module Identifier" registry for the ASN.1 module in Section 5.

9. References

9.1. Normative References

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9.2. Informative References

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