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SERIES G: TRANSMISSION SYSTEMS AND MEDIA,
DIGITAL SYSTEMS AND NETWORKS

Digital sections and digital line system – Optical fibre
submarine cable systems

Forward error correction for high bit-rate DWDM submarine systems

ITU-T Recommendation G.975.1

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ITU-T Recommendation G.975.1

Forward error correction for high bit-rate DWDM submarine systems

Summary

This Recommendation describes the Forward Error Correction (FEC) functions that have higher-correction ability than RS(255,239) code defined in ITU-T Rec. G.975 for the high bit-rate DWDM submarine cable systems. In Appendix I, super FEC schemes, which have higher-correction ability than RS(255,239) code, are also described. The use of this super FEC function in submarine terminal transmission equipments (TTEs) should not be considered as mandatory.

Source

ITU-T Recommendation G.975.1 was approved on 22 February 2004 by ITU-T Study Group 15 (2001-2004) under the ITU-T Recommendation A.8 procedure.

FOREWORD

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ITU-T Recommendation G.975.1

Forward error correction for high bit-rate DWDM submarine systems

1 Scope

This Recommendation describes the Forward Error Correction (FEC) functions that have higher-correction ability than RS(255,239) code defined in ITU-T Rec. G.975 in the optical fibre submarine cable systems. This Recommendation also describes the system requirement concerning supervision for the submarine cable systems. The applications being addressed in this Recommendation are both optically amplified repeatered systems (ITU-T Rec. G.977) and repeaterless optical systems (ITU-T Rec. G.973). The use of this FEC function in submarine terminal transmission equipments (TTEs) should not be considered as mandatory.

It is not the intention of this Recommendation to pursue the transverse compatibility of the system. Therefore, the selection of the FEC frame structures described in this Recommendation is a matter of joint engineering.

The transmission signal under consideration could be STM-16, STM-64, STM-256, ODU1, ODU2, and ODU3, because submarine systems could be considered as one of the IaDI applications defined in ITU-T Rec. G.872. This does not mean that the bit rate is restricted within the above-mentioned signals.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

- ITU-T Recommendation G.691 (2003), *Optical interfaces for single-channel STM-64 and other SDH systems with optical amplifiers*.
- ITU-T Recommendation G.693 (2003), *Optical interfaces for intra-office systems*.
- ITU-T Recommendation G.707/Y.1322 (2003), *Network node interface for the synchronous digital hierarchy (SDH)*.
- ITU-T Recommendation G.709/Y.1331 (2003), *Interfaces for the Optical Transport Network (OTN)*.
- ITU-T Recommendation G.798 (2002), *Characteristics of optical transport network hierarchy equipment functional blocks*.
- ITU-T Recommendation G.805 (2000), *Generic functional architecture of transport networks*.
- ITU-T Recommendation G.872 (2001), *Architecture of optical transport networks*.
- ITU-T Recommendation G.957 (1999), *Optical interfaces for equipments and systems relating to the synchronous digital hierarchy*.
- ITU-T Recommendation G.959.1 (2003), *Optical transport network physical layer interfaces*.

- ITU-T Recommendation G.972 (2000), *Definition of terms relevant to optical fibre submarine cable systems*.
- ITU-T Recommendation G.973 (2003), *Characteristics of repeaterless optical fibre submarine cable systems*.
- ITU-T Recommendation G.975 (2000), *Forward error correction for submarine systems*.
- ITU-T Recommendation G.977 (2000), *Characteristics of optically amplified optical fibre submarine cable systems*.
- IEEE Standard 802.3-2002, *Information Technology – Telecommunication and Information Exchange between Systems – LAN/MAN – Specific Requirements – Part 3: Carrier sense multiple access with collision detection (CSMA/CD) access method and physical layer specifications*.

3 Terms and definitions

3.1 Terms defined in other Recommendations

This Recommendation uses the following terms defined in other Recommendations:

Synchronous Digital Hierarchy (SDH): See ITU-T Rec. G.707/Y.1322.

Synchronous Transport Module (STM): See ITU-T Rec. G.707/Y.1322.

Optical fibre submarine cable system: See ITU-T Rec. G.972.

Terminal Transmission Equipment (TTE): See ITU-T Rec. G.972.

Optical power budget: See ITU-T Rec. G.972.

Service channel: See ITU-T Rec. G.972.

Order wire channel: See ITU-T Rec. G.972.

Line error ratio: See ITU-T Rec. G.972.

Forward Error Correction (FEC): See ITU-T Rec. G.972.

FEC frame: See ITU-T Rec. G.972.

FEC encoder: See ITU-T Rec. G.972.

FEC decoder: See ITU-T Rec. G.972.

Block code: See ITU-T Rec. G.975.

Cyclic code: See ITU-T Rec. G.975.

Systematic code: See ITU-T Rec. G.975.

Information word: See ITU-T Rec. G.975.

Codeword: See ITU-T Rec. G.975.

3.2 Definitions

This Recommendation defines the following terms:

3.2.1 coding gain: Coding gain means the improvement of received optical sensitivity by FEC, without considering penalty by bit rate increasing.

3.2.2 net coding gain: Net coding gain means the improvement of received optical sensitivity by FEC, with considering penalty by bit rate increasing.

4 Abbreviations

This Recommendation uses the following abbreviations:

BCH	Bose-Chaudhuri-Hocquengham
BER	Bit Error Ratio
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Fibre Amplifier
FEC	Forward Error Correction
GF	Galois Field
NCG	Net Coding Gain
RS	Reed-Solomon
TTE	Terminal Transmission Equipment
TTI	Trail Trace Identifier

5 Super FEC features

5.1 General principles of super FEC function

In order to increase transmission bit rate, distance, and capacity utilized in the DWDM technology, the super FEC, which has more effective error correction than RS(255,239) code, could be required for the submarine optical fibre systems.

Figure 1 outlines the fact that the encoding and decoding procedures are performed at the Terminal Transmission Equipment (TTE) level only, on electrical signals, and benefit the overall optical fibre submarine cable system, which comprises the optical fibre and possibly optical modules such as optical amplifiers using EDFA technology.

The super FEC function essentially comprises:

- a super FEC encoder in the transmit Terminal Transmission Equipment (TTE) that accepts information bits and adds computed redundant symbols, producing encoded data at a higher bit rate;
- a super FEC decoder in the receive Terminal Transmission Equipment (TTE) that performs the error correction while extracting the redundancy to regenerate the data that was encoded by the FEC encoder.

The transmission signal under consideration could be STM-16, STM-64, STM-256, ODU1, ODU2, and ODU3. GbE and/or 10GbE may be required for interface of submarine TTEs. However, this does not mean that the bit rate is restricted within the above-mentioned signals.

Several super FEC schemes, their features and correction ability are described in Appendix I.

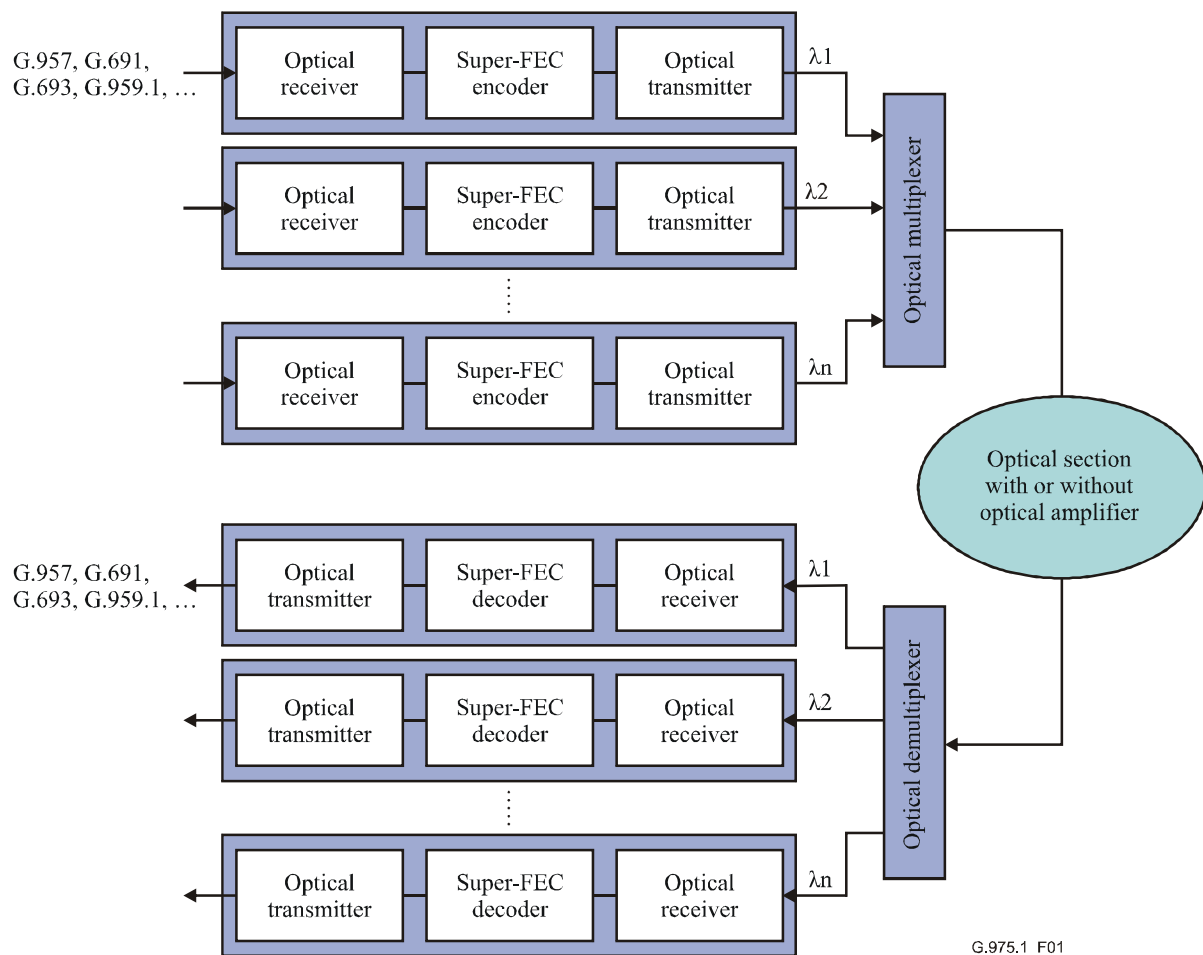


Figure 1/G.975.1 – Block diagram of DWDM submarine optical fibre system

5.2 Super FEC scheme

A Forward Error Correction (FEC) scheme is commonly utilized for both submarine and terrestrial optical fibre systems, which are defined in ITU-T Recs G.975 and G.709/Y.1331, respectively. In those Recommendations, Reed-Solomon (255,239) code is defined as FEC scheme.

In order to achieve higher correction ability, several super FEC schemes are considered. For example, super FEC that uses a combination of two FEC codes is well known, such as [RS code + RS code], [BCH code + BCH code], [RS code + BCH code], etc.

For other techniques, super FEC scheme that uses longer word length is also well known.

6 Definition of super FEC function

6.1 Definition

6.1.1 super FEC code: Various super FEC codes are considered. RS(255,239) that is defined in ITU-T Recs G.975 and G.709/Y.1331 has 5.6 dB Net Coding Gain at 10^{-12} decoder output BER. This Recommendation defines the super FEC code that has higher correction ability than RS(255,239). Improvement value for super FEC compared with RS(255,239) is for further study.

6.1.2 outer code/Inner code: Figure 2 shows Outer code and Inner code for super FEC scheme utilizing two concatenated FEC codes.

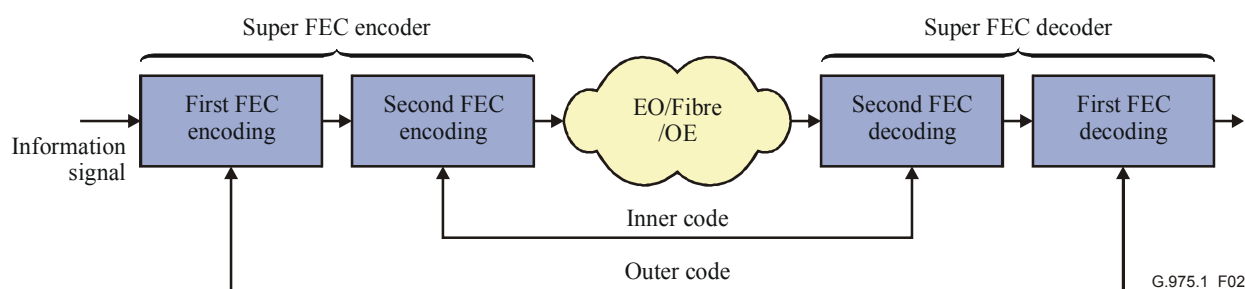


Figure 2/G.975.1 – Outer code and inner code

6.1.3 hard decision decoding: Hard decision decoding refers to the use of a single quantization level in bit sampling, resulting in binary bit information provided to the decoding process.

6.1.4 soft decision decoding: For the same received waveform, soft decision decoders make use of multiple levels of quantization (typically three or more).

6.2 Super FEC code algorithm

A super FEC algorithm depends on target features, such as correction ability, latency, etc. Detailed algorithms for super FEC code are described in Appendix I.

6.3 Properties for super FEC code

Super FEC properties depend on its FEC scheme. One super FEC scheme may take pride in higher correction ability, other super FEC schemes may show lower latency. Detailed properties for super FEC codes are described in Appendix I.

6.4 Super FEC frame structure

Frame structures are described in Appendix I.

7 Parameters for super FEC

The super FEC code is defined in several aspects, such as the feasibility of circuit operation speed, requirement from system transaction delay and theoretical optimum redundancy ratio. Each condition is described in the following subclauses. The parameters described in this clause are represented in Appendix I.

7.1 Correction ability

Error correction ability is indicated by various parameters, such as BER characteristics, net-coding gain, etc. Though all parameters are closely related, each indication is useful for the estimation of super FEC code. The following parameters should be described for each super FEC code in Appendix I.

7.1.1 BER characteristics

A BER characteristic for FEC is shown as relation between BER of decoder input signal and BER of corrected output signal. This BER improvement by FEC is the most interesting characteristics and indicates FEC correction ability.

7.1.2 Coding gain

In the case of randomly distributed errors within the encoded line signal, a FEC decoder reduces the line or raw BER_{in} (B_{in}) to a required reference BER (B_{ref}) value within the payload signal. Coding gain could therefore be regarded as the relation of these Bit Error Ratios. In order to define a coding

gain parameter as a more system related parameter, the BER reduction by the FEC is usually transformed into a dB value based on a theoretical reference system. It is common practice to define the coding gain as the reduction of signal-to-noise ratio at a reference BER.

$$\text{Coding_Gain} = 20 \log_{10} \left[\text{erfc}^{-1}(2B_{ref}) \right] - 20 \log_{10} \left[\text{erfc}^{-1}(2B_{in}) \right] \quad (\text{dB})$$

7.1.3 Net coding gain

NCG is characterized by both the code rate R ($R < 1$, the code rate R is the ratio of bit rate without FEC to bit rate with FEC) and the maximum allowable BERin (B_{in}) of the input signal of the FEC decoder, which can be reduced to a reference BERout = B_{ref} by applying the FEC algorithm. Furthermore, NCG should refer to a binary symmetric channel with added white Gaussian noise:

$$\text{Net_Coding_Gain} = 20 \log_{10} \left[\text{erfc}^{-1}(2B_{ref}) \right] - 20 \log_{10} \left[\text{erfc}^{-1}(2B_{in}) \right] + 10 \log_{10} R \quad (\text{dB})$$

with erfc^{-1} the inverse of the complementary error function, $\text{erfc}(x) = 1 - \text{erf}(x)$.

7.1.4 Q limit

Q limit means the minimum required allowable Q factor of the input signal for the receiver decision circuit in order to achieve a reference BER ($B_{ref} \approx \text{BERout}$). The Q factor is the signal-to-noise ratio at the decision circuit in voltage or current units, and is typically expressed by:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}$$

$\mu_{1/0}$ The mean value of the marks/spaces voltages or currents

$\sigma_{1/0}$ The standard deviations of the marks/spaces voltages or currents

The mathematical relations to BER (in case of non-FEC operation) when the threshold is set to the optimum value are:

$$\text{BER} = \frac{1}{2} \text{erfc} \left(\frac{Q}{\sqrt{2}} \right)$$

Table 1 is a summary table format for correction ability of a super FEC scheme of the above parameters. In order to clarify correction ability, all values should be put into the table. Summary tables for correction ability are described in Appendix I.

Table 1/G.975.1 – Summary table format for correction ability

Input BER	Output BER	Net coding gain (dB)	Coding gain (dB)	Q-limit (dB)
	10^{-9}			
	10^{-10}			
	10^{-11}			
	10^{-12}			
	10^{-13}			
	10^{-14}			
	10^{-15}			

7.2 Redundancy ratio

The redundancy ratio depends on the super-FEC methods. It describes the ratio between the number of information bits covered by the FEC and the number of bits after encoding comprising the same information plus the added redundancy information. It does not take into account any management overhead or stuffing, like as described by ITU-T Rec. G.709/Y.1331.

Some methods have the same redundancy ratio as ITU-T Recs G.709/Y.1331 or G.975, even though the correction ability is better than those.

7.3 Latency

FEC transaction may introduce transmission delay for FEC encoding, decoding, interleaving and de-interleaving. This delay may be described as a physical time value for a given transmission rate. Alternatively, it may be given as the number of intermediately stored information bits while in the process of encoding/decoding. In most cases, this second number is independent of the actual transmission rate.

8 Supervision

When definition of super FEC frames, OH (OverHead) functions shall be described to achieve some maintenance function. These functions that are described in this clause are used for measuring the transmission performance. A concrete way is, however, for further study.

8.1 Signal quality supervision

To evaluate the transmission condition, some error counting technique is required, such as BIP error counting or counting for the number of FEC error correction bit. Performance monitoring using error counting is mandatory for this Recommendation.

8.2 Connectivity supervision

To prevent miss-connection, trail trace such as TTI is needed.

Appendix I

Super FEC schemes

I.1 Overview

Table I.1 shows an overview of super FEC schemes that are described in this appendix. Each super FEC scheme is described in the subclause that is represented in Table I.1.

Table I.1/G.975.1 – Overview of super FEC schemes

Subclause	FEC scheme	
	Concatenated or non-concatenated	Used FEC code
I.2	Concatenated FEC	Outer code: RS(255,239) Inner code: CSOC ($n_0/k_0 = 7/6$, $J = 8$)
I.3	Concatenated FEC	Outer code: BCH(3860,3824) Inner code: BCH(2040,1930)

Table I.1/G.975.1 – Overview of super FEC schemes

Subclause	FEC scheme	
	Concatenated or non-concatenated	Used FEC code
I.4	Concatenated FEC	Outer code: RS(1023,1007) Inner code: BCH(2047,1952)
I.5	Concatenated FEC (Soft Decision capable)	Outer code: RS(1901,1855) Inner code: Extended Hamming Product Code (512,502) × (510,500)
I.6	Non-concatenated FEC	LDPC Code
I.7	Concatenated FEC	Two orthogonally concatenated BCH codes
I.8	Non-concatenated FEC	RS(2720,2550)
I.9	Concatenated FEC	Two interleaved extended BCH(1020,988) codes

I.2 RS(255,239)/CSOC ($n_0/k_0 = 7/6$, $J = 8$) super FEC code

I.2.1 Overview

This clause describes a super-FEC scheme, which provides higher error correction capability than RS(255,239) code. Figure I.1 shows the super-FEC scheme. The super-FEC scheme uses concatenated RS and convolutional self-orthogonal code (CSOC). RS(255,239) is used as the outer code. CSOC ($n_0/k_0 = 7/6$, $J = 8$) is used as the inner code, where k_0 is the number of bits to be encoded, n_0 is the number of coded bits and J is the number of orthogonal check sets. The interleaver and deinterleaver are used between the inner and outer code.

Concatenated codes can apply iterative decoding. Also, CSOCs can apply iterative decoding independently. These techniques can improve the error correction capability without increasing the coding rate. The number of iteration is vendor specific.

The super-FEC scheme provides 7.95 dB net coding gain at $1E-12$ corrected BER with 24.48% redundancy, by using three times iterative CSOC decoding.

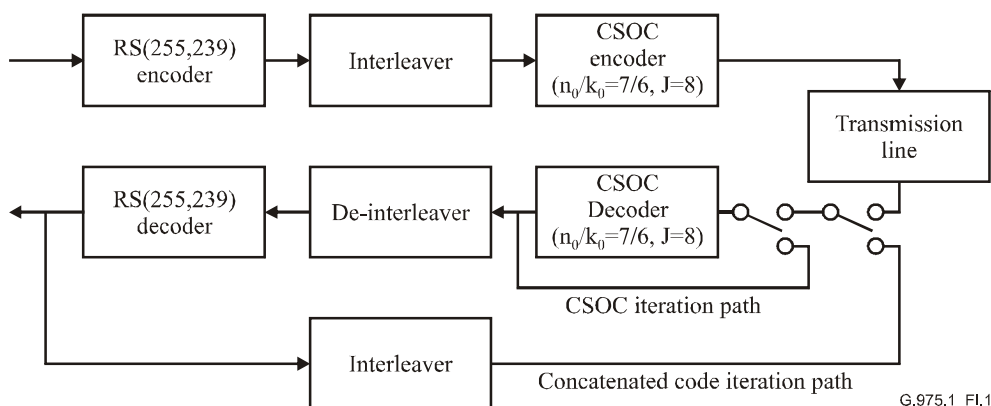


Figure I.1/G.975.1 – Super-FEC scheme

I.2.2 FEC algorithm

The super-FEC scheme uses concatenated RS(255,239) and CSOC ($n_0/k_0 = 7/6$, $J = 8$). The detailed specification of RS(255,239), CSOC ($n_0/k_0 = 7/6$, $J = 8$) and frame structure are described in I.2.2.3.

I.2.2.1 RS(255,239) code

The RS(255,239) code is a non-binary code (the FEC algorithm operates on 8-bit symbols) and belongs to the family of systematic linear cyclic block codes.

The generator polynomial of the code is given by:

$$G(D) = \prod_{i=0}^{15} (D - \alpha^i) \quad (\text{I-1})$$

where α is a root of the binary primitive polynomial $x^8 + x^4 + x^3 + x^2 + 1$. A data byte ($d_7, d_6, \dots, d_1, d_0$) is identified with the element $d_7 \cdot \alpha^7 + d_6 \cdot \alpha^6 + \dots + d_1 \cdot \alpha^1 + d_0$ in GF (256), the finite field with 256 elements. The RS(255,239) codeword consists of 239 information bytes and 16 parity bytes. The RS(255,239) can correct up to 8 symbol errors in a single codeword.

I.2.2.2 CSOC ($n_0/k_0 = 7/6, J = 8$) code

CSOCs are defined by their generator polynomials. The super-FEC code applies following generator polynomials.

$$\begin{aligned} G^{(5)}(D) &= 1 + D^{35} + D^{80} + D^{119} + D^{161} + D^{193} + D^{209} + D^{269} \\ G^{(4)}(D) &= 1 + D^{87} + D^{173} + D^{192} + D^{197} + D^{217} + D^{251} + D^{258} \\ G^{(3)}(D) &= 1 + D^{31} + D^{82} + D^{93} + D^{94} + D^{96} + D^{200} + D^{218} \\ G^{(2)}(D) &= 1 + D^{91} + D^{99} + D^{114} + D^{120} + D^{166} + D^{170} + D^{297} \\ G^{(1)}(D) &= 1 + D^{13} + D^{22} + D^{49} + D^{77} + D^{348} + D^{385} + D^{418} \\ G^{(0)}(D) &= 1 + D^{69} + D^{95} + D^{112} + D^{142} + D^{152} + D^{210} + D^{263} \end{aligned} \quad (\text{I-2})$$

Figure I.2 shows CSOC ($n_0/k_0 = 7/6, J = 8$) encoding and decoding scheme. The CSOC encoder appends a parity bit to each group of six information bits, and transmits seven coded bits in sequence. The parity sequence $P(D)$ is expressed as:

$$P(D) = \sum_{i=0}^5 M^{(i)}(D) G^{(i)}(D) \quad (\text{I-3})$$

where $M^{(i)}(D)$ is the information sequence.

The CSOC decoder generates parity checksum sequence $S(D)$ using an encoder replica. Parity checksum sequence $S(D)$ is calculated as:

$$\begin{aligned} S(D) &= [P(D) + F(D)] + \sum_{i=0}^5 [M^{(i)}(D) + E^{(i)}(D)] G^{(i)}(D) \\ &= \left[\sum_{i=0}^5 M^{(i)}(D) G^{(i)}(D) + F(D) \right] + \sum_{i=0}^5 [M^{(i)}(D) + E^{(i)}(D)] G^{(i)}(D) \\ &= \sum_{i=0}^5 E^{(i)}(D) G^{(i)}(D) + F(D) \end{aligned} \quad (\text{I-4})$$

where $E^{(i)}(D)$ is the error sequence on the information sequence $M^{(i)}(D)$. $F(D)$ is the error sequence on the parity sequence.

CSOC ($n_0/k_0 = 7/6, J = 8$) supplies six sets of eight orthogonal parity checksums. A set is used to check one information bit. The information bit is estimated to be error by threshold decoder if the number of parity checksum equal to one in the set is threshold value (Th) and over. Threshold value

Diagram illustrating the CSOC (Cyclic Synchronization and Error Correction) encoder and decoder structure.

CSOC Encoder:

- Input: Information $M(D)$ (k_0 bits).
- Process: Information $M(D)$ is processed by a Convolutional encoder $G(D)$ to produce Parity $P(D)$ (1 Bit).
- Process: Information $M(D)$ (k_0 bits) is processed by a Convolutional encoder $G(D)$ to produce Information $M(D)$ (k_0 bits).
- Process: Parity $P(D)$ (1 Bit) and Information $M(D)$ (k_0 bits) are combined via summing junctions to produce $F(D)$ and $E(D)$.
- Process: $F(D)$ and $E(D)$ are combined via a summing junction to produce $S(D)$.

CSOC Decoder:

- Input: Received information $M(D) + E(D)$ (k_0 bits).
- Process: Received information $M(D) + E(D)$ is processed by a Parity register and a Parity checksum register to produce $S(D)$.
- Process: $S(D)$ is processed by a Threshold decoder to produce k_0 bits.
- Process: k_0 bits and $S(D)$ are combined via a summing junction to produce the Corrected information $M(D) + E(D)$.

I.2.2.3 Frame structure

Figure I.4 shows frame format fed from interleaver to CSOC encoder. This frame format is named "interleaved RS frame format".

Figure I.5 shows frame format fed from CSOC encoder to transmission line. This frame format is named "CSOC frame format". $m_j^{(i)}$ means j degree coefficient of information sequence polynomial $M^{(i)}(D)$. p_j means j degree coefficient of parity sequence polynomial $P(D)$. Note that CSOC encoders do not process termination at frame boundary.

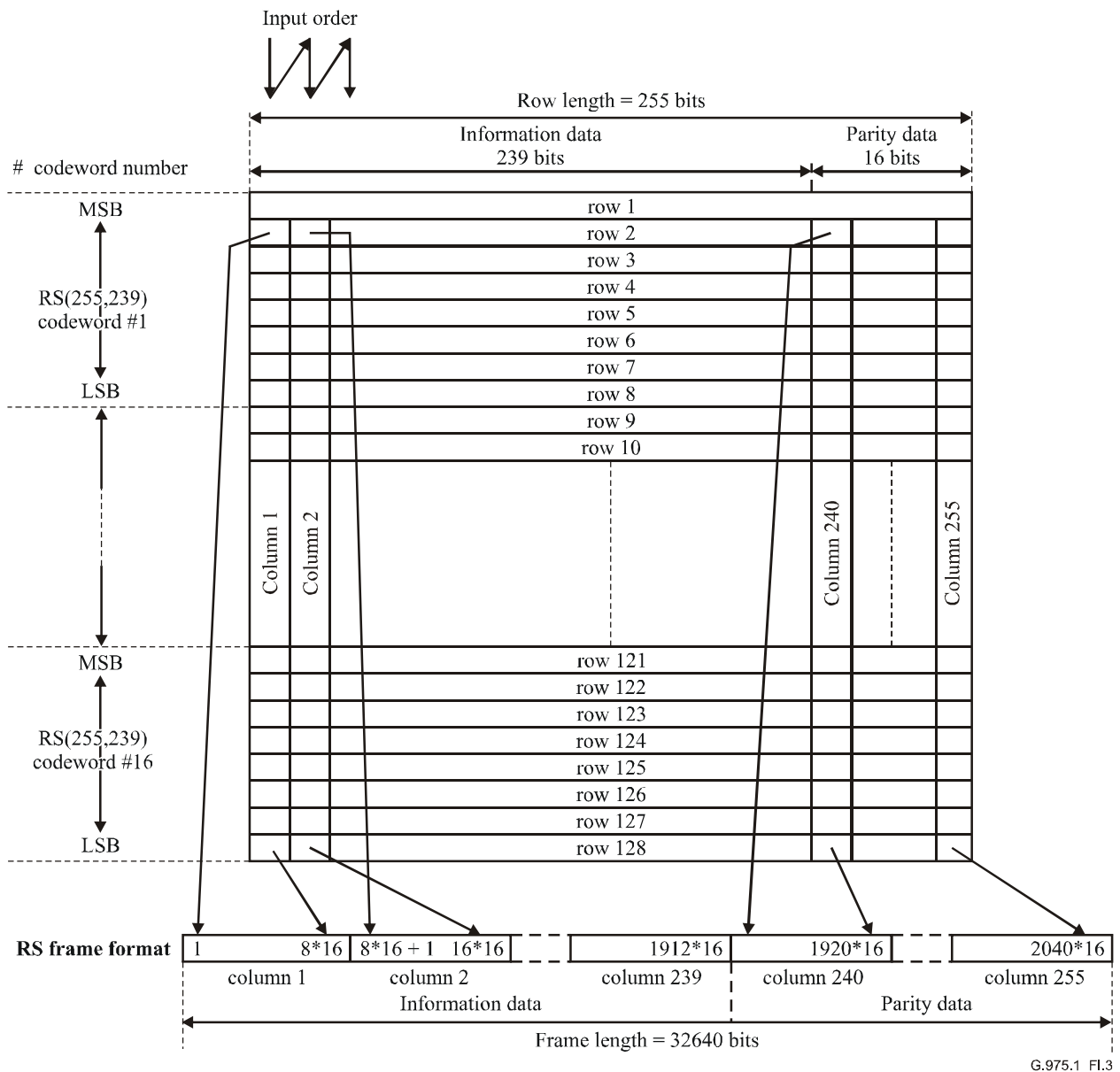


Figure I.3/G.975.1 – RS frame format

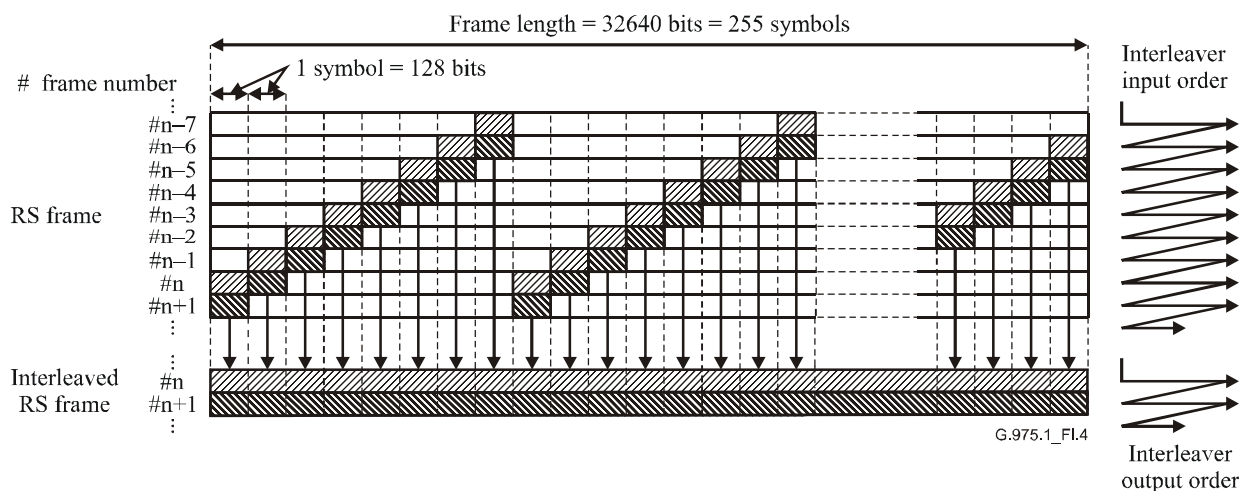


Figure I.4/G.975.1 – Interleaved RS frame format

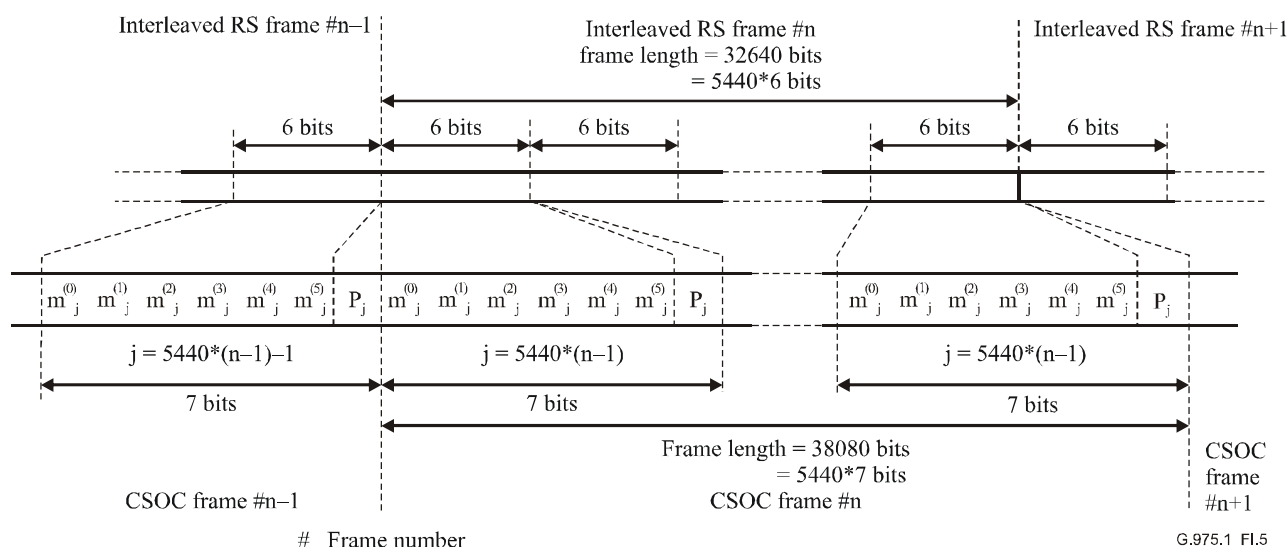


Figure I.5/G.975.1 – CSOC frame format

I.2.3 Error correction ability

Error correction ability of the super-FEC code depends on the number of iteration times and threshold values of CSOC decoder. Figure I.6 shows an example of the super-FEC decoder. This decoder iterates CSOC decoding three times. The threshold value of the first, second and third CSOC decoder is seven, six and five respectively. Table I.2 and Figure I.7 show summary of error correction ability. Figure I.7 shows a comparison of error correction ability between RS(255,239) and super-FEC decoder.

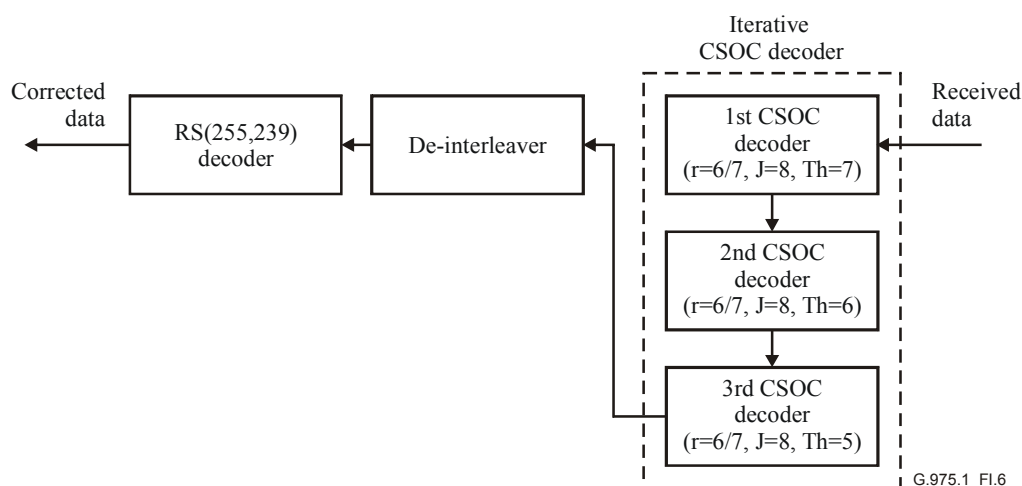


Figure I.6/G.975.1 – An example of the super-FEC decoder