100G – Key Technology Enablers of 100Gbit/s in Carrier Networks

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Abstract: The demand for increased bandwidth is ever present. This paper reviews the attributes of coherent systems in light of the challenges faced by system designers to realize 100 Gb/s optical transmission systems.

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1. Introduction

Today, transmission systems employing advanced modulation formats and coherent receivers with channel capacities of 40 Gb/s are widely deployed. The first coherent commercial 100 Gb/s was put into service in late 2009 [1]. The bit-rate of a channel is the simple product of the symbol-rate, bits per symbol and the number of carriers used. Recent commercial coherent systems at 40 Gb/s and 100 Gb/s have exploited all of these dimensions.

2. Why Coherent?

Coherent detection, with a local oscillator approximately centered on the signal's frequency band, provides a 4.3 dB improvement in noise tolerance compared to the traditional direct detection. The electrical low-pass filter of the coherent receiver front-end provides selection of the signal around the frequency of this local oscillator and significant rejection of other signals. The quest for improvement in noise tolerance, i.e., providing improved receiver sensitivity, combined with the difficulty of the coherent methods, is why coherent systems enjoyed a great deal of research attention in the 1970s and 1980s. However, the invention of the optical amplifier provided a much cheaper and easier method to obtain this improved noise tolerance, and most of the coherent work was abandoned.

Today, in addition to improved noise-tolerance, coherent technology preoccupies both research and commercial development in optical communications because of its ability to address the requirements of distortion compensation, polarization de-multiplexing, and carrier extraction. All of these capabilities are afforded by the most important characteristic of coherent transmission, namely, access to the optical electrical field (E-field), and are enabled by the technology of digital signal processing (DSP). Working hand-in-hand with coherent detection, DSP is the mathematical vehicle through which the appropriate numerical transforms are applied to recover signals from impairments that are physically well-understood, but, until recently, electronically inaccessible.

The major sources of degradation of the optical channel at regular power levels are linear and invertible with respect to the optical E-field. Coherent detection provides electrical signals that are predominantly proportional to the optical E-field, and so linear digital filtering can fully compensate these degradations. Furthermore, the complexity of digital linear filters grows only linearly with the amount of impairment tolerance required.

Chromatic dispersion, the primary signal impairment, is a linear degradation that can be inverted without penalty. The coherent 100 Gb/s product, shown in Fig. 1, uses digital signal processing to perform chromatic dispersion compensation, without recourse to any optical means of dispersion compensation.

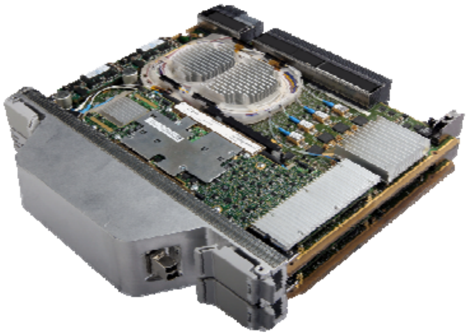

Figure 1 – Commercial coherent 100 Gb/s transceiver platform.

Another source of degradation is the polarization dependence of loss and delay in both the transmission fiber and the optical components in the system. Telecommunications operators have been discovering significant amounts of polarization-dependent delay (also called polarization-mode dispersion or PMD) in many of their installed fibers. The tolerance of direct detection systems to PMD is about 15 ps of delay at 10 Gb/s but only 1.5 ps at 100 Gb/s. This means that many of the fiber routes which support 10 Gb/s transmission today, without any PMD issues, can only be upgraded to 40 Gb/s, 100 G/s , or greater capacities, with the use of coherent receivers that invert the effects of PMD.

3. Multiple Bits Per Symbol

The channel bit-rate can be doubled without affecting bandwidth by combining orthogonal polarizations. This technique can be used with or without coherent detection, but polarization-multiplexed signals are most easily extracted with coherent detection. To double the bit rate again, a symbol can be made up of four optical phases, each phase representing two bits (QPSK).

4. Dual Carriers: Frequency-Division Multiplexing

A dual carrier, parallel processing, architecture was chosen for the commercially available 100 Gb/s product described in [1]. The optical spectrum of this 100 Gb/s solution is shown as the center channel (b) in Fig. 2 accompanied by the spectra of single-carrier 10 Gb/s (a) and dual-polarization 40 Gb/s (c) channels. Each spectrum is centered on a 50-GHz ITU channel.

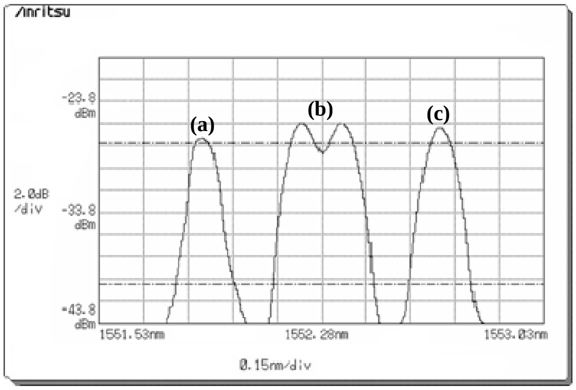

Figure 2 – Optical frequency division multiplexing comparison: (a) 10 Gb/s single-polarization, single-carrier; (b) 100 Gb/s coherent dual-polarization, dual-carrier; (c) 40 Gb/s coherent dual-polarization, single-carrier. Channels are centered on the 50-GHz ITU grid.

In the first commercial deployment of an optical transmission system running at a spectral efficiency greater than 1 bit/s/Hz, increases in all three of these dimensions have enabled 105 Gb/s of net data transmission within a 50-GHz spectral allocation (the standard optical channel plan defined by the ITU). Two carriers are separated by 20 GHz and operate at 14.55 Gbaud with four bits per dual-polarization symbol to transmit at 116 Gb/s. The payload rate is 105 Gb/s after removing the overhead for forward-error correction.

5. Digital Signal Processing

With digital signal processing there is no longer a requirement to phase or frequency lock the local oscillator laser to the transmit laser, as this can be done with digital carrier recovery [2,3]. Linear digital filters can be used to compensate the chromatic dispersion and polarization effects of the optical line. For high capacity signals, this is beyond the capabilities of a processor or field-programmable gate array (FPGA) circuit, and so requires a specific CMOS integrated circuit. An example circuit is shown in Fig. 3, where four 23 GSample/s analog-to-digital converters (ADCs) and high speed signal processing functions are implemented in a custom 90-nm CMOS ASIC.

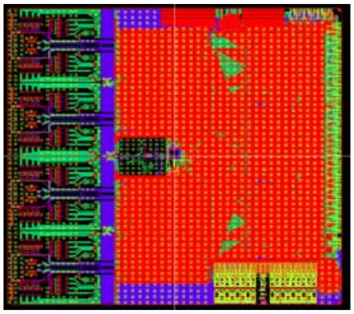

Figure 3 – CMOS receiver ASIC with four 23 GSample/s ADCs and 12 trillion (12 x 10^{12}) operations per second.

6. Forward Error Correction

Current commercial 100 Gb/s transmission products use hard decision forward error correction (FEC), with iterative decoding. Soft-decision decoding such as with Low Density Parity Check (LDPC) codes or Turbo Codes [4], that use multi-bit metrics for each information bit, offer in theory 3 dB better noise mitigation. Given the analog-to-digital conversion and signal processing that is already present in the receiver, the soft metrics are readily available on the CMOS chip. However, there are two major challenges in getting the benefits of soft-decision FEC. Optical transmission systems must provide the network operators with bit error rates that are better than 10^{-15}, and simple soft-decision FEC algorithms that provide good noise tolerance suffer from bit error rate floors in the range of 10^{-3} to 10^{-10}. More complicated algorithms are required to avoid these floors. Multi-bit metrics for each of the greater than 100 billion information bits per second creates huge data flows, and a large processing task. For heat efficiency, this operation must be implemented within the same CMOS chip as the signal processing.

7. CMOS

In the 1990s, channel line rates were increased from less than 1 Gb/s to 10 Gb/s based on increases in symbol rate. Symbols were simple binary intensity modulation (i.e., 1 bit per symbol – a "zero" or a "one"). The required frequency bandwidth of the optical and electrical components is largely determined by symbol rate. It follows that availability and cost of such components at the required bandwidth strongly influence the economics of symbol rate. The commercial success of 10 Gb/s systems from 1995 to 2000 drove a cost reduction of volume manufactured components at 10 Gbaud (10.7 to 12.5 Gbaud when forward error correction is used). Silicon CMOS has displaced electronics composed of III-V elements in these applications, due to lower costs, integration scale, and lower heat. Some recent higher bit-rate systems have exploited the economics of CMOS technology near these same symbol-rates and, instead, expanded the other dimensions.

Commercially installed coherent optical fiber transmission products use the existing 90-nm or 65-nm CMOS processes for the signal processing ASIC. High-quality algorithms that deliver the required performance at 100 Gb/s cannot fit onto one chip at these feature sizes. Two parallel chips have been used, with dual subcarriers, to achieve maximum system reach. When 32-nm CMOS ASICs are available, high-quality signal processing for 100 Gb/s can fit in a single chip without compromising performance.

8. Summary

The dramatic improvements provided by coherent detection have been powered by the engine of electronic digital signal processing. CMOS has driven advances in signal recovery, forward error correction, sequence estimation, and enables the exploitation of the dimensions of symbol-rate, bits-per-symbol, and number of carriers per channel. This is used to cost effectively transmit large amounts of data through existing optical lines.

9. References

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