          Use of Timed Efficient Stream Loss-Tolerant Authentication (TESLA) in
                  the Asynchronous Layered Coding (ALC) and
             NACK-Oriented Reliable Multicast (NORM) Protocols

Abstract

   This document details the Timed Efficient Stream Loss-Tolerant
   Authentication (TESLA) packet source authentication and packet
   integrity verification protocol and its integration within the
   Asynchronous Layered Coding (ALC) and NACK-Oriented Reliable
   Multicast (NORM) content delivery protocols. This document only
   considers the authentication/integrity verification of the packets
   generated by the session's sender. The authentication and integrity
   verification of the packets sent by receivers, if any, is out of the
   scope of this document.

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1. Introduction

   Many applications using multicast and broadcast communications
   require that each receiver be able to authenticate the source of any
   packet it receives as well as the integrity of these packets. This
   is the case with ALC [RFC5775] and NORM [RFC5740], two Content
   Delivery Protocols (CDPs) designed to transfer objects (e.g., files)
   reliably between a session's sender and several receivers. The NORM
   protocol is based on bidirectional transmissions. Each receiver
   acknowledges data received or, in case of packet erasures, asks for
   retransmissions. On the opposite, the ALC protocol is based on
   purely unidirectional transmissions. Reliability is achieved by
   means of the cyclic transmission of the content within a carousel
   and/or by the use of proactive Forward Error Correction (FEC) codes.
   Both protocols have in common the fact that they operate at the
   application level, on top of an erasure channel (e.g., the Internet)
   where packets can be lost (erased) during the transmission.

   The goal of this document is to counter attacks where an attacker
   impersonates the ALC or NORM session's sender and injects forged
   packets to the receivers, thereby corrupting the objects
   reconstructed by the receivers.

   Preventing this attack is much more complex in the case of group
   communications than it is with unicast communications. Indeed, with
   unicast communications, a simple solution exists: the sender and the
   receiver share a secret key to compute a Message Authentication Code
   (MAC) of all messages exchanged. This is no longer feasible in the
   case of multicast and broadcast communications since sharing a group
   key between the sender and all receivers implies that any group
   member can impersonate the sender and send forged messages to other
   receivers.

   The usual solution to provide the source authentication and message
   integrity services in the case of multicast and broadcast
   communications consists of relying on asymmetric cryptography and
   using digital signatures. Yet, this solution is limited by high
   computational costs and high transmission overheads. The Timed
   Efficient Stream Loss-tolerant Authentication (TESLA) protocol is an
   alternative solution that provides the two required services, while
   being compatible with high-rate transmissions over lossy channels.

   This document explains how to integrate the TESLA source
   authentication and packet integrity protocol to the ALC and NORM CDP.
   Any application built on top of ALC and NORM will directly benefit
   from the services offered by TESLA at the transport layer. In
   particular, this is the case of File Delivery over Unidirectional
   Transport (FLUTE).

For more information on the TESLA protocol and its principles, please
refer to [RFC4082] and [Perrig04]. For more information on ALC and
NORM, please refer to [RFC5775], [RFC5651], and [RFC5740],
respectively. For more information on FLUTE, please refer to
[RMT-FLUTE].

1.1. Scope of This Document

This specification only considers the authentication and integrity
verification of the packets generated by the session's sender. This
specification does not consider the packets that may be sent by
receivers, for instance, NORM's feedback packets. [RMT-SIMPLE-AUTH]
describes several techniques that can be used to that purpose. Since
this is usually a low-rate flow (unlike the downstream flow), using
computing intensive techniques like digital signatures, possibly
combined with a Group MAC scheme, is often acceptable. Finally,
Section 5 explains how to use several authentication schemes in a
given session thanks to the "ASID" (Authentication Scheme IDentifier)
field.

This specification relies on several external mechanisms, for
instance:

o to communicate securely the public key or a certificate for the
   session's sender (Section 2.2.2);

o to communicate securely and confidentially the group key, K_g,
   used by the Group MAC feature, when applicable (Section 3.3.3).
   In some situations, this group key will have to be periodically
   refreshed;

o to perform secure time synchronization in indirect mode
   (Section 2.3.2) or in direct mode (Section 2.3.1) to carry the
   request/response messages with ALC, which is purely
   unidirectional;

These mechanisms are required in order to bootstrap TESLA at a sender
and at a receiver and must be deployed in parallel to TESLA.
Besides, the randomness of the Primary Key of the key chain
(Section 3.1.2) is vital to the security of TESLA. Therefore, the
sender needs an appropriate mechanism to generate this random key.

Several technical details of TESLA, like the most appropriate way to
alternate between the transmission of a key disclosure and a
commitment to a new key chain, or the transmission of a key
disclosure and the last key of the previous key chain, or the
disclosure of a key and the compact flavor that does not disclose any
key, are specific to the target use case (Section 3.1.2). For

instance, it depends on the number of packets sent per time interval,
on the desired robustness and the acceptable transmission overhead,
which can only be optimized after taking into account the use-case
specificities.

1.2. Conventions Used in This Document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT",
"SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this
document are to be interpreted as described in [RFC2119].

1.3. Terminology and Notations

The following notations and definitions are used throughout this
document.

1.3.1. Notations and Definitions Related to Cryptographic Functions

Notations and definitions related to cryptographic functions
[RFC4082][RFC4383]:

o PRF is the Pseudo Random Function;

o MAC is the Message Authentication Code;

o HMAC is the keyed-Hash Message Authentication Code;

o F is the one-way function used to create the key chain
   (Section 3.1.2.1);

o F' is the one-way function used to derive the HMAC keys
   (Section 3.1.2.1);

o n_p is the length, in bits, of the F function's output. This is
   therefore the length of the keys in the key chain;

o n_f is the length, in bits, of the F' function's output. This is
   therefore the length of the HMAC keys;

o n_m is the length, in bits, of the truncated output of the MAC
   [RFC2104]. Only the n_m most significant bits of the MAC output
   are kept;

o N is the length of a key chain. There are N+1 keys in a key
   chain: K_0, K_1, ..., K_N. When several chains are used, all the
   chains MUST have the same length and keys are numbered
   consecutively, following the time interval numbering;

o n_c is the number of keys in a key chain. Therefore, n_c = N+1;

o n_tx_lastkey is the number of additional intervals during which
   the last key of the old key chain SHOULD be sent, after switching
   to a new key chain and after waiting for the disclosure delay d.
   These extra transmissions take place after the interval during
   which the last key is normally disclosed. The n_tx_lastkey value
   is either 0 (no extra disclosure) or larger. This parameter is
   sender specific and is not communicated to the receiver;

o n_tx_newkcc is the number of intervals during which the commitment
   to a new key chain SHOULD be sent, before switching to the new key
   chain. The n_tx_newkcc value is either 0 (no commitment sent
   within authentication tags) or larger. This parameter is sender
   specific and is not communicated to the receiver;

o K_g is a shared group key, communicated to all group members,
   confidentially, during the TESLA bootstrapping (Section 2.2);

o n_w is the length, in bits, of the truncated output of the MAC of
   the optional group authentication scheme: only the n_w most
   significant bits of the MAC output are kept. n_w is typically
   small, a multiple of 32 bits (e.g., 32 bits).

1.3.2. Notations and Definitions Related to Time

   Notations and definitions related to time:

o i is the time interval index. Interval numbering starts at 0 and
   increases consecutively. Since the interval index is stored as a
   32-bit unsigned integer, wrapping to 0 might take place in long
   sessions.

o t_s is the sender local time value at some absolute time (in NTP
   timestamp format);

o t_r is the receiver local time value at the same absolute time (in
   NTP timestamp format);

o T_0 is the start time corresponding to the beginning of the
   session, i.e., the beginning of time interval 0 (in NTP timestamp
   format);

o T_int is the interval duration (in milliseconds);

o d is the key disclosure delay (in number of intervals);

   o D_t is the upper bound of the lag of the receiver's clock with
      respect to the clock of the sender;

   o S_sr is an estimated bound of the clock drift between the sender
      and a receiver throughout the duration of the session;

   o D^O_t is the upper bound of the lag of the sender's clock with
      respect to the time reference in indirect time synchronization
      mode;

   o D^R_t is the upper bound of the lag of the receiver's clock with
      respect to the time reference in indirect time synchronization
      mode;

   o D_err is an upper bound of the time error between all the time
      references, in indirect time synchronization mode;

   o NTP timestamp format consists in a 64-bit unsigned fixed-point
      number, in seconds relative to 0h on 1 January 1900. The integer
      part is in the first 32 bits, and the fraction part in the last 32
      bits [RFC1305].

2. Using TESLA with ALC and NORM: General Operations

2.1. ALC and NORM Specificities That Impact TESLA

   The ALC and NORM protocols have features and requirements that
   largely impact the way TESLA can be used.

   In the case of ALC:

   o ALC is massively scalable: nothing in the protocol specification
      limits the number of receivers that join a session. Therefore, an
      ALC session potentially includes a huge number (e.g., millions or
      more) of receivers;

   o ALC can work on top of purely unidirectional transport channels:
      this is one of the assets of ALC, and examples of unidirectional
      channels include satellite (even if a back channel might exist in
      some use cases) and broadcasting networks like Digital Video
      Broadcasting - Handhelds / Satellite services to Handhelds (DVB-
      H/SH);

   o ALC defines an on-demand content delivery model [RFC5775] where
      receivers can arrive at any time, at their own discretion,
      download the content and leave the session. Other models (e.g.,
      push or streaming) are also defined;

   o ALC sessions are potentially very long: a session can last several
      days or months during which the content is continuously
      transmitted within a carousel. The content can be either static
      (e.g., a software update) or dynamic (e.g., a web site).

   Depending on the use case, some of the above features may not apply.
   For instance, ALC can also be used over a bidirectional channel or
   with a limited number of receivers.

   In the case of NORM:

   o NORM has been designed for medium-size sessions: indeed, NORM
      relies on feedback messages and the sender may collapse if the
      feedback message rate is too high;

   o NORM requires a bidirectional transport channel: the back channel
      is not necessarily a high-data rate channel since the control
      traffic sent over it by a single receiver is an order of magnitude
      lower than the downstream traffic. Networks with an asymmetric
      connectivity (e.g., a high-rate satellite downlink and a low-rate
      return channel) are appropriate.

2.2. Bootstrapping TESLA

   In order to initialize the TESLA component at a receiver, the sender
   MUST communicate some key information in a secure way, so that the
   receiver can check the source of the information and its integrity.
   Two general methods are possible:

   o by using an out-of-band mechanism, or

   o by using an in-band mechanism.

   The current specification does not recommend any mechanism to
   bootstrap TESLA. Choosing between an in-band and out-of-band scheme
   is left to the implementer, depending on the target use case.
   However, it is RECOMMENDED that TESLA implementations support the use
   of the in-band mechanism for interoperability purposes.

2.2.1. Bootstrapping TESLA with an Out-Of-Band Mechanism

   For instance, [RFC4442] describes the use of the MIKEY (Multimedia
   Internet Keying) protocol to bootstrap TESLA. As a side effect,
   MIKEY also provides a loose time synchronization feature from which
   TESLA can benefit. Other solutions, for instance, based on an
   extended session description, are possible, on the condition that
   these solutions provide the required security level.

2.2.2. Bootstrapping TESLA with an In-Band Mechanism

   This specification describes an in-band mechanism. In some use
   cases, it might be desired that bootstrapping take place without
   requiring the use of an additional external mechanism. For instance,
   each device may feature a clock with a known time-drift that is
   negligible in front of the time accuracy required by TESLA, and each
   device may embed the public key of the sender. It is also possible
   that the use case does not feature a bidirectional channel that
   prevents the use of out-of-band protocols like MIKEY. For these two
   examples, the exchange of a bootstrap information message (described
   in Section 3.4.1) and the knowledge of a few additional parameters
   (listed below) are sufficient to bootstrap TESLA at a receiver.

   Some parameters cannot be communicated in-band. In particular:

   o the sender or group controller MUST either communicate the public
      key of the sender or a certificate (which also means that a PKI
      has been set up) to all receivers, so that each receiver be able
      to verify the signature of the bootstrap message and direct time
      synchronization response messages (when applicable).

   o when time synchronization is performed with NTP/SNTP (Simple
      Network Time Protocol), the sender or group controller MUST
      communicate the list of valid NTP/SNTP servers to all the session
      members (sender included), so that they are all able to
      synchronize themselves on the same NTP/SNTP servers.

   o when the Group MAC feature is used, the sender or group controller
      MUST communicate the K_g group key to all the session members
      (sender included). This group key may be periodically refreshed.

   The way these parameters are communicated is out of the scope of this
   document.

2.3. Setting Up a Secure Time Synchronization

   The security offered by TESLA heavily relies on time. Therefore, the
   session's sender and each receiver need to be time synchronized in a
   secure way. To that purpose, two general methods exist:

   o direct time synchronization, and

   o indirect time synchronization.

   It is also possible that a given session includes receivers that use
   the direct time synchronization mode while others use the indirect
   time synchronization mode.

2.3.1. Direct Time Synchronization

   When direct time synchronization is used, each receiver asks the
   sender for a time synchronization. To that purpose, a receiver sends
   a direct time synchronization request (Section 4.2.2.1). The sender
   then directly answers each request with a direct time synchronization
   response (Section 3.4.2), signing this reply. Upon receiving this
   response, a receiver first verifies the signature, and then
   calculates an upper bound of the lag of his clock with respect to the
   clock of the sender, D_t. The details on how to calculate D_t are
   given in Section 2.4.1.

   This synchronization method is both simple and secure. Yet, there
   are two potential issues:

   o a bidirectional channel must exist between the sender and each
      receiver, and

   o the sender may collapse if the incoming request rate is too high.

   Relying on direct time synchronization is not expected to be an issue
   with NORM since (1) bidirectional communications already take place,
   and (2) NORM scalability is anyway limited. Yet, it can be required
   that a mechanism, that is out of the scope of this document, be used
   to spread the transmission of direct time synchronization request
   messages over time if there is a risk that the sender may collapse.

   But direct time synchronization is potentially incompatible with ALC
   since (1) there might not be a back channel, and (2) there are
   potentially a huge number of receivers and therefore a risk that the
   sender will collapse.

2.3.2. Indirect Time Synchronization

   When indirect time synchronization is used, the sender and each
   receiver must synchronize securely via an external time reference.
   Several possibilities exist:

   o sender and receivers can synchronize through an NTPv3 (Network
      Time Protocol version 3) [RFC1305] hierarchy of servers. The
      authentication mechanism of NTPv3 MUST be used in order to
      authenticate each NTP message individually. It prevents, for
      instance, an attacker from impersonating an NTP server;

   o they can synchronize through an NTPv4 (Network Time Protocol
      version 4) [NTP-NTPv4] hierarchy of servers. The Autokey security
      protocol of NTPv4 MUST be used in order to authenticate each NTP
      message individually;

   o they can synchronize through an SNTPv4 (Simple Network Time
     Protocol version 4) [RFC4330] hierarchy of servers. The
     authentication features of SNTPv4 must then be used. Note that
     TESLA only needs a loose (but secure) time synchronization, which
     is in line with the time synchronization service offered by SNTP;

   o they can synchronize through a GPS or Galileo (or similar) device
     that also provides a high precision time reference. Spoofing
     attacks on the GPS system have recently been reported. Depending
     on the use case, the security achieved will or will not be
     acceptable;

   o they can synchronize thanks to a dedicated hardware, embedded on
     each sender and receiver, that provides a clock with a time-drift
     that is negligible in front of the TESLA time accuracy
     requirements. This feature enables a device to synchronize its
     embedded clock with the official time reference from time to time
     (in an extreme case once, at manufacturing time), and then to
     remain autonomous for a duration that depends on the known maximum
     clock drift.

   A bidirectional channel is required by the NTP/SNTP schemes. On the
   opposite, with the GPS/Galileo and high precision clock schemes, no
   such assumption is made. In situations where ALC is used on purely
   unidirectional transport channels (Section 2.1), using the NTP/SNTP
   schemes is not possible. Another aspect is the scalability
   requirement of ALC, and to a lesser extent of NORM. From this point
   of view, the above mechanisms usually do not raise any problem,
   unlike the direct time synchronization schemes. Therefore, using
   indirect time synchronization can be a good choice. It should be
   noted that the NTP/SNTP schemes assume that each client trusts the
   sender and accepts aligning its NTP/SNTP configuration to that of the
   sender. If this assumption does not hold, the sender SHOULD offer an
   alternative solution.

   The details on how to calculate an upper bound of the lag of a
   receiver's clock with respect to the clock of the sender, D_t, are
   given in Section 2.4.2.

2.4. Determining the Delay Bounds

   Let us assume that a secure time synchronization has been set up.
   This section explains how to define the various timing parameters
   that are used during the authentication of received packets.

2.4.1. Delay Bound Calculation in Direct Time Synchronization Mode

   In direct time synchronization mode, synchronization between a
   receiver and the sender follows the following protocol [RFC4082]:

   o The receiver sends a direct time synchronization request message
      to the sender, that includes t_r, the receiver local time at the
      moment of sending (Section 4.2.2.1).

   o Upon receipt of this message, the sender records its local time,
      t_s, and sends to the receiver a direct time synchronization
      response that includes t_r (taken from the request) and t_s,
      signing this reply (Section 3.4.2).

   o Upon receiving this response, the receiver first verifies that he
      actually sent a request with t_r and then checks the signature.
      Then he calculates $D_t = t_s - t_r + S_{sr}$, where S_{sr} is an
      estimated bound of the clock drift between the sender and the
      receiver throughout the duration of the session. This document
      does not specify how S_{sr} is estimated.

   After this initial synchronization, at any point throughout the
   session, the receiver knows that: $T_s < T_r + D_t$, where T_s is the
   current time at the sender and T_r is the current time at the
   receiver.

2.4.2. Delay Bound Calculation in Indirect Time Synchronization Mode

   In indirect time synchronization, the sender and the receivers must
   synchronize indirectly using one or several time references.

2.4.2.1. Single Time Reference

   Let us assume that there is a single time reference.

   1. The sender calculates D^O_t, the upper bound of the lag of the
       sender's clock with respect to the time reference. This D^O_t
       value is then communicated to the receivers (Section 3.2.1).

   2. Similarly, a receiver R calculates D^R_t, the upper bound of the
       lag of the receiver's clock with respect to the time reference.

   3. Then, for receiver R, the overall upper bound of the lag of the
       receiver's clock with respect to the clock of the sender, D_t, is
       the sum: $D_t = D^O_t + D^R_t$.

   The D^O_t and D^R_t calculation depends on the time synchronization
   mechanism used (Section 2.3.2). In some cases, the synchronization
   scheme specifications provide these values. In other cases, these
   parameters can be calculated by means of a scheme similar to the one
   specified in Section 2.4.1, for instance, when synchronization is
   achieved via a group controller [RFC4082].

2.4.2.2. Multiple Time References

   Let us now assume that there are several time references (e.g.,
   several NTP/SNTP servers). The sender and receivers first
   synchronize with the various time references, independently. It
   results in D^O_t and D^R_t. Let D_err be an upper bound of the time
   error between all of the time references. Then, the overall value of
   D_t within receiver R is set to the sum: D_t = D^O_t + D^R_t + D_err.

   In some cases, the D_t value is part of the time synchronization
   scheme specifications. For instance, NTPv3 [RFC1305] defines
   algorithms that are "capable of accuracies in the order of a
   millisecond, even after extended periods when synchronization to
   primary reference sources has been lost". In practice, depending on
   the NTP server stratum, the accuracy might be a little bit worse. In
   that case, D_t = security_factor * (1ms + 1ms), where the
   security_factor is meant to compensate several sources of inaccuracy
   in NTP. The choice of the security_factor value is left to the
   implementer, depending on the target use case.

2.5. Cryptographic Parameter Values

   The F (resp. F') function output length is given by the n_p (resp.
   n_f) parameter. The n_p and n_f values depend on the PRF function
   chosen, as specified below:

```
            +-----------------------+--------------------+
            |       PRF name        |    n_p and n_f     |
            +-----------------------+--------------------+
            |       HMAC-SHA-1      | 160 bits (20 bytes) |
            |      HMAC-SHA-224     | 224 bits (28 bytes) |
            | HMAC-SHA-256 (default) | 256 bits (32 bytes) |
            |      HMAC-SHA-384     | 384 bits (48 bytes) |
            |      HMAC-SHA-512     | 512 bits (64 bytes) |
            +-----------------------+--------------------+
```

   The computing of regular MAC (resp. Group MAC) makes use of the n_m
   (resp. n_w) parameter, i.e., the length of the truncated output of
   the function. The n_m and n_w values depend on the MAC function
   chosen, as specified below:

```
+------------------------+--------------------+------------------+
|       MAC name         | n_m (regular MAC)  | n_w (Group MAC)  |
+------------------------+--------------------+------------------+
|        HMAC-SHA-1      |  80 bits (10 bytes) | 32 bits (4 bytes) |
|       HMAC-SHA-224     | 112 bits (14 bytes) | 32 bits (4 bytes) |
| HMAC-SHA-256 (default) | 128 bits (16 bytes) | 32 bits (4 bytes) |
|       HMAC-SHA-384     | 192 bits (24 bytes) | 32 bits (4 bytes) |
|       HMAC-SHA-512     | 256 bits (32 bytes) | 32 bits (4 bytes) |
+------------------------+--------------------+------------------+
```

3. Sender Operations

    This section describes the TESLA operations at a sender. For more
    information on the TESLA protocol and its principles, please refer to
    [RFC4082][Perrig04].

3.1. TESLA Parameters

3.1.1. Time Intervals

    The sender divides the time into uniform intervals of duration T_int.
    Time interval numbering starts at 0 and is incremented consecutively.
    The interval index MUST be stored in an unsigned 32-bit integer so
    that wrapping to 0 takes place only after 2^{32} intervals. For
    instance, if T_int is equal to 0.5 seconds, then wrapping takes place
    after approximately 68 years.

3.1.2. Key Chains

3.1.2.1. Principles

    The sender computes a one-way key chain of n_c = N+1 keys, and
    assigns one key from the chain to each interval, consecutively but in
    reverse order. Key numbering starts at 0 and is incremented
    consecutively, following the time interval numbering: K_0, K_1, ...,
    K_N.

    In order to compute this chain, the sender must first select a
    Primary Key, K_N, and a PRF function, f (Section 7, TESLA-PRF). The
    randomness of the Primary Key, K_N, is vital to the security and no
    one should be able to guess it.

    The function F is a one-way function that is defined as: $F(k) =
    f_k(0)$, where $f_k(0)$ is the result of the application of the PRF f to
    k and 0. When f is an HMAC (Section 7), k is used as the key, and 0
    as the message, using the algorithm described in [RFC2104].

Similarly, the function F' is a one-way function that is defined as:
F'(k) = f_k(1), where f_k(1) is the result of the application of the
same PRF f to k and 1.

The sender then computes all the keys of the chain, recursively,
starting with K_N, using: K_{i-1} = F(K_i). Therefore, K_i = F^{N-i}(K_N), where F^i(x) is the execution of function F with the
argument x, i times. The receiver can then compute any value in the
key chain from K_N, even if it does not have intermediate values
[RFC4082]. The key for MAC calculation can then be derived from the
corresponding K_i key by K'_i = F'(K_i).

The key chain has a finite length, N, which corresponds to a maximum
time duration of (N + 1) * T_int. The content delivery session has a
duration T_delivery, which may either be known in advance, or not. A
first solution consists in having a single key chain of an
appropriate length, so that the content delivery session finishes
before the end of the key chain, i.e., T_delivery <= (N + 1) * T_int.
But the longer the key chain, the higher the memory and computation
required to cope with it. Another solution consists in switching to
a new key chain, of the same length, when necessary [Perrig04].

3.1.2.2. Using Multiple Key Chains

When several key chains are needed, all of them MUST be of the same
length. Switching from the current key chain to the next one
requires that a commitment to the new key chain be communicated in a
secure way to the receiver. This can be done by using either an out-
of-band mechanism or an in-band mechanism. This document only
specifies the in-band mechanism.

```
< -------- old key chain --------- >||< -------- new key chain --...
+-----+-----+ .. +-----+-----+-----+||+-----+-----+-----+-----+-----+
   0     1    ..   N-2   N-1    N   ||  N+1   N+2   N+3   N+4   N+5
                                    ||
Key disclosures:                    ||
  N/A    N/A   .. K_N-4 K_N-3 K_N-2 ||  K_N-1   K_N  K_N+1 K_N+2 K_N+3
                 |                  ||              |                |
                 |< ------------- >||              |< ----------- >|
Additional key        F(K_N+1)      ||                     K_N
disclosures          (commitment to ||               (last key of the
(in parallel):        the new chain) ||                  old chain)
```
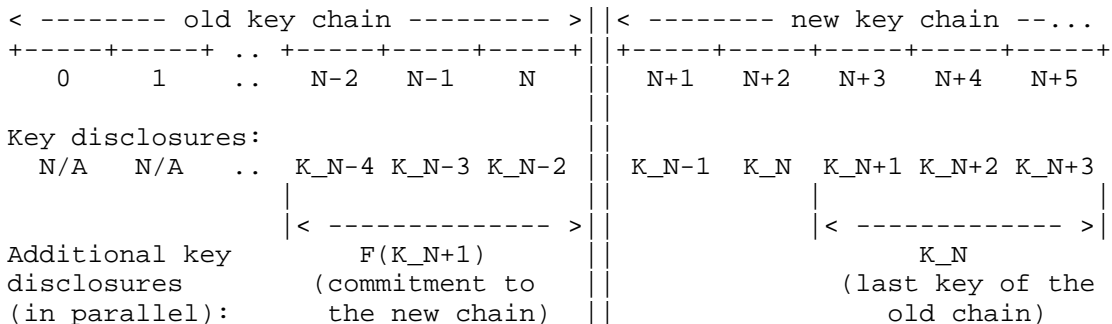
        Figure 1: Switching to the Second Key Chain with the In-Band
         Mechanism, Assuming That d=2, n_tx_newkcc=3, n_tx_lastkey=3

Figure 1 illustrates the switch to the new key chain, using the in-band mechanism. Let us say that the old key chain stops at K_N and the new key chain starts at K_{N+1} (i.e., F(K_{N+1}) and K_N are two different keys). Then, the sender includes the commitment F(K_{N+1}) to the new key chain into packets authenticated with the old key chain (see Section 3.4.5). This commitment SHOULD be sent during n_tx_newkcc time intervals before the end of the old key chain. Since several packets are usually sent during an interval, the sender SHOULD alternate between sending a disclosed key of the old key chain and the commitment to the new key chain. The details of how to alternate between the disclosure and commitment are out of the scope of this document.

The receiver will keep the commitment until the key K_{N+1} is disclosed, at interval N+1+d. Then, the receiver will be able to test the validity of that key by computing F(K_{N+1}) and comparing it to the commitment.

When the key chain is changed, it becomes impossible to recover a previous key from the old key chain. This is a problem if the receiver lost the packets disclosing the last key of the old key chain. A solution consists in re-sending the last key, K_N, of the old key chain (see Section 3.4.6). This SHOULD be done during n_tx_lastkey additional time intervals after the end of the time interval where K_N is disclosed. Since several packets are usually sent during an interval, the sender SHOULD alternate between sending a disclosed key of the new key chain, and the last key of the old key chain. The details of how to alternate between the two disclosures are out of the scope of this document.

In some cases, a receiver having experienced a very long disconnection might have lost the commitment of the new chain. Therefore, this receiver will not be able to authenticate any packet related to the new chain or any of the following ones. The only solution for this receiver to catch up consists in receiving an additional bootstrap information message. This can happen by waiting for the next periodic transmission (if sent in-band) or through an external mechanism (Section 3.2.1).

3.1.2.3. Values of the n_tx_lastkey and n_tx_newkcc Parameters

When several key chains and the in-band commitment mechanism are used, a sender MUST initialize the n_tx_lastkey and n_tx_newkcc parameters in such a way that no overlapping occurs. In other words, once a sender starts transmitting commitments for a new key chain, he MUST NOT send a disclosure for the last key of the old key chain any more. Therefore, the following property MUST be verified:

        d + n_tx_lastkey + n_tx_newkcc <= N + 1

    It is RECOMMENDED, for robustness purposes, that, once n_tx_lastkey
    has been chosen, then:

        n_tx_newkcc = N + 1 - n_tx_lastkey - d

    In other words, the sender starts transmitting a commitment to the
    following key chain immediately after having sent all the disclosures
    of the last key of the previous key chain. Doing so increases the
    probability that a receiver gets a commitment for the following key
    chain.

    In any case, these two parameters are sender specific and need not be
    transmitted to the receivers. Of course, as explained above, the
    sender alternates between the disclosure of a key of the current key
    chain and the commitment to the new key chain (or the last key of the
    old key chain).

3.1.2.4. The Particular Case of the Session Start

    Since a key cannot be disclosed before the disclosure delay, d, no
    key will be disclosed during the first d time intervals (intervals 0
    and 1 in Figure 1) of the session. To that purpose, the sender uses
    the Authentication Tag without Key Disclosure, Section 3.4.4. The
    following key chains, if any, are not concerned since they will
    disclose the last d keys of the previous chain.

3.1.2.5. Managing Silent Periods

    An ALC or NORM sender may stop transmitting packets for some time.
    For instance, it can be the end of the session and all packets have
    already been sent, or the use case may consist in a succession of
    busy periods (when fresh objects are available) followed by silent
    periods. In any case, this is an issue since the authentication of
    the packets sent during the last d intervals requires that the
    associated keys be disclosed, which will take place during d
    additional time intervals.

    To solve this problem, it is recommended that the sender transmit
    empty packets (i.e., without payload) containing the TESLA EXT_AUTH
    Header Extension along with a Standard Authentication Tag during at
    least d time intervals after the end of the regular ALC or NORM
    packet transmissions. The number of such packets and the duration
    during which they are sent must be sufficient for all receivers to
    receive, with a high probability, at least one packet disclosing the
    last useful key (i.e., the key used for the last non-empty packet
    sent).

3.1.3. Time Interval Schedule

   The sender must determine the following parameters:

   o T_0, the start time corresponding to the beginning of the session,
      i.e., the beginning of time interval 0 (in NTP timestamp format);

   o T_int, the interval duration (in milliseconds), usually ranging
      from 100 milliseconds to 1 second;

   o d, the key disclosure delay (in number of intervals). It is the
      time to wait before disclosing a key;

   o N, the length of a key chain.

   The correct choice of T_int, d, and N is crucial for the efficiency
   of the scheme. For instance, a T_int * d product that is too long
   will cause excessive delay in the authentication process. A T_int *
   d product that is too short prevents many receivers from verifying
   packets. An N * T_int product that is too small will cause the
   sender to switch too often to new key chains. An N that is too long
   with respect to the expected session duration (if known) will require
   the sender to compute too many useless keys. Sections 3.2 and 3.6 of
   [RFC4082] give general guidelines for initializing these parameters.

   The T_0, T_int, d, and N parameters MUST NOT be changed during the
   lifetime of the session. This restriction is meant to prevent
   introducing vulnerabilities. For instance, if a sender was
   authorized to change the key disclosure schedule, a receiver that did
   not receive the change notification would still believe in the old
   key disclosure schedule, thereby creating vulnerabilities [RFC4082].

3.1.4. Timing Parameters

   In indirect time synchronization mode, the sender must determine the
   following parameter:

   o D^O_t, the upper bound of the lag of the sender's clock with
      respect to the time reference.

   The D^O_t parameter MUST NOT be changed during the lifetime of the
   session.

3.2. TESLA Signaling Messages

   At a sender, TESLA produces two types of signaling information:

   o The bootstrap information: it can be either sent out-of-band or
      in-band. In the latter case, a digitally signed packet contains
      all the information required to bootstrap TESLA at a receiver;

   o The direct time synchronization response, which enables a receiver
      to finish a direct time synchronization.

3.2.1. Bootstrap Information

   In order to initialize the TESLA component at a receiver, the sender
   must communicate some key information in a secure way. This
   information can be sent in-band or out-of-band, as discussed in
   Section 2.2. In this section, we only consider the in-band scheme.

   The TESLA bootstrap information message MUST be digitally signed
   (Section 3.3.2). The goal is to enable a receiver to check the
   packet source and packet integrity. Then, the bootstrap information
   can be:

   o unicast to a receiver during a direct time synchronization
      request/response exchange;

   o broadcast to all receivers. This is typically the case in
      indirect time synchronization mode. It can also be used in direct
      time synchronization mode, for instance, when a large number of
      clients arrive at the same time, in which case it is more
      efficient to answer globally.

   Let us consider situations where the bootstrap information is
   broadcast. This message should be broadcast at the beginning of the
   session, before data packets are actually sent. This is particularly
   important with ALC or NORM sessions in "push" mode, when all clients
   join the session in advance. For improved reliability, bootstrap
   information might be sent a certain number of times.

   A periodic broadcast of the bootstrap information message could also
   be useful when:

   o the ALC session uses an "on-demand" mode, clients arriving at
      their own discretion;

   o some clients experience an intermittent connectivity. This is
      particularly important when several key chains are used in an ALC
      or NORM session, since there is a risk that a receiver loses all
      the commitments to the new key chain.

   A balance must be found between the signaling overhead and the
   maximum initial waiting time at the receiver before starting the
   delayed authentication process. A period of a few seconds for the
   transmission of this bootstrap information is often a reasonable
   value.

3.2.2. Direct Time Synchronization Response

   In direct time synchronization, upon receipt of a synchronization
   request, the sender records its local time, t_s, and sends a response
   message that contains both t_r and t_s (Section 2.4.1). This message
   is unicast to the receiver. This direct time synchronization
   response message MUST be digitally signed in order to enable a
   receiver to check the packet source and packet integrity
   (Section 3.3.2). The receiver MUST also be able to associate this
   response and his request, which is the reason why t_r is included in
   the response message.

3.3. TESLA Authentication Information

   At a sender, TESLA produces three types of security tags:

   o an authentication tag, in case of data packets, and which contains
      the MAC of the packet;

   o a digital signature, in case of one of the two TESLA signaling
      packets, namely a bootstrap information message or a direct time
      synchronization response; and

   o an optional group authentication tag, that can be added to all the
      packets to mitigate attacks coming from outside of the group.

   Because of interdependencies, their computation MUST follow a strict
   order:

   o first of all, compute the authentication tag (with data packet) or
      the digital signature (with signaling packet);

   o finally, compute the Group Mac.

3.3.1. Authentication Tags

   All the data packets sent MUST have an authentication tag containing:

   o the interval index, i, which is also the index of the key used for
      computing the MAC of this packet;

   o the MAC of the message: MAC(K'_i, M), where K'_i=F'(K_i);

   o either a disclosed key (which belongs to the current key chain or
      the previous key chain), or a commitment to a new key chain, or no
      key at all.

   The computation of MAC(K'_i, M) MUST include the ALC or NORM header
   (with the various header extensions) and the payload (when
   applicable). The UDP/IP headers MUST NOT be included. During this
   computation, the "MAC(K'_i, M)" field of the authentication tag MUST
   be set to 0.

3.3.2. Digital Signatures

   The bootstrap information message (with the in-band bootstrap scheme)
   and direct time synchronization response message (with the indirect
   time synchronization scheme) both need to be signed by the sender.
   These two messages contain a "Signature" field to hold the digital
   signature. The bootstrap information message also contains the
   "Signature Encoding Algorithm", the "Signature Cryptographic
   Function", and the "Signature Length" fields that enable a receiver
   to process the "Signature" field. Note that there are no such
   "Signature Encoding Algorithm", "Signature Cryptographic Function",
   and "Signature Length" fields in the case of a direct time
   synchronization response message since it is assumed that these
   parameters are already known (i.e., the receiver either received a
   bootstrap information message before or these values have been
   communicated out-of-band).

   Several "Signature Encoding Algorithms" can be used, including
   RSASSA-PKCS1-v1_5, the default, and RSASSA-PSS (Section 7). With
   these encodings, SHA-256 is the default "Signature Cryptographic
   Function".

   The computation of the signature MUST include the ALC or NORM header
   (with the various header extensions) and the payload when applicable.
   The UDP/IP headers MUST NOT be included. During this computation,
   the "Signature" field MUST be set to 0 as well as the optional Group
   MAC, when present, since this Group MAC is calculated later.

More specifically, from [RFC4359]: Digital signature generation is
performed as described in [RFC3447], Section 8.2.1 for RSASSA-PKCS1-
v1_5 and Section 8.1.1 for RSASSA-PSS. The authenticated portion of
the packet is used as the message M, which is passed to the signature
generation function. The signer's RSA private key is passed as K.
In summary, (when SHA-256 is used), the signature generation process
computes a SHA-256 hash of the authenticated packet bytes, signs the
SHA-256 hash using the private key, and encodes the result with the
specified RSA encoding type. This process results in a value S,
which is the digital signature to be included in the packet.

With RSASSA-PKCS1-v1_5 and RSASSA-PSS signatures, the size of the
signature is equal to the "RSA modulus", unless the "RSA modulus" is
not a multiple of 8 bits. In that case, the signature MUST be
prepended with between 1 and 7 bits set to zero such that the
signature is a multiple of 8 bits [RFC4359]. The key size, which in
practice is also equal to the "RSA modulus", has major security
implications. [RFC4359] explains how to choose this value depending
on the maximum expected lifetime of the session. This choice is out
of the scope of this document.

3.3.3. Group MAC Tags

An optional Group MAC can be used to mitigate Denial-of-Service (DoS)
attacks coming from attackers that are not group members [RFC4082].
This feature assumes that a group key, K_g, is shared by the sender
and all receivers. When the attacker is not a group member, the
benefits of adding a Group MAC to every packet sent are threefold:

o a receiver can immediately drop faked packets, without having to
   wait for the disclosure delay, d;

o a sender can immediately drop faked direct time synchronization
   requests, and avoid checking the digital signature, a computation
   intensive task;

o a receiver can immediately drop faked direct time synchronization
   response and bootstrap messages, without having to verify the
   digital signature, a computation-intensive task.

The computation of the Group MAC, MAC(K_g, M), MUST include the ALC
or NORM header (with the various header extensions) and the payload
when applicable. The UDP/IP headers MUST NOT be included. During
this computation, the "Group MAC" field MUST be set to 0. However,
the digital signature (e.g., of a bootstrap message) and the "MAC"
fields (e.g., of an authentication tag), when present, MUST have been

calculated since they are included in the Group MAC calculation
itself. Then, the sender truncates the MAC output to keep the n_w
most significant bits and stores the result in the "Group MAC" field.

This scheme features a few limits:

o it is of no help if a group member (who knows K_g) impersonates
   the sender and sends forged messages to other receivers;

o it requires an additional MAC computing for each packet, both at
   the sender and receiver sides;

o it increases the size of the TESLA authentication headers. In
   order to limit this problem, the length of the truncated output of
   the MAC, n_w, SHOULD be kept small (e.g., 32 bits) (see [RFC3711],
   Section 9.5). As a side effect, the authentication service is
   significantly weakened: the probability of any forged packet being
   successfully authenticated becomes one in 2^{32}. Since the Group
   MAC check is only a pre-check that must be followed by the
   standard TESLA authentication check, this is not considered to be
   an issue.

For a given use case, the benefits brought by the Group MAC must be
balanced against these limitations.

Note that the Group MAC function can be different from the TESLA MAC
function (e.g., it can use a weaker but faster MAC function). Note
also that the mechanism by which the group key, K_g, is communicated
to all group members, and perhaps periodically updated, is out of the
scope of this document.

3.4. Format of TESLA Messages and Authentication Tags

This section specifies the format of the various kinds of TESLA
messages and authentication tags sent by the session's sender.
Because these TESLA messages are carried as EXT_AUTH Header
Extensions of the ALC or NORM packets (Section 5), the following
formats do not start on 32-bit word boundaries.

3.4.1. Format of a Bootstrap Information Message

   When bootstrap information is sent in-band, the following message is
   used:

```
     0                   1                   2                   3
     0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                                            +-+-+-+-+-+-+-+-+  ---
                                            | V |resvd|S|G|A|   ^
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  |
    |       d        |    PRF Type   | MAC Func Type |Gr MAC Fun Type|  | f
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  | i
    |   SigEncAlgo   | SigCryptoFunc |       Signature Length        |  | x
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  | e
    |           Reserved            |             T_int             |  | d
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  |
    |                                                               |  | l
    +                 T_0 (NTP timestamp format)                    +  | e
    |                                                               |  | n
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  | g
    |                    N (Key Chain Length)                       |  | t
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  | h
    |                   Current Interval Index i                    |  v
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  ---
    |                                                               |
    ~             Current Key Chain Commitment   +-+-+-+-+-+-+-+-+
    |                                            |     Padding      |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                                                               |
    +                                                               +
    ~                          Signature                            ~
    +                                            +-+-+-+-+-+-+-+-+
    |                                            |     Padding      |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |P|                                                             |
    +-+       D^O_t Extension (optional, present if A==1)           +
    |      (NTP timestamp diff, positive if P==1, negative if P==0) |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    ~                       Group MAC (optional)                    ~
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

                  Figure 2: Bootstrap Information Format

The format of the bootstrap information is depicted in Figure 2. The
fields are:

"V" (Version) field (2 bits):

   The "V" field contains the version number of the protocol. For
   this specification, the value of 0 MUST be used.

"Reserved" field (3 bits):

   This is a reserved field that MUST be set to zero in this
   specification.

"S" (Single Key Chain) flag (1 bit):

   The "S" flag indicates whether this TESLA session is restricted to
   a single key chain (S==1) or relies on one or multiple key chains
   (S==0).

"G" (Group MAC Present) flag (1 bit):

   The "G" flag indicates whether the Group MAC feature is used
   (G==1) or not (G==0). When it is used, a "Group MAC" field is
   added to all the packets containing a TESLA EXT_AUTH Header
   Extension (including this bootstrap message).

"A" flag (1 bit):

   The "A" flag indicates whether the "P" flag and "D^O_t" fields are
   present (A==1) or not (A==0). In indirect time synchronization
   mode, A MUST be equal to 1 since these fields are needed.

"d" field (8 bits):

   "d" is an unsigned integer that defines the key disclosure delay
   (in number of intervals). d MUST be greater than or equal to 2.

"PRF Type" field (8 bits):

   The "PRF Type" is the reference number of the f function used to
   derive the F (for key chain) and F' (for MAC keys) functions
   (Section 7).

"MAC Function Type" field (8 bits):

   The "MAC Function Type" is the reference number of the function
   used to compute the MAC of the packets (Section 7).

"Group MAC Function Type" field (8 bits):

   When G==1, this field contains the reference number of the
   cryptographic MAC function used to compute the Group MAC
   (Section 7). When G==0, this field MUST be set to zero.

"Signature Encoding Algorithm" field (8 bits):

   The "Signature Encoding Algorithm" is the reference number
   (Section 7) of the digital signature used to authenticate this
   bootstrap information and included in the "Signature" field.

"Signature Cryptographic Function" field (8 bits):

   The "Signature Cryptographic Function" is the reference number
   (Section 7) of the cryptographic function used within the digital
   signature.

"Signature Length" field (16 bits):

   The "Signature Length" is an unsigned integer that indicates the
   "Signature" field size in bytes in the "Signature Extension"
   field. This is also the signature key length, since both
   parameters are equal.

"Reserved" fields (16 bits):

   This is a reserved field that MUST be set to zero in this
   specification.

"T_int" field (16 bits):

   "T_int" is an unsigned 16-bit integer that defines the interval
   duration (in milliseconds).

"T_0" field (64 bits):

   "T_0" is a timestamp in NTP timestamp format that indicates the
   beginning of the session, i.e., the beginning of time interval 0.

"N" field (32 bits):

   "N" is an unsigned integer that indicates the key chain length.
   There are N + 1 keys per chain.

"i" (Interval Index of K_i) field (32 bits):

   "i" is an unsigned integer that indicates the current interval
   index when this bootstrap information message is sent.

"Current Key Chain Commitment" field (variable size, padded if
necessary for 32-bit word alignment):

   "Key Chain Commitment" is the commitment to the current key chain,
   i.e., the key chain corresponding to interval i. For instance,
   with the first key chain, this commitment is equal to F(K_0), with
   the second key chain, this commitment is equal to F(K_{N+1}),
   etc.). If need be, this field is padded (with 0) up to a multiple
   of 32 bits.

"Signature" field (variable size, padded if necessary for 32-bit word
alignment):

   The "Signature" field is mandatory. It contains a digital
   signature of this message, as specified by the encoding algorithm,
   cryptographic function, and key length parameters. If the
   signature length is not a multiple of 32 bits, this field is
   padded with 0.

"P" flag (optional, 1 bit if present):

   The "P" flag is optional and only present if the "A" flag is equal
   to 1. It is only used in indirect time synchronization mode.
   This flag indicates whether the D^{O}_t NTP timestamp difference is
   positive (P==1) or negative (P==0).

"D^O_t" field (optional, 63 bits if present):

   The "D^{O}_t" field is optional and only present if the "A" flag is
   equal to 1. It is only used in indirect time synchronization
   mode. It is the upper bound of the lag of the sender's clock with
   respect to the time reference. When several time references are
   specified (e.g., several NTP servers), then D^{O}_t is the maximum
   upper bound of the lag with each time reference. D^{O}_t is
   composed of two unsigned integers, as with NTP timestamps: the
   first 31 bits give the time difference in seconds and the
   remaining 32 bits give the sub-second time difference.

"Group MAC" field (optional, variable length, multiple of 32 bits):

   This field contains the Group MAC, calculated with the group key,
   K_g, shared by all group members. The field length, in bits, is
   given by n_w, which is known once the Group MAC function type is
   known (Section 7).

Note that the first byte and the following seven 32-bit words are
mandatory fixed-length fields. The "Current Key Chain Commitment"
and "Signature" fields are mandatory but variable-length fields. The
remaining "D^O_t" and "Group MAC" fields are optional.

In order to prevent attacks, some parameters MUST NOT be changed
during the lifetime of the session (Sections 3.1.3 and 3.1.4). The
following table summarizes the parameter's status:

```
+-------------------------+---------------------------------------+
|        Parameter        |                Status                 |
+-------------------------+---------------------------------------+
|            V            |      set to 0 in this specification    |
|            S            |       static (during whole session)   |
|            G            |       static (during whole session)   |
|            A            |       static (during whole session)   |
|           T_O           |       static (during whole session)   |
|          T_int          |       static (during whole session)   |
|            d            |       static (during whole session)   |
|            N            |       static (during whole session)   |
|    D^O_t (if present)   |       static (during whole session)   |
|        PRF Type         |       static (during whole session)   |
|    MAC Function Type    |       static (during whole session)   |
|   Signature Encoding    |       static (during whole session)   |
|        Algorithm        |                                       |
|    Signature Crypto.    |       static (during whole session)   |
|        Function         |                                       |
|    Signature Length     |       static (during whole session)   |
|   Group MAC Func.  Type |       static (during whole session)   |
|            i            | dynamic (related to current key chain)|
|           K_i           | dynamic (related to current key chain)|
|        signature        |       dynamic, packet dependent       |
|  Group MAC (if present) |       dynamic, packet dependent       |
+-------------------------+---------------------------------------+
```

3.4.2. Format of a Direct Time Synchronization Response

```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                                                   +-+-+-+-+-+-+-+-+
                                                   |    Reserved   |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   +                     t_s (NTP timestamp)                       +
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   +                     t_r (NTP timestamp)                       +
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   +                                                               +
   ~                         Signature                             ~
   +                                               +-+-+-+-+-+-+-+-+
   |                                               |    Padding    |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   ~                      Group MAC (optional)                     ~
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

           Figure 3: Format of a Direct Time Synchronization Response

   The response to a direct time synchronization request contains the
   following information:

   "Reserved" field (8 bits):

      This is a reserved field that MUST be set to zero in this
      specification.

   "t_s" (NTP timestamp, 64 bits):

      "t_s" is a timestamp in NTP timestamp format that corresponds to
      the sender local time value when receiving the direct time
      synchronization request message.

   "t_r" (NTP timestamp, 64 bits):

      "t_r" is a timestamp in NTP timestamp format that contains the
      receiver local time value received in the direct time
      synchronization request message.

"Signature" field (variable size, padded if necessary for 32-bit word
alignment):

   The "Signature" field is mandatory. It contains a digital
   signature of this message, as specified by the encoding algorithm,
   cryptographic function, and key length parameters communicated in
   the bootstrap information message (if applicable) or out-of-band.
   If the signature length is not a multiple of 32 bits, this field
   is padded with 0.

"Group MAC" field (optional, variable length, multiple of 32 bits):

   This field contains the Group MAC, calculated with the group key,
   K_g, shared by all group members. The field length, in bits, is
   given by n_w, which is known once the Group MAC function type is
   known (Section 7).

3.4.3. Format of a Standard Authentication Tag

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                                                +-+-+-+-+-+-+-+-+
                                                |   Reserved    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    i (Interval Index of K'_i)                 |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
~                    Disclosed Key K_{i-d}                      ~
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
~                    MAC(K'_i, M)               +-+-+-+-+-+-+-+-+
|                                               |   Padding     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
~                    Group MAC (optional)                       ~
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
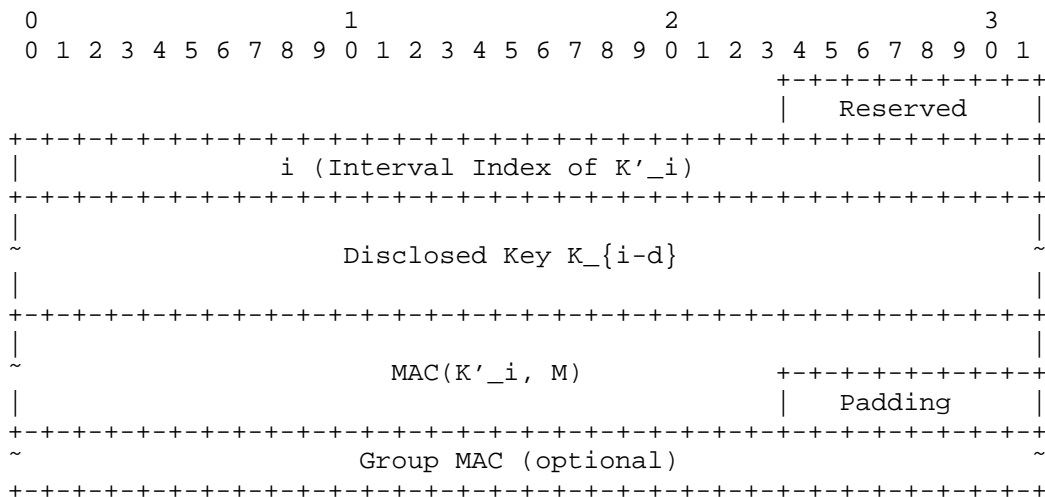
          Figure 4: Format of the Standard Authentication Tag

A Standard Authentication Tag is composed of the following fields:

"Reserved" field (8 bits):

   The "Reserved" field is not used in the current specification and
   MUST be set to zero by the sender.

"i" (Interval Index) field (32 bits):

   "i" is the interval index associated with the key (K'_i) used to
   compute the MAC of this packet.

"Disclosed Key" (variable size, non padded):

   The "Disclosed Key" is the key used for interval i-d: K_{i-d}.
   There is no padding between the "Disclosed Key" and "MAC(K'_i, M)"
   fields, and the latter MAY not start on a 32-bit boundary,
   depending on the n_p parameter.

"MAC(K'_i, M)" (variable size, padded if necessary for 32-bit word
alignment):

   "MAC(K'_i, M)" is the truncated message authentication code of the
   current packet. Only the n_m most significant bits of the MAC
   output are kept [RFC2104].

"Group MAC" field (optional, variable length, multiple of 32 bits):

   This field contains the Group MAC, calculated with a group key,
   K_g, shared by all group members. The field length is given by
   n_w, in bits.

Note that because a key cannot be disclosed before the disclosure
delay, d, the sender MUST NOT use this tag during the first d
intervals of the session: {0 .. d-1} (inclusive). Instead, the
sender MUST use an Authentication Tag without Key Disclosure.

3.4.4. Format of an Authentication Tag without Key Disclosure

   The Authentication Tag without Key Disclosure is meant to be used in
   situations where a high number of packets are sent in a given time
   interval. In such a case, it can be advantageous to disclose the
   K_{i-d} key only in a subset of the packets sent, using a Standard
   Authentication Tag, and to use the shortened version that does not
   disclose the K_{i-d} key in the remaining packets. It is left to the
   implementer to decide how many packets should disclose the K_{i-d}
   key. This Authentication Tag without Key Disclosure MUST also be
   used during the first d intervals: {0 .. d-1} (inclusive).

```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                                                   +-+-+-+-+-+-+-+-+
                                                   |    Reserved   |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                   i (Interval Index of K'_i)                  |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                               |
   ~                   MAC(K'_i, M)                +-+-+-+-+-+-+-+-+
   |                                               |    Padding    |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   ~                   Group MAC (optional)                        ~
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
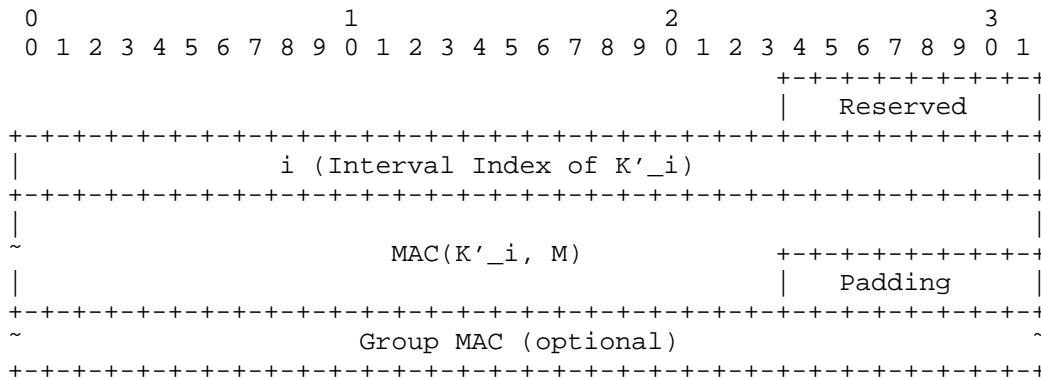
         Figure 5: Format of the Authentication Tag without Key Disclosure

3.4.5. Format of an Authentication Tag with a "New Key Chain"
        Commitment

   During the last n_tx_newkcc intervals of the current key chain, the
   sender SHOULD send commitments to the next key chain. This is done
   by replacing the disclosed key of the Authentication Tag with a New
   Key Chain Commitment, $F(K_{N+1})$ (or $F(K_{2N+2})$) in case of a switch
   between the second and third key chains, etc.) Figure 6 shows the
   corresponding format.

   Note that since there is no padding between the "$F(K_{N+1})$" and
   "MAC(K'_i, M)" fields, the latter MAY not start on a 32-bit boundary,
   depending on the n_p parameter.

```
        0                   1                   2                   3
        0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                                                +-+-+-+-+-+-+-+-+
                                                |    Reserved   |
       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
       |                  i (Interval Index of K'_i)                   |
       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
       |                                                               |
       ~              New Key Commitment F(K_{N+1})                    ~
       |                                                               |
       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
       |                                                               |
       ~                    MAC(K'_i, M)               +-+-+-+-+-+-+-+-+
       |                                               |    Padding    |
       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
       ~                    Group MAC (optional)                       ~
       +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
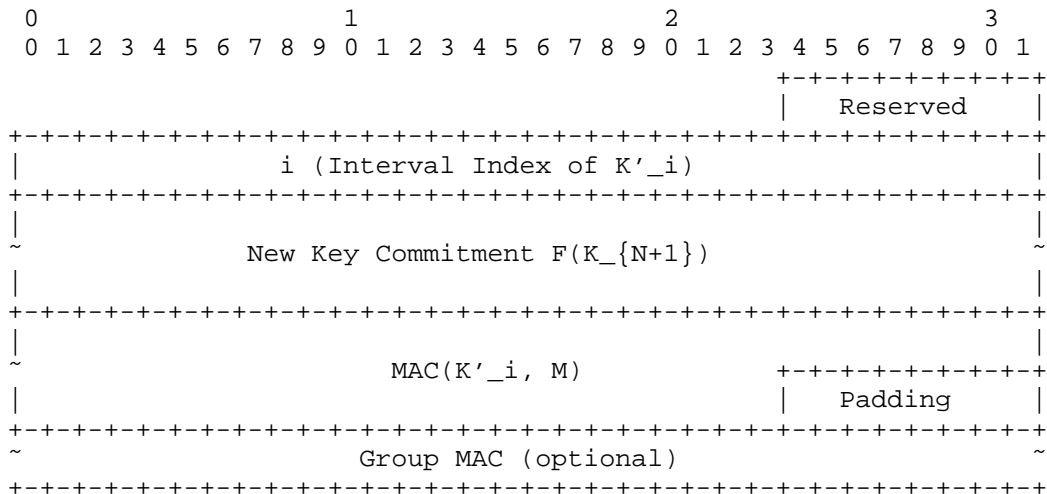
               Figure 6: Format of the Authentication Tag
                     with a New Key Chain Commitment

3.4.6. Format of an Authentication Tag with a "Last Key of Old Chain"
        Disclosure

   During the first n_tx_lastkey intervals of the new key chain after
   the disclosing interval, d, the sender SHOULD disclose the last key
   of the old key chain. This is done by replacing the disclosed key of
   the Authentication Tag with the Last Key of the Old Chain, K_N (or
   K_{2N+1} in case of a switch between the second and third key chains,
   etc.). Figure 7 shows the corresponding format.

   Note that since there is no padding between the "K_N" and "MAC(K'_i,
   M)" fields, the latter MAY not start on a 32-bit boundary, depending
   on the n_p parameter.

```
         0                   1                   2                   3
         0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                                                 +-+-+-+-+-+-+-+-+
                                                 |    Reserved   |
        +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
        |                  i (Interval Index of K'_i)                  |
        +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
        |                                                              |
        ~                  Last Key of Old Chain, K_N                  ~
        |                                                              |
        +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
        |                                                              |
        ~                       MAC(K'_i, M)          +-+-+-+-+-+-+-+-+
        |                                             |    Padding    |
        +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
        ~                    Group MAC (optional)                     ~
        +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
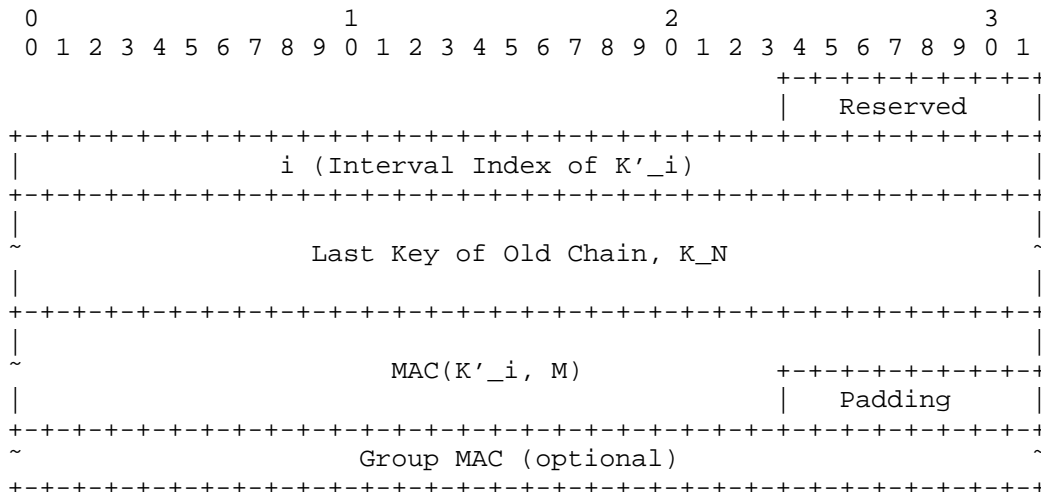
                  Figure 7: Format of the Authentication Tag
                   with an Old Chain Last Key Disclosure

4. Receiver Operations

    This section describes the TESLA operations at a receiver.

4.1. Verification of the Authentication Information

    This section details the computation steps required to verify each of
    the three possible authentication information of an incoming packet.
    The verification MUST follow a strict order:

    o first of all, if the Group MAC is present and if the session uses
       this feature (e.g., if the G bit is set in the bootstrap
       information message), then verify the Group MAC. A packet that
       does not contain a Group MAC tag, whereas the session uses this
       feature, MUST be dropped immediately. On the opposite, if a
       packet contains a Group MAC tag whereas the session does not use
       this feature, this tag MUST be ignored;

    o then, verify the digital signature (with TESLA signaling packets)
       or enter the TESLA authentication process (with data packets).

4.1.1. Processing the Group MAC Tag

    Upon receiving a packet containing a Group MAC tag, the receiver
    recomputes the Group MAC and compares it to the value carried in the
    packet. If the check fails, the packet MUST be dropped immediately.

More specifically, recomputing the Group MAC requires saving the
value of the "Group MAC" field, setting this field to 0, and doing
the same computation as a sender does (see Section 3.3.3).

4.1.2. Processing the Digital Signature

Upon receiving a packet containing a digital signature, the receiver
verifies the signature as follows.

The computation of the signature MUST include the ALC or NORM header
(with the various header extensions) and the payload when applicable.
The UDP/IP headers MUST NOT be included. During this computation,
the "Signature" field MUST be set to 0 as well as the optional Group
MAC, when present.

From [RFC4359]: Digital signature verification is performed as
described in [RFC3447], Section 8.2.2 (RSASSA-PKCS1-v1_5) and
[RFC3447], Section 8.1.2 (RSASSA-PSS). Upon receipt, the digital
signature is passed to the verification function as S. The
authenticated portion of the packet is used as the message M, and the
RSA public key is passed as (n, e). In summary (when SHA-256 is
used), the verification function computes a SHA-256 hash of the
authenticated packet bytes, decrypts the SHA-256 hash in the packet,
and validates that the appropriate encoding was applied. The two
SHA-256 hashes are compared, and if they are identical the validation
is successful.

It is assumed that the receivers have the possibility to retrieve the
sender's public key required to check this digital signature
(Section 2.2). This document does not specify how the public key of
the sender is communicated reliably and in a secure way to all
possible receivers.

4.1.3. Processing the Authentication Tag

When a receiver wants to authenticate a packet using an
authentication tag and when he has the key for the associated time
interval (i.e., after the disclosing delay, d), the receiver
recomputes the MAC and compares it to the value carried in the
packet. If the check fails, the packet MUST be immediately dropped.

More specifically, recomputing the MAC requires saving the value of
the "MAC" field, setting this field to 0, and doing the same
computation as a sender does (see Section 3.3.1).

4.2. Initialization of a Receiver

   A receiver MUST be initialized before being able to authenticate the
   source of incoming packets. This can be done by an out-of-band
   mechanism or an in-band mechanism (Section 2.2). Let us focus on the
   in-band mechanism. Two actions must be performed:

   o receive and process a bootstrap information message, and

   o calculate an upper bound of the sender's local time. To that
      purpose, the receiver must perform time synchronization.

4.2.1. Processing the Bootstrap Information Message

   A receiver must first receive a packet containing the bootstrap
   information, digitally signed by the sender. Once the bootstrap
   information has been authenticated (see Section 4.1), the receiver
   can initialize its TESLA component. The receiver MUST then ignore
   the following bootstrap information messages, if any. There is an
   exception though: when a new key chain is used and if a receiver
   missed all the commitments for this new key chain, then this receiver
   MUST process one of the future bootstrap information messages (if
   any) in order to be able to authenticate the incoming packets
   associated to this new key chain.

   Before TESLA has been initialized, a receiver MUST discard incoming
   packets other than the bootstrap information message and direct time
   synchronization response.

4.2.2. Performing Time Synchronization

   First of all, the receiver must know whether the ALC or NORM session
   relies on direct or indirect time synchronization. This information
   is communicated by an out-of-band mechanism (for instance, when
   describing the various parameters of an ALC or NORM session). In
   some cases, both mechanisms might be available and the receiver can
   choose the preferred technique.

4.2.2.1. Direct Time Synchronization

   In the case of a direct time synchronization, a receiver MUST
   synchronize with the sender. To that purpose, the receiver sends a
   direct time synchronization request message. This message includes
   the local time (in NTP timestamp format) at the receiver when sending
   the message. This timestamp will be copied in the sender's response
   for the receiver to associate the response to the request.

The direct time synchronization request message format is the
following:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                      t_r (NTP timestamp)                      +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
~                      Group MAC (optional)                     ~
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
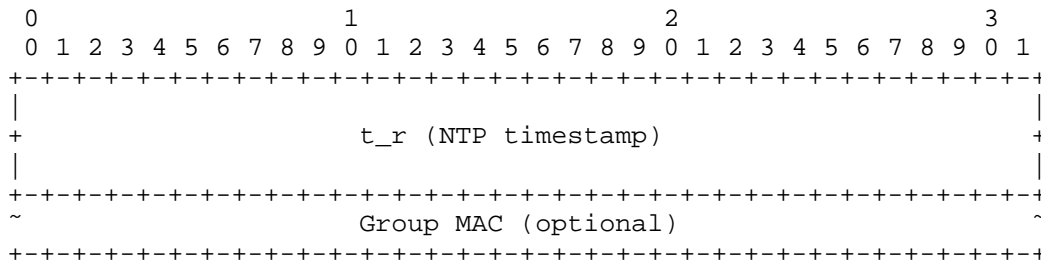
Figure 8: Format of a Direct Time Synchronization Request

The direct time synchronization request (Figure 8) contains the
following information:

"t_r" (NTP timestamp, 64 bits):

   "t_r" is a timestamp in NTP timestamp format that contains the
   receiver local time value when sending this direct time
   synchronization request message;

"Group MAC" field (optional, variable length, multiple of 32 bits):

   This field contains the Group MAC, calculated with the group key,
   K_g, shared by all group members. The field length, in bits, is
   given by n_w, which is known once the Group MAC function type is
   known (Section 7).

The receiver then awaits a response message (Section 3.4.2). Upon
receiving this message, the receiver:

   checks that this response relates to the request, by comparing the
   "t_r" fields;

   checks the Group MAC if present;

   checks the signature;

   retrieves the t_s value and calculates D_t (Section 2.4.1).

Note that in an ALC session, the direct time synchronization request
message is sent to the sender by an out-of-band mechanism that is not
specified by the current document.

4.2.2.2. Indirect Time Synchronization

   With the indirect time synchronization method, the sender MAY provide
   out-of-band the URL or IP address of the NTP server(s) he trusts
   along with an OPTIONAL certificate for each NTP server. When several
   NTP servers are specified, a receiver MUST choose one of them. This
   document does not specify how the choice is made, but for the sake of
   scalability, the clients SHOULD NOT use the same server if several
   possibilities are offered. The NTP synchronization between the NTP
   server and the receiver MUST be authenticated, either using the
   certificate provided by the server or another certificate the client
   may obtain for this NTP server.

   Then the receiver computes the time offset between itself and the NTP
   server chosen. Note that the receiver does not need to update the
   local time, (which often requires root privileges), computing the
   time offset is sufficient.

   Since the offset between the server and the time reference, $D\hat{}O\_t$, is
   indicated in the bootstrap information message (or communicated out-
   of-band), the receiver can now calculate an upper bound of the
   sender's local time (Section 2.4.2).

   Note that this scenario assumes that each client trusts the sender
   and accepts aligning its NTP configuration to that of the sender,
   using one of the NTP server(s) suggested. If this assumption does
   not hold, the client MUST NOT use the NTP indirect time
   synchronization method (Section 2.3.2).

4.3. Authentication of Received Packets

   The receiver can now authenticate incoming packets (other than
   bootstrap information and direct time synchronization response
   packets). To that purpose, he MUST follow different steps (see
   [RFC4082], Section 3.5):

   1. The receiver parses the different packet headers. If none of the
       four TESLA authentication tags are present, the receiver MUST
       discard the packet. If the session is in "Single Key Chain" mode
       (e.g., when the "S" flag is set in the bootstrap information
       message), then the receiver MUST discard any packet containing an
       Authentication Tag with a New Key Chain Commitment or an
       Authentication Tag with a Last Key of Old Chain Disclosure.

   2. Safe packet test: When the receiver receives packet P_j, it first
       records the local time T at which the packet arrived. The
       receiver then computes an upper bound t_j on the sender's clock
       at the time when the packet arrived: $t\_j = T + D\_t$. The receiver

then computes the highest interval the sender could possibly be
in: highest_i = floor((t_j - T_0) / T_int). He also retrieves
the "i" interval index from the authentication tag. The receiver
can now proceed with the "safe packet" test. If highest_i < i +
d, then the sender is not yet in the interval during which it
discloses the key K_i. The packet is safe (but not necessarily
authentic). If the test fails, the packet is unsafe, and the
receiver MUST discard the packet.

3. Group MAC test: if the optional Group MAC tag is present and if
   the session uses this feature, then verify the Group MAC
   (Section 4.1.1). If the verification fails, the packet MUST be
   immediately dropped. A packet that does not contain a Group MAC
   tag whereas the session uses this feature MUST be immediately
   dropped. On the opposite, if a packet contains a Group MAC tag
   whereas the session does not use this feature, this tag MUST be
   ignored.

4. Disclosed Key processing: When the packet discloses a key (i.e.,
   with a Standard Authentication Tag, or with an Authentication Tag
   with a Last Key of Old Chain Disclosure), the following tests are
   performed:

   * New key index test: the receiver checks whether a legitimate
      key already exists with the same index (i.e., i-d). If such a
      legitimate key exists, the receiver compares its value with
      the current disclosed key and if they are identical, skips the
      "Unverifiable key test" and "Key verification test". If such
      a legitimate key exists but the values differ, the receiver
      MUST discard the packet.

   * Unverifiable key test: when the disclosed key index is new, it
      is possible that no earlier disclosed and legitimate key
      exists for this key chain, thereby preventing the verification
      of the disclosed key. This happens when the disclosed key
      belongs to the old key chain and no commitment to this old key
      chain has ever been received (e.g., because the first
      bootstrap packet received by a latecomer is for the current
      key chain, and therefore includes a commitment to the current
      key chain, not the previous one). When this happens, the
      receiver MUST ignore the disclosed key (anyway useless) and
      skip the Key verification test.

   * Key verification test: If the disclosed key index is new and
      the key can be verified, the receiver checks the legitimacy of
      K_{i-d} by verifying, for some earlier disclosed and
      legitimate key K_v (with $v < i-d$), that K_v and $F^{i-d-v}(K_{i-d})$ are identical. In other words, the receiver

checks the disclosed key by computing the necessary number of
PRF functions to obtain a previously disclosed and legitimate
(i.e., verified) key. If the key verification fails, the
receiver MUST discard the packet. If the key verification
succeeds, this key is said to be legitimate and is stored by
the receiver, as well as all the keys between indexes v and
i-d.

5. When applicable, the receiver performs any congestion control
    related action (i.e., the ALC or NORM headers are used by the
    associated congestion control building block, if any), even if
    the packet has not yet been authenticated [RFC5651]. If this
    feature leads to a potential DoS attack (the attacker can send a
    faked packet with a wrong sequence number to simulate packet
    losses), it does not compromise the security features offered by
    TESLA and enables a rapid reaction in front of actual congestion
    problems.

6. The receiver then buffers the packet for a later authentication,
    once the corresponding key will be disclosed (after d time
    intervals) or deduced from another key (if all packets disclosing
    this key are lost). In some situations, this packet might also
    be discarded later, if it turns out that the receiver will never
    be able to deduce the associated key.

7. Authentication test: Let v be the smallest index of the
    legitimate keys known by the receiver so far. For all the new
    keys K_w, with $v < w <= i-d$, that have been either disclosed by
    this packet (i.e., K_{i-d}) or derived by K_{i-d} (i.e., keys in
    interval $\{v+1,.. i-d-1\}$), the receiver verifies the authenticity
    of the safe packets buffered for the corresponding interval w.
    To authenticate one of the buffered packets P_h containing
    message M_h protected with a MAC that used key index w, the
    receiver will compute $K'_w = F'(K_w)$ from which it can compute
    MAC(K'_w, M_h). If this MAC does not equal the MAC stored in
    the packet, the receiver MUST discard the packet. If the two
    MACs are equal, the packet is successfully authenticated and the
    receiver continues processing it.

8. Authenticated new key chain commitment processing: If the
    authenticated packet contains a new key chain commitment and if
    no verified commitment already exists, then the receiver stores
    the commitment to the new key chain. Then, if there are non-
    authenticated packets for a previous chain (i.e., the key chain
    before the current one), all these packets can be discarded
    (Section 4.4).

   9. The receiver continues the ALC or NORM processing of all the
       packets authenticated during the authentication test.

   In this specification, a receiver using TESLA MUST immediately drop
   unsafe packets. But the receiver MAY also decide, at any time, to
   continue an ALC or NORM session in unsafe (insecure) mode, ignoring
   TESLA extensions. There SHOULD be an explicit user action to that
   purpose.

4.3.1. Discarding Unnecessary Packets Earlier

   Following strictly the above steps can lead to excessive processing
   overhead in certain situations. This is the case when a receiver
   receives packets for an unwanted object with the ALC or NORM
   protocols, i.e., an object in which the application (or the end user)
   explicitly mentioned it is not interested. This is also the case
   when a receiver receives packets for an already decoded object, or
   when this object has been partitioned in several blocks, for an
   already decoded block. When such a packet is received, which is
   easily identified by looking at the receiver's status for the
   incoming ALC or NORM packet, the receiver MUST also check that the
   packet is a pure data packet that does not contain any signaling
   information of importance for the session.

   With ALC, a packet containing an "A" flag ("Close Session") or a "B"
   flag ("Close Object") MUST NOT be discarded before having been
   authenticated and processed normally. Otherwise, the receiver can
   safely discard the incoming packet for instance just after step 1 of
   Section 4.3. This optimization can dramatically reduce the
   processing overhead by avoiding many useless authentication checks.

4.4. Flushing the Non-Authenticated Packets of a Previous Key Chain

   In some cases, a receiver having experienced a very long
   disconnection might have lost all the disclosures of the last key(s)
   of a previous key chain. Let j be the index of this key chain for
   which there remains non-authenticated packets. This receiver can
   flush all the packets of the key chain j if he determines that:

   o he has just switched to a chain of index j+2 (inclusive) or
      higher;

   o the sender has sent a commitment to the new key chain of index j+2
      (Section 3.1.2.3). This situation requires that the receiver has
      received a packet containing such a commitment and that he has
      been able to check its integrity. In some cases, it might require
      receiving a bootstrap information message for the current key
      chain.

If one of the above two tests succeeds, the sender can discard all
the awaiting packets since there is no way to authenticate them.

5. Integration in the ALC and NORM Protocols

5.1. Authentication Header Extension Format

The integration of TESLA in ALC or NORM is similar and relies on the
header extension mechanism defined in both protocols. More
precisely, this document details the EXT_AUTH==1 header extension
defined in [RFC5651].

Several fields are added in addition to the "HET" (Header Extension
Type) and "HEL" (Header Extension Length) fields (Figure 9).

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   HET (=1)    |      HEL      | ASID  | Type  |               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+               +
|                                                               |
~                                                               ~
|                            Content                            |
~                                                               ~
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
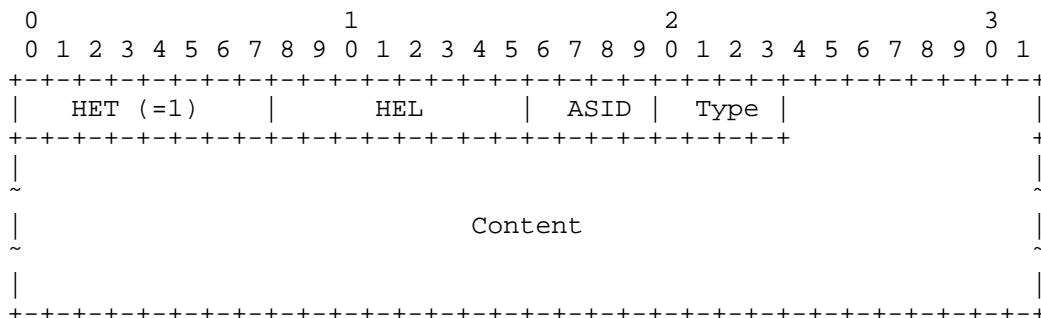
         Figure 9: Format of the TESLA EXT_AUTH Header Extension

The fields of the TESLA EXT_AUTH Header Extension are:

"ASID" (Authentication Scheme IDentifier) field (4 bits):

   The "ASID" identifies the source authentication scheme or protocol
   in use. The association between the "ASID" value and the actual
   authentication scheme is defined out-of-band, at session startup.

"Type" field (4 bits):

   The "Type" field identifies the type of TESLA information carried
   in this header extension. This specification defines the
   following types:

   * 0: Bootstrap information, sent by the sender periodically or
      after a direct time synchronization request;

   * 1: Standard Authentication Tag for the ongoing key chain, sent
      by the sender along with a packet;

   *   2: Authentication Tag without Key Disclosure, sent by the
       sender along with a packet;

   *   3: Authentication Tag with a New Key Chain Commitment, sent by
       the sender when approaching the end of a key chain;

   *   4: Authentication Tag with a Last Key of Old Chain Disclosure,
       sent by the sender some time after moving to a new key chain;

   *   5: Direct time synchronization request, sent by a NORM
       receiver. This type of message is invalid in the case of an
       ALC session since ALC is restricted to unidirectional
       transmissions. Yet, an external mechanism may provide the
       direct time synchronization functionality;

   *   6: Direct time synchronization response, sent by a NORM sender.
       This type of message is invalid in the case of an ALC session
       since ALC is restricted to unidirectional transmissions. Yet,
       an external mechanism may provide the direct time
       synchronization functionality.

   "Content" field (variable length):

      This is the TESLA information carried in the header extension,
      whose type is given by the "Type" field.

5.2. Use of Authentication Header Extensions

   Each packet sent by the session's sender MUST contain exactly one
   TESLA EXT_AUTH Header Extension.

   All receivers MUST recognize EXT_AUTH but MAY not be able to parse
   its content, for instance, because they do not support TESLA. In
   that case, these receivers MUST ignore the TESLA EXT_AUTH extensions.
   In the case of NORM, the packets sent by receivers MAY contain a
   direct synchronization request but MUST NOT contain any of the other
   five TESLA EXT_AUTH Header Extensions.

5.2.1. EXT_AUTH Header Extension of Type Bootstrap Information

   The "bootstrap information" TESLA EXT_AUTH (Type==0) MUST be sent in
   a stand-alone control packet, rather than in a packet containing
   application data. The reason for that is the large size of this
   bootstrap information. By using stand-alone packets, the maximum
   payload size of data packets is only affected by the (mandatory)
   authentication information header extension.

With ALC, the "bootstrap information" TESLA EXT_AUTH MUST be sent in
a control packet, i.e., containing no encoding symbol.

With NORM, the "bootstrap information" TESLA EXT_AUTH MUST be sent in
a NORM_CMD(APPLICATION) message.

```
     0                   1                   2                   3
     0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  ---
    |   HET (=1)    |   HEL (=46)   | ASID |    0    | 0 |  0  |0|1|0|   ^
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+   |
    |       d       |       2       |       2       |       2       |   |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+   |
    |       1       |       3       |              128              |   |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+   |
    |           0 (reserved)        |            T_int              |   |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+   |
    |                                                               |   |
    +                   T_0 (NTP timestamp format)                  +   | 5
    |                                                               |   | 2
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+   |
    |                   N (Key Chain Length)                        |   | b
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+   | y
    |                  Current Interval Index i                     |   | t
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+   | e
    |                                                               |   | s
    +                                                               +   |
    |                                                               |   |
    +                 Current Key Chain Commitment                  +   |
    |                        (20 bytes)                             |   |
    +                                                               +   |
    |                                                               |   |
    +                                                               +   |
    |                                                               |   v
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  ---
    |                                                               |   ^ 1
    +                                                               +   | 2
    |                                                               |   | 8
    .                                                               .   |
    .                          Signature                            .   | b
    .                         (128 bytes)                           .   | y
    |                                                               |   | t
    +                                                               +   | e
    |                                                               |   v s
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+  ---
    |                          Group MAC                            |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
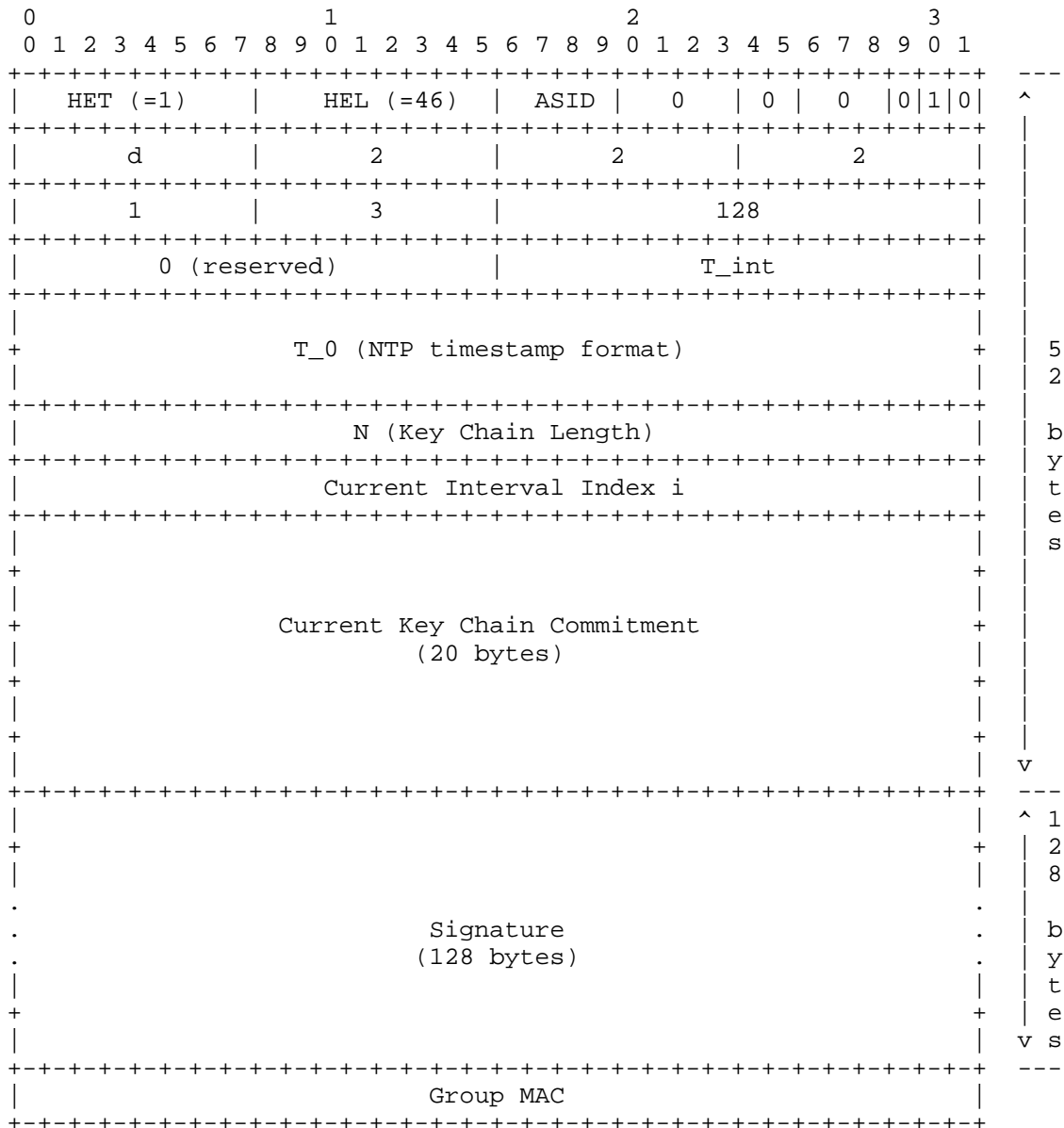
        Figure 10: Example: Format of the Bootstrap Information Message
                 (Type 0) Using SHA-256/1024-Bit Signatures,
                 the Default HMAC-SHA-256, and a Group MAC

For instance, Figure 10 shows the bootstrap information message when
using the HMAC-SHA-256 transform for the PRF, MAC, and Group MAC
functions, along with SHA-256/128 byte (1024 bit) key digital
signatures (which also means that the "Signature" field is 128 bytes
long). The TESLA EXT_AUTH Header Extension is then 184 bytes long
(i.e., 46 words of 32 bits).

5.2.2. EXT_AUTH Header Extension of Type Authentication Tag

The four "authentication tag" TESLA EXT_AUTH Header Extensions (Type
1, 2, 3, and 4) MUST be attached to the ALC or NORM packet (data or
control packet) that they protect.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|    HET (=1)    |   HEL (=10)   | ASID |   1   |    Reserved    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                   i (Interval Index of K'_i)                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                                                               |
+                     Disclosed Key K_{i-d}                     +
|                          (20 bytes)                           |
+                                                               +
|                                                               |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                          MAC(K'_i, M)                         |
+                          (16 bytes)                           +
|                                                               |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
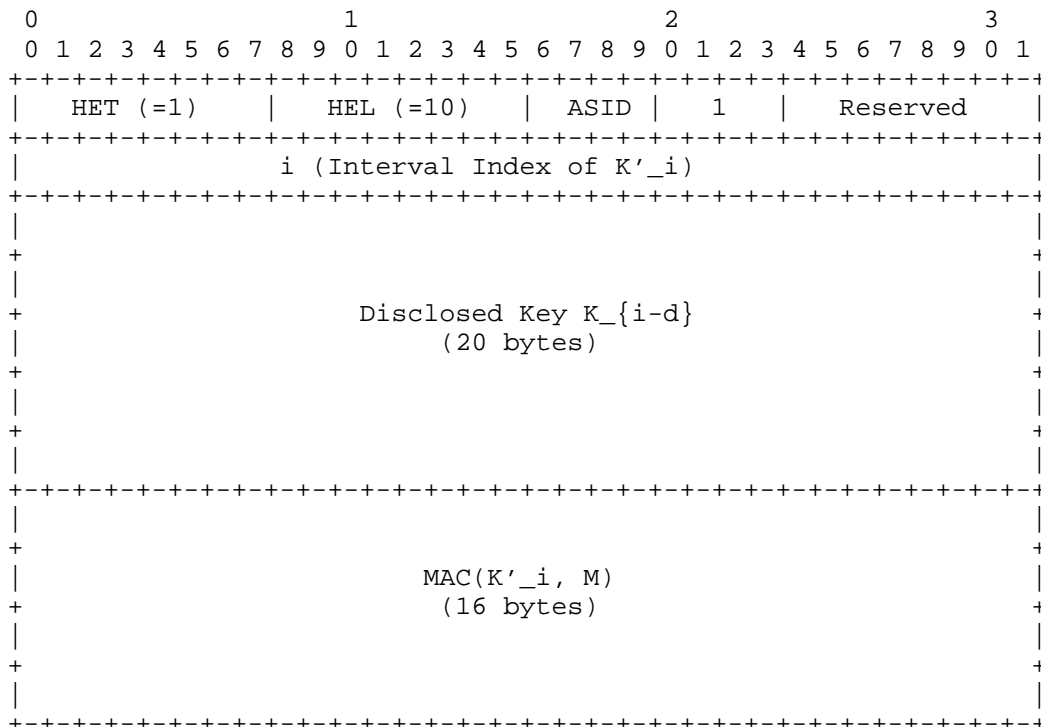
Figure 11: Example: Format of the Standard Authentication Tag
(Type 1) Using the Default HMAC-SHA-256

```
     0                   1                   2                   3
     0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |   HET (=1)    |   HEL (=5)    | ASID |  2   |    Reserved    |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                  i (Interval Index of K'_i)                  |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
    |                                                              |
    +                                                              +
    |                        MAC(K'_i, M)                          |
    +                         (16 bytes)                           +
    |                                                              |
    +                                                              +
    |                                                              |
    +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```
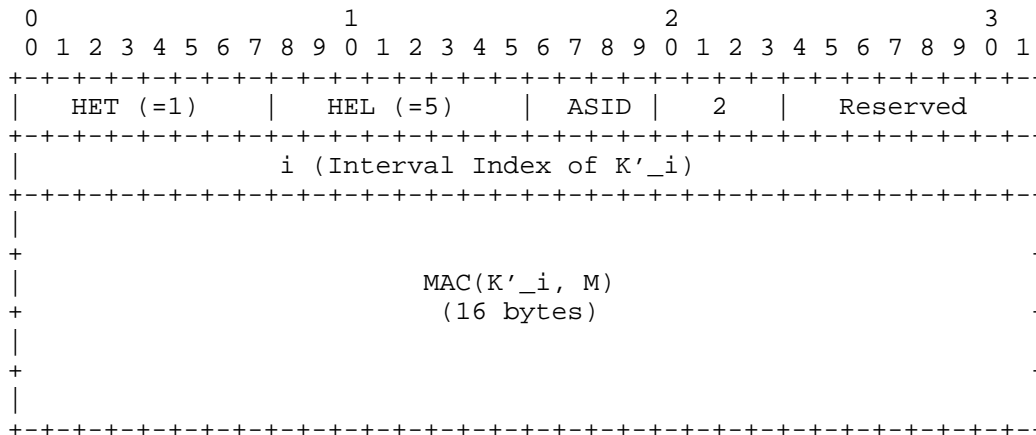
        Figure 12: Example: Format of the Authentication Tag without
          Key Disclosure (Type 2) Using the Default HMAC-SHA-256

   For instance, Figures 11 and 12 show the format of the authentication
   tags, respectively with and without the K_{i-d} key disclosure, when
   using the (default) HMAC-SHA-256 transform for the PRF and MAC
   functions. In these examples, the Group MAC feature is not used.

5.2.3. EXT_AUTH Header Extension of Type Direct Time Synchronization
        Request

   With NORM, the "direct time synchronization request" TESLA EXT_AUTH
   (Type==7) MUST be sent by a receiver in a NORM_CMD(APPLICATION) NORM
   packet.

   With ALC, the "direct time synchronization request" TESLA EXT_AUTH
   cannot be included in an ALC packet, since ALC is restricted to
   unidirectional transmissions, from the session's sender to the
   receivers. An external mechanism must be used with ALC for carrying
   direct time synchronization requests to the session's sender.

   In the case of direct time synchronization, it is RECOMMENDED that
   the receivers spread the transmission of direct time synchronization
   requests over the time (Section 2.3.1).

5.2.4. EXT_AUTH Header Extension of Type Direct Time Synchronization
        Response

   With NORM, the "direct time synchronization response" TESLA EXT_AUTH
   (Type==8) MUST be sent by the sender in a NORM_CMD(APPLICATION)
   message.

   With ALC, the "direct time synchronization response" TESLA EXT_AUTH
   can be sent in an ALC control packet (i.e., containing no encoding
   symbol) or through the external mechanism used to carry the direct
   time synchronization request.

6. Security Considerations

   [RFC4082] discusses the security of TESLA in general. These
   considerations apply to the present specification, namely:

   o great care must be taken in the timing aspects. In particular,
      the D_t parameter is critical and must be correctly initialized;

   o if the sender realizes that the key disclosure schedule is not
      appropriate, then the current session MUST be closed and a new one
      created. Indeed, Section 3.1.3 requires that these parameters be
      fixed during the whole session.

   o when the verifier that authenticates the incoming packets and the
      application that uses the data are two different components, there
      is a risk that an attacker located between these components inject
      faked data. Similarly, when the verifier and the secure timing
      system are two different components, there is a risk that an
      attacker located between these components inject faked timing
      information. For instance, when the verifier reads the local time
      by means of a dedicated system call (e.g., gettimeofday()), if an
      attacker controls the host, he may catch the system call and
      return a faked time information.

   The current specification discusses additional aspects with more
   details.

6.1. Dealing with DoS Attacks

   TESLA introduces new opportunities for an attacker to mount DoS
   attacks. For instance, an attacker can try to saturate the
   processing capabilities of the receiver (faked packets are easy to
   create but checking them requires computing a MAC over the packet or
   sometimes checking a digital signature as with the bootstrap and
   direct time synchronization response messages). An attacker can also
   try to saturate the receiver's memory (since authentication is
   delayed and non-authenticated packets will accumulate), or to make
   the receiver believe that a congestion has happened (since congestion
   control MUST be performed before authenticating incoming packets,
   Section 4.3).

   In order to mitigate these attacks, it is RECOMMENDED to use the
   Group MAC scheme (Section 3.3.3). No mitigation is possible if a
   group member acts as an attacker with Group MAC.

   Generally, it is RECOMMENDED that the amount of memory used to store
   incoming packets waiting to be authenticated be limited to a
   reasonable value.

6.2. Dealing With Replay Attacks

   Replay attacks, whereby an attacker stores a valid message and
   replays it later, can have significant impacts, depending on the
   message type. Two levels of impacts must be distinguished:

   o within the TESLA protocol, and

   o within the ALC or NORM protocol.

6.2.1. Impacts of Replay Attacks on TESLA

   Replay attacks can impact the TESLA component itself. We review here
   the potential impacts of such an attack depending on the TESLA
   message type:

   o bootstrap information: Since most parameters contained in a
      bootstrap information message are static, replay attacks have no
      consequences. The fact that the "i" and "K_i" fields can be
      updated in subsequent bootstrap information messages does not
      create a problem either, since all "i" and "K_i" fields sent
      remain valid. Finally, a receiver that successfully initialized
      its TESLA component MUST ignore the following messages (see
      Section 4.2.1 for an exception to this rule), which voids replay
      attacks, unless he missed all the commitments to a new key chain
      (e.g., after a long disconnection) (Section 3.2.1).

   o direct time synchronization request: If the Group MAC scheme is
      used, an attacker that is not a member of the group can replay a
      packet and oblige the sender to respond, which requires digitally
      signing the response, a time-consuming process. If the Group MAC
      scheme is not used, an attacker can easily forge a request anyway.
      In both cases, the attack will not compromise the TESLA component,
      but might create a DoS. If this is a concern, it is RECOMMENDED,
      when the Group MAC scheme is used, that the sender verify the
      "t_r" NTP timestamp contained in the request and respond only if
      this value is strictly larger than the previous one received from
      this receiver. When the Group MAC scheme is not used, this attack
      can be mitigated by limiting the number of requests per second
      that will be processed.

    o direct time synchronization response: Upon receiving a response, a
       receiver who has no pending request MUST immediately drop the
       packet. If this receiver has previously issued a request, he
       first checks the Group MAC (if applicable), then the "t_r" field,
       to be sure it is a response to his request, and finally the
       digital signature. A replayed packet will be dropped during these
       verifications, without compromising the TESLA component.

    o other messages, containing an authentication tag: Replaying a
       packet containing a TESLA authentication tag will never compromise
       the TESLA component itself (but perhaps the underlying ALC or NORM
       component, see below).

    To conclude, TESLA itself is robust in front of replay attacks.

6.2.2. Impacts of Replay Attacks on NORM

    We review here the potential impacts of a replay attack on the NORM
    component. Note that we do not consider here the protocols that
    could be used along with NORM, for instance, the congestion control
    protocols.

    First, let us consider replay attacks within a given NORM session.
    NORM defines a "sequence" field that can be used to protect against
    replay attacks [RFC5740] within a given NORM session. This
    "sequence" field is a 16-bit value that is set by the message
    originator (sender or receiver) as a monotonically increasing number
    incremented with each NORM message transmitted. It is RECOMMENDED
    that a receiver check this "sequence" field and drop messages
    considered as replayed. Similarly, it is RECOMMENDED that a sender
    check this sequence, for each known receiver, and drop messages
    considered as replayed. In both cases, checking this "sequence"
    field SHOULD be done before TESLA processing of the packet: if the
    "sequence" field has not been corrupted, the replay attack will
    immediately be identified; otherwise, the packet will fail the TESLA
    authentication test. This analysis shows that NORM itself is robust
    in front of replay attacks within the same session.

    Now let us consider replay attacks across several NORM sessions.
    Since the key chain used in each session MUST differ, a packet
    replayed in a subsequent session will be identified as unauthentic.
    Therefore, NORM is robust in front of replay attacks across different
    sessions.

6.2.3. Impacts of Replay Attacks on ALC

   We review here the potential impacts of a replay attack on the ALC
   component. Note that we do not consider here the protocols that
   could be used along with ALC, for instance, the layered or wave-based
   congestion control protocols.

   First, let us consider replay attacks within a given ALC session:

   o Regular packets containing an authentication tag: a replayed
      message containing an encoding symbol will be detected once
      authenticated, thanks to the object/block/symbol identifiers, and
      will be silently discarded. This kind of replay attack is only
      penalizing in terms of memory and processing load, but does not
      compromise the ALC behavior.

   o Control packets containing an authentication tag: ALC control
      packets, by definition, do not include any encoding symbol and
      therefore do not include any object/block/symbol identifier that
      would enable a receiver to identify duplicates. However, a sender
      has a very limited number of reasons to send control packets.
      More precisely:

      * At the end of the session, a "Close Session" ("A" flag) packet
         is sent. Replaying this packet has no impact since the
         receivers already left.

      * Similarly, replaying a packet containing a "Close Object" ("B"
         flag) has no impact since this object is probably already
         marked as closed by the receiver.

   This analysis shows that ALC itself is robust in front of replay
   attacks within the same session.

   Now let us consider replay attacks across several ALC sessions.
   Since the key chain used in each session MUST differ, a packet
   replayed in a subsequent session will be identified as unauthentic.
   Therefore, ALC is robust in front of replay attacks across different
   sessions.

6.3. Security of the Back Channel

   As specified in Section 1.1, this specification does not consider the
   packets that may be sent by receivers, for instance, NORM's feedback
   packets. When a back channel is used, its security is critical to
   the global security, and an appropriate security mechanism MUST be
   used. [RMT-SIMPLE-AUTH] describes several techniques that can be
   used to that purpose. However, the authentication and integrity

verification of the packets sent by receivers on the back channel, if
any, is out of the scope of this document.

7. IANA Considerations

   IANA has registered the following attributes according to this
   document. The registries are provided by [RFC4442] under the "Timed
   Efficient Stream Loss-tolerant Authentication (TESLA) Parameters"
   registry [TESLA-REG]. Following the policies outlined in [RFC4442],
   the values in the range up to 240 (including 240) for the following
   attributes are assigned after expert review by the MSEC working group
   or its designated successor. The values in the range from 241 to 255
   are reserved for private use.

   Cryptographic Pseudo-Random Function, TESLA-PRF: All implementations
   MUST support HMAC-SHA-256 (default).

```
                 +------------------------+-------+
                 |        PRF name        | Value |
                 +------------------------+-------+
                 |        HMAC-SHA1       |   0   |
                 |      HMAC-SHA-224      |   1   |
                 | HMAC-SHA-256 (default) |   2   |
                 |      HMAC-SHA-384      |   3   |
                 |      HMAC-SHA-512      |   4   |
                 +------------------------+-------+
```

   Cryptographic Message Authentication Code (MAC) Function, TESLA-MAC:
   All implementations MUST support HMAC-SHA-256 (default). These MAC
   schemes are used both for the computing of regular MAC and the Group
   MAC (if applicable).

```
                 +------------------------+-------+
                 |        MAC name        | Value |
                 +------------------------+-------+
                 |        HMAC-SHA1       |   0   |
                 |      HMAC-SHA-224      |   1   |
                 | HMAC-SHA-256 (default) |   2   |
                 |      HMAC-SHA-384      |   3   |
                 |      HMAC-SHA-512      |   4   |
                 +------------------------+-------+
```

   Furthermore, IANA has created two new registries. Here also, the
   values in the range up to 240 (including 240) for the following
   attributes are assigned after expert review by the MSEC working group
   or its designated successor. The values in the range from 241 to 255
   are reserved for private use.

   Signature Encoding Algorithm, TESLA-SIG-ALGO: All implementations
   MUST support RSASSA-PKCS1-v1_5 (default).

```
            +----------------------------+-------+
            |   Signature Algorithm Name | Value |
            +----------------------------+-------+
            |          INVALID           |   0   |
            | RSASSA-PKCS1-v1_5 (default)|   1   |
            |         RSASSA-PSS         |   2   |
            +----------------------------+-------+
```

   Signature Cryptographic Function, TESLA-SIG-CRYPTO-FUNC: All
   implementations MUST support SHA-256 (default).

```
            +----------------------------+-------+
            | Cryptographic Function Name| Value |
            +----------------------------+-------+
            |          INVALID           |   0   |
            |           SHA-1            |   1   |
            |          SHA-224           |   2   |
            |      SHA-256 (default)     |   3   |
            |          SHA-384           |   4   |
            |          SHA-512           |   5   |
            +----------------------------+-------+
```

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