APPENDIX H

CONCATENATION OF REED–SOLOMON (RS) OUTER CODING WITH THE EXISTING FEC

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APPENDIX H

CONCATENATION OF REED–SOLOMON (RS) OUTER CODING WITH THE EXISTING FEC

H.1. GENERAL

Reed–Solomon (RS) codes are a class of block codes which can be concatenated with the existing QPSK/IDR FEC (convolutional encoding/Viterbi decoding) to significantly enhance the clear–sky BER performance and availability of QPSK/IDR links. The Reed–Solomon code constitutes the outer code while the convolutional code is designated as the inner code.

This Appendix specifies the outer Reed–Solomon codes, the method of interleaving used between the inner and outer codes and the synchronization method used for the descrambler, de–interleaver and Reed–Solomon decoder. The outer Reed–Solomon coding scheme can be applied to both small QPSK/IDR carriers with rates less than 1.544 Mbit/s (with IBS overhead framing), as well as QPSK/IDR carriers with rates greater than or equal to 1.544 Mbit/s (with 96 kbit/s ESC overhead).

The use of Reed–Solomon outer coding is optional and shall be determined on the basis of bilateral agreement between two (or more, in the case of multi–destinational QPSK/IDR) corresponding users.

H.2. REED–SOLOMON OUTER CODE

H.2.1. Polynomials

H.2.1.1. Field Generating Polynomial

The binary primitive polynomial for generating the extended field of 256 elements, $GF(2^8)$, is:

$$p(x) = x^8 + x^7 + x^2 + x + 1$$

H.2.1.2. Code Generator Polynomials

The generator polynomials of the selected RS codes are given by:

$$\prod_{i=120}^{119+2t} (x - \alpha^i)$$

where:

α = a root of p(x), i.e., $p(\alpha) = 0$ over the extended field.

t = the maximum number of symbol errors per RS codeword that can be corrected (error–correction capability). For the selected RS codes, t = 7, 8, 9 or 10 (see Table H.1).

Since each RS symbol is an element of the Galois Field, GF (2^8), it can be represented by a binary octet (8–bit tuple). For the selected RS codes, the octet

$$(d_7, d_6, ..., d_1, d_0);$$

with

$$d_j = 0 \text{ or } 1; \quad 0 \leq j \leq 7$$

is identified with the element

$$d_7\,\alpha^7 + d_6\,\alpha^6 + ... + d_1\,\alpha + d_0$$

in GF (2^8).

H.2.2. Code Parameters

The RS codes selected for QPSK/IDR are derived by block length shortening of RS codes over the finite Galois Field, GF (2^8), using the following parameters:

n = 255 RS symbols per codeword (block length)

m = 8, the number of bits per RS symbol

t = the maximum number of symbol errors per RS codeword that can be corrected (error–correction capability).

k = n – 2t, the number of RS symbols in a RS codeword representing information (encoder input data). This block of k RS symbols is referred to as the information block.

n – k = 2t, the number of RS symbols representing error check symbols.

The selected RS codes are systematic codes, i.e., each RS codeword (block length of n RS symbols) consists of an information block (k x RS symbols), which is unaffected by the RS encoding process, to which a block of (n – k) RS check symbols is appended (see Figure H.1).

H.2.3. Shortened Codes

The block length of the RS codes described in Section H.2.1 is shortened using the following procedure (refer to Figure H.1):

(a) For RS encoding and decoding the leading (in the order of transmission) q complete symbols within the information block of each RS codeword of length n = 255 are all preset to logical "0".

(b) The leading q all–zero symbols are not transmitted.

(c) The resulting transmitted codeword consists of n' = (n – q) RS symbols and the transmitted information block has length, k = (k – q). The number of RS check symbols (n – k) = (n' – k') and the error–correction capability, t, is not affected by the described method of shortening the block length.

To preclude the possibility of misinterpretation, all subsequent references in the remainder of this Appendix to the RS code parameters n, k and t shall refer exclusively to the shortened RS codes shown in Figure H.1.

H.2.4. Reed–Solomon Codes for QPSK/IDR

The shortened systematic Reed–Solomon codes which shall be used for QPSK/IDR are listed in Figure H.1. Different RS codes have been selected in order to accommodate modem clock designs that are based on integer multiples of 8 kHz.

H.2.5. Interleaving

Since errors from the Viterbi decoder tend to occur in bursts, block interleaving shall be employed in conjunction with the RS outer code to reduce the correlation among erroneous symbols in a RS codeword. This minimizes the occurrences of error bursts at the output of the Viterbi decoder which might exceed the error–correcting capability of the RS decoder.

H.2.5.1. Information Rates ≤ 10 Mbit/s

The data stream at the output of the RS encoder shall be written into a block interleaver which has an interleaving depth, I_d, of 4 codewords and a span of 'n' RS, symbols wide, where n is the RS codeword's block length and each RS symbol is 8 bits long.

On the transmit (modulator) side, the data stream shall be written into the interleaver row–wise with each row being occupied by only one codeword. The codeword written into the first row of the interleaver (the first, fifth, ninth, etc.) shall occupy the entire span (n x RS symbols) of the interleaver. Each succeeding codeword (i.e., the second, third and fourth) shall be displaced by d_i symbols relative to the preceding codeword, where d_i is defined as:

$d_i = \lceil (n - 1) / I_d \rceil$, i.e., the smallest integer $\geq (n - 1) / I_d$.

Symbols shall be read out of the interleaver in a column–wise manner. To ensure that successive symbols of the same RS codeword are transmitted in an orderly time sequence, i.e., the i'th symbol is always transmitted before the j'th symbol (i being always less than j) of the same codeword, the start of the read–out cycle shall not be delayed by more than one (1) RS symbol clock period relative to the start of the write–in cycle.

To illustrate the interleaver 'page' structure and the interleaver's output symbol sequence, Figure H.2 shows the simplified case of a RS (7, 5, 1) codeword and a block interleaver with an interleaving depth, I_d, of 4.

On the receive (demodulator) side, the reverse process shall occur at the de–interleaver. That is, the RS symbol stream from the Viterbi decoder shall be written into the de–interleaver column–wise and read out of the de–interleaver row–wise. To ensure that successive symbols of the same RS codeword are read out of the de–interleaver in an orderly time sequence, i.e, the i'th symbol is always read out before the j'th symbol (i being always less than j) of the same codeword, the start of the read–out cycle shall not be delayed by more than one (1) RS symbol clock period relative to the start of the write–in cycle.

Figure H.3 illustrates the de–interleaving process using the same RS codeword example given above for the interleaver.

H.2.5.2. Information Rates > 10 Mbit/s

For QPSK/IDR information rates above 10 Mbit/s, the inner FEC encoder/decoder comprises three (3) parallel encoders/decoders in order to operate up to 45 Mbit/s.

To ensure proper operation of the RS decoder, RS symbol integrity and the full interleaving depth (i.e., 4) shall be maintained at the input to the FEC encoder and, on the receive side (demodulator), at the input to the RS decoder. The signal formats at the interface between the output of the interleaver and the three (3) inputs (1, 2 and 3) to the parallel FEC encoders are shown in Figure H.4.

H.3. IMPLEMENTATION OF THE REED–SOLOMON OUTER CODEC

H.3.1. QPSK/IDR Carriers With Rates < 1.544 Mbit/s (With IBS Overhead)

For QPSK/IDR carriers with rates less than 1.544 Mbit/s and which use the IBS overhead framing, the RS encoder/interleaver shall be inserted following the IBS overhead framing unit and before the inner FEC encoder. On the receive side (demodulator), the RS decoder/de–interleaver shall be inserted after the inner FEC decoder and before the IBS overhead deframing unit (Figure H.5).

H.3.2. QPSK/IDR Carriers With Rates ≥ 1.544 Mbit/s (With Optional 96 kbit/s ESC Overhead)

For QPSK/IDR carriers with rates greater than or equal to 1.544 Mbit/s, the RS encoder/interleaver shall be inserted after the 96 kbit/s ESC overhead framing unit and before the FEC encoder. On the receive side (demodulator), the RS decoder/de–interleaver shall be inserted after the FEC decoder and before the 96 kbit/s ESC overhead deframing unit (Figure H.5).

H.3.3. Switchability of the RS Codec

It shall be possible to enable or disable the use of RS outer coding by switching the RS codec in or out of the QPSK/IDR channel unit. This function should be performed preferably from the front–panel control for the QPSK/IDR channel unit and is necessary: (a) to enable SSOG lineup testing; (b) to ensure that the QPSK/IDR channel unit can be used with digital TV codecs which might already employ their own RS encoding; and (c) to ensure compatibility with other QPSK/IDR channel units which might not be equipped with the RS outer coding capability.

H.3.4. Selectability and Programmability of RS Codes

H.3.4.1. RS Code Selectability

Since the transmission rate and FEC used for the QPSK/IDR modulator and demodulator may be different for the transmit (modulator) and receive (demodulator) paths, it shall be possible to independently select the same or different RS codes for the RS encoder and decoder, respectively, in order to be compatible with the transmission rates (hence, RS codewords) being used by the QPSK/IDR modulator and demodulator.

H.3.4.2. RS Code Programmability

Programmability of the RS codec shall be provided to allow maximum flexibility and ease of use in selecting the different RS codes corresponding to the various QPSK/IDR information rates.

H.4. SYNCHRONIZATION

To ensure that complete Reed–Solomon codewords reach the RS decoder and in the proper sequence, it is necessary to synchronize the descrambler, the de–interleaver, the RS decoder and, at information rates greater than 10 Mbit/s, the interface demultiplexer function. Synchronization of all three functions is accomplished by detecting a unique word (UW) which is inserted in certain RS codewords at the transmitting earth station, as specified below.

H.4.1. Unique Word Definition

The unique word which shall be used for the synchronization of the descrambler, RS de–interleaver and RS decoder is the following 32–bit binary word:

First bit transmitted
↓
Binary: 01011010 00001111 10111110 01100110

or,

Hexadecimal: 5A 0F BE 66

Note that the serial–to–parallel interpretation of the information bit stream given here is preserved during the byte–oriented RS processing. That is, the left–most bit, which is the most–significant bit (MSB), of each RS symbol is the bit that is transmitted first.

H.4.2. Insertion of Unique Word

The 32–bit (4–byte) unique word shall be inserted, after RS encoding has been performed, into the last two (2) RS symbols (in the order of transmission) of the last two (2) consecutive codeword outputs from the block interleaver by overwriting these RS error check symbols. With reference to the example illustrated in Figure H.2, the 4–byte unique word would be substituted for the C_5, C_6, D_5 and D_6 error check symbols.

The RS error check symbols overwritten by the unique word shall be declared and treated as erasures by the RS codec and shall be recovered by the RS decoder using erasure decoding.

Insertion of the unique word shall occur periodically once every 16 RS codewords at information rates less than or equal to 10 Mbit/s, and once every 24 RS codewords at information rates greater than 10 Mbit/s. Insertion of the unique word shall be done so that the last byte of the unique word is the last byte of a three byte bit–multiplexer group. That is, the last unique word byte shall be serially shifted out of switch position number 1, as seen in the block diagram of Figure H.4.

H.4.3. Sync Acquisition

H.4.3.1. Initial Acquisition and Unique Word Detection

Detection of the 32–bit unique word shall be based on the total Hamming distance, d, being less than or equal to a detection threshold, E.

The detection of the unique word is expected to occur within a window which can be either fully open or have a width of 32 bits.

During initial acquisition, the window shall be fully open. Following the first detection of a unique word, the window shall be narrowed to a width of 32 bits and centered about the expected arrival of the unique word 16 (or 24) RS codewords later.

Valid detection of a unique word ("sync acquired") shall be declared if d is less than or equal to E = 1 and if, 16 RS codewords (24 RS codewords if the information rate is greater than 10 Mbit/s) before, d was also less than or equal to E = 1. The first valid unique word detected in the window shall be the only one employed. If valid detection of the unique word is not declared in the window, the unique word shall be considered "missed".

H.4.3.2. Steady State and Loss of Synchronization

To ensure synchronization is maintained after initial acquisition, the occurrence of the unique word every 16 RS codewords (24 RS codewords if the information rate is greater than 10 Mbit/s) shall be monitored continuously. Loss of synchronization ("sync loss") shall be declared if d is greater than or equal to E = 6 for four (4) consecutive detections of the unique word.

Following the loss of synchronization, the initial acquisition sequence described in Section H.4.3.1 shall be initiated.

H.5. SCRAMBLING

H.5.1. Small QPSK/IDR Carriers < 1.544 Mbit/s (With IBS Overhead)

For small QPSK/IDR carriers < 1.544 Mbit/s with IBS overhead framing, the synchronous IBS scrambler available in the IBS overhead framing unit shall be utilized.

H.5.2. QPSK/IDR Carriers ≥ 1.544 Mbit/s (With 96 kbit/s ESC Overhead)

For QPSK/IDR carriers greater than or equal to 1.544 Mbit/s, the self–synchronizing scrambler used in the QPSK/IDR channel unit shall be disabled. A synchronous IBS scrambler with the configuration depicted in Figure H.7 shall be employed instead in the RS encoder.

The polynomial of Figure H.7 is $1 + X^{-14} + X^{-15}$. Loading of the initial sequence 001001001001001 shall be performed at each insertion of the unique word, i.e., every 16 RS codewords (or 24 RS codewords if the information rate is greater than 10 Mbit/s) to aid the descrambling synchronization process. The right‑most bit in the sequence (i.e., the "1") shall be located in shift register stage number 15 as indicated in Figure H.7.

Loading of the initial sequence shall occur at the start of the first RS codeword following the last codeword in which unique word substitution has been performed (codeword "D" in Figure H.2).

Whenever the RS outer codec is not being used (i.e., switched out of the modulator and demodulator paths), for example, during SSOG lineup, the QPSK/IDR self‑synchronizing scrambler shall be switched on (active). This is to ensure that scrambling is always applied to the information data stream.

H.6. EFFECTS OF BANDWIDTH EXPANSION DUE TO RS OUTER CODING

H.6.1. Modulator/Demodulator Filter Response Guidelines

H.6.1.1. Analog Filters

For modems equipped with analog filters, the modulator/demodulator filter masks for QPSK/IDR carriers employing the optional RS outer coding may be determined, as indicated in the main text (Figures 5 and 6), with respect to R, where R is the transmission rate without RS outer coding.

H.6.1.2. Digital Filters

For QPSK/IDR modems equipped with digital filters, the modulator/demodulator filter masks for QPSK/IDR carriers employing the optional RS outer coding may be determined, as indicated in the main text (Figure 5), but the value of R is multiplied by (n/k).

H.6.2. Power Spectral Density Requirement

The power spectral density mask at the output of the modulator for QPSK/IDR carriers employing the optional RS outer coding shall be determined, as specified in the main text (Figure 8), as follows:

- Points B, D, F, H and K shall be determined with respect to the transmission rate without RS outer coding (R).
- Points A, C, E, G, I, J, L, M, N and O shall be determined with respect to R multiplied by (n/k).

H.6.3. Noise Bandwidth and Allocated RF Bandwidth

H.6.3.1. Noise Bandwidth

The noise bandwidth for QPSK/IDR carriers employing the optional RS outer coding shall be [(n/k) – 1] x 100% greater than the noise bandwidths shown in Appendices B, C, D, E, F and G.

H.6.3.2. Allocated RF Bandwidth

The allocated bandwidths shall remain as currently specified in Appendices B, C, D, E, F and G.

H.6.4. Maximum Uplink EIRP Requirements

The maximum earth station uplink EIRP levels assigned to QPSK/IDR carriers employing the optional RS outer coding shall remain as currently specified in Appendices B, C, D, E, F and G.

H.7. BER PERFORMANCE CHARACTERISTICS FOR THE CONCATENATED REED–SOLOMON PLUS INNER FEC CODING (IF Loopback)

For the Reed–Solomon outer code concatenated with the inner FEC code, the channel unit shall meet the performance requirements given in this paragraph in an IF back–to–back mode. These values apply with the QPSK/IDR self–synchronizing scrambler disabled, the synchronous scrambler enabled, the use of RS outer coding and inner convolutional encoding/Viterbi decoding, and under the conditions outlined in Section 9.2.1 of the main text.

BER better than:	Composite Data Rate E_b/N_o (dB) (Rate 3/4 FEC)
10^{-6}	5.6
10^{-7}	5.8
10^{-8}	6.0
10^{-10}	6.3

The E_b/N_o is referred to the modulated carrier power and to the composite data rate (information rate plus overhead) entering the RS encoder. These E_b/N_o values include a 0.3 dB allowance for increased intersymbol interference (ISI) caused by allowing the use of analog modem filters whose designs are based on the transmission rate without the use of RS outer coding.

For transmission over the satellite, an RF link degradation of 0.4 dB for 10^{-6}, 10^{-7} and 10^{-8}, relative to the modem's IF loopback performance, is needed to account for possible degradation due to phase noise, imperfect amplitude/group delay equalization, adjacent channel interference (ACI) and transponder nonlinearities. At a BER of 10^{-10}, the IF–to–RF degradation for Rate 3/4 FEC is 0.7 dB.

H.8. BER PERFORMANCE AND SYSTEM MARGINS

Since SSOG lineups will be performed on the assumption that the RS outer code is not switched in, the clear–sky BER performance and link availability achieved with the RS outer coding activated will be substantially improved:

- For Intelsat VI, the clear–sky BER will improve from 10^{-7} to less than 10^{-10} and the system margin to 10^{-6} will improve from 0.7 dB to 2.7 dB (Rate 3/4 FEC).

- For Intelsat VII, VIIA and VIII, the clear–sky BER will improve from 10^{-10} to much less than 10^{-10} while the system margin to 10^{-6} will improve from 3.0 dB to 5.0 dB (Rate 3/4 FEC).

- In the case of two 45 Mbit/s Rate 3/4 FEC QPSK/IDR carriers in a 72 MHz C-Band transponder on Intelsat VI, VII, VIIA and VIII (provisional), the clear–sky BER will improve from 10^{-7} to 10^{-10}, while the system margin to 10^{-6} will improve from 1 dB to 3.5 dB. The two–carrier case is provisional when used with the Reed–Solomon outer code.

H.9. IN–SERVICE PERFORMANCE MONITORING AND ALARM REQUIREMENTS

To facilitate in–service performance monitoring and alarming when using the RS outer coding, the following shall be provided:

1. An indication of the composite rate (i.e., information rate plus overhead) E_b/N_o at the input to the RS decoder. The E_b/N_o reading shall be derived from the inner FEC/QPSK modem and shall have an accuracy of equal to or better than ± 0.5 dB over a range extending from the point at which the inner FEC/QPSK modem loses synchronization to a maximum value of at least 10 dB. Design objectives are: an E_b/N_o measurement accuracy of ± 0.25 dB (or better) for E_b/N_o values less than or equal to 10 dB and a maximum E_b/N_o readout of 15 dB (± 1 dB accuracy, for 10 dB $< E_b/N_o \leq$ 15 dB).

2. A "low E_b/N_o" alarm to signify the onset of degraded RS decoder performance. The activation of this alarm shall only trigger appropriate audible and visual indicators. It shall be possible to adjust the trigger level for this alarm over an E_b/N_o range of 5 dB to 7 dB in incremental steps of 0.25 dB.

3. The BER at the input to the RS decoder shall be displayed over a range of about 10^{-2} to at least 10^{-9}.

4. The BER at the output of the RS decoder shall be displayed over a range of 10^{-4} to at least 10^{-10}. This BER value shall be derived from the input BER versus output BER performance characteristic of the RS decoder (e.g., by using a look–up table of the transfer characteristic).

The above mandatory requirements are considered design objectives in the case of existing modem designs (i.e., modem models being produced prior to 4 December 1992).

Table H.1
Reed–Solomon Codes For QPSK/IDR

Type of Service	Info. Rate (kbit/s)	RS Code* (n, k, t)†	Bandwidth Expansion [(n/k)–1]	Inter–leaving Depth	Maximum‡ RS Codec Delay (ms)
Small QPSK/IDR (With IBS O/H)	64	(126, 112, 7)	0.125	4	115
	128	(126, 112, 7)	0.125	4	58
	256	(126, 112, 7)	0.125	4	29
	384	(126, 112, 7)	0.125	4	19
	512	(126, 112, 7)	0.125	4	15
	768	(126, 112, 7)	0.125	4	10
	1024	(126, 112, 7)	0.125	4	8
	1536	(126, 112, 7)	0.125	4	5
QPSK/IDR (With 96 kbit/s O/H)	1544	(225, 205, 10)	0.0976	4	9
	2048	(219, 201, 9)	0.0896	4	7
	6312	(194, 178, 8)	0.0899	4	2
	8448	(194, 178, 8)	0.0899	4	< 2
	32064	(208, 192, 8)	0.0833	4	< 2
	34368	(208, 192, 8)	0.0833	4	< 2
	44736§	(208, 192, 8)	0.0833	4	< 2

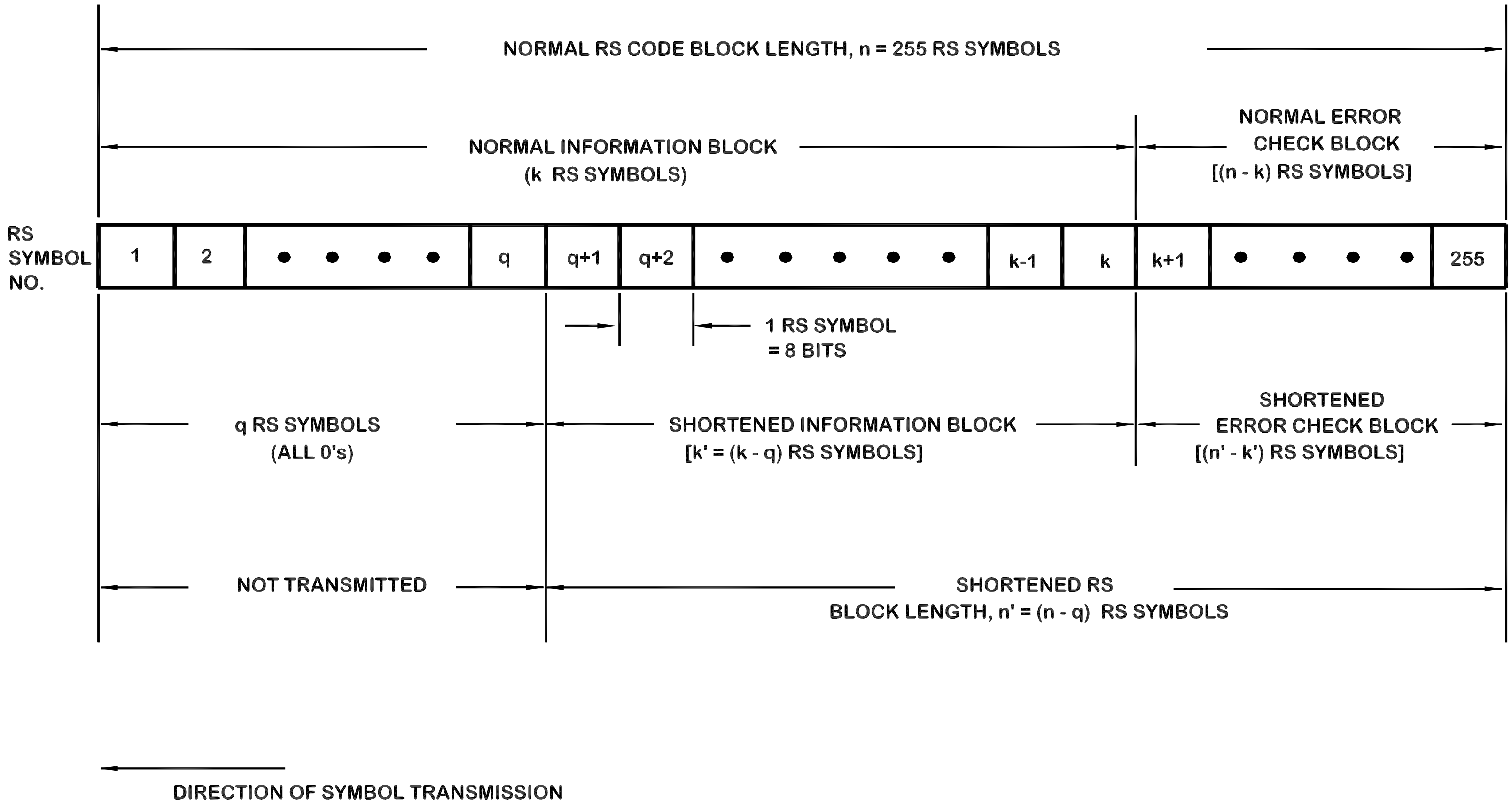
* These codes are applicable to inner FEC Rates 1/2 and 3/4.

† n = code length, k = information symbols and t = symbol error–correcting capability.

‡ Design objective.

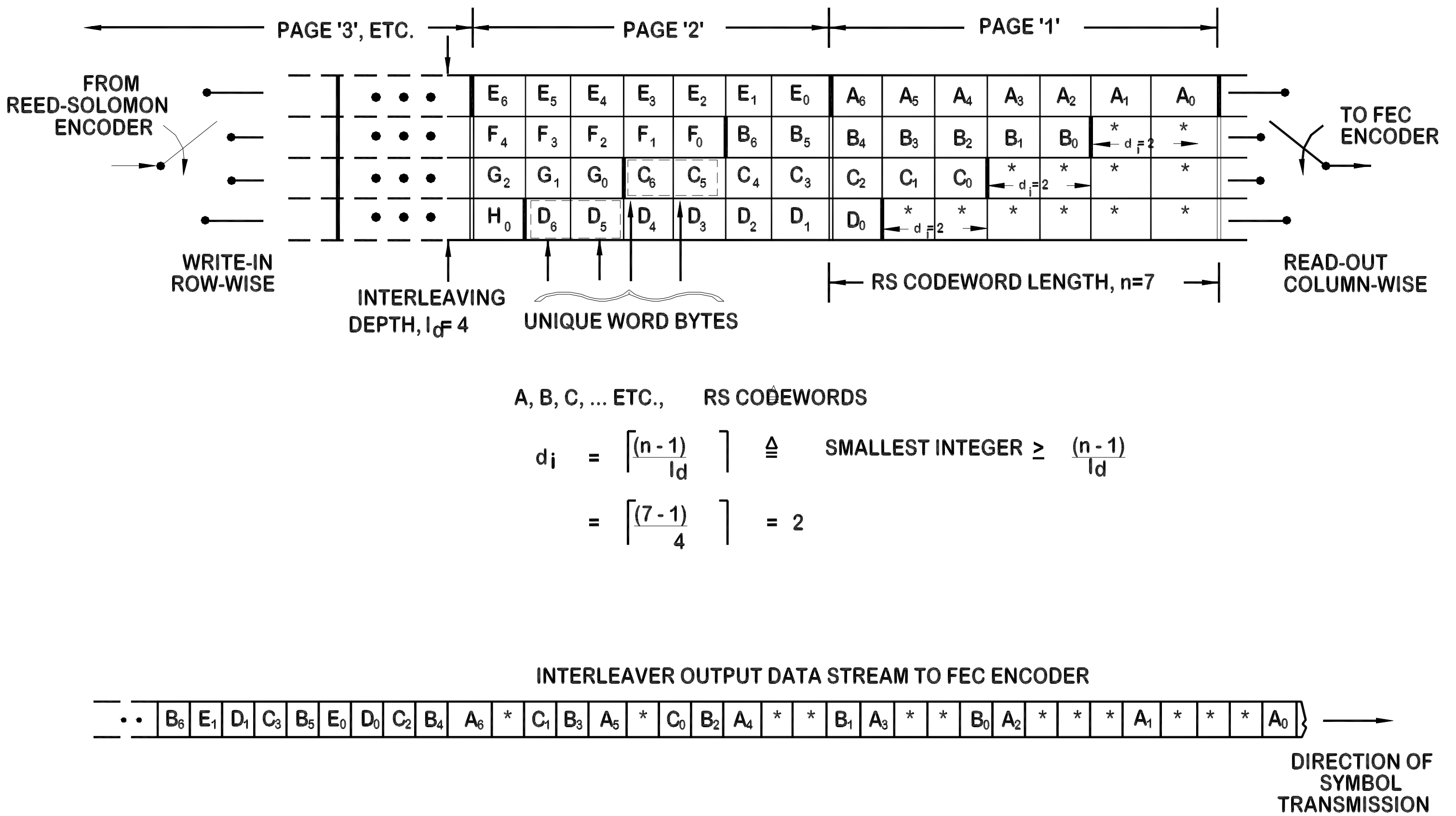
§ The use of RS outer coding for the case of two 45 Mbit/s Rate 3/4 FEC carriers in a single 72 MHz C-Band transponder is provisional, pending the outcome of further studies.

Figure H.1
Reed–Solomon Codeword Configuration



P:\CAD\IESS\308NEW\308-H1.DWG
TITLE: SYSTEMATIC REED-SOLOMON CODEWORD CONFIGURATION

Figure H.2
Interleaver Structure

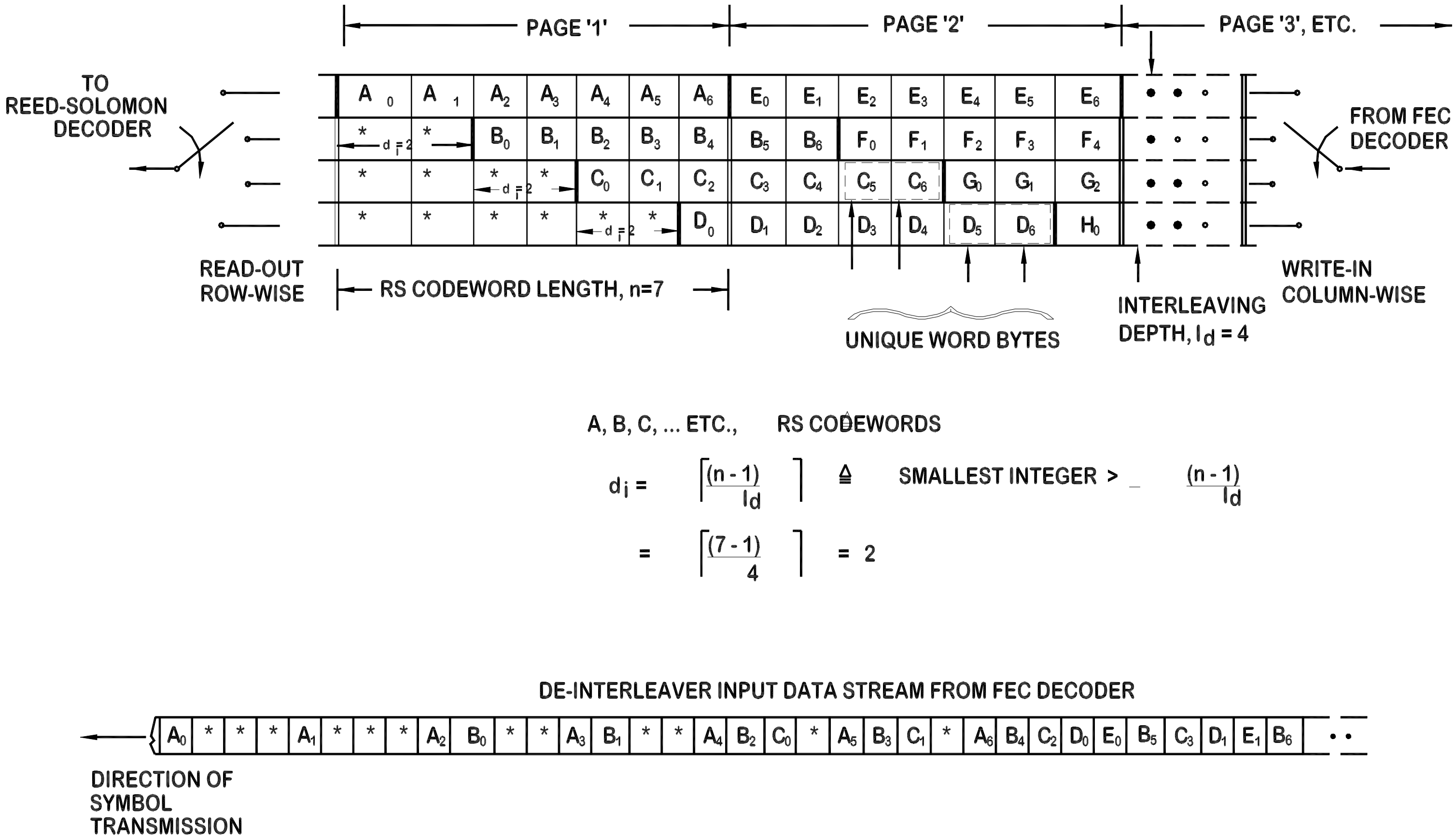


$$d_i = \left\lceil \frac{(n-1)}{I_d} \right\rceil \triangleq \text{SMALLEST INTEGER} \geq \frac{(n-1)}{I_d}$$

$$= \left\lceil \frac{(7-1)}{4} \right\rceil = 2$$

P:\CAD\IESS\308NEW\308-H2.DWG
TITLE: EXAMPLE INTERLEAVING PAGE STRUCTURE
[RS (7, 5, 1) Codeword, Interleaving Depth (I_d) = 4, Information Rates < 1.544 Mbit/s]

Figure H.3
De–Interleaver Structure

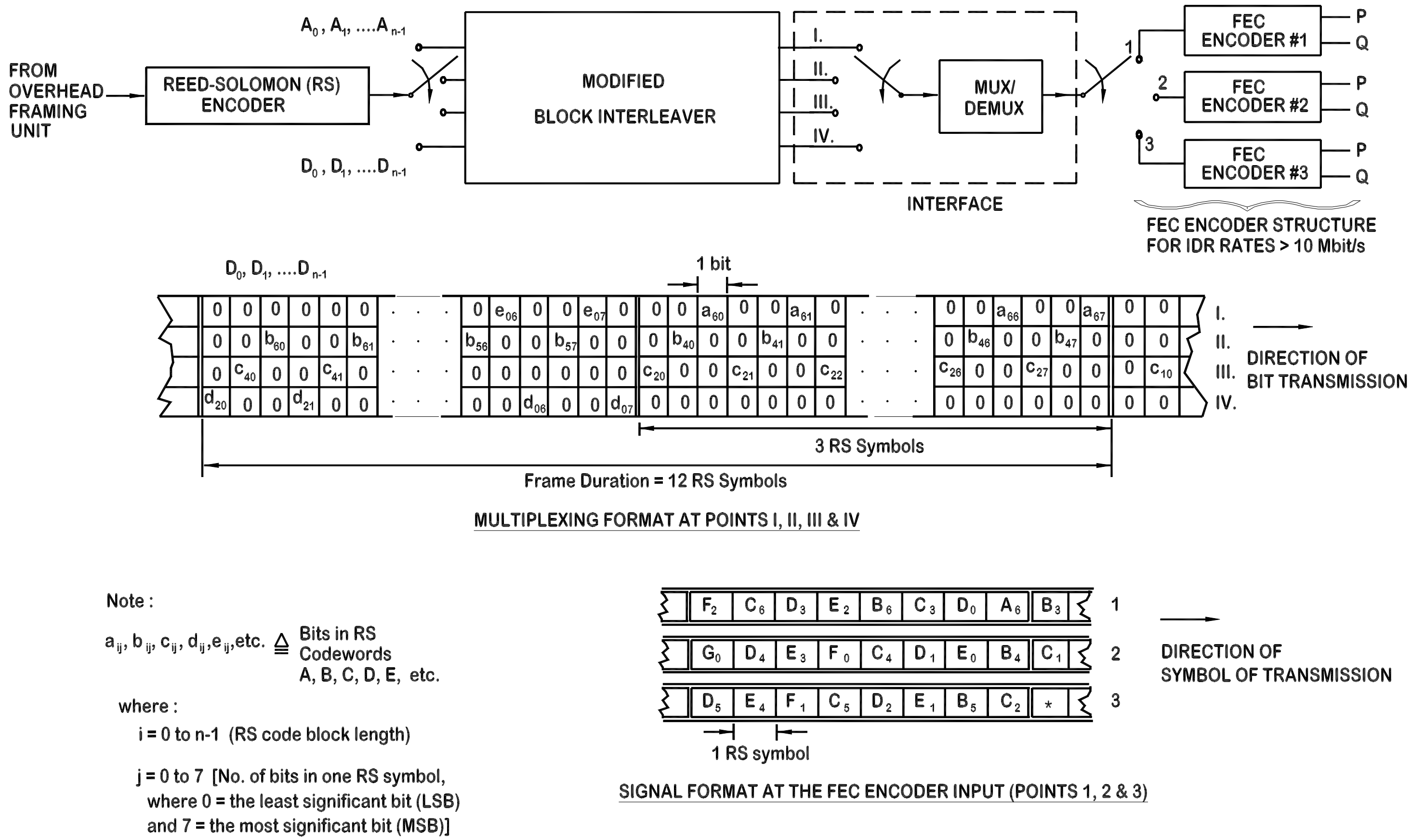


$$d_i = \left\lceil \frac{(n-1)}{I_d} \right\rceil \triangleq \text{SMALLEST INTEGER} \geq \frac{(n-1)}{I_d}$$

$$= \left\lceil \frac{(7-1)}{4} \right\rceil = 2$$

P:\CAD\IESS\308NEW\308-H3.DWG
TITLE: EXAMPLE DE-INTERLEAVING PAGE STRUCTURE
[RS (7, 5, 1) Codeword, Interleaving Depth (I_d) = 4, Information Rates < 1.544 Mbit/s]

Figure H.4
Interleaving For Rates Greater Than 10 Mbit/s



P:\CAD\IESS\308NEW\308-H4.DWG
TITLE: EXAMPLE INTERLEAVING/DE-INTERLEAVING FOR IDR RATES GREATER THAN 10 Mbit/s
[RS (7, 5, 1) Coderword, Interleaving Depth (I_d) = 4]

Figure H.5
Block Diagram Of Reed–Solomon Outer Codec
(Small QPSK/IDR Rates < 1544 kbit/s With IBS Overhead)

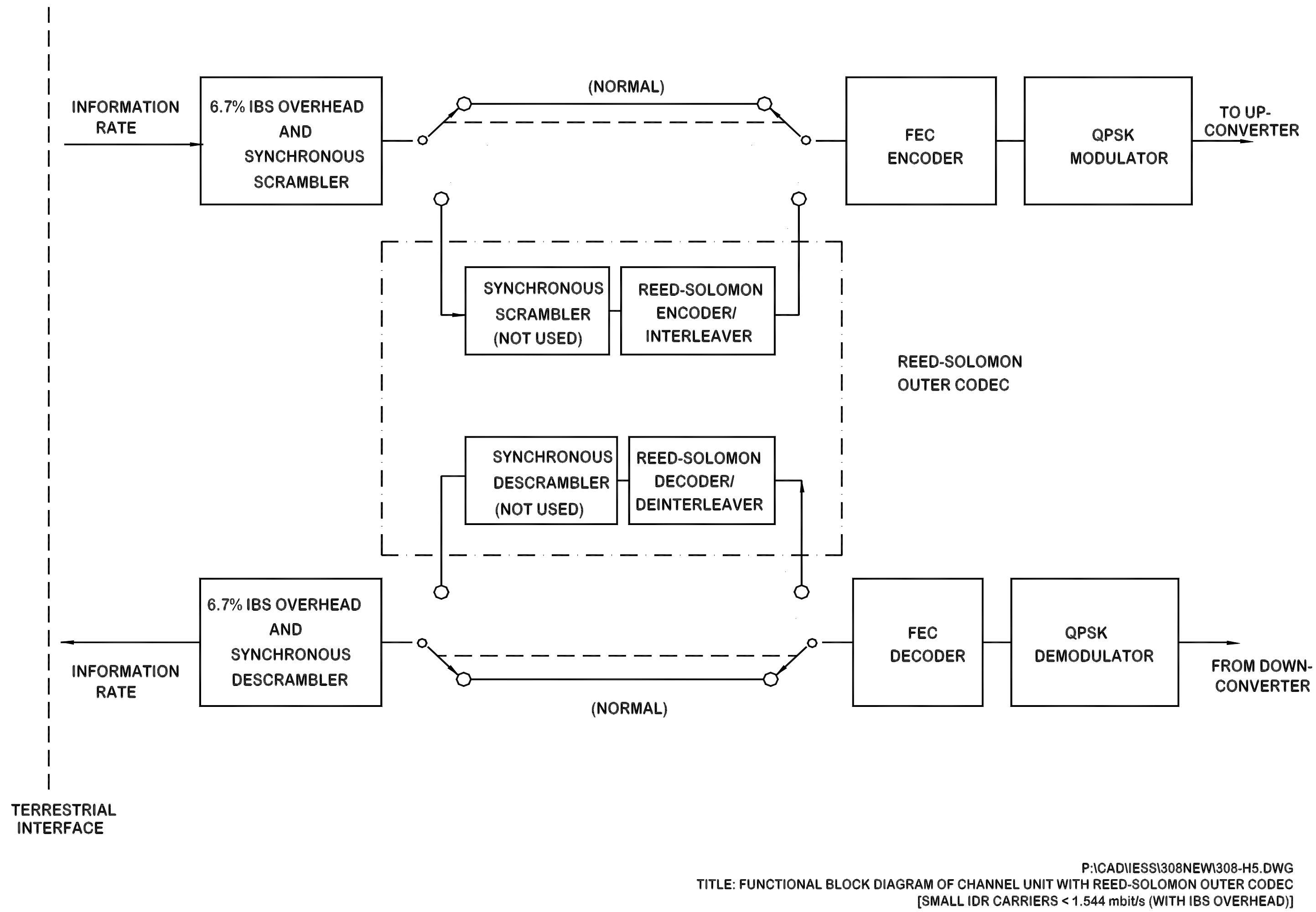


Figure H.6
Block Diagram Of Reed–Solomon Outer Codec
(QPSK/IDR Rates ≥ 1544 kbit/s, With Optional 96 kbit/s ESC Overhead)

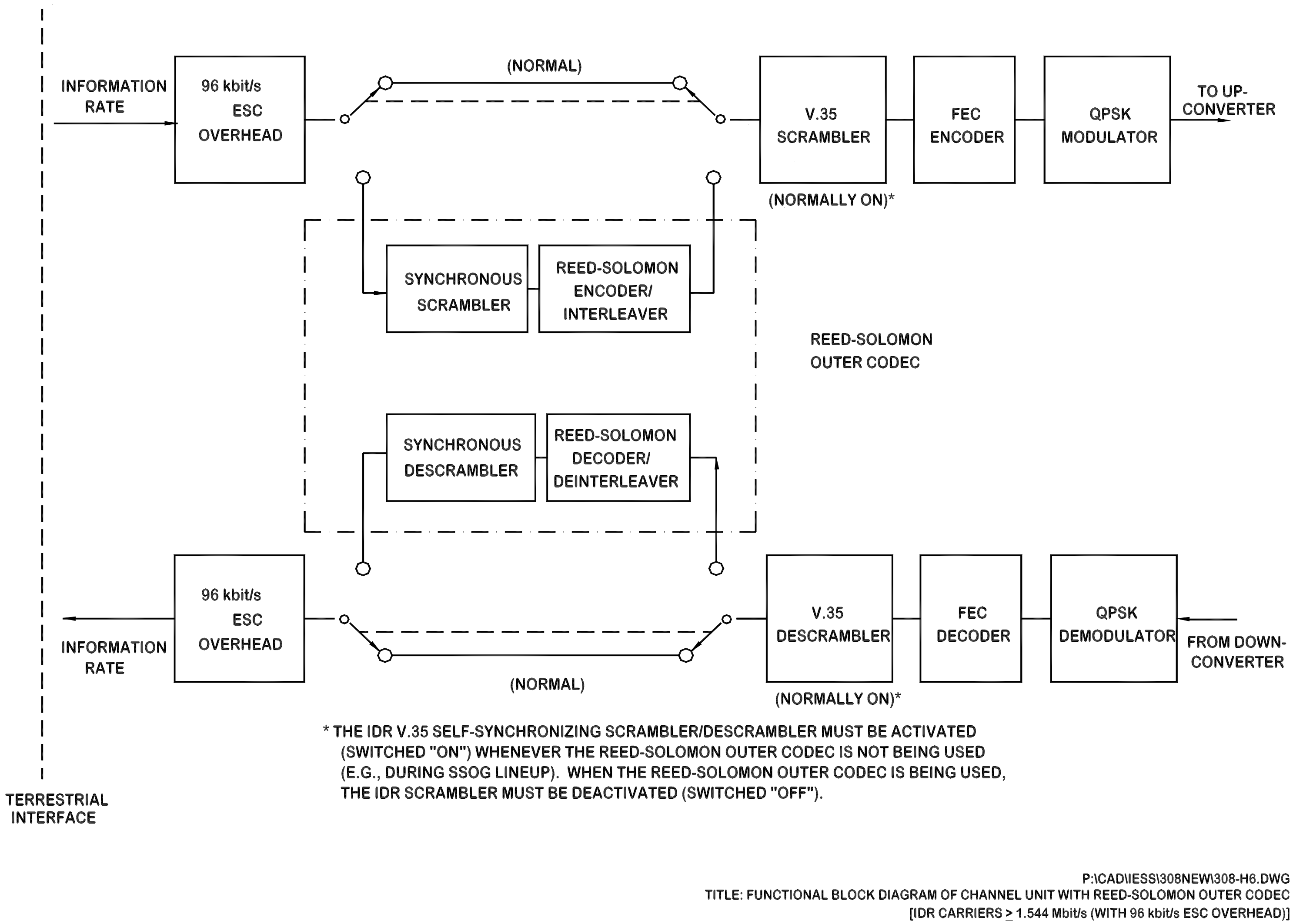
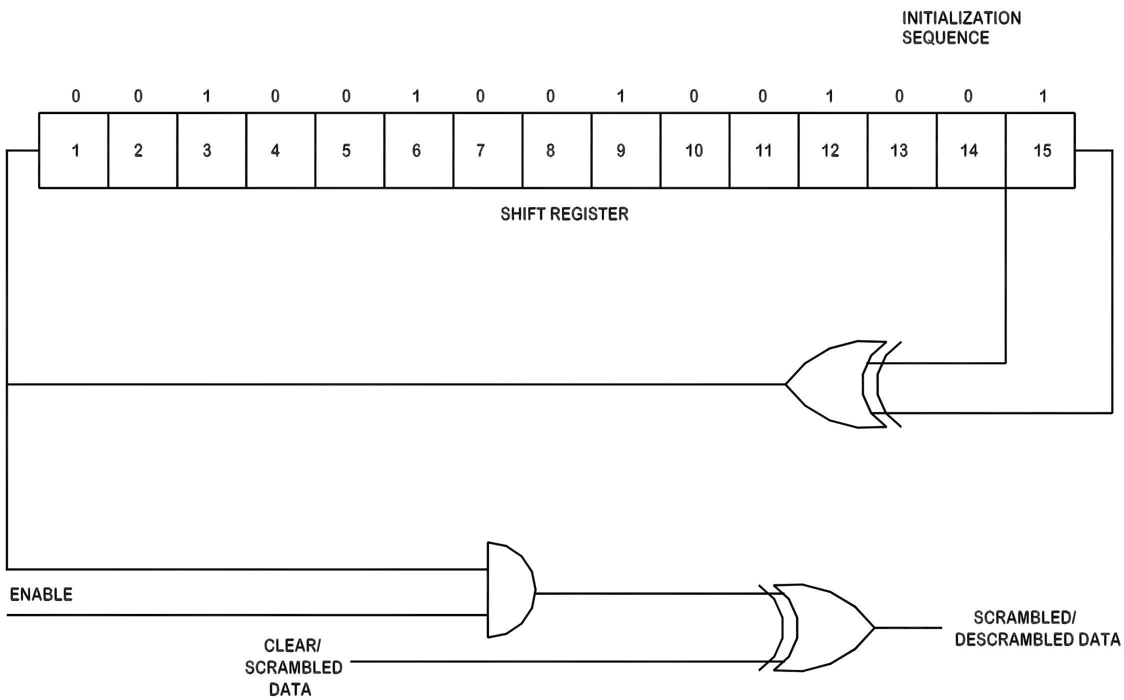
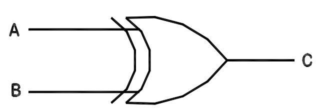
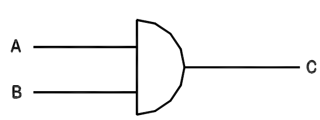


Figure H.7
Scrambler And Descrambler Schematic
(QPSK/IDR Rates ≥ 1544 kbit/s, With/Without Optional 96 kbit/s ESC Overhead)



SYMBOL	FUNCTION	LOGIC TABLE A B C
	EXCLUSIVE OR	0 0 0 0 1 1 1 0 1 1 1 0
	AND	0 0 0 0 1 0 1 0 0 1 1 1

P:\CAD\IESS\308NEW\308-H7.DWG
TITLE: SYNCHRONOUS SCRAMBLER AND DESCRAMBLER SCHEMATIC