Forward Error Correction (FEC) computation in Optical Transmission Systems

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Abstract - The Forward Error Correction (FEC) in transmission systems increase the bit rate effectively. Also it helps to increase the span length and capacity of the digital system which may be either of single channel/multi channel. The paper discussess two FEC schemes recommended for optical transmission system. They are in- band FEC for SDH system and Out-off-band FEC for OTN. Different terminologies related to FEC have been discussed and the results for the SDH and OTN systems have been discussed.

Keywords-- FEC, SDH, OTN, NCG, CG

I. INTRODUCTION

Forward Error Correction (FEC) is rapidly becoming an important way of improving the performance of large capacity long –haul optical transmission systems and is already well established in wireless communication systems. Employing FEC in optical transmission systems yields system designs that can accept relatively large BER (much more than 10^{-12}) in the optical transmission line (before decoding). FEC application may allow the optical parameters to be significantly relaxed and encourages the construction of large capacity long- haul optical transmission systems in a cost effective manner. Two different FEC schemes have been discussed and implemented in this paper.

II. FEC TERMINOLOGIES AND PERFORMANCE

At present, two FEC schemes are recommended for optical transmission systems. They are “in- band FEC” for SDH systems and “out – of – band FEC” for optical transport networks (OTNs). (Out- of – band FEC was originally recommended for submarine optical systems). The terminology in or out refers to the client bandwidth. In-band FEC parity Bits are encoded in a previously unused band of the section Overhead of SDH signals, so the bit rate is not increased. In contrast to SDH, OTN signals including space for FEC bits (OTUk) have a higher bit rate than the equivalent signal before the FEC is added (ODUk). So, OTN signals are encoded using out-of – band FEC resulting in significantly increased line-rate.ITU-T Rec.G.709/Y.1331 also offers the option of non- standard out of band FEC optimized for higher efficiency.

A. In band FEC in SDH system:

In band FEC is described in 9.2.4/G.707/Y.1322, Annex A/G.707/Y.1322, appendix IX/G.707/Y.1322, and Appendix X/G.707/Y.1322. The code is optional in STM-16, -64, and -256 single and multichannel systems. The code is triple error correcting binary BCH code, more exactly a shortened BCH (4359,4320) code. Up to three bit errors can be corrected in a 4359-bit code word. The code word is an 8-bit interleaved signal stream of 270x 16 bytes from 1 row of the STM-N frame. Therefore, up to 24-bit continues errors in each row of an STM-16, -64 or -256 frames can be corrected. I error occur randomly, BER after decoding P_c = BER_{out} is expressed, using raw BER_p= BER_{in} (before decoding), as follows for N=4359.

$$P_c = \sum_{i=4}^{N} \frac{i}{N} \times \binom{N}{i} \times p^i \times (1-p)^{N-i} \qquad (1)$$

B. Out- of –Band FEC in optical transport networks (OTNs)

Out- of- band FEC is described in 11.1/G.709/Y.1331 and Annex A/G.709/Y.1331 as a modification of the out – of – band code in ITU-T Rec. G.975. ITU- T Rec. G.709/Y.1331 specifies the network Node Interface (NNI) in OTN where the RS(255, 239) code is optionally included. ITU-T Rec. G.975 recommends the frame format for submarine systems and also describes the performance of the RS (255,239) code. This code is a symbol error correcting RS code, so the byte number is used in the description. Up to eight bytes in the code word can be corrected. The G.709/Y.1331 frame employs 16- byte interleaving, so 1024 bits continuous errors can be corrected.

If errors occur randomly, BER after decoding $P_c = BER_{out}$ is expressed, using original raw $BER_p = BER_{in}$ (before decoding), as follows.

$$P_{UE} = \sum_{i=9}^{N} \frac{i}{N} \times \begin{pmatrix} N \\ i \end{pmatrix} \times P_{SE}^{i} \times (1 - P_{SE})^{N-i}$$

$$p = 1 - (1 - P_{SE})^{1/8} \qquad (2)$$

$$p_c = 1 - (1 - P_{UE})^{1/8}$$

P_{UE} is the probability of uncorrectable error, and P_{SE} is the probability of symbol (byte) error, N=225.

C. Coding Gain and Net Coding Gain (NCG)

In the case of a randomly distributed error within the encoded line signal, a FEC decoder reduces the line or raw BER to a required reference BER value within the payload signal. Coding gain could therefore be regarded as the relation of the bit error ratios, in order to define a coding gain as a more system related parameter, BER reduction by FEC is usually transformed into a dB value based on a theoretical reference system. It is common practice to define coding gain as a reduction of signal –to noise ratio at a reference BER. This definition is directly applicable to an in- band FEC because its use does not imply an increase of the bit rate and therefore also no noise increase at the decision circuit due to receiver bandwidth expansion. The performance of an out- of – band FEC can be characterized better by a modified coding gain parameter. In wireless transmission systems the Net Coding Gain (NCG) parameter is well established for out -of -band FEC. It takes into account the fact that the bandwidth extension needed for these FEC scheme is associated with increased noise in the receiver.

Based on the NCG value, the achievable system gain in optical signal- to – noise ratio (OSNR) limited systems can be estimated accurately. In this case, the reduction of the electrical signal to noise ratio as consequence of higher line BER reflects the allowable reduction in OSNR. In systems involving additional non white noise contributions, the trade-off between sensitivity reduction due to bandwidth expansion and coding gain is much more complicated. For comparison of high efficiency FEC schemes with different (but similar) code rates used in long- haul systems, the NCG parameter is a good measure. It should be noted, however, that this comparison is only valid in systems limited by white noise sources. In the case that, there is a significant penalty due to (nearly deterministic) signal degradation, the penalty may increase rapidly with increasing bit rate and invalidate the comparison. Even in systems operating in a very non- linear regime of the transmission fiber, the application of NCG is of limited value due to the fact that the associated noise cannot be characterized by white Gaussian noise.

D. Net Coding Gain Definition

NCG is characterized by both the code rate R and the maximum allowable BER_{in} of the input signal of the FEC decoder, which can be reduced to a reference BER_{out}= B_{ref} by applying the FEC algorithm. Furthermore, NCG should refer to a binary symmetric channel with added white Gaussian noise:

$$NCG = 20\log_{10}\left[erfc^{-1}(2B_{ref})\right] - 20\log_{10}\left[erfc^{-1}(2B_{in})\right] + \qquad (3)$$
$$10\log_{10} R \quad (dB)$$

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

Note 2- R=1 for in- band FEC.

III. ALGORITHM AND IMPLEMENTATION

The algorithm for the encoder of FEC scheme is as follows and the flowchart is shown in Fig. 1 below.

- Error word polynomial $e(x) = e_0 + e_1 x + ... + e_{n-1} x^{n-1}$
- The received word polynomial is given by $w(x) = c(x) + e(X)$
- Syndromes

$$S_j = w(\alpha^j) = \sum_{i=0}^{n-1} e_i \alpha^{ij}; \cdots for j = 0,..,2t - 1$$

- Syndromes can be computed using the Horner algorithm:

- Suppose that there are r errors, r<=t, occurred
  - At locations $i_1,\ldots i_r \quad (let\ X_l = \alpha^{il})$
  - With values $e_{i1},\ldots e_{ir} \quad (let\, Y_l = e_{il}\alpha^{il} = e_{il}X_l$
- Reformulate $S_j = \sum_{i=1}^{r} e_i \alpha^{ij}$
- Solve s(x)=0
- Find the error locations
- Compute error magnitude at error locations and correct the errors
- Clearly finding [M] and M^{-1} is not easy for large t

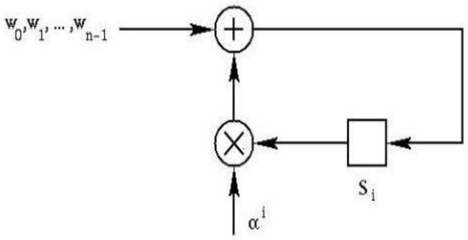

Fig. 1 Flowchart for the encoder of FEC scheme

IV. Results and Discussion:

The graphical results for the gain v/s BER for SDH and OTN have been shown in Fig. 2 and Fig. 3 respectively.

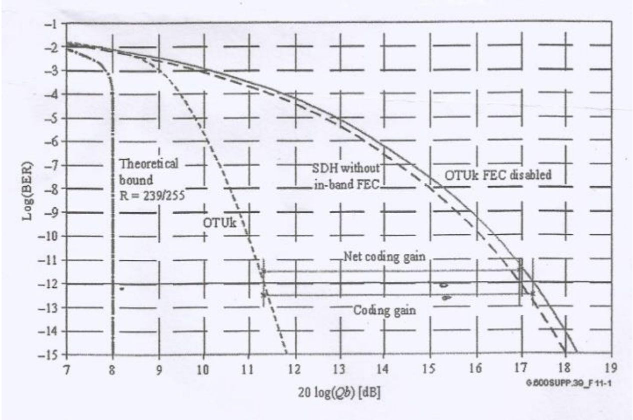

Fig. 2 Performance estimation of G.709/Y.1331 FEC scheme

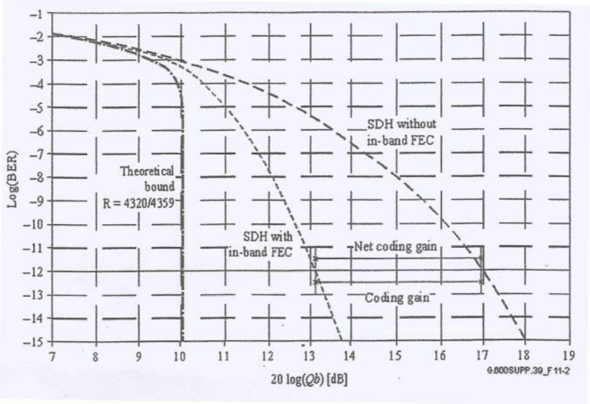

Fig.3 Performance estimation of G.707/Y.1322 FEC scheme

Note that:

$$20\log_{10} Qb = 20\log_{10} Q - 10\log_{10} R \quad (4)$$

In Fig. 2 and Fig. 3, the horizontal axis is $20\log_{10} Qb$ in dB and the vertical axis is log(BER). Net coding gain in terms of $20\log_{10} Qb$ is equivalent to allowable OSNR reduction when the line system uses optical amplifiers and ASE induced noise is the only significant noise at the decision circuit.

Table 2 indicates the results for in-band FEC and out-off-band FEC for different applications. It is observed that for $BER_{out}=BER_{ref}=10^{-12}$, the BER_{in} for SDH is found to be $2.9x10^{-6}$ whereas for OTN the same equals $1.8x10^{-12}$. Also the coding gain is 3.8 and 5.9 for SDH and OTN respectively. It is found that the NCG is 3.8dB for SDH and the 5.6dB for OTN. Above results have been found for the code rate of 1 for SDH and 239/255 for OTN.

Table 2 : Performance of standard FECs

	In- band FEC BCH(4359,4320)	Out-of-band FEC RS(255,239)
Application	SDH	OTN
BER_{in} for $BER_{out} = BER_{ref}=10^{-12}$	$2.9x10^{-6}$	$1.8x10^{-4}$
Coding gain($BER_{ref}=10^{-12}$) in dB	3.8	5.9
Net coding gain ($BER_{ref}=10^{-12}$) in dB	3.8	5.6
Code rate	1	239/255

V. CONCLUSION

The paper gives the detailed discussion of two different FEC schemes. From the discussion we can conclude that, using FEC scheme BER has significantly reduced to a great extent. Also coding gain i.e. CG and the NCG i.e. net coding gain are significantly improved in both SDH and OTN applications and effectively increased the transmission bit rate, span length and capacity of the digital system of single channel/multi channel system.

REFERENCES

[1] Timothy P. Walker, “Optical Transport Network (OTN)”, International Telecommunication Union Manual, USA

[2] “Transmission Systems and Media, Digital Systems and Networks”, International Telecommunication Union Standardization Sector of ITU, G. 707/Y.1322(01/2007)

[3] “Transmission Systems and Media, Digital Systems and Networks”, International Telecommunication Union Standardization Sector of ITU, G. 709/Y.1331/2009)

[4] Kamran Azadet, Member, IEEE, Erich F. Haratsch, Helen Kim, Fadi Saibi, Jeffrey H. Saunders, Michael Shaffer, “Equalization and FEC Techniques for Optical Transceivers”, IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 37, NO. 3, MARCH 2002, pp. 317-327

[5] O. Ait Sab et al., “Concatenated forward error correction schemes for long-haul DWDM optical transmission systems”, in Proc. Eur. Conf. Optical Communication (ECOC), 1999, pp. II–290.

[6] R. M. Pyndiah, “Near optimum decoding of product codes”, IEEE Trans. Commun., vol. 46, pp. 1003–1010, Aug. 1998.

[7] B. Sklar, “A primer on turbo code concepts”, IEEE Commun. Mag., vol. 29, pp. 94–102, Dec. 1997.

[8] Clifford Headley And Govind P. Agrawal, “Raman Amplification In Fiber Optical Communication Systems”, Elsevier Publication, ISBN: 978-0-12-044506-6

[9] Kamran Azadet, Mark Yu, “Forward Error Correction (FEC) techniques for optical communications”, IEEE 802.3 High Speed Study Group Plenary Meeting, Montreal, July 1999

[10] “40 Channels Dense Wavelength Division Multiplexing (DWDM) Bit Rate up to 10 Gbps”, Technical Manual Model No. : UTL-MP-0072, United Telecoms Ltd.

[11] Afxendious Tychopoulos, Odysseas Koufopavlou, “Optical Transmission Networks”, Electrical and computer Enginering Department of the University of Patrasin Greece.Ioannis TomkosfromAthens InformationTechnology in Greece