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FORWARD ERROR CORRECTION TECHNIQUES IN LONG-HAUL OPTICAL TRANSMISSION SYSTEMS

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Motivation for Forward Error Correction

Forward error correction (FEC) is one of the more recent of critical technologies, together with optical amplification and dispersion management, brought to bear in the drive for increased transmission capacity in WDM long-haul fiber-optic links. Optical transmission systems typically require performance margin against line impairments such as ASE, channel cross talk, nonlinear pulse distortion, and repair- and fiber aging-induced losses. The goal of forward error correction coding is, by adding intelligent redundancy, to increase overall system capacity while securing margin against impairments and sacrificing the least amount of bandwidth overhead. The added margin can be expended on added transmission distances, increase amplifier spacing, and / or reduced optical power. FEC codes are now standard practice in undersea systems (e.g., the ITU G.975 Reed-Solomon code with 7% overhead, as well as other more advanced proprietary systems), and are starting to be deployed in terrestrial systems.

Principles of FEC

Forward error correction is the incorporation of a suitable code into a data stream for the detection and correction of data errors about which there is no *a priori* information. A consequence of encoding the data is that the rate of signal transmission (i.e. line rate) includes the *code overhead* and therefore exceeds the rate at which the original information is actually transmitted.

Shannon proved in his landmark paper [1] that a noisy channel with a given bandwidth can transmit information with arbitrarily low bit error probabilities, provided the rate of transmission of information does not exceed a maximum rate or *capacity* of the channel. Stated differently, for a given rate of data transmission and overhead, there is a lower bound for the SNR on a channel that can be decoded error-free. Transmission at a higher rate due to the code overhead requires at the least a wider electrical filter bandwidth, which results in additional noise. In fiber optic transmission the higher rate also results in stronger nonlinear penalties [11]. This yields a slightly reduced *net coding gain*, where the coding gain is defined as the difference in the lowest possible SNR for error-free detection between uncoded and coded transmission. The 'ultimate' coding gain, given the *ideal code*, is defined by Shannon's theorem for channel capacity.

Classes of FEC Codes

The challenge in implementation of FEC in a system is to devise suitable codes that can be efficient in terms of both terminal equipment complexity and cost. Algebraic block codes, such as Reed Solomon (RS) and Bose-Chaudhuri-Hocquenghem (BCH), are codes whose words may be bits (BCH) or bytes (RS). These codes are capable of correcting multiple bit errors in each *block* (or word) of data, where the block consists of information plus overhead (or redundant check) bits. For example, the ITU G.975 RS code has 239 data bytes plus 16 check bytes in a 255 byte block. The encoding process, a deterministic algebraic transformation, maps a data word uniquely to a code word [2]. During transmission, errors can transform the code word. The number of positions is which two code words differ from each other is referred to as their *Hamming distance*. The degree to which the errored word can be associated back to the original code word unambiguously is the code's 'distance property'; *the distance spectrum* of a code is related to its maximum error correction capability.

RS codes are inherently *maximum distance* codes, i.e. a large number of bit errors can occur before decoding becomes erroneous. In particular, they are also capable of correcting *bursty* errors because of their *non-binary alphabet*. Several bits are grouped together as *words*, and the error correcting capability is defined as the number of words per block that can be detected and corrected, regardless of whether only one or all of the bits in a word are likely to be in error. One of the most important attributes of RS codes is that they offer error correction at high *code rate*, or equivalently low overhead, where the code rate is the ratio of information bits to code bits (e.g. a (255,239) RS code has rate R = 239/255, and overhead OH = 1/R - 1 = 6.7%). It is these properties of RS codes that make them attractive for use in optical transmission systems.

Concatenated codes, first expounded by Fourney [3], achieve an impressive improvement in performance by balancing an increase in block length with only a moderate increase in hardware complexity. In the most common application, the input binary stream is processed by an outer decoder, interleaved, then processed by an inner decoder of different properties. Concatenated codes implement sequential decoding of a block (or set of words),

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with performance improvement from the fact that any residual errors from the first (inner) stage of decoding will be corrected further at the second (outer) stage. Key to this strategy is the use of an appropriate algebraic *interleaver*, which spreads the errors over the two stages of decoding.

Concatenated codes can be decoded iteratively [4], i.e. the two stages of inner and outer decoding can be repeated, with subsequent iterations increasing the coding gain. Such iterative decoding schemes do not increase the code overhead, and do not change the encoder, but achieve performance gain at the expense of small latency. Other even more powerful iterative codes such as Turbo Product Codes [5], Product Accumulate Codes [6], and Low Density Parity Check Codes [7] relay valuable information back to the decoder after each iteration, thereby providing significant improvement. These latter families of codes also are able to effectively exploit the advantage of *soft decision* decoding. In addition to the "1" or "0" choice delivered in hard decoding, soft decision also provides information on the *confidence* of that choice by delivering a real number rather than integer result.

The performance of RS and other codes can be largely approximated from analytical upper bounds on the BER after correction [8]. Such analytical models for code performance are further validated by Monte-Carlo simulations, in which various noise models, such as additive white Gaussian noise (AWGN), can be evaluated to test the properties of a code. However, since pulse distortion on a real optical channel is not modeled accurately by AWGN, by far the most reliable method of validation of code performance is by testing in system experiments.

FEC in Systems Experiments

Various optical transmission experiments have been performed to determine the performance and robustness of the FEC codes. In a 6200 km looped test bed experiment, transmission of 1.12 Tb/s (56 channels in the C band at 21.4 Gb/s line rate) has been demonstrated with the assistance of a RS FEC code with 7% overhead [9]. Using a more sophisticated concatenated RS (CRS) code with 10% overhead, 2.4 Tb/s transmission (120 channels at 21.4 Gb/s) was subsequently reported [10]. Using a stronger CRS code (23% overhead) with iterative decoding, 1.8 Tb/s (180 channels at 10 Gb/s in the C band) was successfully transmitted over a 7000 km test bed loop [11]. In a recent evaluation of high-gain code with lower overhead, a 14% CRS, (239,223) (255,239), was tested both analytically and experimentally [12]. The authors claim a 2 dB gain in performance at 11500 km relative to ITU G.975 FEC. In a 40 Gb/s experiment, 77 channels were propagated over a 1200 km loop test bed to deliver 3.08 Tb/s aided by 7% RS code [13].

RS codes have been evaluated for correction of errors from various line impairments, such as ASE, channel cross talk, and nonlinearity-induced self- and cross-phase modulation. A 14%-overhead RS code was used to obtain error-free transmission of 10 Gb/s data over 10,000 km (line rate ~ 11.4 Gb/s) [14]. A $2^{23}-1$ PRBS pattern was used, and errors were induced by (1) noise-loading for ASE (2) reduction of channel spacing from 0.6 to 0.24 nm for cross talk, and (3) increase of channel power for nonlinear impairments. Very good agreement in the decoded BER was obtained between experiment and Monte-Carlo simulations, indicating that the RS code performed well with errors typical of AWGN, as well as with pulse distortions from nonlinearity and interchannel cross talk.

Conclusions

The use of FEC provides significant coding gain, which has been used to demonstrate error-free transmission under severely-errored operating conditions, with high spectral efficiency, over distances exceeding 10,000 km, and at high bit rates. Recent experiments using FEC have demonstrated aggregate transmission capacity exceeding 2 Tb/s. FEC-coded transmission can tolerate a lower optical SNR on the line, which in turn reduces impairments induced by nonlinearities, with the net effect being an *increase* in the Q^2-factor when signal power is reduced. Due to the nonlinear relation between raw and corrected bit error rates, it is critical to adhere to the necessity of decoding each frame in an FEC experiment and not merely evaluating average Q-factor, as observed in Ref. [10]. There is presently significant activity directed towards developing more powerful codes as well as more efficient decoding algorithms.

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