Complexity Comparison of Multi-band CAP and DMT for Practical High Speed Data Center Interconnects

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Abstract: We analyze and compare the complexity of IMDD-based 56-Gb/s Multi-band CAP and DMT over 80-km DCF-free SMFs for data center interconnects. Multi-band CAP with small sub-band count has comparable complexity to DMT at similar OSNR performance.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

The widespread of cloud services has triggered high speed optical links for data center interconnects at typically multiple 400 Gb/s bit rate over a single fiber [1]. Advanced modulation formats in combination with coding and digital signal processing (DSP) are enabling technologies to handle such large amount of data traffic [2]. The link length covered by inter-data center connects is typically up to 80 km. For such a reach, coherent systems are technically viable to offer efficient data transmission with a single wavelength capacity up to 200/400 Gb/s. However, in the very near future, coherent solutions may not satisfy the stringent requirements on cost, power and footprint. Therefore, direct detection (DD) schemes are potential low-cost solutions by up-scaling from and leveraging the ecosystem of short reach transceivers for a wavelength division multiplexing (WDM) link [1,3-7]. PAM-4 [1,3,4], multi-band carrierless amplitude and phase modulation (CAP) [1,5] and discrete multi-tone (DMT) [1,6,7] are the main schemes considered.

Demonstrations have shown that 56 /112 Gb/s PAM-4 signals can successfully transmit over 80 km SMFs [1,3,4]. The advantage of PAM-4 is its simple implementation and the availability of the DSP technology [3]. However, PAM-4 has very limited dispersion tolerance therefore a dispersion compensation fiber (DCF) is required to handle the fiber chromatic dispersion (CD) [1,3]. Otherwise, optical vestigial sideband (VSB) PAM-4 can be incorporated to increase dispersion tolerance but the system requires very high optical signal to noise ratio (OSNR) [4]. Multi-band CAP or DMT using multiple bands/tones naturally have strong resilience to fiber CD. Together with optical VSB via simple asymmetrical optical filtering, the two schemes show very little penalty after transmission through 80 km DCF-free SMFs and achieve reasonably high OSNR performance [5,6] at 56 Gb/s bit rate or beyond.

Our previous demonstrations show that under the same hardware components and setup, 56 Gb/s optical VSB Multi-band CAP and DMT achieve similar OSNR performance [5.6]. A very interesting question remains unsolved on their relative complexity, which is an important concern regarding transceiver DSP power. This paper dedicates to the detailed analysis and fair comparison of the transceiver complexity of a 56 Gb/s multi-band CAP and DMT for 80-km IMDD DCF-free SMF link.

2. Experimental Setup

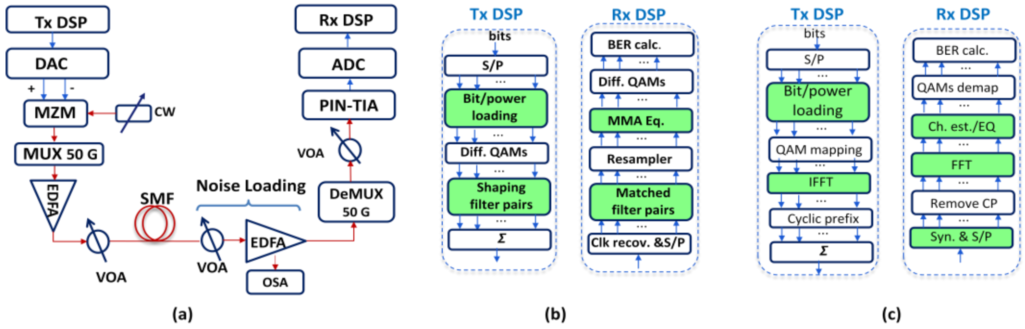

Fig. 1 (a) Experimental setup for 56 Gb/s (b) Multi-band CAP and (c) DMT systems. The green blocks contribute the major complexity

Figure 1 shows the experimental setup for 56 Gb/s Multi-band CAP and DMT systems. It consists of transceiver DSPs and optics. The offline Tx DSP generates the wanted waveform which is then converted into an analogue

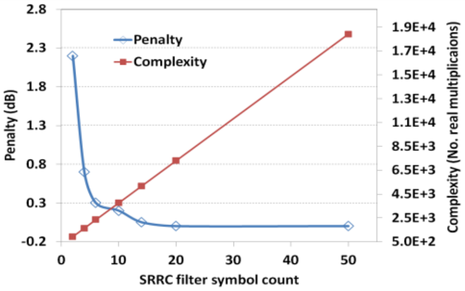

Fig. 2: OSNR penalty and DSP complexity versus SRRC filter symbol count

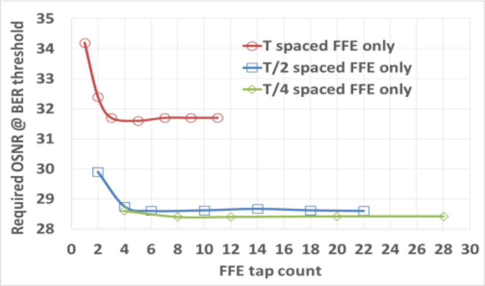

Fig. 3: OSNR versus FFE MMA equalizer tap count.T is symbol time period.

signal via a digital to analogue convertor (DAC) operating at 80 GS/s (84 GS/s) for Multi-band CAP (DMT). The DAC output directly drives a Mach-Zehnder modulator (MZM). A following multiplexer (MUX) with a 50-G DWDM grid and a 3-dB bandwidth of approximately 39 GHz is adopted and its output is amplified by a booster erbium-doped fiber amplifier (EDFA) and adjusted by a variable optical attenuator (VOA). By tuning the wavelength of the laser a frequency offset between the laser frequency and the MUX center frequency is introduced leading to a VSB multi-band CAP or DMT signal. After transmission over a DCF-free 80-km SMF, a combined VOA and pre-amplifier EDFA is used to load optical noise onto the received signal. The resulting OSNR is measured by an optical spectrum analyzer (OSA) which is connected to the pre-amplifier. Then a 50-G de-multiplexer (De-MUX) further filters the optical signal and a VOA is used to optimize the input power injected into a 28-G PIN-TIA. The detected signal is then converted into a digital signal by an ADC with the same sampling rate of DAC and then undergoes offline signal processing.

The transmitter and receiver DSPs for Multi-band CAP are shown in Fig. 1(b). As detailed in [5], the multi-band CAP Tx DSP consists a few blocks and the major DSP comes from the power loading (PL), and square-root raised cosine (SRRC) pulse shaping for signal at each band. The Rx DSP complexity takes into account matched filter pairs as well as the modified multi-modulus algorithm (MMA)-based equalization. Note that zero overhead signal recovery is achieved in multi-band CAP by combining MMA equalizer and partial differential coded QAM [5]. The transceiver DSP for DMT is depicted in Fig. 1(c) and its detailed explanations can be found in [6]. The major complexity comes from the transmitter PL and IFFT, as well as the receiver training symbol based frame synchronization and channel estimation, the FFT and one-tap equalizers. The cyclic prefix and training symbols induced overhead must be considered in the following complexity analysis.

3. DSP Complexity

Throughout this paper, the DSP complexity is measured as the required number of real-valued multiplications per second since multiplication arithmetic operation is most resource consuming. These blocks are filled with green background in Fig. 1 (b) and (c). We assume one complex multiplication (division) needs four (six) real-valued multiplications.

For multi-band CAP, the transceiver complexity is mainly from the Tx PL which requires $2*N$ multiplications and N is the sub-band count, the Tx shaping filter (Rx matched filter) with SRRC impulse response, and the Rx feedforward MMA equalizer (FFE). Since the Tx shaping filters can be implemented as look-up tables (LUTs) [8], we analyze the time domain matched FIR filters' complexity, which depends on two factors: the symbol count (L) and the required samples count (M_k) per symbol for the k-th sub-band. According to Nyquist theory, we have $M_k R_s \geq k(1+a)R_s$ namely $M_k \geq k(1+a)$ where R_s is the symbol rate (which is 2 GBaud here) and a is the roll-off coefficient of SRRC filters and a = 0.1. In order to construct the SRRC filter, Mk must be an integer. To reduce complexity we choose the minimum integer that satisfies $M_k \geq k(1+\alpha)$ for the k-th sub-band. As a result, the overall required multiplication count for the matched filters (I and Q) is $2\sum_{k=1}^{N} M_k * L$ per symbol. For the complex MMA FFE equalization, similarly, the multiplication count is $4*L'*N$ with L' being the FFE tap count.

It is now clear that Multi-CAP complexity is mainly dependent on the SRRC filter symbol count L and the FFE filter tap count L'. It is important to optimize the filters. Fig. 2 shows the OSNR penalty (left y axis) and the complexity (right y axis) versus the receiver SRRC filter symbol count. The OSNR penalty decreases with increasing the SRRC filter symbol count. The penalty is negligible when the symbol count exceeds 10. The complexity simply increases linearly with symbol count. Therefore, we choose L=10 symbols for matched filters.

Fig. 3 reflects the influence of the MMA FFE equalizer tap count on required OSNR @ BER = 3.8e-3. Three tap space cases, namely, T, T/2 and T/4 space are considered. The penalty shows significant reduction with increasing the tap count regardless of tap space, and then begins to converge once tap count exceeds a certain value. The OSNR performance improves significantly when tap space reduces from T to T/2 but little change is observed when further reduces to T/4. Thus 4 taps T/2 space FFE filter can achieve optimum performance.

Tab. 1: Calculation of transceiver DSP complexity of multi-band CAP and DMT

Scheme	**Multi-band CAP**			**DMT**			
DSP part	**PL**	**Rx SRRC filt.**	**EQ**	**PL**	**Tx&Rx (I)FFT**	**ch. Estim.**	**EQ**
Multiplications per symbol or frame	2N	$2\sum_{k=1}^{N} M_k L$	4L'N	$\frac{123N}{\text{ɧ}_{os}}$	128*4N*log$_2$N	$\frac{128 * 3N * \text{ɧ}_{tr}}{\text{ɧ}_{os}}$	$\frac{128 * 2N(1-\text{ɧ}_{tr})}{\text{ɧ}_{os}}$
Percentage	0.7%	94.2%	5.1%	2.4%	92.6%	0.3%	4.7%
Time taken	1/R$_S$			1/f$_{DAC}$*(N+N$_{cp}$)*128			
(Optimum) values	$\sum_{k=1}^{N} M_k$ = 177, L = 10, L' = 4, R$_S$ = 2 GBaud			N$_{cp}$ = 32, ɧ$_{os}$ = 1.05, ɧ$_{tr}$ = 5/128, f$_{DAC}$ = 84 GS/s			
N	12	6	3	1024		512	256
Multiplications per second	7.5e12	4.35e12	2.83e12	3.49e12		3.1e12	2.6e12
Normalized	2.89	1.67	1.09	1.34		1.18	1

Similarly, the major DSP complexity for DMT is from the transmitter PL and IFFT and the receiver frame synchronization, channel estimation, FFT and one-tap equalizer. To achieve similar OSNR (about 28 dB) performance to Multi-CAP [5,6], the required IFFT/FFT size is N = 512 [6]. In order to support anti-aliasing filtering, an oversampling factor of ɧos = 1.05 is used meaning only N/2/ɧos subcarriers carry data. The VSB-DMT works in a training mode thus requires overhead. For an 80-km SMF, the optimized training symbol overhead is ɧ_{tr} = 5/128 meaning one DMT frame consists of 128 DMT symbols 5 of which are training symbols, and the optimized cyclic prefix sample count is N_{cp} = 32 [6]. Within a DMT frame, the real multiplication count for transmitter PL and IFFT is (128-5)*2*N/2/ɧ_{os} and 128*2N*log$_2 N$ [2], respectively. The receiver FFT has the same complexity compared to IFFT and the one-tap equalizer needs 128*4*N/2/ɧ_{os}*(1- ɧ_{tr}) real multiplications. Frame synchronization usually involves cross-correlation, which can be implemented simply using adders since training symbols are known thus no multiplications are needed [9]. The channel estimation involves complex divisions in frequency domain needing 128*6*N*ɧ_{tr}/2/ɧ_{os} real multiplications.

Table 1 summarizes the complexity of the two schemes by adopting the optimized systems parameters obtained above and in [6]. It clearly shows that SRRC filters and (I)FFT take the majority complexity of multi-band CAP and DMT, respectively, and the complexity is dependent on sub-band/sub-carrier count for both schemes. The sub-band or sub-carrier count variation shown in Table 1 introduces less than 1 dB OSNR penalty [6, 10] for both schemes. The corresponding complexity variation is also presented, which indicates that multi-band CAP shows much stronger dependence of complexity on sub-band count than DMT. When Multi-band CAP uses a small band count, it shows similar complexity to DMT.

4. Conclusions

Analysis and fair comparison of DSP complexity is conducted for 56 Gb/s multi-band CAP and DMT over 80 km IMDD based DCF-free SMF links. Multi-band CAP with small sub-band count shows similar complexity relative to DMT at similar OSNR performance.

Acknowledgement

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