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PUBLIC DATA NETWORKS

NETWORK ASPECTS

GENERAL PRINCIPLES FOR THE DETECTION AND CORRECTION OF ERRORS IN PUBLIC DATA NETWORKS

ITU-T Recommendation X.141

(Extract from the *Blue Book*)

NOTES

1 ITU-T Recommendation X.141 was published in Fascicle VIII.3 of the *Blue Book*. This file is an extract from the *Blue Book*. While the presentation and layout of the text might be slightly different from the *Blue Book* version, the contents of the file are identical to the *Blue Book* version and copyright conditions remain unchanged (see below).

2 In this Recommendation, the expression “Administration” is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

Recommendation X.141

GENERAL PRINCIPLES FOR THE DETECTION AND CORRECTION OF ERRORS IN PUBLIC DATA NETWORKS

(Malaga-Torremolinos, 1984)

The CCITT,

considering

(a) that errors have to be detected and corrected with a very high degree of reliability;

(b) that some error correction procedures may be more advantageous than others depending on transmission delays in the network and on the distribution (with time) of errors;

(c) that the distribution (with time) of errors at the ends of a path may depend on forward error correction procedures implemented in one or more of the path segments;

(d) that the applicability of some error correction procedures may be affected by the number of satellite systems in the connection, which may be in national or international links or in the Maritime Mobile Service;

(e) that different error correction procedures may be concatenated in some connections,

unanimously recommends

that the general principles identified in this Recommendation be taken into account in the design and application of procedures for the detection and correction of errors in public data networks.

1 General

1.1 The purpose of this Recommendation is to describe general principles applicable to the detection and correction or recovery of link transmission errors in public data networks.

1.2 Two fundamental objectives of error control procedures are:

- to ensure an incidence of undetected errors that is within acceptably low probability limits;
- to ensure that detected errors are corrected or recovered using an error control procedure consistent with data throughput and sequencing requirements which apply when the error rate of the Physical Layer is within the fully acceptable and the tolerance limits of specified performance.

1.3 In the context of the Reference Model of Open Systems Interconnection, it is noted in Recommendation X.200 that each (N) peer protocol should include sufficient control information to enable the (N) entities to detect or recover from error conditions within its purview. Reporting detected but unrecovered errors is a service that must be provided by each layer.

Specifically, it is an objective of the Data Link Layer to detect and possibly correct errors which may occur in the Physical Layer.

1.4 For any particular error detection arrangement the probability of undetected errors will generally tend to increase:

- with increasing error rate,
- for any given error rate, as the error distribution becomes less random and as the length of error bursts increases,
- with increasing frame length,
- possibly due to scrambling arrangements which may have factors in common with the generating polynomial used for error detection.

1.5 Data throughput in the presence of errors depends on the design of the error control procedure, which in turn depends on the following conditions:

- error rate,
- error distribution,
- scrambling and/or multiplexing arrangements insofar as they affect the error distribution or error rate,
- transmission path (propagation) time delay,
- data signalling rate,
- frame length,
- window size,
- buffer memory resources at the sending and receiving end of the link.

2 Types of error occurrences

Error occurrences are typically of three types distinguished by characteristic error distributions with time:

- random errors,
- burst errors,
- errors due to uncontrolled slip.

It is likely that one type of error occurrence will be predominant in any particular link, depending on the type of transmission systems employed (i.e. cable, microwave radio relay, or satellite, with or without forward error correction).

In the design of error control procedures for a link, it is important to identify any tendency for the predominance of a particular type of error occurrence.

3 Error control procedures

3.1 *Types of procedure*

Two types of error control commonly employed in public data networks (PDNs) are:

- forward error correction, a coding method employed with the objective of detecting and correcting errors in received data instead of requesting retransmission,
- ARQ procedures wherein transmitted information is formatted in frames with error detection encoding, and error recovery is achieved by automatic repetition upon request from the data receiver of a frame or of all information already transmitted starting with the requested frame. Timeout recovery serves as a backup for the ARQ procedure.

3.2 *Forward error correction*

Forward error correction (FEC) does not require the provision of a backward mechanism in order to operate. FEC is usually applied at the Physical Layer of the reference model, typically within transmission systems whose error performance might not otherwise meet required limits.

The capability of FEC techniques commonly used in PDNs to control errors tends to be restricted to the correction of a limited number of errors (typically 2 or 3 errors) within each coded information block or constraint of block length. For this reason these FEC procedures are most effective in situations where error occurrences are predominantly random.

Depending on multiplexing arrangements and sometimes on other arrangements in the Physical Layer such as scrambling and encryption, residual uncorrected errors after FEC may tend to be grouped in clusters or error bursts. When the number of errors within a coded information frame or constraint length of code exceeds the correction capability of the FEC algorithm, the total number of errors in the cluster or burst may be increased rather than reduced by the FEC facility.

Usually, it will not be feasible to notify the Data Link Layer of detected but uncorrected errors via FEC facilities of the Physical Layer which may perform their error control function at a multichannel, multiplexed signal level of the transmission system.

In the adaptation of data signals at recommended bit rates below 64 kbit/s for transmission at 64 kbit/s, sufficient redundancy will be introduced in some cases for forward error correction to be undertaken on a majority voting basis without special forward error correction encoding. With this arrangement, a large number of different error patterns can be detected and corrected.

Alternatively, or in addition, the frame checking sequence of the ARQ error control procedure may also be used to distinguish between correctly and incorrectly received information in redundant signal streams.

3.3 *ARQ procedures*

3.3.1 *General*

ARQ procedures require the provision of forward and backward channels, usually with simultaneous transmission capability.

ARQ control procedures of error detection and error recovery are included in the functions of the Data Link Layer and may also be implemented in the functions of higher layers of the reference model.

3.3.2 *Error detection*

3.3.2.1 *Frame checking sequence*

The 16-bit frame checking sequence (FCS) described below is used for error detection in the packet transfer procedures of Recommendations X.25 and X.75, in the Signalling System No. 7 signalling link procedure of Recommendation Q.703 and in the Link Access Procedure on the D-channel of an ISDN as described in Recommendation Q.921 (I.441).

The same generator polynomial is also used in the encoding and checking process of Recommendation V.41.

The 16 FCS bits are generated at the transmitter. They are the 1s complement of the sum (modulo 2) of:

1) the remainder of x^h $(x^{15} + x^{14} + x^{13} + . . . + x^2 + x + 1)$ divided (modulo 2) by the generator polynomial $x^{16} + x^{12} + x^5 + 1$, where h is the number of bits in the frame existing between, but not including, the final bit of the opening flag and the first bit of the FCS, excluding bits inserted for transparency, and

2) the remainder after multiplication by x^{16} then division (modulo 2) by the generator polynomial $x^{16} + x^{12} + x^5 + 1$ of the content of the frame existing between, but not including the final bit of the opening flag and the first bit of the FCS, excluding bits inserted for transparency.

As a typical implementation, at the transmitter, the initial remainder of the division is preset to all 1s and is then modified by division by the generator polynomial (as described above) on the address, control and information fields; the 1s complement of the resulting remainder is transmitted as the 16-bit FCS sequence.

At the receiver the correspondence between the check bits and the remaining part of the frame is checked. If a complete correspondence is not found the appropriate error recovery procedure is initiated.

As a typical implementation at the receivers, the initial remainder is preset to all 1, and the serial incoming protected bits including the check bits (after the bits inserted for transparency are removed) when multiplied by x^{16} and then divided by the generator polynomial will result in a remainder of 0001110100001111 (x^{15} through x^0 respectively) in the absence of transmission errors.

Explanatory notes concerning the FCS error detection procedure described above are given in Appendix I

The procedure will detect:

a) all odd numbers of errors within a frame,

b) any error burst not exceeding 16 bits in length,

c) all two-bit errors when the code length is less than 32768 bits,

d) a large percentage of other error patterns (with even numbers of errors).

3.3.2.2 *Use of scramblers*

The following system design consideration should be taken into account concerning the use of self-synchronizing scramblers:

Where self-synchronizing scramblers (i.e. scramblers which effectively divide the message polynomial by the scrambler polynomial at the transmitter and multiply the received polynomial by the scrambler polynomial at the receiver) are used, the scrambler polynomial and the generating polynomial for error detection must have no common factors in order to ensure satisfactory performance of the error-detecting system. Where this condition cannot be maintained, the scrambling process must precede the error detection encoding process and the descrambler process must follow the error detection decoding process. Where additive (i.e. non-self-synchronizing) scramblers are used or where the scrambling takes place at a multi-channel multiplexed signal level, this design precaution need not be observed.

3.3.2.3 *Frame integrity*

The integrity of the frame format must be maintained in order to assure proper functioning of the error detection procedure described in § 3.3.2.1.

The frame structure for all transmissions is distinguished by opening and closing flags, each consisting of one 0 followed by six contiguous 1s and one 0. A single flag may be used as both the closing flag for one frame and the opening flag for the next frame. To ensure that the unique flag sequence is not simulated, the entire frame content between two flag sequences is examined at the transmitter and a 0 bit is inserted after all sequences of 5 contiguous 1 bits (including the last 5 bits of the FCS). At the receiver, the frame content is reexamined and any 0 bit which directly follows 5 contiguous 1 bits is discarded.

At the receiver, a frame validity check is carried out to detect any invalid frames not properly bounded by two flags or having fewer than the specified minimum number of bits. Invalid frames are treated in the same way as frames with detected errors.

3.3.3 *Error recovery procedures*

In accordance with ARQ concepts, error recovery is vested in the traffic control procedure wherein all information frames are numbered sequentially in order of transmission, from 0 through modulus minus 1 (where *modulus* is the modulus of the sequence numbers). Typically, the modulus equals 8 or 128 and the sequence numbers cycle through the entire range.

Valid frames without errors received in proper sequence are acknowledged in responses from the receiver to the transmitter, while invalid frames and frames with errors are discarded by the receiver and completely ignored. Frame recovery action is initiated by the receiver when a valid frame without errors does not have the expected sequence number. Consequently, when one or more frames are discarded for lack of validity or for errors, the number of the next correctly received frame will be out of sequence, causing the receiver to initiate the prescribed frame recovery procedure.

If, due to a transmission error, the receiver does not receive (or receives and discards) a single information frame or the last in a sequence of information frames, then the out-of-sequence condition which would otherwise serve to initiate error recovery procedures at the receiver will not be detected. In this case, frame recovery will be initiated at the transmitter via a time-out procedure as follows:

For traffic control purposes, the receiver must send acknowledgment response to the transmitter confirming the receipt of valid, error free frames. After a specified time-out period with outstanding transmitted frames and no acknowledgement or frame recovery responses from the receiver, appropriate recovery action is initiated at the transmitter to determine the point at which retransmission must begin.

Alternative types of error recovery procedure are available as follows:

- reject procedure,
- selective reject procedure,
- selective reject-reject procedure.

Each of these procedures requires that storage be provided at the transmitter for all information frames already sent but not yet acknowledged to be correctly received.

The data throughput efficiency obtainable as a function of error rate and distribution may depend significantly on the type of error recovery procedure, particularly in transmission links with associated long time delays (e.g. links via satellite). The complexity of error recovery implementation, including frame storage requirements at the receiver, is another consideration which plays an important part in selecting the most advantageous error recovery procedure to suit a particular situation.

3.3.3.1 *Reject (REJ) procedure*

The *reject* (REJ) error recovery procedure is used by the receiver to request retransmission of information frames commencing with a specified sequence number and to simultaneously acknowledge satisfactory reception of all preceding information frames.

The rejected frame and all subsequent information frames already in transit at the time that the REJ response reaches the transmitter will be retransmitted.

After sending the REJ response, the receiver discards all incoming information frames until the lost frame is recovered. This procedure minimizes frame storage requirements at the receiver, but under marginal conditions of error performance it may result in poor throughput efficiency depending on the round-trip transmission delay between the transmitter and receiver.

With the REJ error recovery procedure, the window size should allow a maximum number *k* of outstanding frames, where *k* is the smallest integer not less than *r*, calculated as follows:

$$r = \frac{T \cdot D}{L}$$

where

T is the transmission rate (bit/s)

D is the round-trip delay (seconds)

L is the information frame length (bits).

3.3.3.2 *Selective reject procedure*

The *selective reject* (SREJ) response is used by the receiver to request retransmission of a single information frame identified by its sequence number and to simultaneously acknowledge satisfactory reception of all preceding information frames.

In accordance with the foregoing definition of the SREJ request, only one SREJ condition can be outstanding at any one time. Consequently, the ability of the SREJ procedure to make efficient use of the Physical Layer falls off very quickly as the rate of frame error occurrence exceeds one per round-trip propagation delay.

This difficulty may be alleviated by an alternative SREJ procedure which suppresses the acknowledgement function of the SREJ request and consequently allows a station to send a following SREJ request for retransmission of another fault information frame before the information frame in response to the first SREJ request has been correctly received. This alternative procedure can be particularly advantageous in the case of high speed transmission via satellite.

Pursuant to the alternative procedure, the selective reject frame SREJ is used to request retransmission of a single information frame numbered N(R) and the information frames numbered up to N(R) - 1 are not considered as accepted.

Subsequent information frames already in transit when the SREJ response reaches the transmitter will not be repeated (if received correctly). Hence, there is a minimum reduction in throughput efficiency as a function of increasing error rate on transmission paths with long time delays.

This advantage of the SREJ procedure, is realized at the cost of providing considerable frame storage capability and some processing for frame resequencing at the receiver.

With the SREJ recovery procedure, the window size should allow a maximum number *k* of outstanding frames where *k* is an integer not less than *r* as follows:

$$r = 2\,\frac{T \cdot D}{L}$$

3.3.3.3 *Selective reject-reject procedure*

A proposed selective reject-reject procedure is described below:

If the receiver detects the loss of a single information frame then, after satisfactory receipt of the next information frame, it sends a SREJ response to recover the lost frame. All information frames received satisfactorily in sequence after the lost frame are stored at the receiver pending recovery of the lost frame.

If the receiver detects the sequential loss of two information frames, it sends a REJ response and discards all subsequently received information frames until the lost frame is recovered.

If the loss of another information frame is detected prior to recovery from the SREJ exception condition, the receiver will store all information frames received subsequent to the first lost frame and prior to the second lost frame and will discard all information frames thereafter until the first lost frame is recovered. After recovery of the first lost frame, the receiver will send a REJ response for recovery of the second lost frame and the subsequently received but discarded frames.

Operated over transmission paths with long time delays, the SREJ-REJ error recovery procedure results in values of throughput efficiency as a function of error rate which are somewhat inferior to those obtained with the SREJ procedure and significantly better than those obtained with the REJ procedure.

For any prevailing error rate, the average occupancy of buffer memory for frame storage at the receiver with the SREJ-REJ procedure is significantly less than corresponding average buffer occupancy with the SREJ procedure.

With the SREJ-REJ error recovery procedure, the window size should allow a maximum number of outstanding frames, k, where k is the smallest integer not less than r calculated as follows:

$$r = 2 \frac{T \cdot D}{L}$$

4 Concatenation of error control procedure

4.1 *Concatenation of FEC and ARQ procedures*

In links via satellite, the reduction in data throughput as a function of increasing error rate may be minimized by the concatenated use of both forward error correction and ARQ procedures.

Since forward error correction reduces the effective data throughput of the transmission medium under acceptable operating conditions when the error rate is low and is most effective for only a small percentage of the time when the error performance is marginal, the use of a more efficient ARQ procedure (e.g. SREJ instead of REJ) may be considered as an alternative to the concatenation of FEC and ARQ procedures.

4.2 *Concatenation of FEC procedures*

The utilization of two stages of forward error correction (FEC) coding may yield a very significant improvement in the performance of a satellite link. Figure 1/X.141 illustrates the general configuration of such a two-stage concatenated coding system. The diagram shows two pairs of interleavers which are discussed below and may be omitted in some cases.

The purpose of the interleaver pairs is to break up bursts of errors and to scatter these errors in a manner so as to minimize the probability that a long uncorrectable error burst will be presented to a decoder. The channel symbol interleaver pair may be deleted if the channel errors are known to be statistically independent. When an inner decoder error occurs, the decoder will output a burst of errors. Therefore, it is necessary to include an intercode interleaved pair which is designed to transform the occasional inner decoder error bursts so that they can be efficiently corrected by the outer decoder. Thus, a well designed concatenated coding system includes codes and interleavers designed to complement each other. The inner code should correct nearly all of the channel errors and the outer code should correct the residual errors caused by inner decoder failures and errors.

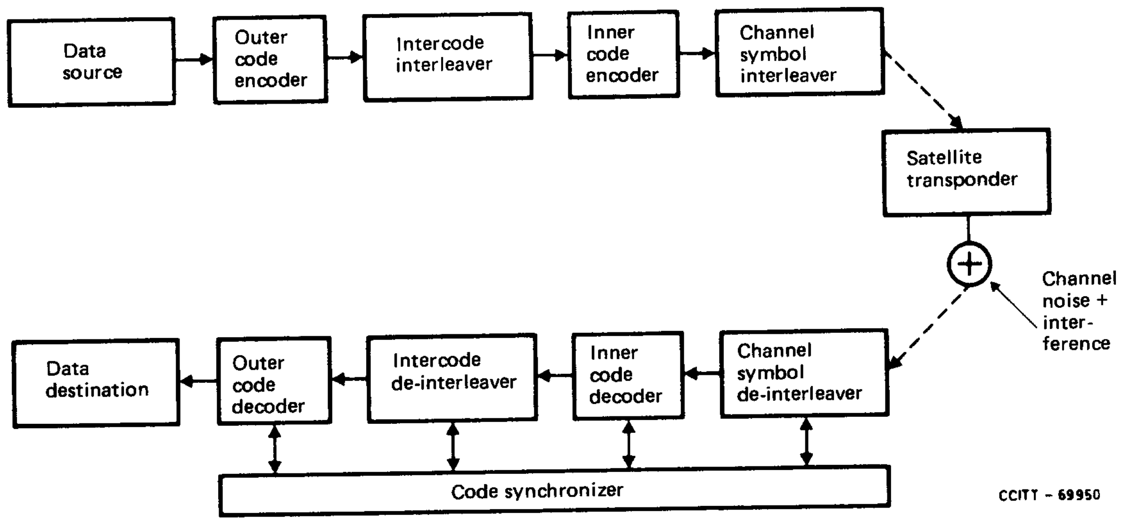

FIGURE 1/X.141

Two-stage concatenated FEC configuration

A final consideration in the selection of a concatenated code is that of decoding delay and synchronization. Care must be taken in selecting the codes and interleavers to ensure that:

1) the delay introduced by the FEC system is small with respect to the satellite propagation time (approximately 250 ms), and

2) the data loss incurred due to a loss of synchronization is minimized.

APPENDIX I

(to Recommendation X.141)

Explanatory notes concerning the frame checking sequence

The following abbreviations are used in the explanatory notes given below:

$G(x)$ is the polynomial representing the k-bit sequence between the opening flag and the start of the FCS

$P(x)$ is the generator polynomial $(x^{16} + x^{12} + x^5 + 1)$

$L(x)$ is the polynomial representing 16 contiguous ones, $(x^{16} + x^{15} + x^{14} + \dots + x + 1)$

$R(x) = \overline{\text{FCS}}$ is the remainder obtained from the modulo 2 division:

$$\frac{x^{16}\,G(x) + x^k\,L(x)}{P(x)} = Q(x) + \frac{R(x)}{P(x)}$$

In the frame checking sequence (FCS), the multiplication of *G(x)* by x^{16} corresponds to shifting the message *G(x)* 16 places, thus providing the space of 16 bits for the FCS.

The addition of $x^k L(x)$ to $x^{16} G(x)$ is equivalent to inverting the first 16 bits of $x^{16} G(x)$ and corresponds to initializing the initial remainder to a value of all ones. This addition is provided to protect against the obliteration of leading flags, which may be non-detectable if the initial remainder is zero. The complementing of $R(x)$, by the transmitter, at the completion of the division ensures that the received, error-free message will result in a unique, non-zero remainder at the receiver. The non-zero remainder provides protection against potential non-detectability of the obliteration of trailing flags.

At the transmitter, the FCS is added to x^{16} $G(x)$ and results in a total message $M(x)$ of length:

$$n = k + 16, \text{ where } M(x) = x^{16} G(x) + FCS$$

At the receiver, the incoming $M(x)$ is multiplied by x^{16}, added to x^n $L(x)$ and divided by $P(x)$ as shown below:

$$\frac{x^{16}\ M(x) + x^n\ L(x)}{P(x)} = \frac{x^{16}\ [x^{16}\ G(x) + FCS + x^k\ L(x)]}{P(x)}$$

The following expressions are derived from those shown above, noting that the addition of $L(x)$ without carry to a polynomial $R(x)$ of the same length is equivalent to a bit by bit inversion of $R(x)$ and substituting $FCS = \overline{R(x)} = R(x) + L(x)$, then rearranging the terms of the numerator:

$$\frac{x^{16}\ [x^{16}\ G(x) + R(x) + L(x) + x^k\ L(x)]}{P(x)} =$$

$$\frac{x^{16}\ [x^{16}\ G(x) + x^k\ L(x) + R(x)] + x^{16}\ L(x)}{P(x)} = Qr(x) + \frac{Rr(x)}{P(x)}$$

If the transmission is error-free, the term $[x^{16}$ $G(x) + x^k$ $L(x) + R(x)]$ will be divisible by $P(x)$ and the remainder after division will be:

$$\frac{x^{16}\ L(x)}{P(x)},$$

or 0001110100001111 (x^{15} through x^0 respectively).

If the transmission is error-free and the FCS is inverted before division at the receiver, the remainder will be zero because inverting the FCS is equivalent to adding another x^{16} $L(x)$ to the numerator and

$$\frac{x^{16}\ L(x) + x^{16}\ L(x)}{P(x)} = 0.$$