Simple Low-Density Parity Check (LDPC) Staircase Forward Error Correction (FEC) Scheme for FECFRAME

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Abstract

This document describes a fully specified simple Forward Error Correction (FEC) scheme for Low-Density Parity Check (LDPC) Staircase codes that can be used to protect media streams along the lines defined by FECFRAME. These codes have many interesting properties: they are systematic codes, they perform close to ideal codes in many use-cases, and they also feature very high encoding and decoding throughputs. LDPC-Staircase codes are therefore a good solution to protect a single high bitrate source flow or to protect globally several mid-rate flows within a single FECFRAME instance. They are also a good solution whenever the processing load of a software encoder or decoder must be kept to a minimum.

Status of This Memo

This is an Internet Standards Track document.

This document is a product of the Internet Engineering Task Force (IETF). It represents the consensus of the IETF community. It has received public review and has been approved for publication by the Internet Engineering Steering Group (IESG). Further information on Internet Standards is available in Section 2 of RFC 5741.

Information about the current status of this document, any errata, and how to provide feedback on it may be obtained at http://www.rfc-editor.org/info/rfc6816.

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1. Introduction

The use of Forward Error Correction (FEC) codes is a classic solution to improve the reliability of unicast, multicast, and broadcast Content Delivery Protocols (CDPs) and applications [RFC3453]. "Forward Error Correction (FEC) Framework" [RFC6363] describes a generic framework to use FEC schemes with media delivery applications and, for instance, with real-time streaming media applications based on the RTP real-time protocol. Similarly, "Forward Error Correction (FEC) Building Block" [RFC5052] describes a generic framework to use FEC schemes with objects (e.g., files) delivery applications based on either the Asynchronous Layered Coding (ALC) [RFC5775] or the NACK-Oriented Reliable Multicast (NORM) [RFC5740] protocols.

More specifically, the [RFC5053] (Raptor) and [RFC5170] (LDPC-Staircase and LDPC-Triangle) FEC schemes introduce erasure codes based on sparse parity check matrices for object delivery protocols like ALC and NORM. Similarly, "Reed-Solomon Forward Error Correction (FEC) Schemes" [RFC5510] introduces Reed-Solomon codes based on Vandermonde matrices for the same object delivery protocols. All these codes are systematic codes, meaning that the k source symbols are part of the n encoding symbols. Additionally, the Reed-Solomon FEC codes belong to the class of Maximum Distance Separable (MDS) codes that are optimal in terms of erasure recovery capabilities. It means that a receiver can recover the k source symbols from any set of exactly k encoding symbols out of n. This is not the case with either Raptor or LDPC-Staircase codes, and these codes require a certain number of encoding symbols in excess to k. However, this number is small in practice when an appropriate decoding scheme is used at the receiver [Cunche08]. Another key difference is the high encoding/decoding complexity of Reed-Solomon codecs compared to Raptor or LDPC-Staircase codes. A difference of one or more orders of magnitude in terms of encoding/decoding speed exists between the Reed-Solomon and LDPC-Staircase software codecs [Cunche08][CunchePHD10]. Finally, Raptor and LDPC-Staircase codes are large block FEC codes, in the sense of [RFC3453], since they can efficiently deal with a large number of source symbols.

The present document focuses on LDPC-Staircase codes that belong to the well-known class of "Low Density Parity Check" codes. Because of their key features, these codes are a good solution in many situations, as detailed in Section 7.

This document inherits from [RFC5170], Section 6 "Full Specification of the LDPC-Staircase Scheme", the specifications of the core LDPC-Staircase codes, and from Section 5.7 "Pseudo-Random Number Generator", the specifications of the PRNG used by these codes. Therefore, this document specifies only the information specific to

the FECFRAME context and refers to [RFC5170] for the core specifications of the codes. To that purpose, the present document introduces:

- o the Fully Specified FEC Scheme with FEC Encoding ID 7 that specifies a simple way of using LDPC-Staircase codes in order to protect arbitrary Application Data Unit (ADU) flows.

Therefore Sections 4 and 5 (except Section 5.7, see above) of [RFC5170], that define [RFC5052] specific Formats and Procedures, are not considered and are replaced by FECFRAME specific Formats and Procedures.

Finally, publicly available reference implementations of these codes are available [LDPC-codec] [LDPC-codec-OpenFEC].

2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

3. Definitions Notations and Abbreviations

3.1. Definitions

This document uses the following terms and definitions. Those in the list below are FEC scheme specific and are in line with [RFC5052]:

Source symbol: unit of data used during the encoding process. In this specification, there is always one source symbol per ADU.

Encoding symbol: unit of data generated by the encoding process. With systematic codes, source symbols are part of the encoding symbols.

Repair symbol: encoding symbol that is not a source symbol.

Code rate: the k/n ratio, i.e., the ratio between the number of source symbols and the number of encoding symbols. By definition, the code rate is such that: 0 < code rate <= 1. A code rate close to 1 indicates that a small number of repair symbols have been produced during the encoding process.

Systematic code: FEC code in which the source symbols are part of the encoding symbols. The LDPC-Staircase codes introduced in this document are systematic.

Source block: a block of k source symbols that are considered together for the encoding.

Packet erasure channel: a communication path where packets are either dropped (e.g., by a congested router, or because the number of transmission errors exceeds the correction capabilities of the physical layer codes) or received. When a packet is received, it is assumed that this packet is not corrupted.

The following are FECFRAME specific and are in line with [RFC6363]:

Application Data Unit (ADU): the unit of source data provided as payload to the transport layer. Depending on the use-case, an ADU may use an RTP encapsulation.

(Source) ADU Flow: a sequence of ADUs associated with a transport-layer flow identifier (such as the standard 5-tuple {Source IP address, source port, destination IP address, destination port, transport protocol}). Depending on the use-case, several ADU flows may be protected together by FECFRAME.

ADU Block: a set of ADUs that are considered together by the FECFRAME instance for the purpose of the FEC scheme. Along with the flow ID (F[]), length (L[]), and padding (Pad[]) fields, they form the set of source symbols over which FEC encoding will be performed.

ADU Information (ADUI): a unit of data constituted by the ADU and the associated Flow ID, Length, and Padding fields (Section 4.3). This is the unit of data that is used as source symbol.

FEC Framework Configuration Information (FFCI): information that controls the operation of the FEC Framework. The FFCI enables the synchronization of the FECFRAME sender and receiver instances.

FEC Source Packet: at a sender (respectively, at a receiver) a payload submitted to (respectively, received from) the transport protocol containing an ADU along with an optional Explicit Source FEC Payload ID.

FEC Repair Packet: at a sender (respectively, at a receiver) a payload submitted to (respectively, received from) the transport protocol containing one repair symbol along with a Repair FEC Payload ID and possibly an RTP header.

The above terminology is illustrated in Figure 1 (sender’s point of view):

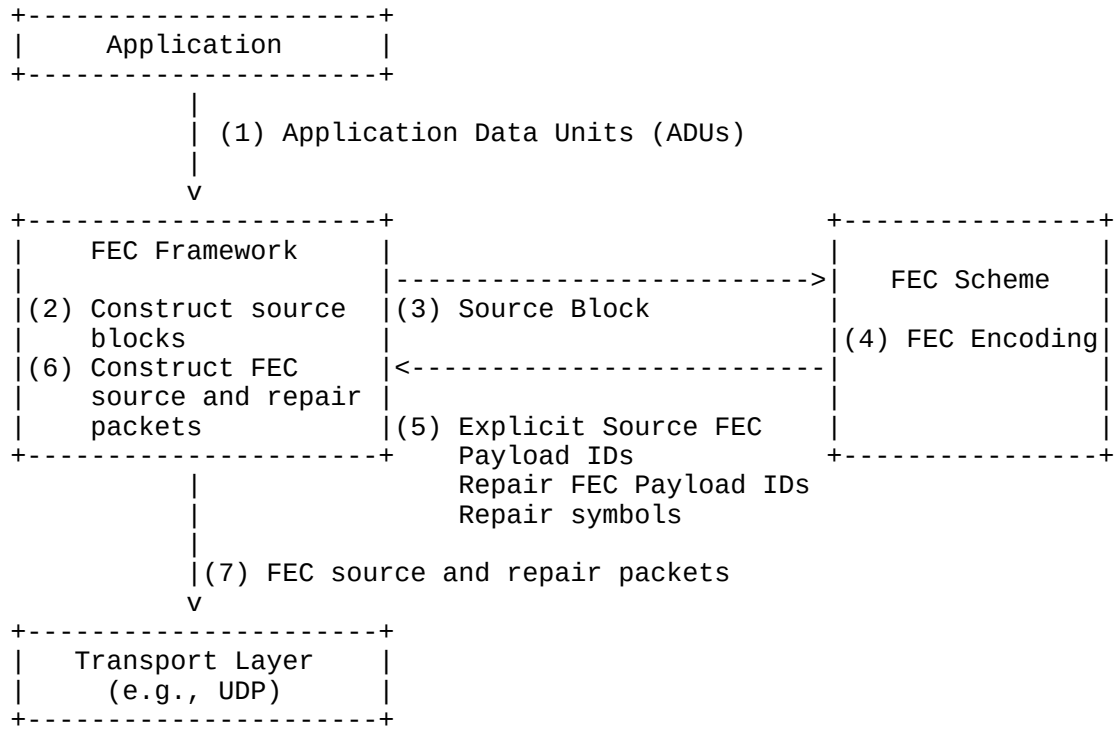

Figure 1: Terminology Used in This Document (Sender)

3.2. Notations

This document uses the following notations. Those in the list below are FEC scheme specific:

k denotes the number of source symbols in a source block.

max_k denotes the maximum number of source symbols for any source block.

n denotes the number of encoding symbols generated for a source block.

E denotes the encoding symbol length in bytes.

CR denotes the "code rate", i.e., the k/n ratio.

N1 denotes the target number of "1s" per column in the left side of the parity check matrix.

N1m3 denotes the value N1 - 3.

G G denotes the number of encoding symbols per group, i.e., the number of symbols sent in the same packet.

a^^b denotes a raised to the power b.

The following are FECFRAME specific:

B denotes the number of ADUs per ADU block.

max_B denotes the maximum number of ADUs for any ADU block.

3.3. Abbreviations

This document uses the following abbreviations:

ADU Application Data Unit

ESI Encoding Symbol ID

FEC Forward Error (or Erasure) Correction

FFCI FEC Framework Configuration Information

FSSI FEC Scheme-Specific Information

LDPC Low-Density Parity Check

MDS Maximum Distance Separable

PRNG Pseudo-Random Number Generator

SDP Session Description Protocol

4. Common Procedures Related to the ADU Block and Source Block Creation

This section introduces the procedures that are used during the ADU block and related source block creation, for the FEC scheme considered.

4.1. Restrictions

This specification has the following restrictions:

- there MUST be exactly one source symbol per ADUI, and therefore per ADU;
- there MUST be exactly one repair symbol per FEC repair packet;
- there MUST be exactly one source block per ADU block;
- the use of the LDPC-Staircase scheme is such that there MUST be exactly one encoding symbol per group; i.e., G MUST be equal to 1 [RFC5170];

4.2. ADU Block Creation

Two kinds of limitations exist that impact the ADU block creation:

- at the FEC scheme level: the FEC scheme and the FEC codec have limitations that define a maximum source block size;
- at the FECFRAME instance level: the target use-case can have real-time constraints that can/will define a maximum ADU block size;

Note that the use of the terminology "maximum source block size" and "maximum ADU block size" depends on the point of view that is adopted (FEC scheme versus FECFRAME instance). However, in this document, both refer to the same value since Section 4.1 requires there be exactly one source symbol per ADU. We now detail each of these aspects.

The maximum source block size in symbols, max_k, depends on several parameters: the code rate (CR) and the Encoding Symbol ID (ESI) field length in the Explicit Source/Repair FEC Payload ID (16 bits), as well as possible internal codec limitations. More specifically, max_k cannot be larger than the following values, derived from the ESI field size limitation, for a given code rate:

```
max1_k = 2^^(16 - ceil(Log2(1/CR)))
```

Some common max1_k values are:

- CR == 1 (no repair symbol): max1_k = 2^^16 = 65536 symbols
- 1/2 <= CR < 1: max1_k = 2^^15 = 32,768 symbols
- 1/4 <= CR < 1/2: max1_k = 2^^14 = 16,384 symbols

Additionally, a codec can impose other limitations on the maximum source block size, for instance, because of a limited working memory size. This decision MUST be clarified at implementation time, when the target use-case is known. This results in a max2_k limitation.

Then, max_k is given by:

```
max_k = min(max1_k, max2_k)
```

Note that this calculation is only required at the encoder (sender), since the actual k parameter (k <= max_k) is communicated to the decoder (receiver) through the Explicit Source/Repair FEC Payload ID.

The source ADU flows can have real-time constraints. When there are multiple flows, with different real-time constraints, let us consider the most stringent constraints (see [RFC6363], Section 10.2, item 6, for recommendations when several flows are globally protected). In that case the maximum number of ADUs of an ADU block must not exceed a certain threshold since it directly impacts the decoding delay. The larger the ADU block size, the longer a decoder may have to wait until it has received a sufficient number of encoding symbols for decoding to succeed, and therefore the larger the decoding delay. When the target use-case is known, these real-time constraints result in an upper bound to the ADU block size, max_rt.

For instance, if the use-case specifies a maximum decoding latency, l, and if each source ADU covers a duration d of a continuous media (we assume here the simple case of a constant bit rate ADU flow), then the ADU block size must not exceed:

```
max_rt = floor(l / d)
```

After encoding, this block will produce a set of at most n = max_rt / CR encoding symbols. These n encoding symbols will have to be sent at a rate of n / l packets per second. For instance, with d = 10 ms, l = 1 s, max_rt = 100 ADUs.

If we take into account all these constraints, we find:

```
max_B = min(max_k, max_rt)
```

This max_B parameter is an upper bound to the number of ADUs that can constitute an ADU block.

4.3. Source Block Creation

In its most general form, FECFRAME and the LDPC-Staircase FEC Scheme are meant to protect a set of independent flows. Since the flows have no relationship to one another, the ADU size of each flow can potentially vary significantly. Even in the special case of a single flow, the ADU sizes can largely vary (e.g., the various frames of a Group of Pictures (GOP) of an H.264 flow). This diversity must be addressed since the LDPC-Staircase FEC Scheme requires a constant encoding symbol size (E parameter) per source block. Since this specification requires that there be only one source symbol per ADU, E must be large enough to contain all the ADUs of an ADU block along with their prepended 3 bytes (see below).

In situations where E is determined per source block (default, specified by the FFCI/FSSI with S = 0, Section 5.1.1.2), E is equal to the size of the largest ADU of this source block plus three (for the prepended 3 bytes, see below). In this case, upon receiving the first FEC repair packet for this source block, since this packet MUST contain a single repair symbol (Section 5.1.3), a receiver determines the E parameter used for this source block.

In situations where E is fixed (specified by the FFCI/FSSI with S = 1, Section 5.1.1.2), then E must be greater or equal to the size of the largest ADU of this source block plus three (for the prepended 3 bytes, see below). If this is not the case, an error is returned. How to handle this error is use-case specific (e.g., a larger E parameter may be communicated to the receivers in an updated FFCI message, using an appropriate mechanism) and is not considered by this specification.

The ADU block is always encoded as a single source block. There are a total of B <= max_B ADUs in this ADU block. For the ADU i, with 0 <= i <= B-1, 3 bytes are prepended (Figure 2):

- The first byte, F[i] (Flow ID), contains the integer identifier associated to the source ADU flow to which this ADU belongs. It is assumed that a single byte is sufficient, or said differently, that no more than 256 flows will be protected by a single instance of FECFRAME.

- The following two bytes, L[i] (Length), contain the length of this ADU, in network byte order (i.e., big endian). This length is for the ADU itself and does not include the F[i], L[i], or Pad[i] fields.

Then, zero padding is added to ADU i (if needed) in field Pad[i], for alignment purposes up to a size of exactly E bytes. The data unit resulting from the ADU i and the F[i], L[i], and Pad[i] fields is called ADU Information (or ADUI). Each ADUI contributes to exactly one source symbol of the source block.

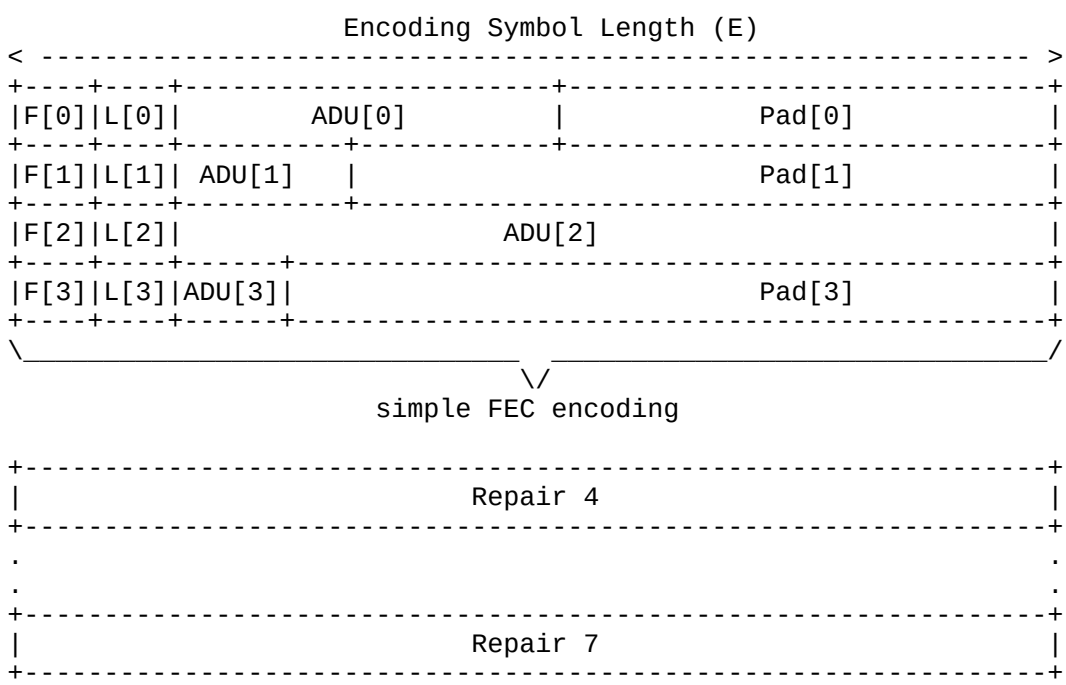

Figure 2: Source Block Creation, for Code Rate 1/2 (Equal Number of Source and Repair Symbols, 4 in This Example), and S = 0

Note that neither the initial 3 bytes nor the optional padding are sent over the network. However, they are considered during FEC encoding. It means that a receiver who lost a certain FEC source packet (e.g., the UDP datagram containing this FEC source packet) will be able to recover the ADUI if FEC decoding succeeds. Thanks to the initial 3 bytes, this receiver will get rid of the padding (if any) and identify the corresponding ADU flow.

5. LDPC-Staircase FEC Scheme for Arbitrary ADU Flows

5.1. Formats and Codes

5.1.1. FEC Framework Configuration Information

The FEC Framework Configuration Information (or FFCI) includes information that MUST be communicated between the sender and receiver(s). More specifically, it enables the synchronization of the FECFRAME sender and receiver instances. It includes both mandatory elements and scheme-specific elements, as detailed below.

5.1.1.1. Mandatory Information

- FEC Encoding ID: the value assigned to this fully specified FEC scheme MUST be 7, as assigned by IANA (Section 8).

When SDP is used to communicate the FFCI, this FEC Encoding ID is carried in the 'encoding-id' parameter.

5.1.1.2. FEC Scheme-Specific Information

The FEC Scheme-Specific Information (FSSI) includes elements that are specific to the present FEC scheme. More precisely:

- PRNG seed (seed): a non-negative 32-bit integer used as the seed of the Pseudo-Random Number Generator, as defined in [RFC5170].

- Encoding symbol length (E): a non-negative integer that indicates either the length of each encoding symbol in bytes (strict mode, i.e., if S = 1) or the maximum length of any encoding symbol (i.e., if S = 0).

- Strict (S) flag: when set to 1, this flag indicates that the E parameter is the actual encoding symbol length value for each block of the session (unless otherwise notified by an updated FFCI if this possibility is considered by the use-case or CDP). When set to 0, this flag indicates that the E parameter is the maximum encoding symbol length value for each block of the session (unless otherwise notified by an updated FFCI if this possibility is considered by the use-case or CDP).

- N1 minus 3 (n1m3): an integer between 0 (default) and 7, inclusive. The number of "1s" per column in the left side of the parity check matrix, N1, is then equal to N1m3 + 3, as specified in [RFC5170].

These elements are required both by the sender (LDPC-Staircase encoder) and the receiver(s) (LDPC-Staircase decoder).

When SDP is used to communicate the FFCI, this FEC scheme-specific information is carried in the 'fssi' parameter in textual representation as specified in [RFC6364]. For instance:

fssi=seed:1234,E:1400,S:0,n1m3:0

If another mechanism requires the FSSI to be carried as an opaque octet string (for instance, after a Base64 encoding), the encoding format consists of the following 7 octets:

- PRNG seed (seed): 32-bit field.
- Encoding symbol length (E): 16-bit field.
- Strict (S) flag: 1-bit field.
- Reserved: a 4-bit field that MUST be set to zero.
- N1m3 parameter (n1m3): 3-bit field.

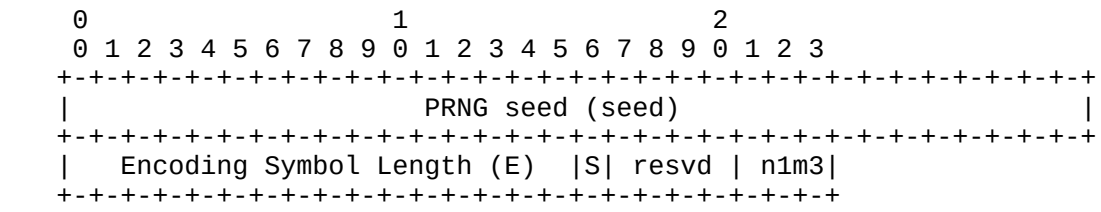

Figure 3: FSSI Encoding Format

5.1.2. Explicit Source FEC Payload ID

A FEC source packet MUST contain an Explicit Source FEC Payload ID that is appended to the end of the packet as illustrated in Figure 4.

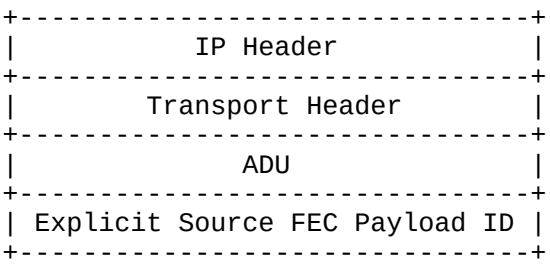

Figure 4: Structure of a FEC Source Packet with the Explicit Source FEC Payload ID

More precisely, the Explicit Source FEC Payload ID is composed of the following fields (Figure 5):

- Source Block Number (SBN) (16-bit field): this field identifies the source block to which this FEC source packet belongs.
- Encoding Symbol ID (ESI) (16-bit field): this field identifies the source symbol contained in this FEC source packet. This value is such that 0 <= ESI <= k - 1 for source symbols.
- Source Block Length (k) (16-bit field): this field provides the number of source symbols for this source block, i.e., the k parameter.

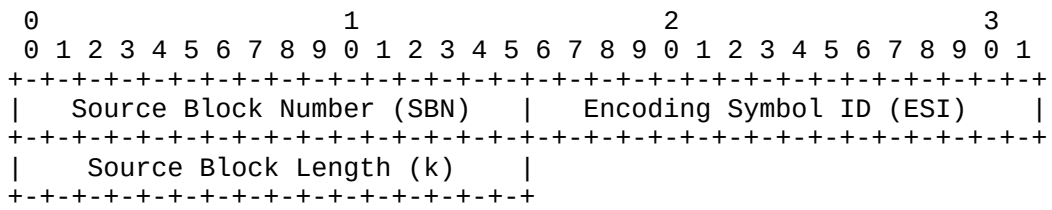

Figure 5: Source FEC Payload ID Encoding Format

5.1.3. Repair FEC Payload ID

A FEC repair packet MUST contain a Repair FEC Payload ID that is prepended to the repair symbol(s) as illustrated in Figure 6. There MUST be a single repair symbol per FEC repair packet.

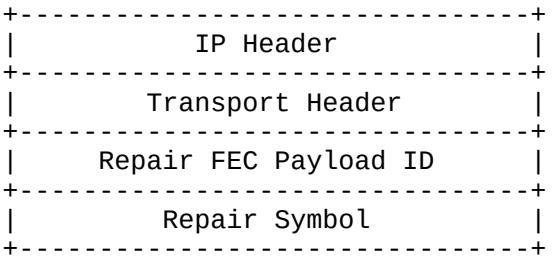

Figure 6: Structure of a FEC Repair Packet with the Repair Payload ID

More precisely, the Repair FEC Payload ID is composed of the following fields (Figure 7):

- Source Block Number (SBN) (16-bit field): this field identifies the source block to which the FEC repair packet belongs.
- Encoding Symbol ID (ESI) (16-bit field): this field identifies the repair symbol contained in this FEC repair packet. This value is such that k <= ESI <= n - 1 for repair symbols.
- Source Block Length (k) (16-bit field): this field provides the number of source symbols for this source block, i.e., the k parameter.
- Number of Encoding Symbols (n) (16-bit field): this field provides the number of encoding symbols for this source block, i.e., the n parameter.

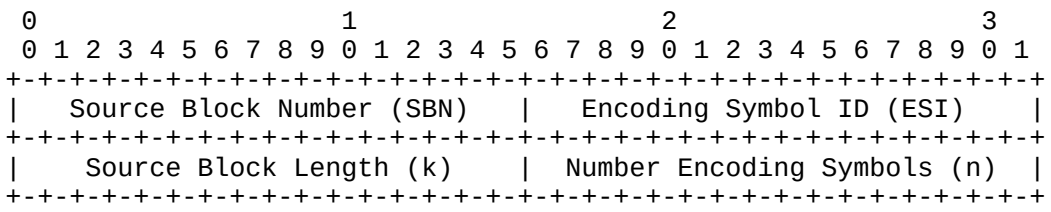

Figure 7: Repair FEC Payload ID Encoding Format

5.2. Procedures

The following procedures apply:

- The source block creation MUST follow the procedures specified in Section 4.3.
- The SBN value MUST start with value 0 for the first block of the ADU flow and MUST be incremented by 1 for each new source block. Wrapping to zero will happen for long sessions, after value 2^^16 - 1.
- The ESI of encoding symbols MUST start with value 0 for the first symbol and MUST be managed sequentially. The first k values (0 <= ESI <= k - 1) identify source symbols whereas the last n-k values (k <= ESI <= n - 1) identify repair symbols.
- The FEC repair packet creation MUST follow the procedures specified in Section 5.1.3.

5.3. FEC Code Specification

The present document inherits from [RFC5170] the specification of the core LDPC-Staircase codes for a packet erasure transmission channel (see Section 1).

Because of the requirement to have exactly one encoding symbol per group, i.e., because G MUST be equal to 1 (Section 4.1), several parts of [RFC5170] are not of use. In particular, this is the case of Section 5.6, "Identifying the G Symbols of an Encoding Symbol Group".

6. Security Considerations

The FEC Framework document [RFC6363] provides a comprehensive analysis of security considerations applicable to FEC schemes. Therefore, the present section follows the security considerations section of [RFC6363] and only discusses topics that are specific to the use of LDPC-Staircase codes.

6.1. Attacks against the Data Flow

6.1.1. Access to Confidential Content

The LDPC-Staircase FEC Scheme specified in this document does not change the recommendations of [RFC6363]. To summarize, if confidentiality is a concern, it is RECOMMENDED that one of the solutions mentioned in [RFC6363] be used, with special considerations

to the way this solution is applied (e.g., Is encryption applied before or after FEC protection? Is it within the end-system or in a middlebox?), to the operational constraints (e.g., performing FEC decoding in a protected environment may be complicated or even impossible) and to the threat model.

6.1.2. Content Corruption

The LDPC-Staircase FEC Scheme specified in this document does not change the recommendations of [RFC6363]. To summarize, it is RECOMMENDED that one of the solutions mentioned in [RFC6363] be used on both the FEC source and repair packets.

6.2. Attacks against the FEC Parameters

The FEC scheme specified in this document defines parameters that can be the basis of several attacks. More specifically, the following parameters of the FFCI may be modified by an attacker (Section 5.1.1.2):

- FEC Encoding ID: changing this parameter leads the receiver to consider a different FEC scheme, which enables an attacker to create a Denial of Service (DoS).

- Encoding symbol length (E): setting this E parameter to a value smaller than the valid one enables an attacker to create a DoS since the repair symbols and certain source symbols will be larger than E, which is an incoherency for the receiver. Setting this E parameter to a value larger than the valid one has similar impacts when S=1 since the received repair symbol size will be smaller than expected. Contrarily, it will not lead to any incoherency when S=0 since the actual symbol length value for the block is determined by the size of any received repair symbol, as long as this value is smaller than E. However, setting this E parameter to a larger value may have impacts on receivers that pre-allocate memory space in advance to store incoming symbols.

- Strict (S) flag: flipping this S flag from 0 to 1 (i.e., E is now considered as a strict value) enables an attacker to mislead the receiver if the actual symbol size varies over different source blocks. Flipping this S flag from 1 to 0 has no major consequences unless the receiver requires to have a fixed E value (e.g., because the receiver pre-allocates memory space).

- N1 minus 3 (n1m3): changing this parameter leads the receiver to consider a different code, which enables an attacker to create a DoS.

Therefore, it is RECOMMENDED that security measures be taken to guarantee the FFCI integrity, as specified in [RFC6363]. How to achieve this depends on the way the FFCI is communicated from the sender to the receiver, which is not specified in this document.

Similarly, attacks are possible against the Explicit Source FEC Payload ID and Repair FEC Payload ID: by modifying the Source Block Number (SBN), or the Encoding Symbol ID (ESI), or the Source Block Length (k), or the Number Encoding Symbols (n), an attacker can easily corrupt the block identified by the SBN. Other consequences, that are use-case and/or CDP dependent, may also happen. It is therefore RECOMMENDED that security measures be taken to guarantee the FEC source and repair packets as stated in [RFC6363].

6.3. When Several Source Flows Are to Be Protected Together

The LDPC-Staircase FEC Scheme specified in this document does not change the recommendations of [RFC6363].

6.4. Baseline Secure FEC Framework Operation

The LDPC-Staircase FEC Scheme specified in this document does not change the recommendations of [RFC6363] concerning the use of the IPsec/ESP security protocol as a mandatory to implement (but not mandatory to use) security scheme. This is well suited to situations where the only insecure domain is the one over which the FEC Framework operates.

7. Operations and Management Considerations

The FEC Framework document [RFC6363] provides a comprehensive analysis of operations and management considerations applicable to FEC schemes. Therefore, the present section only discusses topics that are specific to the use of LDPC-Staircase codes as specified in this document.

7.1. Operational Recommendations

LDPC-Staircase codes have excellent erasure recovery capabilities with large source blocks, close to ideal MDS codes. For instance, independently of FECFRAME, let us consider a source block of size k=1024 symbols, CR=2/3 (i.e., 512 repair symbols are added), N1=7, G=1, a transmission scheme where all the symbols are sent in a random order, and a hybrid ITerative/Maximum Likelihood (IT/ML) decoder (see below). An ideal MDS code with code rate 2/3 can recover from erasures up to a 33.33% channel loss rate. With LDPC-Staircase codes, the average overhead amounts to 0.237% (i.e., receiving 2.43 symbols in addition to k, which corresponds to a 33.18% channel loss

rate, enables a successful decoding with a probability 0.5), and an overhead of 1.46% (i.e., receiving 15 symbols in addition to k, which corresponds to a 32.36% channel loss rate) is sufficient to reduce the probability that decoding fails down to 8.2*10^^-5. This is why these codes are a good solution to protect a single high bitrate source flow as in [Matsuzono10] or to protect globally several mid-rate source flows within a single FECFRAME instance: in both cases, the source block size can be assumed to be equal to a few hundred (or more) source symbols.

LDPC-Staircase codes are also a good solution whenever the processing load at a software encoder or decoder must be kept to a minimum. This is true when the decoder uses an IT decoding algorithm, an ML algorithm (we use a Gaussian Elimination as the ML algorithm) when carefully implemented, or a mixture of both techniques, which is the recommended solution [Cunche08][CunchePHD10][LDPC-codec-OpenFEC]. Let us consider the same conditions as above (k=1024 source symbols, CR=2/3, N1=7, G=1), with encoding symbols of size 1024 bytes. With an Intel Xeon 5120/1.86 GHz workstation running Linux/64 bits, the average decoding speed is between 1.78 Gbps (overhead of 2 symbols in addition to k, corresponding to a very bad channel with a 33.20% loss rate, close to the theoretical decoding limit, where ML decoding is required) and 3.91 Gbps (corresponding to a good channel with a 5% loss rate only, where IT decoding is sufficient). Under the same conditions, on a Samsung Galaxy SII smartphone (GT-I9100P model, featuring an ARM Cortex-A9/1.2 GHz processor and running Android 2.3.4), the decoding speed is between 397 Mbps (bad channel with a 33.20% loss rate, close to the theoretical decoding limit) and 813 Mbps (good channel with a 5% loss rate only).

As the source block size decreases, the erasure recovery capabilities of LDPC codes in general also decrease. In the case of LDPC-Staircase codes, in order to limit this phenomenon, it is recommended to use a value of the N1 parameter at least equal to 7 (e.g., experiments carried out in [Matsuzono10] use N1=7 if k=170 symbols, and N1=5 otherwise). For instance, independently of FECFRAME, with a source block of size k=256 symbols, CR=2/3 (i.e., 128 repair symbols are added), N1=7, and G=1, the average overhead amounts to 0.706% (i.e., receiving 1.8 symbols in addition to k enables a successful decoding with a probability 0.5), and an overhead of 5.86% (i.e., receiving 15 symbols in addition to k) is sufficient to reduce the decoding failure probability to 5.9*10^^-5.

The processing load also decreases with the source block size. For instance, under these conditions (k=256 source symbols, CR=2/3, N1=7, and G=1), with encoding symbols of size 1024 bytes, on a Samsung Galaxy SII smartphone, the decoding speed is between 518 Mbps (bad channel) and 863 Mbps (good channel with a 5% loss rate only).

With very small source blocks (e.g., a few tens of symbols), using for instance Reed-Solomon codes [SIMPLE_RS] or 2D parity check codes may be more appropriate.

The way the FEC repair packets are transmitted is of high importance. A good strategy, that works well for any kind of channel loss model, consists in sending FEC repair packets in random order (rather than in sequence) while FEC source packets are sent first and in sequence. Sending all packets in a random order is another possibility, but it requires that all repair symbols for a source block be produced first, which adds some extra delay at a sender.

8. IANA Considerations

This document registers one value in the "FEC Framework (FECFRAME) FEC Encoding IDs" registry [RFC6363] as follows:

- 7 refers to the Simple LDPC-Staircase FEC Scheme for Arbitrary Packet Flows, as defined in Section 5 of this document.

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