Power Efficient Coherent Detection for Short-Reach System

Hongbin Zhang
Cisco Systems, Inc., 101 Crawfords Corner Rd, Holmdel, NJ 07733
hongbinz@cisco.com

Abstract: Faster-than-Nyquist QPSK based on symbol-rate DSP can maximize the link loss budget and enable a single laser solution and low-power driver design in 1.6 Tb/s DR4 short-reach systems.

1. Introduction

Short-reach systems have become the key infrastructures in modern society. Traditionally, intensity-modulation direct-detection (IM-DD) has been used in intra-data centers (500m-2km) as well as campus interconnections (2-10km). As switch interface speeds approach 1.6 Tb/s and higher, IM-DD cannot continuously scale optical lanes and baud rate because of its small tolerance to several optical impairments, including chromatic dispersion, polarization mode dispersion, and four-wave mixing.

To support higher per-wavelength bit rates, and meet strict requirements of power consumption and module cost in future short-reach systems, various coherent-lite schemes have been proposed to replace IM-DD. Among them, Kramers-Kronig (KK) receivers and self-homodyne detection (SHD) have gained popularity. Both schemes receive an unmodulated carrier from the transmitter (TX) as a local oscillator (LO), such that KK reconstructs the carrier phase using direct detection and SHD avoids the frequency and phase recovery in a digital signal processor (DSP). However, without a strong LO for the amplification during optical-to-electrical down conversion, the receiver (RX) sensitivity is limited. Many demonstration works have relied on optical amplifiers to improve the loss budget, even in short-reach systems [1].

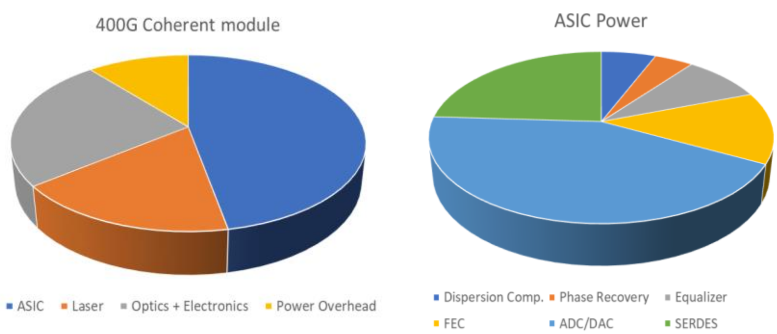

Fig. 1. Power breakdown of 400G ZR coherent transceiver

To achieve a better strategy for coherent-lite, we study the power breakdown of a 400G ZR coherent transceiver using 7nm CMOS technology [2-3]. Inside the ASIC chip in Fig. 1 (right), coherent and IM-DD share many functional blocks. Carrier phase/frequency recovery and polarization demultiplexing equalizer are the only extra DSP blocks to restore the four-dimensional (4D) information in a coherent DSP. Their power consumption is approximately 10% of the total ASIC power. This indicates that a coherent DSP could potentially consume at most 10% more power than IM-DD. Additionally, ADC and DAC have the biggest share of power consumption, and thus need a symbol-rate DSP to reduce the ASIC's power. At the module level in Fig. 1 (left), coherent laser and driver/TIA electronics constitute 40% of total power consumption. The percentage of power consumption from laser and driver/TIA will increase as improvements to CMOS technology further reduce ASIC power consumption. Therefore, a good strategy for coherent-lite is to enable a single laser solution and a low-power driver design. Our analysis shows that faster-than-Nyquist (FTN) QPSK based on symbol-rate DSP is a workable solution for future short-reach systems.

2. Low Power and Low Modulation Loss Coherent Transmitter

To achieve a single laser solution for 1.6 Tb/s in intra-data centers (500m-2km) without optical amplification, coherent receivers need to meet a link loss budget (e.g., 4dB for DR4) with a limited laser power per channel. Although coherent detection has a high RX power sensitivity, it has a much higher modulation-dependent loss (MDL) compared with

IM-DD PAM at the same modulation order per driver lane, e.g., 16QAM vs. PAM4 [4]. To achieve a large link loss budget, it is necessary to improve the MDL of the coherent TX. MDL can be expressed in terms of the peak-to-average ratio (PAPR) and driver swing V_{pp} into the modulator in Eq. (1). Therefore, one can improve MDL by reducing PAPR and/or increasing driver swing.

$$MDL_{dB} \approx PAPR_{dB} - 20\log_{10}\left[\sin\left(\frac{\pi V_{pp}}{4V_\pi}\right)\right] \tag{1}$$

Nyquist signaling $s_N(t)$ is usually generated by a TX using a root raised cosine (RRC) pulse shaping filter $h(t)$ in Eq. (2) to achieve an optimum matched filter and zero inter-symbol interference (ISI). Instead, FTN signaling $s_{FTN}(t)$ in Eq. (3) offers a higher data rate than Nyquist signaling but results in ISI.

$$s_N(t) = \sum_n a_n h(t - nT) \tag{2}$$

$$s_{FTN}(t) = \sum_n a_n h(t - n\tau T), 0 \le \tau < 1 \tag{3}$$

where a_n is the transmit symbol from DSP, T is the symbol period, and τ is a time acceleration factor. $s_N(t)$ achieves minimum PAPR when $h(t)$ has an excess-bandwidth factor α near 0.5 but requires the DAC sampling rate of x1.5 baud rate. To save DAC power, one can use non-oversampling (NOS) DACs and control the TX S21 transfer function to generate a desired signal spectrum for both Nyquist and FTN signaling.

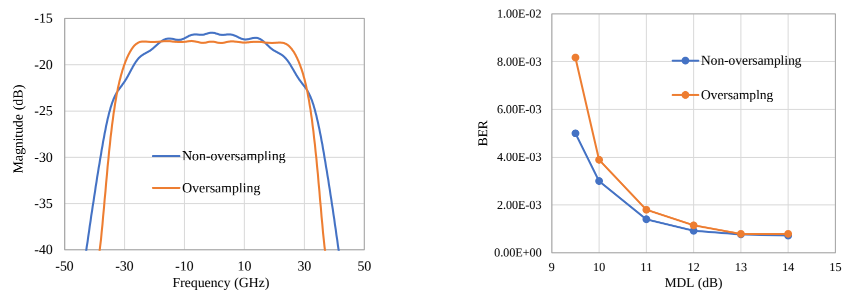

Fig. 2. Comparison of signal spectrum and BER performance between RRC pulse shaping using x1.2 DAC sampling ratio and non-oversampling.

Fig. 2 shows the spectrum and BER performance at -10dBm received power from a 400G 16QAM coherent module. The NOS scheme has α greater than what x1.2 DAC sampling ratio can achieve. The BER performances are almost identical in the linear region (or large MDL). But, in the nonlinear region (or low MDL), the NOS scheme requires a smaller driver swing and suffers less driver nonlinearity because it has a smaller PAPR. When the baud rate is further increased (e.g., 400G QPSK), FTN signaling relaxes the TX S21 transfer function as shown in Fig. 3 (middle). Additionally, Fig. 3 (right) shows FTN signaling has a smaller MDL at low 6-dB BW because of shorter-length ISI.

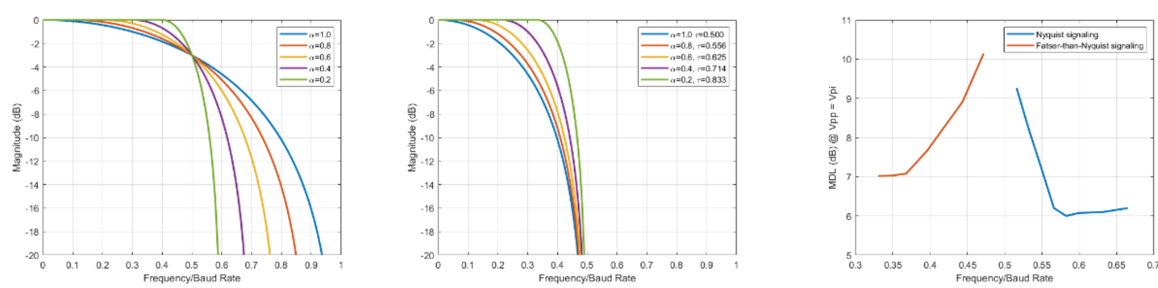

Fig. 3. Nyquist signaling (left) and Fast-than-Nyquist signaling (middle) with the same RRC pulse shaping function $h(t)$ at different excess-bandwidth factor α. FTN signaling has a time acceleration factor $\tau = \frac{1}{1+\alpha}$ such that the signal spectrum is limited within the Nyquist frequency (i.e., 1/2 baud rate). Nyquist signaling and FTN have different MDL vs. 6-dB BW characteristics (right).

MDL improves with a larger driver swing V_{pp}. However, there are often trade-offs between the power consumption, driver swing, and linearity in regular class A and class AB amplifiers. But if we transmit a non-oversampling QPSK signal, we do not have a linearity requirement, and driver power can be significantly improved. Because QPSK only has binary levels, we can eliminate DAC. More importantly, we can switch from traditional class A and class AB amplifiers such as current-mode logic (CML) to a limiting amplifier using source-series termination (SST) as shown in Fig. 4. Because termination resistors are inserted in series rather than parallel, SST drivers require only 0.25 the current of CML for the same driver swing [5]. The limiting amplifier is power efficient because the transistors act as switches (realized by CMOS inverters) to the supply and ground. In conclusion, non-oversampling FTN-QPSK can achieve a low MDL using a small analog bandwidth and facilitate power efficient driver designs.

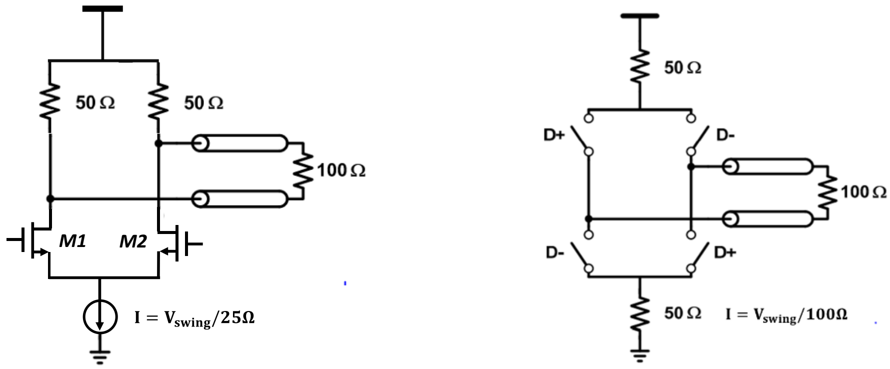

Fig. 4. CML (left) and SST (right) driver output stage

3. Low Power Symbol-Rate DSP Receiver

Symbol-rate DSP receivers have been used in IM-DD PAM systems, but not yet in coherent systems. The reason is that clock timing error detection (TED) from symbol-rate samples is normally achieved by the Muller-Muller method. Coherent Muller-Muller TED must be placed after a linear equalizer and carrier phase recovery because it is a decision-based method. It has a longer delay to the VCO control loop of ADCs than IM-DD. Secondly, the symbol-rate equalizer is sensitive to the ADC sampling time [4]. To solve this problem, we propose a non-decision aided symbol-rate clock TED and place it before the carrier phase recovery. The clock timing error is used to resample the received waveform before the equalizer. Fig. 5 shows the comparison between Muller-Muller and our non-decision aided timing error detectors, and the performance sensitivity to the sampling phase with and without clock recovery.

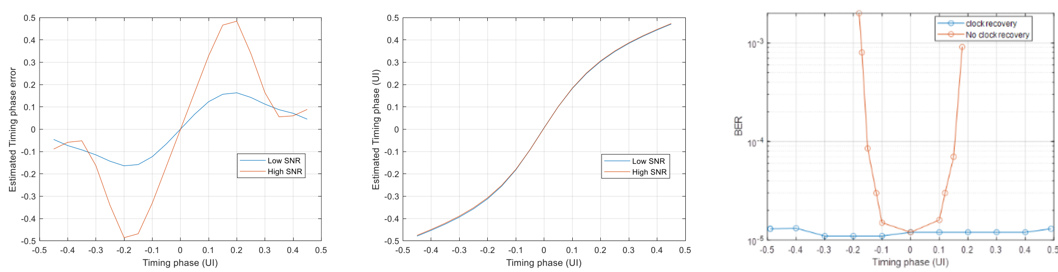

Fig. 5. Mull-Muller (left), Cisco (middle), Ber vs clock phase error (right)

At symbol-rate DSP, the FTN discussed on the TX side avoids aliasing effects with the signals that have undergone chromatic dispersion [6]. For FTN-QPSK, the DSP receiver implements a MLSE with a complexity of $O(2^L L)$, where L is the ISI memory length. When TX S21 is designed to have a short-length ISI, e.g., L=2, FTN-QPSK can maintain high power sensitivity with a simple MLSE and large Tx power, therefore, a large loss budget.

4. Conclusion

The ASIC power of a symbol-rate coherent receiver is potentially at most 10% higher than IM-DD because of 4D demodulation. In return, the 4 degrees of freedom give the coherent receiver room to reduce the spectral efficiency such that QPSK achieves 400 Gbps per wavelength. QPSK has a large link loss budget due to high RX power sensitivity and low TX MDL, which enables a single DFB laser in 1.6 Tb/s DR4 (4x400G). The power consumption from the laser and driver is potentially lower than that of IM-DD. FTN relaxes the analog bandwidth and functions as an anti-aliasing filter for symbol-rate DSP. In conclusion, FTN-QPSK is a good solution for 1.6 Tb/s and beyond in short distance connections.

5. References

[1] J.K. Perin et al., “Coherent data center Links,” JLT **39**, pp, 730-741, 2021.
[2] R. Nagarajan et al., “Low Power DSP-Based Transceivers for Data Center Optical Fiber Communications,” JLT **54**, pp, 5221-5231, 2021.
[3] H. Zhang, “1.6 Tb/s SiPh Coherent Solution for Intra data Center Interconnection”, OFC Panel 2022.
[4] X. Zhou et al., “Beyond 1 Tb/s Intra-data Center Interconnect technology: IM-DD OR Coherent?”, JLT **38**, pp, 475-484 2020.
[5] B. Razavi, “Design Techniques for High-Speed Wireline Transmitters,” OJSSCS, **1**, pp, 53-66 2021.
[6] D.S. Millar et al., “A Baud-Rate Sampled Coherent Transceiver with Digital Pulse Shaping and Interpolation,” OFC OTu2I.2, 2013.