Linphone Instant Message Encryption v2.0 (Lime v2.0)

Johan Pascal

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Version 1.2

Contents

1 Changelog

Revision History

Revision	Date	Author(s)	Description
1.2	Feb 27, 2025	JP	Update PQC description with MLKem and add multialgo support
1.1	June 15, 2024	JP	Add support to Post-Quantum Cryptography
1.0	March 6, 2019	JP	Initial version

2 Introduction

Linphone Instant Message Encryption (Lime) v2.0 implements the Signal protocol allowing users to privately and asynchronously exchange messages. Detailed specification of the Signal protocol can be found on the Signal website. Lime supports multiple devices per user and multiple users per device.

Lime is designed to be used with Linphone, an open source SIP phone. Lime establishes encrypted sessions and encrypts messages but relies on Linphone to acquire the unique identification string of peer devices and route the messages to their recipients. The use of Lime with other message delivery software is possible but is out of the scope of this document.

Lime is written in C++17 and the library uses templates to provide support for Curve25519, Curve448 and hybrids Curve25519/Kyber512, Curve25519/MLKem512, Curve448/MLKem1024 based cryptographic algorithms. The library supports one or several cryptographics bases according to build settings.

Notes: Lime v1.0 was based on SCIMP. This document presents Lime v2.0, which is neither related to nor compatible with Lime v1.0. In this document the use of the term Lime refers to Lime v2.0.

This document(version 1.2) refers to the implementation tagged 5.4.0 on the official repository.

3 Notations

$A||B$ denotes the concatenation of byte sequences A and B

$A\langle value\rangle$ the bytes sequence A size is $value$. For example, $key\langle 32bytes\rangle$ denotes a 32 bytes long buffer called key. Several values may be included in a comma-separated list, indicating that several sizes are possible.

$element\{instances\}$ denotes the number of occurrences of a given $element$. $Instances$ may be a number, a range or a comma-separated list of possible values. For example, $key\{4\}$ means 4 $keys$, $key\{0,1\}$ means either 0 or 1 key.

$element[values]$: element value can be one of the values given in a comma-separated list. For example, $type[1,2,3]$ means $type$ equals either 1, 2, or 3.

4 Brief introduction to Signal protocol specification documents

4.1 The Double Ratchet Algorithm

"*The Double Ratchet algorithm[1] is used by two parties to exchange encrypted messages based on a shared secret key. Typically the parties will use some key agreement protocol (such as X3DH[2]) to agree on the shared secret key. Following this, the parties will use the Double Ratchet to send and receive encrypted messages.*

The parties derive new keys for every Double Ratchet message so that earlier keys cannot be calculated from later ones. The parties also send Diffie-Hellman public values attached to their messages. The results of Diffie-Hellman calculations are mixed into the derived keys so that later keys cannot be calculated from earlier ones. These properties give some protection to earlier or later encrypted messages in case of a compromise of a party's keys."

4.2 The X3DH Key Agreement Protocol

"*'X3DH'(or 'Extended Triple Diffie-Hellman')[2] key agreement protocol establishes a shared secret key between two parties who mutually authenticate each other based on public keys. X3DH provides forward secrecy and cryptographic deniability.*

X3DH is designed for asynchronous settings where one user ('Bob') is offline but has published some information to a server. Another user ('Alice') wants to use that information to send encrypted data to Bob and also to establish a shared secret key for future communication."

4.3 The PQXDH Key Agreement Protocol

"*'PQXDH'(or 'Post-Quantum Extended Diffie-Hellman')[3] key agreement protocol establishes a shared secret key between two parties who mutually authenticate each other based on public keys. PQXDH provides post-quantum forward secrecy and a form of cryptographic deniability but still relies on the hardness of the discrete log problem for mutual authentication.*"

4.4 The Sesame Algorithm

"*The Sesame algorithm[4] manages message encryption sessions in an asynchronous and multi-device setting. Sesame was designed to manage Double Ratchet sessions[1] created with a X3DH key agreement[2]. However, Sesame is a generic algorithm that works with any session-based message encryption algorithm that meets certain conditions.*"

5 Major discrepancies between Lime v2.0 and Signal protocol

This section will not go into the details of the Signal protocol specification but will focus only on the points where the Lime v2.0 implementation does not follow the Signal specification documentation[1][2][4]. A prior knowledge of these specs is essential to understand the possible effects of such discrepancies.

5.1 Double Ratchet

5.1.1 Group chat management

The group chat mechanism implemented by Whisper Systems in libsignal-protocol-c[13] uses an unspecified (at least in Double Ratchet document[1]) feature, the sender key, which:

1. When accepting membership, a group member creates its sender key and distributes it to all other members using pairwise Double Ratchet sessions; then
2. Members use their sender key to encrypt messages to the group, deriving it by using a simple symmetric ratcheting.

This mechanism allows an efficient server-side fan-out but loses the break-in recovery property provided by the Double Ratchet mechanism.

Operating in a multi device environment, Lime provides the following mechanism to save bandwith when sending message to multiple devices:

1. Generate a random key and use it to encrypt the message.
2. Use Double Ratchet sessions to encrypt the random key.
3. Send to server a bundle of:

$$\begin{gathered}\textit{DR encrypted random key}\{\textit{one for each recipient device}\}\\ \|\ \textit{Message encrypted using the random key}\end{gathered}$$

4. Server fans out the messages to recipients mailboxes posting only the appropriate double ratchet encrypted random key and encrypted message.

This mechanism is optional and the default behavior of the library is to use it when it saves upload bandwidth, using a regular encryption in the Double Ratchet message otherwise.

The bandwidth and computational power consumption is greater than the Whisper System implementation but all the exchanges are protected by an actual Double Ratchet; maintaining the break-in recovery property.

Silent members/devices (lost devices and users quitting the network are good candidates) may result in weakness in the break-in recovery as no Diffie-Hellman ratchet step is ever performed. This is mitigated by setting a limit to the sending chain length. The sending device would create a new Double Ratchet session fetching keys from X3DH key server if the limit is reached.

Note : The actual implementation generates a 32 bytes random seed derived through HKDF[11] into a 32 bytes key and a 16 bytes nonce. The DR session encrypts the 32 bytes random seed using AES256-GCM (with 16 bytes authentication tag); producing a 48 bytes output to transmit the key.

5.1.2 Post Quantum cryptography

When PQX3DH is used, the Double Ratchet asymmetric ratchet also uses Post quantum cryptography to ensure break-in recovery. In that case the double ratchet symmetric key also differs from the original specification by including the index in the key derivation function label as recommended in [8, section 4.2].

PQXDH thus also provides DR with a KEM public key, so DR initialisation can encapsulate a secret to it. It is the SPk. This implementation then always uses a KEM public key in the SPk unlike PQXDH using it only when the OPk is missing.

5.1.3 AEAD encryption scheme: AES256-GCM

The Double Ratchet specification [1, section 5.2] recommends the use of a SIV based AEAD encryption scheme.

The Lime implementation of the Double Ratchet Chain Key derivation is described in 6.3.3 of this document. The message key$\langle 32 bytes\rangle$ and initialisation vector $\langle 16 bytes\rangle$ are generated, used and destroyed during the encryption process. The direct use of an AES256-GCM as the AEAD encryption scheme is assumed to be secure as the key and IV are not reused.

5.2 X3DH Identity Key signature

The X3DH specification uses ECDH keys only in combination with XEdDSA[5] to provide an EdDSA-compatible signature using its Identity key (Ik) formatted for X25519 or X448 ECDH functions.

Lime performs the same signature and ECDH operations but the identity key (Ik) is generated, stored and transmitted in its EdDSA format and then converted into X25519 or X448 format when an ECDH computation is performed on it.

The X3DH $Encode(PK)$ function recommends the usage of a single byte constant to represent the type of curve followed by the encoding specified in [6]. Lime uses direct encoding specified in [6] for its ECDH public keys and [9] for its EdDSA keys but the type of curve is present in the messages header.

5.3 Authentication

X3DH specification mentions [2, section 4.1] the necessity of an identity authentication mechanism and libsignal[13] implements a key fingerprints comparison to provide it. Lime makes use of a ZRTP[12] call with an oral SAS verification to provide mutual identity authentication. See implementation details in section 6.8

5.4 PQXDH

In Lime, the key server will allways provide a SPk KEM public key to be able to pass it to the double ratchet init and an OPk KEM key if available.

KEM OPk keys are not signed to improve the deniability property, see [7]

In order not to rely on KEM properties (Kyber or MLKem), the key derivation functions generating the PQXDH output includes a transcript of all public material (public keys and cipher text) used in the generation of the shared secrets.

5.5 Optional features not implemented

- Double ratchet with header encryption as in [1, section 4]
- Retry request as in [4, section 4.1]
- Session expiration as in [4, section 4.2] but a related mechanism is implemented: A Double Ratchet session expires after encrypting a certain number of messages without performing any Diffie-Hellman ratchet step.

6 Implementation details

6.1 Preliminaries

For clarity, the different terms used in this document are defined here:

- device Id: a unique string associated to a device, provided to Lime by Linphone. It shall be the GRUU[10]. Internally a lime user is identified by the pair device Id, base algorithm.
- user Id: a unique string defining a user or a group of users, provided to Lime by Linphone. It shall be the sip URI.
- source: the device generating and encrypting a message.
- recipient: the parties targeted to receive and decrypt the message. Multiple devices can be associated to the it so any mention of recipient must specify user Id or device Id to clarify the intent.

6.2 HKDF

The HKDF function, as described in RFC5869 [11] is used in both X3DH and Double Ratchet. Lime uses an implementation of HKDF based on SHA512. Its prototype in the pseudo-code is as follow, all inputs and output have variable size. *salt* is optionnal and the function may be used without(set to *null* in the pseudo-code). The size of the generated output key material, *okm*, is arbitrary and depends only on request not on input or hash algorithm used.

```
function HKDFSha512($salt, ikm, info$)
    return $okm$
end function
```

6.3 Double Ratchet

6.3.1 ECDH only Asymmetric Ratchet

The ECDH function can be either X448 or X25519 as described in [6].

Root Key Derivation function

As recommended in [1, section 5.2], this function uses HKDF[11] based on SHA512. The *salt* is RK and *ikm* is the output of ECDH(*DH_ out*). The info string is "*DR Root Chain Key Derivation*". *DH_ out* size depends on ECDH function used, X25519 produces a 32 bytes output, X448 a 56 bytes output.

```
function KDF_RK(RK$\langle 32bytes\rangle, DH\_out\langle 32, 56bytes\rangle$)
    $info \leftarrow$ "DR Root Chain Key Derivation"
    $RK\langle 32bytes\rangle \| CK\langle 32bytes\rangle \leftarrow$ HKDFSha512($RK, DH\_out, info$)
    return $RK\langle 32bytes\rangle, CK\langle 32bytes\rangle$
end function
```

Sender Asymmetric Ratchet

This function is executed during a message encryption, only when an ECDH peer public key is available(and was never used before)

```
function asymmetricRatchetSender($peerPublicKey\langle 32, 56bytes\rangle$)
    $selfPublicKey, selfPrivateKey \leftarrow$ generateDHKeyPair
            ▷ tag peerPublicKey as used to avoid triggering another DH with it
    $DH\_out \leftarrow DH(selfPrivateKey, peerPublicKey)$
    $RK, CKs \leftarrow$ KDF_RK($RK, DH\_out$)
end function
```

Receiver Asymmetric Ratchet

This function is executed during a message decryption upon reception of a new ECDH peer public key

```
function asymmetricRatchetReceiver($peerPublicKey\langle 32, 56bytes\rangle$)
            ▷ tag peerPublicKey as new so we will use it at next message encryption
    $DH\_out \leftarrow DH(selfPrivateKey, peerPublicKey)$
    $RK, CKr \leftarrow$ KDF_RK($RK, DH\_out$)
end function
```

6.3.2 ECDH and KEM Asymmetric Ratchet

The mixed KEM and ECDH asymmetric ratchet uses X25519 and Kyber512 algorithm

Root key derivation function

As recommended in [1, section 5.2], this function uses HKDF[11] based on SHA512. The *salt* is RK and *ikm* is the output of ECDH(DH_out), the KEM shared secret(KEM_out) and a transcript of the key exchanges: public keys and cipher text. The info string is "*DR Root Chain Key Derivation*".

```
$transcript \leftarrow ECDHSenderPk || ECDHReceiverPk || KEMPk || KEMCt$
function KDF_KEM_RK(RK$\langle 32bytes\rangle$, $DH\_out\langle 32bytes\rangle$,
                    $KEM\_out\langle 32bytes\rangle$, $transcript\langle 1632bytes\rangle$)
    $info \leftarrow$ "DR Root Chain Key Derivation"
    $RK\langle 32bytes\rangle || CK\langle 32bytes\rangle \leftarrow$ HKDFSha512($RK, DH\_out || KEM\_out || transcript, info$)
    return $RK\langle 32bytes\rangle, CK\langle 32bytes\rangle$
end function
```

Sender Asymmetric Ratchet

This function is executed during a message encryption, only when an ECDH peer public key is available(and was never used before)

```
function asymmetricRatchetSender($peerDHPublicKey\langle 32, 56bytes\rangle$)
                                                        ▷ Perform a DH ratchet
    $selfDHPublicKey, selfDHPrivateKey \leftarrow$ generateDHKeyPair
            ▷ tag peerPublicKey as used to avoid triggering another DH with it
    $DH\_out \leftarrow DH(selfDHPrivateKey, peerDHPublicKey)$

                                        ▷ Check if we should also perform a KEM ratchet
    if $peerKEMPublicKey$ available  and
    ( $lastReceiverKemRatchet > 1$ day
    or $ratchetChainSize > 42$ )  then
                                        ▷ Encapsulate a secret to current peer's public key
        $KEM\_CipherText, KEM\_out \leftarrow$ ENCAPSULATE($peerKEMPublicKey$)
        $RK, CKs \leftarrow$ KDF_KEM_RK($RK, DH\_out, KEM\_out,$
            $selfDHPublicKey||peerDHPublicKey||peerKEMPublicKey||KEM\_CipherText$)

                        ▷ Generate a new KEM key pair so peer may encapsulate a secret to us
                              ▷ The public key is sent along the previously created ciphertext
        $selfKEMPublicKey, selfKEMPrivateKey \leftarrow$ GENERATEKEMKEYPAIR
    else
                                                    ▷ No KEM ratchet, just perform a DH one
        $RK, CKs \leftarrow$ KDF_RK($RK, DH\_out$)
    end if
end function
```

Receiver Asymmetric Ratchet

This function is executed during a message decryption upon reception of a new ECDH peer public key

```
function ASYMMETRICRATCHETRECEIVER($peerDHPublicKey\langle 32bytes\rangle, KEMCipherText\langle 768bytes\rangle$)
                ▷ tag peerDHPublicKey as new so we will use it at next message encryption
    $DH\_out \leftarrow DH(selfDHPrivateKey, peerDHPublicKey)$
                              ▷ When a new KEM Public key arrives, perform a KEM ratchet
    if $KEMCipherText$ is new then
        $KEM\_out \leftarrow$ DECAPSULATE($selfKEMPublicKey, KEM\_CipherText$)
        $RK, CKs \leftarrow$ KDF_KEM_RK($RK, DH\_out, KEM\_out,$
            $peerDHPublicKey||selfDHPublicKey||selfKEMPublicKey||KEM\_CipherText$)
    else                                            ▷ No KEM ratchet, just perform a DH one
        $RK, CKr \leftarrow$ KDF_RK($RK, DH\_out$)
    end if
end function
```

6.3.3 Symmetric Ratchet

KDF_CK

Implemented as described in [1, section 5.2]. Message key derivation outputs 48 bytes as it generates the message key ($MK\langle 32bytes\rangle$) and the AEAD nonce ($IV\langle 16bytes\rangle$) as suggested in [1, section 3.1 - ENCRYPT].

```
function KDF_CK(CK$\langle 32bytes\rangle$)
    $MK||IV \leftarrow$ HMACSHA512($ChainKey, 0x01$)
    $CK \leftarrow$ HMACSHA512($ChainKey, 0x02$)
    return $CK\langle 32bytes\rangle, MK\langle 32bytes\rangle, IV\langle 16bytes\rangle$
end function
```

When KEM is also used, this function includes the chain key derivation index as suggested in [8]

```
**function** KDF_CK(CK⟨32bytes⟩, index⟨2bytes⟩)
    $MK\|IV \leftarrow \textsc{HmacSha512}(ChainKey, 0x01, ||index)$
    $CK \leftarrow \textsc{HmacSha512}(ChainKey, 0x02||index)$
    **return** $CK\langle 32bytes\rangle, MK\langle 32bytes\rangle, IV\langle 16bytes\rangle$
**end function**
```

6.3.4 RatchetEncrypt

The ratchet encrypt function performs an asymmetric ratchet when possible: if a peer ECDH public key is available. If the base algorithm includes a KEM, the asymmetric ratchet involves a KEM encapsulation: if a peer KEM public key is available and if more than *maxKEMRatchetChainPeriod* seconds have passed or more than *KEMRatchetChainSize* messages have been exchanged since the last KEM ratchet.

The RatchetEncrypt function described in [1, section 3.4] is not directly used to encrypt the message. Instead, to provide the group chat (see section 5.1.1) capabilities, an encryption request must include a list of recipient devices (can contain one or more elements).
Each recipient in the list is composed of:
$recipientDeviceId$: the recipient device Id
$DRsession$: an active Double Ratchet session with the recipient device
$DRmessage$: encryption output ($Double\ Ratchet\ Message$) for this recipient device
peerDeviceStatus: an ouput giving a status on the recipient: unknown(till now thus), untrusted or trusted

The ouput may be completed by a $Cipher\ Message$ holding the encrypted plain text according to the selected encryption policy,

The message is sent from the sender device to one recipient user (with one user Id and one or more associated device Id) but also distributed to other devices registered to the same sender user. Recipient devices in the list must all be linked to this, unique, recipient user Id or to the sender user Id. For example:

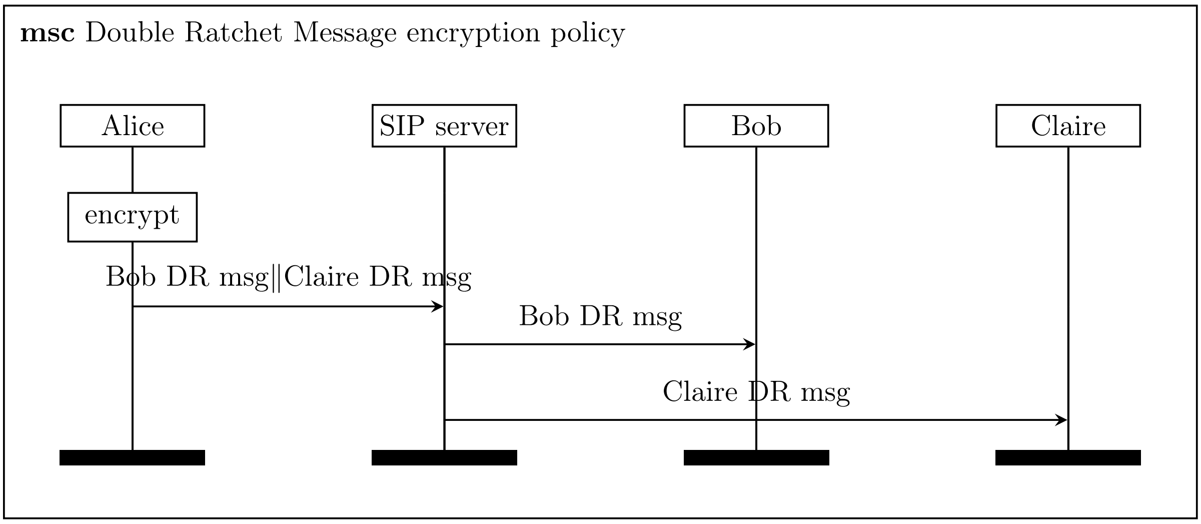
- *Alice*, *Bob* and *Claire* are users Id. Each of them have several (nA, nB, nC) associated devices with devices Id *Alice*.1, *Alice*.2, .., *Alice*.*nA*
- *Alice*, *Bob* and *Claire* are members of a group with user Id *Group*
- If *Alice*.1 sends a message to *Bob*, the inputs for the RatchetEncrypt function must include *Bob* as recipient user and *Bob*.1, .., *Bob*.*nB*, *Alice*.2, .., *Alice*.*nA* as list of recipient devices.
- If *Alice*.1 sends a message to *Group*, the inputs for the RatchetEncrypt function must include *Group* as recipient user and *Bob*.1, .., *Bob*.*nB*, *Alice*.2, .., *Alice*.*nA*, *Claire*.1, .., *Claire*.*nC* as list of recipient devices.
- The Lime library does not perform any check on the link between user Id and device Id and will not generate any error if the RatchetEncrypt arguments are *Bob*

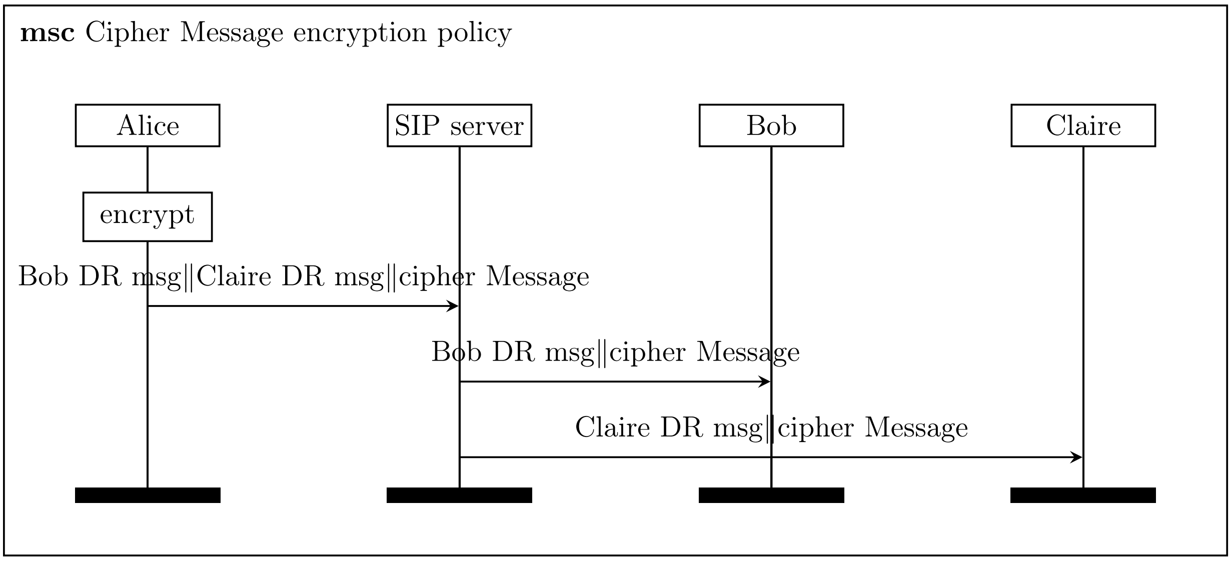
as recipient user and *Bob*.1, .., *Bob.nB*, *Alice*.2, .., *Alice.nA*, *Claire*.1 as list of recipient devices. The error would instead be detected by *Claire*.1 during decryption. See 6.3.6 for details on the use of Associated Data to detect mismatching association of user Id and device Id.

Encryption policy : As stated in section 5.1.1, the plain message can be:

- encrypted directly in the Double Ratchet messages.*(Double Ratchet Message encryption policy)*
- encrypted by a random key in a common cipher message, the random key being encrypted into the Double Ratchet messages.*(Cipher Message encryption policy)*

The two policies are represented on the following diagrams. It is assumed that the server will dispatch only the requested parts to recipients and not the whole upload. Double Ratchet sessions establishment are not shown on the diagram but are assumed to be already completed between all participants. All participants have one device only.


msc Double Ratchet Message encryption policy
Alice
SIP server
Bob
Claire
encrypt
Bob DR msg||Claire DR msg
Bob DR msg
Claire DR msg


msc Cipher Message encryption policy
Alice
SIP server
Bob
Claire
encrypt
Bob DR msg||Claire DR msg||cipher Message
Bob DR msg||cipher Message
Claire DR msg||cipher Message

Selection of the encryption policy according to policy parameter, recipientLists and plain text characteristics. The policy parameter is given at runtime by caller and default to *optimize Upload Size* if omitted. Possible values of this parameter are:

- *Double Ratchet Message*: the plain text is encrypted and embeded in the Double Ratchet message.
- *cipher Message*: the plain text is encrypted in a cipher message with a random key, itself encrypted in the DR message.
- *optimize Upload Size*: for each message, select the mode which minimize the upload size. This is the default policy.
- *optimize Global Bandwidth*: for each message, select the mode which minimize upload + download size.

Note : the optimize modes do not take in consideration the multipart boundary added by the presence of an extra part holding the cipher Message.

```
function MessageEncrypt($recipientList, plain, sourceDeviceId, recipientUserId, policy$)
    switch $policy$ do
        case $DoubleRachetMessage$
            DRMessageEncrypt($recipientList, plain, sourceDeviceId, recipientUserId$)
        case $cipherMessage$
            cipherMessageEncrypt($recipientList, plain, sourceDeviceId, recipientUserId$)
        case $optimize\ Upload\ Size$
            $n \leftarrow number\ of\ recipients\ in\ the\ recipientList$
            $DRMessageSize \leftarrow n \times plain\ size$
            $cipherMessageSize \leftarrow (plain\ size{+}authTag\ size){+}n{\times}(randomSeed\ size)$
            if $DRmessageSize \leq cipherMessageSize$ then
                DRMessageEncrypt($recipientList, plain, sourceDeviceId, recipientUserId$)
            else
                cipherMessageEncrypt($recipientList, plain, sourceDeviceId, recipientUserId$)
            end if
        case $optimize\ Global\ Bandwidth$
            $n \leftarrow number\ of\ recipients\ in\ the\ recipientList$
            $DRMessageSize \leftarrow 2 \times n \times plain\ size$
            $cipherMessageSize \leftarrow (plain\ size + authTag\ size)$
                                    $+n{\times}(2{\times}randomSeed\ size{+}plain\ size{+}authTag\ size)$
            if $DRmessageSize \leq cipherMessageSize$ then
                DRMessageEncrypt($recipientList, plain, sourceDeviceId, recipientUserId$)
            else
                cipherMessageEncrypt($recipientList, plain, sourceDeviceId, recipientUserId$)
            end if
end function
```

with following functions definitions:

```
function DRMessageEncrypt($recipientList, plain, sourceDeviceId, recipientUserId$)
▷ Encrypts the plain in the Double Ratchet message
```

```
    for all $r \in recipientList$ do
        $AD \leftarrow recipientUserId \| sourceDeviceId \| r.recipientDeviceId$
        $r.DRmessage \leftarrow$ RatchetEncrypt($r.session, plain, AD$)
    end for
    return $recipientList$
end function

function cipherMessageEncrypt($recipientList, plain, sourceDeviceId, recipientUserId$)
▷ Generate a random key and nonce to encrypt the plain
    $randomSeed\langle 32bytes\rangle \leftarrow$ RandomSource
    $info \leftarrow$ "DR Message Key Derivation"
    $key\langle 32bytes\rangle \| IV\langle 16bytes\rangle \leftarrow$ HKDFSha512($null, randomSeed, info$)
    $cipherMessage\langle plainsize{+}16bytes\rangle \leftarrow$ Encrypt($key, IV, plain, sourceDeviceId \| recipientUserId$)

 ▷ Use Double Ratchet sessions to encrypt the random seed used to encrypt the plain
    for all $r \in recipientList$ do
        $AD \leftarrow tag \| sourceDeviceId \| r.recipientDeviceId$
        $r.DRmessage \leftarrow$ RatchetEncrypt($r.session, randomSeed, AD$)
    end for
    return $recipientList, cipherMessage$
end function

function RatchetEncrypt($DRsession, plaintext, AD$)
    if $peerECpublickeyavailable$ then
        asymmetricRatchetSender
    end if
     as described in [1, section 3.4]:
    $CKs, mK, IV \leftarrow$ KDF_CK($CKs, Ns$)
    $header \leftarrow$ header($DHs, PN, Ns$)
    $Ns{+} = 1$
    UpdateDRsessionInLocalStorage(DRsession)
    return $header \|$ Encrypt($mK, IV, plaintext, AD \| X3DH\ provided\ AD \| header$)
end function


function Encrypt($key\langle 32bytes\rangle, IV\langle 16bytes\rangle, plain, associatedData$)
    return AES256-GCM output||Auth tag (on plain and associatedData)$\langle 16bytes\rangle$
end function
```

Header function is specified in section 7.1.1

6.3.5 RatchetDecrypt

The decryption function described in [1, section 3.5] is not directly used to decrypt the message. Lime first assess the presence of a cipher message and depending on it use directly the Double Ratchet or perform the two steps of encryption: first decrypt the Double Ratchet message to retrieve the random Key and IV, then decrypt the message itself.

The receiving process described in Sesame specifications [4, section 3.4] is partly implemented in the Double Ratchet decryption process: the message decrypt function accepts a list of Double Ratchet sessions and tries them all until one decrypts correctly the message (or all fail).

The decryption returns the peer device's status(unknown, unsafe, untrusted or trusted) in case of success or fail in case of failure.

```
function MessageDecrypt($sourceDeviceId$,
                        $recipientDeviceId, recipientUserId$,
                        $DRsessionList, DRmessage, cipherMessage$)
    if $cipherMessage\exists$ then
        return cipherMessageDecrypt($sourceDeviceId, recipientDeviceId$,
                        $recipientDeviceId, recipientUserId$
                        $DRsessionList, DRmessage, cipherMessage$)
    else
        return DRMessageDecrypt($sourceDeviceId, recipientDeviceId$,
                        $recipientDeviceId, recipientUserId$
                        $DRsessionList, DRmessage$)
    end if
end function

function DRMessageDecrypt($sourceDeviceId$,
                        $recipientDeviceId, recipientUserId$,
                        $DRsessionList, DRmessage$)

    $AD \leftarrow recipientUserId \| sourceDeviceId \| recipientDeviceId$
    for all $DRsession \in DRsessionList$ do
        if $plain \leftarrow$ RatchetDecrypt($DRsession, DRmessage, AD$) then
            return $plain$
        end if
    end for
    return fail
end function

function cipherMessageDecrypt($sourceDeviceId$,
                        $recipientDeviceId, recipientUserId$,
                        $DRsessionList, DRmessage, cipherMessage$)

    $AD \leftarrow tag \| sourceDeviceId \| recipientDeviceId$
    for all $DRsession \in DRsessionList$ do
        if $randomSeed \leftarrow$ RatchetDecrypt($DRsession, DRmessage, AD$) then
            $info \leftarrow$ "DR Message Key Derivation"
            $key\langle 32bytes\rangle \| IV\langle 16bytes\rangle \leftarrow$ HKDFSha512($null, randomSeed\langle 32bytes\rangle, info$)
            return AEADDecrypt&auth($key, IV, cipher, tag, sourceDeviceId \| recipientUserId$)
        end if
    end for
    return fail
```

```
end function
function RatchetDecrypt($DRsession, header\|payload\|tag, AD$)
    As described in [1, section 3.5]
    Try to decrypt the incoming message with stored skipped message keys
    if Success then
        UpdateDRsessionInLocalStorage(DRsession)
        return
    end if
    if header does not match current peers Public Key then
        asymmetricRatchetReceiver(header public material)
    end if
     as described in [1, section 3.4]:
    $CKr, mK, IV \leftarrow$ KDF_CK($CKr, Nr$)

    Associated Data given to AEAD is $AD\|X3DHprovidedAD\|header$
    if AES256-GCMDecrypt($message\|AuthTag$, $IV$, $MK$) successful then
        UpdateDRsessionInLocalStorage(DRsession)
    end if
end function
```

6.3.6 Associated Data

The double ratchet encryption and decryption AEAD scheme uses Associated Data as recommended by X3DH and Double Ratchet specifications[2, section 3.3], [1, section 3.4]. The Associated Data authenticated is composed of:

Cipher Message encryption policy

$Message\,Tag\langle 16bytes\rangle\|Source\ deviceId\|Recipient\ deviceId\|X3DH AD\langle 32bytes\rangle\|DR\,Header$

Double Ratchet Message encryption policy

$Recipient\,UserId\|Source\ deviceId\|Recipient\ deviceId\|X3DH AD\langle 32bytes\rangle\|DR\,Header$

- $Message\,Tag$: AEAD authentication tag computed on plaintext and the associated data given to AEAD in cipher Message mode: $Source\ deviceId\|Recipient\ UserId$.
- $Recipient\ UserId$: The inclusion of $Recipient\ UserId$ allows the recipient device to verify the original intended recipient user. The $Recipient\ UserId$ is provided to the recipient device along the message by the routing protocol as it may not be the $UserId$ linked to the recipient device but a group user Id.
- $Source\ deviceId$ and $Recipient\ deviceId$: Enforce identification of source and recipient device.
- $X3DH\ AD$: Associated data computed at session creation by the X3DH protocol, based on both parties Identity keys and devices Id. See 6.4.3 for details. It is present in the device local storage from the X3DH initialisation completion.
- $DR\ Header$: as specified in [1, section 3.4]. See 7.1.1 for details.

6.4 X3DH

As stated in section 5.2, Lime does not use XEdDSA but manipulates two key formats: the identity key is stored in EdDSA format (as defined in [9]); while all the other keys are stored in ECDH format (as defined is [6]).

6.4.1 DH

Available Diffie-Hellman algorithms are X25519 and X448, the DH computations performed strictly follow the X3DH specifications.

6.4.2 Sig

The signature/verify operation performed is an EdDSA (both EdDSA25519 and EdDSA448 are available). The identity key used is stored in EdDSA format so there is no need to use XEdDSA contrary to the X3DH specifications [2, section 2.2].

6.4.3 Shared Secrets generation

SK is computed as specified in [2, section 3.3 and 2.2]. The salt used for the HKDF function is a zero filled buffer the size of the hash function used, the *info* parameter is "*Lime*".

$ZeroBuffer\langle SHA512outputsize(64bytes)\rangle \leftarrow 0$
$SK\langle 32bytes\rangle \leftarrow \text{HKDFS}\textsc{ha}512(ZeroBuffer, F\langle 32, 57bytes\rangle \| DH1 \| DH2 \| DH3 \| DH4, \text{"\textit{Lime}"})$

F is a 32 (when using curve25519) or 57 (when using curve448) bytes 0xFF filled buffer.

Associated Data is computed from identity keys and devices Id as specified in [2, section 3.3]. For implementation convenience, the actual AD used by the Double Ratchet session is derived from these inputs by the HKDF function producing a fixed size buffer as following:

$Salt\langle SHA512outputsize(64bytes)\rangle \leftarrow 0$
$ADinput \leftarrow initiatorIk \| receiverIk \| initiatorDeviceId \| receiverDeviceId$
$AD\langle 32bytes\rangle \leftarrow \text{HKDFS}\textsc{ha}512(Salt, ADinput, \text{"\textit{X3DH Associated Data}"})$

initiator being the device who initiates the session (Alice in the X3DH spec) by fetching a keys bundle on the X3DH server and *receiver* being the recipient device of the first message (Bob in the X3DH spec).

6.5 PQXDH

All operations performed in X3DH are also performed by PQXDH, as specified in [3].

6.5.1 KEM

In addition, PQXDH performs a key encapsulation. The algorithm available is Kyber512.

6.5.2 Shared Secrets generation

SK is computed as specified in [3]. The salt used for the HKDF function is a zero filled buffer the size of the hash function used, the *info* parameter is "*Lime*". In addition, a transcript of all public material is used in the Shared secret derivation

$$
\begin{aligned}
&Salt\langle SHA512 outputsize(64 bytes)\rangle \leftarrow 0 \\
&Info \leftarrow "Lime\_\langle CurveId\rangle\_SHA512\_\langle KEMId\rangle \\
&SK\langle 32bytes\rangle \leftarrow \text{HKDF}\textsc{Sha}512(Salt, \\
&\qquad\qquad F\langle 32,57bytes\rangle \| DH1 \| DH2 \| DH3 \| DH4 \| KEM1 \\
&\qquad\qquad || Alice\ Ik || Alice\ Ek || Bob\ DH\ SPk || [Bob\ DH\ OPk] || Bob\ KEM\ Pk || KEM\ CT, \\
&\qquad\qquad Info)
\end{aligned}
$$

F is a 32 (when using curve25519) or 57 (when using curve448) bytes 0xFF filled buffer. *CurveId* and *KEMId* are strings identifying the algorithm: CURVE25519, CURVE448, KYBER512. *BOB KEM Pk* is the KEM public key used to perform the encapsulation: the OPk if present or the SPk otherwise.

6.6 Lime key test server

Nodejs : An X3DH test server running on nodejs is provided with the Lime library source code. This server is not meant to be used in production and its purpose is for testing only. This server lacks user authentication layer, which in real use case is provided by the linphone ecosystem.

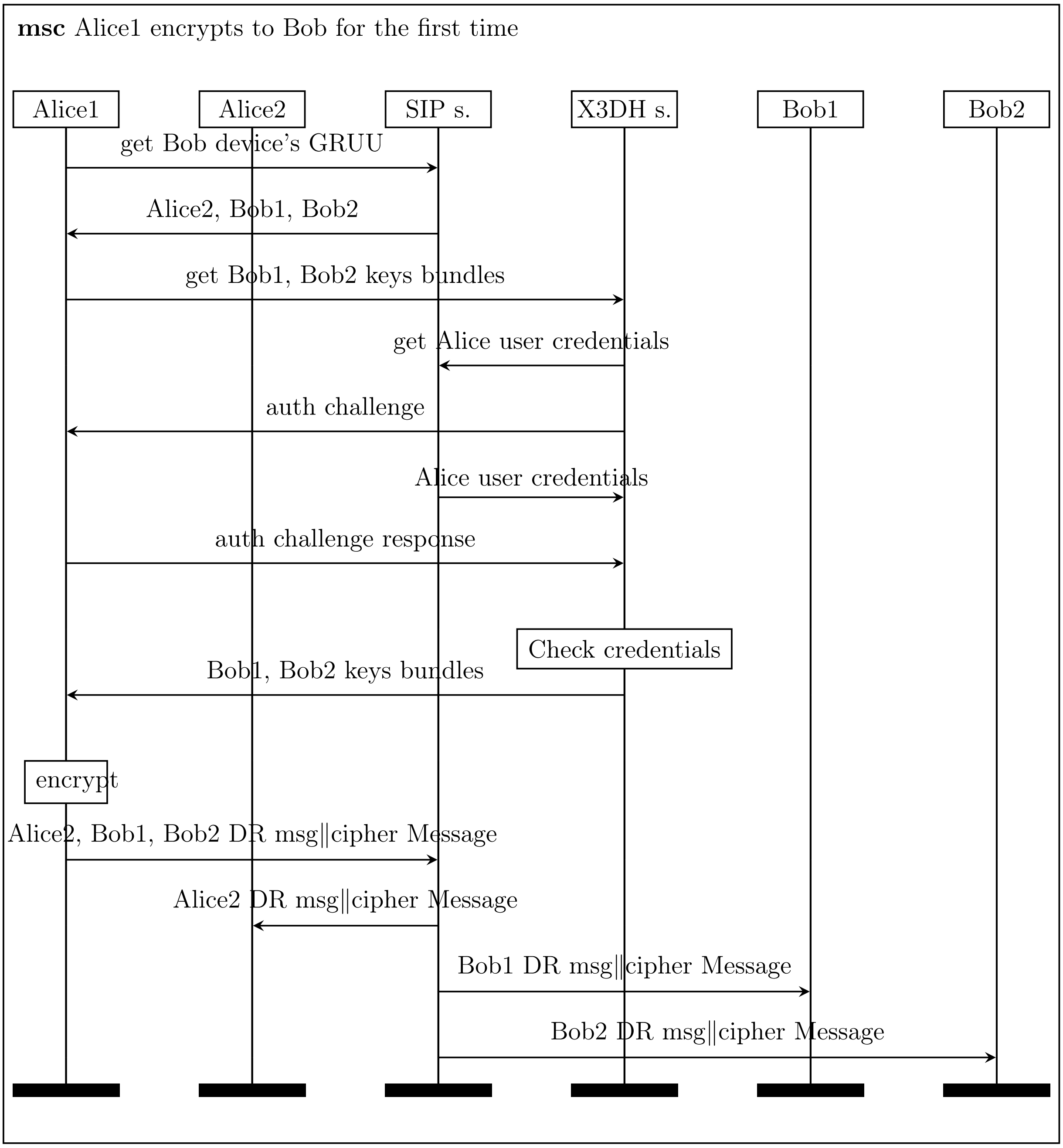
6.7 Sesame

The Sesame requirements are fulfilled as follow:

- Lime is operating in per-device identity keys mode.
- Providing an updated list of Devices Id to match the intended recipients (and sender user other devices) is performed by the linphone ecosystem (SIP and conference server). So the loop between client and server during encryption described in the Sesame spec[4] is not relevant. Lime relies on the SIP or conference server to provide an updated list of recipient devices before the message encryption.
- Encrypt message to multiple recipient device is performed by the Lime Double Ratchet *messageEncrypt* function (see section 6.3.4).
- Support for multiple sessions between devices is performed by Lime Double Ratchet *messageDecrypt* trying multiples sessions, if present, to find one able to decrypt the incoming message.
- User and device identifications are provided by the linphone ecosystem: a user Id is its sip:uri, also used to identify groups. A device Id is its GRUU[10]. The connection to the X3DH server is performed over HTTPS and uses the user authentication associated to the SIP user account.
- Mailboxes and message routing are provided by the linphone ecosystem

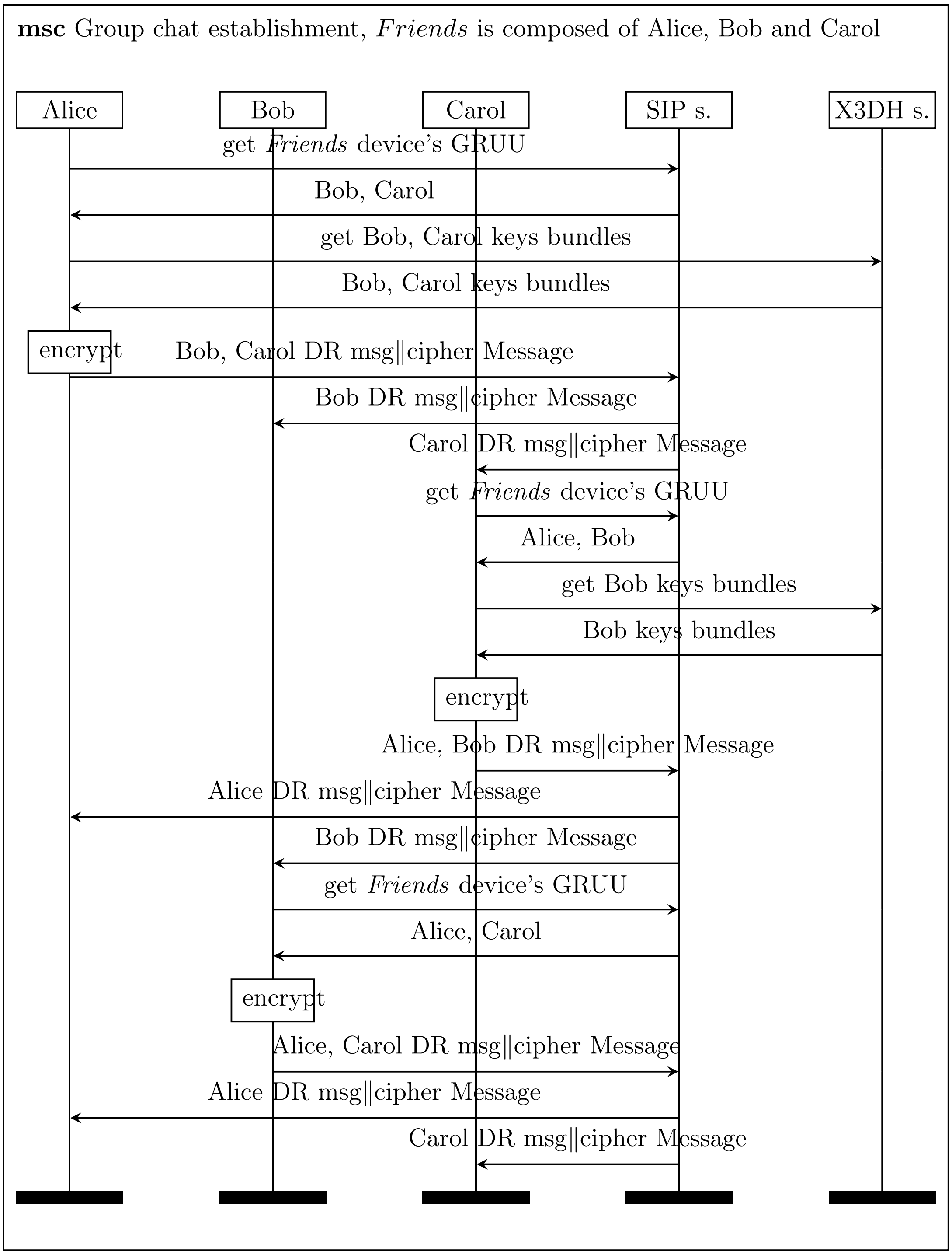
6.7.1 Scenario 1: first encryption, multiple devices

Alice1 encrypts a message to Bob for the first time. Alice1 must establish Double Ratchet sessions and, for that, requests key bundles. It is assumed that Alice2 is known to Alice1; so there is no request for an Alice2 key bundle. The cipher message encryption policy is used.


msc Alice1 encrypts to Bob for the first time
Alice1
Alice2
SIP s.
X3DH s.
Bob1
Bob2
get Bob device's GRUU
Alice2, Bob1, Bob2
get Bob1, Bob2 keys bundles
get Alice user credentials
auth challenge
Alice user credentials
auth challenge response
Check credentials
Bob1, Bob2 keys bundles
encrypt
Alice2, Bob1, Bob2 DR msg||cipher Message
Alice2 DR msg||cipher Message
Bob1 DR msg||cipher Message
Bob2 DR msg||cipher Message

6.7.2 Scenario 2: group chat

Alice sends a first message to a group called Friends composed of Alice, Bob and Carol. Alice's message is dispatched and then Carol posts a message to the group. Carol's message is dispatched and finally Bob sends a message to the group. It is assumed that users did not exchanged any message prior and that they have one device each. User authentication messages to and from X3DH server are not shown for better readability but the users authentication by X3DH server and X3DH server authentication by users must take place. The cipher message encryption policy is used.


msc Group chat establishment, *Friends* is composed of Alice, Bob and Carol
Alice
Bob
Carol
SIP s.
X3DH s.
get *Friends* device's GRUU
Bob, Carol
get Bob, Carol keys bundles
Bob, Carol keys bundles
encrypt
Bob, Carol DR msg||cipher Message
Bob DR msg||cipher Message
Carol DR msg||cipher Message
get *Friends* device's GRUU
Alice, Bob
get Bob keys bundles
Bob keys bundles
encrypt
Alice, Bob DR msg||cipher Message
Alice DR msg||cipher Message
Bob DR msg||cipher Message
get *Friends* device's GRUU
Alice, Carol
encrypt
Alice, Carol DR msg||cipher Message
Alice DR msg||cipher Message
Carol DR msg||cipher Message

6.8 Mutual authentication and peer device status

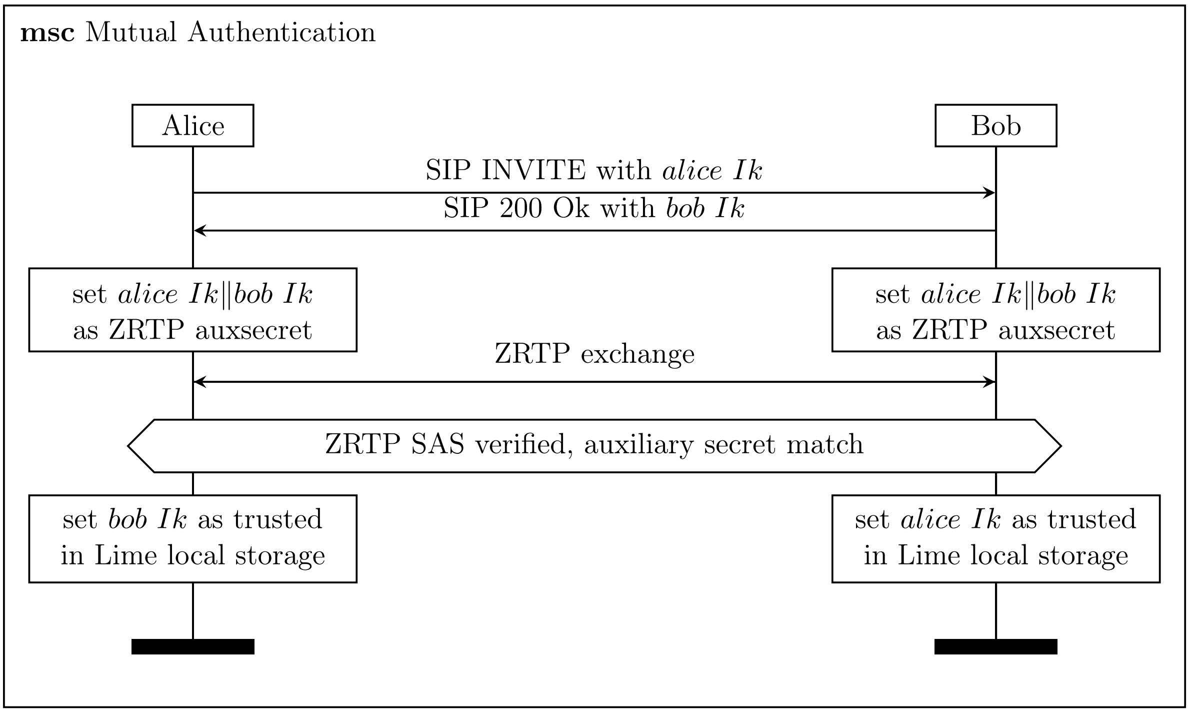
As stated in [2, section 4.1], the parties shall compare their identity public keys otherwise they receive no cryptographic guarantee as to whom they are communicating with. Each peer device has a status available after any encryption or decryption operation which can be:

- *unknown*: we had no information about this device in the local storage(before the last encryption or decryption), this status spots a newly encountered device and shall be clearly made available to the end user.
- *untrusted*: it's is not the first interaction with this device, but we never established mutual authentication
- *trusted*: we already performed the mutual authentication ritual with this peer device.
- $unsafe$: we know this device, it has been tagged as unsafe by the application(Linphone).

Lime provides an API to set/get peer devices identity keys and trust level indexed by its device Id. Linphone uses a ZRTP[12] audio call leveraging the MiTM detection offered by the ZRTP short authentication string to authenticate the peer identity key. ZRTP auxiliary secret is used to compare both parties' identity public keys in the following way:

- parties exchange their identity public keys in the signaling channel at call establishment;
- parties use *caller Ik*$\|$*receiver Ik* as ZRTP auxiliary secret;
- when ZRTP key exchange is complete, parties check that the auxiliary secret is matching and perform a vocal SAS comparison (if not performed before); and
- if the verification succeeds, each party sets the peer Ik status as *trusted* in the Lime local storage. If the peer key is already present in the Lime local storage, Lime verifies that it matches the one obtained through the ZRTP channel.

In the following diagram *alice Ik* and *bob Ik* refer to the identity public key associated to the particular devices used by Alice and Bob to perform the ZRTP audio call.


msc Mutual Authentication
Alice
Bob
SIP INVITE with alice Ik
SIP 200 Ok with bob Ik
set alice Ik||bob Ik as ZRTP auxsecret
set alice Ik||bob Ik as ZRTP auxsecret
ZRTP exchange
ZRTP SAS verified, auxiliary secret match
set bob Ik as trusted in Lime local storage
set alice Ik as trusted in Lime local storage

6.9 Keys and sessions management

Key lifetime management is the responsibility of the client device; the X3DH server is not involved in their management. On a regular schedule (once a day is recommended), the device must run the *update* function to check keys validity, renew and delete outdated ones. Several settings are involved in the *update* operation and are all defined in *lime_ settings.hpp*.

6.9.1 Identity Key

Is valid for the lifetime of a device.

6.9.2 Signed Pre-key

SPK_lifeTime_days is a constant (7 days default) defining the key validity period. Once a key is outdated, a new one is generated, signed and uploaded on the X3DH server. Old keys are kept in storage with an *invalid* status so valid but delayed X3DH initiation messages using this signed pre-key can still be processed.

SPK_limboTime_days is a constant (30 days default) defining the period invalid keys are kept by the device.

6.9.3 One-time Pre-key

These can be used only once, so any use implies immediate deletion:

- when the server delivers a One-time Pre-key, it immediately deletes it; and
- when a client makes use of one of its One-time Pre-key (upon reception from peer of an X3DH init message using that key), it immediately deletes it.

During *update*, a device requests from the X3DH server the list of its own OPk available on the server. The device can upload more keys if there are not enough online and track which keys where delivered by the server but not yet used by comparing the server's OPk list and the OPk actually in local storage.

The three following constants can be overridden at runtime by parameters passed to the *update* or *create_user* functions:

OPK_serverLowLimit is a constant (100 default) defining the lower bound of keys count present on server. During an update, if there are fewer occurrences of keys on the X3DH server, the client will generate and upload a batch of One-time Pre-keys.

OPK_batchSize is a constant (25 default) defining the number of keys generated and uploaded to the server if an upload is needed.

OPK_initialBatchSize is a constant (100 default) defining the number of keys generated and uploaded to the server at the registration of a new user device.

During *update*, the client will update the status of One-time Pre-keys in local storage to reflect the information provided by the server. Any key still in local storage but no longer on the server is assigned the *dispatched* status.

During *update*, the device deletes One-time Pre-keys having the *dispatched* status for a longer than pre-determined period of time.

OPK_limboTime_days is a constant (37 days default) defining the period dispatched One-time Pre-keys are kept by the device.

6.9.4 Double Ratchet Sessions

More than one double ratchet session may exist between two devices but only one shall be active. The encryption is always performed by the active session and, on reception, the session successfully decrypting the message becomes the active session. Stalled sessions are kept for a pre-determined period of time to allow decrypting of delayed or unordered messages:

DRSession_limboTime_days is a constant (30 days default) defining the period stalled sessions are kept by the device.

In case a peer device is silent, the double ratchet session will never perform a Diffie-Hellman ratchet but only symmetric ratchet steps. To mitigate this problem, a predefined limit on the number of messages encrypted without performing Diffie-Hellman is set (effectively being a limit on the length of the sending chain, each Diffie-Hellman ratchet reset the sending chain counter):

maxSendingChain is a constant (500 default) defining the maximum length of a sending chain. When reached, the Double Ratchet session status is stalled, forcing the sender device to create a new session; fetching a new key bundle from the X3DH server in order to keep on sending messages.

KEMRatchetChainSize is a constant (42 default) defining the minimum size of the cummulated sending and receiving chain before a new KEM ratchet can be initiated by a message encryption.

maxKEMRatchetChainPeriod is a constant (86400 seconds/1day default) defining the amount of time elapsed since the last KEM ratchet that will trigger a new KEM ratchet step regardless to the size of the KEM ratchet chain.

6.9.5 Skipped message keys

As messages may be out of order on reception, Double Ratchet specifies how skipped intermediate messages keys, generated to decrypt a received message, shall be stored to allow the decryption of out-of-order messages. After a pre-determined number of messages successfully decrypted by a double ratchet session, skipped messages are considered lost and their stored message keys are deleted from local storage:

maxMessagesReceivedAfterSkip is a constant (128 default) linked to a double ratchet receiving chain (a new chain is started within the session each time a Diffie-Hellman ratchet is performed). Each time a skipped message key is stored in this chain, the counter is reset. Each time a message is decrypted by the session, all skipped message key chain counters are increase by one. When the counter reaches $maxMessagesReceivedAfterSkip$, the skipped message key chain is deleted.

6.10 Multiple base algorithm support

To enable migration from one base algorithm to another (mostly to migrate from elliptic curve cryptography to elliptic curve and post quantum cryptography), the lime library supports the concurrent usage of multiple base algorithms.

The base mechanims of this support is:

- devices are identitied by the pair deviceId (GRUU)/base algorithm
- most of the API gets as input parameters: the deviceId and an ordered list of base algorithms

6.10.1 user creation

The API provides a function to check user existence, getting as parameter the deviceId and a list of base algorithms. When at least one pair is not a active user(public key publication confirmed by the key server), it will returns false.

The user creation function gets the deviceId/ordered base algorithm list parameters and check, in the given order, that the lime user deviceId/base algorithm exists. Every non existing user is created. When all potential users have been processed, the provided callback is called.

6.10.2 encryption

Given the localDeviceId/ordered base algorithms list, the library tries to encrypt for all recipients using the first user localDeviceId/base algo. Any recipient non sastified after this round will try with the next base algorithm in the list until all recipients get a cipher text or all algorithm in the list have been tried.

When using the cipher message encryption policy, the plain text is encrypted with a random key itself encrypted with Double Ratchet protocol. The MessageEncrypt function (see section 6.3.4) in that case produces a cipher message common to all recipients on top of their individual double ratchet cipher text. In order to keep this functionnality in the context of several calls to $MessageEncrypt$ made by different local users(same device Id but different base algorithm), the random key can be stored in a callback accesible buffer by the $MesssageEncrypt$ function caller. The first call to $MessageEncrypt$ will generate the random key (and the cipher message) and store it in the buffer using the provided callback. Successive calls retrieve the random key using the same mechanism.

6.10.3 decryption

Upon cipher text reception, the recipient parses the message header which contains the base algorithm id. This allows to load the appropriate user to decrypt the incoming message.

6.11 Local Storage

The local storage is provided by an sqlite3 database accessed using the SOCI library [17].

6.11.1 Devices tables

lime_LocalUsers stores data relative to local devices.

- Uid: integer primary key.
- $UserId$: the device Id provided by linphone, it shall be the GRUU.
- Ik: Identity key, an EdDSA key stored as public key || private key.
- $server$: the X3DH server URL to be used by this user.
- $curveId$: An unsigned integer, mapped as following:
  - LSB(bit 7 to 0) stores the curve id mapped to integers: 0x01 for Curve 25519 or 0x02 for Curve 448. This value must match the X3DH server setting.
  - bit 8 is the active flag : 0 for active user, 1 for inactive user

lime_PeerDevices *Note:* Records in this table are not linked to a local user but shared among local users in order to avoid storing multiple records containing the same information.

- Did: integer primary key.
- $DeviceId$: the peer device Id, it shall be its GRUU.

- *curveId*: the base algorithm used by this peer device.
- *Ik*: the peer's public EdDSA identity key.
- *Active*: this peer device is the active one, used to select a peer device when asked for status.
- *Status*: status flag:
  - 0 for untrusted: peer's identity is not verified(default value)
  - 1 for trusted: peer's identity was already verified
  - 2 for unsafe: peer's device has been flagged as unsafe

  see this document section 6.8 for usage.

6.11.2 X3DH tables

The X3DH dedicated tables store local users' Signed Pre-keys and One-time Pre-keys, records are linked to a local user through a foreign key: *Uid*.

X3DH_SPK *Note:* signature is computed and uploaded to the server at key generation but is then not needed, so not stored locally.

- *SPKid*: a random Id (unsigned integer on 31 bits) to identify the key. This value being public, it is not a sequence but a random number.
- *SPK*: an ECDH key (stored as public key||private key).
- *timeStamp*: is set to current time when the key status is set to invalid.
- *Status*: set to valid (1) at creation and then to invalid (0) when a new key is generated.
- *Uid*: link to *lime_LocalUsers*: identifies which local user owns this record.

X3DH_OPK

- *OPKid*: a random Id (unsigned integer on 31 bits) to identify the key. This value being public, it is not a sequence but a random number.
- *OPK*: an ECDH key (stored as public key||private key).
- *timeStamp*: is set to current time when the key status is set to dispatched.
- *Status*: set to online (1) at key generation and then to dispatched (0) when the key is not found anymore on the X3DH server by the *update* request.
- *Uid*: link to *lime_LocalUsers*: identify which local user owns this record.

KEM version

When the base algorithm includes a KEM (curve25519/kyber512), SPks and OPks also holds a KEM key pair. They are stored in the tables along the EC ones as EC public key||EC private key||KEM public key|| KEM private key

6.11.3 Double ratchet tables

The Double Ratchet tables store all material needed for the Double Ratchet session, including dedicated tables for skipped keys. Records are linked to local and peer devices through foreign keys: Uid and Did.

DR_sessions

- *Did*: link to *lime_PeerDevices*: identify peer device for this session.
- *Uid*: link to *lime_LocalUsers*: identify local device for this session.
- *sessionId*: integer primary key.
- *Ns*: index of current sending chain.
- *Nr*: index of current receiving chain.
- *PN*: index of previous sending chain.
- *DHr*: peer's ECDH public key or (EC public||KEM public)
- *DHs*: self ECDH key (public||private) or (EC public||EC private||KEM public||KEM private))
- *RK*: Diffie-Hellman Ratchet Root key.
- *CKr*: Symmetric Ratchet receiver chain key.
- *CKs*: Symmetric Ratchet sender chain key.
- *AD*: session Associated Data (provided at session creation by X3DH).
- *Status*: active (1) or stale (0), only one session can be active between two devices.
- *DHrStatus*: a 4 bytes integer mapped as follow
  - *KEMChainSize*(23 bits): cumulative number of sent and received (or skipped) messages since the last KEM receiver ratchet
  - *KEMforce flag*: force a KEM ratchet as soon as possible: is set when creating a session in receiver mode to force the KEM ratchet at first reply
  - *KEMpeerPk flag*: is set when a peer KEM public key is available for encapsulation (only one encapsulation is performed to a peer's Pk)
  - *KEMselfPk flag*: is set when from some replies we deduce that peer's know our current KEM public key so we do not need to send it anymore in the header
  - *DHpeerPk flag*: is set when a peer DH public key is available to perform a DH ratchet step with a fresh generated DH key pair
- *timeStamp*: Two purposes:
  - while the session is active: is updated at each KEM receiving ratchet to be able to trigger a new KEM ratchet step when the last one is old enough

  - is updated to current time when the status is switched from active to stale, so we know when we should delete a stale session from DB

- *X3DHInit*: holds the X3DH init message while it is requested to insert it in message header.

The two following tables store the skipped message keys, indexed by peer's ECDH public key and receiving chain index:

DR_MSk_DHr stores key chain information: peer's ECDH public keys.

- *DHid*: integer primary key
- *sessionId*: link to *DR_sessions*: identifies to which session this chain of skipped message keys belongs.
- *DHr*: peer's ECDH public key associated to this message key chain or SHA512(EC public||KEM public)
- *received*: counts the messages successfully decrypted after the last insertion of a skipped message key in this chain. Is used to delete old message keys.

DR_MSk_MK is the actual storage of message keys.

- *DHid*: link to *DR_MSk_DHr*: identifies to which receiving chain this message key belongs.
- *Nr*: index of the skipped message in the receiving chain.
- *MK*: the message key$\langle 32bytes \rangle$||initial vector$\langle 16bytes \rangle$.

6.12 Summary of cryptographic algorithms used

6.12.1 Double Ratchet

- Diffie-Hellman using either X25519 or X448
- KEM: Kyber512 or MLKEM512(with X25519), MLKEM1024 (with X448)
- KDF are HKDF[11] based on Sha512
- ENCRYPT is AES256-GCM with a 128bits authentication tag

6.12.2 X3DH

- Diffie-Hellman using either X25519 or X448
- KEM: Kyber512 (always used with X25519)
- HKDF uses Sha512
- Signature uses EdDSA25519 or EdDSA448
- EdDSA keys are converted to ECDH keys to perform classic ECDH

6.12.3 Cryptographic libraries

Elliptic curves operations are provided by decaf library[14], version 0.9.4 or above: X25519, X448, EdDSA25519, EdDSA448 and conversion function from EdDSA key to ECDH key format.

Hash (HmacSha512), HKDF-Sha512 and encryption (AES256-GCM) are provided by mbedtls library[15]. Version 3.4 or above.

Kyber512 is provided by liboqs library[16], version 0.9.1 or above. The Kyber512 version provided is the one from NIST round3

Note : These libraries are not accessed directly but through the bctoolbox abstraction library or the postquantumcryptoengine library.

7 Protocol specification

This section describes the details of messages structures.

Notes : Keys are intended as public keys and their size depends on the selected base algorithm indicated in the messages header. The following sizes apply:

- Curve 25519 ECDH: 32 bytes
- Curve 25519 EdDSA: 32 bytes
- Curve 25519 Signature: 64 bytes
- Curve 448 ECDH: 56 bytes
- Curve 448 EdDSA: 57 bytes
- Curve 448 Signature: 114 bytes
- Kyber/MLKEM 512 Public Key: 800 bytes
- Kyber/MLKEM 512 Cipher Text: 768 bytes
- MLKEM 1024 Public Key: 1568 bytes
- MLKEM 1024 Cipher Text: 1568 bytes

Keys are stored and distributed in the formats described in [6] and [9].
Others numeric values (counts, Ids, counters) are unsigned integers in big endian.

7.1 Double Ratchet message

These messages are exchanged among devices. The system runs in asynchronous mode, and messages are sent to and stored by a server and are fetched by final recipients when online. The server in charge of storing/routing the messages shall fan-out to the respective recipients not all the incoming message but only the part addressed to them.

Double Ratchet messages are composed of header and payload. The payload is the AEAD output (cipher text and authentication tag) of either a random seed used to encrypt the plain message or the plain message itself according to selected encryption policy. The sender produces one Double Ratchet message per recipient device.
Definitions:

- Protocol Version: 0x01.
- Message Type is a byte with following bit mapping:
  - bit 7 to 3: not used.
  - bit 2: KEM public key index flag: (used only when the base algorithm includes a KEM)
    - 1: Peer and Self KEM public indexes only are present in this message
    - 0: A KEM public key and Cipher Text are present in this message
  - bit 1: Payload encryption flag:

        - 1: payload in the DR message
        - 0: payload in a cipher message, DR holds the random seed
    - bit 0: X3DH init flag:
        - 1: (X3DH init in the header)
        - 0: (no X3DH init in the header)

- Curve Id:
    - 0x01: curve 25519
    - 0x02: curve 448
    - 0x03: curve 25519 + Kyber512
    - 0x04: curve 25519 + MLKEM512
    - 0x05: curve 448 + MLKEM1024

7.1.1 Header

For DH only

<table>
<tr><th>byte 0</th><th>byte 1</th><th>byte 2</th><th>byte 3</th></tr>
<tr><td>Protocol Version [0x01]</td><td>Message type</td><td>Curve Id</td><td></td></tr>
<tr><td colspan="4">X3DH Init ⟨variable size⟩{0,1}
This part is present only if Message type X3DH init flag is set</td></tr>
<tr><td colspan="2">Ns</td><td colspan="2">PN</td></tr>
<tr><td colspan="4">DHs$\langle 32, 56\mathit{bytes}\rangle$
...</td></tr>
</table>

KEM based, when a KEM ratchet took place

<table>
<tr><th>byte 0</th><th>byte 1</th><th>byte 2</th><th>byte 3</th></tr>
<tr><td>Protocol Version [0x01]</td><td>Message type</td><td>Curve Id</td><td></td></tr>
<tr><td colspan="4">X3DH Init ⟨variable size⟩{0,1}
This part is present only if Message type X3DH init flag is set</td></tr>
<tr><td colspan="2">Ns</td><td colspan="2">PN</td></tr>
<tr><td colspan="4">DHs$\langle 32, 56\mathit{bytes}\rangle$
...</td></tr>
<tr><td colspan="4">KEM self public key$\langle 800, 1568\mathit{bytes}\rangle$
...</td></tr>
<tr><td colspan="4">KEM cipherText(encapsulation to peer’s KEM pk)$\langle 768, 1568\mathit{bytes}\rangle$
...</td></tr>
</table>

KEM based, when the KEM ratchet is skipped (signaled in Message Type bit 3)

<table>
<tr><th>byte 0</th><th>byte 1</th><th>byte 2</th><th>byte 3</th></tr>
<tr><td>Protocol Version [0x01]</td><td>Message type</td><td>Curve Id</td><td></td></tr>
<tr><td colspan="4">X3DH Init ⟨variable size⟩{0,1}
This part is present only if Message type X3DH init flag is set</td></tr>
<tr><td colspan="2">Ns</td><td colspan="2">PN</td></tr>
<tr><td colspan="4">DHs$\langle 32, 56\mathit{bytes}\rangle$
...</td></tr>
<tr><td colspan="4">Self KEM Pk index$\langle 12\mathit{bytes}\rangle$
...</td></tr>
<tr><td colspan="4">Peer KEM Pk index$\langle 12\mathit{bytes}\rangle$
...</td></tr>
</table>

7.1.2 Payload in cipher message encryption policy

byte 0	byte 1	byte 2	byte 3
Random Seed encrypted using DR session$\langle 32 bytes \rangle$ ...			
Double Ratchet AEAD authentication tag$\langle 16 bytes \rangle$ ...			

7.1.3 Payload in Double Ratchet message encryption policy

byte 0	byte 1	byte 2	byte 3
plaintext encrypted using DR session$\langle variable\ size,\ same\ as\ plaintext \rangle$ ...			
Double Ratchet AEAD authentication tag$\langle 16 bytes \rangle$ ...			

7.1.4 X3DH init

DH only

byte 0	byte 1	byte 2	byte 3
OPk flag [0x00,0x01]	EdDSA Identity Key$\langle 32, 57 bytes \rangle$ ...		
ECDH Ephemeral Key$\langle 32, 56 bytes \rangle$ ...			
Signed Pre-key Id			
One Time Pre-key Id{0,1} only if OPk flag = 0x01			

KEM based

byte 0	byte 1	byte 2	byte 3
OPk flag [0x00,0x01]	EdDSA Identity Key$\langle 32, 57 bytes \rangle$ ...		
ECDH Ephemeral Key$\langle 32, 56 bytes \rangle$ ...			
KEM cipherText(encapsulation to OPk - or SPk$\langle 768, 1568 bytes \rangle$ ...			
Signed Pre-key Id			
One Time Pre-key Id{0,1} only if OPk flag = 0x01			

7.2 Cipher Message

. The cipher message is produced only when selecting the cipher message encryption policy. The sender produces one cipher message common to all recipients. When present, the cipher message is dispatched along the Double Ratchet messages.(see 6.3.4 for details)

byte 0	byte 1	byte 2	byte 3
Cipher text produced by AEAD using a derivative of Random Seed <variable size> ...			
AEAD authentication tag$\langle 16 bytes \rangle$ ...			

7.3 X3DH message

Theses messages are exchanged between devices and the X3DH key server.

The messages are sent to the server using the HTTPS protocol. Clients identify themselves to the server by setting their device Id (GRUU) in the HTTPS packet custom header *X-Lime-user-identity* field. Server challenges the client with a nonce and expects a digest of the password of their user account on the SIP server. X3DH server must have access to the SIP register server database to be able to authenticate clients. Communications between clients and X3DH server are assumed to be secure and the details of this assumption are out of the scope of this document.

X3DH messages are composed of a header and the content:
Protocol Version$\langle 1byte\rangle \|$ Message Type $\langle 1byte\rangle \|$ Curve Id $\langle 1byte\rangle \|$ Message content.
Definitions:

- Protocol Version: 0x01.
- Message Type:
  - *0x01: deprecated register User*: a device registers its Id and Identity key on X3DH server, this message holds the Ik only and shall be supported for retro-compatibility with old clients only.
  - *0x02: delete User*: a device deletes its Id and Identity key from X3DH server.
  - *0x03: post Signed Pre-key*: a device publishes a Signed Pre-key on X3DH server.
  - *0x04: post One-time Pre-keys*: a device publishes a batch of One-time Pre-keys on X3DH server.
  - *0x05: get peers key bundles*: a device requests key bundles for a list of peer devices.
  - *0x06: peers key bundles*: X3DH server responds to device with the list of requested key bundles.
  - *0x07: get self One-time Pre-keys*: ask server for self One-time Pre-keys Ids available.
  - *0x08: self One-time Pre-keys*: server response with a count and list of all One-time Pre-keys Ids available.
  - *0x09: register User*: a device registers its Id and Identity key, Signed Pre-key and a batch of One-time Pre-keys on X3DH server.
  - *0xFF: error*: something went wrong on server side during processing of client message, server respond with details on failure.
- Curve Id: [0x01 (curve 25519), 0x02 (curve 448), 0x03 (curve25519/kyber512)]

To device generated messages *(deprecated) register User, delete User, post Signed Pre-key* and *post One-time Pre-key*, on success, the X3DH server responds with the original message header:
Protocol Version || Message type || Curve Id

OPk and SPk keys, when based on multiple scheme (ECDH and KEM), are a concatenation of the ECDH public key with the KEM public key.

7.3.1 Register User Message

byte 0	byte 1	byte 2	byte 3
Protocol Version [0x01]	Message type [0x09]	Curve Id	
EdDSA Identity Key$\langle 32, 57 \mathit{bytes}\rangle$ ...			
Signed Pre-key$\langle 32, 56, 832, 1600 \mathit{bytes}\rangle$ ...			
Signed Pre-key Signature$\langle 64, 114 \mathit{bytes}\rangle$ ...			
Signed Pre-key Id			
keys Count		One-time Pre-key bundle$\langle 36, 60, 836, 1604 \mathit{bytes}\rangle$\{keys Count\}	
...			

with One-time Pre-key bundle:

byte 0	byte 1	byte 2	byte 3
One-Time Pre-key$\langle 32, 56, 832, 1600 \mathit{bytes}\rangle$ ...			
One-Time Pre-key Id			

7.3.2 Delete User Message

byte 0	byte 1	byte 2	byte 3
Protocol Version [0x01]	Message type [0x02]	Curve Id	

7.3.3 post Signed Pre-key Message

byte 0	byte 1	byte 2	byte 3
Protocol Version [0x01]	Message type [0x03]	Curve Id	
Signed Pre-key$\langle 32, 56, 832, 1600 \mathit{bytes}\rangle$ ...			
ECDH Signed Pre-key Signature$\langle 64, 114 \mathit{bytes}\rangle$ ...			
Signed Pre-key Id			

7.3.4 post One-time Pre-key Message

byte 0	byte 1	byte 2	byte 3
Protocol Version [0x01]	Message type [0x04]	Curve Id	keys Count MSB
keys Count LSB	One-time Pre-key bundle$\langle 36, 60 \mathit{bytes}\rangle$\{keys Count\}		
...			

with One-time Pre-key bundle:

byte 0	byte 1	byte 2	byte 3
One-Time Pre-key$\langle 32, 56, 832, 1600 \mathit{bytes}\rangle$ ...			
One-Time Pre-key Id			

7.3.5 get peers key bundles Message

byte 0	byte 1	byte 2	byte 3
Protocol Version [0x01]	Message type [0x05]	Curve Id	request Count MSB
request Count LSB	request{request Count}		
...			

with request:

byte 0	byte 1	byte 2	byte 3
Device Id size		Device Id⟨variable size⟩...	
...Device Id⟨variable size⟩			

7.3.6 peers key bundles Message

byte 0	byte 1	byte 2	byte 3
Protocol Version [0x01]	Message type [0x06]	Curve Id	bundles Count MSB
bundles Count LSB	key Bundle{bundles Count}		
...			

with key Bundle(if a the device has published keys on the server):

byte 0	byte 1	byte 2	byte 3
Device Id size		Device Id⟨variable size⟩...	
...Device Id⟨variable size⟩			
bundle flag [0x00,0x01]			
EdDSA Identity Key$\langle 32, 57 \mathit{bytes} \rangle$ ...			
Signed Pre-key$\langle 32, 56, 832, 1600 \mathit{bytes} \rangle$ ...			
Signed Pre-key Id			
Signed Pre-key Signature$\langle 64, 114 \mathit{bytes} \rangle$ ...			
One-Time Pre-key$\langle 32, 56, 832, 1600 \mathit{bytes} \rangle${0,1} only if bundle flag = 0x01 ...			
One-Time Pre-key Id{0,1} only if bundle flag = 0x01			

or key Bundle(if a the device has not published keys on the server):

byte 0	byte 1	byte 2	byte 3
Device Id size		Device Id⟨variable size⟩...	
...Device Id⟨variable size⟩			
bundle flag [0x02]			

7.3.7 get Self OPks Message

byte 0	byte 1	byte 2	byte 3
Protocol Version [0x01]	Message type [0x07]	Curve Id	

7.3.8 self OPks Message

byte 0	byte 1	byte 2	byte 3
Protocol Version [0x01]	Message type [0x08]	Curve Id	OPk Count MSB
OPk Count LSB	OPk Id$\langle 4 \mathit{bytes} \rangle${OPk Count}		
...			

7.3.9 Error Message

byte 0	byte 1	byte 2	byte 3
Protocol Version [0x01]	Message type [0xFF]	Curve Id	Error Code[0x00-0x08]
Optional error message of variable size Null terminated ASCII string ...			

With Error codes in:

- 0x00: **bad content type**: HTTPS packet *content-type* is not "x3dh/octet-stream"
- 0x01: **bad curve**: client and server curve mismatch.
- 0x02: **missing Sender Id**: HTTPS packet *from* is not set.
- 0x03: **bad protocol version**: client and server X3DH protocol version number mismatch.
- 0x04: **bad size**: the size of received Message is not the expected one
- 0x05: **user already in**: trying to register a user on X3DH server but it is already in the database
- 0x06: **user not found**: an operation concerning a user could not be performed because the user was not found in server database.
- 0x07: **db error**: server encountered problem with its database.
- 0x08: **bad request**: malformed peer bundle request.
- 0x09: **server failure**: server is badly configured and cannot run correctly.
- 0x0a: **resource limit reached**: the request temporarily cannot be served as the user reached the usage limit.

7.3.10 Deprecated Register User Message

byte 0	byte 1	byte 2	byte 3
Protocol Version [0x01]	Message type [0x01]	Curve Id	
EdDSA Identity Key$\langle 32, 57 bytes \rangle$ ...			

8 Acknowledgements

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9 IPR

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