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Formal Notation for RObust Header Compression (ROHC-FN)

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Abstract

This document defines Robust Header Compression - Formal Notation (ROHC-FN), a formal notation to specify field encodings for compressed formats when defining new profiles within the ROHC framework. ROHC-FN offers a library of encoding methods that are often used in ROHC profiles and can thereby help to simplify future profile development work.

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1. Introduction

Robust Header Compression - Formal Notation (ROHC-FN) is a formal notation designed to help with the definition of ROHC [RFC4995] header compression profiles. Previous header compression profiles have been so far specified using a combination of English text together with ASCII Box notation. Unfortunately, this was sometimes unclear and ambiguous, revealing the limitations of defining complex structures and encodings for compressed formats this way. The primary objective of the Formal Notation is to provide a more rigorous means to define header formats -- compressed and uncompressed -- as well as the relationships between them. No other formal notation exists that meets these requirements, so ROHC-FN aims to meet them.

In addition, ROHC-FN offers a library of encoding methods that are often used in ROHC profiles, so that the specification of new profiles using the formal notation can be achieved without having to redefine this library from scratch. Informally, an encoding method defines a two-way mapping between uncompressed data and compressed data.

2. Terminology

- Compressed format

  A compressed format consists of a list of fields that provides bindings between encodings and the fields it compresses. One or more compressed formats can be combined to represent an entire compressed header format.

- Context

  Context is information about the current (de)compression state of the flow. Specifically, a context for a specific field can be either uninitialised, or it can include a set of one or more values for the field's attributes defined by the compression algorithm, where a value may come from the field's attributes corresponding to a previous packet. See also a more generalized definition in Section 2.2 of [RFC4995].

- Control field

  Control fields are transmitted from a ROHC compressor to a ROHC decompressor, but are not part of the uncompressed header itself.

- Encoding method, encodings

  Encoding methods are two-way relations that can be applied to compress and decompress fields of a protocol header.

- Field

  The protocol header is divided into a set of contiguous bit patterns known as fields. Each field is defined by a collection of attributes that indicate its value and length in bits for both the compressed and uncompressed headers. The way the header is divided into fields is specific to the definition of a profile, and it is not necessary for the field divisions to be identical to the ones given by the specification(s) for the protocol header being compressed.

- Library of encoding methods

  The library of encoding methods contains a number of commonly used encoding methods for compressing header fields.

- Profile

  A ROHC [RFC4995] profile is a description of how to compress a certain protocol stack. Each profile consists of a set of formats (for example, uncompressed and compressed formats) along with a set of rules that control compressor and decompressor behaviour.

- ROHC-FN specification

  The specification of the set of formats of a ROHC profile using ROHC-FN.

- Uncompressed format

  An uncompressed format consists of a list of fields that provides the order of the fields to be compressed for a contiguous set of bits whose bit layout corresponds to the protocol header being compressed.

3. Overview of ROHC-FN

This section gives an overview of ROHC-FN. It also explains how ROHC-FN can be used to specify the compression of header fields as part of a ROHC profile.

3.1. Scope of the Formal Notation

This section explains how the formal notation relates to the ROHC framework and to specifications of ROHC profiles.

The ROHC framework [RFC4995] provides the general principles for performing robust header compression. It defines the concept of a profile, which makes ROHC a general platform for different compression schemes. It sets link layer requirements, and in particular negotiation requirements, for all ROHC profiles. It defines a set of common functions such as Context Identifiers (CIDs), padding, and segmentation. It also defines common formats (IR, IR-DYN, Feedback, Add-CID, etc.), and finally it defines a generic, profile independent, feedback mechanism.

A ROHC profile is a description of how to compress a certain protocol stack. For example, ROHC profiles are available for RTP/UDP/IP and many other protocol stacks.

At a high level, each ROHC profile consists of a set of formats (defining the bits to be transmitted) along with a set of rules that control compressor and decompressor behaviour. The purpose of the formats is to define how to compress and decompress headers. The formats define one or more compressed versions of each uncompressed header, and simultaneously define the inverse: how to relate a compressed header back to the original uncompressed header.

The set of formats will typically define compression of headers relative to a context of field values from previous headers in a flow, improving the overall compression by taking into account redundancies between headers of successive packets. Therefore, in addition to defining the formats, a profile has to:

- specify how to manage the context for both the compressor and the decompressor,
- define when and what to send in feedback messages, if any, from decompressor to compressor,
- outline compression principles to make the profile robust against bit errors and dropped packets.

All this is needed to ensure that the compressor and decompressor contexts are kept consistent with each other, while still facilitating the best possible compression performance.

The ROHC-FN is designed to help in the specification of compressed formats that, when put together based on the profile definition, make

up the formats used in a ROHC profile. It offers a library of encoding methods for compressing fields, and a mechanism for combining these encoding methods to create compressed formats tailored to a specific protocol stack.

The scope of ROHC-FN is limited to specifying the relationship between the compressed and uncompressed formats. To form a complete profile specification, the control logic for the profile behaviour needs to be defined by other means.

3.2. Fundamentals of the Formal Notation

There are two fundamental elements to the formal notation:

1. Fields and their encodings, which define the mapping between a header's uncompressed and compressed forms.

2. Encoding methods, which define the way headers are broken down into fields. Encoding methods define lists of uncompressed fields and the lists of compressed fields they map onto.

These two fundamental elements are at the core of the notation and are outlined below.

3.2.1. Fields and Encodings

Headers are made up of fields. For example, version number, header length, and sequence number are all fields used in real protocols.

Fields have attributes. Attributes describe various things about the field. For example:

```
field.ULENGTH
```

The above indicates the uncompressed length of the field. A field is said to have a value attribute, i.e., a compressed value or an uncompressed value, if the corresponding length attribute is greater than zero. See Section 4.4 for more details on field attributes.

The relationship between the compressed and uncompressed attributes of a field are specified with encoding methods, using the following notation:

```
field   =:=   encoding_method;
```

In the field definition above, the symbol "=:=" means "is encoded by". This field definition does not represent an assignment operation from the right hand side to the left side. Instead, it is

a two-way mapping between the compressed and uncompressed attributes of the field. It both represents the compression and the decompression operation in a single field definition, through a process of two-way matching.

Two-way matching is a binary operation that attempts to make the operands (i.e., the compressed and uncompressed attributes) match. This is similar to the unification process in logic. The operands represent one unspecified data object and one specified object. Values can be matched from either operand.

During compression, the uncompressed attributes of the field are already defined. The given encoding matches the compressed attributes against them. During decompression, the compressed attributes of the field are already defined, so the uncompressed attributes are matched to the compressed attributes using the given encoding method. Thus, both compression and decompression are defined by a single field definition.

Therefore, an encoding method (including any parameters specified) creates a reversible binding between the attributes of a field. At the compressor, a format can be used if a set of bindings that is successful for all the attributes in all its fields can be found. At the decompressor, the operation is reversed using the same bindings and the attributes in each field are filled according to the specified bindings; decoding fails if the binding for an attribute fails.

For example, the "static" encoding method creates a binding between the attribute corresponding to the uncompressed value of the field and the corresponding value of the field in the context.

- For the compressor, the "static" binding is successful when both the context value and the uncompressed value are the same. If the two values differ then the binding fails.

- For the decompressor, the "static" binding succeeds only if a valid context entry containing the value of the uncompressed field exists. Otherwise, the binding will fail.

Both the compressed and uncompressed forms of each field are represented as a string of bits; the most significant bit first, of the length specified by the length attribute. The bit string is the binary representation of the value attribute of the field, modulo "2^length", where "length" is the length attribute of the field. However, this is only the representation of the bits exchanged between the compressor and the decompressor, designed to allow

maximum compression efficiency. The FN itself uses the full range of integers. See Section 4.4.2 for further details.

3.2.2. Formats and Encoding Methods

The ROHC-FN provides a library of commonly used encoding methods. Encoding methods can be defined using plain English, or using a formal definition consisting of, for example, a collection of expressions (Section 4.7) and "ENFORCE" statements (Section 4.9).

ROHC-FN also provides mechanisms for combining fields and their encoding methods into higher level encoding methods following a well-defined structure. This is similar to the definition of functions and procedures in an ordinary programming language. It allows complexity to be handled by being broken down into manageable parts. New encoding methods are defined at the top level of a profile. These can then be used in the definition of other higher level encoding methods, and so on.

```
new_encoding_method         // This block is an encoding method
{
  UNCOMPRESSED {            // This block is an uncompressed format
    field_1   [ 16 ];
    field_2   [ 32 ];
    field_3   [ 48 ];
  }

  CONTROL {                 // This block defines control fields
    ctrl_field_1;
    ctrl_field_2;
  }

  DEFAULT {                 // This block defines default encodings
                            // for specified fields
    ctrl_field_2 =:= encoding_method_2;
    field_1      =:= encoding_method_1;
  }

  COMPRESSED format_0 {     // This block is a compressed format
    field_1;
    field_2      =:= encoding_method_2;
    field_3      =:= encoding_method_3;
    ctrl_field_1 =:= encoding_method_4;
    ctrl_field_2;
  }
```

```
    COMPRESSED format_1 {     // This block is a compressed format
      field_1;
      field_2      =:= encoding_method_3;
      field_3      =:= encoding_method_4;
      ctrl_field_2 =:= encoding_method_5;
      ctrl_field_3 =:= encoding_method_6; // This is a control field
                                          // with no uncompressed value
    }
  }
```

In the example above, the encoding method being defined is called "new_encoding_method". The section headed "UNCOMPRESSED" indicates the order of fields in the uncompressed header, i.e., the uncompressed header format. The number of bits in each of the fields is indicated in square brackets. After this is another section, "CONTROL", which defines two control fields. Following this is the "DEFAULT" section which defines default encoding methods for two of the fields (see below). Finally, two alternative compressed formats follow, each defined in sections headed "COMPRESSED". The fields that occur in the compressed formats are either:

- fields that occur in the uncompressed format; or
- control fields that have an uncompressed value and that occur in the CONTROL section; or
- control fields that do not have an uncompressed value and thus are defined as part of the compressed format.

Central to each of these formats is a "field list", which defines the fields contained in the format and also the order that those fields appear in that format. For the "DEFAULT" and "CONTROL" sections, the field order is not significant.

In addition to specifying field order, the field list may also specify bindings for any or all of the fields it contains. Fields that have no bindings defined for them are bound using the default bindings specified in the "DEFAULT" section (see Section 4.12.1.5).

Fields from the compressed format have the same name as they do in the uncompressed format. If there are any fields that are present exclusively in the compressed format, but that do have an uncompressed value, they must be declared in the "CONTROL" section of the definition of the encoding method (see Section 4.12.1.3 for more details on defining control fields).

Fields that have no uncompressed value do not appear in an "UNCOMPRESSED" field list and do not have to appear in the "CONTROL"

field list either. Instead, they are only declared in the compressed field lists where they are used.

In the example above, all the fields that appear in the compressed format are also found in the uncompressed format, or the control field list, except for ctrl_field_3; this is possible because ctrl_field_3 has no "uncompressed" value at all. Fields such as a checksum on the compressed information fall into this category.

3.3. Example Using IPv4

This section gives an overview of how the notation is used by means of an example. The example will develop the formal notation for an encoding method capable of compressing a single, well-known header: the IPv4 header [RFC791].

The first step is to specify the overall structure of the IPv4 header. To do this, we use an encoding method that we will call "ipv4_header". More details on definitions of encoding methods can be found in Section 4.12. This is notated as follows:

```
ipv4_header
{
```

The fragment of notation above declares the encoding method "ipv4_header", the definition follows the opening brace (see Section 4.12).

Definitions within the pair of braces are local to "ipv4_header". This scoping mechanism helps to clarify which fields belong to which formats; it is also useful when compressing complex protocol stacks with several headers, often with the same field names occurring in multiple headers (see Section 4.2).

The next step is to specify the fields contained in the uncompressed IPv4 header to represent the uncompressed format for which the encoding method will define one or more compressed formats. This is accomplished using ROHC-FN as follows:

```
    UNCOMPRESSED {
      version          [  4 ];
      header_length    [  4 ];
      dscp             [  6 ];
      ecn              [  2 ];
      length           [ 16 ];
      id               [ 16 ];
      reserved         [  1 ];
      dont_frag        [  1 ];
      more_fragments   [  1 ];
      offset           [ 13 ];
      ttl              [  8 ];
      protocol         [  8 ];
      checksum         [ 16 ];
      src_addr         [ 32 ];
      dest_addr        [ 32 ];
    }
```

The width of each field is indicated in square brackets. This part of the notation is used in the example for illustration to help the reader's understanding. However, indicating the field lengths in this way is optional since the width of each field can also normally be derived from the encoding that is used to compress/decompress it for a specific format. This part of the notation is formally defined in Section 4.10.

The next step is to specify the compressed format. This includes the encodings for each field that map between the compressed and uncompressed forms of the field. In the example, these encoding methods are mainly taken from the ROHC-FN library (see Section 4.11). Since the intention here is to illustrate the use of the notation, rather than to describe the optimum method of compressing IPv4 headers, this example uses only three encoding methods.

The "uncompressed_value" encoding method (defined in Section 4.11.1) can compress any field whose uncompressed length and value are fixed, or can be calculated using an expression. No compressed bits need to be sent because the uncompressed field can be reconstructed using its known size and value. The "uncompressed_value" encoding method is used to compress five fields in the IPv4 header, as described below:

```
    COMPRESSED {
      header_length  =:= uncompressed_value(4, 5);
      version        =:= uncompressed_value(4, 4);
      reserved       =:= uncompressed_value(1, 0);
      offset         =:= uncompressed_value(13, 0);
      more_fragments =:= uncompressed_value(1, 0);
```

The first parameter indicates the length of the uncompressed field in bits, and the second parameter gives its integer value.

Note that the order of the fields in the compressed format is independent of the order of the fields in the uncompressed format.

The "irregular" encoding method (defined in Section 4.11.3) can be used to encode any field for which both uncompressed attributes (ULENGTH and UVALUE) are defined, and whose ULENGTH attribute is either fixed or can be calculated using an expression. It is a fail-safe encoding method that can be used for such fields in the case where no other encoding method applies. All of the bits in the uncompressed form of the field are present in the compressed form as well; hence this encoding does not achieve any compression.

```
      src_addr       =:= irregular(32);
      dest_addr      =:= irregular(32);
      length         =:= irregular(16);
      id             =:= irregular(16);
      ttl            =:= irregular(8);
      protocol       =:= irregular(8);
      dscp           =:= irregular(6);
      ecn            =:= irregular(2);
      dont_frag      =:= irregular(1);
```

Finally, the third encoding method is specific only to the uncompressed format defined above for the IPv4 header, "inferred_ip_v4_header_checksum":

```
      checksum       =:= inferred_ip_v4_header_checksum [ 0 ];
    }
  }
```

The "inferred_ip_v4_header_checksum" encoding method is different from the other two encoding methods in that it is not defined in the ROHC-FN library of encoding methods. Its definition could be given either by using the formal notation as part of the profile definition itself (see Section 4.12) or by using plain English text (see Section 4.13).

In our example, the "inferred_ip_v4_header_checksum" is a specific encoding method that calculates the IP checksum from the rest of the header values. Like the "uncompressed_value" encoding method, no compressed bits need to be sent, since the field value can be reconstructed at the decompressor. This is notated explicitly by specifying, in square brackets, a length of 0 for the checksum field in the compressed format. Again, this notation is optional since the encoding method itself would be defined as sending zero compressed

bits, however it is useful to the reader to include such notation (see Section 4.10 for details on this part of the notation).

Finally the definition of the format is terminated with a closing brace. At this point, the above example has defined a compressed format that can be used to represent the entire compressed IPv4 header, and provides enough information to allow an implementation to construct the compressed format from an uncompressed format (compression) and vice versa (decompression).

4. Normative Definition of ROHC-FN

This section gives the normative definition of ROHC-FN. ROHC-FN is a declarative language that is referentially transparent, with no side effects. This means that whenever an expression is evaluated, there are no other effects from obtaining the value of the expression; the same expression is thus guaranteed to have the same value wherever it appears in the notation, and it can always be interchanged with its value in any of the formats it appears in (subject to the scope rules of identifiers of Section 4.2).

The formal notation describes the structure of the formats and the relationships between their uncompressed and compressed forms, rather than describing how compression and decompression is performed.

In various places within this section, text inside angle brackets has been used as a descriptive placeholder. The use of angle brackets in this way is solely for the benefit of the reader of this document. Neither the angle brackets, nor their contents form a part of the notation.

4.1. Structure of a Specification

The specification of the compressed formats of a ROHC profile using ROHC-FN is called a ROHC-FN specification. ROHC-FN specifications are case sensitive and are written in the 7-bit ASCII character set (as defined in [RFC2822]) and consist of a sequence of zero or more constant definitions (Section 4.3), an optional global control field list (Section 4.12.1.3) and one or more encoding method definitions (Section 4.12).

Encoding methods can be defined using the formal notation or can be predefined encoding methods.

Encoding methods are defined using the formal notation by giving one or more uncompressed formats to represent the uncompressed header and one or more compressed formats. These formats are related to each other by "fields", each of which describes a certain part of an

uncompressed and/or a compressed header. In addition to the formats, each encoding method may contain control fields, initial values, and default field encodings sections. The attributes of a field are bound by using an encoding method for it and/or by using "ENFORCE" statements (Section 4.9) within the formats. Each of these are terminated by a semi-colon.

Predefined encoding methods are not defined in the formal notation. Instead they are defined by giving a short textual reference explaining where the encoding method is defined. It is not necessary to define the library of encoding methods contained in this document in this way, their definition is implicit to the usage of the formal notation.

4.2. Identifiers

In ROHC-FN, identifiers are used for any of the following:

- encoding methods
- formats
- fields
- parameters
- constants

All identifiers may be of any length and may contain any combination of alphanumeric characters and underscores, within the restrictions defined in this section.

All identifiers must start with an alphabetic character.

It is illegal to have two or more identifiers that differ from each other only in capitalisation, in the same scope.

All letters in identifiers for constants must be upper case.

It is illegal to use any of the following as identifiers (including alternative capitalisations):

- "false", "true"
- "ENFORCE", "THIS", "VARIABLE"
- "ULENGTH", "UVALUE"

- "CLENGTH", "CVALUE"
- "UNCOMPRESSED", "COMPRESSED", "CONTROL", "INITIAL", or "DEFAULT"

Format names cannot be referred to in the notation, although they are considered to be identifiers. (See Section 4.12.3.1 for more details on format names.)

All identifiers used in ROHC-FN have a "scope". The scope of an identifier defines the parts of the specification where that identifier applies and from which it can be referred to. If an identifier has a "global" scope, then it applies throughout the specification that contains it and can be referred to from anywhere within it. If an identifier has a "local" scope, then it only applies to the encoding method in which it is defined, it cannot be referenced from outside the local scope of that encoding method. If an identifier has a local scope, that identifier can therefore be used in multiple different local scopes to refer to different items.

All instances of an identifier within its scope refer to the same item. It is not possible to have different items referred to by a single identifier within any given scope. For this reason, if there is an identifier that has global scope it cannot be used separately in a local scope, since a globally-scoped identifier is already applicable in all local scopes.

The identifiers for each encoding method and each constant all have a global scope. Each format and field also has an identifier. The scope of format and field identifiers is local, with the exception of global control fields, which have a global scope. Therefore it is illegal for a format or field to have the same identifier as another format or field within the same scope, or as an encoding method or a constant (since they have global scope).

Note that although format names (see Section 4.12.3.1) are considered to be identifiers, they are not referred to in the notation, but are primarily for the benefit of the reader.

4.3. Constant Definitions

Constant values can be defined using the "=" operator. Identifiers for constants must be all upper case. For example:

```
SOME_CONSTANT = 3;
```

Constants are defined by an expression (see Section 4.7) on the right-hand side of the "=" operator. The expression must yield a constant value. That is, the expression must be one whose terms are

all either constants or literals and must not vary depending on the header being compressed.

Constants have a global scope. Constants must be defined at the top level, outside any encoding method definition. Constants are entirely equivalent to the value they refer to, and are completely interchangeable with that value. Unlike field attributes, which may change from packet to packet, constants have the same value for all packets.

4.4. Fields

Fields are the basic building blocks of a ROHC-FN specification. Fields are the units into which headers are divided. Each field may have two forms: a compressed form and an uncompressed form. Both forms are represented as bits exchanged between the compressor and the decompressor in the same way, as an unsigned string of bits; the most significant bit first.

The properties of the compressed form of a field are defined by an encoding method and/or "ENFORCE" statements. This entirely characterises the relationship between the uncompressed and compressed forms of that field. This is achieved by specifying the relationships between the field's attributes.

The notation defines four field attributes, two for the uncompressed form and a corresponding two for the compressed form. The attributes available for each field are:

uncompressed attributes of a field:

- "UVALUE" and "ULENGTH",

compressed attributes of a field:

- "CVALUE" and "CLENGTH".

The two value attributes contain the respective numerical values of the field, i.e., "UVALUE" gives the numerical value of the uncompressed form of the field, and the attribute "CVALUE" gives the numerical value of the compressed form of the field. The numerical values are derived by interpreting the bit-string representations of the field as bit strings; the most significant bit first.

The two length attributes indicate the length in bits of the associated bit string; "ULENGTH" for the uncompressed form, and "CLENGTH" for the compressed form.

Attributes are undefined unless they are bound to a value, in which case they become defined. If two conflicting bindings are given for a field attribute then the bindings fail along with the (combination of) formats in which those bindings were defined.

Uncompressed attributes do not always reflect an aspect of the uncompressed header. Some fields do not originate from the uncompressed header, but are control fields.

4.4.1. Attribute References

Attributes of a particular field are formally referred to by using the field's name followed by a "." and the attribute's identifier.

For example:

```
rtp_seq_number.UVALUE
```

The above gives the uncompressed value of the rtp_seq_number field. The primary reason for referencing attributes is for use in expressions, which are explained in Section 4.7.

4.4.2. Representation of Field Values

Fields are represented as bit strings. The bit string is calculated using the value attribute ("val") and the length attribute ("len"). The bit string is the binary representation of "val % (2 ^ len)".

For example, if a field's "CLENGTH" attribute was 8, and its "CVALUE" attribute was -1, the compressed representation of the field would be "-1 % (2 ^ 8)", which equals "-1 % 256", which equals 255, 11111111 in binary.

ROHC-FN supports the full range of integers for use in expressions (see Section 4.7), but the representation of the formats (i.e., the bits exchanged between the compressor and the decompressor) is in the above form.

4.5. Grouping of Fields

Since the order of fields in a "COMPRESSED" field list (Section 4.12.1.2) do not have to be the same as the order of fields in an "UNCOMPRESSED" field list (Section 4.12.1.1), it is possible to group together any number of fields that are contiguous in a "COMPRESSED" format, to allow them all to be encoded using a single encoding method. The group of fields is specified immediately to the left of "=:=" in place of a single field name.

The group is notated by giving a colon-separated list of the fields to be grouped together. For example there may be two non-contiguous fields in an uncompressed header that are two halves of what is effectively a single sequence number:

```
grouping_example
{
  UNCOMPRESSED {
    minor_seq_num;  // 12 bits
    other_field;    //  8 bits
    major_seq_num;  //  4 bits
  }

  COMPRESSED {
    other_field     =:= irregular(8);
    major_seq_num
    : minor_seq_num =:= lsb(3, 0);
  }
}
```

The group of fields is presented to the encoding method as a contiguous group of bits, assembled by the concatenation of the fields in the order they are given in the group. The most significant bit of the combined field is the most significant bit of the first field in the list, and the least significant bit of the combined field is the least significant bit of the last field in the list.

Finally, the length attributes of the combined field are equal to the sum of the corresponding length attributes for all the fields in the group.

4.6. "THIS"

Within the definition of an encoding method, it is possible to refer to the field (i.e., the group of contiguous bits) the method is encoding, using the keyword "THIS".

This is useful for gaining access to the attributes of the field being encoded. For example it is often useful to know the total uncompressed length of the uncompressed format that is being encoded:

```
THIS.ULENGTH
```

4.7. Expressions

ROHC-FN includes the usual infix style of expressions, with parentheses "(" and ")" used for grouping. Expressions can be made up of any of the components described in the following subsections.

The semantics of expressions are generally similar to the expressions in the ANSI-C programming language [C90]. The definitive list of expressions in ROHC-FN follows in the next subsections; the list below provides some examples of the difference between expressions in ANSI-C and expressions in ROHC-FN:

- There is no limit on the range of integers.
- "x ^ y" evaluates to x raised to the power of y. This has a precedence higher than *, / and %, but lower than unary - and is right to left associative.
- There is no comma operator.
- There are no "modify" operators (no assignment operators and no increment or decrement).
- There are no bitwise operators.

Expressions may refer to any of the attributes of a field (as described in Section 4.4), to any defined constant (see Section 4.3) and also to encoding method parameters, if any are in scope (see Section 4.12).

If any of the attributes, constants, or parameters used in the expression are undefined, the value of the expression is undefined. Undefined expressions cause the environment (for example, the compressed format) in which they are used to fail if a defined value is required. Defined values are required for all compressed attributes of fields that appear in the compressed format. Defined values are not required for all uncompressed attributes of fields which appear in the uncompressed format. It is up to the profile creator to define what happens to the unbound field attributes in this case. It should be noted that in such a case, transparency of the compression process will be lost; i.e., it will not be possible for the decompressor to reproduce the original header.

Expressions cannot be used as encoding methods directly because they do not completely characterise a field. Expressions only specify a single value whereas a field is made up of several values: its attributes. For example, the following is illegal:

```
tcp_list_length =:= (data_offset + 20) / 4;
```

There is only enough information here to define a single attribute of "tcp_list_length". Although this makes no sense formally, this could intuitively be read as defining the "UVALUE" attribute. However, that would still leave the length of the uncompressed field undefined at the decompressor. Such usage is therefore prohibited.

4.7.1. Integer Literals

Integers can be expressed as decimal values, binary values (prefixed by "0b"), or hexadecimal values (prefixed by "0x"). Negative integers are prefixed by a "-" sign. For example "10", "0b1010", and "-0x0a" are all valid integer literals, having the values 10, 10, and -10 respectively.

4.7.2. Integer Operators

The following "integer" operators are available, which take integer arguments and return an integer result:

- ^, for exponentiation. "x ^ y" returns the value of "x" to the power of "y".
- *, / for multiplication and division. "x * y" returns the product of "x" and "y". "x / y" returns the quotient, rounded down to the next integer (the next one towards negative infinity).
- +, - for addition and subtraction. "x + y" returns the sum of "x" and "y". "x - y" returns the difference.
- % for modulo. "x % y" returns "x" modulo "y"; x - y * (x / y).

4.7.3. Boolean Literals

The boolean literals are "false", and "true".

4.7.4. Boolean Operators

The following "boolean" operators are available, which take boolean arguments and return a boolean result:

- &&, for logical "and". Returns true if both arguments are true. Returns false otherwise.
- ||, for logical "or". Returns true if at least one argument is true. Returns false otherwise.

- !, for logical "not". Returns true if its argument is false. Returns false otherwise.

4.7.5. Comparison Operators

The following "comparison" operators are available, which take integer arguments and return a boolean result:

- ==, !=, for equality and its negative. "x == y" returns true if x is equal to y. Returns false otherwise. "x != y" returns true if x is not equal to y. Returns false otherwise.

- <, >, for less than and greater than. "x < y" returns true if x is less than y. Returns false otherwise. "x > y" returns true if x is greater than y. Returns false otherwise.

- >=, <=, for greater than or equal and less than or equal, the inverse functions of <, >. "x >= y" returns false if x is less than y. Returns true otherwise. "x <= y" returns false if x is greater than y. Returns true otherwise.

4.8. Comments

Free English text can be inserted into a ROHC-FN specification to explain why something has been done a particular way, to clarify the intended meaning of the notation, or to elaborate on some point.

The FN uses an end of line comment style, which makes use of the "//" comment marker. Any text between the "//" marker and the end of the line has no formal meaning. For example:

```
//-----------------------------------------------------------------
//    IR-REPLICATE header formats
//-----------------------------------------------------------------

// The following fields are included in all of the IR-REPLICATE
// header formats:
//
UNCOMPRESSED {
  discriminator;    //  8 bits
  tcp_seq_number;   // 32 bits
  tcp_flags_ecn;    //  2 bits
```

Comments do not affect the formal meaning of what is notated, but can be used to improve readability. Their use is optional.

Comments may help to provide clarifications to the reader, and serve different purposes to implementers. Comments should thus not be

considered of lesser importance when inserting them into a ROHC-FN specification; they should be consistent with the normative part of the specification.

4.9. "ENFORCE" Statements

The "ENFORCE" statement provides a way to add predicates to a format, all of which must be fulfilled for the format to succeed. An "ENFORCE" statement shares some similarities with an encoding method. Specifically, whereas an encoding method binds several field attributes at once, an "ENFORCE" statement typically binds just one of them. In fact, all the bindings that encoding methods create can be expressed in terms of a collection of "ENFORCE" statements. Here is an example "ENFORCE" statement which binds the "UVALUE" attribute of a field to 5.

```
ENFORCE(field.UVALUE == 5);
```

An "ENFORCE" statement must only be used inside a field list (see Section 4.12). It attempts to force the expression given to be true for the format that it belongs to.

An abbreviated form of an "ENFORCE" statement is available for binding length attributes using "[" and "]", see Section 4.10.

Like an encoding method, an "ENFORCE" statement can only be successfully used in a format if the binding it describes is achievable. A format containing the example "ENFORCE" statement above would not be usable if the field had also been bound within that same format with "uncompressed_value" encoding, which gave it a "UVALUE" other than 5.

An "ENFORCE" statement takes a boolean expression as a parameter. It can be used to assert that the expression is true, in order to choose a particular format from a list of possible formats specified in an encoding method (see Section 4.12), or just to bind an expression as in the example above. The general form of an "ENFORCE" statement is therefore:

```
ENFORCE(<boolean expression>);
```

There are three possible conditions that the expression may be in:

1. The boolean expression evaluates to false, in which case the local scope of the format that contains the "ENFORCE" statement cannot be used.

2. The boolean expression evaluates to true, in which case the binding is created and successful.

3. The value of the boolean expression is undefined. In this case, the binding is also created and successful.

In all three cases, any undefined term becomes bound by the expression. Generally speaking, an "ENFORCE" statement is either being used as an assignment (condition 3 above) or being used to test if a particular format is usable, as is the case with conditions 1 and 2.

4.10. Formal Specification of Field Lengths

In many of the examples each field has been followed by a comment indicating the length of the field. Indicating the length of a field like this is optional, but can be very helpful for the reader. However, whilst useful to the reader, comments have no formal meaning.

One of the most common uses for "ENFORCE" statements (see Section 4.9) is to explicitly define the length of a field within a header. Using "ENFORCE" statements for this purpose has formal meaning but is not so easy to read. Therefore, an abbreviated form is provided for this use of "ENFORCE", which is both easy to read and has formal meaning.

An expression defining the length of a field can be specified in square brackets after the appearance of that field in a format. If the field can take several alternative lengths, then the expressions defining those lengths can be enumerated as a comma separated list within the square brackets. For example:

```
field_1                  [ 4 ];
field_2                  [ a+b, 2 ];
field_3 =:= lsb(16, 16)  [ 26 ];
```

The actual length attribute, which is bound by this notation, depends on whether it appears in a "COMPRESSED", "UNCOMPRESSED", or "CONTROL" field list (see Section 4.12.1 and its subsections). In a "COMPRESSED" field list, the field's "CLENGTH" attribute is bound. In "UNCOMPRESSED" and "CONTROL" field lists, the field's "ULENGTH" attribute is bound. Abbreviated "ENFORCE" statements are not allowed in "DEFAULT" sections (see Section 4.12.1.5). Therefore, the above notation would not be allowed to appear in a "DEFAULT" section. However, if the above appeared in an "UNCOMPRESSED" or "CONTROL" section, it would be equivalent to:

```
  field_1;                  ENFORCE(field_1.ULENGTH == 4);
  field_2;                  ENFORCE((field_2.ULENGTH == 2)
                                    || (field_2.ULENGTH == a+b));
  field_3 =:= lsb(16, 16); ENFORCE(field_3.ULENGTH == 26);
```

A special case exists for fields that have a variable length that the notator does not wish, or is not able to, define using an expression. The keyword "VARIABLE" can be used in the following case:

```
  variable_length_field  [ VARIABLE ];
```

Formally, this provides no restrictions on the field length, but maps onto any positive integer or to a value of zero. It will therefore be necessary to define the length of the field elsewhere (see the final paragraphs of Section 4.12.1.1 and Section 4.12.1.2). This may either be in the notation or in the English text of the profile within which the FN is contained. Within the square brackets, the keyword "VARIABLE" may be used as a term in an expression, just like any other term that normally appears in an expression. For example:

```
      field  [ 8 * (5 + VARIABLE) ];
```

This defines a field whose length is a whole number of octets and at least 40 bits (5 octets).

4.11. Library of Encoding Methods

A number of common techniques for compressing header fields are defined as part of the ROHC-FN library so that they can be reused when creating new ROHC-FN specifications. Their notation is described below.

As an alternative, or a complement, to this library of encoding methods, a ROHC-FN specification can define its own set of encoding methods, using the formal notation (see Section 4.12) or using a textual definition (see Section 4.13).

4.11.1. uncompressed_value

The "uncompressed_value" encoding method is used to encode header fields for which the uncompressed value can be defined using a mathematical expression (including constant values). This encoding method is defined as follows:

```
uncompressed_value(len, val) {
  UNCOMPRESSED {
    field;
    ENFORCE(field.ULENGTH == len);
    ENFORCE(field.UVALUE == val);
  }
  COMPRESSED {
    field;
    ENFORCE(field.CLENGTH == 0);
  }
}
```

To exemplify the usage of "uncompressed_value" encoding, the IPv6 header version number is a 4-bit field that always has the value 6:

```
version   =:=   uncompressed_value(4, 6);
```

Here is another example of value encoding, using an expression to calculate the length:

```
padding =:= uncompressed_value(nbits - 8, 0);
```

The expression above uses an encoding method parameter, "nbits", that in this example specifies how many significant bits there are in the data to calculate how many pad bits to use. See Section 4.12.2 for more information on encoding method parameters.

4.11.2. compressed_value

The "compressed_value" encoding method is used to define fields in compressed formats for which there is no counterpart in the uncompressed format (i.e., control fields). It can be used to specify compressed fields whose value can be defined using a mathematical expression (including constant values). This encoding method is defined as follows:

```
compressed_value(len, val) {
  UNCOMPRESSED {
    field;
    ENFORCE(field.ULENGTH == 0);
  }
  COMPRESSED {
    field;
    ENFORCE(field.CLENGTH == len);
    ENFORCE(field.CVALUE == val);
  }
}
```

One possible use of this encoding method is to define padding in a compressed format:

```
pad_to_octet_boundary      =:=   compressed_value(3, 0);
```

A more common use is to define a discriminator field to make it possible to differentiate between different compressed formats within an encoding method (see Section 4.12). For convenience, the notation provides syntax for specifying "compressed_value" encoding in the form of a binary string. The binary string to be encoded is simply given in single quotes; the "CLENGTH" attribute of the field binds with the number of bits in the string, while its "CVALUE" attribute binds with the value given by the string. For example:

```
discriminator     =:=   '01101';
```

This has exactly the same meaning as:

```
discriminator     =:=   compressed_value(5, 13);
```

4.11.3. irregular

The "irregular" encoding method is used to encode a field in the compressed format with a bit pattern identical to the uncompressed field. This encoding method is defined as follows:

```
irregular(len) {
  UNCOMPRESSED {
    field;
    ENFORCE(field.ULENGTH == len);
  }
  COMPRESSED {
    field;
    ENFORCE(field.CLENGTH == len);
    ENFORCE(field.CVALUE == field.UVALUE);
  }
}
```

For example, the checksum field of the TCP header is a 16-bit field that does not follow any predictable pattern from one header to another (and so it cannot be compressed):

```
tcp_checksum  =:=   irregular(16);
```

Note that the length does not have to be constant, for example, an expression can be used to derive the length of the field from the value of another field.

4.11.4. static

The "static" encoding method compresses a field whose length and value are the same as for a previous header in the flow, i.e., where the field completely matches an existing entry in the context:

```
field            =:=   static;
```

The field's "UVALUE" and "ULENGTH" attributes bind with their respective values in the context and the "CLENGTH" attribute is bound to zero.

Since the field value is the same as a previous field value, the entire field can be reconstructed from the context, so it is compressed to zero bits and does not appear in the compressed format.

For example, the source port of the TCP header is a field whose value does not change from one packet to the next for a given flow:

```
src_port  =:=   static;
```

4.11.5. lsb

The least significant bits encoding method, "lsb", compresses a field whose value differs by a small amount from the value stored in the context. The least significant bits of the field value are transmitted instead of the original field value.

```
field  =:=   lsb(<num_lsbs_param>, <offset_param>);
```

Here, "num_lsbs_param" is the number of least significant bits to use, and "offset_param" is the interpretation interval offset as defined below.

The parameter "num_lsbs_param" binds with the "CLENGTH" attribute, the "UVALUE" attribute binds to the value within the interval whose least significant bits match the "CVALUE" attribute. The value of the "ULENGTH" can be derived from the information stored in the context.

For example, the TCP sequence number:

```
tcp_sequence_number   =:=   lsb(14, 8192);
```

This takes up 14 bits, and can communicate any value that is between 8192 lower than the value of the field stored in context and 8191 above it.

The interpretation interval can be described as a function of a value stored in the context, ref_value, and of num_lsbs_param:

```
  f(context_value, num_lsbs_param) = [ref_value - offset_param,
             ref_value + (2^num_lsbs_param - 1) - offset_param]
```

where offset_param is an integer.

```
       <-- interpretation interval (size is 2^num_lsbs_param) -->
        |--------------------------+----------------------------|
     lower                      ref_value                      upper
     bound                                                     bound
```

where:

```
     lower bound = ref_value - offset_param
     upper bound = ref_value + (2^num_lsbs_param-1) - offset_param
```

The "lsb" encoding method can therefore compress a field whose value lies between the lower and the upper bounds, inclusively, of the interpretation interval. In particular, if offset_param = 0, then the field value can only stay the same or increase relative to the reference value ref_value. If offset_param = -1, then it can only increase, whereas if offset_param = 2^num_lsbs_param, then it can only decrease.

The compressed field takes up the specified number of bits in the compressed format (i.e., num_lsbs_param).

The compressor may not be able to determine the exact reference value stored in the decompressor context and that will be used by the decompressor, since some packets that would have updated the context may have been lost or damaged. However, from feedback received or by making assumptions, the compressor can limit the candidate set of values. The compressor can then select a format that uses "lsb" encoding, defined with suitable values for its parameters num_lsbs_param and offset_param, such that no matter which context value in the candidate set the decompressor uses, the resulting decompression is correct. If that is not possible, the "lsb" encoding method fails (which typically results in a less efficient compressed format being chosen by the compressor). How the compressor determines what reference values it stores and maintains in its set of candidate references is outside the scope of the notation.

4.11.6. crc

The "crc" encoding method provides a CRC calculated over a block of data. The algorithm used to calculate the CRC is the one specified in [RFC4995]. The "crc" method takes a number of parameters:

- the number of bits for the CRC (crc_bits),
- the bit-pattern for the polynomial (bit_pattern),
- the initial value for the CRC register (initial_value),
- the value of the block of data, represented using either the "UVALUE" or "CVALUE" attribute of a field (block_data_value); and
- the size in octets of the block of data (block_data_length).

That is:

```
field   =:=   crc(<num_bits>, <bit_pattern>, <initial_value>,
                  <block_data_value>, <block_data_length>);
```

When specifying the bit pattern for the polynomial, each bit represents the coefficient for the corresponding term in the polynomial. Note that the highest order term is always present (by definition) and therefore does not need specifying in the bit pattern. Therefore, a CRC polynomial with n terms in it is represented by a bit pattern with n-1 bits set.

The CRC is calculated in least significant bit (LSB) order.

For example:

```
// 3 bit CRC, C(x) = x^0 + x^1 + x^3
crc_field =:= crc(3, 0x6, 0xF, THIS.CVALUE, THIS.CLENGTH);
```

Usage of the "THIS" keyword (see Section 4.6) as shown above, is typical when using "crc" encoding. For example, when used in the encoding method for an entire header, it causes the CRC to be calculated over all fields in the header.

4.12. Definition of Encoding Methods

New encoding methods can be defined in a formal specification. These compose groups of individual fields into a contiguous block.

Encoding methods have names and may have parameters; they can also be used in the same way as any other encoding method from the library of

encoding methods. Since they can contain references to other encoding methods, complicated formats can be broken down into manageable pieces in a hierarchical fashion.

This section describes the various features used to define new encoding methods.

4.12.1. Structure

This simplest form of defining an encoding method is to specify a single encoding. For example:

```
compound_encoding_method
{
  UNCOMPRESSED {
    field_1;  //  4 bits
    field_2;  // 12 bits
  }

  COMPRESSED {
    field_2 =:= uncompressed_value(12, 9); //  0 bits
    field_1 =:= irregular(4);              //  4 bits
  }
}
```

The above begins with the new method's identifier, "compound_encoding_method". The definition of the method then follows inside curly brackets, "{" and "}". The first item in the definition is the "UNCOMPRESSED" field list, which gives the order of the fields in the uncompressed format. This is followed by the compressed format field list ("COMPRESSED"). This list gives the order of fields in the compressed format and also gives the encoding method for each field.

In the example, both the formats list each field exactly once. However, sometimes it is necessary to specify more than one binding for a given field, which means it appears more than once in the field list. In this case, it is the first occurrence of the field in the list that indicates its position in the field order. The subsequent occurrences of the field only specify binding information, not field order information.

The different components of this example are described in more detail below. Other components that can be used in the definition of encoding methods are also defined thereafter.

4.12.1.1. Uncompressed Format - "UNCOMPRESSED"

The uncompressed field list is defined by "UNCOMPRESSED", which specifies the fields of the uncompressed format in the order that they appear in the uncompressed header. The sum of the lengths of each individual uncompressed field in the list must be equal to the length of the field being encoded. Finally, the representation of the uncompressed format described using the list of fields in the "UNCOMPRESSED" section, for which compressed formats are being defined, always consists of one single contiguous block of bits.

In the example above in Section 4.12.1, the uncompressed field list is "field_1", followed by "field_2". This means that a field being encoded by this method is divided into two subfields, "field_1" and "field_2". The total uncompressed length of these two fields therefore equals the length of the field being encoded:

```
field_1.ULENGTH + field_2.ULENGTH == THIS.ULENGTH
```

In the example, there are only two fields, but any number of fields may be used. This relationship applies to however many fields are actually used. Any arrangement of fields that efficiently describes the content of the uncompressed header may be chosen -- this need not be the same as the one described in the specifications for the protocol header being compressed.

For example, there may be a protocol whose header contains a 16-bit sequence number, but whose sessions tend to be short-lived. This would mean that the high bits of the sequence number are almost always constant. The "UNCOMPRESSED" format could reflect this by splitting the original uncompressed field into two fields, one field to represent the almost-always-zero part of the sequence number, and a second field to represent the salient part.

An "UNCOMPRESSED" field list may specify encoding methods in the same way as the "COMPRESSED" field list in the example. Encoding methods specified therein are used whenever a packet with that uncompressed format is being encoded. The encoding of a packet with a given uncompressed format can only succeed if all of its encoding methods and "ENFORCE" statements succeed (see Section 4.9).

The total length of each uncompressed format must always be defined. The length of each of the fields in an uncompressed format must also be defined. This means that the bindings in the "UNCOMPRESSED", "COMPRESSED" (see Section 4.12.1.2 below), "CONTROL" (see Section 4.12.1.3 below), "INITIAL" (see Section 4.12.1.4 below), and "DEFAULT" (see Section 4.12.1.5 below) field lists must, between them, define the "ULENGTH" attribute of every field in an

uncompressed format so that there is an unambiguous mapping from the bits in the uncompressed format to the fields listed in the "UNCOMPRESSED" field list.

4.12.1.2. Compressed Format - "COMPRESSED"

Similar to the uncompressed field list, the fields in the compressed header will appear in the order specified by the compressed field list given for a compressed format. Each individual field is encoded in the manner given for that field. The total length of the compressed data will be the sum of the compressed lengths of all the individual fields. In the example from Section 4.12.1, the encoding methods used for these fields indicate that they are zero and 4 bits long, making a total of 4 bits.

The order of the fields specified in a "COMPRESSED" field list does not have to match the order they appear in the "UNCOMPRESSED" field list. It may be desirable to reorder the fields in the compressed format to align the compressed header to the octet boundary, or for other reasons. In the above example, the order is in fact the opposite of that in the uncompressed format.

The compressed field list specifies that the encoding for "field_1" is "irregular", and takes up 4 bits in both the compressed format and uncompressed format. The encoding for "field_2" is "uncompressed_value", which means that the field has a fixed value, so it can be compressed to zero bits. The value it takes is 9, and it is 12 bits wide in the uncompressed format.

Fields like "field_2", which compress to zero bits in length, may appear anywhere in the field list without changing the compressed format because their position in the list is not significant. In fact, if the encoding method for this field were defined elsewhere (for example, in the "UNCOMPRESSED" section), this field could be omitted from the "COMPRESSED" section altogether:

```
compound_encoding_method
{
  UNCOMPRESSED {
    field_1;                                  //  4 bits
    field_2 =:= uncompressed_value(12, 9);  // 12 bits
  }

  COMPRESSED {
    field_1 =:= irregular(4);                 //  4 bits
  }
}
```

The total length of each compressed format must always be defined. The length of each of the fields in a compressed format must also be defined. This means that the bindings in the "UNCOMPRESSED", "COMPRESSED", "CONTROL" (see Section 4.12.1.3 below), "INITIAL" (see Section 4.12.1.4 below), and "DEFAULT" (see Section 4.12.1.5 below) field lists must between them define the "CLENGTH" attribute of every field in a compressed format so that there is an unambiguous mapping from the bits in the compressed format to the fields listed in the "COMPRESSED" field list.

4.12.1.3. Control Fields - "CONTROL"

Control fields are defined using the "CONTROL" field list. The control field list specifies all fields that do not appear in the uncompressed format, but that have an uncompressed value (specifically those with an "ULENGTH" greater than zero). Such fields may be used to help compress fields from the uncompressed format more efficiently. A control field could be used to improve efficiency by representing some commonality between a number of the uncompressed fields, or by representing some information about the flow that is not explicitly contained in the protocol headers.

For example in IPv4, the behaviour of the IP-ID field in a flow varies depending on how the endpoints handle IP-IDs. Sometimes the behaviour is effectively random and sometimes the IP-ID follows a predictable sequence. The type of IP-ID behaviour is information that is never communicated explicitly in the uncompressed header.

However, a profile can still be designed to identify the behaviour and adjust the compression strategy according to the identified behaviour, thereby improving the compression performance. To do so, the ROHC-FN specification can introduce an explicit field to communicate the IP-ID behaviour in compressed format -- this is done by introducing a control field:

```
ipv4
{
  UNCOMPRESSED {
    version;       // 4 bits
    hdr_length;    // 4 bits
    protocol;      // 8 bits
    dscp;          // 6 bits
    ip_ecn_flags;  // 2 bits
    ttl_hopl;      // 8 bits
    df;            // 1 bit
    mf;            // 1 bit
    rf;            // 1 bit
    frag_offset;   // 13 bits
```

```
      ip_id;          // 16 bits
      src_addr;       // 32 bits
      dst_addr;       // 32 bits
      checksum;       // 16 bits
      length;         // 16 bits
    }

    CONTROL {
      ip_id_behavior; // 1 bit
         :
         :
```

The "CONTROL" field list is equivalent to the "UNCOMPRESSED" field list for fields that do not appear in the uncompressed format. It defines a field that has the same properties (the same defined attributes, etc.) as fields appearing in the uncompressed format.

Control fields are initialised by using the appropriate encoding methods and/or by using "ENFORCE" statements. This may be done inside the "CONTROL" field list.

For example:

```
  example_encoding_method_definition
  {
    UNCOMPRESSED {
      field_1 =:= some_encoding;
    }

    CONTROL {
      scaled_field;
      ENFORCE(scaled_field.UVALUE == field_1.UVALUE / 8);
      ENFORCE(scaled_field.ULENGTH == field_1.ULENGTH - 3);
    }

    COMPRESSED {
      scaled_field =:= lsb(4, 0);
    }
  }
```

This control field is used to scale down a field in the uncompressed format by a factor of 8 before encoding it with the "lsb" encoding method. Scaling it down makes the "lsb" encoding more efficient.

Control fields may also be used with a global scope. In this case, their declaration must be outside of any encoding method definition. They are then visible within any encoding method, thus allowing information to be shared between encoding methods directly.

4.12.1.4. Initial Values - "INITIAL"

In order to allow fields in the very first usage of a specific format to be compressed with "static", "lsb", or other encoding methods that depend on the context, it is possible to specify initial bindings for such fields. This is done using "INITIAL", for example:

```
INITIAL {
   field =:= uncompressed_value(4, 6);
}
```

This initialises the "UVALUE" of "field" to 6 and initialises its "ULENGTH" to 4. Unlike all other bindings specified in the formal notation, these bindings are applied to the context of the field, if the field's context is undefined. This is particularly useful when using encoding methods that rely on context being present, such as "static" or "lsb", with the first packet in a flow.

Because the "INITIAL" field list is used to bind the context alone, it makes no sense to specify initial bindings that themselves rely on the context, for example, "lsb". Such usage is not allowed.

4.12.1.5. Default Field Bindings - "DEFAULT"

Default bindings may be specified for each field or attribute. The default encoding methods specify the encoding method to use for a field if no binding is given elsewhere for the value of that field. This is helpful to keep the definition of the formats concise, as the same encoding method need not be repeated for every format, when defining multiple formats (see Section 4.12.3).

Default bindings are optional and may be given for any combination of fields and attributes which are in scope.

The syntax for specifying default bindings is similar to that used to specify a compressed or uncompressed format. However, the order of the fields in the field list does not affect the order of the fields in either the compressed or uncompressed format. This is because the field order is specified individually for each "COMPRESSED" format and "UNCOMPRESSED" format.

Here is an example:

```
DEFAULT {
  field_1 =:= uncompressed_value(4, 1);
  field_2 =:= uncompressed_value(4, 2);
  field_3 =:= lsb(3, -1);
  ENFORCE(field_4.ULENGTH == 4);
```

```
    }
```

Here default bindings are specified for fields 1 to 3. A default binding for the "ULENGTH" attribute of field_4 is also specified.

Fields for which there is a default encoding method do not need their bindings to be specified in the field list of any format that uses the default encoding method for that field. Any format that does not use the default encoding method must explicitly specify a binding for the value of that field's attributes.

If elsewhere a binding is not specified for the attributes of a field, the default encoding method is used. If the default encoding method always compresses the field down to zero bits, the field can be omitted from the compressed format's field list. Like any other zero-bit field, its position in the field list is not significant.

The "DEFAULT" field list may contain default bindings for individual attributes by using "ENFORCE" statements. A default binding for an individual attribute will only be used if elsewhere there is no binding given for that attribute or the field to which it belongs. If elsewhere there is an "ENFORCE" statement binding that attribute, or an encoding method binding the field to which it belongs, the default binding for the attribute will not be used. This applies even if the specified encoding method does not bind the particular attribute given in the "DEFAULT" section. However, an "ENFORCE" statement elsewhere that only binds the length of the field still allows the default bindings to be used, except for default "ENFORCE" statements which bind nothing but the field's length.

To clarify, assuming the default bindings given in the example above, the first three of the following four compressed formats would not use the default binding for "field_4.ULENGTH":

```
    COMPRESSED format1 {
      ENFORCE(field_4.ULENGTH == 3); // set ULENGTH to 3
      ENFORCE(field_4.UVALUE == 7);  // set UVALUE to 7
    }

    COMPRESSED format2 {
      field_4 =:= irregular(3);      // set ULENGTH to 3
    }

    COMPRESSED format3 {
      field_4 =:= '1010';            // set ULENGTH to zero
    }
```

```
    COMPRESSED format4 {
      ENFORCE(field_4.UVALUE == 12); // use default ULENGTH
    }
```

The fourth format is the only one that uses the default binding for "field_4.ULENGTH".

In summary, the default bindings of an encoding method are only used for formats that do not already specify a binding for the value of all of their fields. For the formats that do use default bindings, only those fields and attributes whose bindings are not specified are looked up in the "DEFAULT" field list.

4.12.2. Arguments

Encoding methods may take arguments that control the mapping between compressed and uncompressed fields. These are specified immediately after the method's name, in parentheses, as a comma-separated list.

For example:

```
  poor_mans_lsb(variable_length)
  {
    UNCOMPRESSED {
      constant_bits;
      variable_bits;
    }

    COMPRESSED {
      variable_bits =:= irregular(variable_length);
      constant_bits =:= static;
    }
  }
```

As with any encoding method, all arguments take individual values, such as an integer literal or a field attribute, rather than entire fields. Although entire fields cannot be passed as arguments, it is possible to pass each of their attributes instead, which is equivalent.

Recall that all bindings are two-way, so that rather than the arguments acting as "inputs" to the encoding method, the result of an encoding method may be to bind the parameters passed to it.

For example:

```
set_to_double(arg1, arg2)
{
  CONTROL {
    ENFORCE(arg1 == 2 * arg2);
  }
}
```

This encoding method will attempt to bind the first argument to twice the value of the second. In fact this "encoding" method is pathological. Since it defines no fields, it does not do any actual encoding at all. "CONTROL" sections are more appropriate to use for this purpose than "UNCOMPRESSED".

4.12.3. Multiple Formats

Encoding methods can also define multiple formats for a given header. This allows different compression methods to be used depending on what is the most efficient way of compressing a particular header.

For example, a field may have a fixed value most of the time, but the value may occasionally change. Using a single format for the encoding, this field would have to be encoded using "irregular" (see Section 4.11.3), even though the value only changes rarely. However, by defining multiple formats, we can provide two alternative encodings: one for when the value remains fixed and another for when the value changes.

This is the topic of the following sub-sections.

4.12.3.1. Naming Convention

When compressed formats are defined, they must be defined using the reserved word "COMPRESSED". Similarly, uncompressed formats must be defined using the reserved word "UNCOMPRESSED". After each of these keywords, a name may be given for the format. If no name is given to the format, the name of the format is empty.

Format names, except for the case where the name is empty, follow the syntactic rules of identifiers as described in Section 4.2.

Format names must be unique within the scope of the encoding method to which they belong, except for the empty name, which may be used for one "COMPRESSED" and one "UNCOMPRESSED" format.

4.12.3.2. Format Discrimination

Each of the compressed formats has its own field list. A compressor may pick any of these alternative formats to compress a header, as long as the field bindings it employs can be used with the uncompressed format. For example, the compressor could not choose to use a compressed format that had a "static" encoding for a field whose "UVALUE" attribute differs from its corresponding value in the context.

More formally, the compressor can choose any combination of an uncompressed format and a compressed format for which no binding for any of the field's attributes "fail", i.e., the encoding methods and "ENFORCE" statements (see Section 4.9) that bind their compressed attributes succeed. If there are multiple successful combinations, the compressor can choose any one. Otherwise if there are no successful combinations, the encoding method "fails". A format will never fail due to it not defining the "UVALUE" attribute of a field. A format only fails if it fails to define one of the compressed attributes of one of the fields in the compressed format, or leaves the length of the uncompressed format undefined.

Because the compressor has a choice, it must be possible for the decompressor to discriminate between the different compressed formats that the compressor could have chosen. A simple approach to this problem is for each compressed format to include a "discriminator" that uniquely identifies that particular "COMPRESSED" format. A discriminator is a control field; it is not derived from any of the uncompressed field values (see Section 4.11.2).

4.12.3.3. Example of Multiple Formats

Putting this all together, here is a complete example of the definition of an encoding method with multiple compressed formats:

```
example_multiple_formats
{
  UNCOMPRESSED {
    field_1;  //  4 bits
    field_2;  //  4 bits
    field_3;  // 24 bits
  }

  DEFAULT {
    field_1 =:= static;
    field_2 =:= uncompressed_value(4, 2);
    field_3 =:= lsb(4, 0);
  }
```

```
    COMPRESSED format0 {
      discriminator =:= '0'; // 1 bit
      field_3;               // 4 bits
    }

    COMPRESSED format1 {
      discriminator =:= '1';           //  1 bit
      field_1       =:= irregular(4);  //  4 bits
      field_3       =:= irregular(24); // 24 bits
    }
  }
```

Note the following:

- "field_1" and "field_3" both have default encoding methods specified for them, which are used in "format0", but are overridden in "format1"; the default encoding method of "field_2" however, is not overridden.

- "field_1" and "field_2" have default encoding methods that compress to zero bits. When these are used in "format0", the field names do not appear in the field list.

- "field_3" has an encoding method that does not compress to zero bits, so whilst "field_3" has no encoding specified for it in the field list of "format0", it still needs to appear in the field list to specify where it goes in the compressed format.

- In the example, all the fields in the uncompressed format have default encoding methods specified for them, but this is not a requirement. Default encodings can be specified for only some or even none of the fields of the uncompressed format.

- In the example, all the default encoding methods are on fields from the uncompressed format, but this is not a requirement. Default encoding methods can be specified for control fields.

4.13. Profile-Specific Encoding Methods

The library of encoding methods defined by ROHC-FN in Section 4.11 provides a basic and generic set of field encoding methods. When using a ROHC-FN specification in a ROHC profile, some additional encodings specific to the particular protocol header being compressed may, however, be needed, such as methods that infer the value of a field from other values.

These methods are specific to the properties of the protocol being compressed and will thus have to be defined within the profile

specification itself. Such profile-specific encoding methods, defined either in ROHC-FN syntax or rigorously in plain text, can be referred to in the ROHC-FN specification of the profile's formats in the same way as any method in the ROHC-FN library.

Encoding methods that are not defined in the formal notation are specified by giving their name, followed by a short description of where they are defined, in double quotes, and a semi-colon.

For example:

```
inferred_ip_v4_header_checksum "defined in RFCxxxx Section 6.4.1";
```

5. Security Considerations

This document describes a formal notation similar to ABNF [RFC4234], and hence is not believed to raise any security issues (note that ABNF has a completely separate purpose to the ROHC formal notation).

6. Contributors

Richard Price did much of the foundational work on the formal notation. He authored the initial document describing a formal notation on which this document is based.

Kristofer Sandlund contributed to this work by applying new ideas to the ROHC-TCP profile, by providing feedback, and by helping resolve different issues during the entire development of the notation.

Carsten Bormann provided the translation of the formal notation syntax using ABNF in Appendix A, and also contributed with feedback and reviews to validate the completeness and correctness of the notation.

7. Acknowledgements

A number of important concepts and ideas have been borrowed from ROHC [RFC3095].

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Additional thanks: this document was reviewed during working group last-call by committed reviewers Mark West, Carsten Bormann, and Joe Touch, as well as by Sally Floyd who provided a review at the request of the Transport Area Directors. Thanks also to Magnus Westerlund for his feedback in preparation for the IESG review.

8. References

8.1. Normative References

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[RFC4234] Crocker, D., Ed. and P. Overell, "Augmented BNF for Syntax Specifications: ABNF", RFC 4234, October 2005.

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8.2. Informative References

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[RFC791] University of Southern California, "DARPA INTERNET PROGRAM PROTOCOL SPECIFICATION", RFC 791, September 1981.

Appendix A. Formal Syntax of ROHC-FN

This section gives a definition of the syntax of ROHC-FN in ABNF [RFC4234], using "fnspec" as the start rule.

```
; overall structure
fnspec     = S *(constdef S) [globctl S] 1*(methdef S)
constdef   = constname S "=" S expn S ";"
globctl    = CONTROL S formbody
methdef    = id S [parmlist S] "{" S 1*(formatdef S) "}"
           / id S [parmlist S] STRQ *STRCHAR STRQ S ";"
parmlist   = "(" S id S *( "," S id S ) ")"
formatdef  = formhead S formbody
formhead   = UNCOMPRESSED [ 1*WS id ]
           / COMPRESSED [ 1*WS id ]
           / CONTROL / INITIAL / DEFAULT
formbody   = "{" S *((fielddef/enforcer) S) "}"
fielddef   = fieldgroup S ["=:=" S encspec S] [lenspec S] ";"
fieldgroup = fieldname *( S ":" S fieldname )
fieldname  = id
encspec    = "'" *("0"/"1") "'"
           / id [ S "(" S expn S *( "," S expn S ) ")"]
lenspec    = "[" S expn S *("," S expn S) "]"
enforcer   = ENFORCE S "(" S expn S ")" S ";"


; expressions
expn  = *(expnb S "||" S) expnb
expnb = *(expna S "&&" S) expna
expna = *(expn7 S ("=="/"!=") S) expn7
expn7 = *(expn6 S ("<"/"<="/">"/">=") S) expn6
expn6 = *(expn4 S ("+"/"-") S) expn4
expn4 = *(expn3 S ("*"/"/"/"%") S) expn3
expn3 = expn2 [S "^" S expn3]
expn2 = ["!" S] expn1
expn1 = expn0 / attref / constname / litval / id
expn0 = "(" S expn S ")" / VARIABLE
attref       = fieldnameref "." attname
fieldnameref = fieldname / THIS
attname      = ( U / C ) ( LENGTH / VALUE )
litval       = ["-"] "0b" 1*("0"/"1")
             / ["-"] "0x" 1*(DIGIT/"a"/"b"/"c"/"d"/"e"/"f")
             / ["-"] 1*DIGIT
             / false / true
```

```
; lexical categories
constname = UPCASE *(UPCASE / DIGIT / "_")
id        = ALPHA *(ALPHA / DIGIT / "_")
ALPHA     = %x41-5A / %x61-7A
UPCASE    = %x41-5A
DIGIT     = %x30-39
COMMENT   = "//" *(SP / HTAB / VCHAR) CRLF
SP        = %x20
HTAB      = %x09
VCHAR     = %x21-7E
CRLF      = %x0A / %x0D.0A
NL        = COMMENT / CRLF
WS        = SP / HTAB / NL
S         = *WS
STRCHAR   = SP / HTAB / %x21 / %x23-7E
STRQ      = %x22


; case-sensitive literals
C            = %d67
COMPRESSED   = %d67.79.77.80.82.69.83.83.69.68
CONTROL      = %d67.79.78.84.82.79.76
DEFAULT      = %d68.69.70.65.85.76.84
ENFORCE      = %d69.78.70.79.82.67.69
INITIAL      = %d73.78.73.84.73.65.76
LENGTH       = %d76.69.78.71.84.72
THIS         = %d84.72.73.83
U            = %d85
UNCOMPRESSED = %d85.78.67.79.77.80.82.69.83.83.69.68
VALUE        = %d86.65.76.85.69
VARIABLE     = %d86.65.82.73.65.66.76.69
false        = %d102.97.108.115.101
true         = %d116.114.117.101
```

Appendix B. Bit-level Worked Example

This section gives a worked example at the bit level, showing how a simple ROHC-FN specification describes the compression of real data from an imaginary protocol header. The example used has been kept fairly simple, whilst still aiming to illustrate some of the intricacies that arise in use of the notation. In particular, fields have been kept short to make it possible to read the binary representation of the headers without too much difficulty.

B.1. Example Packet Format

Our imaginary header is just 16 bits long, and consists of the following fields:

1. version number -- 2 bits

2. type -- 2 bits

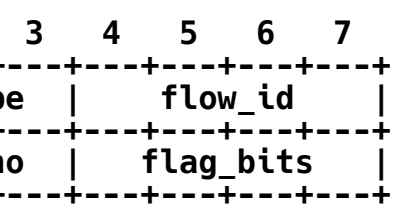
3. flow id -- 4 bits

4. sequence number -- 4 bits

5. flag bits -- 4 bits

So for example 0101000100010000 indicates a header with a version number of one, a type of one, a flow id of one, a sequence number of one, and all flag bits set to zero.

Here is an ASCII box notation diagram of the imaginary header:



B.2. Initial Encoding

An initial definition based solely on the above information is as follows:

```
  eg_header
  {
    UNCOMPRESSED {
      version_no   [ 2 ];
      type         [ 2 ];
      flow_id      [ 4 ];
      sequence_no  [ 4 ];
      flag_bits    [ 4 ];
    }

    COMPRESSED initial_definition {
      version_no  =:= irregular(2);
      type        =:= irregular(2);
      flow_id     =:= irregular(4);
      sequence_no =:= irregular(4);
      flag_bits   =:= irregular(4);
    }
  }
```

This defines the format nicely, but doesn't actually offer any compression. If we use it to encode the above header, we get:

```
  Uncompressed header: 0101000100010000
  Compressed header:   0101000100010000
```

This is because we have stated that all fields are "irregular" -- i.e., we haven't specified anything about their behaviour.

Note that since we have only one compressed format and one uncompressed format, it makes no difference whether the encoding methods for each field are specified in the compressed or uncompressed format. It would make no difference at all if we wrote the following instead:

```
  eg_header
  {
    UNCOMPRESSED {
      version_no  =:= irregular(2);
      type        =:= irregular(2);
      flow_id     =:= irregular(4);
      sequence_no =:= irregular(4);
      flag_bits   =:= irregular(4);
    }
```

```
    COMPRESSED initial_definition {
      version_no   [ 2 ];
      type         [ 2 ];
      flow_id      [ 4 ];
      sequence_no  [ 4 ];
      flag_bits    [ 4 ];
    }
  }
```

B.3. Basic Compression

In order to achieve any compression we need to notate more knowledge about the header and its behaviour in a flow. For example, we may know the following facts about the header:

1. version number -- indicates which version of the protocol this is: always one for this version of the protocol.

2. type -- may take any value.

3. flow id -- may take any value.

4. sequence number -- make take any value.

5. flag bits -- contains three flags, a, b, and c, each of which may be set or clear, and a reserved flag bit, which is always clear (i.e., zero).

We could notate this knowledge as follows:

```
  eg_header
  {
    UNCOMPRESSED {
      version_no     [ 2 ];
      type           [ 2 ];
      flow_id        [ 4 ];
      sequence_no    [ 4 ];
      abc_flag_bits  [ 3 ];
      reserved_flag  [ 1 ];
    }

    COMPRESSED basic {
      version_no    =:= uncompressed_value(2, 1)  [ 0 ];
      type          =:= irregular(2)              [ 2 ];
      flow_id       =:= irregular(4)              [ 4 ];
      sequence_no   =:= irregular(4)              [ 4 ];
      abc_flag_bits =:= irregular(3)              [ 3 ];
      reserved_flag =:= uncompressed_value(1, 0)  [ 0 ];
```

```
    }
  }
```

Using this simple scheme, we have successfully encoded the fact that one of the fields has a permanently fixed value of one, and therefore contains no useful information. We have also encoded the fact that the final flag bit is always zero, which again contains no useful information. Both of these facts have been notated using the "uncompressed_value" encoding method (see Section 4.11.1).

Using this new encoding on the above header, we get:

```
Uncompressed header: 0101000100010000
Compressed header:   0100010001000
```

This reduces the amount of data we need to transmit by roughly 20%. However, this encoding fails to take advantage of relationships between values of a field in one packet and its value in subsequent packets. For example, every header in the following sequence is compressed by the same amount despite the similarities between them:

```
Uncompressed header: 0101000100010000
Compressed header:   0100010001000


Uncompressed header: 0101000101000000
Compressed header:   0100010100000


Uncompressed header: 0110000101110000
Compressed header:   1000010111000
```

B.4. Inter-Packet Compression

The profile we have defined so far has not compressed the sequence number or flow ID fields at all, since they can take any value. However the value of each of these fields in one header has a very simple relationship to their values in previous headers:

- the sequence number is unusual -- it increases by three each time,
- the flow_id stays the same -- it always has the same value that it did in the previous header in the flow,
- the abc_flag_bits stay the same most of the time -- they usually have the same value that they did in the previous header in the flow.

An obvious way of notating this is as follows:

```
// This obvious encoding will not work (correct encoding below)
eg_header
{
  UNCOMPRESSED {
    version_no     [ 2 ];
    type           [ 2 ];
    flow_id        [ 4 ];
    sequence_no    [ 4 ];
    abc_flag_bits  [ 3 ];
    reserved_flag  [ 1 ];
  }

  COMPRESSED obvious {
    version_no    =:= uncompressed_value(2, 1);
    type          =:= irregular(2);
    flow_id       =:= static;
    sequence_no   =:= lsb(0, -3);
    abc_flag_bits =:= irregular(3);
    reserved_flag =:= uncompressed_value(1, 0);
  }
}
```

The dependency on previous packets is notated using the "static" and "lsb" encoding methods (see Section 4.11.4 and Section 4.11.5 respectively). However there are a few problems with the above notation.

Firstly, and most importantly, the "flow_id" field is notated as "static", which means that it doesn't change from packet to packet. However, the notation does not indicate how to communicate the value of the field initially. There is no point saying "it's the same value as last time" if there has not been a first time where we define what that value is, so that it can be referred back to. The above notation provides no way of communicating that. Similarly with the sequence number -- there needs to be a way of communicating its initial value. In fact, except for the explicit notation indicating their lengths, even the lengths of these two fields would be left undefined. This problem will be solved below, in Appendix B.5.

Secondly, the sequence number field is communicated very efficiently in zero bits, but it is not at all robust against packet loss. If a packet is lost then there is no way to handle the missing sequence number. When communicating sequence numbers, or any other field encoded with "lsb" encoding, a very important consideration for the notator is how robust against packet loss the compressed protocol should be. This will vary a lot from protocol stack to protocol

stack. For the example protocol we'll assume short, low overhead flows and say we need to be robust to the loss of just one packet, which we can achieve with two bits of "lsb" encoding (one bit isn't enough since the sequence number increases by three each time -- see Section 4.11.5). This will be addressed below in Appendix B.5.

Finally, although the flag bits are usually the same as in the previous header in the flow, the profile doesn't make any use of this fact; since they are sometimes not the same as those in the previous header, it is not safe to say that they are always the same, so "static" encoding can't be used exclusively. This problem will be solved later through the use of multiple formats in Appendix B.6.

B.5. Specifying Initial Values

To communicate initial values for fields compressed with a context dependent encoding such as "static" or "lsb" we use an "INITIAL" field list. This can help with fields whose start value is fixed and known. For example, if we knew that at the start of the flow that "flow_id" would always be 1 and "sequence_no" would always be 0, we could notate that like this:

```
// This encoding will not work either (correct encoding below)
eg_header
{
  UNCOMPRESSED {
    version_no     [ 2 ];
    type           [ 2 ];
    flow_id        [ 4 ];
    sequence_no    [ 4 ];
    abc_flag_bits  [ 3 ];
    reserved_flag  [ 1 ];
  }

  INITIAL {
    // set initial values of fields before flow starts
    flow_id     =:= uncompressed_value(4, 1);
    sequence_no =:= uncompressed_value(4, 0);
  }

  COMPRESSED obvious {
    version_no    =:= uncompressed_value(2, 1);
    type          =:= irregular(2);
    flow_id       =:= static;
    sequence_no   =:= lsb(2, -3);
    abc_flag_bits =:= irregular(3);
    reserved_flag =:= uncompressed_value(1, 0);
  }
```

```
  }
```

However, this use of "INITIAL" is no good since the initial values of both "flow_id" and "sequence_no" vary from flow to flow. "INITIAL" is only applicable where the initial value of a field is fixed, as is often the case with control fields.

B.6. Multiple Packet Formats

To communicate initial values for the sequence number and flow ID fields correctly, and to take advantage of the fact that the flag bits are usually the same as in the previous header, we need to depart from the single format encoding we are currently using and instead use multiple formats. Here, we have expressed the encodings for two of the fields in the uncompressed format, since they will always be true for uncompressed headers of that format. The remaining fields, whose encoding method may depend on exactly how the header is being compressed, have their encodings specified in the compressed formats.

```
  eg_header
  {
    UNCOMPRESSED {
      version_no    =:= uncompressed_value(2, 1) [ 2 ];
      type                                       [ 2 ];
      flow_id                                    [ 4 ];
      sequence_no                                [ 4 ];
      abc_flag_bits                              [ 3 ];
      reserved_flag =:= uncompressed_value(1, 0) [ 1 ];
    }


    COMPRESSED irregular_format {
      discriminator =:= '0'           [ 1 ];
      version_no                      [ 0 ];
      type          =:= irregular(2)  [ 2 ];
      flow_id       =:= irregular(4)  [ 4 ];
      sequence_no   =:= irregular(4)  [ 4 ];
      abc_flag_bits =:= irregular(3)  [ 3 ];
      reserved_flag                   [ 0 ];
    }

    COMPRESSED compressed_format {
      discriminator =:= '1'           [ 1 ];
      version_no                      [ 0 ];
      type          =:= irregular(2)  [ 2 ];
      flow_id       =:= static        [ 0 ];
      sequence_no   =:= lsb(2, -3)    [ 2 ];
```

```
      abc_flag_bits =:= static       [ 0 ];
      reserved_flag                  [ 0 ];
    }
  }
```

Note that we have added a discriminator field, so that the decompressor can tell which format has been used by the compressor. The format with a "static" flow ID and "lsb" encoded sequence number is now 5 bits long. Note that despite having to add the discriminator field, this format is still the same size as the original incorrect "obvious" format because it takes advantage of the fact that the abc flag bits rarely change.

However, the original "basic" format has also grown by one bit due to the addition of the discriminator ("irregular_format"). An important consideration when creating multiple formats is whether each format occurs frequently enough that the average compressed header length is shorter as a result of its usage. For example, if in fact the flag bits always changed between packets, the "compressed_format" encoding could never be used; all we would have achieved is lengthening the "basic" format by one bit.

Using the above notation, we now get:

```
Uncompressed header: 0101000100010000
Compressed header:   00100010001000


Uncompressed header: 0101000101000000
Compressed header:   10100 ; 00100010100000


Uncompressed header: 0110000101110000
Compressed header:   11011 ; 01000010111000
```

The first header in the stream is compressed the same way as before, except that it now has the extra 1-bit discriminator at the start (0). When a second header arrives with the same flow ID as the first and its sequence number three higher, it can be compressed in two possible ways: either by using "compressed_format" or, in the same way as previously, by using "irregular_format".

Note that we show all theoretically possible encodings of a header as defined by the ROHC-FN specification, separated by semi-colons. Either of the above encodings for each header could be produced by a valid implementation, although a good implementation would always aim to pick the encoding that leads to the best compression. A good implementation would also take robustness into account and therefore

probably wouldn't assume on the second packet that the decompressor had available the context necessary to decompress the shorter "compressed_format" form.

Finally, note that the fields whose encoding methods are specified in the uncompressed format have zero length when compressed. This means their position in the compressed format is not significant. In this case, there is no need to notate them when defining the compressed formats. In the next part of the example we will see that they have been removed from the compressed formats altogether.

B.7. Variable Length Discriminators

Suppose we do some analysis on flows of our example protocol and discover that whilst it is usual for successive packets to have the same flags, on the occasions when they don't, the packet is almost always a "flags set" packet in which all three of the abc flags are set. To encode the flow more efficiently a format needs to be written to reflect this.

This now gives a total of three formats, which means we need three discriminators to differentiate between them. The obvious solution here is to increase the number of bits in the discriminator from one to two and use discriminators 00, 01, and 10 for example. However we can do slightly better than this.

Any uniquely identifiable discriminator will suffice, so we can use 00, 01, and 1. If the discriminator starts with 1, that's the whole thing. If it starts with 0, the decompressor knows it has to check one more bit to determine the kind of format.

Note that care must be taken when using variable length discriminators. For example, it would be erroneous to use 0, 01, and 10 as discriminators since after reading an initial 0, the decompressor would have no way of knowing if the next bit was a second bit of discriminator, or the first bit of the next field in the format. However, 0, 10, and 11 would be correct, as the first bit again indicates whether or not there are further discriminator bits to follow.

This gives us the following:

```
eg_header
{
  UNCOMPRESSED {
    version_no    =:= uncompressed_value(2, 1) [ 2 ];
    type                                       [ 2 ];
    flow_id                                    [ 4 ];
    sequence_no                                [ 4 ];
    abc_flag_bits                              [ 3 ];
    reserved_flag =:= uncompressed_value(1, 0) [ 1 ];
  }

  COMPRESSED irregular_format {
    discriminator =:= '00'          [ 2 ];
    type          =:= irregular(2)  [ 2 ];
    flow_id       =:= irregular(4)  [ 4 ];
    sequence_no   =:= irregular(4)  [ 4 ];
    abc_flag_bits =:= irregular(3)  [ 3 ];
  }

  COMPRESSED flags_set {
    discriminator =:= '01'                     [ 2 ];
    type          =:= irregular(2)             [ 2 ];
    flow_id       =:= static                   [ 0 ];
    sequence_no   =:= lsb(2, -3)               [ 2 ];
    abc_flag_bits =:= uncompressed_value(3, 7) [ 0 ];
  }

  COMPRESSED flags_static {
    discriminator =:= '1'           [ 1 ];
    type          =:= irregular(2)  [ 2 ];
    flow_id       =:= static        [ 0 ];
    sequence_no   =:= lsb(2, -3)    [ 2 ];
    abc_flag_bits =:= static        [ 0 ];
  }
}
```

Here is some example output:

```
Uncompressed header: 0101000100010000
Compressed header:   000100010001000


Uncompressed header: 0101000101000000
Compressed header:   10100 ; 000100010100000
```

```
Uncompressed header: 0110000101110000
Compressed header:   11011 ; 001000010111000


Uncompressed header: 0111000110101110
Compressed header:   011110 ; 001100011010111
```

Here we have a very similar sequence to last time, except that there is now an extra message on the end that has the flag bits set. The encoding for the first message in the stream is now one bit larger, the encoding for the next two messages is the same as before, since that format has not grown; thanks to the use of variable length discriminators. Finally, the packet that comes through with all the flag bits set can be encoded in just six bits, only one bit more than the most common format. Without the extra format, this last packet would have to be encoded using the longest format and would have taken up 14 bits.

B.8. Default Encoding

Some of the common encoding methods used so far have been "factored out" into the definition of the uncompressed format, meaning that they don't need to be defined for every compressed format. However, there is still some redundancy in the notation. For a number of fields, the same encoding method is used several times in different formats (though not necessarily in all of them), but the field encoding is redefined explicitly each time. If the encoding for any of these fields changed in the future, then every format that uses that encoding would have to be modified to reflect this change.

This problem can be avoided by specifying default encoding methods for these fields. Doing so can also lead to a more concisely notated profile:

```
eg_header
{
  UNCOMPRESSED {
    version_no    =:= uncompressed_value(2, 1) [ 2 ];
    type                                       [ 2 ];
    flow_id                                    [ 4 ];
    sequence_no                                [ 4 ];
    abc_flag_bits                              [ 3 ];
    reserved_flag =:= uncompressed_value(1, 0) [ 1 ];
  }

  DEFAULT {
    type          =:= irregular(2);
    flow_id       =:= static;
```

```
      sequence_no   =:= lsb(2, -3);
    }

    COMPRESSED irregular_format {
      discriminator =:= '00'          [ 2 ];
      type                            [ 2 ]; // Uses default
      flow_id       =:= irregular(4) [ 4 ]; // Overrides default
      sequence_no   =:= irregular(4) [ 4 ]; // Overrides default
      abc_flag_bits =:= irregular(3) [ 3 ];
    }

    COMPRESSED flags_set {
      discriminator =:= '01' [ 2 ];
      type                   [ 2 ]; // Uses default
      sequence_no            [ 2 ]; // Uses default
      abc_flag_bits =:= uncompressed_value(3, 7);
    }

    COMPRESSED flags_static {
      discriminator =:= '1' [ 1 ];
      type                  [ 2 ]; // Uses default
      sequence_no           [ 2 ]; // Uses default
      abc_flag_bits =:= static;
    }
  }
```

The above profile behaves in exactly the same way as the one notated previously, since it has the same meaning. Note that the purpose behind the different formats becomes clearer with the default encoding methods factored out: all that remains are the encodings that are specific to each format. Note also that default encoding methods that compress down to zero bits have become completely implicit. For example the compressed formats using the default encoding for "flow_id" don't mention it (the default is "static" encoding that compresses to zero bits).

B.9. Control Fields

One inefficiency in the compression scheme we have produced thus far is that it uses two bits to provide the "lsb" encoded sequence number with robustness for the loss of just one packet. In theory, only one bit should be needed. The root of the problem is the unusual sequence number that the protocol uses -- it counts up in increments of three. In order to encode it at maximum efficiency we need to translate this into a field that increments by one each time. We do this using a control field.

A control field is extra data that is communicated in the compressed format, but which is not a direct encoding of part of the uncompressed header. Control fields can be used to communicate extra information in the compressed format, that allows other fields to be compressed more efficiently.

The control field that we introduce scales the sequence number down by a factor of three. Instead of encoding the original sequence number in the compressed packet, we encode the scaled sequence number, allowing us to have robustness to the loss of one packet by using just one bit of "lsb" encoding:

```
  eg_header
  {
    UNCOMPRESSED {
      version_no    =:= uncompressed_value(2, 1) [ 2 ];
      type                                       [ 2 ];
      flow_id                                    [ 4 ];
      sequence_no                                [ 4 ];
      abc_flag_bits                              [ 3 ];
      reserved_flag =:= uncompressed_value(1, 0) [ 1 ];
    }

    CONTROL {
      // need modulo maths to calculate scaling correctly,
      // due to 4 bit wrap around
      scaled_seq_no   [ 4 ];
      ENFORCE(sequence_no.UVALUE
                == (scaled_seq_no.UVALUE * 3) % 16);
    }

    DEFAULT {
      type          =:= irregular(2);
      flow_id       =:= static;
      scaled_seq_no =:= lsb(1, -1);
    }

    COMPRESSED irregular_format {
      discriminator =:= '00'          [ 2 ];
      type                            [ 2 ];
      flow_id       =:= irregular(4) [ 4 ];
      scaled_seq_no =:= irregular(4) [ 4 ]; // Overrides default
      abc_flag_bits =:= irregular(3) [ 3 ];
    }

    COMPRESSED flags_set {
      discriminator =:= '01' [ 2 ];
      type                   [ 2 ];
```

```
        scaled_seq_no          [ 1 ]; // Uses default
        abc_flag_bits =:= uncompressed_value(3, 7);
      }

      COMPRESSED flags_static {
        discriminator =:= '1' [ 1 ];
        type                  [ 2 ];
        scaled_seq_no         [ 1 ]; // Uses default
        abc_flag_bits =:= static;
      }
    }
```

Normally, the encoding method(s) used to encode a field specifies the length of the field. In the above notation, since there is no encoding method using "sequence_no" directly, its length needs to be defined explicitly using an "ENFORCE" statement. This is done using the abbreviated syntax, both for consistency and also for ease of readability. Note that this is unusual: whereas the majority of field length indications are redundant (and thus optional), this one isn't. If it was removed from the above notation, the length of the "sequence_no" field would be undefined.

Here is some example output:

```
  Uncompressed header: 0101000100010000
  Compressed header:   000100011011000


  Uncompressed header: 0101000101000000
  Compressed header:   1010 ; 000100011100000


  Uncompressed header: 0110000101110000
  Compressed header:   1101 ; 001000011101000


  Uncompressed header: 0111000110101110
  Compressed header:   01110 ; 001100011110111
```

In this form, we see that this gives us a saving of a further bit in most packets. Assuming the bulk of a flow is made up of "flags_static" headers, the mean size of the headers in a compressed flow is now just over a quarter of their size in an uncompressed flow.

B.10. Use of "ENFORCE" Statements as Conditionals

Earlier, we created a new format "flags_set" to handle packets with all three of the flag bits set. As it happens, these three flags are always all set for "type 3" packets, and are never all set for other packet types (a "type 3" packet is one where the type field is set to three).

This allows extra efficiency in encoding such packets. We know the type is three, so we don't need to encode the type field in the compressed header. The type field was previously encoded as "irregular(2)", which is two bits long. Removing this reduces the size of the "flags_set" format from five bits to three, making it the smallest format in the encoding method definition.

In order to notate that the "flags_set" format should only be used for "type 3" headers, and the "flags_static" format only when the type isn't three, it is necessary to state these conditions inside each format. This can be done with an "ENFORCE" statement:

```
  eg_header
  {
    UNCOMPRESSED {
      version_no    =:= uncompressed_value(2, 1) [ 2 ];
      type                                       [ 2 ];
      flow_id                                    [ 4 ];
      sequence_no                                [ 4 ];
      abc_flag_bits                              [ 3 ];
      reserved_flag =:= uncompressed_value(1, 0) [ 1 ];
    }

    CONTROL {
      // need modulo maths to calculate scaling correctly,
      // due to 4 bit wrap around
      scaled_seq_no   [ 4 ];
      ENFORCE(sequence_no.UVALUE
                == (scaled_seq_no.UVALUE * 3) % 16);
    }

    DEFAULT {
      type          =:= irregular(2);
      scaled_seq_no =:= lsb(1, -1);
      flow_id       =:= static;
    }

    COMPRESSED irregular_format {
      discriminator =:= '00'          [ 2 ];
      type                            [ 2 ];
```

```
      flow_id       =:= irregular(4) [ 4 ];
      scaled_seq_no =:= irregular(4) [ 4 ];
      abc_flag_bits =:= irregular(3) [ 3 ];
    }

    COMPRESSED flags_set {
      ENFORCE(type.UVALUE == 3); // redundant condition
      discriminator =:= '01'                          [ 2 ];
      type          =:= uncompressed_value(2, 3)      [ 0 ];
      scaled_seq_no                                   [ 1 ];
      abc_flag_bits =:= uncompressed_value(3, 7)      [ 0 ];
    }

    COMPRESSED flags_static {
      ENFORCE(type.UVALUE != 3);
      discriminator =:= '1'    [ 1 ];
      type                     [ 2 ];
      scaled_seq_no            [ 1 ];
      abc_flag_bits =:= static [ 0 ];
    }
  }
```

The two "ENFORCE" statements in the last two formats act as "guards". Guards prevent formats from being used under the wrong circumstances. In fact, the "ENFORCE" statement in "flags_set" is redundant. The condition it guards for is already enforced by the new encoding method used for the "type" field. The encoding method "uncompressed_value(2,3)" binds the "UVALUE" attribute to three. This is exactly what the "ENFORCE" statement does, so it can be removed without any change in meaning. The "uncompressed_value" encoding method on the other hand is not redundant. It specifies other bindings on the type field in addition to the one that the "ENFORCE" statement specifies. Therefore it would not be possible to remove the encoding method and leave just the "ENFORCE" statement.

Note that a guard is solely preventative. A guard can never force a format to be chosen by the compressor. A format can only be guaranteed to be chosen in a given situation if there are no other formats that can be used instead. This is demonstrated in the example output below. The compressor can still choose the "irregular" format if it wishes:

```
  Uncompressed header: 0101000100010000
  Compressed header:   000100011011000


  Uncompressed header: 0101000101000000
  Compressed header:   1010 ; 000100011100000
```

```
     Uncompressed header: 0110000101110000
     Compressed header:   1101 ; 001000011101000


     Uncompressed header: 0111000110101110
     Compressed header:   010 ; 001100011110111
```

   This saves just two extra bits (a 7% saving) in the example flow.

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