Study on Forward Error Correction Codes for Optical Networks

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***Abstract* –** Due to ever growing internet traffic, many telecom operators had started to increase the data rates of their optical networks to 100 GB/s and beyond. However, the system performance of optical transport network is often limited by transmission impairments. Forward error correction (FEC) codes have been considered as a strong and cost effective way to improve quality of transmission. This paper presents a study of evolution of FEC codes and a comparative study of HD-FEC and SD-FEC codes based on their applications. Also, state-of-the art advanced FEC schemes with their challenges and possible directions of implementations are pointed with the existing bibliography.

Keywords – Forward Error Correction (FEC), Hard Decision FEC (HD-FEC), Soft Decision FEC (SD-FEC), 100G.

I. INTRODUCTION

Global Internet Protocol (IP) traffic has increased fourfold over the past 5 years, and will increase three fold over the next 5 years. Over all, IP traffic grows at a compound and growth rate (CAGR) of 23 percent from 2012-2017 [1]. High bandwidth services like cloud computing, 3G/4G smart phone services, internet video services and social networks are demanding the needs for improvements in optical transport networks (OTN). The role of forward error correction was started at 1950. R.W Hamming invented Hamming codes at Bell Laboratories [2] to avoid read errors in electro mechanical relay based systems. In 1948, C. Elwood Shannon introduced channel coding theorem [3] which states that channel noise limits the transmission rate not the error probability. In between 1950s and 1960s, the basic concepts of several codes like Reed–Muller codes [4], Convolutional codes [5], cyclic codes [6], Bose - Chaudhri Hocquenghem codes [7, 8], Reed- Solomon codes [9] have been developed. As a continuation of this, in 1960s and 1970s, several effective decoding algorithms such as Viterbi algorithm [10] for Convolutional codes, Berlekamp – Massey algorithm [11, 12] for BCH codes, and Euclid Algorithm [13] for Reed-Solomon codes were developed.

In 1988, Grover [14] recorded about the first practical FEC experiments in optical communications having encoding (244, 216) Hamming code with a redundancy rate of 3.7% giving a 0.96 code rate and FEC coding gain of about 2.5db at an output BER of 10^{-13}Then in early 1990s the system designers gradually have started to use FEC codes in many applications like submarine cable systems, broad range of long-haul systems and terrestrial systems. This paper aims to provide a brief review on the evolution of FEC codes and a state of the art method of third generation FEC codes for optical communication systems based on their applications. The paper is organized as follows: Section II provides the information of Error control coding and basics of Forward error correction. Section III presents a discussion of Performance metrics. Section IV gives an Evolution of FEC codes and comparative study of HD-FEC and SD-FEC codes based on the different parameters and for different applications. Section V briefly gives state-of-the art FEC Schemes as conclusion.

II. ERROR CONTROL CODING

A typical transmission system may be represented by a block diagram as shown in *Fig.1*. The concept behind the forward error correction is they employ error correcting codes that automatically correct errors by adding some redundancy to the message.

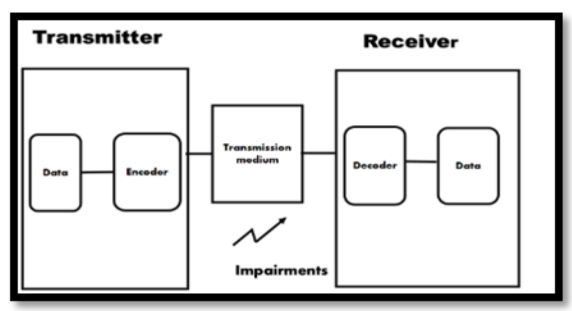

Fig.1. Typical Transmission system

Hence FEC is suitable for one way communication like broad casting. If it is two way communication systems, where transmitter can also act as a receiver (transceiver), then the error control strategy will be Automatic repeat request (ARQ). In an ARQ system, when errors are detected at the receiver, a request is sent by it to repeat the message and this repeat request will be continued till the message is correctly received. Since optical communication system is a long-haul system, an effective FEC codes are preferred.

A. Basics of Forward Error Correcting Codes

An information sequence of k bits or symbols is encoded to a longer sequence of n bits as shown in *Fig.2* [15] where n-k redundant bits are added to the information. This redundancy causes a limited transmission bit rate. Hence Code Rate(R) is a key metric which can be expressed as the ratio of bit rate without FEC (k) to the bit rate with FEC (n). i.e R=k/n. The overhead is the ratio of the redundancy bits (n-k) and the information bits (k).

Then, $OH = (n-k)/k = (1/R) - 1$ (1)

Here OH and redundancy are of complementary each other while assuming line rate is fixed.

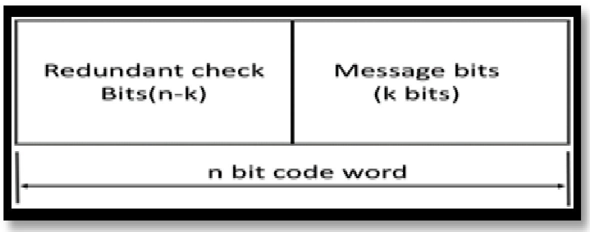

Fig.2. Systematic format of a codeword

However rate and redundancy should not be considered as measures of efficiency because high rate codes are not more efficient than low rate codes. A well designed low rate code can withstand a greater level of noise than that of high rate code [16]. Here rate gives a sense of noise immunity. Hence rate of a code must be chosen based on the noise level on the channel.

In general, FEC can be applied in three ways viz., block, convolutional and combination of block and convolutional (hybrid). block codes are having finite and constant length code words as given in the fig.2. whereas convolutional codes have memory so that large minimum distances and low error probabilities can be achieved by increasing memory order. Yet another classification on forward error correcting code is between Hard-Decision (HD) and Soft-Decision (SD). HD – FEC uses a single quantization level for bit sampling but SD-FEC uses 2^{N-1} quantization levels between 0 and 1 to indicate the reliability of a decision.

III. PERFORMANCE METRICS

The bit error rate (BER) is a common performance metric of a digital light wave system. The BER can be defined as the number of errors made per second which depends on the bit rate. It can also be viewed as the average probability of incorrect bit identification [17]. Also, the performance of a data- transmission code used on an AWGN channel is expressed as a function of E_b/N_o of the channel waveform. Where E_b is the average energy per data bit and N_o is the noise power spectral density. Hence error correcting ability of the code is determined by the reduction in the E_b/N_o is needed to ensure the specified bit error rate not by the reduction in the bit error rate. To be more specific, coding gain can be considered- as the reduction in the required E_b/N_o at the same bit error rate. For example, a simple binary communication system on an AWGN channel operates at a BER of 10^{-5} at an E_b/N_o of 9.6 dB using bipolar signal constellation, and if adding of a sufficient strong code to the communication system results the reduction of E_b/N_o ratio to 6.6 dB for the same BER, then we say that the code has a coding gain of 3dB at a BER of 10^{-5}[18].

The definitions of coding gain and net coding gain can be obtained from ITU-TG.975.1 [19]. coding gain is the improvement of received optical sensitivity by using FEC, without considering penalty by bit rate increasing. Net coding gain has bit rate increasing penalty in addition to the coding gain. It is a common practice to define the coding gain as the reduction of signal to noise ratio at a reference BER.

$$CG = 20\log_{10}[(\mathrm{erfc}^{-1}(2B_{ref}))/(\mathrm{erfc}^{-1}(2B_{in}))] \text{ dB} \quad (2)$$

where

B_{in} – BER of input signal to the FEC decoder

B_{ref} - BER of corrected output signal

$$NCG = CG + 10\log_{10}(R) \text{ dB} \quad (3)$$

As the code rate R<1, a net coding gain (NCG) is always smaller than the corresponding coding gain. where $\mathrm{erfc}(x) = 1-\mathrm{erf}(x)$

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

IV. EVOLUTION OF FEC CODES

FEC codes are classified under three generations with coding gains of approximately 6 dB, 8 dB and greater than 10 dB respectively [20].

A. First Generation FEC Codes

The first generation FEC codes had been implemented for long- haul optical transmission as defined by ITU-T G.709 [21] and G.975 recommendations [22] on their use for optical submarine communications. These conventional codes use hard decision block codes like Hamming, BCH and RS codes. The data rates supported for these codes are up to 5 Gbps [20]. Since it is conventional method, due to its limiting data rate and correcting performance, it became obsolete for longer reach applications.

B. Second Generation FEC Codes

As transmission rates gradually increased towards 10 Gbps, system designers started to find stronger FEC codes than the first generation FEC [23]. As seen, the second generation FEC codes emerged and characterized by the coding gain of 8 dB. There are two directions of research interest in this second generation FEC: codes to improve error correcting performance and codes against transmission impairments.

During this era, several types of FECs have been developed based on the concatenated codes [24]. Various kinds of concatenated codes are listed in ITU-T G.975.1.comparison between first generation and second generation FEC codes based on period, type of codes used, NCG achieved, code rate and redundancy are listed as shown in table 1. Besides an error correcting capability, codes were generated to mitigate optical transmission impairments like chromatic dispersion (CD), polarization mode dispersion (PMD). This is also a hard-decision based algorithm which achieves better coding gain with the use of concatenated codes, interleaving, iterative and convolutional decoding techniques [24]. Both serial and parallel concatenation techniques were developed. The idea behind this is of increasing hamming distance by forming inner and outer loops in the coding schemes. The selection process for second generation FEC frame structures described in G.975.1

TABLE 1. COMPARISON OF FIRST AND SECOND GENERATION FEC CODES

Generation	Period	Code Used	NCG	Code Rate R	Redundancy
First	1987-1993	RS code	5.8dB	0.93	7%
Second	2000-2004	Concatenated Code	9.4dB	0.8	25%

C. *Third Generation FEC codes*

During the past decade, Soft decision FECs called third generation have been developed using coherent detection and an integrated circuitry in optical communication. Though the algorithms have been already used in wireless technology, due to unavailability and high cost of required Analog- to-Digital (A/D) converters which would be used after coherent detection in optical communication, development of soft decision FECs are still in infancy state. In recent years, researchers are interested towards iterative SD decoding of various codes giving the highest possible coding gain. In practice, the 1-2 dB of coding gain can be raised to 20-40% in total achievable distances for 100 Gps optical communication systems at the expense of high implementation complexity than HD - FECs. [25],[26]. In the case of SD-FECs, apart from coding gain, critical performance limiting factors like latency and complexity of the proposed system which affect the delay and power consumption of the system should be considered seriously. Also Low Density Parity Check (LDPC) [27],[28] and Quasi cycle LDPC (QC-LDPC) codes [29] have been developed with an efficient architecture and low computational complexity. For this reason, instead of concatenated codes, use of single LDPC codes with low error floor have been evolved [30]–[32]. However, Length of these LDPC codes have to be designed by considering the elimination of an unwanted error floor and the routing and latency. Having considering this trade-off, advanced modulation formats (coded modulation) with an efficient hardware implemented using non-binary approaches have been proposed recently [33], [34]. Yet another factor to be considered for SD-FEC is the number of quantization bits. When the number of quantization bits increased, the system leads to more expensive solutions, and their reduction gives low correcting performance. Having this trade-off in mind a demonstration of SD-FEC with only two quantization bits has been presented in [35]. Also, under this concept, implementation of optical front end for SD-FEC codes giving low power solutions even without A/D converters is presented in [36], [37].

V. CONCLUSION

In this paper, a historical overview of the generation of error correction codes and their progress has been addressed. The fundamentals and the basic principles of error correction codes have been outlined. There are many FEC systems with various transmission overhead, implementation complexity, coding gain, BER performance, burst error correction ability and error floor based on their applications. As far as high data rate optical networks are concerned, the joint design of coding and advanced modulation format will be a promising solution. However as the size of signal constellation is increased, the signal to noise ratio will also be increased to achieve a certain bit error rate. Hence the development of integrated solutions like irregular structured LDPC codes which will improve the spectral efficiency of these channels for the same system configuration with low power requirements are needed in the near future. Also, instead of having different FEC codes for different applications, the dynamic structure of next generation flexible networks is also possible by considering hardware realization of these schemes due to their high implementation complexity and the need to perform effectively in different signal qualities, transmission rates and power requirements.

VI. REFERENCES

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