Chapter 5

Turbo Codes for Single-Mode and Multimode Fiber Optic Communications

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In this chapter, the application of turbo product codes in both single-mode and multimode fiber optic links is reviewed. In the case of single-mode fiber links, it is shown that turbo product codes outperform the current standard forward error correction approach which is using a hard-decision Reed-Solomon code. Furthermore, for multimode fiber links, it is demonstrated that turbo product codes can be combined with spatial equalization techniques to enable significant enhancement of fiber reach.

5.1 Forward Error Correction in Fiber Optic Links

Fiber optic links are now widely deployed for high-speed communications. When compared to their electrical counterparts, i.e., copper cables (twisted pair or coax), optical fiber has the following advantages [1]: (i) Higher bandwidth, (ii) smaller diameter and light weight, (iii) no crosstalk between parallel fiber cables, (iv) immunity to inductive interference, (v) security, (vi) safety, (vii) long life span, etc. Today’s optical fiber systems are mainly of intensity modulation / direct detection (IM/DD) type [2]. In these systems, either lasers or light emitting diodes (LED’s) are employed as optical transmitters [3]. LED’s are usually used for short-distance applications, whereas long-haul (or long-distance) systems use lasers. Typical transmission wavelengths are about 850, 1300, and 1550 nm, where optical fiber has low attenuation. Furthermore, the major portion of optical receivers are of direct detection type, where incident optical power is converted to a proportional electrical current. A direct detection receiver consists usually of a photodetector [PIN (positive-intrinsic-negative) or Avalanche photodiode] followed by a transimpedance amplifier (TIA), which can be viewed as a current-to-voltage converter [3].

Receiver noise is one of the important design parameters of optical fiber links. Major noise sources at the receiver side are [4] : (i) Quantum or shot noise, (ii) dark-current noise, (iii) thermal noise, and (iv) amplifier noise. Besides these receiver noise factors, the main impairment in optical fiber links is...
dispersion. Dispersion is basically the broadening of a light pulse as it travels along the fiber. At high data rates, this introduces intersymbol interference (ISI) [5] that must be compensated for. Dispersion is also the dominant limiting factor in multimode fiber (MMF) links, since each mode inside the fiber travels at different speeds (this is also termed as intermodal distortion [4]).

The application of turbo codes [6] can reduce the negative effects of noise and dispersion in fiber optic communications by many orders of magnitude. Nevertheless, the turbo implementation is challenging, since especially the extraction of soft-information from the optical channel can be costly. Furthermore, although forward error control (FEC) codes in general have been applied to many types of communications systems, their application to optical communications can be considered as recent. The main reason for the late consideration of FEC codes for optical systems is due to the outstanding properties and low bit error probabilities of optical devices and subsystems.

On the other hand, with the increasing demand for higher capacity for dense wavelength division multiplexing (DWDM) systems, and with the demand for fiber links with longer repeater or amplifier spacing, FEC codes attract much attention. In general, FEC codes can provide increased system margins and relaxed component tolerances. FEC codes for optical networks are classified as in-band and out-of-band [9]. Out-of-band FEC codes can provide unrestricted error correcting capability and are protocol independent. However, out-of-band FEC codes also increase the data rate due to code redundancy. On the other hand, in-band FEC codes use idle periods of the transmission protocol; therefore, in-band FEC codes preserve the transmission data rate. For example, for the SONET (synchronous optical network) protocol, a shortened version of a triple error correcting (8191,8152) Bose, Chaudhuri, and Hocquenghem (BCH) code is applied for in-band FEC. This code is shortened so that the number of information bits is equal to 4320, and the code length is 4359. The 39 redundant bits of a codeword are sent in unused slots of the SONET protocol. Hence, the line rate is preserved. When compared to out-of-band codes, the main disadvantage of in-band codes is that they have limited strength because of the limited amount of idle periods depending on the applied protocol. As an example for out-of-band codes, a (255,239) Reed-Solomon (RS) code with hard-decision decoding is now widely applied in most modern trans-oceanic optical transmission systems [7][8]. In addition, critical aspects for the application of FEC codes (and especially turbo codes) in high-speed optical communications systems are reframe time and decoding latency. Reframe time is the time it takes for the FEC decoder to obtain all information before it can start decoding of the received codewords. Decoding latency is the delay until the decoder outputs the corrected codeword.

As the requirements for fiber link lengths and noise margins increase, soft-decision decoding will likely replace the current hard-decision decoding approach, and the application of turbo codes, and in particular turbo product codes (TPC) [10], also called block turbo codes (BTC), will be possible. In