Coherent optical communications via digital signal processing

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Using digital signal processing techniques to detect advanced optical modulation formats increases the information-carrying capacity of optical fiber.

Most currently deployed optical fiber communication systems exploit intensity modulation and direct detection (IMDD) to transmit information. In this scheme the binary information is translated to optical intensity, that is, 1s are determined by high optical intensity and 0’s by low intensity. At the receiver a simple detector’s electrical output is high for the 1s and low for the 0s. This technique is simple to implement, but it places several limits on information capacity. First, light can be characterized not only by its intensity but also by its frequency, phase, and polarization. Encoding information on the phase, for example, enables constant intensity, which is preferable in optical fiber transmission. Moreover, combination of any of the four properties also increases the amount of information that can be carried by a fiber. Accordingly, these advanced modulation formats require more complex coherent receivers—which extract the information by mixing the incoming signal with a known reference, a local oscillator (LO)—to obtain the signal phase and polarization information.

Traditionally, coherent receivers equipped with complicated phase-locked LOs fulfilled this purpose. But recent advances in analog-to-digital (A/D) conversion technology make it possible to use digital signal processing (DSP) techniques to demodulate high-speed optically modulated signals. Pairing DSP with coherent optical receivers have attracted attention recently due to the potential of demodulating advanced formats. This ultimately translates to being able to send more information through optical fibers.

Coherent detection techniques for advanced formats are well established; however, their complexity and cost of deployment have made IMDD systems a more attractive and cost-effective alternative. High-speed A/D conversion makes it possible to digitally compensate for various defects of the optical equipment (e.g., faulty transmitter and receiver lasers, or damaged fiber). Two major functionalities for which DSP could be used in this context are carrier-phase estimation and fiber chromatic dispersion compensation (DC). The phase estimation is needed in coherent detection to synchronize between the received signal and

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reference, and the dispersion compensation reverses the degrading effect of the fiber on the transmitted signal.

A key challenge in coherent detection of phase-modulated formats is locking the phase of the LO to the transmitter laser phase. This phase synchronization is required for proper demodulation of the incoming signal and is usually obtained using a phase-locked loop (PLL). But the high-speed nature of optically modulated signals restricts the PLL, since its inherent feedback must respond very fast to any variation in the signal. DSP requires only phase tracking (and not phase locking), which can be achieved using a feedforward technique and in real time. Figure 1 shows a plan for accomplishing phase tracking. Coherent detection (where both signal quadratures are recognized) with subsequent DSP is suited to advanced modulation formats (in this case quaternary phase-shift-keying, QPSK), without a PLL. The digital feedforward carrier recovery technique is compatible with specifications of commercially available lasers used today for IMDD schemes. We have published elsewhere the results of an analysis we performed of the bit-error rate using this method.

Another critical issue in optical transmission systems is how to compensate for optical fiber chromatic dispersion (generally termed channel equalization, in our case the channel being optical fiber). Chromatic dispersion is modeled as an all-pass (unity gain across all frequencies) filter with a quadratic phase as a function of frequency. The slope of this function depends on the fiber characteristics (namely, the dispersion coefficient) and length. Figure 2 shows the phase response of standard single-mode fiber for several fiber lengths. DC is achieved by filtering the incoming signal using a phase response opposite to that of the fiber. Note that DC requires the sampling rate to be twice the symbol rate (e.g., for a 10Gbaud system, 20G samples/s are needed). Phase estimation, in contrast, calls for only one sample per symbol.

DC filtering can be done two ways: finite impulse response (FIR) or infinite impulse response (IIR). Design and implementation of the FIR filter is straightforward: the filter coefficients are obtained by an inverse Fourier transform of the desired transfer function. FIR filtering involves only feedforward paths and hence is highly compatible with real-time implementation. As the transmission distance increases, however, more taps are required to obtain equalization. This presents a heavy computational load and increased latency. For these reasons, we suggest a scheme using IIR filtering, shown in Figure 3. The received signal can be decomposed into real and imaginary parts ($y_r$ and $y_i$), which are processed to obtain the real part of the dispersion-compensated signal, $x_r$. Although this approach is substantially more complicated than FIR filtering, the feedback path (intrinsic to IIR) allows DC to be achieved with significantly less computational load (and negligible penalty), as illustrated in Figure 3 (right).

Optical coherent receivers with subsequent DSP show great promise as enabling technologies for ultra-high-information-rate optical transmission systems. DSP alleviates the need to lock the phases of the LO and transmitter signal, which is one of the barriers to using coherent receivers in the optical domain. Various optical impairment issues can be addressed in the digital domain, allowing great flexibility in the design, deployment, and operation of optical systems.

One of the major issues still to be addressed to make this technology practical is how to optimize the algorithms and implementation methods used for DSP demodulation. Current DSP speeds cannot keep up with high-speed optical signals (e.g., 10Gbaud). Hence, parallelization and pipelining techniques (which make it possible to divide large calculation tasks into several smaller operations performed in parallel) bear considering. Moreover, rigorous theoretical analysis of the performance of

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such receivers is under way to improve the various parameters critical to the algorithms.

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**References**


