Workgroup: Network Working Group
Internet-Draft: draft-ietf-mls-architecture-06
Published: 8 March 2021
Intended Status: Informational
Expires: 9 September 2021
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The Messaging Layer Security (MLS) Architecture

Abstract

The Messaging Layer Security (MLS) protocol [MLSPROTO] document has the role of defining a Group Key Agreement, all the necessary cryptographic operations, and serialization/deserialization functions necessary to create a scalable and secure group messaging protocol. The MLS protocol is meant to protect against eavesdropping, tampering, message forgery, and provide good properties such as forward-secrecy (FS) and post-compromise security (PCS) in the case of past or future device compromises.

This document, on the other hand is intended to describe a general secure group messaging infrastructure and its security goals. It provides guidance on building a group messaging system and discusses security and privacy tradeoffs offered by multiple security mechanism that are part of the MLS protocol (ie. frequency of public encryption key rotation).

The document also extends the guidance to parts of the infrastructure that are not standardized by the MLS Protocol document and left to the application or the infrastructure architects to design.

While the recommendations of this document are not mandatory to follow in order to interoperate at the protocol level, most will vastly influence the overall security guarantees that are achieved by the overall messaging system. This is especially true in case of active adversaries that are able to compromise clients, the delivery service or the authentication service.

Discussion Venues

This note is to be removed before publishing as an RFC.

Discussion of this document takes place on the MLS Working Group mailing list (mls@ietf.org), which is archived at https://mailarchive.ietf.org/arch/browse/mls/.

Source for this draft and an issue tracker can be found at https://github.com/mlswg/mls-architecture.

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 9 September 2021.

Copyright Notice

Table of Contents

1. Introduction

RFC EDITOR: PLEASE REMOVE THE FOLLOWING PARAGRAPH

The source for this draft is maintained in GitHub. Suggested changes should be submitted as pull requests at https://github.com/mlswg/mls-architecture. Instructions are on that page as well. Editorial

changes can be managed in GitHub, but any substantive change should be discussed on the MLS mailing list.

DISCLAIMER: A lot of work is still ongoing on the current version of this draft. Especially, this preliminary writing of the security considerations has not been reviewed by the working group yet and might contain errors. Please file an issue on the document's GitHub if you find errors.

[[TODO: Remove disclaimer.]]

End-to-end security is a requirement for instant messaging systems and is commonly deployed in many such systems. In this context, "end-to-end" captures the notion that users of the system enjoy some level of security -- with the precise level depending on the system design -- even when the service provider they are using performs unsatisfactorily.

Messaging Layer Security (MLS) specifies an architecture (this document) and an abstract protocol [MLSPROTO] for providing end-to-end security in this setting. MLS is not intended as a full instant messaging protocol but rather is intended to be embedded in concrete protocols, such as XMPP [RFC6120]. In addition, it does not specify a complete wire encoding, but rather a set of abstract data structures which can then be mapped onto a variety of concrete encodings, such as TLS [RFC8446], CBOR [RFC7049], and JSON [RFC7159]. Implementations which adopt compatible encodings will have some degree of interoperability at the message level, though they may have incompatible identity/authentication infrastructures. The MLS protocol has been designed to provide the same security guarantees to all users, for all group sizes, even when it reduces to only two users.

2. General Setting

Informally, a group is a set of users who possibly use multiple endpoint devices to interact with the Service Provider (SP). A group may be as small as two members (the simple case of person to person messaging) or as large as thousands.

In order to communicate securely, users initially interact with services at their disposal to establish the necessary values and credentials required for encryption and authentication.

The Service Provider presents two abstract functionalities that allow clients to prepare for sending and receiving messages securely:

* An Authentication Service (AS) functionality which is responsible for maintaining a binding between a unique identifier (identity)

and the public key material (credential) used for authentication in the MLS protocol. This functionality must also be able to generate these credentials or validate them if they are provided by MLS clients.

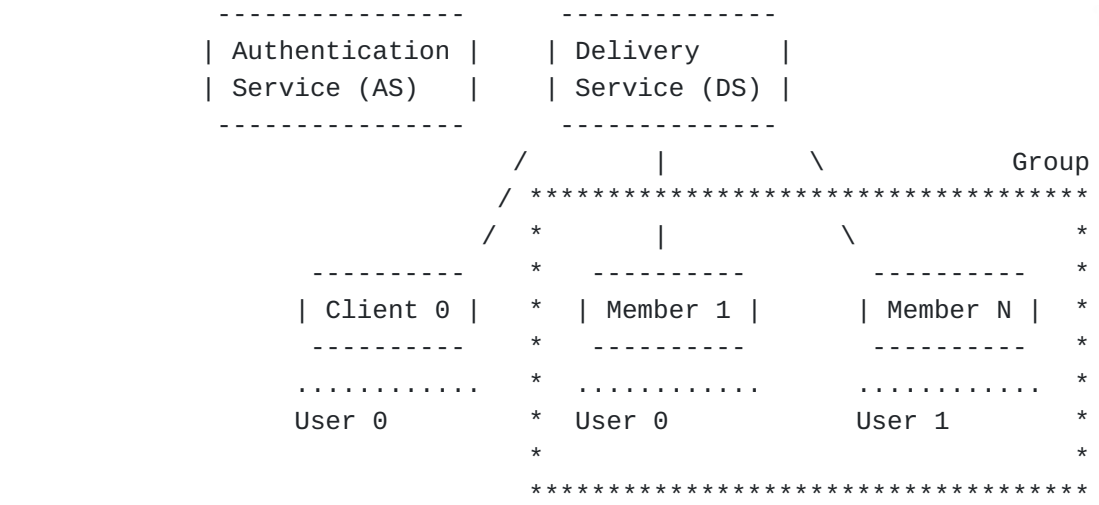
*A Delivery Service (DS) functionality which can receive and redistributing messages between group members. In the case of group messaging, the delivery service may also be responsible for acting as a "broadcaster" where the sender sends a single message which is then forwarded to each recipient in the group by the DS. The DS is also responsible for storing and delivering initial public key material required by MLS clients in order to proceed with the group secret key establishment that is part of the MLS protocol.

For convenience, this document adopts the representation of these services being standalone servers, however the MLS protocol design is made so that it is not necessarily the case.

It is important to note that the Authentication Service functionality can be completely abstract in the case of a Service Provider which allows MLS clients to generate, redistribute and validate their credentials themselves.

Similarly to the AS, the Delivery Service can be completely abstract if users are able to distribute credentials and messages without relying on a central Delivery Service. Note, though, that the MLS protocol requires group operation messages to be processed in-order by all MLS clients.

In some sense, a set of MLS clients which can achieve the AS and DS functionalities without relying on an external party do not need a Service Provider.



In many systems, the AS and the DS are actually operated by the same entity and may even be the same server. However, they are logically distinct and, in other systems, may be operated by different entities. Other partitions are also possible, such as having a separate directory functionality or service.

According to this architecture design, a typical group messaging scenario might look like this:

1. Alice, Bob and Charlie create accounts with a service provider and obtain credentials from the AS.

2. Alice, Bob and Charlie authenticate to the DS and store some initial keying material which can be used to send encrypted messages to them for the first time. This keying material is authenticated with their long term credentials.

3. When Alice wants to send a message to Bob and Charlie, she contacts the DS and looks up their initial keying material. She uses these keys to establish a new set of keys which she can use to send encrypted messages to Bob and Charlie. She then sends the encrypted message(s) to the DS, which forwards them to the recipients.

4. Bob and/or Charlie respond to Alice's message. In addition, they might choose to update their key material which provides post-compromise security Section 2.4.2. As a consequence of that change, the group secrets are updated

Clients may wish to do the following:

*create a group by inviting a set of other clients;

*add one or more clients to an existing group;

*remove one or more members from an existing group;

*update their own key material

*join an existing group;

*leave a group;

*send a message to everyone in the group;

*receive a message from someone in the group.

At the cryptographic level, clients (and by extension members in groups) have equal permissions. For instance, any member can add or remove another client in a group. This is in contrast to some

designs in which there is a single group controller who can modify the group. MLS is compatible with having group administration restricted to certain users, but we assume that those restrictions are enforced by authentication and access control at the application layer.

Thus, for instance, while the MLS protocol allows for any existing member of a group to add a new client, applications which use MLS might enforce additional restrictions for which only a subset of members can qualify, and thus will handle enforcing group policies (such as determining if a user is allowed to add new users to the group) at the application level.

2.1. Group, Members and Clients

While informally, a group can be considered to be a set of users possibly using multiple endpoint devices to interact with the Service Provider, this definition is too simplistic.

Formally, a Client is a set of cryptographic objects composed by public values such as a name (an identity), a public encryption key and a public signature key. Ownership of a Client by a user is determined by the fact that the user has knowledge of the associated secret values. When a Client is part of a Group, it is called a Member and its signature key pair uniquely defines its identity to other clients or members in the Group. In some messaging systems, clients belonging to the same user must all share the same identity key pair, but MLS does not assume this.

Users will typically own multiple Clients, potentially one or more per end-user devices (phones, web clients or other devices...) and may choose to authenticate using the same signature key across devices, using one signature key per device or even one signature key per group.

The formal definition of a Group in MLS is the set of clients that have knowledge of the shared group secret established in the group key establishment phase of the protocol and have contributed to it. Until a Member has contributed to the group secret, other members cannot assume they are a member of the group.

2.2. Authentication Service

The basic function of the Authentication Service (AS) is to provide a trusted mapping from user identities (usernames, phone numbers, etc.), to long-term identity keys, which may either be one per Client or may be shared amongst the clients attached to a user.

The Authentication Service (AS) is expected to play multiple roles in the architecture:

- A certification authority or similar service which signs some sort of portable credential binding an identity to a signature key.

- A directory server which provides the key for a given identity (presumably this connection is secured via some form of transport security such as TLS).

The MLS protocol assumes a signature keypair for authentication of messages. It is important to note that this signature keypair might be the identity keypair itself, or a different signature keypair for which the public key has been, for example, signed by the identity private key. This flexibility allows for multiple infrastructure considerations and has the benefit of providing ways to use different signature keys across different groups by using hierarchical authentication keys. This flexibility also comes at the price of a security tradeoff, described in the security considerations, between potential unlinkability of the signature keys across groups and the amount of time required to reinstate authentication and secrecy of messages after the compromise of a device.

Ultimately, the only requirement is for the applications to be able to check the credential containing the protocol signing key and the identity against the Authentication Service at any time.

By definition, the Authentication Service is invested with a large amount of trust. A malicious AS can impersonate -- or allow an attacker to impersonate -- any user of the system. As a corollary, by impersonating identities authorized to be members of a group, an AS can break confidentiality.

This risk can be mitigated by publishing the binding between identities and keys in a public log such as Key Transparency (KT) [KeyTransparency]. It is possible to build a functional MLS system without any kind of public key logging, but such a system will necessarily be somewhat vulnerable to attack by a malicious or untrusted AS.

2.3. Delivery Service

The Delivery Service (DS) is expected to play multiple roles in the Service Provider architecture:

- To act as a directory service providing the initial keying material for clients to use. This allows a client to establish a

shared key and send encrypted messages to other clients even if the other client is offline.

* To route messages between clients and to act as a message broadcaster, taking in one message and forwarding it to multiple clients (also known as "server side fanout").

Because the MLS protocol provides a way for Clients to send and receive application messages asynchronously, it only provides causal ordering of application messages from senders while it has to enforce global ordering of group operations to provide Group Agreement.

Depending on the level of trust given by the group to the Delivery Service, the functional and privacy guarantees provided by MLS may differ but the Authentication and Confidentiality guarantees remain the same.

Unlike the Authentication Service which is trusted for authentication and secrecy, the Delivery Service is completely untrusted regarding this property. While privacy of group membership might be a problem in the case of a DS server fanout, the Delivery Service can be considered as an active adaptative network attacker from the point of view of the security analysis.

2.3.1. Key Storage

Upon joining the system, each client stores its initial cryptographic key material with the Delivery Service. This key material, called KeyPackage, advertises the functional abilities of the Client such as supported protocol versions and extensions and the following cryptographic information:

* A credential from the Authentication Service attesting to the binding between the identity and the client's signature key.

* The client's asymmetric encryption public key material signed with the signature public key associated with the credential.

As noted above, users may own multiple clients, each with their own keying material, and thus there may be multiple entries stored by each user.

The Delivery Service is also responsible for allowing users to add, remove or update their initial keying material and to ensure that the identifier for these keys are unique across all keys stored on the DS.

2.3.2. Key Retrieval

When a client wishes to establish a group, it first contacts the DS to request a KeyPackage for each other client, authenticate it using the signature keys, and then can use those to form the group.

2.3.3. Delivery of messages and attachments

The main responsibility of the Delivery Service is to ensure delivery of messages. Specifically, we assume that DSs provide:

- Reliable delivery: when a message is provided to the DS, it is eventually delivered to all clients.

- In-order delivery: messages are delivered to the group in the order they are received by the Delivery Service and in approximately the order in which they are sent by clients. The latter is an approximate guarantee because multiple clients may send messages at the same time and so the DS needs some latitude in enforcing ordering across clients.

- Consistent ordering: the DS must ensure that all clients have the same view of message ordering for cryptographically relevant operations. This means that the DS MUST enforce global consistency of the ordering of group operation messages.

Note that the protocol provides three important information within an MLSCiphertext message in order to provide ordering:

- The Group Identifier (GID) to allow to distinguish the group for which the message has been sent;

- The Epoch number, which represent the number of changes (version) of the group associated with a specific GID, and allows for lexicographical ordering of two messages from the same group;

- The Content Type of the message, which allows the DS to determine the ordering requirement on the message.

The MLS protocol itself can verify these properties. For instance, if the DS reorders messages from a Client or provides different Clients with inconsistent orderings, then Clients can detect this misconduct. However, the protocol relies on the ordering, and on the fact that only one honest group operation message is fanned-out to clients per Epoch, to provide Clients with a consistent view of the evolving Group State.

Note that some forms of DS misbehavior are still possible and difficult to detect. For instance, a DS can simply refuse to relay messages to and from a given client. Without some sort of side

information, other clients cannot generally distinguish this form of Denial of Service (DoS) attack.

2.3.4. Membership knowledge

Group membership is itself sensitive information and MLS is designed to drastically limit the amount of persisted metadata. However, large groups often require an infrastructure which provides server fanout. In the case of client fanout, the destinations of a message is known by all clients, hence the server usually does not need this information. However, they may learn this information through traffic analysis. Unfortunately, in a server side fanout model, the DS can learn that a given client is sending the same message to a set of other clients. In addition, there may be applications of MLS in which the group membership list is stored on some server associated with the DS.

While this knowledge is not a break of authentication or confidentiality, it is a serious issue for privacy. In the case where metadata has to be persisted for functionality, it SHOULD be stored encrypted at rest.

2.3.5. Membership and offline members

Because Forward Secrecy (FS) and Post-Compromise Security (PCS) rely on the active deletion and replacement of keying material, any client which is persistently offline may still be holding old keying material and thus be a threat to both FS and PCS if it is later compromised.

MLS cannot inherently defend against this problem, especially in the case where the Client hasn't processed messages but MLS-using systems can enforce some mechanism to try retaining these properties. Typically this will consist of evicting clients which are idle for too long, thus containing the threat of compromise. The precise details of such mechanisms are a matter of local policy and beyond the scope of this document.

2.4. Functional Requirements

MLS is designed as a large scale group messaging protocol and hence aims to provide performance and safety to its users. Messaging systems that implement MLS provide support for conversations involving two or more members, and aim to scale to groups as large as 50,000 members, typically including many users using multiple devices.

2.4.1. Message Secrecy and Authentication

The trust establishment step of the MLS protocol is followed by a conversation protection step where encryption is used by clients to transmit authenticated messages to other clients through the DS. This ensures that the DS does not have access to the group's private content.

MLS aims to provide secrecy, integrity and authentication for all messages.

Message Secrecy in the context of MLS means that only intended recipients (current group members), can read any message sent to the group, even in the context of an active attacker as described in the threat model.

Message Integrity and Authentication mean that an honest Client can only accept a message if it was sent by a group member and that no Client can send a message which other Clients accept as being from another Client.

A corollary to this statement is that the AS and the DS cannot read the content of messages sent between Members as they are not Members of the Group. MLS optionally provides additional protections regarding traffic analysis so as to reduce the ability of attackers, or a compromised member of the messaging system, to deduce the content of the messages depending on (for example) their size. One of these protections includes padding messages in order to produce ciphertexts of standard length. While this protection is highly recommended it is not mandatory as it can be costly in terms of performance for clients and the SP.

Message content can be deniable if the signature keys are exchanged over a deniable channel prior to signing messages.

2.4.2. Forward and Post-Compromise Security

MLS provides additional protection regarding secrecy of past messages and future messages. These cryptographic security properties are Forward Secrecy (FS) and Post-Compromise Security (PCS).

FS means that access to all encrypted traffic history combined with an access to all current keying material on clients will not defeat the secrecy properties of messages older than the oldest key of the compromised client. Note that this means that clients have the extremely important role of deleting appropriate keys as soon as they have been used with the expected message, otherwise the secrecy of the messages and the security for MLS is considerably weakened.

PCS means that if a group member's state is compromised at some time t but the group member subsequently performs an update at some time t', then all MLS guarantees apply to messages sent by the member after time t', and by other members after they have processed the update. For example, if an attacker learns all secrets known to Alice at time t, including both Alice's long-term secret keys and all shared group keys, but Alice performs a key update at time t', then the attacker is unable to violate any of the MLS security properties after the updates have been processed.

Both of these properties are satisfied even against compromised DSs and ASs.

2.4.3. Membership Changes

MLS aims to provide agreement on group membership, meaning that all group members have agreed on the list of current group members.

Some applications may wish to enforce ACLs to limit addition or removal of group members, to privileged clients or users. Others may wish to require authorization from the current group members or a subset thereof. Regardless, MLS does not allow addition or removal of group members without informing all other members.

Once a client is part of a group, the set of devices controlled by the user can only be altered by an authorized member of the group. This authorization could depend on the application: some applications might want to allow certain other members of the group to add or remove devices on behalf of another member, while other applications might want a more strict policy and allow only the owner of the devices to add or remove them at the potential cost of weaker PCS guarantees.

Members who are removed from a group do not enjoy special privileges: compromise of a removed group member does not affect the security of messages sent after their removal but might affect previous messages if the group secrets have not been deleted properly.

2.4.4. Parallel Groups

Any user may have membership in several Groups simultaneously. The set of members of any group may or may not form a subset of the members of another group. MLS guarantees that the FS and PCS goals are maintained and not weakened by user membership in multiple groups.

2.4.5. Security of Attachments

The security properties expected for attachments in the MLS protocol are very similar to the ones expected from messages. The distinction between messages and attachments stems from the fact that the typical average time between the download of a message and the one from the attachments may be different. For many reasons (a typical reason being the lack of high bandwidth network connectivity), the lifetime of the cryptographic keys for attachments is usually higher than for messages, hence slightly weakening the PCS guarantees for attachments.

2.4.6. Non-Repudiation vs Deniability

As described in Section 3.6, MLS provides strong authentication within a group, such that a group member cannot send a message that appears to be from another group member. Additionally, some services require that a recipient be able to prove to the service provider that a message was sent by a given client, in order to report abuse. MLS supports both of these use cases. In some deployments, these services are provided by mechanisms which allow the receiver to prove a message's origin to a third party (this if often called "non-repudiation"), but it should also be possible to operate MLS in a "deniable" mode where such proof is not possible.

2.4.7. Asynchronous Usage

No operation in MLS requires two distinct clients or members to be online simultaneously. In particular, members participating in conversations protected using MLS can update shared keys, add or remove new members, and send messages and attachments without waiting for another user's reply.

Messaging systems that implement MLS have to provide a transport layer for delivering messages asynchronously and reliably.

2.4.8. Access Control

The MLS protocol allows each member of the messaging group to perform operations equally. This is because all clients within a group (members) have access to the shared cryptographic material. However every service/infrastructure have control over policies applied to their own clients. Applications managing MLS clients can be configured to allow for specific Group operations. An application can, for example, decide to provide specific permissions to a group administrator that will be the one to perform add and remove operations, but the flexibility is immense here. On the other hand, in many settings such as open discussion forums, joining can be allowed for anyone.

The MLS protocol can in certain modes can exchange unencrypted group operation messages. This flexibility is to allow services to perform access control tasks on behalf of the group.

While the Application messages will always be encrypted, having the handshake messages in plaintext has inconveniences in terms of privacy as someone could collect the signatures on the handshake messages and use it for tracking.

> **RECOMMENDATION:** Prefer using encrypted group operation messages to avoid privacy issues related to non-encrypted signatures.

Note that in the default case of encrypted handshake messages, the application level must make sure that the access control policies are consistent across all clients to make sure that they remain in sync. If two different policies were applied, the clients might not accept or reject a group operation and end-up in different cryptographic states, breaking their ability to communicate.

> **RECOMMENDATION:** Avoid using inconsistent access control policies in the case of encrypted group operations.

2.4.9. Recovery After State Loss

Conversation participants whose local MLS state is lost or corrupted can reinitialize their state and continue participating in the conversation.

[[OPEN ISSUE: The previous statement seems too strong, establish what exact functional requirement we have regarding state recovery. Previously: "This may entail some level of message loss, but does not result in permanent exclusion from the group."]]

2.4.10. Support for Multiple Devices

It is typically expected for users within a Group to own different devices.

A new device can be added to a group and be considered as a new client by the protocol. This client will not gain access to the history even if it is owned by someone who owns another member of the Group. Restoring history is typically not allowed at the protocol level but applications can elect to provide such a mechanism outside of MLS. Such mechanisms, if used, may undermine the FS and PCS guarantees provided by MLS.

2.4.11. Extensibility / Pluggability

Messages that do not affect the group state can carry an arbitrary payload with the purpose of sharing that payload between group members. No assumptions are made about the format of the payload.

2.4.12. Federation

The protocol aims to be compatible with federated environments. While this document does not specify all necessary mechanisms required for federation, multiple MLS implementations can interoperate to form federated systems if they use compatible authentication mechanisms and infrastructure functionalities.

2.4.13. Compatibility with future versions of MLS

It is important that multiple versions of MLS be able to coexist in the future. Thus, MLS offers a version negotiation mechanism; this mechanism prevents version downgrade attacks where an attacker would actively rewrite messages with a lower protocol version than the ones originally offered by the endpoints. When multiple versions of MLS are available, the negotiation protocol guarantees that the version agreed upon will be the highest version supported in common by the group.

In MLS 1.0, the creator of the group is responsible for selecting the best ciphersuite proposed across clients. Each client is able to verify availability of protocol version, ciphersuites and extensions at all times once he has at least received the first group operation message.

3. Security and Privacy Considerations

MLS adopts the Internet threat model [RFC3552] and therefore assumes that the attacker has complete control of the network. It is intended to provide the security services described in the face of such attackers.

-- The attacker can monitor the entire network

-- The attacker can read unprotected messages

-- The attacker can generate and inject any message in the unprotected transport layer.

In addition, these guarantees are intended to degrade gracefully in the presence of compromise of the transport security links as well as of both Clients and elements of the messaging system, as described in the remainder of this section.

Generally, MLS is designed under the assumption that the transport layer is present to protect metadata and privacy in general, while the MLS protocol is providing stronger guarantees such as confidentiality, integrity and authentication guarantees. Stronger properties such as deniability can also be achieved in specific architecture designs.

3.1. Considerations for attacks outside of the threat model

Physical attacks on devices storing and executing MLS principals are not considered in depth in the threat model of the MLS protocol. While non-permanent, non-invasive attacks can sometime be equivalent to software attacks, physical attacks are considered outside of the MLS threat model.

Compromise scenarios, typically consist in a software adversary, which can maintain active adaptative compromise and arbitrarily change the behavior of the client or service.

On the other hand, security goals consider that honest clients will always run the protocol according to its specification. This relies on implementations of the protocol to securely implement the specification, which remains non-trivial.

> **RECOMMENDATION:** Additional steps should be taken to protect the device and the MLS clients from physical compromise. In such setting, HSMs and secure enclaves can be used to protect signature keys.
>
> More information will be available in the Server-Assist draft.

[[TODO: Reference to server assist when the draft is available.]]

3.2. Transport Security Links

Any secure channel can be used as a transport layer to protect MLS messages such as QUIC, TLS, WireGuard or TOR. Though the MLS protocol is designed to consider the following threat-model:

-- The attacker can read and write arbitrary messages inside the secure transport channel.

This departs from most threat models where we consider that the secure channel used for transport always provides secrecy. The reason for this consideration is that in the group setting active malicious insiders or adversarial services are be considered.

3.2.1. Metadata protection for unencrypted group operations

The main use of the secure transport layer for MLS is to protect the already limited amount of metadata. Very little information is contained in the unencrypted header of the MLS Protocol message format for group operation messages, and application messages are always encrypted in MLS.

Contrary to popular messaging services, the full list of recipients cannot be sent to the server for dispatching messages because that list is potentially extremely large in MLS. So, the metadata typically consists of a pseudo-random Group Identifier (GID), an numerical index referring to the key needed to decrypt the ciphertext content and another numerical value to determine the epoch of the group (the number of group operations that have been performed).

MLS protocol provides an authenticated "Authenticated Additional Data" field for application to make data available outside the MLSCiphertext.

> **RECOMMENDATION:** Use the "Authenticated Additional Data" field of the MLSCiphertext message instead of using other unauthenticated means of sending metadata throughout the infrastructure. If the data is private, the infrastructure should use encrypted Application messages instead.

Even though, some of these metadata information are not secret payloads, in correlation with other data, a network observer might be able to reconstruct sensitive information. Using a secure channel to transfer this information will prevent a network attacker to access this MLS protocol metadata if it cannot compromise the secure channel.

More importantly, there is one specific case where having no secure channel to exchange the MLS messages can have a serious impact on privacy. In the case of unencrypted group operation messages, observing the signatures of the Group Operation messages may lead an adversary to extract information about the group memberships.

> **RECOMMENDATION:** Never use the unencrypted mode for group operations without using a secure channel for the transport layer.

3.2.2. DoS protection

In general we do not consider Denial of Service (DoS) resistance to be the responsibility of the protocol. However, it should not be possible for anyone aside from the DS to perform a trivial DoS

attack from which it is hard to recover. This can be achieved through the secure transport layer.

In the centralized setting DoS protection can typically be performed by using tickets or cookies which identify users to a service for a certain number of connections. Such a system helps preventing anonymous clients to send arbitrary numbers of Group Operation messages to the Delivery Service or the MLS clients.

> **RECOMMENDATION:** Anonymous credentials can be used in order to help DoS attacks prevention, in a privacy preserving manner. Note that the privacy of these mechanisms has to be adjusted in accordance with the privacy expected from the secure transport links. (See more discussion further down.)

3.2.3. Message suppression and error correction

The MLS protocol is particularly sensitive about Group Operation message loss and reordering. This is because in the default setting, MLS clients have to process those specific messages in order to have a synchronized group state, after what the MLS protocol efficiently generates keys for application messages.

The Delivery Service can have the role of helping with reliability, but is mainly useful for reliability in the asynchronous aspect of the communication between MLS clients.

While it is difficult or impossible to prevent a network adversary to suppress payloads in transit, in certain infrastructures such as banks or governments settings, unidirectional transports can be used and be enforced via electronic or physical devices such as diodes. This can lead to payload corruption which does not affect the security or privacy properties of the MLS Protocol but does affect the reliability of the service. In that case specific measures can be taken to ensure the appropriate level of redundancy and quality of service for MLS.

> **RECOMMENDATION:** If unidirectional transport is used for the secure transport channel, prefer using a protocol which provides Forward Error Correction.

3.3. Delivery Service Compromise

MLS is intended to provide strong guarantees in the face of compromise of the DS. Even a totally compromised DS should not be able to read messages or inject messages that will be acceptable to legitimate clients. It should also not be able to undetectably remove, reorder or replay messages.

However, a DS can mount a variety of DoS attacks on the system, including total DoS attacks (where it simply refuses to forward any messages) and partial DoS attacks (where it refuses to forward messages to and from specific clients). As noted in Section 2.3.3, these attacks are only partially detectable by clients without an out-of-band channel. Ultimately, failure of the DS to provide reasonable service must be dealt with as a customer service matter, not via technology.

Because the DS is responsible for providing the initial keying material to clients, it can provide stale keys. This does not inherently lead to compromise of the message stream, but does allow it to attack forward security to a limited extent. This threat can be mitigated by having initial keys expire.

3.3.1. Privacy of delivery and push notifications

An important mechanism that is often ignored from the privacy considerations are the push-tokens. In many modern messaging architectures, applications are using push notification mechanisms typically provided by OS vendors. This is to make sure that when messages are available at the Delivery Service (or by other mechanisms if the DS is not a central server), the recipient application on a device knows about it. Sometimes the push notification can contain the application message itself which saves a round trip with the DS.

To "push" this information to the device, the service provider and the OS infrastructures use unique per-device, per-application identifiers called push-tokens. This means that the push notification provider and the service provider have information on which devices receive information and at which point in time.

Even though they can't necessarily access the content, which is typically encrypted MLS messages, the service provider and the push notification provider have to be trusted to avoid making correlation on which devices are recipients of the same message.

For secure messaging systems, push notification are often sent real-time as it is not acceptable to create artificial delays for message retrieval.

> **RECOMMENDATION:** If real time notification are not necessary and that specific steps must be taken to improve privacy, one can delay notifications randomly across recipient devices using a mixnet or other techniques.

Note that it is quite easy for legal requests to ask the service provider for the push-token associated to an identifier and perform a second request to the company operating the push-notification

system to get information about the device, which is often linked with a real identity via a cloud account, a credit card or other information.

> **RECOMMENDATION:** If stronger privacy guarantees are needed vis-a-vis of the push notification provider, the client can choose to periodically connect to the Delivery Service without the need of a dedicated push notification infrastructure.

3.4. Authentication Service Compromise

The Authentication Service design is left to the infrastructure designers. In most designs, a compromised AS is a serious matter, as the AS can serve incorrect or attacker-provided identities to clients.

-- The attacker can link an identity to a credential

-- The attacker can generate new credentials

-- The attacker can sign new credentials

-- The attacker can publish or distribute credentials

Infrastructures that provide cryptographic material or credentials in place of the MLS client (which is under the control of the user) have often the ability to use the associated secrets to perform operations on behalf of the user, which is unacceptable in many situations. Other mechanisms can be used to prevent this issue, such as the service blessing cryptographic material used by an MLS client.

> **RECOMMENDATION:** Make clients submit signature public keys to the AS, this is usually better than the AS generating public key pairs because the AS cannot sign on behalf of the client. This is a benefit of a Public Key Infrastructure in the style of the Internet PKI.

An attacker that can generate or sign new credential may or may not have access to the underlying cryptographic material necessary to perform such operations. In that last case, it results in windows of time for which all emitted credentials might be compromised.

> **RECOMMENDATION:** Using HSMs to store the root signature keys to limit the ability of an adversary with no physical access to extract the top-level signature key.

3.4.1. Authentication compromise: Ghost users and impersonations

One thing for which the MLS Protocol is designed for is to make sure that all clients know who is in the group at all times. This means that - if all Members of the group and the Authentication Service are honest - no other parties than the members of the current group can read and write messages protected by the protocol for that Group.

Beware though, the link between the cryptographic identity of the Client and the real identity of the User is important. With some Authentication Service designs, a private or centralized authority can be trusted to generate or validate signature keypairs used in the MLS protocol. This is typically the case in some of the biggest messaging infrastructures.

While this service is often very well protected from external attackers, it might be the case that this service is compromised. In such infrastructure, the AS could generate or validate a signature keypair for an identity which is not the expected one. Because a user can have many MLS clients running the MLS protocol, it possibly has many signature keypairs for multiple devices.

In the case where an adversarial keypair is generated for a specific identity, an infrastructure without any transparency mechanism or out-of-band authentication mechanism could inject a malicious client into a group by impersonating a user. This is especially the case in large groups where the UI might not reflect all the changes back the the users.

> **RECOMMENDATION:** Make sure that MLS clients reflect all the membership changes to the users as they happen. If a choice has to be made because the number of notifications is too high, a public log should be maintained in the state of the device so that user can examine it.

While the ways to handle MLS credentials are not defined by the protocol or the architecture documents, the MLS protocol has been designed with a mechanism that can be used to provide out-of-band authentication to users. The "authentication_secret" generated for each user at each epoch of the group is a one-time, per client, authentication secret which can be exchanged between users to prove their identity to each other. This can be done for instance using a QR code that can be scanned by the other parties.

Another way to improve the security for the users is to provide a transparency mechanism which allows each user to check if credentials used in groups have been published in the transparency log. Another benefit of this mechanism is for revocation. The users

of a group could check for revoked keys (in case of compromise detection) using a mechanism such as CRLite or some more advanced privacy preserving technology.

> **RECOMMENDATION:** Provide a Key Transparency and Out-of-Band authentication mechanisms to limit the impact of an Authentication Service compromise.

We note, again, that as described prior to that section, the Authentication Service is facultative to design a working infrastructure and can be replaced by many mechanisms such as establishing prior one-to-one deniable channels, gossiping, or using TOFU for credentials used by the MLS Protocol.

Another important consideration is the ease of redistributing new keys on client compromise, which helps recovering security faster in various cases.

3.4.2. Privacy of the Group Membership

Often, expectation from users is that the infrastructure will not retain the ability to constantly map the user identity to signature public keys of the MLS protocol. Some infrastructures will keep a mapping between signature public keys of clients and user identities. This can benefit an adversary that has compromised the AS (or required access according to regulation) the ability of monitoring unencrypted traffic and correlate the messages exchanged within the same group.

> **RECOMMENDATION:** Always use encrypted group operation messages to reduce issues related to privacy.

In certain cases, the adversary can access to specific bindings between public keys and identities. If the signature keys are reused across groups, the adversary can get more information about the targeted user.

> **RECOMMENDATION:** Do not use the same signature keypair across groups.

> **RECOMMENDATION:** Separate the service binding the identities and the public keys from the service which generates or validates the credentials or cryptographic material of the Clients.

3.5. Shared considerations regarding adversarial AS or DS services

3.5.1. Privacy of the network connections

There are many scenarios leading to communication between the application on a device and the Delivery Service or the Authentication Service. In particular when:

- The application connects to the Authentication Service to generate or validate a new credential before distributing it.
- The application fetches credentials at the Delivery Service prior to creating a messaging group (one-to-one or more than two clients).
- The application fetches service provider information or messages on the Delivery Service.
- The application sends service provider information or messages to the Delivery Service.

In all these cases, the application will often connect to the device via a secure transport which leaks information about the origin of the request such as the IP address and depending on the protocol the MAC address of the device.

Similar concern exist in the peer-to-peer use cases of MLS.

> **RECOMMENDATION:** In the case where privacy or anonymity is important, using adequate protection such as TOR or a VPN can improve metadata protection.

More generally, using anonymous credential in an MLS based architecture might not be enough to provide strong privacy or anonymity properties.

3.6. Client Compromise

The MLS protocol adopts a threat model which includes multiple forms of Client compromises. While adversaries are in a very strong position if they have compromised an MLS client, there are still situations where security guarantees can be recovered thanks to the PCS properties achieved by the MLS protocol.

In this section we will explore the consequences and recommendations regarding the following compromise scenarios:

-- The attacker has access to a specific symmetric encryption key

-- The attacker has access to the group secrets for one group

-- The attacker has access to a signature oracle for any group

-- The attacker has access to the signature key for one group

-- The attacker has access to all secrets of a user for all groups (full state compromise)

[[TODO: Cite the research papers in the context of these compromise models]]

Recall that the MLS protocol provides chains of AEAD keys, per sender that are generated from Group Secrets. These keys are used to protect MLS Plaintext messages which can be Group Operation or Application messages. The Group Operation messages offer an additional protection as the secret exchanged within the TreeKEM group key agreement are public-key encrypted to subgroups with HPKE.

3.6.1. Compromise of AEAD key material

In some circumstances, adversaries may have access to specific AEAD keys and nonces which protect an Application or a Group Operation message. While this is a very weak kind of compromise, it can be realistic in cases of implementation vulnerabilities where only part of the memory leaks to the adversary.

When an AEAD key is compromised, the adversary has access to a set of AEAD keys for the same chain and the same epoch, hence can decrypt messages sent using keys of this chain. An adversary cannot send a message to a group which appears to be from any valid client since they cannot forge the signature.

The MLS protocol will ensure that an adversary cannot compute any previous AEAD keys for the same epoch, or any other epochs. Because of its Forward Secrecy guarantees, MLS will also retain secrecy of all other AEAD keys generated for *other* MLS clients, outside this dedicated chain of AEAD keys and nonces, even within the epoch of the compromise. However the MLS protocol does not provide Post Compromise Secrecy for AEAD encryption within an epoch. This means that if the AEAD key of a chain is compromised, the adversary can compute an arbitrary number of subsequent AEAD keys for that chain.

These guarantees are ensured by the structure of the MLS key schedule which provides Forward Secrecy for these AEAD encryptions, across the messages within the epoch and also across previous epochs. Those chains are completely disjoint and compromising keys across the chains would mean that some Group Secrets have been compromised, which is not the case in this attack scenario (we explore stronger compromise scenarios as part of the following sections).

MLS provides Post-Compromise Secrecy against an active adaptative attacker across epochs for AEAD encryption, which means that as soon as the epoch is changed, if the attacker does not have access to more secret material they won't be able to access any protected messages from future epochs.

In the case of an Application message, an AEAD key compromise means that the encrypted application message will be leaked as well as the signature over that message. This means, that the compromise has both confidentiality and privacy implications on the future AEAD encryptions of that chain. In the case of a Group Operation message, only the privacy is affected, as the signature is revealed, because the secrets themselves are protected by HPKE encryption.

Note that under that compromise scenario, authentication is not affected in neither of these cases. As every member of the group can compute the AEAD keys for all the chains (they have access to the Group Secrets) in order to send and receive messages, the authentication provided by the AEAD encryption layer of the common framing mechanism is very weak. Successful decryption of an AEAD encrypted message only guarantees that a member of the group sent the message.

3.6.2. Compromise of the Group Secrets of a single group for one or more group epochs

The attack scenario considering an adversary gaining access to a set of Group secrets is significantly stronger. This can typically be the case when a member of the group is compromised. For this scenario, we consider that the signature keys are not compromised. This can be the case for instance if the adversary has access to part of the memory containing the group secrets but not to the signature keys which might be stored in a secure enclave.

In this scenario, the adversary gains the ability to compute any number of AEAD encryption keys for any AEAD chains and can encrypt and decrypt all messages for the compromised epochs.

If the adversary is passive, it is expected from the PCS properties of the MLS protocol that, as soon as an honest Commit message is sent by the compromised party, the next epochs will provide message secrecy.

If the adversary is active, the adversary can follow the protocol and perform updates on behalf of the compromised party with no ability to an honest group to recover message secrecy. However, MLS provides PCS against active adaptative attackers through its Remove group operation. This means that, as long as other members of the group are honest, the protocol will guarantee message secrecy for

all messages exchanged in the epochs after the compromised party has been removed.

3.6.3. Compromise by an active adversary with the ability to sign messages

Under such a scenario, where an active adversary has compromised an MLS client, two different settings emerge. In the strongest compromise scenario, the attacker has access to the signing key and can forge authenticated messages. In a weaker, yet realistic scenario, the attacker has compromised a client but the client signature keys are protected with dedicated hardware features which do not allow direct access to the value of the private key and instead provide a signature API.

When considering an active adaptative attacker with access to a signature oracle, the compromise scenario implies a significant impact on both the secrecy and authentication guarantees of the protocol, especially if the attacker also has access to the group secrets. In that case both secrecy and authentication are broken. The attacker can generate any message, for the current and future epochs until an honest update from the compromised client happens.

Note that under this compromise scenario, the attacker can perform all operations which are available to an legitimate client even without access to the actual value of the signature key.

Without access to the group secrets, the adversary will not have the ability to generate messages which look valid to other members of the group and to the infrastructure as they need to have access to group secrets to compute the encryption keys or the membership tag.

3.6.4. Compromise of the authentication with access to a signature key

DISCLAIMER: Significant work remains in this section. [[TODO: Remove disclaimer.]]

The difference between having access to the value of the signature key and only having access to a signing oracle is not about the ability of an active adaptative network attacker to perform different operations during the time of the compromise, the attacker can perform every operations available to a legitimate client in both cases.

There is a significant difference, however in terms of recovery after a compromise.

Because of the PCS guarantees provided by the MLS protocol, when a previously compromised client performs an honest Commit which is not under the control of the adversary, both secrecy and authentication

of messages can be recovered in the case where the attacker didn't get access to the key. Because the adversary doesn't have the key and has lost the ability to sign messages, they cannot authenticate messages on behalf of the compromised party, even if they still have control over some group keys by colluding with other members of the group.

This is in contrast with the case where the signature key is leaked. In that case PCS of the MLS protocol will eventually allow recovery of the authentication of messages for future epochs but only after compromised parties refresh their credentials securely.

Beware that in both oracle and private key access, an active adaptative attacker, can follow the protocol and request to update its own credential. This in turn induce a signature key rotation which could provide the attacker with part or the full value of the private key depending on the architecture of the service provider.

> **RECOMMENDATION:** Signature private keys should be compartmentalized from other secrets and preferably protected by an HSM or dedicated hardware features to allow recovery of the authentication for future messages after a compromised.

Even if the dedicated hardware approach is used, ideally, neither the Client or the Authentication service alone should provide the signature private key. Both should contribute to the key and it should be stored securely by the client with no direct access.

3.6.5. Security consideration in the context of a full state compromise

In real-world compromise scenarios, it is often the case that adversaries target specific devices to obtain parts of the memory or even the ability to execute arbitrary code in the targeted device.

Also, recall that in this setting, the application will often retain the unencrypted messages. If so, the adversary does not have to break encryption at all to access sent and received messages. Messages may also be send by using the application to instruct the protocol implementation.

> **RECOMMENDATION:** If messages are stored on the device, they should be protected using encryption at rest, and the keys used should be stored securely using dedicated mechanisms on the device.

> **RECOMMENDATION:** If the threat model of the system is against an adversary which can access the messages on the device without even needing to attack MLS, the application should delete plaintext messages and ciphertexts immediately after encryption or decryption.

Even though, from the strict point of view of the security formalization, a ciphertext is always public and will forever be, there is no loss in trying to erase ciphertexts as much as possible.

Note that this document makes a clear distinction between the way signature keys and other group shared secrets must be handled. In particular, a large set of group secrets cannot necessarily assumed to be protected by an HSM or secure enclave features. This is especially true because these keys are extremely frequently used and changed with each message received by a client.

However, the signature private keys are mostly used by clients to send a message. They also are providing the strong authentication guarantees to other clients, hence we consider that their protection by additional security mechanism should be a priority.

Overall there is no way to detect or prevent these compromise, as discussed in the previous sections, performing separation of the application secret states can help recovery after compromise, this is the case for signature keys but similar concern exists for the encryption private key used in the TreeKEM Group Key Agreement.

> **RECOMMENDATION:** The secret keys used for public key encryption should be stored similarly to the way the signature keys are stored as key can be used to decrypt the group operation messages and contain the secret material used to compute all the group secrets.

Even if secure enclaves are not perfectly secure, or even completely broken, adopting additional protections for these keys can ease recovery of the secrecy and authentication guarantees after a compromise where for instance, an attacker can sign messages without having access to the key. In certain contexts, the rotation of credentials might only be triggered by the AS through ACLs, hence be outside of the capabilities of the attacker.

[[TODO: Considerations for Signature keys being reused or not across groups]]

3.6.6. More attack scenarios

[[TODO: Make examples for more complex attacks, cross groups, multi collusions...]]

[[TODO: Do we discuss PCFS in this document? If yes, where?]]

4. IANA Considerations

This document makes no requests of IANA.

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