

FecFrame
Internet-Draft
Intended status: Standards Track
Expires: March 17, 2012

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September 14, 2011

**Simple Reed-Solomon Forward Error Correction (FEC) Scheme for FECFRAME
draft-ietf-fecframe-simple-rs-01**

Abstract

This document describes a fully-specified simple FEC scheme for Reed-Solomon codes over $GF(2^m)$, with $2 \leq m \leq 16$, that can be used to protect arbitrary media streams along the lines defined by the FECFRAME framework. Reed-Solomon codes belong to the class of Maximum Distance Separable (MDS) codes which means they offer optimal protection against packet erasures. They are also systematic codes, which means that the source symbols are part of the encoding symbols. The price to pay is a limit on the maximum source block size, on the maximum number of encoding symbols, and a computational complexity higher than that of LDPC codes for instance.

Status of this Memo

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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 (CDP) and applications. The [\[RFC6363\]](#) document 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 the [\[RFC5052\]](#) document describes a generic framework to use FEC schemes with objects (e.g., files) delivery applications based on the ALC [\[RFC5775\]](#) and NORM [\[RFC5740\]](#) reliable multicast transport protocols.

More specifically, the [\[RFC5053\]](#) and [\[RFC5170\]](#) FEC schemes introduce erasure codes based on sparse parity check matrices for object delivery protocols like ALC and NORM. These codes are efficient in terms of processing but not optimal in terms of erasure recovery capabilities when dealing with "small" objects.

The Reed-Solomon FEC codes described in this document belong to the class of Maximum Distance Separable (MDS) codes that are optimal in terms of erasure recovery capability. It means that a receiver can recover the k source symbols from any set of exactly k encoding symbols. These codes are also systematic codes, which means that the k source symbols are part of the encoding symbols. However they are limited in terms of maximum source block size and number of encoding symbols. Since the real-time constraints of media delivery applications usually limit the maximum source block size, this is not considered to be a major issue in the context of the FEC Framework for many (but not necessarily all) use-cases. Additionally, if the encoding/decoding complexity is higher with Reed-Solomon codes than it is with [\[RFC5053\]](#) or [\[RFC5170\]](#) codes, it remains reasonable for most use-cases, even in case of a software codec.

Many applications dealing with reliable content transmission or content storage already rely on packet-based Reed-Solomon erasure recovery codes. In particular, many of them use the Reed-Solomon codec of Luigi Rizzo [\[RS-codec\]](#) [\[Rizzo97\]](#). The goal of the present document is to specify a simple Reed-Solomon scheme that is compatible with this codec.

More specifically, the [\[RFC5510\]](#) document introduced such Reed-Solomon codes and several associated FEC schemes that are compatible with the [\[RFC5052\]](#) framework. The present document inherits from [\[RFC5510\]](#) the specification of the core Reed-Solomon codes based on Vandermonde matrices, and specifies a simple FEC scheme that is compatible with the FECFRAME framework [\[RFC6363\]](#). Therefore this document specifies only the information specific to the FECFRAME

context and refers to [[RFC5510](#)] for the core specifications of the codes. To that purpose, the present document introduces:

- o the Fully-Specified FEC Scheme with FEC Encoding ID XXX that specifies a simple way of using of Reed-Solomon codes over $GF(2^m)$, with $2 \leq m \leq 16$, with a simple FEC encoding for arbitrary packet flows;

For instance, with this scheme, a set of Application Data Units (or ADUs) coming from one or several (resp. one) media delivery applications (e.g., a set of RTP packets), are grouped in an ADU block and FEC encoded as a whole. With Reed-Solomon codes over $GF(2^8)$, there is a strict limit over the number of ADUs that can be protected together, since the number of encoded symbols, n , must be inferior or equal to 255. This constraint is relaxed when using a higher finite field size ($m > 8$), at the price of an increased computational complexity.

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. Some of them 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: $0 < \text{code rate} \leq 1$. 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 Reed-Solomon 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.

Some of them are FECFRAME framework specific and are in line with [\[RFC6363\]](#):

Application Data Unit (ADU): a unit of data coming from (sender) or given to (receiver) the media delivery application. Depending on the use-case, an ADU can use an RTP encapsulation. In this specification, there is always one source symbol per ADU.

(Source) ADU Flow: a flow of ADUs from a media delivery application and to which FEC protection is applied. Depending on the use-case, several ADU flows can be protected together by the FECFRAME framework.

ADU Block: a set of ADUs that are considered together by the FECFRAME instance for the purpose of the FEC scheme. Along with the $F[]$, $L[]$, and $Pad[]$ 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: the FEC scheme specific information that enables the synchronization of the FECFRAME sender and receiver instances.

FEC Source Packet: a data packet submitted to (sender) or received from (receiver) the transport protocol. It contains an ADU along with its optional Explicit Source FEC Payload ID.

FEC Repair Packet: a repair packet submitted to (sender) or received from (receiver) the transport protocol. It contains a repair symbol along with its Repair FEC Payload ID.

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

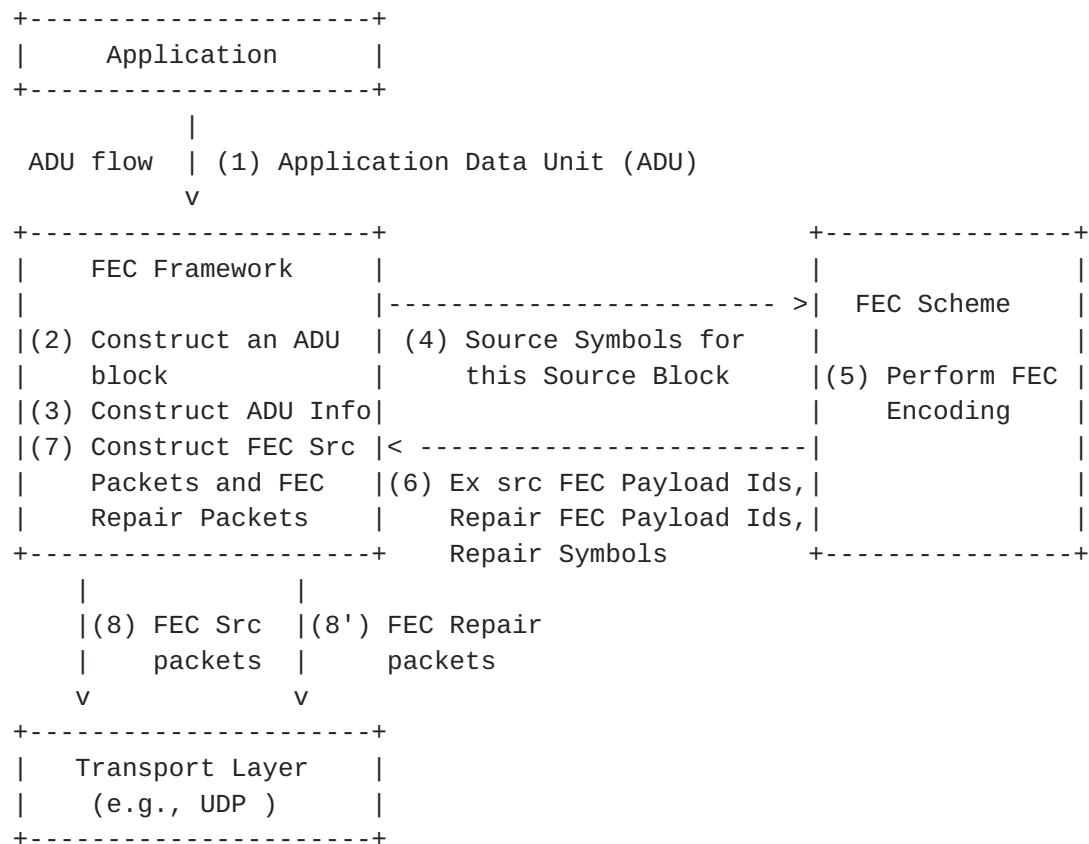


Figure 1: Terminology used in this document (sender).

3.2. Notations

This document uses the following notations: Some of them are FEC scheme specific:

- k denotes the number of source symbols in a source block.
- $\text{max_}k$ 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.
- $\text{GF}(q)$ denotes a finite field (also known as Galois Field) with q elements. We assume that $q = 2^m$ in this document.
- m defines the length of the elements in the finite field, in bits. In this document, m is such that $2 \leq m \leq 16$.
- q defines the number of elements in the finite field. We have: $q = 2^m$ in this specification.
- CR denotes the "code rate", i.e., the k/n ratio.

a^b denotes a raised to the power b .

Some of them are FECFRAME framework 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 stands for Application Data Unit.

ESI stands for Encoding Symbol ID.

FEC stands for Forward Error (or Erasure) Correction code.

FFCI stands for FEC Framework Configuration Information.

FSSI stands for FEC Scheme Specific Information.

MDS stands for Maximum Distance Separable code.

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 the related source block creation, for the FEC scheme considered.

4.1. Restrictions

This specification has the following restrictions:

- o there MUST be exactly one source symbol per ADUI, and therefore per ADU;
- o there MUST be exactly one repair symbol per FEC Repair Packet;
- o there MUST be exactly one source block per ADU block;

4.2. ADU Block Creation

Several aspects must be considered, that impact the ADU block creation:

- o the maximum source block size (k parameter) and number of encoding symbols (n parameter), that are constrained by the finite field size (m parameter);
- o the potential real-time constraints, that impact the maximum ADU block size, since the larger the block size, the larger the decoding delay;

We now detail each of these aspects.

The finite field size parameter, m , defines the number of non zero elements in this field which is equal to: $q - 1 = 2^m - 1$. This $q - 1$ value is also the theoretical maximum number of encoding symbols that can be produced for a source block. For instance, when $m = 8$ (default) there is a maximum of $2^8 - 1 = 255$ encoding symbols. So:

$k < n \leq 255$. Given the target FEC code rate (e.g., provided by the end-user or upper application when starting the FECFRAME framework, and taking into account the (known or estimated) packet loss rate), the sender calculates:

$$\text{max_k} = \text{floor}((2^m - 1) * \text{CR})$$

This max_k value leaves enough room for the sender to produce the desired number of repair symbols. Since there is one source symbol per ADU, max_k is also an upper bound to the maximum number of ADUs per ADU block.

The source ADU flows usually have real-time constraints. It means that the maximum number of ADUs of an ADU block must not exceed a certain threshold since it directly impacts the decoding delay. It is the role of the developer, who knows the flow real-time features, to define an appropriate upper bound to the ADU block size, max_rt.

If we take into account these constraints, we find: max_B = min(max_k, max_rt). Then max_B gives an upper bound to the number of ADUs that can constitute an ADU block.

4.3. Source Block Creation

In its most general form the FECFRAME framework and the Reed-Solomon 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 Reed-Solomon FEC scheme requires a constant encoding symbol size (E parameter) per source block. Since this specification requires that there is 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 $B \leq \text{max_B}$ ADUs in this ADU block. For the ADU i , with $0 \leq i \leq B-1$, 3 bytes are prepended (Figure 2):

- o The first byte, $\text{FID}[i]$ (Flow ID), contains the integer identifier associated to the source ADU flow to which this ADU belongs to. 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 the FECFRAME framework.
- o The following two bytes, $\text{L}[i]$ (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 $\text{FID}[i]$, $\text{L}[i]$, or $\text{Pad}[i]$ fields.

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

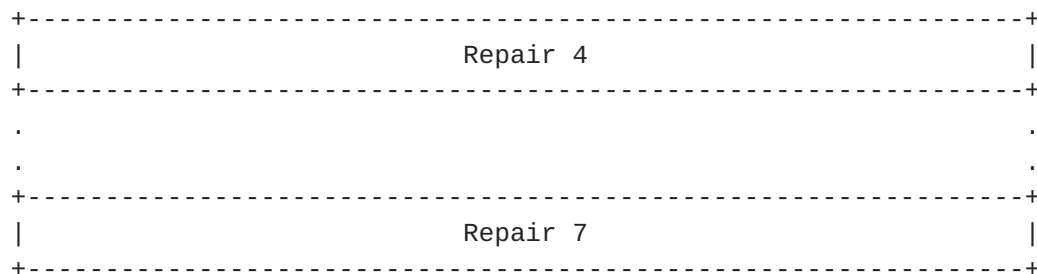
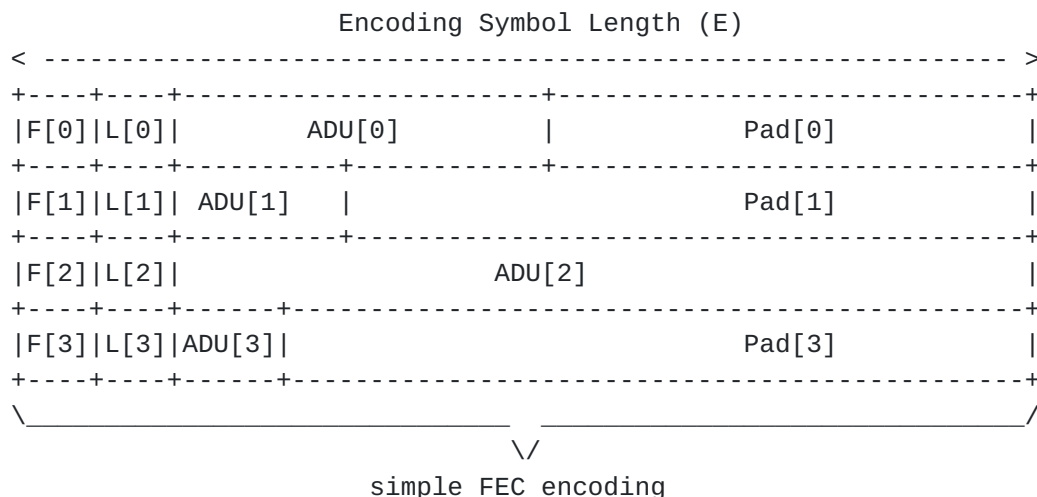


Figure 2: Source block creation, for code rate 1/2 (equal number of source and repair symbols, 4 in this example), and $S = 0$.

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. Simple Reed-Solomon FEC Scheme over $GF(2^m)$ for Arbitrary ADU Flows

This Fully-Specified FEC Scheme specifies the use of Reed-Solomon codes over $GF(2^m)$, with $2 \leq m \leq 16$, with a simple FEC encoding for arbitrary packet 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 XXX, 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:

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).

m parameter (m): an integer that defines the length of the elements in the finite field, in bits. We have: $2 \leq m \leq 16$. These elements are required both by the sender (Reed-Solomon encoder) and the receiver(s) (Reed-Solomon 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 [\[SDP ELEMENTS\]](#). For instance:

```
fssi = E:1400,S:0,m:8
```

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 3 octets:

- o Encoding symbol length (E): 16 bit field.
- o Strict (S) flag: 1 bit field.
- o m parameter (m): 7 bit field.

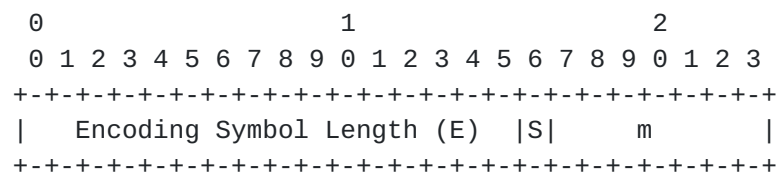


Figure 3: FSSI encoding format.

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.

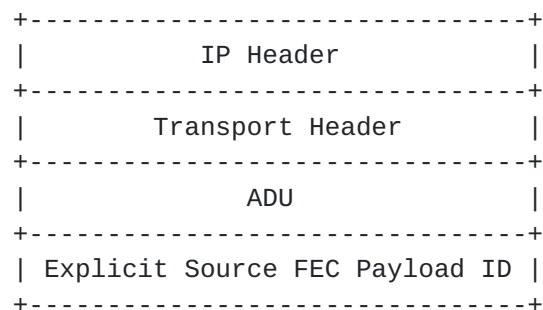


Figure 4: Structure of a FEC Source Packet with the Explicit Source FEC Payload ID.

More precisely, the Explicit Source FEC Payload ID is composed of the Source Block Number, the Encoding Symbol ID, and the Source Block Length. The length of the first two fields depends on the `m` parameter (transmitted separately in the FFCI, [Section 5.1.1.2](#)):

Source Block Number (SBN) (32-m bit field): this field identifies the source block to which this FEC source packet belongs.

Encoding Symbol ID (ESI) (m bit field): this field identifies the source symbol contained in this FEC source packet. This value is such that $0 \leq \text{ESI} \leq k - 1$ 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. If 16 bits are too much when $m \leq 8$, it is needed when $8 < m \leq 16$. Therefore we provide a single common format regardless of m.

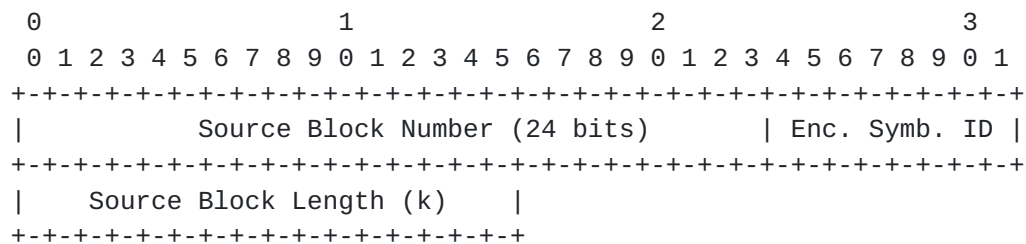


Figure 5: Source FEC Payload ID encoding format for m = 8 (default).

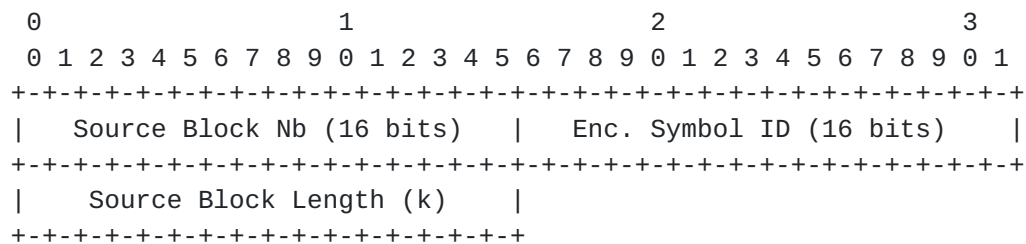


Figure 6: Source FEC Payload ID encoding format for m = 16.

The format of the Source FEC Payload ID for m = 8 and m = 16 are illustrated in Figure 5 and Figure 6 respectively.

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 7. There MUST be a single repair symbol per FEC repair packet.

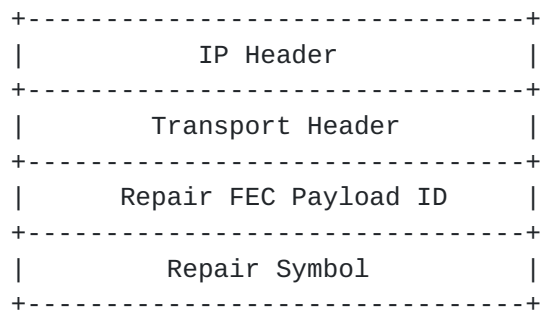


Figure 7: Structure of a FEC Repair Packet with the Repair FEC Payload ID.

More precisely, the Repair FEC Payload ID is composed of the Source Block Number, the Encoding Symbol ID, and the Source Block Length. The length of the first two fields depends on the m parameter (transmitted separately in the FFCI, [Section 5.1.1.2](#)):

Source Block Number (SBN) (32- m bit field): this field identifies the source block to which the FEC repair packet belongs.

Encoding Symbol ID (ESI) (m bit field) this field identifies the repair symbol contained in this FEC repair packet. This value is such that $k \leq \text{ESI} \leq n - 1$ 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. If 16 bits are too much when $m \leq 8$, it is needed when $8 < m \leq 16$. Therefore we provide a single common format regardless of m .

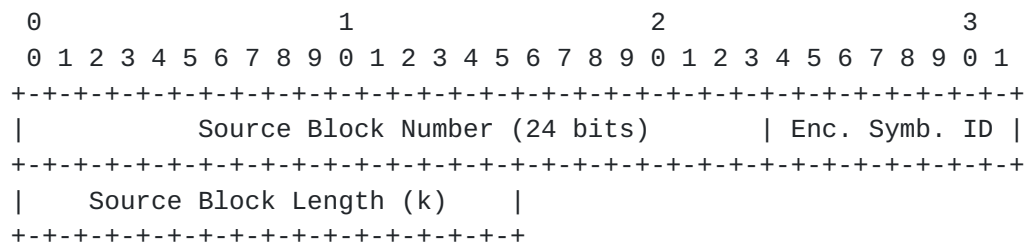


Figure 8: Repair FEC Payload ID encoding format for $m = 8$ (default).

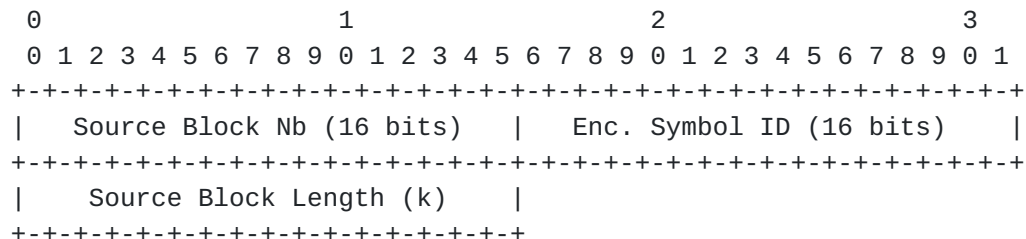


Figure 9: Repair FEC Payload ID encoding format for $m = 16$.

The format of the Repair FEC Payload ID for $m = 8$ and $m = 16$ are illustrated in Figure 8 and Figure 9 respectively.

5.2. Procedures

The following procedures apply:

- o The source block creation procedures are specified in [Section 4.3](#).
- o The SBN value is incremented for each new source block, starting at 0 for the first block of the ADU flow. Wrapping to zero will happen for long sessions, after value $2^{(32-m)} - 1$.
- o The ESI of encoding symbols is managed sequentially, starting at 0 for the first symbol. The first k values ($0 \leq \text{ESI} \leq k - 1$) identify source symbols, whereas the last $n-k$ values ($k \leq \text{ESI} \leq n - 1$) identify repair symbols.
- o The FEC repair packet creation procedures are specified in [Section 5.1.3](#).

5.3. FEC Code Specification

The present document inherits from [\[RFC5510\]](#) the specification of the core Reed-Solomon codes based on Vandermonde matrices for a packet transmission channel.

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 Reed-Solomon codes.

6.1. Attacks Against the Data Flow

6.1.1. Access to Confidential Content

The Reed-Solomon 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 [\[RFC6363\]](#) is used, with special considerations to the way this solution is applied (e.g., before versus after FEC protection, and within the end-system versus 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 Reed-Solomon 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 [\[RFC6363\]](#) is 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](#)):

- o 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).
- o 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. On the opposite 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.
- o 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).
- o m parameter: changing this parameter triggers a DoS since the receiver and sender will consider different codes, and the receiver will interpret the Explicit Source FEC Payload ID and Repair FEC Payload ID differently. Additionally, by increasing this m parameter to a larger value (typically m=16 rather than 8, when both values are possible in the target use-case) will create additional processing load at a receiver if decoding is attempted.

It is therefore RECOMMENDED that security measures are 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), an attacker can easily corrupt the block identified by the SBN. Other consequences, that are use-case and/or CDP dependant, may also happen. It is therefore RECOMMENDED that security measures are 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 Reed-Solomon FEC Scheme specified in this document does not change the recommendations of [\[RFC6363\]](#).

6.4. Baseline Secure FEC Framework Operation

The Reed-Solomon 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 Reed-Solomon codes as specified in this document.

7.1. Operational Recommendations: Finite Field Size (m)

The present document requires that m, the length of the elements in the finite field, in bits, is such that $2 \leq m \leq 16$. However all possibilities are not equally interesting from a practical point of view. It is expected that $m=8$, the default value, will be mostly used since it offers the possibility to have small to medium sized source blocks and/or a significant number of repair symbols (i.e., $k < n \leq 255$). Additionally, elements in the finite field are 8 bits long which makes read/write memory operations aligned on bytes during encoding and decoding.

An alternative when it is known that only very small source blocks will be used is $m=4$ (i.e., $k < n \leq 15$). Elements in the finite field are 4 bits long, so if two elements are accessed at a time, read/write memory operations are aligned on bytes during encoding and decoding.

An alternative when very large source blocks are needed is $m=16$ (i.e., $k < n \leq 65535$). However this choice has significant impacts on the processing load. For instance using pre-calculated tables to speedup operations over the finite field (as done with smaller finite fields) may require a prohibitive amount of memory to be used on embedded platforms. Alternative lightweight solutions (e.g., [\[RFC5170\]](#)) MAY be preferred in situations where the processing load is an issue [\[Matsuzono10\]](#).

Since several values for the m parameter are possible, the use-case SHOULD define which value(s) need(s) to be supported. In situations where this is not specified, the default $m=8$ value SHOULD be supported and used.

8. IANA Considerations

Values of FEC Encoding IDs are subject to IANA registration. [\[RFC6363\]](#) defines general guidelines on IANA considerations. In particular it defines a registry called FEC Framework (FECFRAME) FEC Encoding IDs whose values are granted on an IETF Consensus basis.

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

- o XXX refers to the Simple Reed-Solomon [\[RFC5510\]](#) FEC Scheme over $GF(2^m)$ for Arbitrary Packet Flows.

9. Acknowledgments

The authors want to thank Hitoshi Asaeda for his valuable comments.

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