Analysis of Complexity and Power Consumption in DSP-Based Optical Modulation Formats

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Abstract: Analysis shows that 400 GbE links using DSP-enabled 5×80Gb/s PAM-4, 4×100Gb/s hybrid CAP-16/QAM-16 and 4×100Gb/s QAM-16-OFDM have relative complexities of 1:5.4:5.7 and consume power of 0.71, 0.67 and 0.75 times that of 16×25Gb/s NRZ benchmark links.

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

1 Introduction

Internet traffic continues to grow exponentially fuelled by bandwidth-hungry applications such as high definition TV, video-on-demand, online gaming/conferencing/healthcare, virtual private networks, and cloud computing etc. To fulfil the bandwidth demand, optical fibre data links have been widely adopted for high speed short-haul interconnectivity. Intensity modulation and direct detection (IMDD) systems are preferred in data links due to their cost-effectiveness. Although digital signal processing (DSP) has gained strong momentum mainly in long haul transmissions where digital coherent receivers are used [1], the use of DSP in short-haul applications has also attracted significant attention due to the continuous advances in CMOS technology [2-4]. In this respect, the complexity of the DSP solution has become a critical factor in determining the system cost of short reach communication systems. Moreover, power dissipation has gained more importance in the ICT sector as a result of concerns about global warming. Thus energy-efficiency is also an important criterion for technology evolution [5].

Ethernet has been the dominant technology for short reach optical interconnects [6]. In March 2013, the IEEE 802.3 started the 400 Gb/s Ethernet Study Group and most likely that multi-lane solutions will be adopted due to component bandwidth limitations [7]. It is possible that 1st generation 400 GbE might be based on 8 lanes with 50 Gb/s rate lane rate over 2 fiber pairs, and the 2nd generation may adopt 4 lanes each operating at 100 Gb/s based on only 1 fiber pair [7]. Recent research efforts have shown a number of DSP-based demonstrations of various advanced modulation formats appropriate for such applications. There have been 50 Gb/s per polarization PAM-4 signal transmission over 100 m SMF link [8], 102 Gb/s multiband CAP signal transmission over 15 km SMF [2], 112 Gb/s quadrature amplitude modulation-16 (QAM-16) over a 4 km SMF link [3], and 100 Gb/s optical OFDM system with 10 km SMF transmission [4]. All these demonstrations are based on IMDD and components having a bandwidth of ~25 GHz. This paper aims to provide the first known comprehensive review of the above mentioned modulation schemes on DSP complexity and power dissipation for 400 Gigabit Ethernet scenarios.

2 System Architecture

Fig. 1 depicts the system architectures for a single lane 50 Gb/s PAM-4, 100 Gb/s hybrid CAP-16/QAM-16, and 100 Gb/s 16-QAM-OFDM. Components having bandwidth ~25 GHz and directly modulated DFB lasers (DMLs) are considered based on parameters detailed in [9], which indicates only CAP and OFDM can support single lane 100 Gb/s transmission while PAM-4 cannot. Therefore, 4 (8) transceivers are considered for 4×100 Gb/s CAP/QAM and OFDM (8×50 Gb/s PAM-4) to analyze the overall DSP complexity and power dissipation. For PAM-4, the encoded PAM symbols first passed through a pre-equalizer prior to conversion to analogue pulses via a DAC. After electrical to optical (E/O) conversion based on a DML, the optical PAM signal propagates through a fibre link and is converted into an electrical signal by a photo-diode (PD) followed by signal processing in the receiver that is the inverse of that in the transmitter. In practise, the equalizers in PAM-4 transceivers are used to mitigate the ISI caused by the RF circuit/path. For hybrid CAP-16/QAM-16, it generates a QAM like signal by combining two multi-level signals using two electrical filters whose impulse responses form an orthogonal Hilbert pair [10]. At the receiver, a modified QAM receiver is used to eliminate the crosstalk between I and Q channels that a CAP receiver otherwise has [11, 12]. Such a hybrid CAP/QAM system offers not only improved tolerance to timing jitter but also increased system power margin compared with a conventional CAP receiver [11, 12]. For OFDM, the generation of an electrical OFDM signal in the OFDM transmitter is performed by an OFDM modem, whose major operations include data modulation format mapping using QAM-16 constellations, power loading, inverse fast Fourier transform (IFFT), cyclic prefix insertion, OFDM symbol serialization and DAC. The generated electrical OFDM signal is then converted into an optical signal. On the receiver side, the optical OFDM signal is converted back into an electrical signal. The received electrical OFDM signal is then digitized and processed by the receiver OFDM modem with an inverse procedure compared to that adopted in the OFDM transmitter.

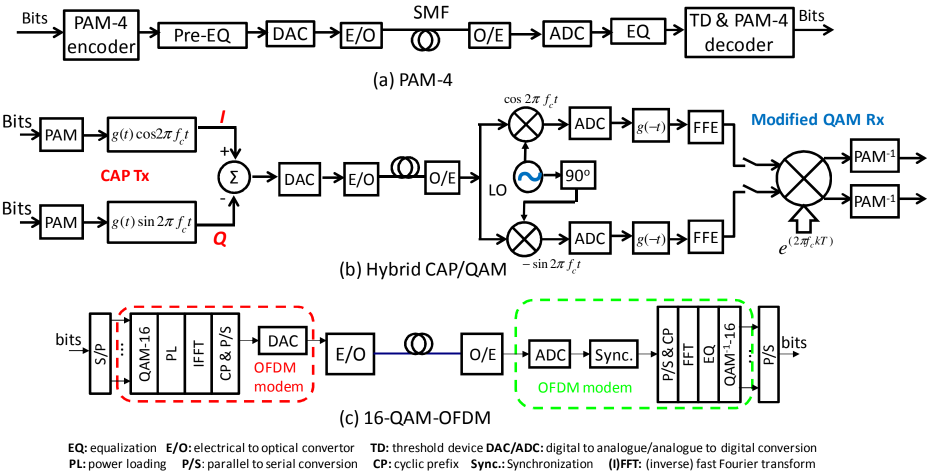

Fig. 1 System architecture a single lane (a) PAM-6, (b) hybrid CAP-16/QAM-16 and (c) QAM-16-OFDM.

3 Results and Discussions

The DSP complexity is evaluated as the number of basic real-valued arithmetic operations required. The DSP blocks considered only contain the transmitter components prior to the DAC and the receiver components after the ADC, as shown in Fig. 1. Taking PAM-4 as an example, the transceiver blocks include the PAM-4 encoder/decoder, equalizers and threshold device (TD). PAM-4 is the simplest architecture and thus is considered to be a suitable reference system. The arithmetic operations of the PAM-4 transceiver include 4 comparisons per symbol in the worst case for the PAM-4 encoder or decoder based on a look-up table, 3 comparisons in the worst case for the TD. A simple 2 tap T space FFE based pre-equalization or receiver equalizer needs 2 multiplications and 1 addition. In total, 17 operations per symbol are required for a single lane 50 Gb/s PAM-4 link. Thus the overall required operations per second for 400 GbE using PAM-4 is given by 8×17/Ts with Ts being the symbol period. For CAP-16/QAM-16, the transceiver DSP blocks include two PAM-4 encoders/decoders and two 12-tap T/4 spaced shaping filters/matched filters, two 20-tap T/4 space FFE filters, one symbol rotator operating at symbol rate and two TDs. The single lane hybrid CAP-16/QAM-16 transceiver needs 184 operations. For 16-QAM-OFDM, the transceiver involves a number of DSP blocks including a QAM-16 encoder/decoder, power loading, IFFT/FFT, receiver symbol synchronization, FFT and single-tap equalization. Detailed analyses of the complexity of each DSP component of the CAP-16/QAM-16 and 16-QAM-OFDM transceivers are not described here due to space but will be presented in the conference.

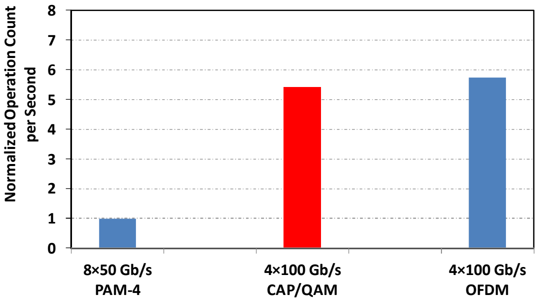

Fig. 2 Normalized arithmetic operation count per second for each scheme.

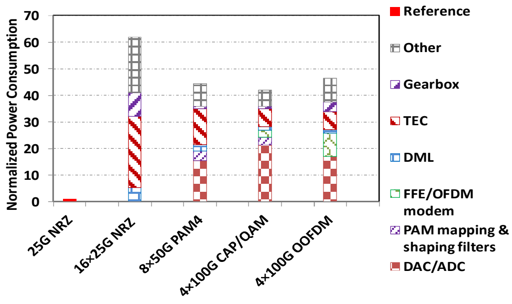

Fig. 3. Normalized transceiver power dissipation for each scheme.

The normalized arithmetic operation count per second for a 400 GbE link using the proposed modulation schemes are summarized in Fig. 2. The total number of operation count is normalized to that of the reference PAM-

4 system. It shows that PAM-4 needs the least computational effort to support a 400 Gb/s overall net bit rate simply because of its relatively simple transceiver configuration, while CAP-16/QAM-16 and QAM-16-OFDM shows about 5.4 and 5.7 times operations relative to that of PAM-4.

The power dissipation of various 400 Gigabit Ethernet links are estimated assuming the use of 65nm CMOS technology and a benchmark 100GBASE-LR4 link which adopts 4 parallel DWDM lanes with each lane operating at 25 Gb/s. The single lane 25 Gb/s NRZ of 100GBASE-LR4 has a transceiver power dissipation of about 1 watt without considering thermoelectric cooler (TEC), which is used to normalize the power consumption of the various 400 GbE modulation format schemes considered here. The transceiver power consumption for each scheme takes into account all transceivers to support 400 Gb/s data transmission. A pair of WDM MUXs/DeMUXs is required for each fiber link. Fig. 3 indicates that the benchmark 16×25 Gb/s NRZ system consumes the most power compared with the other schemes. This is mainly attributed to the TEC used in each transmitter to stabilize laser wavelength, which typically has a power consumption as high as 1.5 W [13]. The power dissipations of 8×50 Gb/s PAM-4, 4×100 Gb/s hybrid CAP/QAM and OFDM are approximately 0.71, 0.67 and 0.75 times that of 16 lane NRZ links, respectively, as a direct result of reduced number of TECs and other components.

It should be noted from Fig. 3 that the DAC/ADCs consume substantial power. Analogue implementations can be adopted for PAM-4 and hybrid CAP/QAM without the need of DAC/ADCs and thus can further improve power efficiency [12]. Alternatively, photonic integration can improve system power efficiency. For example, four lasers of an optical module based on the above-mentioned modulation formats can share one TEC instead of four via integration. This leads to about 75% reduction of TEC power consumption shown in Fig. 3. If a Course WDM wavelength plan was used, instead of DWDM, it may be possible to use uncooled DML's which could halve the total power dissipation of all schemes.

4 Conclusions

The first known comprehensive review on 400 Gigabit Ethernet using advanced DSP-enabled modulation formats has been performed with quantitative analysis of DSP complexity and transceiver power dissipation. Results have shown that 8×50 Gb/s PAM-4 has the least complexity, while 4×100 Gb/s hybrid CAP-16/QAM-16 and QAM-16-OFDM have a complexity of 5.4 and 5.7 times to that of PAM-4, respectively. The three schemes consume power of 0.71, 0.67 and 0.75 times that of a 16×25 Gb/s NRZ benchmark link.

5 References

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