        RObust Header Compression (ROHC): A Profile for TCP/IP (ROHC-TCP)

Status of This Memo

   This document specifies an Internet standards track protocol for the
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Abstract

   This document specifies a ROHC (Robust Header Compression) profile
   for compression of TCP/IP packets. The profile, called ROHC-TCP,
   provides efficient and robust compression of TCP headers, including
   frequently used TCP options such as SACK (Selective Acknowledgments)
   and Timestamps.

   ROHC-TCP works well when used over links with significant error rates
   and long round-trip times. For many bandwidth-limited links where
   header compression is essential, such characteristics are common.

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1. Introduction

   There are several reasons to perform header compression on low- or
   medium-speed links for TCP/IP traffic, and these have already been
   discussed in [RFC2507]. Additional considerations that make
   robustness an important objective for a TCP [RFC0793] compression
   scheme are introduced in [RFC4163]. Finally, existing TCP/IP header
   compression schemes ([RFC1144], [RFC2507]) are limited in their
   handling of the TCP options field and cannot compress the headers of
   handshaking packets (SYNs and FINs).

   It is thus desirable for a header compression scheme to be able to
   handle loss on the link between the compression and decompression
   points as well as loss before the compression point. The header
   compression scheme also needs to consider how to efficiently compress
   short-lived TCP transfers and TCP options, such as SACK ([RFC2018],
   [RFC2883]) and Timestamps ([RFC1323]).

   The ROHC WG has developed a header compression framework on top of
   which various profiles can be defined for different protocol sets, or
   for different compression strategies. This document defines a TCP/IP
   compression profile for the ROHC framework [RFC4995], compliant with
   the requirements listed in [RFC4163].

   Specifically, it describes a header compression scheme for TCP/IP
   header compression (ROHC-TCP) that is robust against packet loss and
   that offers enhanced capabilities, in particular for the compression
   of header fields including TCP options. The profile identifier for
   TCP/IP compression is 0x0006.

2. Terminology

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

   This document reuses some of the terminology found in [RFC4995]. In
   addition, this document uses or defines the following terms:

   Base context

      The base context is a context that has been validated by both the
      compressor and the decompressor. A base context can be used as
      the reference when building a new context using replication.

   Base Context Identifier (Base CID)

      The Base CID is the CID that identifies the base context, from
      which information needed for context replication can be extracted.

   Base header

      A compressed representation of the innermost IP and TCP headers of
      the uncompressed packet.

   Chaining of items

      A chain groups fields based on similar characteristics. ROHC-TCP
      defines chain items for static, dynamic, replicable, or irregular
      fields. Chaining is done by appending an item for each header
      e.g., to the chain in their order of appearance in the
      uncompressed packet. Chaining is useful to construct compressed
      headers from an arbitrary number of any of the protocol headers
      for which ROHC-TCP defines a compressed format.

   Context Replication (CR)

      Context replication is the mechanism that establishes and
      initializes a new context based on another existing valid context
      (a base context). This mechanism is introduced to reduce the
      overhead of the context establishment procedure, and is especially
      useful for compression of multiple short-lived TCP connections
      that may be occurring simultaneously or near-simultaneously.

   ROHC-TCP packet types

      ROHC-TCP uses three different packet types: the Initialization and
      Refresh (IR) packet type, the Context Replication (IR-CR) packet
      type, and the Compressed packet (CO) type.

   Short-lived TCP transfer

      Short-lived TCP transfers refer to TCP connections transmitting
      only small amounts of packets for each single connection.

3. Background

   This section provides some background information on TCP/IP header
   compression. The fundamentals of general header compression can be
   found in [RFC4995]. In the following subsections, two existing
   TCP/IP header compression schemes are first described along with a
   discussion of their limitations, followed by the classification of
   TCP/IP header fields. Finally, some of the characteristics of
   short-lived TCP transfers are summarized.

   A behavior analysis of TCP/IP header fields is found in [RFC4413].

3.1. Existing TCP/IP Header Compression Schemes

   Compressed TCP (CTCP) and IP Header Compression (IPHC) are two
   different schemes that may be used to compress TCP/IP headers. Both
   schemes transmit only the differences from the previous header in
   order to reduce the size of the TCP/IP header.

   The CTCP [RFC1144] compressor detects transport-level retransmissions
   and sends a header that updates the context completely when they
   occur. While CTCP works well over reliable links, it is vulnerable
   when used over less reliable links as even a single packet loss
   results in loss of synchronization between the compressor and the
   decompressor. This in turn leads to the TCP receiver discarding all
   remaining packets in the current window because of a checksum error.
   This effectively prevents the TCP fast retransmit algorithm [RFC2581]
   from being triggered. In such a case, the compressor must wait until
   TCP times out and retransmits a packet to resynchronize.

   To reduce the errors due to the inconsistent contexts between
   compressor and decompressor when compressing TCP, IPHC [RFC2507]
   improves somewhat on CTCP by augmenting the repair mechanism of CTCP
   with a local repair mechanism called TWICE and with a link-layer
   mechanism based on negative acknowledgments to request a header that
   updates the context.

The TWICE algorithm assumes that only the Sequence Number field of
TCP segments is changing with the deltas between consecutive packets
being constant in most cases. This assumption is however not always
true, especially when TCP Timestamps and SACK options are used.

The full header request mechanism requires a feedback channel that
may be unavailable in some circumstances. This channel is used to
explicitly request that the next packet be sent with an uncompressed
header to allow resynchronization without waiting for a TCP timeout.
In addition, this mechanism does not perform well on links with long
round-trip times.

Both CTCP and IPHC are also limited in their handling of the TCP
options field. For IPHC, any change in the options field (caused by
Timestamps or SACK, for example) renders the entire field
uncompressible, while for CTCP, such a change in the options field
effectively disables TCP/IP header compression altogether.

Finally, existing TCP/IP compression schemes do not compress the
headers of handshaking packets (SYNs and FINs). Compressing these
packets may greatly improve the overall header compression ratio for
the cases where many short-lived TCP connections share the same
channel.

3.2. Classification of TCP/IP Header Fields

Header compression is possible due to the fact that there is much
redundancy between header field values within packets, especially
between consecutive packets. To utilize these properties for TCP/IP
header compression, it is important to understand the change patterns
of the various header fields.

All fields of the TCP/IP packet header have been classified in detail
in [RFC4413]. The main conclusion is that most of the header fields
can easily be compressed away since they seldom or never change. The
following fields do however require more sophisticated mechanisms:

   - IPv4 Identification   (16 bits) - IP-ID
   - TCP Sequence Number   (32 bits) - SN
   - TCP Acknowledgment Number (32 bits)
   - TCP Reserved   (4 bits)
   - TCP ECN flags   (2 bits) - ECN
   - TCP Window   (16 bits)

      - TCP Options
        o Maximum Segment Size   (32 bits) - MSS
        o Window Scale   (24 bits) - WSCALE
        o SACK Permitted   (16 bits)
        o TCP SACK   (80, 144, 208, or 272 bits) - SACK
        o TCP Timestamp   (80 bits) - TS

   The assignment of IP-ID values can be done in various ways, usually
   one of sequential, sequential jump, or random, as described in
   Section 4.1.3 of [RFC4413]. Some IPv4 stacks do use a sequential
   assignment when generating IP-ID values but do not transmit the
   contents of this field in network byte order; instead, it is sent
   with the two octets reversed. In this case, the compressor can
   compress the IP-ID field after swapping the bytes. Consequently, the
   decompressor also swaps the bytes of the IP-ID after decompression to
   regenerate the original IP-ID. With respect to TCP compression, the
   analysis in [RFC4413] reveals that there is no obvious candidate
   among the TCP fields suitable to infer the IP-ID.

   The change pattern of several TCP fields (Sequence Number,
   Acknowledgment Number, Window, etc.) is very hard to predict. Of
   particular importance to a TCP/IP header compression scheme is the
   understanding of the sequence and acknowledgment numbers [RFC4413].

   Specifically, the TCP Sequence Number can be anywhere within a range
   defined by the TCP Window at any point on the path (i.e., wherever a
   compressor might be deployed). Missing packets or retransmissions
   can cause the TCP Sequence Number to fluctuate within the limits of
   this window. The TCP Window also bounds the jumps in acknowledgment
   number.

   Another important behavior of the TCP/IP header is the dependency
   between the sequence number and the acknowledgment number. TCP
   connections can be either near-symmetrical or show a strong
   asymmetrical bias with respect to the data traffic. In the latter
   case, the TCP connections mainly have one-way traffic (Web browsing
   and file downloading, for example). This means that on the forward
   path (from server to client), only the sequence number is changing
   while the acknowledgment number remains constant for most packets; on
   the backward path (from client to server), only the acknowledgment
   number is changing and the sequence number remains constant for most
   packets. A compression scheme for TCP should thus have packet
   formats suitable for either cases, i.e., packet formats that can
   carry either only sequence number bits, only acknowledgment number
   bits, or both.

   In addition, TCP flows can be short-lived transfers. Short-lived TCP
   transfers will degrade the performance of header compression schemes

that establish a new context by initially sending full headers.
Multiple simultaneous or near simultaneous TCP connections may
exhibit much similarity in header field values and context values
among each other, which would make it possible to reuse information
between flows when initializing a new context. A mechanism to this
end, context replication [RFC4164], makes the context establishment
step faster and more efficient, by replicating part of an existing
context to a new flow. The conclusion from [RFC4413] is that part of
the IP sub-context, some TCP fields, and some context values can be
replicated since they seldom change or change with only a small jump.

ROHC-TCP also compresses the following headers: IPv6 Destination
Options header [RFC2460], IPv6 Routing header [RFC2460], IPv6 Hop-by-
Hop Options header [RFC2460], Authentication Header (AH) [RFC4302],
NULL-encrypted Encapsulating Security Payload (ESP) header [RFC4303],
Generic Routing Encapsulation (GRE) [RFC2784][RFC2890] and the
Minimal Encapsulation header (MINE) [RFC2004].

Headers specific to Mobile IP (for IPv4 or IPv6) do not receive any
special treatment in this document, for reasons similar to those
described in [RFC3095].

4. Overview of the TCP/IP Profile (Informative)

4.1. General Concepts

   ROHC-TCP uses the ROHC protocol as described in [RFC4995]. ROHC-TCP
   supports context replication as defined in [RFC4164]. Context
   replication can be particularly useful for short-lived TCP flows
   [RFC4413].

4.2. Compressor and Decompressor Interactions

4.2.1. Compressor Operation

   Header compression with ROHC can be conceptually characterized as the
   interaction of a compressor with a decompressor state machine. The
   compressor's task is to minimally send the information needed to
   successfully decompress a packet, based on a certain confidence
   regarding the state of the decompressor context.

   For ROHC-TCP compression, the compressor normally starts compression
   with the initial assumption that the decompressor has no useful
   information to process the new flow, and sends Initialization and
   Refresh (IR) packets. Alternatively, the compressor may also support
   Context Replication (CR) and use IR-CR packets [RFC4164], which
   attempts to reuse context information related to another flow.

The compressor can then adjust the compression level based on its
confidence that the decompressor has the necessary information to
successfully process the Compressed (CO) packets that it selects. In
other words, the task of the compressor is to ensure that the
decompressor operates in the state that allows decompression of the
most efficient CO packet(s), and to allow the decompressor to move to
that state as soon as possible otherwise.

4.2.2. Decompressor Feedback

The ROHC-TCP profile can be used in environments with or without
feedback capabilities from decompressor to compressor. ROHC-TCP
however assumes that if a ROHC feedback channel is available and if
this channel is used at least once by the decompressor for a specific
ROHC-TCP context, this channel will be used during the entire
compression operation for that context. If the feedback channel
disappears, compression should be restarted.

The reception of either positive acknowledgment (ACKs) or negative
acknowledgment (NACKs) establishes the feedback channel from the
decompressor for the context for which the feedback was received.
Once there is an established feedback channel for a specific context,
the compressor should make use of this feedback to estimate the
current state of the decompressor. This helps in increasing the
compression efficiency by providing the information needed for the
compressor to achieve the necessary confidence level.

The ROHC-TCP feedback mechanism is limited in its applicability by
the number of (least significant bit (LSB) encoded) master sequence
number (MSN) (see Section 6.1.1) bits used in the FEEDBACK-2 format
(see Section 8.3). It is not suitable for a decompressor to use
feedback altogether where the MSN bits in the feedback could wrap
around within one round-trip time. Instead, unidirectional operation
-- where the compressor periodically sends larger context-updating
packets -- is more appropriate.

4.3. Packet Formats and Encoding Methods

The packet formats and encoding methods used for ROHC-TCP are defined
using the formal notation [RFC4997]. The formal notation is used to
provide an unambiguous representation of the packet formats and a
clear definition of the encoding methods.

4.3.1. Compressing TCP Options

   The TCP options in ROHC-TCP are compressed using a list compression
   encoding that allows option content to be established so that TCP
   options can be added to the context without having to send all TCP
   options uncompressed.

4.3.2. Compressing Extension Headers

   ROHC-TCP compresses the extension headers as listed in Section 3.2.
   These headers are treated exactly as other headers and thus have a
   static chain, a dynamic chain, an irregular chain, and a chain for
   context replication (Section 6.2).

   This means that headers appearing in or disappearing from the flow
   being compressed will lead to changes to the static chain. However,
   the change pattern of extension headers is not deemed to impair
   compression efficiency with respect to this design strategy.

4.4. Expected Compression Ratios with ROHC-TCP

   The following table illustrates typical compression ratios that can
   be expected when using ROHC-TCP and IPHC [RFC2507].

   The figures in the table assume that the compression context has
   already been properly initialized. For the TS option, the Timestamp
   is assumed to change with small values. All TCP options include a
   suitable number of No Operation (NOP) options [RFC0793] for padding
   and/or alignment. Finally, in the examples for IPv4, a sequential
   IP-ID behavior is assumed.

		Total Header Size (octets)				
		ROHC-TCP		IPHC		
	Unc.	DATA	ACK	DATA	ACK	
IPv4+TCP+TS	52	8	8	18	18	
IPv4+TCP+TS	52	7	6	16	16	(1)
IPv6+TCP+TS	72	8	7	18	18	
IPv6+TCP+no opt	60	6	5	6	6	
IPv6+TCP+SACK	80	–	15	–	80	(2)
IPv6+TCP+SACK	80	–	9	–	26	(3)

   (1) The payload size of the data stream is constant.
   (2) The SACK option appears in the header, but was not present
       in the previous packet. Two SACK blocks are assumed.
   (3) The SACK option appears in the header, and was also present
       in the previous packet (with different SACK blocks).
       Two SACK blocks are assumed.

The table below illustrates the typical initial compression ratios
for ROHC-TCP and IPHC. The data stream in the example is assumed to
be IPv4+TCP, with a sequential behavior for the IP-ID. The following
options are assumed present in the SYN packet: TS, MSS, and WSCALE,
with an appropriate number of NOP options.

```
                  Total Header Size (octets)
                   Unc.   ROHC-TCP   IPHC
1st packet (SYN)   60        49      60
2nd packet         52        12      52
```

The figures in the table assume that the compressor has received an
acknowledgment from the decompressor before compressing the second
packet, which can be expected when feedback is used in ROHC-TCP.
This is because in the most common case, the TCP ACKs are expected to
take the same return path, and because TCP does not send more packets
until the TCP SYN packet has been acknowledged.

5. Compressor and Decompressor Logic (Normative)

5.1. Context Initialization

   The static context of ROHC-TCP flows can be initialized in either of
   two ways:

   1. By using an IR packet as in Section 7.1, where the profile number
       is 0x06 and the static chain ends with the static part of a TCP
       header.

   2. By replicating an existing context using the mechanism defined by
       [RFC4164]. This is done with the IR-CR packet defined in
       Section 7.2, where the profile number is 0x06.

5.2. Compressor Operation

5.2.1. Compression Logic

   The task of the compressor is to determine what data must be sent
   when compressing a TCP/IP packet, so that the decompressor can
   successfully reconstruct the original packet based on its current
   state. The selection of the type of compressed header to send thus
   depends on a number of factors, including:

   o The change behavior of header fields in the flow, e.g., conveying
      the necessary information within the restrictions of the set of
      available packet formats.

   o The compressor's level of confidence regarding decompressor state,
      e.g., by selecting header formats updating the same type of
      information for a number of consecutive packets or from the
      reception of decompressor feedback (ACKs and/or NACKs).

   o Additional robustness required for the flow, e.g., periodic
      refreshes of static and dynamic information using IR and IR-DYN
      packets when decompressor feedback is not expected.

   The impact of these factors on the compressor's packet type selection
   is described in more detail in the following subsections.

   In this section, a "higher compression state" means that less data
   will be sent in compressed packets, i.e., smaller compressed headers
   are used, while a lower compression state means that a larger amount
   of data will be sent using larger compressed headers.

5.2.1.1. Optimistic Approach

   The optimistic approach is the principle by which a compressor sends
   the same type of information for a number of packets (consecutively
   or not) until it is fairly confident that the decompressor has
   received the information. The optimistic approach is useful to
   ensure robustness when ROHC-TCP is used to compress packet over lossy
   links.

   Therefore, if field X in the uncompressed packet changes value, the
   compressor MUST use a packet type that contains an encoding for field
   X until it has gained confidence that the decompressor has received
   at least one packet containing the new value for X. The compressor
   SHOULD choose a compressed format with the smallest header that can
   convey the changes needed to fulfill the optimistic approach
   condition used.

5.2.1.2. Periodic Context Refreshes

   When the optimistic approach is used, there will always be a
   possibility of decompression failures since the decompressor may not
   have received sufficient information for correct decompression.

   Therefore, until the decompressor has established a feedback channel,
   the compressor SHOULD periodically move to a lower compression state
   and send IR and/or IR-DYN packets. These refreshes can be based on
   timeouts, on the number of compressed packets sent for the flow, or
   any other strategy specific to the implementation. Once the feedback
   channel is established, the decompressor MAY stop performing periodic
   refreshes.

5.2.2. Feedback Logic

   The semantics of feedback messages, acknowledgments (ACKs) and
   negative acknowledgments (NACKS or STATIC-NACKs), are defined in
   Section 5.2.4.1 of [RFC4995].

5.2.2.1. Optional Acknowledgments (ACKs)

   The compressor MAY use acknowledgment feedback (ACKs) to move to a
   higher compression state.

   Upon reception of an ACK for a context-updating packet, the
   compressor obtains confidence that the decompressor has received the
   acknowledged packet and that it has observed changes in the packet
   flow up to the acknowledged packet.

   This functionality is optional, so a compressor MUST NOT expect to
   get such ACKs, even if a feedback channel is available and has been
   established for that flow.

5.2.2.2. Negative Acknowledgments (NACKs)

   The compressor uses feedback from the decompressor to move to a lower
   compression state (NACKs).

   On reception of a NACK feedback, the compressor SHOULD:

   o assume that only the static part of the decompressor is valid, and

   o re-send all dynamic information (via an IR or IR-DYN packet) the
      next time it compresses a packet for the indicated flow

   unless it has confidence that information sent after the packet being
   acknowledged already provides a suitable response to the NACK
   feedback. In addition, the compressor MAY use a CO packet carrying a
   7-bit Cyclic Redundancy Check (CRC) if it can determine with enough
   confidence what information provides a suitable response to the NACK
   feedback.

   On reception of a STATIC-NACK feedback, the compressor SHOULD:

   o assume that the decompressor has no valid context, and

   o re-send all static and all dynamic information (via an IR packet)
      the next time it compresses a packet for the indicated flow

   unless it has confidence that information sent after the packet that
   is being acknowledged already provides a suitable response to the
   STATIC-NACK feedback.

5.2.3. Context Replication

   A compressor MAY support context replication by implementing the
   additional compression and feedback logic defined in [RFC4164].

5.3. Decompressor Operation

5.3.1. Decompressor States and Logic

   The three states of the decompressor are No Context (NC), Static
   Context (SC), and Full Context (FC). The decompressor starts in its
   lowest compression state, the NC state. Successful decompression
   will always move the decompressor to the FC state. The decompressor
   state machine normally never leaves the FC state once it has entered
   this state; only repeated decompression failures will force the
   decompressor to transit downwards to a lower state.

   Below is the state machine for the decompressor. Details of the
   transitions between states and decompression logic are given in the
   subsections following the figure.

```
                             Success
                +-->------>------>------>------>------>--+
                |                                       |
    No Static   |          No Dynamic      Success      |   Success
     +-->--+    |          +-->--+      +--->-----> ---+   +-->--+
     |     |    |          |     |      |              |   |     |
     |     v    |          |     v      |              v   |     v
  +----------------+    +--------------------+   +------------------+
  | No Context (NC) |    | Static Context (SC) |   | Full Context (FC) |
  +----------------+    +--------------------+   +------------------+
     ^                          |        ^                        |
     |    Static Context        |        | Context Damage Assumed  |
     |    Damage Assumed        |        |                         |
     +-----<------<------<-----+        +-----<------<------<-----+
```
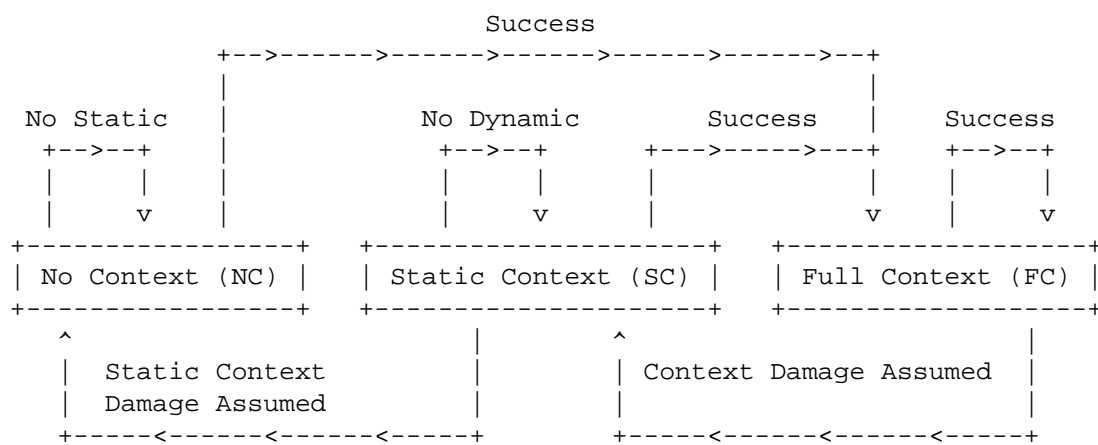
5.3.1.1. Reconstruction and Verification

   When decompressing an IR or an IR-DYN packet, the decompressor MUST
   validate the integrity of the received header using CRC-8 validation
   [RFC4995]. If validation fails, the packet MUST NOT be delivered to
   upper layers.

Upon receiving an IR-CR packet, the decompressor MUST perform the
actions as specified in [RFC4164].

When decompressing other packet types (e.g., CO packets), the
decompressor MUST validate the outcome of the decompression attempt
using CRC verification [RFC4995]. If verification fails, a
decompressor implementation MAY attempt corrective or repair measures
on the packet, and the result of any attempt MUST be validated using
the CRC verification; otherwise, the packet MUST NOT be delivered to
upper layers.

When the CRC-8 validation or the CRC verification of the received
header is successful, the decompressor SHOULD update its context with
the information received in the current header; the decompressor then
passes the reconstructed packet to the system's network layer.
Otherwise, the decompressor context MUST NOT be updated.

If the received packet is older than the current reference packet,
e.g., based on the master sequence number (MSN) in the compressed
packet, the decompressor MAY refrain from updating the context using
the information received in the current packet, even if the
correctness of its header was successfully verified.

5.3.1.2. Detecting Context Damage

All header formats carry a CRC and are context updating. A packet
for which the CRC succeeds updates the reference values of all header
fields, either explicitly (from the information about a field carried
within the compressed header) or implicitly (fields that are inferred
from other fields).

The decompressor may assume that some or the entire context is
invalid, following one or more failures to validate or verify a
header using the CRC. Because the decompressor cannot know the exact
reason(s) for a CRC failure or what field caused it, the validity of
the context hence does not refer to what exact context entry is
deemed valid or not.

Validity of the context rather relates to the detection of a problem
with the context. The decompressor first assumes that the type of
information that most likely caused the failure(s) is the state that
normally changes for each packet, i.e., context damage of the dynamic
part of the context. Upon repeated failures and unsuccessful
repairs, the decompressor then assumes that the entire context,
including the static part, needs to be repaired, i.e., static context
damage.

Context Damage Detection

   The assumption of context damage means that the decompressor will
   not attempt decompression of a CO header that carries a 3-bit CRC,
   and only attempt decompression of IR, IR-DYN, or IR-CR headers or
   CO headers protected by a CRC-7.

Static Context Damage Detection

   The assumption of static context damage means that the
   decompressor refrains from attempting decompression of any type of
   header other than the IR header.

How these assumptions are made, i.e., how context damage is detected,
is open to implementations. It can be based on the residual error
rate, where a low error rate makes the decompressor assume damage
more often than on a high-rate link.

The decompressor implements these assumptions by selecting the type
of compressed header for which it may attempt decompression. In
other words, validity of the context refers to the ability of a
decompressor to attempt or not attempt decompression of specific
packet types.

5.3.1.3. No Context (NC) State

   Initially, while working in the No Context (NC) state, the
   decompressor has not yet successfully decompressed a packet.

   Allowing decompression:

      In the NC state, only packets carrying sufficient information on
      the static fields (IR and IR-CR packets) can be decompressed;
      otherwise, the packet MUST NOT be decompressed and MUST NOT be
      delivered to upper layers.

   Feedback logic:

      In the NC state, the decompressor should send a STATIC-NACK if a
      packet of a type other than IR is received, or if decompression of
      an IR packet has failed, subject to the feedback rate limitation
      as described in Section 5.3.2

   Once a packet has been validated and decompressed correctly, the
   decompressor MUST transit to the FC state.

5.3.1.4. Static Context (SC) State

   When the decompressor is in the Static Context (SC) state, only the
   static part of the decompressor context is valid.

   From the SC state, the decompressor moves back to the NC state if
   static context damage is detected.

   Allowing decompression:

      In the SC state, packets carrying sufficient information on the
      dynamic fields covered by an 8-bit CRC (e.g., IR and IR-DYN) or CO
      packets covered by a 7-bit CRC can be decompressed; otherwise, the
      packet MUST NOT be decompressed and MUST NOT be delivered to upper
      layers.

   Feedback logic:

      In the SC state, the decompressor should send a STATIC-NACK if CRC
      validation of an IR/IR-DYN/IR-CR fails and static context damage
      is assumed. If any other packet type is received, the
      decompressor should send a NACK. Both of the above cases are
      subject to the feedback rate limitation as described in
      Section 5.3.2.

   Once a packet has been validated and decompressed correctly, the
   decompressor MUST transit to the FC state.

5.3.1.5. Full Context (FC) State

   In the Full Context (FC) state, both the static and the dynamic parts
   of the decompressor context are valid. From the FC state, the
   decompressor moves back to the SC state if context damage is
   detected.

   Allowing decompression:

      In the FC state, decompression can be attempted regardless of the
      type of packet received.

   Feedback logic:

      In the FC state, the decompressor should send a NACK if the
      decompression of any packet type fails and context damage is
      assumed, subject to the feedback rate limitation as described in
      Section 5.3.2.

5.3.2. Feedback Logic

   The decompressor MAY send positive feedback (ACKs) to initially
   establish the feedback channel for a particular flow. Either
   positive feedback (ACKs) or negative feedback (NACKs) establishes
   this channel.

   Once the feedback channel is established, the decompressor is
   REQUIRED to continue sending NACKs or STATIC-NACKs for as long as the
   context is associated with the same profile, in this case with
   profile 0x0006, as per the logic defined for each state in
   Section 5.3.1.

   The decompressor MAY send ACKs upon successful decompression of any
   packet type. In particular, when a packet carrying a significant
   context update is correctly decompressed, the decompressor MAY send
   an ACK.

   The decompressor should limit the rate at which it sends feedback,
   for both ACKs and STATIC-NACK/NACKs, and should avoid sending
   unnecessary duplicates of the same type of feedback message that may
   be associated to the same event.

5.3.3. Context Replication

   ROHC-TCP supports context replication; therefore, the decompressor
   MUST implement the additional decompressor and feedback logic defined
   in [RFC4164].

6. Encodings in ROHC-TCP (Normative)

6.1. Control Fields in ROHC-TCP

   In ROHC-TCP, a number of control fields are used by the decompressor
   in its interpretation of the format of the packets received from the
   compressor.

   A control field is a field that is transmitted from the compressor to
   the decompressor, but is not part of the uncompressed header. Values
   for control fields can be set up in the context of both the
   compressor and the decompressor. Once established at the
   decompressor, the values of these fields should be kept until updated
   by another packet.

6.1.1. Master Sequence Number (MSN)

   There is no field in the TCP header that can act as the master
   sequence number for TCP compression, as explained in [RFC4413],
   Section 5.6.

   To overcome this problem, ROHC-TCP introduces a control field called
   the Master Sequence Number (MSN) field. The MSN field is created at
   the compressor, rather than using one of the fields already present
   in the uncompressed header. The compressor increments the value of
   the MSN by one for each packet that it sends.

   The MSN field has the following two functions:

   1. Differentiating between packets when sending feedback data.

   2. Inferring the value of incrementing fields such as the IP-ID.

   The MSN field is present in every packet sent by the compressor. The
   MSN is LSB encoded within the CO packets, and the 16-bit MSN is sent
   in full in IR/IR-DYN packets. The decompressor always sends the MSN
   as part of the feedback information. The compressor can later use
   the MSN to infer which packet the decompressor is acknowledging.

   When the MSN is initialized, it SHOULD be initialized to a random
   value. The compressor should only initialize a new MSN for the
   initial IR or IR-CR packet sent for a CID that corresponds to a
   context that is not already associated with this profile. In other
   words, if the compressor reuses the same CID to compress many TCP
   flows one after the other, the MSN is not reinitialized but rather
   continues to increment monotonically.

   For context replication, the compressor does not use the MSN of the
   base context when sending the IR-CR packet, unless the replication
   process overwrites the base context (i.e., Base CID == CID).
   Instead, the compressor uses the value of the MSN if it already
   exists in the ROHC-TCP context being associated with the new flow
   (CID); otherwise, the MSN is initialized to a new value.

6.1.2. IP-ID Behavior

   The IP-ID field of the IPv4 header can have different change
   patterns. Conceptually, a compressor monitors changes in the value
   of the IP-ID field and selects encoding methods and packet formats
   that are the closest match to the observed change pattern.

   ROHC-TCP defines different types of compression techniques for the
   IP-ID, to provide the flexibility to compress any of the behaviors it

may observe for this field: sequential in network byte order (NBO),
sequential byte-swapped, random (RND), or constant to a value of
zero.

The compressor monitors changes in the value of the IP-ID field for a
number of packets, to identify which one of the above listed
compression alternatives is the closest match to the observed change
pattern. The compressor can then select packet formats and encoding
methods based on the identified field behavior.

If more than one level of IP headers is present, ROHC-TCP can assign
a sequential behavior (NBO or byte-swapped) only to the IP-ID of the
innermost IP header. This is because only this IP-ID can possibly
have a sufficiently close correlation with the MSN (see also
Section 6.1.1) to compress it as a sequentially changing field.
Therefore, a compressor MUST NOT assign either the sequential (NBO)
or the sequential byte-swapped behavior to tunneling headers.

The control field for the IP-ID behavior determines which set of
packet formats will be used. These control fields are also used to
determine the contents of the irregular chain item (see Section 6.2)
for each IP header.

6.1.3. Explicit Congestion Notification (ECN)

When ECN [RFC3168] is used once on a flow, the ECN bits could change
quite often. ROHC-TCP maintains a control field in the context to
indicate whether or not ECN is used. This control field is
transmitted in the dynamic chain of the TCP header, and its value can
be updated using specific compressed headers carrying a 7-bit CRC.

When this control field indicates that ECN is being used, items of
all IP and TCP headers in the irregular chain include bits used for
ECN. To preserve octet-alignment, all of the TCP reserved bits are
transmitted and, for outer IP headers, the entire Type of Service/
Traffic Class (TOS/TC) field is included in the irregular chain.
When there is only one IP header present in the packet (i.e., no IP
tunneling is used), this compression behavior allows the compressor
to handle changes in the ECN bits by adding a single octet to the
compressed header.

The reason for including the ECN bits of all IP headers in the
compressed packet when the control field is set is that the profile
needs to efficiently compress flows containing IP tunnels using the
"full-functionality option" of Section 9.1 of [RFC3168]. For these
flows, a change in the ECN bits of an inner IP header is propagated
to the outer IP headers. When the "limited-functionality" option is
used, the compressor will therefore sometimes send one octet more

than necessary per tunnel header, but this has been considered a
reasonable tradeoff when designing this profile.

6.2. Compressed Header Chains

Some packet types use one or more chains containing sub-header
information. The function of a chain is to group fields based on
similar characteristics, such as static, dynamic, or irregular
fields. Chaining is done by appending an item for each header to the
chain in their order of appearance in the uncompressed packet,
starting from the fields in the outermost header.

Chains are defined for all headers compressed by ROHC-TCP, as listed
below. Also listed are the names of the encoding methods used to
encode each of these protocol headers.

o TCP [RFC0793], encoding method: "tcp"

o IPv4 [RFC0791], encoding method: "ipv4"

o IPv6 [RFC2460], encoding method: "ipv6"

o AH [RFC4302], encoding method: "ah"

o GRE [RFC2784][RFC2890], encoding method: "gre"

o MINE [RFC2004], encoding method: "mine"

o NULL-encrypted ESP [RFC4303], encoding method: "esp_null"

o IPv6 Destination Options header [RFC2460], encoding method:
   "ip_dest_opt"

o IPv6 Hop-by-Hop Options header [RFC2460], encoding method:
   "ip_hop_opt"

o IPv6 Routing header [RFC2460], encoding method: "ip_rout_opt"

Static chain:

   The static chain consists of one item for each header of the chain
   of protocol headers to be compressed, starting from the outermost
   IP header and ending with a TCP header. In the formal description
   of the packet formats, this static chain item for each header is a
   format whose name is suffixed by "_static". The static chain is
   only used in IR packets.

Dynamic chain:

   The dynamic chain consists of one item for each header of the
   chain of protocol headers to be compressed, starting from the
   outermost IP header and ending with a TCP header. The dynamic
   chain item for the TCP header also contains a compressed list of
   TCP options (see Section 6.3). In the formal description of the
   packet formats, the dynamic chain item for each header type is a
   format whose name is suffixed by "_dynamic". The dynamic chain is
   used in both IR and IR-DYN packets.

Replicate chain:

   The replicate chain consists of one item for each header in the
   chain of protocol headers to be compressed, starting from the
   outermost IP header and ending with a TCP header. The replicate
   chain item for the TCP header also contains a compressed list of
   TCP options (see Section 6.3). In the formal description of the
   packet formats, the replicate chain item for each header type is a
   format whose name is suffixed by "_replicate". Header fields that
   are not present in the replicate chain are replicated from the
   base context. The replicate chain is only used in the IR-CR
   packet.

Irregular chain:

   The structure of the irregular chain is analogous to the structure
   of the static chain. For each compressed packet, the irregular
   chain is appended at the specified location in the general format
   of the compressed packets as defined in Section 7.3. This chain
   also includes the irregular chain items for TCP options as defined
   in Section 6.3.6, which are placed directly after the irregular
   chain item of the TCP header, and in the same order as the options
   appear in the uncompressed packet. In the formal description of
   the packet formats, the irregular chain item for each header type
   is a format whose name is suffixed by "_irregular". The irregular
   chain is used only in CO packets.

   The format of the irregular chain for the innermost IP header
   differs from the format of outer IP headers, since this header is
   part of the compressed base header.

6.3. Compressing TCP Options with List Compression

   This section describes in detail how list compression is applied to
   the TCP options. In the definition of the packet formats for ROHC-
   TCP, the most frequent TCP options have one encoding method each, as
   listed in the table below.

```
        +-----------------+------------------------+
        |   Option name   | Encoding method name   |
        +-----------------+------------------------+
        |       NOP       | tcp_opt_nop            |
        |       EOL       | tcp_opt_eol            |
        |       MSS       | tcp_opt_mss            |
        |  WINDOW SCALE   | tcp_opt_wscale         |
        |   TIMESTAMP     | tcp_opt_ts             |
        | SACK-PERMITTED  | tcp_opt_sack_permitted |
        |      SACK       | tcp_opt_sack           |
        | Generic options | tcp_opt_generic        |
        +-----------------+------------------------+
```

   Each of these encoding methods has an uncompressed format, a format
   suffixed by "_list_item" and a format suffixed by "_irregular". In
   some cases, a single encoding method may have multiple "_list_item"
   or "_irregular" formats, in which case bindings inside these formats
   determine what format is used. This is further described in the
   following sections.

6.3.1. List Compression

   The TCP options in the uncompressed packet can be represented as an
   ordered list, whose order and presence are usually constant between
   packets. The generic structure of such a list is as follows:

```
        +--------+--------+--...--+--------+
  list: | item 1 | item 2 |       | item n |
        +--------+--------+--...--+--------+
```

   To compress this list, ROHC-TCP uses a list compression scheme, which
   compresses each of these items individually and combines them into a
   compressed list.

   The basic principles of list-based compression are the following:

      1) When a context is being initialized, a complete representation
      of the compressed list of options is transmitted. All options
      that have any content are present in the compressed list of items
      sent by the compressor.

Then, once the context has been initialized:

    2) When the structure AND the content of the list are unchanged,
    no information about the list is sent in compressed headers.

    3) When the structure of the list is constant, and when only the
    content defined within the irregular format for one or more
    options is changed, no information about the list needs to be sent
    in compressed base headers; the irregular content is sent as part
    of the irregular chain, as described in Section 6.3.6.

    4) When the structure of the list changes, a compressed list is
    sent in the compressed base header, including a representation of
    its structure and order. Content defined within the irregular
    format of an option can still be sent as part of the irregular
    chain (as described in Section 6.3.6), provided that the item
    content is not part of the compressed list.

6.3.2. Table-Based Item Compression

   The Table-based item compression compresses individual items sent in
   compressed lists. The compressor assigns a unique identifier,
   "Index", to each item, "Item", of a list.

   Compressor Logic

      The compressor conceptually maintains an item table containing all
      items, indexed using "Index". The (Index, Item) pair is sent
      together in compressed lists until the compressor gains enough
      confidence that the decompressor has observed the mapping between
      items and their respective index. Confidence is obtained from the
      reception of an acknowledgment from the decompressor, or by
      sending (Index, Item) pairs using the optimistic approach. Once
      confidence is obtained, the index alone is sent in compressed
      lists to indicate the presence of the item corresponding to this
      index.

      The compressor may reassign an existing index to a new item, by
      re-establishing the mapping using the procedure described above.

   Decompressor Logic

      The decompressor conceptually maintains an item table that
      contains all (Index, Item) pairs received. The item table is
      updated whenever an (Index, Item) pair is received and
      decompression is successfully verified using the CRC. The
      decompressor retrieves the item from the table whenever an index
      without an accompanying item is received.

If an index without an accompanying item is received and the
decompressor does not have any context for this index, the header
MUST be discarded and a NACK SHOULD be sent.

6.3.3. Encoding of Compressed Lists

Each item present in a compressed list is represented by:

o an index into the table of items

o a presence bit indicating if a compressed representation of the
   item is present in the list

o an item (if the presence bit is set)

Decompression of an item will fail if the presence bit is not set and
the decompressor has no entry in the context for that item.

A compressed list of TCP options uses the following encoding:

```
   0   1   2   3   4   5   6   7
 +---+---+---+---+---+---+---+---+
 | Reserved  |PS |       m       |
 +---+---+---+---+---+---+---+---+
 |        XI_1, ..., XI_m        | m octets, or m * 4 bits
 /               --- --- --- ---/
 |              :    Padding     : if PS = 0 and m is odd
 +---+---+---+---+---+---+---+---+
 |                               |
 /      item_1, ..., item_n      / variable
 |                               |
 +---+---+---+---+---+---+---+---+
```

   Reserved: MUST be set to zero; otherwise, the decompressor MUST
   discard the packet.

   PS: Indicates size of XI fields:

      PS = 0 indicates 4-bit XI fields;

      PS = 1 indicates 8-bit XI fields.

   m: Number of XI item(s) in the compressed list.

   XI_1, ..., XI_m: m XI items. Each XI represents one TCP option in
   the uncompressed packet, in the same order as they appear in the
   uncompressed packet.

The format of an XI item is as follows:

```
          +---+---+---+---+
PS = 0: | X |   Index   |
          +---+---+---+---+

            0   1   2   3   4   5   6   7
          +---+---+---+---+---+---+---+---+
PS = 1: | X | Reserved  |     Index     |
          +---+---+---+---+---+---+---+---+
```

X: Indicates whether the item is present in the list:

   X = 1 indicates that the item corresponding to the Index is
   sent in the item_1, ..., item_n list;

   X = 0 indicates that the item corresponding to the Index is
   not sent and is instead included in the irregular chain.

Reserved: MUST be set to zero; otherwise, the decompressor MUST
discard the packet.

Index: An index into the item table. See Section 6.3.4.

When 4-bit XI items are used, the XI items are placed in octets
in the following manner:

```
    0   1   2   3   4   5   6   7
  +---+---+---+---+---+---+---+---+
  |     XI_k      |    XI_k + 1   |
  +---+---+---+---+---+---+---+---+
```

Padding: A 4-bit padding field is present when PS = 0 and the
number of XIs is odd. The Padding field MUST be set to zero;
otherwise, the decompressor MUST discard the packet.

Item 1, ..., item n: Each item corresponds to an XI with X = 1 in
XI 1, ..., XI m. The format of the entries in the item list is
described in Section 6.2.

6.3.4. Item Table Mappings

   The item table for TCP options list compression is limited to 16
   different items, since it is unlikely that any packet flow will
   contain a larger number of unique options.

The mapping between the TCP option type and table indexes are listed
in the table below:

```
+-----------------+---------------+
|   Option name   |  Table index  |
+-----------------+---------------+
|       NOP       |       0       |
|       EOL       |       1       |
|       MSS       |       2       |
|   WINDOW SCALE  |       3       |
|    TIMESTAMP    |       4       |
|  SACK-PERMITTED |       5       |
|       SACK      |       6       |
|  Generic options|      7-15     |
+-----------------+---------------+
```

Some TCP options are used more frequently than others. To simplify
their compression, a part of the item table is reserved for these
option types, as shown on the table above. Both the compressor and
the decompressor MUST use these mappings between item and indexes to
(de)compress TCP options when using list compression.

It is expected that the option types for which an index is reserved
in the item table will only appear once in a list. However, if an
option type is detected twice in the same options list and if both
options have a different content, the compressor should compress the
second occurrence of the option type by mapping it to a generic
compressed option. Otherwise, if the options have the exact same
content, the compressor can still use the same table index for both.

The NOP option

   The NOP option can appear more than once in the list. However,
   since its value is always the same, no context information needs
   to be transmitted. Multiple NOP options can thus be mapped to the
   same index. Since the NOP option does not have any content when
   compressed as a "_list_item", it will never be present in the item
   list. For consistency, the compressor should still establish an
   entry in the list by setting the presence bit, as done for the
   other type of options.

   List compression always preserves the original order of each item
   in the decompressed list, whether or not the item is present in
   the compressed "_list_item" or if multiple items of the same type
   can be mapped to the same index, as for the NOP option.

   The EOL option

      The size of the compressed format for the EOL option can be larger
      than one octet, and it is defined so that it includes the option
      padding. This is because the EOL should terminate the parsing of
      the options, but it can also be followed by padding octets that
      all have the value zero.

   The Generic option

      The Generic option can be used to compress any type of TCP option
      that does not have a reserved index in the item table.

6.3.5. Compressed Lists in Dynamic Chain

   A compressed list for TCP options that is part of the dynamic chain
   (e.g., in IR or IR-DYN packets) must have all its list items present,
   i.e., all X-bits in the XI list MUST be set.

6.3.6. Irregular Chain Items for TCP Options

   The "_list_item" represents the option inside the compressed item
   list, and the "_irregular" format is used for the option fields that
   are expected to change with each packet. When an item of the
   specified type is present in the current context, these irregular
   fields are present in each compressed packet, as part of the
   irregular chain. Since many of the TCP option types are not expected
   to change for the duration of a flow, many of the "_irregular"
   formats are empty.

   The irregular chain for TCP options is structured analogously to the
   structure of the TCP options in the uncompressed packet. If a
   compressed list is present in the compressed packet, then the
   irregular chain for TCP options must not contain irregular items for
   the list items that are transmitted inside the compressed list (i.e.,
   items in the list that have the X-bit set in its XI). The items that
   are not present in the compressed list, but are present in the
   uncompressed list, must have their respective irregular items present
   in the irregular chain.

6.3.7. Replication of TCP Options

   The entire table of TCP options items is always replicated when using
   the IR-CR packet. In the IR-CR packet, the list of options for the
   new flow is also transmitted as a compressed list in the IR-CR
   packet.

6.4. Profile-Specific Encoding Methods

   This section defines encoding methods that are specific to this
   profile. These methods are used in the formal definition of the
   packet formats in Section 8.

6.4.1. inferred_ip_v4_header_checksum

   This encoding method compresses the Header Checksum field of the IPv4
   header. This checksum is defined in [RFC0791] as follows:

      Header Checksum: 16 bits

         A checksum on the header only. Since some header fields change
         (e.g., time to live), this is recomputed and verified at each
         point that the internet header is processed.

      The checksum algorithm is:

         The checksum field is the 16 bit one's complement of the one's
         complement sum of all 16 bit words in the header. For purposes
         of computing the checksum, the value of the checksum field is
         zero.

   As described above, the header checksum protects individual hops from
   processing a corrupted header. When almost all IP header information
   is compressed away, and when decompression is verified by a CRC
   computed over the original header for every compressed packet, there
   is no point in having this additional checksum; instead, it can be
   recomputed at the decompressor side.

   The "inferred_ip_v4_header_checksum" encoding method thus compresses
   the IPv4 header checksum down to a size of zero bits. Using this
   encoding method, the decompressor infers the value of this field
   using the computation above.

   This encoding method implicitly assumes that the compressor will not
   process a corrupted header; otherwise, it cannot guarantee that the
   checksum as recomputed by the decompressor will be bitwise identical
   to its original value before compression.

6.4.2. inferred_mine_header_checksum

   This encoding method compresses the minimal encapsulation header
   checksum. This checksum is defined in [RFC2004] as follows:

      Header Checksum

         The 16-bit one's complement of the one's complement sum of all
         16-bit words in the minimal forwarding header. For purposes of
         computing the checksum, the value of the checksum field is 0.
         The IP header and IP payload (after the minimal forwarding
         header) are not included in this checksum computation.

   The "inferred_mine_header_checksum" encoding method compresses the
   minimal encapsulation header checksum down to a size of zero bits,
   i.e., no bits are transmitted in compressed headers for this field.
   Using this encoding method, the decompressor infers the value of this
   field using the above computation.

   The motivations and the assumptions for inferring this checksum are
   similar to the ones explained above in Section 6.4.1.

6.4.3. inferred_ip_v4_length

   This encoding method compresses the Total Length field of the IPv4
   header. The Total Length field of the IPv4 header is defined in
   [RFC0791] as follows:

      Total Length: 16 bits

         Total Length is the length of the datagram, measured in octets,
         including internet header and data. This field allows the
         length of a datagram to be up to 65,535 octets.

   The "inferred_ip_v4_length" encoding method compresses the IPv4
   header checksum down to a size of zero bits. Using this encoding
   method, the decompressor infers the value of this field by counting
   in octets the length of the entire packet after decompression.

6.4.4. inferred_ip_v6_length

   This encoding method compresses the Payload Length field of the IPv6
   header. This length field is defined in [RFC2460] as follows:

      Payload Length: 16-bit unsigned integer

         Length of the IPv6 payload, i.e., the rest of the packet
         following this IPv6 header, in octets. (Note that any
         extension headers present are considered part of the payload,
         i.e., included in the length count.)

   The "inferred_ip_v6_length" encoding method compresses the Payload
   Length field of the IPv6 header down to a size of zero bits. Using
   this encoding method, the decompressor infers the value of this field
   by counting in octets the length of the entire packet after
   decompression.

6.4.5. inferred_offset

   This encoding method compresses the data offset field of the TCP
   header.

   The "inferred_offset" encoding method is used on the Data Offset
   field of the TCP header. This field is defined in [RFC0793] as:

      Data Offset: 4 bits

         The number of 32 bit words in the TCP Header. This indicates
         where the data begins. The TCP header (even one including
         options) is an integral number of 32 bits long.

   The "inferred_offset" encoding method compresses the Data Offset
   field of the TCP header down to a size of zero bits. Using this
   encoding method, the decompressor infers the value of this field by
   first decompressing the TCP options list, and by then setting:

              data offset = (options length / 4) + 5

   The equation above uses integer arithmetic.

6.4.6. baseheader_extension_headers

   In CO packets (see Section 7.3), the innermost IP header and the TCP
   header are combined to create a compressed base header. In some
   cases, the IP header will have a number of extension headers between
   itself and the TCP header.

To remain formally correct, the base header must define some
representation of these extension headers, which is what this
encoding method is used for. This encoding method skips over all the
extension headers and does not encode any of the fields. Changed
fields in these headers are encoded in the irregular chain.

6.4.7. baseheader_outer_headers

This encoding method, as well as the baseheader_extension_headers
encoding method described above, is needed for the specification to
remain formally correct. It is used in CO packets (see Section 7.3)
to describe tunneling IP headers and their respective extension
headers (i.e., all headers located before the innermost IP header).

This encoding method skips over all the fields in these headers and
does not perform any encoding. Changed fields in outer headers are
instead handled by the irregular chain.

6.4.8. Scaled Encoding of Fields

Some header fields will exhibit a change pattern where the field
increases by a constant value or by multiples of the same value.

Examples of fields that may have this behavior are the TCP Sequence
Number and the TCP Acknowledgment Number. For such fields, ROHC-TCP
provides the means to downscale the field value before applying LSB
encoding, which allows the compressor to transmit fewer bits.

To be able to use scaled encoding, the field is required to fulfill
the following equation:

     unscaled_value = scaling_factor * scaled_value + residue

To use the scaled encoding, the compressor must be confident that the
decompressor has established values for the "residue" and the
"scaling_factor", so that it can correctly decompress the field when
only an LSB-encoded "scaled_value" is present in the compressed
packet.

Once the compressor is confident that the value of the scaling_factor
and the value of the residue have been established in the
decompressor, the compressor may send compressed packets using the
scaled representation of the field. The compressor MUST NOT use
scaled encoding with the value of the scaling_factor set to zero.

If the compressor detects that the value of the residue has changed,
or if the compressor uses a different value for the scaling factor,

it MUST NOT use scaled encoding until it is confident that the
decompressor has received the new value(s) of these fields.

When the unscaled value of the field wraps around, the value of the
residue is likely to change, even if the scaling_factor remains
constant. In such a case, the compressor must act in the same way as
for any other change in the residue.

The following subsections describe how the scaled encoding is applied
to specific fields in ROHC-TCP, in particular, how the scaling_factor
and residue values are established for the different fields.

6.4.8.1. Scaled TCP Sequence Number Encoding

For some TCP flows, such as data transfers, the payload size will be
constant over periods of time. For such flows, the TCP Sequence
Number is bound to increase by multiples of the payload size between
packets, which means that this field can be a suitable target for
scaled encoding. When using this encoding, the payload size will be
used as the scaling factor (i.e., as the value for scaling_factor) of
this encoding. This means that the scaling factor does not need to
be explicitly transmitted, but is instead inferred from the length of
the payload in the compressed packet.

Establishing scaling_factor:

   The scaling factor is established by sending unscaled TCP Sequence
   Number bits, so that the decompressor can infer the scaling_factor
   from the payload size.

Establishing residue:

   The residue is established identically as the scaling_factor,
   i.e., by sending unscaled TCP Sequence Number bits.

A detailed specification of how the TCP Sequence Number uses the
scaled encoding can be found in the definitions of the packet
formats, in Section 8.2.

6.4.8.2. Scaled Acknowledgment Number Encoding

Similar to the pattern exhibited by the TCP Sequence Number, the
expected increase in the TCP Acknowledgment Number is often constant
and is therefore suitable for scaled encoding.

For the TCP Acknowledgment Number, the scaling factor depends on the
size of packets flowing in the opposite direction; this information
might not be available to the compressor/decompressor pair. For this

reason, ROHC-TCP uses an explicitly transmitted scaling factor to
compress the TCP Acknowledgment Number.

Establishing scaling_factor:

   The scaling factor is established by explicitly transmitting the
   value of the scaling factor (called ack_stride in the formal
   notation in Section 8.2) to the decompressor, using one of the
   packet types that can carry this information.

Establishing residue:

   The scaling factor is established by sending unscaled TCP
   Acknowledgment Number bits, so that the decompressor can infer its
   value from the unscaled value and the scaling factor (ack_stride).

A detailed specification of how the TCP Acknowledgment Number uses
the scaled encoding can be found in the definitions of the packet
formats, in Section 8.2.

The compressor MAY use the scaled acknowledgment number encoding;
what value it will use as the scaling factor is up to the compressor
implementation. In the case where there is a co-located decompressor
processing packets of the same TCP flow in the opposite direction,
the scaling factor for the sequence number used for that flow can be
used by the compressor to determine a suitable scaling factor for the
TCP Acknowledgment number for this flow.

6.5. Encoding Methods With External Parameters

A number of encoding methods in Section 8.2 have one or more
arguments for which the derivation of the parameter's value is
outside the scope of the ROHC-FN specification of the header formats.
This section lists the encoding methods together with a definition of
each of their parameters.

o esp_null(next_header_value):

      next_header_value: Set to the value of the Next Header field
      located in the ESP trailer, usually 12 octets from the end of
      the packet. Compression of null-encrypted ESP headers should
      only be performed when the compressor has prior knowledge of
      the exact location of the Next Header field.

   o ipv6(is_innermost, ttl_irregular_chain_flag, ip_inner_ecn):

         is_innermost: This Boolean flag is set to true when processing
         the innermost IP header; otherwise, it is set to false.

         ttl_irregular_chain_flag: This parameter must be set to the
         value that was used for the corresponding
         "ttl_irregular_chain_flag" parameter of the "co_baseheader"
         encoding method (as defined below) when extracting the
         irregular chain for a compressed header; otherwise, it is set
         to zero and ignored for other types of chains.

         ip_inner_ecn: This parameter is bound by the encoding method,
         and therefore it should be undefined when calling this encoding
         method. This value is then used to bind the corresponding
         parameter in the "tcp" encoding method, as its value is needed
         when processing the irregular chain for TCP. See the
         definition of the "ip_inner_ecn" parameter for the "tcp"
         encoding method below.

   o ipv4(is_innermost, ttl_irregular_chain_flag, ip_inner_ecn):

         See definition of arguments for "ipv6" above.

   o tcp_opt_eol(nbits):

         nbits: This parameter is set to the length of the padding data
         located after the EOL option type octet to the end of the TCP
         options in the uncompressed header.

   o tcp_opt_sack(ack_value):

         ack_value: Set to the value of the Acknowledgment Number field
         of the TCP header.

   o tcp(payload_size, ack_stride_value, ip_inner_ecn):

         payload_size: Set to the length (in octets) of the payload
         following the TCP header.

         ack_stride_value: This parameter is the scaling factor used
         when scaling the TCP Acknowledgment Number. Its value is set
         by the compressor implementation. See Section 6.4.8.2 for
         recommendations on how to set this value.

         ip_inner_ecn: This parameter binds with the value given to the
         corresponding "ip_inner_ecn" parameter by the "ipv4" or the
         "ipv6" encoding method when processing the innermost IP header

          of this packet. See also the definition of the "ip_inner_ecn"
          parameter to the "ipv6" and "ipv4" encoding method above.

   o co_baseheader(payload_size, ack_stride_value,
      ttl_irregular_chain_flag):

          payload_size: Set to the length (in octets) of the payload
          following the TCP header.

          ack_stride_value: This parameter is the scaling factor used
          when scaling the TCP Acknowledgment Number. Its value is set
          by the compressor implementation. See Section 6.4.8.2 for
          recommendations on how to set this value.

          ttl_irregular_chain_flag: This parameter is set to one if the
          TTL/Hop Limit of an outer header has changed compared to its
          reference in the context; otherwise, it is set to zero. The
          value used for this parameter is also used for the
          "ttl_irregular_chain_flag" argument for the "ipv4" and "ipv6"
          encoding methods when processing the irregular chain, as
          defined above for the "ipv6" and "ipv4" encoding methods.

7. Packet Types (Normative)

   ROHC-TCP uses three different packet types: the Initialization and
   Refresh (IR) packet type, the Context Replication (IR-CR) packet
   type, and the Compressed (CO) packet type.

   Each packet type defines a number of packet formats: two packet
   formats are defined for the IR type, one packet format is defined for
   the IR-CR type, and two sets of eight base header formats are defined
   for the CO type with one additional format that is common to both
   sets.

   The profile identifier for ROHC-TCP is 0x0006.

7.1. Initialization and Refresh (IR) Packets

   ROHC-TCP uses the basic structure of the ROHC IR and IR-DYN packets
   as defined in [RFC4995] (Sections 5.2.2.1 and 5.2.2.2, respectively).

   Packet type: IR

      This packet type communicates the static part and the dynamic part
      of the context.

      For the ROHC-TCP IR packet, the value of the x bit MUST be set to
      one. It has the following format, which corresponds to the

"Header" and "Payload" fields described in Section 5.2.1 of
[RFC4995]:

```
   0   1   2   3   4   5   6   7
 --- --- --- --- --- --- --- ---
:          Add-CID octet       : if for small CIDs and (CID != 0)
+---+---+---+---+---+---+---+---+
| 1   1   1   1   1   1   0   1 | IR type octet
+---+---+---+---+---+---+---+---+
:                              :
/        0-2 octets of CID     / 1-2 octets if for large CIDs
:                              :
+---+---+---+---+---+---+---+---+
|          Profile = 0x06      | 1 octet
+---+---+---+---+---+---+---+---+
|             CRC              | 1 octet
+---+---+---+---+---+---+---+---+
|                              |
/         Static chain         / variable length
|                              |
 - - - - - - - - - - - - - - - -
|                              |
/        Dynamic chain         / variable length
|                              |
 - - - - - - - - - - - - - - - -
|                              |
/            Payload           / variable length
|                              |
 - - - - - - - - - - - - - - - -
```
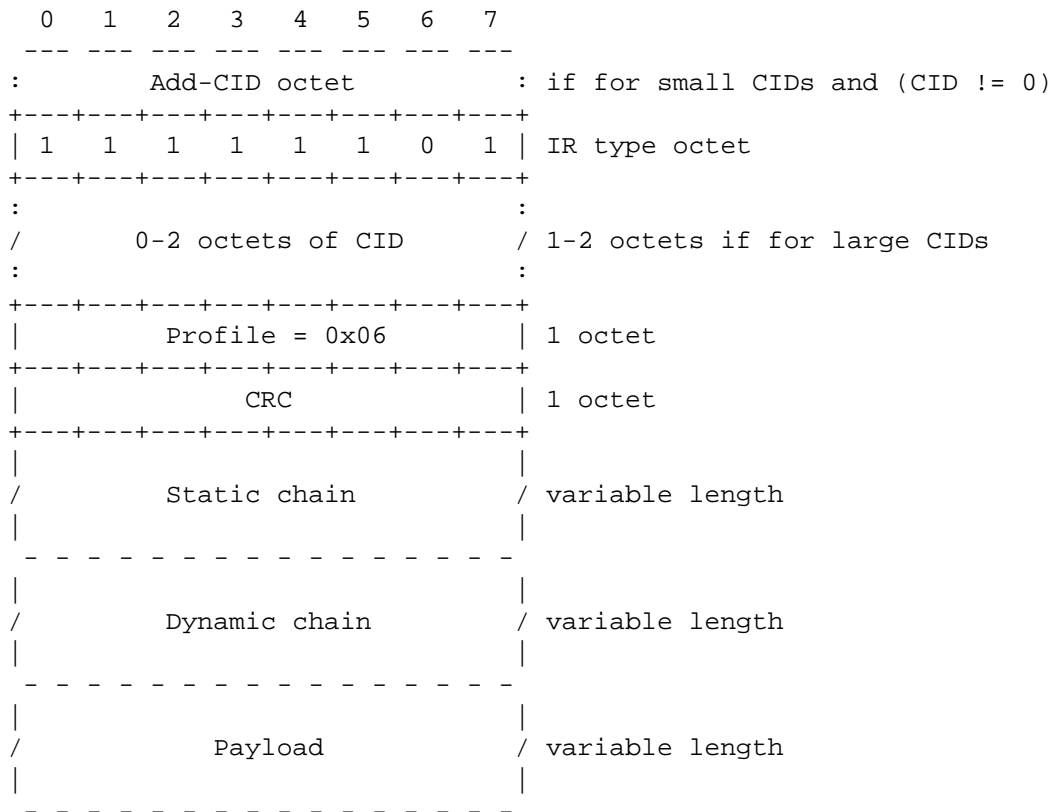
CRC: 8-bit CRC, computed according to Section 5.3.1.1. of
[RFC4995]. The CRC covers the entire IR header, thus excluding
payload, padding, and feedback, if any.

Static chain: See Section 6.2.

Dynamic chain: See Section 6.2.

Payload: The payload of the corresponding original packet, if any.
The payload consists of all data after the last octet of the TCP
header to end of the uncompressed packet. The presence of a
payload is inferred from the packet length.

Packet type: IR-DYN

This packet type communicates the dynamic part of the context.

The ROHC-TCP IR-DYN packet has the following format, which
corresponds to the "Header" and "Payload" fields described in
Section 5.2.1 of [RFC4995]:

```
     0   1   2   3   4   5   6   7
   --- --- --- --- --- --- --- ---
  :           Add-CID octet          : if for small CIDs and (CID != 0)
  +---+---+---+---+---+---+---+---+
  | 1   1   1   1   1   0   0   0 | IR-DYN type octet
  +---+---+---+---+---+---+---+---+
  :                               :
  /        0-2 octets of CID       / 1-2 octets if for large CIDs
  :                               :
  +---+---+---+---+---+---+---+---+
  |           Profile = 0x06       | 1 octet
  +---+---+---+---+---+---+---+---+
  |               CRC             | 1 octet
  +---+---+---+---+---+---+---+---+
  |                               |
  /         Dynamic chain         / variable length
  |                               |
   - - - - - - - - - - - - - - - -
  |                               |
  /             Payload           / variable length
  |                               |
   - - - - - - - - - - - - - - - -
```

CRC: 8-bit CRC, computed according to Section 5.3.1.1 of
[RFC4995]. The CRC covers the entire IR-DYN header, thus
excluding payload, padding, and feedback, if any.
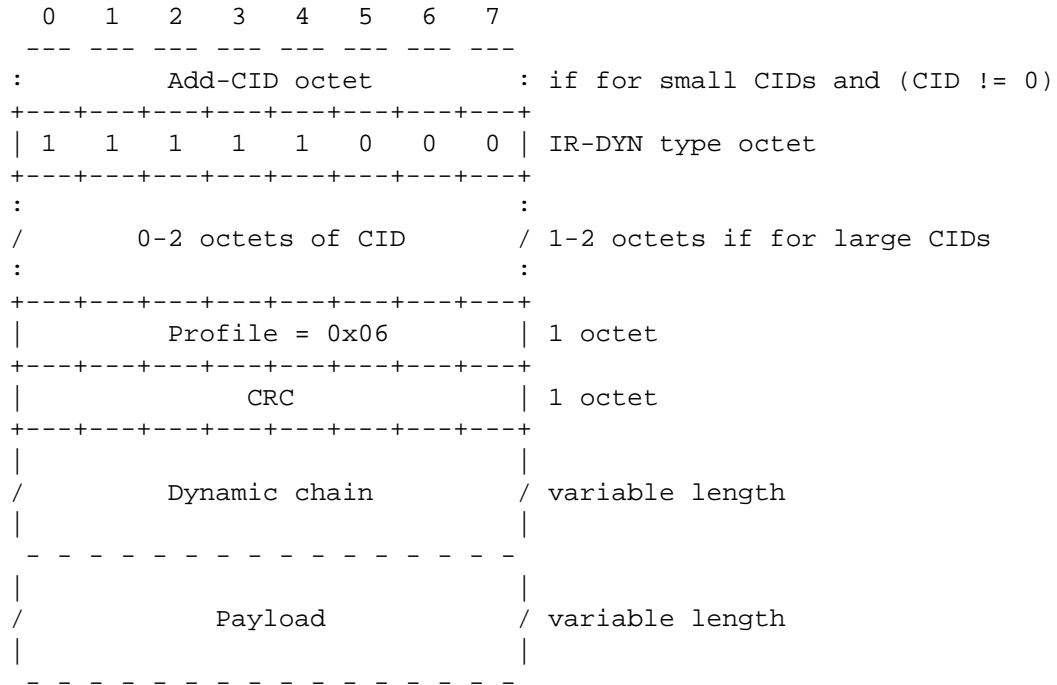
Dynamic chain: See Section 6.2.

Payload: The payload of the corresponding original packet, if any.
The payload consists of all data after the last octet of the TCP
header to end of the uncompressed packet. The presence of a
payload is inferred from the packet length.

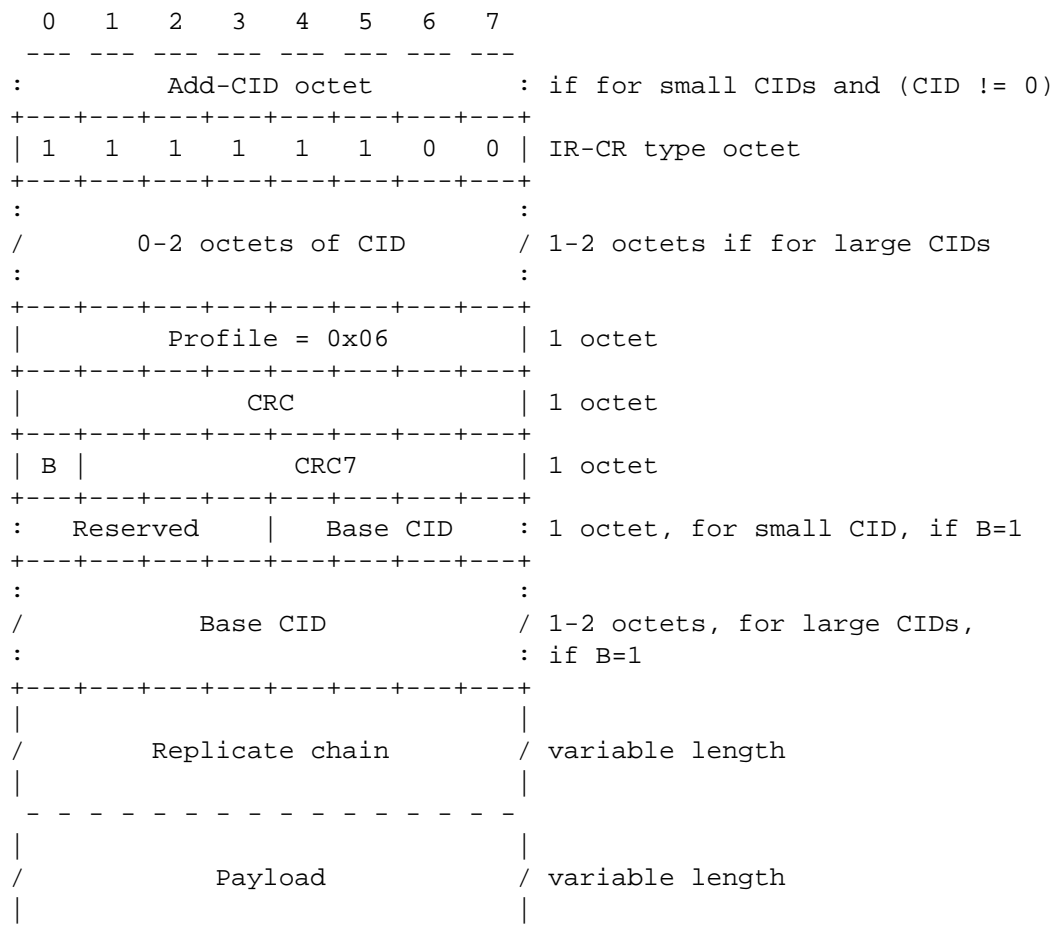7.2. Context Replication (IR-CR) Packets

Context replication requires a dedicated IR packet format that
uniquely identifies the IR-CR packet for the ROHC-TCP profile. This
section defines the profile-specific part of the IR-CR packet
[RFC4164].

   Packet type: IR-CR

      This packet type communicates a reference to a base context along
      with the static and dynamic parts of the replicated context that
      differs from the base context.

   The ROHC-TCP IR-CR packet follows the general format of the ROHC CR
   packet, as defined in [RFC4164], Section 3.5.2. With consideration
   to the extensibility of the IR packet type defined in [RFC4995], the
   ROHC-TCP profile supports context replication through the profile-
   specific part of the IR packet. This is achieved using the bit (x)
   left in the IR header for "Profile specific information". For ROHC-
   TCP, this bit is defined as a flag indicating whether this packet is
   an IR packet or an IR-CR packet. For the ROHC-TCP IR-CR packet, the
   value of the x bit MUST be set to zero.

The ROHC-TCP IR-CR has the following format, which corresponds to the "Header" and "Payload" fields described in Section 5.2.1 of [RFC4995]:

```
      0   1   2   3   4   5   6   7
     --- --- --- --- --- --- --- ---
     :           Add-CID octet        : if for small CIDs and (CID != 0)
     +---+---+---+---+---+---+---+---+
     | 1   1   1   1   1   1   0   0 | IR-CR type octet
     +---+---+---+---+---+---+---+---+
     :                               :
     /       0-2 octets of CID        / 1-2 octets if for large CIDs
     :                               :
     +---+---+---+---+---+---+---+---+
     |          Profile = 0x06       | 1 octet
     +---+---+---+---+---+---+---+---+
     |             CRC               | 1 octet
     +---+---+---+---+---+---+---+---+
     | B |            CRC7           | 1 octet
     +---+---+---+---+---+---+---+---+
     :   Reserved    |   Base CID    : 1 octet, for small CID, if B=1
     +---+---+---+---+---+---+---+---+
     :                               :
     /          Base CID             / 1-2 octets, for large CIDs,
     :                               : if B=1
     +---+---+---+---+---+---+---+---+
     |                               |
     /        Replicate chain        / variable length
     |                               |
      - - - - - - - - - - - - - - - -
     |                               |
     /           Payload             / variable length
     |                               |
      - - - - - - - - - - - - - - - -
```

B: B = 1 indicates that the Base CID field is present.

CRC: This CRC covers the entire IR-CR header, thus excluding payload, padding, and feedback, if any. This 8-bit CRC is calculated according to Section 5.3.1.1 of [RFC4995].

CRC7: The CRC over the original, uncompressed, header. Calculated according to Section 3.5.1.1 of [RFC4164].

Reserved: MUST be set to zero; otherwise, the decompressor MUST discard the packet.

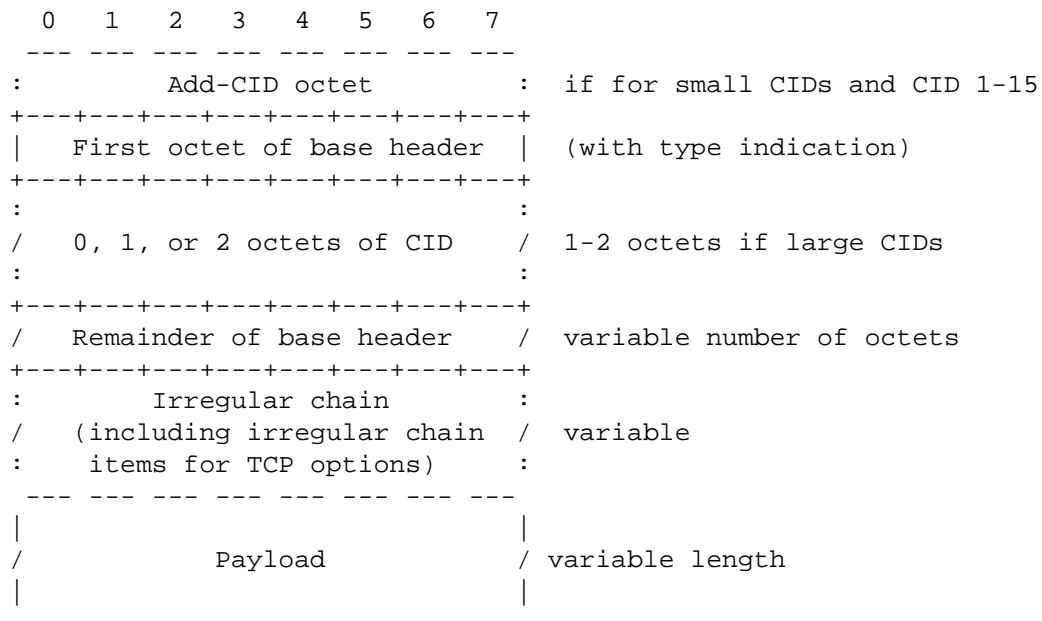Base CID: CID of base context. Encoded according to [RFC4164],
Section 3.5.3.

Replicate chain: See Section 6.2.

Payload: The payload of the corresponding original packet, if any.
The presence of a payload is inferred from the packet length.

7.3. Compressed (CO) Packets

   The ROHC-TCP CO packets communicate irregularities in the packet
   header. All CO packets carry a CRC and can update the context.

   The general format for a compressed TCP header is as follows, which
   corresponds to the "Header" and "Payload" fields described in Section
   5.2.1 of [RFC4995]:

```
        0   1   2   3   4   5   6   7
      --- --- --- --- --- --- --- ---
     :           Add-CID octet        :  if for small CIDs and CID 1-15
     +---+---+---+---+---+---+---+---+
     |   First octet of base header  |  (with type indication)
     +---+---+---+---+---+---+---+---+
     :                               :
     /   0, 1, or 2 octets of CID    /  1-2 octets if large CIDs
     :                               :
     +---+---+---+---+---+---+---+---+
     /   Remainder of base header    /  variable number of octets
     +---+---+---+---+---+---+---+---+
     :          Irregular chain      :
     /   (including irregular chain  /  variable
     :     items for TCP options)    :
      --- --- --- --- --- --- --- ---
     |                               |
     /            Payload            /  variable length
     |                               |
      - - - - - - - - - - - - - - - -
```

Base header: The complete set of base headers is defined in
Section 8.

Irregular chain: See Section 6.2 and Section 6.3.6.

Payload: The payload of the corresponding original packet, if any.
The presence of a payload is inferred from the packet length.

8. Header Formats (Normative)

   This section describes the set of compressed TCP/IP packet formats.
   The normative description of the packet formats is given using the
   formal notation for ROHC profiles defined in [RFC4997]. The formal
   description of the packet formats specifies all of the information
   needed to compress and decompress a header relative to the context.

   In particular, the notation provides a list of all the fields present
   in the uncompressed and compressed TCP/IP headers, and defines how to
   map from each uncompressed packet to its compressed equivalent and
   vice versa.

8.1. Design Rationale for Compressed Base Headers

   The compressed header formats are defined as two separate sets: one
   set for the packets where the innermost IP header contains a
   sequential IP-ID (either network byte order or byte swapped), and one
   set for the packets without sequential IP-ID (either random, zero, or
   no IP-ID).

   These two sets of header formats are referred to as the "sequential"
   and the "random" set of header formats, respectively.

   In addition, there is one compressed format that is common to both
   sets of header formats and that can thus be used regardless of the
   type of IP-ID behavior. This format can transmit rarely changing
   fields and also send the frequently changing fields coded in variable
   lengths. It can also change the value of control fields such as
   IP-ID behavior and ECN behavior.

   All compressed base headers contain a 3-bit CRC, unless they update
   control fields such as "ip_id_behavior" or "ecn_used" that affect the
   interpretation of subsequent headers. Headers that can modify these
   control fields carry a 7-bit CRC instead.

   When discussing LSB-encoded fields below, "p" equals the
   "offset_param" and "k" equals the "num_lsbs_param" in [RFC4997]. The
   encoding methods used in the compressed base headers are based on the
   following design criteria:

   o MSN

         Since the MSN is a number generated by the compressor, it only
         needs to be large enough to ensure robust operation and to
         accommodate a small amount of reordering [RFC4163]. Therefore,
         each compressed base header has an MSN field that is LSB-
         encoded with k=4 and p=4 to handle a reordering depth of up to

4 packets. Additional guidance to improve robustness when
reordering is possible can be found in [RFC4224].

o TCP Sequence Number

ROHC-TCP has the capability to handle bulk data transfers
efficiently, for which the sequence number is expected to
increase by about 1460 octets (which can be represented by 11
bits). For the compressed base headers to handle
retransmissions (i.e., negative delta to the sequence number),
the LSB interpretation interval has to handle negative offsets
about as large as positive offsets, which means that one more
bit is needed.

Also, for ROHC-TCP to be robust to losses, two additional bits
are added to the LSB encoding of the sequence number. This
means that the base headers should contain at least 14 bits of
LSB-encoded sequence number when present. According to the
logic above, the LSB offset value is set to be as large as the
positive offset, i.e., $p = 2^{(k-1)}-1$.

o TCP Acknowledgment Number

The design criterion for the acknowledgment number is similar
to that of the TCP Sequence Number. However, often only every
other data packet is acknowledged, which means that the
expected delta value is twice as large as for sequence numbers.

Therefore, at least 15 bits of acknowledgment number should be
used in compressed base headers. Since the acknowledgment
number is expected to constantly increase, and the only
exception to this is packet reordering (either on the ROHC
channel [RFC3759] or prior to the compression point), the
negative offset for LSB encoding is set to be 1/4 of the total
interval, i.e., $p = 2^{(k-2)}-1$.

o TCP Window

The TCP Window field is expected to increase in increments of
similar size as the TCP Sequence Number, and therefore the
design criterion for the TCP window is to send at least 14 bits
when used.

o IP-ID

For the "sequential" set of packet formats, all the compressed
base headers contain LSB-encoded IP-ID offset bits, where the
offset is the difference between the value of the MSN field and

        the value of the IP-ID field. The requirement is that at least
        3 bits of IP-ID should always be present, but it is preferable
        to use 4 to 7 bits. When k=3 then p=1, and if k>3 then p=3
        since the offset is expected to increase most of the time.

   Each set of header formats contains eight different compressed base
   headers. The reason for having this large number of header formats
   is that the TCP Sequence Number, TCP Acknowledgment Number, and TCP
   Window are frequently changing in a non-linear pattern.

   The design of the header formats is derived from the field behavior
   analysis found in [RFC4413].

   All of the compressed base headers transmit LSB-encoded MSN bits, the
   TCP Push flag, and a CRC, and in addition to this, all the base
   headers in the sequential packet format set contain LSB-encoded IP-ID
   bits.

   The following header formats exist in both the sequential and random
   packet format sets:

   o Format 1: This header format carries changes to the TCP Sequence
      Number and is expected to be used on the downstream of a data
      transfer.

   o Format 2: This header format carries the TCP Sequence Number in
      scaled form and is expected to be useful for the downstream of a
      data transfer where the payload size is constant for multiple
      packets.

   o Format 3: This header format carries changes in the TCP
      Acknowledgment Number and is expected to be useful for the
      acknowledgment direction of a data transfer.

   o Format 4: This header format is similar to format 3, but carries a
      scaled TCP Acknowledgment Number.

   o Format 5: This header format carries both the TCP Sequence Number
      and the TCP Acknowledgment Number and is expected to be useful for
      flows that send data in both directions.

   o Format 6: This header format is similar to format 5, but carries
      the TCP Sequence Number in scaled form, when the payload size is
      static for certain intervals in a data flow.

   o Format 7: This header format carries changes to both the TCP
      Acknowledgment Number and the TCP Window and is expected to be
      useful for the acknowledgment flows of data connections.

   o Format 8: This header format is used to convey changes to some of
      the more seldom changing fields in the TCP flow, such as ECN
      behavior, RST/SYN/FIN flags, the TTL/Hop Limit, and the TCP
      options list. This format carries a 7-bit CRC, since it can
      change the structure of the contents of the irregular chain for
      subsequent packets. Note that this can be seen as a reduced form
      of the common packet format.

   o Common header format: The common header format can be used for all
      kinds of IP-ID behavior and should be useful when some of the more
      rarely changing fields in the IP or TCP header change. Since this
      header format can update control fields that decide how the
      decompressor interprets packets, it carries a 7-bit CRC to reduce
      the probability of context corruption. This header can basically
      convey changes to any of the dynamic fields in the IP and TCP
      headers, and it uses a large set of flags to provide information
      about which fields are present in the header format.

8.2. Formal Definition of Header Formats

 //////////////////////////////////////
 // Constants
 //////////////////////////////////////

 IP_ID_BEHAVIOR_SEQUENTIAL = 0;
 IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED = 1;
 IP_ID_BEHAVIOR_RANDOM = 2;
 IP_ID_BEHAVIOR_ZERO = 3;

 //////////////////////////////////////
 // Global control fields
 //////////////////////////////////////

 CONTROL {
   ecn_used   [1];
   msn   [16];
 }

 //
 // Encoding methods not specified in FN syntax
 //

 list_tcp_options   "defined in Section 6.3.3";
 inferred_ip_v4_header_checksum "defined in Section 6.4.1";
 inferred_mine_header_checksum "defined in Section 6.4.2";
 inferred_ip_v4_length   "defined in Section 6.4.3";
 inferred_ip_v6_length   "defined in Section 6.4.4";
 inferred_offset   "defined in Section 6.4.5";

```
baseheader_extension_headers   "defined in Section 6.4.6";
baseheader_outer_headers       "defined in Section 6.4.7";

//////////////////////////////////////////
// General encoding methods
//////////////////////////////////////////

static_or_irreg(flag, width)
{
  UNCOMPRESSED {
    field [ width ];
  }

  COMPRESSED irreg_enc {
    field =:= irregular(width) [ width ];
    ENFORCE(flag == 1);
  }

  COMPRESSED static_enc {
    field =:= static [ 0 ];
    ENFORCE(flag == 0);
  }
}

zero_or_irreg(flag, width)
{
  UNCOMPRESSED {
    field [ width ];
  }

  COMPRESSED non_zero {
    field =:= irregular(width) [ width ];
    ENFORCE(flag == 0);
  }

  COMPRESSED zero {
    field =:= uncompressed_value(width, 0) [ 0 ];
    ENFORCE(flag == 1);
  }
}

variable_length_32_enc(flag)
{
  UNCOMPRESSED {
    field [ 32 ];
  }

  COMPRESSED not_present {
```

```
    field =:= static [ 0 ];
    ENFORCE(flag == 0);
  }

  COMPRESSED lsb_8_bit {
    field =:= lsb(8, 63) [ 8 ];
    ENFORCE(flag == 1);
  }

  COMPRESSED lsb_16_bit {
    field =:= lsb(16, 16383) [ 16 ];
    ENFORCE(flag == 2);
  }

  COMPRESSED irreg_32_bit {
    field =:= irregular(32) [ 32 ];
    ENFORCE(flag == 3);
  }
}

optional32(flag)
{
  UNCOMPRESSED {
    item [ 0, 32 ];
  }

  COMPRESSED present {
    item =:= irregular(32) [ 32 ];
    ENFORCE(flag == 1);
  }

  COMPRESSED not_present {
    item =:= compressed_value(0, 0) [ 0 ];
    ENFORCE(flag == 0);
  }
}
lsb_7_or_31
{
  UNCOMPRESSED {
    item [ 32 ];
  }

  COMPRESSED lsb_7 {
    discriminator =:= '0'        [ 1 ];
    item          =:= lsb(7, 8) [ 7 ];
  }

  COMPRESSED lsb_31 {
```

```
      discriminator =:= '1'          [ 1 ];
      item          =:= lsb(31, 256) [ 31 ];
    }
  }

  opt_lsb_7_or_31(flag)
  {
    UNCOMPRESSED {
      item [ 0, 32 ];
    }

    COMPRESSED present {
      item =:= lsb_7_or_31 [ 8, 32 ];
      ENFORCE(flag == 1);
    }

    COMPRESSED not_present {
      item =:= compressed_value(0, 0) [ 0 ];
      ENFORCE(flag == 0);
    }
  }

  crc3(data_value, data_length)
  {
    UNCOMPRESSED {
    }

    COMPRESSED {
      crc_value =:=
        crc(3, 0x06, 0x07, data_value, data_length) [ 3 ];
    }
  }

  crc7(data_value, data_length)
  {
    UNCOMPRESSED {
    }

    COMPRESSED {
      crc_value =:=
        crc(7, 0x79, 0x7f, data_value, data_length) [ 7 ];
    }
  }

  one_bit_choice
  {
    UNCOMPRESSED {
      field [ 1 ];
```

```
   }

   COMPRESSED zero {
     field [ 1 ];
     ENFORCE(field.UVALUE == 0);
   }

   COMPRESSED nonzero {
     field [ 1 ];
     ENFORCE(field.UVALUE == 1);
   }
}


// Encoding method for updating a scaled field and its associated
// control fields.  Should be used both when the value is scaled
// or unscaled in a compressed format.
field_scaling(stride_value, scaled_value, unscaled_value)
{
  UNCOMPRESSED {
    residue_field [ 32 ];
  }

  COMPRESSED no_scaling {
    ENFORCE(stride_value == 0);
    ENFORCE(residue_field.UVALUE == unscaled_value);
    ENFORCE(scaled_value == 0);
  }

  COMPRESSED scaling_used {
    ENFORCE(stride_value != 0);
    ENFORCE(residue_field.UVALUE == (unscaled_value % stride_value));
    ENFORCE(unscaled_value ==
            scaled_value * stride_value + residue_field.UVALUE);
  }
}
/////////////////////////////////////////
// IPv6 Destination options header
/////////////////////////////////////////

ip_dest_opt
{
  UNCOMPRESSED {
    next_header [ 8 ];
    length      [ 8 ];
    value       [ length.UVALUE * 64 + 48 ];
  }
```

```
   DEFAULT {
     length      =:= static;
     next_header =:= static;
     value       =:= static;
   }

   COMPRESSED dest_opt_static {
     next_header =:= irregular(8) [ 8 ];
     length      =:= irregular(8) [ 8 ];
   }

   COMPRESSED dest_opt_dynamic {
     value =:=
       irregular(length.UVALUE * 64 + 48) [ length.UVALUE * 64 + 48 ];
   }

   COMPRESSED dest_opt_0_replicate {
     discriminator =:= '00000000' [ 8 ];
   }

   COMPRESSED dest_opt_1_replicate {
     discriminator =:= '10000000'                    [ 8 ];
     length        =:= irregular(8)                  [ 8 ];
     value         =:=
       irregular(length.UVALUE*64+48) [ length.UVALUE * 64 + 48 ];
   }

   COMPRESSED dest_opt_irregular {
   }
 }

 ///////////////////////////////////////
 // IPv6 Hop-by-Hop options header
 ///////////////////////////////////////

 ip_hop_opt
 {
   UNCOMPRESSED {
     next_header [ 8 ];
     length      [ 8 ];
     value       [ length.UVALUE * 64 + 48 ];
   }

   DEFAULT {
     length      =:= static;
     next_header =:= static;
     value       =:= static;
   }
```

```
  COMPRESSED hop_opt_static {
    next_header =:= irregular(8) [ 8 ];
    length      =:= irregular(8) [ 8 ];
  }

  COMPRESSED hop_opt_dynamic {
    value =:=
      irregular(length.UVALUE*64+48) [ length.UVALUE * 64 + 48 ];
  }

  COMPRESSED hop_opt_0_replicate {
    discriminator =:= '00000000' [ 8 ];
  }

  COMPRESSED hop_opt_1_replicate {
    discriminator =:= '10000000'                   [ 8 ];
    length        =:= irregular(8)                 [ 8 ];
    value         =:=
      irregular(length.UVALUE*64+48) [ length.UVALUE * 64 + 48 ];
  }

  COMPRESSED hop_opt_irregular {
  }
}

/////////////////////////////////////////
// IPv6 Routing header
/////////////////////////////////////////

ip_rout_opt
{
  UNCOMPRESSED {
    next_header [ 8 ];
    length      [ 8 ];
    value       [ length.UVALUE * 64 + 48 ];
  }

  DEFAULT {
    length      =:= static;
    next_header =:= static;
    value       =:= static;
  }

  COMPRESSED rout_opt_static {
    next_header =:= irregular(8)                    [ 8 ];
    length      =:= irregular(8)                    [ 8 ];
    value       =:=
      irregular(length.UVALUE*64+48) [ length.UVALUE * 64 + 48 ];
```

```
  }

  COMPRESSED rout_opt_dynamic {
  }

  COMPRESSED rout_opt_0_replicate {
    discriminator =:= '00000000' [ 8 ];
  }

  COMPRESSED rout_opt_0_replicate {
    discriminator =:= '10000000'                    [ 8 ];
    length        =:= irregular(8)                  [ 8 ];
    value         =:=
       irregular(length.UVALUE*64+48) [ length.UVALUE * 64 + 48 ];
  }

  COMPRESSED rout_opt_irregular {
  }
}

/////////////////////////////////////////////
// GRE Header
/////////////////////////////////////////////

optional_checksum(flag_value)
{
  UNCOMPRESSED {
    value    [ 0, 16 ];
    reserved1 [ 0, 16 ];
  }

  COMPRESSED cs_present {
    value   =:= irregular(16)             [ 16 ];
    reserved1 =:= uncompressed_value(16, 0) [ 0 ];
    ENFORCE(flag_value == 1);
  }

  COMPRESSED not_present {
    value    =:= compressed_value(0, 0) [ 0 ];
    reserved1 =:= compressed_value(0, 0) [ 0 ];
    ENFORCE(flag_value == 0);
  }
}

gre_proto
{
  UNCOMPRESSED {
    protocol [ 16 ];
```

```
   }

   COMPRESSED ether_v4 {
     discriminator =:= compressed_value(1, 0)        [ 1 ];
     protocol      =:= uncompressed_value(16, 0x0800) [ 0 ];
   }

   COMPRESSED ether_v6 {
     discriminator =:= compressed_value(1, 1)        [ 1 ];
     protocol      =:= uncompressed_value(16, 0x86DD) [ 0 ];
   }
 }

 gre
 {
   UNCOMPRESSED {
     c_flag                                  [ 1 ];
     r_flag    =:= uncompressed_value(1, 0) [ 1 ];
     k_flag                                  [ 1 ];
     s_flag                                  [ 1 ];
     reserved0 =:= uncompressed_value(9, 0) [ 9 ];
     version   =:= uncompressed_value(3, 0) [ 3 ];
     protocol                                [ 16 ];
     checksum_and_res                        [ 0, 32 ];
     key                                     [ 0, 32 ];
     sequence_number                         [ 0, 32 ];
   }

   DEFAULT {
     c_flag          =:= static;
     k_flag          =:= static;
     s_flag          =:= static;
     protocol        =:= static;
     key             =:= static;
     sequence_number =:= static;
   }

   COMPRESSED gre_static {
     protocol =:= gre_proto                  [ 1 ];
     c_flag   =:= irregular(1)               [ 1 ];
     k_flag   =:= irregular(1)               [ 1 ];
     s_flag   =:= irregular(1)               [ 1 ];
     padding  =:= compressed_value(4, 0)     [ 4 ];
     key      =:= optional32(k_flag.UVALUE) [ 0, 32 ];
   }

   COMPRESSED gre_dynamic {
     checksum_and_res =:=
```

```
      optional_checksum(c_flag.UVALUE)          [ 0, 16 ];
    sequence_number  =:= optional32(s_flag.UVALUE) [ 0, 32 ];
  }

  COMPRESSED gre_0_replicate {
    discriminator    =:= '00000000'    [ 8 ];
    checksum_and_res =:=
      optional_checksum(c_flag.UVALUE) [ 0, 16 ];
    sequence_number  =:=
      optional32(s_flag.UVALUE)        [ 0, 8, 32 ];
  }

  COMPRESSED gre_1_replicate {
    discriminator    =:= '10000'                 [ 5 ];
    c_flag           =:= irregular(1)            [ 1 ];
    k_flag           =:= irregular(1)            [ 1 ];
    s_flag           =:= irregular(1)            [ 1 ];
    checksum_and_res =:=
      optional_checksum(c_flag.UVALUE)           [ 0, 16 ];
    key              =:= optional32(k_flag.UVALUE) [ 0, 32 ];
    sequence_number  =:= optional32(s_flag.UVALUE) [ 0, 32 ];
  }

  COMPRESSED gre_irregular {
    checksum_and_res =:=
      optional_checksum(c_flag.UVALUE) [ 0, 16 ];
    sequence_number  =:=
      opt_lsb_7_or_31(s_flag.UVALUE)   [ 0, 8, 32 ];
  }
}

//////////////////////////////////////////
// MINE header
//////////////////////////////////////////

mine
{
  UNCOMPRESSED {
    next_header [ 8 ];
    s_bit       [ 1 ];
    res_bits    [ 7 ];
    checksum    [ 16 ];
    orig_dest   [ 32 ];
    orig_src    [ 0, 32 ];
  }

  DEFAULT {
    next_header =:= static;
```

```
    s_bit       =:= static;
    res_bits    =:= static;
    checksum    =:= inferred_mine_header_checksum;
    orig_dest   =:= static;
    orig_src    =:= static;
  }

  COMPRESSED mine_static {
    next_header =:= irregular(8)            [ 8 ];
    s_bit       =:= irregular(1)            [ 1 ];
    // Reserved bits are included to achieve byte-alignment
    res_bits    =:= irregular(7)            [ 7 ];
    orig_dest   =:= irregular(32)           [ 32 ];
    orig_src    =:= optional32(s_bit.UVALUE) [ 0, 32 ];
  }

  COMPRESSED mine_dynamic {
  }

  COMPRESSED mine_0_replicate {
    discriminator =:= '00000000' [ 8 ];
  }

  COMPRESSED mine_1_replicate {
    discriminator =:= '10000000'            [ 8 ];
    s_bit         =:= irregular(1)          [ 1 ];
    res_bits      =:= irregular(7)          [ 7 ];
    orig_dest     =:= irregular(32)         [ 32 ];
    orig_src      =:= optional32(s_bit.UVALUE) [ 0, 32 ];
  }

  COMPRESSED mine_irregular {
  }
}

//////////////////////////////////////////
// Authentication Header (AH)
//////////////////////////////////////////

ah
{
  UNCOMPRESSED {
    next_header     [ 8 ];
    length          [ 8 ];
    res_bits        [ 16 ];
    spi             [ 32 ];
    sequence_number [ 32 ];
    auth_data       [ length.UVALUE*32-32 ];
```

```
   }

   DEFAULT {
     next_header     =:= static;
     length          =:= static;
     res_bits        =:= static;
     spi             =:= static;
     sequence_number =:= static;
   }

   COMPRESSED ah_static {
     next_header =:= irregular(8)  [ 8 ];
     length      =:= irregular(8)  [ 8 ];
     spi         =:= irregular(32) [ 32 ];
   }

   COMPRESSED ah_dynamic {
     res_bits        =:= irregular(16) [ 16 ];
     sequence_number =:= irregular(32) [ 32 ];
     auth_data       =:=
        irregular(length.UVALUE*32-32) [ length.UVALUE*32-32 ];
   }

   COMPRESSED ah_0_replicate {
     discriminator   =:= '00000000'    [ 8 ];
     sequence_number =:= irregular(32) [ 32 ];
     auth_data       =:=
        irregular(length.UVALUE*32-32) [ length.UVALUE*32-32 ];
   }

   COMPRESSED ah_1_replicate {
     discriminator   =:= '10000000'    [ 8 ];
     length          =:= irregular(8)  [ 8 ];
     res_bits        =:= irregular(16) [ 16 ];
     spi             =:= irregular(32) [ 32 ];
     sequence_number =:= irregular(32) [ 32 ];
     auth_data       =:=
        irregular(length.UVALUE*32-32) [ length.UVALUE*32-32 ];
   }

   COMPRESSED ah_irregular {
     sequence_number =:= lsb_7_or_31  [ 8, 32 ];
     auth_data       =:=
        irregular(length.UVALUE*32-32) [ length.UVALUE*32-32 ];
   }
 }

 /////////////////////////////////////////////
```

```
 // ESP header (NULL encrypted)
 /////////////////////////////////////////

 // The value of the Next Header field from the trailer
 // part of the packet is passed as a parameter.
 esp_null(next_header_value)
 {
   UNCOMPRESSED {
     spi             [ 32 ];
     sequence_number [ 32 ];
   }

   CONTROL {
     nh_field [ 8 ];
   }

   DEFAULT {
     spi             =:= static;
     sequence_number =:= static;
     nh_field        =:= static;
   }

   COMPRESSED esp_static {
     nh_field =:= compressed_value(8, next_header_value) [ 8 ];
     spi      =:= irregular(32)                          [ 32 ];
   }

   COMPRESSED esp_dynamic {
     sequence_number =:= irregular(32) [ 32 ];
   }

   COMPRESSED esp_0_replicate {
     discriminator   =:= '00000000'    [ 8 ];
     sequence_number =:= irregular(32) [ 32 ];
   }
   COMPRESSED esp_1_replicate {
     discriminator   =:= '10000000'    [ 8 ];
     spi             =:= irregular(32) [ 32 ];
     sequence_number =:= irregular(32) [ 32 ];
   }

   COMPRESSED esp_irregular {
     sequence_number =:= lsb_7_or_31 [ 8, 32 ];
   }
 }

 /////////////////////////////////////////
 // IPv6 Header
```

```
     /////////////////////////////////////

     fl_enc
     {
       UNCOMPRESSED {
         flow_label [ 20 ];
       }

       COMPRESSED fl_zero {
         discriminator =:= '0'                     [ 1 ];
         flow_label    =:= uncompressed_value(20, 0) [ 0 ];
         reserved      =:= '0000'                    [ 4 ];
       }

       COMPRESSED fl_non_zero {
         discriminator =:= '1'           [ 1 ];
         flow_label    =:= irregular(20) [ 20 ];
       }
     }

     // The is_innermost flag is true if this is the innermost IP header
     // If extracting the irregular chain for a compressed packet:
     //   - ttl_irregular_chain_flag must have the same value as it had when
     //     processing co_baseheader.
     //   - ip_inner_ecn is bound in this encoding method and the value that
     //     it gets bound to should be passed to the tcp encoding method
     //   For other formats than the irregular chain, these two are ignored
     ipv6(is_innermost, ttl_irregular_chain_flag, ip_inner_ecn)
     {
       UNCOMPRESSED {
         version        =:= uncompressed_value(4, 6) [ 4 ];
         dscp                                        [ 6 ];
         ip_ecn_flags                                [ 2 ];
         flow_label                                  [ 20 ];
         payload_length                              [ 16 ];
         next_header                                 [ 8 ];
         ttl_hopl                                    [ 8 ];
         src_addr                                    [ 128 ];
         dst_addr                                    [ 128 ];
       }

       DEFAULT {
         dscp           =:= static;
         ip_ecn_flags   =:= static;
         flow_label     =:= static;
         payload_length =:= inferred_ip_v6_length;
         next_header    =:= static;
         ttl_hopl       =:= static;
```

```
     src_addr       =:= static;
     dst_addr       =:= static;
   }

   COMPRESSED ipv6_static {
     version_flag =:= '1'             [ 1 ];
     reserved     =:= '00'            [ 2 ];
     flow_label   =:= fl_enc          [ 5, 21 ];
     next_header  =:= irregular(8)    [ 8 ];
     src_addr     =:= irregular(128) [ 128 ];
     dst_addr     =:= irregular(128) [ 128 ];
   }

   COMPRESSED ipv6_dynamic {
     dscp         =:= irregular(6) [ 6 ];
     ip_ecn_flags =:= irregular(2) [ 2 ];
     ttl_hopl     =:= irregular(8) [ 8 ];
   }

   COMPRESSED ipv6_replicate {
     dscp         =:= irregular(6) [ 6 ];
     ip_ecn_flags =:= irregular(2) [ 2 ];
     reserved     =:= '000'        [ 3 ];
     flow_label   =:= fl_enc       [ 5, 21 ];
   }

   COMPRESSED ipv6_outer_without_ttl_irregular {
     dscp         =:= static_or_irreg(ecn_used.UVALUE, 6) [ 0, 6 ];
     ip_ecn_flags =:= static_or_irreg(ecn_used.UVALUE, 2) [ 0, 2 ];
     ENFORCE(ttl_irregular_chain_flag == 0);
     ENFORCE(is_innermost == false);
   }

   COMPRESSED ipv6_outer_with_ttl_irregular {
     dscp         =:= static_or_irreg(ecn_used.UVALUE, 6) [ 0, 6 ];
     ip_ecn_flags =:= static_or_irreg(ecn_used.UVALUE, 2) [ 0, 2 ];
     ttl_hopl     =:= irregular(8)                        [ 8 ];
     ENFORCE(ttl_irregular_chain_flag == 1);
     ENFORCE(is_innermost == false);
   }

   COMPRESSED ipv6_innermost_irregular {
     ENFORCE(ip_inner_ecn == ip_ecn_flags.UVALUE);
     ENFORCE(is_innermost == true);
   }
 }

 //////////////////////////////////////////////
```

```
 // IPv4 Header
 /////////////////////////////////////////

 ip_id_enc_dyn(behavior)
 {
   UNCOMPRESSED {
     ip_id [ 16 ];
   }

   COMPRESSED ip_id_seq {
     ip_id =:= irregular(16) [ 16 ];
     ENFORCE((behavior == IP_ID_BEHAVIOR_SEQUENTIAL) ||
             (behavior == IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED) ||
             (behavior == IP_ID_BEHAVIOR_RANDOM));
   }

   COMPRESSED ip_id_zero {
     ip_id =:= uncompressed_value(16, 0) [ 0 ];
     ENFORCE(behavior == IP_ID_BEHAVIOR_ZERO);
   }
 }

 ip_id_enc_irreg(behavior)
 {
   UNCOMPRESSED {
     ip_id [ 16 ];
   }

   COMPRESSED ip_id_seq {
     ENFORCE(behavior == IP_ID_BEHAVIOR_SEQUENTIAL);
   }

   COMPRESSED ip_id_seq_swapped {
     ENFORCE(behavior == IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED);
   }
   COMPRESSED ip_id_rand {
     ip_id =:= irregular(16) [ 16 ];
     ENFORCE(behavior == IP_ID_BEHAVIOR_RANDOM);
   }

   COMPRESSED ip_id_zero {
     ip_id =:= uncompressed_value(16, 0) [ 0 ];
     ENFORCE(behavior == IP_ID_BEHAVIOR_ZERO);
   }
 }

 ip_id_behavior_choice(is_inner)
 {
```

```
  UNCOMPRESSED {
    behavior [ 2 ];
  }

  DEFAULT {
    behavior =:= irregular(2);
  }

  COMPRESSED sequential {
    behavior [ 2 ];
    ENFORCE(is_inner == true);
    ENFORCE(behavior.UVALUE == IP_ID_BEHAVIOR_SEQUENTIAL);
  }

  COMPRESSED sequential_swapped {
    behavior [ 2 ];
    ENFORCE(is_inner == true);
    ENFORCE(behavior.UVALUE ==
            IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED);
  }

  COMPRESSED random {
    behavior [ 2 ];
    ENFORCE(behavior.UVALUE == IP_ID_BEHAVIOR_RANDOM);
  }

  COMPRESSED zero {
    behavior [ 2 ];
    ENFORCE(behavior.UVALUE == IP_ID_BEHAVIOR_ZERO);
  }
}

// The is_innermost flag is true if this is the innermost IP header
// If extracting the irregular chain for a compressed packet:
//   - ttl_irregular_chain_flag must have the same value as it had when
//     processing co_baseheader.
//   - ip_inner_ecn is bound in this encoding method and the value that
//     it gets bound to should be passed to the tcp encoding method
//   For other formats than the irregular chain, these two are ignored
ipv4(is_innermost, ttl_irregular_chain_flag, ip_inner_ecn)
{
  UNCOMPRESSED {
    version         =:= uncompressed_value(4, 4)  [ 4 ];
    hdr_length      =:= uncompressed_value(4, 5)  [ 4 ];
    dscp                                          [ 6 ];
    ip_ecn_flags                                  [ 2 ];
    length                                        [ 16 ];
    ip_id                                         [ 16 ];
```

```
     rf              =:= uncompressed_value(1, 0)  [ 1 ];
     df                                            [ 1 ];
     mf              =:= uncompressed_value(1, 0)  [ 1 ];
     frag_offset     =:= uncompressed_value(13, 0) [ 13 ];
     ttl_hopl                                      [ 8 ];
     protocol                                      [ 8 ];
     checksum                                      [ 16 ];
     src_addr                                      [ 32 ];
     dst_addr                                      [ 32 ];
   }

   CONTROL {
     ip_id_behavior [ 2 ];
   }

   DEFAULT {
     dscp          =:= static;
     ip_ecn_flags  =:= static;
     length        =:= inferred_ip_v4_length;
     df            =:= static;
     ttl_hopl      =:= static;
     protocol      =:= static;
     checksum      =:= inferred_ip_v4_header_checksum;
     src_addr      =:= static;
     dst_addr      =:= static;
     ip_id_behavior =:= static;
   }

   COMPRESSED ipv4_static {
     version_flag =:= '0'          [ 1 ];
     reserved     =:= '0000000'    [ 7 ];
     protocol     =:= irregular(8) [ 8 ];
     src_addr     =:= irregular(32) [ 32 ];
     dst_addr     =:= irregular(32) [ 32 ];
   }

   COMPRESSED ipv4_dynamic {
     reserved        =:= '00000'                [ 5 ];
     df              =:= irregular(1)           [ 1 ];
     ip_id_behavior  =:= ip_id_behavior_choice(is_innermost) [ 2 ];
     dscp            =:= irregular(6)           [ 6 ];
     ip_ecn_flags    =:= irregular(2)           [ 2 ];
     ttl_hopl        =:= irregular(8)           [ 8 ];
     ip_id           =:=
       ip_id_enc_dyn(ip_id_behavior.UVALUE) [ 0, 16 ];
   }

   COMPRESSED ipv4_replicate {
```

```
     reserved      =:= '0000'                   [ 4 ];
     ip_id_behavior =:= ip_id_behavior_choice(is_innermost) [ 2 ];
     ttl_flag      =:= irregular(1)             [ 1 ];
     df            =:= irregular(1)             [ 1 ];
     dscp          =:= irregular(6)             [ 6 ];
     ip_ecn_flags  =:= irregular(2)             [ 2 ];
     ip_id         =:=
        ip_id_enc_dyn(ip_id_behavior.UVALUE) [ 0, 16 ];
     ttl_hopl     =:=
          static_or_irreg(ttl_flag.UVALUE, 8) [ 0, 8 ];
   }

   COMPRESSED ipv4_outer_without_ttl_irregular {
     ip_id         =:=
        ip_id_enc_irreg(ip_id_behavior.UVALUE) [ 0, 16 ];
     dscp          =:= static_or_irreg(ecn_used.UVALUE, 6) [ 0, 6 ];
     ip_ecn_flags =:= static_or_irreg(ecn_used.UVALUE, 2) [ 0, 2 ];
     ENFORCE(ttl_irregular_chain_flag == 0);
     ENFORCE(is_innermost == false);
   }

   COMPRESSED ipv4_outer_with_ttl_irregular {
     ip_id         =:=
        ip_id_enc_irreg(ip_id_behavior.UVALUE)         [ 0, 16 ];
     dscp          =:= static_or_irreg(ecn_used.UVALUE, 6) [ 0, 6 ];
     ip_ecn_flags =:= static_or_irreg(ecn_used.UVALUE, 2) [ 0, 2 ];
     ttl_hopl     =:= irregular(8)                     [ 8 ];
     ENFORCE(is_innermost == false);
     ENFORCE(ttl_irregular_chain_flag == 1);
   }

   COMPRESSED ipv4_innermost_irregular {
     ip_id         =:=
        ip_id_enc_irreg(ip_id_behavior.UVALUE) [ 0, 16 ];
     ENFORCE(ip_inner_ecn == ip_ecn_flags.UVALUE);
     ENFORCE(is_innermost == true);
   }
}

 ////////////////////////////////////////////
 // TCP Options
 ////////////////////////////////////////////

 // nbits is bound to the remaining length (in bits) of TCP
 // options, including the EOL type byte.
 tcp_opt_eol(nbits)
 {
   UNCOMPRESSED {
```

```
      type    =:= uncompressed_value(8, 0) [ 8 ];
      padding =:=
        uncompressed_value(nbits-8, 0)     [ nbits-8 ];
    }

    CONTROL {
      pad_len [ 8 ];
    }

    COMPRESSED eol_list_item {
      pad_len =:= compressed_value(8, nbits-8) [ 8 ];
    }

    COMPRESSED eol_irregular {
      pad_len =:= static;
      ENFORCE(nbits-8 == pad_len.UVALUE);
    }
  }

  tcp_opt_nop
  {
    UNCOMPRESSED {
      type =:= uncompressed_value(8, 1) [ 8 ];
    }

    COMPRESSED nop_list_item {
    }

    COMPRESSED nop_irregular {
    }
  }

  tcp_opt_mss
  {
    UNCOMPRESSED {
      type   =:= uncompressed_value(8, 2) [ 8 ];
      length =:= uncompressed_value(8, 4) [ 8 ];
      mss                                 [ 16 ];
    }

    COMPRESSED mss_list_item {
      mss =:= irregular(16) [ 16 ];
    }

    COMPRESSED mss_irregular {
      mss    =:= static;
    }
  }
```

```
 tcp_opt_wscale
 {
   UNCOMPRESSED {
     type   =:= uncompressed_value(8, 3) [ 8 ];
     length =:= uncompressed_value(8, 3) [ 8 ];
     wscale                              [ 8 ];
   }

   COMPRESSED wscale_list_item {
     wscale =:= irregular(8) [ 8 ];
   }

   COMPRESSED wscale_irregular {
     wscale =:= static;
   }
 }

 ts_lsb
 {
   UNCOMPRESSED {
     tsval [ 32 ];
   }

   COMPRESSED tsval_7 {
     discriminator =:= '0'        [ 1 ];
     tsval         =:= lsb(7, -1) [ 7 ];
   }

   COMPRESSED tsval_14 {
     discriminator =:= '10'        [ 2 ];
     tsval         =:= lsb(14, -1) [ 14 ];
   }

   COMPRESSED tsval_21 {
     discriminator =:= '110'               [ 3 ];
     tsval         =:= lsb(21, 0x00040000) [ 21 ];
   }

   COMPRESSED tsval_29 {
     discriminator =:= '111'               [ 3 ];
     tsval         =:= lsb(29, 0x04000000) [ 29 ];
   }
 }

 tcp_opt_ts
 {
   UNCOMPRESSED {
     type   =:= uncompressed_value(8, 8)  [ 8 ];
```

```
      length =:= uncompressed_value(8, 10) [ 8 ];
      tsval                                 [ 32 ];
      tsecho                                [ 32 ];
   }

   COMPRESSED tsopt_list_item {
     tsval  =:= irregular(32) [ 32 ];
     tsecho =:= irregular(32) [ 32 ];
   }

   COMPRESSED tsopt_irregular {
     tsval  =:= ts_lsb [ 8, 16, 24, 32 ];
     tsecho =:= ts_lsb [ 8, 16, 24, 32 ];
   }
 }

 sack_var_length_enc(base)
 {
   UNCOMPRESSED {
     sack_field [ 32 ];
   }

   CONTROL {
     sack_offset [ 32 ];
     ENFORCE(sack_offset.UVALUE == (sack_field.UVALUE - base));
   }


   COMPRESSED lsb_15 {
     discriminator =:= '0'         [ 1 ];
     sack_offset   =:= lsb(15, -1) [ 15 ];
   }

   COMPRESSED lsb_22 {
     discriminator =:= '10'        [ 2 ];
     sack_offset   =:= lsb(22, -1) [ 22 ];
   }

   COMPRESSED lsb_30 {
     discriminator =:= '11'        [ 2 ];
     sack_offset   =:= lsb(30, -1) [ 30 ];
   }
 }

 sack_block(prev_block_end)
 {
   UNCOMPRESSED {
     block_start [ 32 ];
```

```
    block_end   [ 32 ];
  }

  COMPRESSED {
    block_start =:=
      sack_var_length_enc(prev_block_end) [ 16, 24, 32 ];
    block_end   =:=
      sack_var_length_enc(block_start)    [ 16, 24, 32 ];
  }
}

// The value of the parameter is set to the ack_number value
// of the TCP header
tcp_opt_sack(ack_value)
{

  UNCOMPRESSED {
    type    =:= uncompressed_value(8, 5) [ 8 ];
    length                               [ 8 ];
    block_1                              [ 64 ];
    block_2                              [ 0, 64 ];
    block_3                              [ 0, 64 ];
    block_4                              [ 0, 64 ];
  }

  DEFAULT {
    length  =:= static;
    block_2 =:= uncompressed_value(0, 0);
    block_3 =:= uncompressed_value(0, 0);
    block_4 =:= uncompressed_value(0, 0);
  }

  COMPRESSED sack1_list_item {
    discriminator =:= '00000001';
    block_1       =:= sack_block(ack_value);
    ENFORCE(length.UVALUE == 10);
  }

  COMPRESSED sack2_list_item {
    discriminator =:= '00000010';
    block_1       =:= sack_block(ack_value);
    block_2       =:= sack_block(block_1_end.UVALUE);
    ENFORCE(length.UVALUE == 18);
  }

  COMPRESSED sack3_list_item {
    discriminator =:= '00000011';
    block_1       =:= sack_block(ack_value);
```

```
   block_2        =:= sack_block(block_1_end.UVALUE);
   block_3        =:= sack_block(block_2_end.UVALUE);
   ENFORCE(length.UVALUE == 26);
 }

 COMPRESSED sack4_list_item {
   discriminator =:= '00000100';
   block_1        =:= sack_block(ack_value);
   block_2        =:= sack_block(block_1_end.UVALUE);
   block_3        =:= sack_block(block_2_end.UVALUE);
   block_4        =:= sack_block(block_3_end.UVALUE);
   ENFORCE(length.UVALUE == 34);
 }

 COMPRESSED sack_unchanged_irregular {
   discriminator =:= '00000000';
   block_1        =:= static;
   block_2        =:= static;
   block_3        =:= static;
   block_4        =:= static;
 }

 COMPRESSED sack1_irregular {
   discriminator =:= '00000001';
   block_1        =:= sack_block(ack_value);
   ENFORCE(length.UVALUE == 10);
 }

 COMPRESSED sack2_irregular {
   discriminator =:= '00000010';
   block_1        =:= sack_block(ack_value);
   block_2        =:= sack_block(block_1_end.UVALUE);
   ENFORCE(length.UVALUE == 18);
 }

 COMPRESSED sack3_irregular {
   discriminator =:= '00000011';
   block_1        =:= sack_block(ack_value);
   block_2        =:= sack_block(block_1_end.UVALUE);
   block_3        =:= sack_block(block_2_end.UVALUE);
   ENFORCE(length.UVALUE == 26);
 }

 COMPRESSED sack4_irregular {
   discriminator =:= '00000100';
   block_1        =:= sack_block(ack_value);
   block_2        =:= sack_block(block_1_end.UVALUE);
   block_3        =:= sack_block(block_2_end.UVALUE);
```

```
      block_4        =:= sack_block(block_3_end.UVALUE);
      ENFORCE(length.UVALUE == 34);
    }
  }

  tcp_opt_sack_permitted
  {
    UNCOMPRESSED {
      type   =:= uncompressed_value(8, 4) [ 8 ];
      length =:= uncompressed_value(8, 2) [ 8 ];
    }

    COMPRESSED sack_permitted_list_item {
    }

    COMPRESSED sack_permitted_irregular {
    }
  }

  tcp_opt_generic
  {
    UNCOMPRESSED {
      type                                  [ 8 ];
      length_msb =:= uncompressed_value(1, 0) [ 1 ];
      length_lsb                            [ 7 ];
      contents                        [ length_len.UVALUE*8-16 ];
    }

    CONTROL {
      option_static [ 1 ];
    }

    DEFAULT {
      type       =:= static;
      length_lsb =:= static;
      contents   =:= static;
    }

    COMPRESSED generic_list_item {
      type          =:= irregular(8)      [ 8 ];
      option_static =:= one_bit_choice    [ 1 ];
      length_lsb    =:= irregular(7)      [ 7 ];
      contents      =:=
        irregular(length_lsb.UVALUE*8-16) [ length_len.UVALUE*8-16 ];
    }

    // Used when context of option has option_static set to one
    COMPRESSED generic_static_irregular {
```

```
      ENFORCE(option_static.UVALUE == 1);
   }

   // An item that can change, but currently is unchanged
   COMPRESSED generic_stable_irregular {
     discriminator =:= '11111111' [ 8 ];
     ENFORCE(option_static.UVALUE == 0);
   }

   // An item that is assumed to change constantly.
   // Length is not allowed to change here, since a length change is
   // most likely to cause new NOPs or an EOL length change.
   COMPRESSED generic_full_irregular {
     discriminator =:= '00000000'        [ 8 ];
     contents      =:=
       irregular(length_lsb.UVALUE*8-16) [ length_lsb.UVALUE*8-16 ];
     ENFORCE(option_static.UVALUE == 0);
   }
 }

 tcp_list_presence_enc(presence)
 {
   UNCOMPRESSED {
     tcp_options;
   }

   COMPRESSED list_not_present {
     tcp_options =:= static [ 0 ];
     ENFORCE(presence == 0);
   }

   COMPRESSED list_present {
     tcp_options =:= list_tcp_options [ VARIABLE ];
     ENFORCE(presence == 1);
   }
 }

 /////////////////////////////////////////////
 // TCP Header
 /////////////////////////////////////////////

 port_replicate(flags)
 {
   UNCOMPRESSED {
     port [ 16 ];
   }

   COMPRESSED port_static_enc {
```

```
    port =:= static [ 0 ];
    ENFORCE(flags == 0b00);
  }

  COMPRESSED port_lsb8 {
    port =:= lsb(8, 64) [ 8 ];
    ENFORCE(flags == 0b01);
  }

  COMPRESSED port_irr_enc {
    port =:= irregular(16) [ 16 ];
    ENFORCE(flags == 0b10);
  }
}

tcp_irreg_ip_ecn(ip_inner_ecn)
{
  UNCOMPRESSED {
    ip_ecn_flags [ 2 ];
  }

  COMPRESSED ecn_present {
    // This field does not exist in the uncompressed header
    // and therefore cannot use uncompressed_value.
    ip_ecn_flags =:=
      compressed_value(2, ip_inner_ecn) [ 2 ];
    ENFORCE(ecn_used.UVALUE == 1);
  }

  COMPRESSED ecn_not_present {
    ip_ecn_flags =:= static [ 0 ];
    ENFORCE(ecn_used.UVALUE == 0);
  }
}

rsf_index_enc
{
  UNCOMPRESSED {
    rsf_flag [ 3 ];
  }

  COMPRESSED none {
    rsf_idx  =:= '00' [ 2 ];
    rsf_flag =:= uncompressed_value(3, 0x00);
  }

  COMPRESSED rst_only {
    rsf_idx  =:= '01' [ 2 ];
```

```
      rsf_flag =:= uncompressed_value(3, 0x04);
   }

   COMPRESSED syn_only {
     rsf_idx  =:= '10' [ 2 ];
     rsf_flag =:= uncompressed_value(3, 0x02);
   }

   COMPRESSED fin_only {
     rsf_idx  =:= '11' [ 2 ];
     rsf_flag =:= uncompressed_value(3, 0x01);
   }
}

optional_2bit_padding(used_flag)
{
   UNCOMPRESSED {
   }

   COMPRESSED used {
     padding =:= compressed_value(2, 0x0) [ 2 ];
     ENFORCE(used_flag == 1);
   }

   COMPRESSED unused {
     padding =:= compressed_value(0, 0x0);
     ENFORCE(used_flag == 0);
   }
}

// ack_stride_value is the user-selected stride for scaling the
// TCP ack_number
// ip_inner_ecn is the value bound when processing the innermost
// IP header (ipv4 or ipv6 encoding method)
tcp(payload_size, ack_stride_value, ip_inner_ecn)
{
   UNCOMPRESSED {
     src_port      [ 16 ];
     dst_port      [ 16 ];
     seq_number    [ 32 ];
     ack_number    [ 32 ];
     data_offset   [ 4 ];
     tcp_res_flags [ 4 ];
     tcp_ecn_flags [ 2 ];
     urg_flag      [ 1 ];
     ack_flag      [ 1 ];
     psh_flag      [ 1 ];
     rsf_flags     [ 3 ];
```

```
      window         [ 16 ];
      checksum       [ 16 ];
      urg_ptr        [ 16 ];
      options        [ (data_offset.UVALUE-5)*32 ];
    }

    CONTROL {
      seq_number_scaled                   [ 32 ];
      seq_number_residue =:=
          field_scaling(payload_size, seq_number_scaled.UVALUE,
                        seq_number.UVALUE) [ 32 ];
      ack_stride                          [ 16 ];
      ack_number_scaled                   [ 32 ];
      ack_number_residue =:=
          field_scaling(ack_stride.UVALUE, ack_number_scaled.UVALUE,
                        ack_number.UVALUE) [ 32 ];
      ENFORCE(ack_stride.UVALUE == ack_stride_value);
    }

    INITIAL {
      ack_stride    =:= uncompressed_value(16, 0);
    }

    DEFAULT {
      src_port      =:= static;
      dst_port      =:= static;
      seq_number    =:= static;
      ack_number    =:= static;
      data_offset   =:= inferred_offset;
      tcp_res_flags =:= static;
      tcp_ecn_flags =:= static;
      urg_flag      =:= static;
      ack_flag      =:= uncompressed_value(1, 1);
      rsf_flags     =:= uncompressed_value(3, 0);
      window        =:= static;
      urg_ptr       =:= static;
    }

    COMPRESSED tcp_static {
      src_port =:= irregular(16) [ 16 ];
      dst_port =:= irregular(16) [ 16 ];
    }

    COMPRESSED tcp_dynamic {
      ecn_used        =:= one_bit_choice         [ 1 ];
      ack_stride_flag =:= irregular(1)           [ 1 ];
      ack_zero        =:= irregular(1)           [ 1 ];
      urp_zero        =:= irregular(1)           [ 1 ];
```

```
   tcp_res_flags    =:= irregular(4)             [ 4 ];
   tcp_ecn_flags    =:= irregular(2)             [ 2 ];
   urg_flag         =:= irregular(1)             [ 1 ];
   ack_flag         =:= irregular(1)             [ 1 ];
   psh_flag         =:= irregular(1)             [ 1 ];
   rsf_flags        =:= irregular(3)             [ 3 ];
   msn              =:= irregular(16)            [ 16 ];
   seq_number       =:= irregular(32)            [ 32 ];
   ack_number       =:=
     zero_or_irreg(ack_zero.CVALUE, 32)          [ 0, 32 ];
   window           =:= irregular(16)            [ 16 ];
   checksum         =:= irregular(16)            [ 16 ];
   urg_ptr          =:=
     zero_or_irreg(urp_zero.CVALUE, 16)          [ 0, 16 ];
   ack_stride       =:=
     static_or_irreg(ack_stride_flag.CVALUE, 16) [ 0, 16 ];
   options          =:= list_tcp_options         [ VARIABLE ];
 }

 COMPRESSED tcp_replicate {
   reserved          =:= '0'                     [ 1 ];
   window_presence   =:= irregular(1)            [ 1 ];
   list_present      =:= irregular(1)            [ 1 ];
   src_port_presence =:= irregular(2)            [ 2 ];
   dst_port_presence =:= irregular(2)            [ 2 ];
   ack_stride_flag   =:= irregular(1)            [ 1 ];
   ack_presence      =:= irregular(1)            [ 1 ];
   urp_presence      =:= irregular(1)            [ 1 ];
   urg_flag          =:= irregular(1)            [ 1 ];
   ack_flag          =:= irregular(1)            [ 1 ];
   psh_flag          =:= irregular(1)            [ 1 ];
   rsf_flags         =:= rsf_index_enc           [ 2 ];
   ecn_used          =:= one_bit_choice          [ 1 ];
   msn               =:= irregular(16)           [ 16 ];
   seq_number        =:= irregular(32)           [ 32 ];
   src_port          =:=
     port_replicate(src_port_presence)     [ 0, 8, 16 ];
   dst_port          =:=
     port_replicate(dst_port_presence)     [ 0, 8, 16 ];
   window            =:=
     static_or_irreg(window_presence, 16)  [ 0, 16 ];
   urg_point         =:=
     static_or_irreg(urp_presence, 16)     [ 0, 16 ];
   ack_number        =:=
     static_or_irreg(ack_presence, 32)     [ 0, 32 ];
   ecn_padding       =:=
     optional_2bit_padding(ecn_used.CVALUE)    [ 0, 2 ];
   tcp_res_flags =:=
```

```
     static_or_irreg(ecn_used.CVALUE, 4)        [ 0, 4 ];
   tcp_ecn_flags    =:=
     static_or_irreg(ecn_used.CVALUE, 2)        [ 0, 2 ];
   checksum         =:= irregular(16)            [ 16 ];
   ack_stride       =:=
     static_or_irreg(ack_stride_flag.CVALUE, 16) [ 0, 16 ];
   options          =:=
     tcp_list_presence_enc(list_present.CVALUE) [ VARIABLE ];
 }

 COMPRESSED tcp_irregular {
   ip_ecn_flags  =:= tcp_irreg_ip_ecn(ip_inner_ecn) [ 0, 2 ];
   tcp_res_flags =:=
     static_or_irreg(ecn_used.CVALUE, 4)             [ 0, 4 ];
   tcp_ecn_flags =:=
     static_or_irreg(ecn_used.CVALUE, 2)             [ 0, 2 ];
   checksum      =:= irregular(16)                    [ 16 ];
 }
}

/////////////////////////////////////////////////
// Encoding methods used in compressed base headers
/////////////////////////////////////////////////

dscp_enc(flag)
{
  UNCOMPRESSED {
    dscp [ 6 ];
  }

  COMPRESSED static_enc {
    dscp =:= static [ 0 ];
    ENFORCE(flag == 0);
  }

  COMPRESSED irreg {
    dscp    =:= irregular(6)          [ 6 ];
    padding =:= compressed_value(2, 0) [ 2 ];
    ENFORCE(flag == 1);
  }
}

ip_id_lsb(behavior, k, p)
{
  UNCOMPRESSED {
    ip_id [ 16 ];
  }
```

```
  CONTROL {
    ip_id_offset [ 16 ];
    ip_id_nbo    [ 16 ];
  }

  COMPRESSED nbo {
    ip_id_offset =:= lsb(k, p) [ k ];
    ENFORCE(behavior == IP_ID_BEHAVIOR_SEQUENTIAL);
    ENFORCE(ip_id_offset.UVALUE == ip_id.UVALUE - msn.UVALUE);
  }

  COMPRESSED non_nbo {
    ip_id_offset =:= lsb(k, p) [ k ];
    ENFORCE(behavior == IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED);
    ENFORCE(ip_id_nbo.UVALUE ==
            (ip_id.UVALUE / 256) + (ip_id.UVALUE % 256) * 256);
    ENFORCE(ip_id_nbo.ULENGTH == 16);
    ENFORCE(ip_id_offset.UVALUE == ip_id_nbo.UVALUE - msn.UVALUE);
  }
}

optional_ip_id_lsb(behavior, indicator)
{
  UNCOMPRESSED {
    ip_id [ 16 ];
  }

  COMPRESSED short {
    ip_id =:= ip_id_lsb(behavior, 8, 3) [ 8 ];
    ENFORCE((behavior == IP_ID_BEHAVIOR_SEQUENTIAL) ||
            (behavior == IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED));
    ENFORCE(indicator == 0);
  }

  COMPRESSED long {
    ip_id =:= irregular(16)  [ 16 ];
    ENFORCE((behavior == IP_ID_BEHAVIOR_SEQUENTIAL) ||
            (behavior == IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED));
    ENFORCE(indicator == 1);
  }

  COMPRESSED not_present {
    ENFORCE((behavior == IP_ID_BEHAVIOR_RANDOM) ||
            (behavior == IP_ID_BEHAVIOR_ZERO));
  }
}

dont_fragment(version)
```

```
 {
   UNCOMPRESSED {
     df [ 1 ];
   }

   COMPRESSED v4 {
     df =:= irregular(1) [ 1 ];
     ENFORCE(version == 4);
   }

   COMPRESSED v6 {
     df =:= compressed_value(1, 0) [ 1 ];
     ENFORCE(version == 6);
   }
 }

 ////////////////////////////////
 // Actual start of compressed packet formats
 // Important note:
 //   The base header is the compressed representation
 //   of the innermost IP header AND the TCP header.
 ////////////////////////////////

 // ttl_irregular_chain_flag is set by the user if the TTL/Hop Limit
 // of an outer header has changed.  The same value must be passed as
 // an argument to the ipv4/ipv6 encoding methods when extracting
 // the irregular chain items.
 co_baseheader(payload_size, ack_stride_value,
               ttl_irregular_chain_flag)
 {
   UNCOMPRESSED v4 {
     outer_headers  =:= baseheader_outer_headers       [ VARIABLE ];
     version        =:= uncompressed_value(4, 4)        [ 4 ];
     header_length  =:= uncompressed_value(4, 5)        [ 4 ];
     dscp                                               [ 6 ];
     ip_ecn_flags                                       [ 2 ];
     length                                             [ 16 ];
     ip_id                                              [ 16 ];
     rf             =:= uncompressed_value(1, 0)        [ 1 ];
     df                                                 [ 1 ];
     mf             =:= uncompressed_value(1, 0)        [ 1 ];
     frag_offset    =:= uncompressed_value(13, 0)       [ 13 ];
     ttl_hopl                                           [ 8 ];
     next_header                                        [ 8 ];
     checksum                                           [ 16 ];
     src_addr                                           [ 32 ];
     dest_addr                                          [ 32 ];
     extension_headers =:= baseheader_extension_headers [ VARIABLE ];
```

```
      src_port                                         [ 16 ];
      dest_port                                        [ 16 ];
      seq_number                                       [ 32 ];
      ack_number                                       [ 32 ];
      data_offset                                      [ 4 ];
      tcp_res_flags                                    [ 4 ];
      tcp_ecn_flags                                    [ 2 ];
      urg_flag                                         [ 1 ];
      ack_flag                                         [ 1 ];
      psh_flag                                         [ 1 ];
      rsf_flags                                        [ 3 ];
      window                                           [ 16 ];
      tcp_checksum                                     [ 16 ];
      urg_ptr                                          [ 16 ];
      options                       [ (data_offset.UVALUE-5)*32 ];
    }

    UNCOMPRESSED v6 {
      outer_headers  =:= baseheader_outer_headers      [ VARIABLE ];
      version =:= uncompressed_value(4, 6)             [ 4 ];
      dscp                                             [ 6 ];
      ip_ecn_flags                                     [ 2 ];
      flow_label                                       [ 20 ];
      payload_length                                   [ 16 ];
      next_header                                      [ 8 ];
      ttl_hopl                                         [ 8 ];
      src_addr                                         [ 128 ];
      dest_addr                                        [ 128 ];
      extension_headers =:= baseheader_extension_headers [ VARIABLE ];
      src_port                                         [ 16 ];
      dest_port                                        [ 16 ];
      seq_number                                       [ 32 ];
      ack_number                                       [ 32 ];
      data_offset                                      [ 4 ];
      tcp_res_flags                                    [ 4 ];
      tcp_ecn_flags                                    [ 2 ];
      urg_flag                                         [ 1 ];
      ack_flag                                         [ 1 ];
      psh_flag                                         [ 1 ];
      rsf_flags                                        [ 3 ];
      window                                           [ 16 ];
      tcp_checksum                                     [ 16 ];
      urg_ptr                                          [ 16 ];
      options                       [ (data_offset.UVALUE-5)*32 ];
      ENFORCE(ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_RANDOM);
    }

    CONTROL {
```

```
   ip_id_behavior                        [ 2 ];
   seq_number_scaled                     [ 32 ];
   seq_number_residue =:=
       field_scaling(payload_size, seq_number_scaled.UVALUE,
                     seq_number.UVALUE) [ 32 ];
   ack_stride                            [ 16 ];
   ack_number_scaled                     [ 32 ];
   ack_number_residue =:=
       field_scaling(ack_stride.UVALUE, ack_number_scaled.UVALUE,
                     ack_number.UVALUE) [ 32 ];
   ENFORCE(ack_stride_value == ack_stride.UVALUE);
 }

 INITIAL {
   ack_stride     =:= uncompressed_value(16, 0);
 }

 DEFAULT {
   tcp_ecn_flags  =:= static;
   data_offset    =:= inferred_offset;
   tcp_res_flags  =:= static;
   rsf_flags      =:= uncompressed_value(3, 0);
   dest_port      =:= static;
   dscp           =:= static;
   src_port       =:= static;
   urg_flag       =:= uncompressed_value(1, 0);
   window         =:= static;
   dest_addr      =:= static;
   version        =:= static;
   ttl_hopl       =:= static;
   src_addr       =:= static;
   df             =:= static;
   ack_number     =:= static;
   urg_ptr        =:= static;
   seq_number     =:= static;
   ack_flag       =:= uncompressed_value(1, 1);
   // The default for "options" is case 2) and 3) from
   // the list in section 6.3.1 (i.e. nothing present in the
   // baseheader itself).
   payload_length =:= inferred_ip_v6_length;
   checksum       =:= inferred_ip_v4_header_checksum;
   length         =:= inferred_ip_v4_length;
   flow_label     =:= static;
   next_header    =:= static;
   ip_ecn_flags   =:= static;
   // The tcp_checksum has no default,
   // it is considered a part of tcp_irregular
   ip_id_behavior =:= static;
```

```
   ecn_used       =:= static;

   // Default is to have no TTL in irregular chain
   // Can only be nonzero if co_common is used
   ENFORCE(ttl_irregular_chain_flag == 0);
}

//////////////////////////////////////////
// Common compressed packet format
//////////////////////////////////////////

COMPRESSED co_common {
  discriminator       =:= '1111101'                [ 7 ];
  ttl_hopl_outer_flag =:=
      compressed_value(1, ttl_irregular_chain_flag) [ 1 ];
  ack_flag            =:= irregular(1)             [ 1 ];
  psh_flag            =:= irregular(1)             [ 1 ];
  rsf_flags           =:= rsf_index_enc            [ 2 ];
  msn                 =:= lsb(4, 4)                [ 4 ];
  seq_indicator       =:= irregular(2)             [ 2 ];
  ack_indicator       =:= irregular(2)             [ 2 ];
  ack_stride_indicator =:= irregular(1)            [ 1 ];
  window_indicator    =:= irregular(1)             [ 1 ];
  ip_id_indicator     =:= irregular(1)             [ 1 ];
  urg_ptr_present     =:= irregular(1)             [ 1 ];
  reserved            =:= compressed_value(1, 0)   [ 1 ];
  ecn_used            =:= one_bit_choice           [ 1 ];
  dscp_present        =:= irregular(1)             [ 1 ];
  ttl_hopl_present    =:= irregular(1)             [ 1 ];
  list_present        =:= irregular(1)             [ 1 ];
  ip_id_behavior      =:= ip_id_behavior_choice(true)    [ 2 ];
  urg_flag            =:= irregular(1)             [ 1 ];
  df                  =:= dont_fragment(version.UVALUE)  [ 1 ];
  header_crc          =:= crc7(THIS.UVALUE, THIS.ULENGTH) [ 7 ];
  seq_number          =:=
    variable_length_32_enc(seq_indicator.CVALUE) [ 0, 8, 16, 32 ];
  ack_number          =:=
    variable_length_32_enc(ack_indicator.CVALUE) [ 0, 8, 16, 32 ];
  ack_stride          =:=
    static_or_irreg(ack_stride_indicator.CVALUE, 16)  [ 0, 16 ];
  window              =:=
    static_or_irreg(window_indicator.CVALUE, 16)      [ 0, 16 ];
  ip_id               =:=
    optional_ip_id_lsb(ip_id_behavior.UVALUE,
                       ip_id_indicator.CVALUE)        [ 0, 8, 16 ];
  urg_ptr             =:=
    static_or_irreg(urg_ptr_present.CVALUE, 16)       [ 0, 16 ];
  dscp                =:=
```

```
      dscp_enc(dscp_present.CVALUE)                 [ 0, 8 ];
    ttl_hopl            =:=
      static_or_irreg(ttl_hopl_present.CVALUE, 8)   [ 0, 8 ];
    options            =:=
      tcp_list_presence_enc(list_present.CVALUE)    [ VARIABLE ];
  }

  // Send LSBs of sequence number
  COMPRESSED rnd_1 {
    discriminator =:= '101110'                      [ 6 ];
    seq_number    =:= lsb(18, 65535)                [ 18 ];
    msn           =:= lsb(4, 4)                     [ 4 ];
    psh_flag      =:= irregular(1)                  [ 1 ];
    header_crc    =:= crc3(THIS.UVALUE, THIS.ULENGTH) [ 3 ];
    ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_RANDOM) ||
            (ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_ZERO));
  }

  // Send scaled sequence number LSBs
  COMPRESSED rnd_2 {
    discriminator     =:= '1100'                    [ 4 ];
    seq_number_scaled  =:= lsb(4, 7)                [ 4 ];
    msn                =:= lsb(4, 4)                [ 4 ];
    psh_flag           =:= irregular(1)             [ 1 ];
    header_crc         =:= crc3(THIS.UVALUE, THIS.ULENGTH) [ 3 ];
    ENFORCE(payload_size != 0);
    ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_RANDOM) ||
            (ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_ZERO));
  }

  // Send acknowledgment number LSBs
  COMPRESSED rnd_3 {
    discriminator =:= '0'                           [ 1 ];
    ack_number    =:= lsb(15, 8191)                 [ 15 ];
    msn           =:= lsb(4, 4)                     [ 4 ];
    psh_flag      =:= irregular(1)                  [ 1 ];
    header_crc    =:= crc3(THIS.UVALUE, THIS.ULENGTH) [ 3 ];
    ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_RANDOM) ||
            (ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_ZERO));
  }

  // Send acknowledgment number scaled
  COMPRESSED rnd_4 {
    discriminator     =:= '1101'                    [ 4 ];
    ack_number_scaled  =:= lsb(4, 3)                [ 4 ];
    msn                =:= lsb(4, 4)                [ 4 ];
    psh_flag           =:= irregular(1)             [ 1 ];
    header_crc         =:= crc3(THIS.UVALUE, THIS.ULENGTH) [ 3 ];
```

```
  ENFORCE(ack_stride.UVALUE != 0);
  ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_RANDOM) ||
          (ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_ZERO));
}

// Send ACK and sequence number
COMPRESSED rnd_5 {
  discriminator =:= '100'                       [ 3 ];
  psh_flag      =:= irregular(1)                [ 1 ];
  msn           =:= lsb(4, 4)                    [ 4 ];
  header_crc    =:= crc3(THIS.UVALUE, THIS.ULENGTH) [ 3 ];
  seq_number    =:= lsb(14, 8191)               [ 14 ];
  ack_number    =:= lsb(15, 8191)               [ 15 ];
  ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_RANDOM) ||
          (ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_ZERO));
}

// Send both ACK and scaled sequence number LSBs
COMPRESSED rnd_6 {
  discriminator      =:= '1010'                     [ 4 ];
  header_crc         =:= crc3(THIS.UVALUE, THIS.ULENGTH) [ 3 ];
  psh_flag           =:= irregular(1)               [ 1 ];
  ack_number         =:= lsb(16, 16383)             [ 16 ];
  msn                =:= lsb(4, 4)                  [ 4 ];
  seq_number_scaled  =:= lsb(4, 7)                  [ 4 ];
  ENFORCE(payload_size != 0);
  ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_RANDOM) ||
          (ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_ZERO));
}

// Send ACK and window
COMPRESSED rnd_7 {
  discriminator =:= '101111'                    [ 6 ];
  ack_number    =:= lsb(18, 65535)              [ 18 ];
  window        =:= irregular(16)               [ 16 ];
  msn           =:= lsb(4, 4)                    [ 4 ];
  psh_flag      =:= irregular(1)                [ 1 ];
  header_crc    =:= crc3(THIS.UVALUE, THIS.ULENGTH) [ 3 ];
  ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_RANDOM) ||
          (ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_ZERO));
}

// An extended packet type for seldom-changing fields
// Can send LSBs of TTL, RSF flags, change ECN behavior, and
// options list
COMPRESSED rnd_8 {
  discriminator =:= '10110'                     [ 5 ];
  rsf_flags     =:= rsf_index_enc               [ 2 ];
```

```
    list_present  =:= irregular(1)                       [ 1 ];
    header_crc    =:= crc7(THIS.UVALUE, THIS.ULENGTH) [ 7 ];
    msn           =:= lsb(4, 4)                           [ 4 ];
    psh_flag      =:= irregular(1)                        [ 1 ];
    ttl_hopl      =:= lsb(3, 3)                           [ 3 ];
    ecn_used      =:= one_bit_choice                     [ 1 ];
    seq_number    =:= lsb(16, 65535)                     [ 16 ];
    ack_number    =:= lsb(16, 16383)                     [ 16 ];
    options       =:=
      tcp_list_presence_enc(list_present.CVALUE)     [ VARIABLE ];
    ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_RANDOM) ||
            (ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_ZERO));
  }

  // Send LSBs of sequence number
  COMPRESSED seq_1 {
    discriminator =:= '1010'                            [ 4 ];
    ip_id         =:= ip_id_lsb(ip_id_behavior.UVALUE, 4, 3) [ 4 ];
    seq_number    =:= lsb(16, 32767)                         [ 16 ];
    msn           =:= lsb(4, 4)                              [ 4 ];
    psh_flag      =:= irregular(1)                           [ 1 ];
    header_crc    =:= crc3(THIS.UVALUE, THIS.ULENGTH)        [ 3 ];
    ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_SEQUENTIAL) ||
            (ip_id_behavior.UVALUE ==
             IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED));
  }

  // Send scaled sequence number LSBs
  COMPRESSED seq_2 {
    discriminator     =:= '11010'                           [ 5 ];
    ip_id             =:=
      ip_id_lsb(ip_id_behavior.UVALUE, 7, 3)                [ 7 ];
    seq_number_scaled =:= lsb(4, 7)                         [ 4 ];
    msn               =:= lsb(4, 4)                         [ 4 ];
    psh_flag          =:= irregular(1)                      [ 1 ];
    header_crc        =:= crc3(THIS.UVALUE, THIS.ULENGTH) [ 3 ];
    ENFORCE(payload_size != 0);
    ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_SEQUENTIAL) ||
            (ip_id_behavior.UVALUE ==
             IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED));
  }

  // Send acknowledgment number LSBs
  COMPRESSED seq_3 {
    discriminator =:= '1001'                            [ 4 ];
    ip_id         =:= ip_id_lsb(ip_id_behavior.UVALUE, 4, 3) [ 4 ];
    ack_number    =:= lsb(16, 16383)                        [ 16 ];
    msn           =:= lsb(4, 4)                             [ 4 ];
```

```
   psh_flag      =:= irregular(1)                          [ 1 ];
   header_crc    =:= crc3(THIS.UVALUE, THIS.ULENGTH)       [ 3 ];
   ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_SEQUENTIAL) ||
           (ip_id_behavior.UVALUE ==
            IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED));
 }

 // Send scaled acknowledgment number scaled
 COMPRESSED seq_4 {
   discriminator     =:= '0'                               [ 1 ];
   ack_number_scaled =:= lsb(4, 3)                         [ 4 ];
   // Due to having very few ip_id bits, no negative offset
   ip_id        =:= ip_id_lsb(ip_id_behavior.UVALUE, 3, 1) [ 3 ];
   msn               =:= lsb(4, 4)                         [ 4 ];
   psh_flag          =:= irregular(1)                      [ 1 ];
   header_crc        =:= crc3(THIS.UVALUE, THIS.ULENGTH)   [ 3 ];
   ENFORCE(ack_stride.UVALUE != 0);
   ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_SEQUENTIAL) ||
           (ip_id_behavior.UVALUE ==
            IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED));
 }

 // Send ACK and sequence number
 COMPRESSED seq_5 {
   discriminator =:= '1000'                                [ 4 ];
   ip_id         =:= ip_id_lsb(ip_id_behavior.UVALUE, 4, 3) [ 4 ];
   ack_number    =:= lsb(16, 16383)                        [ 16 ];
   seq_number    =:= lsb(16, 32767)                        [ 16 ];
   msn           =:= lsb(4, 4)                             [ 4 ];
   psh_flag      =:= irregular(1)                          [ 1 ];
   header_crc    =:= crc3(THIS.UVALUE, THIS.ULENGTH)       [ 3 ];
   ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_SEQUENTIAL) ||
           (ip_id_behavior.UVALUE ==
            IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED));
 }

 // Send both ACK and scaled sequence number LSBs
 COMPRESSED seq_6 {
   discriminator     =:= '11011'                           [ 5 ];
   seq_number_scaled =:= lsb(4, 7)                         [ 4 ];
   ip_id         =:= ip_id_lsb(ip_id_behavior.UVALUE, 7, 3) [ 7 ];
   ack_number        =:= lsb(16, 16383)                    [ 16 ];
   msn               =:= lsb(4, 4)                         [ 4 ];
   psh_flag          =:= irregular(1)                      [ 1 ];
   header_crc        =:= crc3(THIS.UVALUE, THIS.ULENGTH)   [ 3 ];
   ENFORCE(payload_size != 0);
   ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_SEQUENTIAL) ||
           (ip_id_behavior.UVALUE ==
```

```
                   IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED));
   }

   // Send ACK and window
   COMPRESSED seq_7 {
     discriminator =:= '1100'                                [ 4 ];
     window        =:= lsb(15, 16383)                        [ 15 ];
     ip_id         =:= ip_id_lsb(ip_id_behavior.UVALUE, 5, 3) [ 5 ];
     ack_number    =:= lsb(16, 32767)                        [ 16 ];
     msn           =:= lsb(4, 4)                             [ 4 ];
     psh_flag      =:= irregular(1)                          [ 1 ];
     header_crc    =:= crc3(THIS.UVALUE, THIS.ULENGTH)       [ 3 ];
     ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_SEQUENTIAL) ||
             (ip_id_behavior.UVALUE ==
              IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED));
   }

   // An extended packet type for seldom-changing fields
   // Can send LSBs of TTL, RSF flags, change ECN behavior, and
   // options list
   COMPRESSED seq_8 {
     discriminator =:= '1011'                                [ 4 ];
     ip_id         =:= ip_id_lsb(ip_id_behavior.UVALUE, 4, 3) [ 4 ];
     list_present  =:= irregular(1)                          [ 1 ];
     header_crc    =:= crc7(THIS.UVALUE, THIS.ULENGTH)       [ 7 ];
     msn           =:= lsb(4, 4)                             [ 4 ];
     psh_flag      =:= irregular(1)                          [ 1 ];
     ttl_hopl      =:= lsb(3, 3)                             [ 3 ];
     ecn_used      =:= one_bit_choice                        [ 1 ];
     ack_number    =:= lsb(15, 8191)                         [ 15 ];
     rsf_flags     =:= rsf_index_enc                         [ 2 ];
     seq_number    =:= lsb(14, 8191)                         [ 14 ];
     options       =:=
       tcp_list_presence_enc(list_present.CVALUE)        [ VARIABLE ];
     ENFORCE((ip_id_behavior.UVALUE == IP_ID_BEHAVIOR_SEQUENTIAL) ||
             (ip_id_behavior.UVALUE ==
              IP_ID_BEHAVIOR_SEQUENTIAL_SWAPPED));
   }
 }
```

8.3. Feedback Formats and Options

8.3.1. Feedback Formats

   This section describes the feedback formats for the ROHC-TCP profile,
   following the general ROHC feedback format described in Section 5.2.3
   of [RFC4995].

   All feedback formats carry a field labeled MSN. The MSN field
   contains LSBs of the MSN control field described in Section 6.1.1.
   The sequence number to use is the MSN corresponding to the last
   header that was successfully CRC-8 validated or CRC verified.

   FEEDBACK-1

        0   1   2   3   4   5   6   7
      +---+---+---+---+---+---+---+---+
      | MSN |
      +---+---+---+---+---+---+---+---+

      MSN: The LSB-encoded master sequence number.

   A FEEDBACK-1 is an ACK. In order to send a NACK or a STATIC-NACK,
   FEEDBACK-2 must be used.

   FEEDBACK-2

        0   1   2   3   4   5   6   7
      +---+---+---+---+---+---+---+---+
      |Acktype| MSN |
      +---+---+---+---+---+---+---+---+
      | MSN |
      +---+---+---+---+---+---+---+---+
      | CRC |
      +---+---+---+---+---+---+---+---+
      /   Feedback options   /
      +---+---+---+---+---+---+---+---+

      Acktype:

         0 = ACK

         1 = NACK

         2 = STATIC-NACK

         3 is reserved (MUST NOT be used for parsability)

MSN: The LSB-encoded master sequence number.

CRC: 8-bit CRC computed over the entire feedback element (as
defined in Section 5.3.1.1 of [RFC4995]). For the purpose of
computing the CRC, the CRC field is zero. The CRC is calculated
using the polynomial defined in [RFC4995].

Feedback options: A variable number of feedback options, see
Section 8.3.2. Options may appear in any order.

A FEEDBACK-2 of type NACK or STATIC-NACK is always implicitly an
acknowledgment for a successfully decompressed packet, which packet
corresponds to the MSN of the feedback element, unless the MSN-NOT-
VALID option (Section 8.3.2.2) appears in the feedback element.

The FEEDBACK-2 format always carries a CRC and is thus more robust
than the FEEDBACK-1 format. When receiving FEEDBACK-2, the
compressor MUST verify the information by computing the CRC and by
comparing the result with the CRC carried in the feedback format. If
the two are not identical, the feedback element MUST be discarded.

8.3.2. Feedback Options

A ROHC-TCP feedback option has variable length and the following
general format:

```
    0   1   2   3   4   5   6   7
  +---+---+---+---+---+---+---+---+
  |   Opt Type    |   Opt Len     |
  +---+---+---+---+---+---+---+---+
  /          option data          /  Opt Length (octets)
  +---+---+---+---+---+---+---+---+
```

Each ROHC-TCP feedback option can appear at most once within a
FEEDBACK-2.

8.3.2.1. The REJECT Option

The REJECT option informs the compressor that the decompressor does
not have sufficient resources to handle the flow.

```
  +---+---+---+---+---+---+---+---+
  | Opt Type = 2  |  Opt Len = 0  |
  +---+---+---+---+---+---+---+---+
```

When receiving a REJECT option, the compressor MUST stop compressing
the packet flow, and SHOULD refrain from attempting to increase the
number of compressed packet flows for some time. The REJECT option

MUST NOT appear more than once in the FEEDBACK-2 format; otherwise,
the compressor MUST discard the entire feedback element.

8.3.2.2. The MSN-NOT-VALID Option

The MSN-NOT-VALID option indicates that the MSN of the feedback is
not valid.

```
    +---+---+---+---+---+---+---+---+
    |  Opt Type = 3 |  Opt Len = 0  |
    +---+---+---+---+---+---+---+---+
```

A compressor MUST ignore the MSN of the feedback element when this
option is present. Consequently, a NACK or a STATIC-NACK feedback
type sent with the MSN-NOT-VALID option is equivalent to a STATIC-
NACK with respect to the semantics of the feedback message.

The MSN-NOT-VALID option MUST NOT appear more than once in the
FEEDBACK-2 format and MUST NOT appear in the same feedback element as
the MSN option; otherwise, the compressor MUST discard the entire
feedback element.

8.3.2.3. The MSN Option

The MSN option provides 2 additional bits of MSN.

```
    +---+---+---+---+---+---+---+---+
    |  Opt Type = 4 |  Opt Len = 1  |
    +---+---+---+---+---+---+---+---+
    |  MSN  |        Reserved       |
    +---+---+---+---+---+---+---+---+
```

These 2 bits are the least significant bits of the MSN and are thus
concatenated with the 14 bits already present in the FEEDBACK-2
format.

The MSN option MUST NOT appear more than once in the FEEDBACK-2
format and MUST NOT appear in the same feedback element as the MSN-
NOT-VALID option; otherwise, the compressor MUST discard the entire
feedback element.

8.3.2.4. The CONTEXT_MEMORY Feedback Option

The CONTEXT_MEMORY option means that the decompressor does not have
sufficient memory resources to handle the context of the packet flow,
as the flow is currently compressed.

```
       0   1   2   3   4   5   6   7
     +---+---+---+---+---+---+---+---+
     |  Opt Type = 9 |  Opt Len = 0  |
     +---+---+---+---+---+---+---+---+
```

When receiving a CONTEXT_MEMORY option, the compressor SHOULD take
actions to compress the packet flow in a way that requires less
decompressor memory resources, or stop compressing the packet flow.

The CONTEXT_MEMORY option MUST NOT appear more than once in the
FEEDBACK-2 format; otherwise, the compressor MUST discard the entire
feedback element.

8.3.2.5. Unknown Option Types

If an option type unknown to the compressor is encountered, the
compressor MUST continue parsing the rest of the FEEDBACK element,
which is possible since the length of the option is explicit, but
MUST otherwise ignore the unknown option.

9. Security Considerations

A malfunctioning or malicious header compressor could cause the
header decompressor to reconstitute packets that do not match the
original packets but still have valid IP and TCP headers, and
possibly also valid TCP checksums. Such corruption may be detected
with end-to-end authentication and integrity mechanisms that will not
be affected by the compression. Moreover, this header compression
scheme uses an internal checksum for verification of reconstructed
headers. This reduces the probability of producing decompressed
headers not matching the original ones without this being noticed.

Denial-of-service attacks are possible if an intruder can introduce
(for example) bogus IR, CO, or FEEDBACK packets onto the link and
thereby cause compression efficiency to be reduced. However, an
intruder having the ability to inject arbitrary packets at the link
layer in this manner raises additional security issues that dwarf
those related to the use of header compression.

10. IANA Considerations

The ROHC profile identifier 0x0006 has been reserved by the IANA for
the profile defined in this document.

A ROHC profile identifier has been reserved by the IANA for the
profile defined in this document. Profiles 0x0000-0x0005 have
previously been reserved; this profile is 0x0006. As for previous

ROHC profiles, profile numbers 0xnn06 have been reserved for future
updates of this profile.

    Profile   Usage   Document
    identifier

    0x0006   ROHC TCP   [RFC4996]
    0xnn06   Reserved

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