100 Gigabit Ethernet Transmission Enabled by Carrierless Amplitude and Phase Modulation Using QAM Receivers

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Abstract: Simulations have investigated single laser 100G Ethernet links enabled by CAP-16 using QAM receivers that not only lower significantly system timing jitter sensitivity but also outperform PAM and standard CAP in terms of power margin.  
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1. Introduction
To address the ever-increasing bandwidth requirements in local area networks, the 40 and 100 Gigabit Ethernet standards were completed in 2009. The standard typically adopted four coarse wavelength division multiplexing (CWDM) channels [1], an implementation which inevitably has a high system cost as a result of the number of optoelectronic components used. System cost reduction is primarily driven by a reduction in optoelectronic component count and by the associated optical packaging complexity [2,3]. Multilevel modulation schemes featuring high spectral efficiency are therefore attractive solutions in this scenario. This is because, in addition to a reduced number of optical channels, high bit rates can be achieved by using relatively low speed electronics and optoelectronic components. The IEEE 802.3 Next Generation (NG) 100 Gigabit Ethernet study group has recently proposed pulse amplitude modulation (PAM) schemes to support transmission over 500m to 2km single mode fiber (SMF) [2,3].

Compared with PAM, optical orthogonal frequency division multiplexing (OFDM) [4] and standard carrierless amplitude and phase modulation (CAP) [5,6] can further improve spectral efficiency and system flexibility without increasing digital signal processing (DSP) requirements greatly. OOFDM leveraging advanced DSP shows great resilience to linear system effects such as fiber dispersion, while standard CAP allows more simple non-DSP implementation and hence has the potential of being lower cost but with high performance. It has been shown that, using a single directly modulated laser, 100Gb/s OOFDM and standard CAP can successfully support transmission over 2 km SMF whilst PAM systems cannot [4], indicating the great potential for these advanced modulation techniques. On the other hand, power dissipation has gained more and more importance in the ICT sector. Thus energy-efficiency is an important criterion for determining the adoption of the optimum modulation technique for NG 100 Gigabit Ethernet based on a single optical channel. From an energy-efficiency point of view, CAP systems implemented without using ADCs and DACs exhibit much better performance than OOFDM [4] and consume even less power than the 4x25Gb/s non-return-to-zero (NRZ) CWDM version of 100G Ethernet [4]. These advantages indicate that CAP is a promising candidate, with both cost and energy superiority.

In this paper, we demonstrate that CAP-16 using a quadrature amplitude modulation (QAM) receiver can not only lower the timing jitter sensitivity significantly, but also further improve the system power margin compared with both standard CAP-16 and PAM-4. It shows that excellent receiver signal quality is obtained without receiver equalization under stringent transceiver bandwidth conditions due to its wide eye opening; whilst a PAM-4 modulation scheme has to perform equalization in the receiver to recover the transmitted signal.

2. System architecture of CAP using QAM receiver
Figure 1 shows the block diagram of a NG 100 Gb/s CAP system using a QAM receiver. In the transmitter, the four 25 Gb/s data tributaries are first encoded with FEC and then converted into two parallel streams. Each tributary stream is mapped into PAM-4 symbols and then pulse shaping is performed using a square root raised cosine filter [5]. The two shaped signals are combined and modulate a Mach-Zehnder modulator (MZM). The optical signal propagates through a length of SMF and is detected by a square-law photo-detector (PD). The detected electrical signal is then processed in a QAM receiver which consists of two mixers, two matched filters for the in-phase (I) and quadrature (Q) channels and a phase rotator [6]. The DSP following the QAM receiver is the inverse of that in the transmitter. For comparison, a standard CAP receiver is also presented in Fig. 1, which simply consists of two matched filters for the I and Q signal demodulations, respectively. The remainder of the receiver is identical to that
after the QAM receiver. By removing the Q channel, the shaping filters and matched filters, the standard CAP transceiver shown in Fig. 1 is equivalent to a PAM-4 system. Note that under limited (less than 50 GHz) bandwidth conditions, PAM-4 has to use feedforward equalization (FFE) and decision feedback equalization (DFE) to offer channel equalization due to its doubled symbol rate compared with CAP-16.

![Fig.1 Diagram of NG 100G Ethernet PMD based on CAP system using QAM receiver. For comparison, the standard CAP receiver is also plotted in the red block. The inset eye diagrams are obtained by using 50 GHz transceiver](image)

Via simulation, three types of transceivers and reference NRZ systems are considered: The first type is a 50 GHz bandwidth transceiver including a MZM with 3-dB bandwidth (1st order RC response) of 50 GHz, and an optical receiver with 3-dB bandwidth of 37.5 GHz. Using this transceiver, a reference 50 Gb/s NRZ signal has a receiver sensitivity of -10 dBm @ BER of 10^-12. The other types are a 40 GHz (30GHz) transceivers which include a MZM with 3-dB bandwidth of 40 GHz (30GHz), and an optical receiver with 3-dB bandwidth of 30 GHz (22.5GHz). A reference 40 Gb/s (30Gb/s) NRZ signal has a receiver sensitivity of -10 dBm @ BER of 10^-12. The responsivity for all the PDs is 0.9A/W. The launch power is set to be 0 dBm. Therefore, by using FEC(10^-3,10^-12) and FEC(10^-5,10^-15) with BER thresholds of 10^-3 and 10^-5 respectively, the total link power budget is 13.8 dB and 12.3 dB, respectively. For CAP-16, the square root raised cosine shaping filter has a roll-off coefficient of 1.5. For PAM-4 the receiver equalizer consists of a 10 tap, T/2 spaced FFE and a 3 tap DFE, with T being the PAM-4 signal symbol rate.

3. Simulation results

![Fig.2 Eyediagrams for (a)-(c) 100 Gb/s CAP-16 system using QAM receiver, (d)-(f) 100 Gb/s standard CAP-16 system, and (g)-(i) 100 Gb/s PAM-4 system. (a), (d) and (g) are for 50 GHz transceiver, (b), (e) and (h) are for 40 GHz transceiver, and (c), (f) and (i) are for 30 GHz transceiver. (a)-(g) are obtained without receiver equalizer and (h)-(i) are obtained using 10 taps T/2 spaced FFE and 3 taps DFE.](image)

Figure 2 shows the eye diagrams for each modulation scheme using the three different transceivers. In obtaining Fig. 2, the FEC overhead is not considered. For the bandwidth relaxed 50 GHz transceiver, all the three schemes can work without receiver equalization. However, for the restricted bandwidth 40GHz and 30 GHz transceivers, PAM-4 has to use an equalizer to recover the transmitted signal. For all transceiver variants, it is interesting to note that the CAP-16 with the QAM receiver has the best horizontal eye opening compared with the other two cases, in particular...
much better than that of the standard CAP-16. This is mainly because, compared with standard CAP, CAP using the QAM receiver effectively eliminates the inter-channel crosstalk. PAM-4 doubles the symbol rate leading to relative narrow horizontal eye even if equalization is used.

Fig. 3 shows the system power budget comparisons between PAM-4 and CAP-16 with the QAM receiver using the various transceivers listed in Section 2. Note that the power budget for standard CAP-16 is not presented here as PAM-4 outperforms standard CAP-16 and all other PAM schemes [4]. The link power penalty comprises contributions from the relative receiver sensitivity, dispersion penalty, relative intensity noise (RIN) penalty, link loss (fiber attenuation + connector loss), deterministic timing jitter (DJ), baseline wander, link reflection, mixer penalty (for CAP-16 only), and unallocated penalty if available. The unallocated penalty is a direct reflection of the system power margin. If there is a negative unallocated penalty, then the link fails (and no power budget line is shown in the figure). The detailed descriptions of each constituent penalty can be found in [2,3]. In obtaining Fig. 3, a target SMF length of 2 km is used. It can be seen from Fig. 3 that CAP-16 with QAM receiver outperforms PAM-4 in terms of power margin, though the power margin superiority decreases with decreasing transceiver bandwidth.

For example, by using FEC(10\(^5\),10\(^{15}\)), CAP-16 with QAM receiver has ~2dBo, ~1dBo and ~0.3dBo more power margin than PAM-4 for the 50GHz, 40GHz and 30 GHz transceivers, respectively. This increases to ~2.8dBo, ~2.2dBo and ~1.1dBo, respectively, when FEC(10\(^2\),10\(^{15}\)) is used. The better power margin obtained by CAP-16 with the QAM receiver is because, though QAM receivers introduces a mixer penalty of about 3 dBo due to noise amplification, it gives rise to much lower relative receiver sensitivity attributed to noise filtering by the followed baseband matched filter and no noise enhancement is involved related to receiver equalization. Comparing Fig. 3 (a) and (b), the larger power margin difference obtained by using FEC (10\(^5\),10\(^{15}\)) is because PAM-4 undergoes severe baseline wander effect while CAP-16 is insusceptible to this [7].

5. Conclusion

We have proposed and investigated single-laser 100 Gigabit Ethernet enabled by CAP-16 using a QAM receiver. Results show that the QAM receiver not only lowers significantly the system timing jitter sensitivity but also outperforms PAM-4 and standard CAP-16 in terms of power margin.

6. Acknowledgement

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7. References