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Performance Comparison of Advanced Modulation Formats for Low-bandwidth optics-based 50-Gb/s/λ PON at O-band

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***Abstract*-A comprehensive comparison of PAM-4, CAP-16QAM and DMT-16QAM modulations is simulated in 50-Gb/s/λ PON based on bandwidth-limited optics at O-band. The power budget, thermal noise performance and DSP complexity are discussed. The results show that over 29 dB power budget at 3.8×10^{-3} threshold can be achieved.**

***Keywords*-Passive optical network(PON); Bandwidth-limited optics; Advanced modulation formats; Power budget; Computational complexity.**

I. Introduction

The increasing bandwidth demand in access network segment requires not only higher transmission speed but also lower costs. In the ITU-T standards development organization, the standardization of single-wavelength 50 Gb/s TDM PON has begun in project G. hsp [1]. For 50 Gb/s PON system, bandwidth-limited optics are desired to reuse the existing devices and minimize the deployment cost [2]. Therefore, the bandwidth of the transceiver is generally limited and significantly smaller than the baud-rate of the signal. Considering the limited bandwidth of low-cost optics, advanced modulation formats with spectral efficiency and advanced digital signal processing (DSP) are researched in order to reduce the baud-rate of the signal [3].

However, complicated DSPs need high-speed digital-to-analog or analog-to-digital converters (DAC/ADC), which are not cost-effective especially for the optical network units (ONUs) located at the user side. Therefore, for a single-wavelength 50-Gb/s PON based on intensity modulation and direct detection (IM/DD), advanced modulation schemes such as multi-level pulse amplitude modulation (PAM), carrier-less amplitude and phase modulation (CAP) and discrete multi-tone (DMT) modulations are the most potential research topics due to its simpler DSP architecture and lower complexity [4]. In cost-effective 50-Gb/s/λ PON system, the adoption of legacy low-bandwidth optics has been intensively investigated in order to reduce the CAPEX and OPEX for both the network operators and the customers [5-7]. Some performance comparisons of PAM, CAP and DMT for metro networks and access networks with high bandwidth have been reported. The PAM-4 modulation scheme has been studied for 50G PON. However, there is no a comprehensive comparison of PAM, CAP and DMT for 50G PON system using bandwidth-limited optics.

In this paper, we simulated and compared the performance of PAM, CAP and DMT modulation formats for 50G PON at O-band using 10G-class optics and simple DSP for the first time. There is no pre-distortion method at transmitter and no nonlinear equalization method at receiver. Performance comparison of 50 Gb/s/λ PON is carried out using the same simulation setup for different formats in terms of DAC and ADC resolution, computational complexity, thermal noise, sensitivity and power budget of the receiver. Some of these parameters cannot be measured in the experiment. The results show that over 29 dB link loss budget at HD-FEC threshold based on bandwidth-limited optics can be achieved. Moreover, the computational complexity of algorithm is evaluated, and DMT-16QAM has the best performance and the lowest complexity.

II. Simulation Setup

Figure 1 shows the simulation setup for 50-Gb/s/λ PON based on bandwidth-limited optics at O-band. The 50 Gb/s signals with different modulations are generated and performed offline by MATLAB and uploaded into a 64 GSa/s DAC with a resolution of 8 bits, and then filtered by a 4th order Bessel low pass filter (LPF) with a 3 dB bandwidth of 10 GHz in order to simulate the bandwidth limitation of the transmitter. The output of the LPF is directly modulated by a directly modulated laser (DML) with a power output of 17.68 dBm at the central wavelength of 1310 nm. The modulated optical signal transmits 20 km standard single-mode fiber (SSMF) with an average loss of 0.35 dB/km. At receiver side, a variable optical attenuator (VOA) is placed after SSMF to adjust the received optical power for sensitivity measurement. A photodiode (PD) is used for signal detection. An electric 4th order Bessel LPF with a 3 dB bandwidth of 15 GHz is placed after PD in order to simulate the bandwidth limitation of the receiver. After LPF, the detected signal is processed by a 64GSa/s ADC for offline DSP.

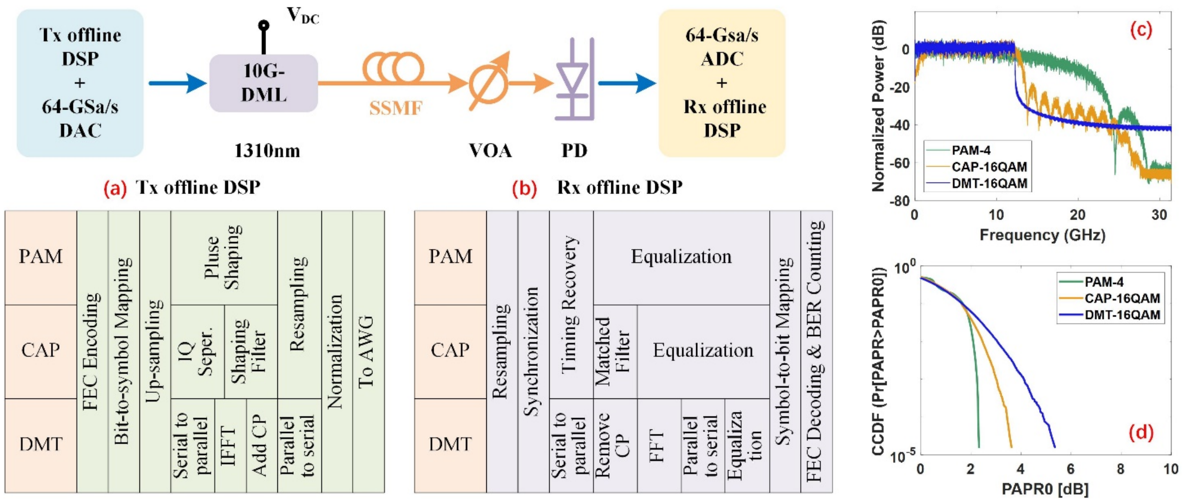

Fig.1. Simulation setup for 50-Gb/s/λ PON system based on bandwidth-limited optics at O-band: (a) and (b) Tx and Rx offline DSPs, (c)spectra and (d) PAPR for PAM-4, CAP-16QAM and DMT-16QAM signals, respectively.

Figures 1 (a) and (b) show Tx and Rx offline DSPs for PAM-4, CAP-16QAM and DMT-16QAM signal, respectively. There are no pre-distortion methods at the transmitter side, and neither nonlinear equalization at receiver side to simplify the DSP process and reduce the complexity. Fig. 1 (c) and (d) shows the spectra and PAPR of 50 Gb/s signals with different modulation formats. The roll-off factor of PAM-4 signal is chosen 1 to verify the performance of modulation formats using bandwidth-limited optics. The bandwidth of PAM-4, CAP-16QAM and DMT-16QAM are 25GHz, 13.75 and 12.5 GHz, respectively. Thus, CAP and DMT modulations have higher spectrum efficiency than PAM modulation. From Fig. 1 (d), it is clear that PAM-4 modulation has the lowest PAPR. Comparing with PAM-4 and DMT-16QAM, CAP-16QAM is regarded as a more attractive format for 50 Gb/s PON in terms of spectra and PAPR.

III. RESULTS AND DISCUSSION

From Fig. 2 (a), it can be found that 4-bit DAC resolution is enough to achieve below 3.8×10^{-3} threshold after 20km SSMF transmission and there is error floor when the DAC resolution increases for three modulation formats. Similarly, the trend of BER performance versus ADC resolution are simulated and shown in Fig. 2 (b). 6-bit ADC resolution can achieve 3.8×10^{-3} threshold. In order to verify the performance of modulation formats, 8-bit DAC and ADC are chosen for the simulation. Fig.2 (c) shows the receiver sensitivity penalty versus thermal noise of the optical receiver. The performance of three modulation formats is similar at high thermal noise. However, at low thermal noise, PAM-4 has better tolerance.

The BER performance of 50-Gb/s PON versus received optical power (ROP) with three modulation formats are shown in Fig. 3 (a) and (b). The receiver power for PAM-4, CAP-16QAM and DMT-16QAM after 20km SSMF transmission at HD-FEC (3.8×10^{-3}) threshold are -13.6 dBm, -12.2 dBm and -13.7 dBm, respectively. It can be found that PAM-4 and DMT-16QAM outperforms CAP-16QAM. PAM-4 and DMT-16QAM can realize error-free transmission at high receiving power, but CAP-16QAM has an error floor. There is no obvious dispersion penalty after back-to-back (BtB) and 20-km transmission. The performances of all modulation formats have around 0.1 dB penalty in sensitivity after 20 km fiber transmission compared to BtB case.

The complexity of DSP has effects on the hardware costs and power consumption of the transmission systems.

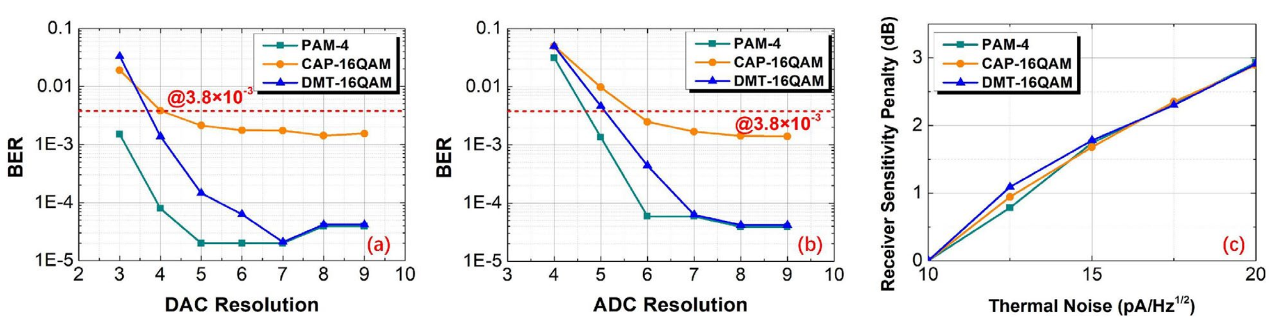

Fig. 2. (a) BER versus DAC resolution; (b) BER versus ADC resolution; (c) Receiver sensitivity penalty versus thermal noise.

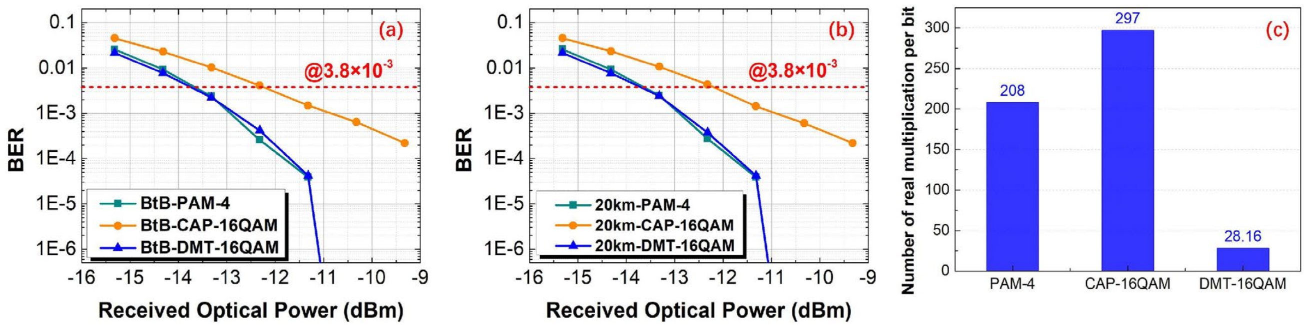

Fig. 3. BER versus ROP for 50-Gb/s/λ PON with different formats: (a) BtB; (b) 20 km; (c) Computational complexity of three modulation formats.

Considering there are many common functions in the DSP for different modulation formats and some functions are simple to implement, only functions with high computational complexity are used to evaluate the computational complexity of DSP for each format [8]. They are two-stage equalizer based on 189-tap FFE/DFE and 19-tap DDLMS for PAM-4, two-stage equalizer based on 99-tap LMS and 99-tap DD-LMS for CAP-16QAM and 2048 FFT/IFFT for DMT signal. Since the cost of a multiplier is much higher than that of an adder, the computational complexity of those functions is evaluated in terms of the number of real multipliers per bit. As shown in Fig. 3 (c), the number of real multipliers per bit of PAM-4, DMT-16QAM and CAP-16QAM is about 208, 297 and 28.16 respectively. PAM-4 and CAP-16QAM have similar computational complexity. DMT-16QAM offers lower complexity than the other two formats.

The summary of receiver sensitivity and power budget performance after 20 km transmission at HD-FEC threshold using bandwidth-limited optics for the three modulation formats are listed in Table 1. Over 29 dB power budget can be achieved for all modulations at BER threshold of 3.8×10^{-3}. DMT- 16QAM has the largest power budget.

TABLE I. SUMMARY OF RECEIVER SENSITIVITY AND POWER BUDGET FOR THREE MODULATION FORMATS AT HD-FEC THRESHOLD

Modulation Formats	Launched Power/dBm	Sensitivity @3.8×10^{-3}/dBm	Power budget @3.8×10^{-3}/dB
PAM-4	17.68	-13.6	31.28
CAP-16QAM		-12.2	29.88
DMT-16QAM		-13.7	31.38

IV. CONCLUSION

In conclusion, we have intensively simulated and compared the single-wavelength 50-Gb/s PON with PAM, CAP and DMT modulation formats in the O-band based on bandwidth-limited optics, without pre-distortion and nonlinear equalization methods. The feasibilities of using all three formats to achieve 50 Gb/s PON transmission system are verified by simulation. PAM-4 has the best thermal noise tolerance performance and DMT-16QAM has the largest power budget. The results show that over 29 dB power budget at HD-FEC threshold can be achieved. DMT-16QAM offers much lower computational complexity than PAM-4 and CAP-16QAM.

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