IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 10, Number 2, April 2018

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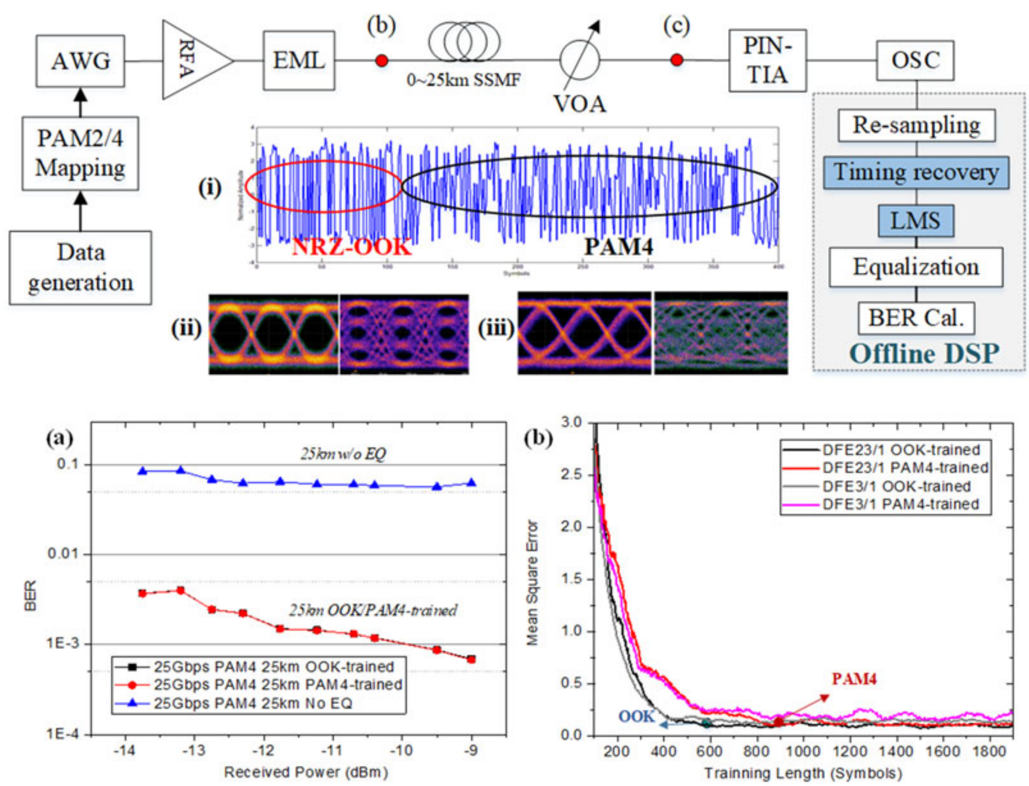

Experimental setup and performance comparison between OOK- and PAM4-assited adaptive equalization

DOI: 10.1109/JPHOT.2018.2800099

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OOK-Assisted Adaptive Equalization and Timing Recovery for PAM4 Demodulation

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DOI:10.1109/JPHOT.2018.2800099

Manuscript received January 5, 2018; revised January 25, 2018; accepted January 28, 2018. Date of publication January 31, 2018; date of current version April 6, 2018. This work was supported in part by the Natural Science Foundation of China under Project 61420106011, 61601277, and 61601279, in part by the China Postdoctoral Science Foundation funded project (2016M601564), and in part by the the Shanghai Science and Technology Development Funds under Project 17010500400, 15530500600, 16511104100, and 16YF1403900. Corresponding author: Zhengxuan Li (e-mail: antlzx@shu.edu.cn).

Abstract: In this paper, an OOK-assisted symbol timing recovery and adaptive equalization mechanism is proposed to facilitate the four-level pulse amplitude modulation (PAM4) signal demodulation. Efficient symbol timing recovery and tap adaption is realized using a short OOK-header preceding the PAM4 signal packet. Experimental results show that compared with the PAM4 format, the OOK-header can realize accurate tap training with a faster convergence rate and low-jitter symbol timing recovery with much less symbols required for calculation. In this case, the demand for a lengthy overhead is relaxed and the bandwidth efficiency is further increased.

Index Terms: Four-level pulse amplitude modulation (PAM4), symbol timing recovery, adaptive equalization.

1. Introduction

Due to rapid growth of cloud computing, 4K TVs and mobile internet services, the bandwidth demand for short reach optics keeps surging, such as data center interconnections, passive optical networks (PONs) and wireless backhaul systems. One of the promising way to realize capacity upgrade is to increase the data rate on each wavelength channel. However, for the practical realization of these systems, optical transceivers with small package size, low cost, and reduced power consumption are preferred, which makes the mature on-off-keying (OOK) format unsuitable because it requires expensive high-bandwidth optics and electronics. Advanced modulation formats that could support high data rate modulation on single channel has been intensively discussed recently [1], [2]. Compared with OOK, four-level pulse amplitude modulation (PAM4) could decrease the bandwidth requirement by a half without introducing complex digital signal processing (DSP) modules, therefore attracting plenty of attentions. PAM4 based system demonstrations with a data rate ranges from 25-Gb/s to 112-Gb/s are being reported [3], [4]. Due to the multi-level property, PAM4 has higher requirement on equipment linearity, and it can be easily distorted by the nonlinearity of devices. Also, the signal would be further distorted by the chromatic dispersion during fiber transmission, especially for high data rate situations. Therefore, digital equalizers are utilized

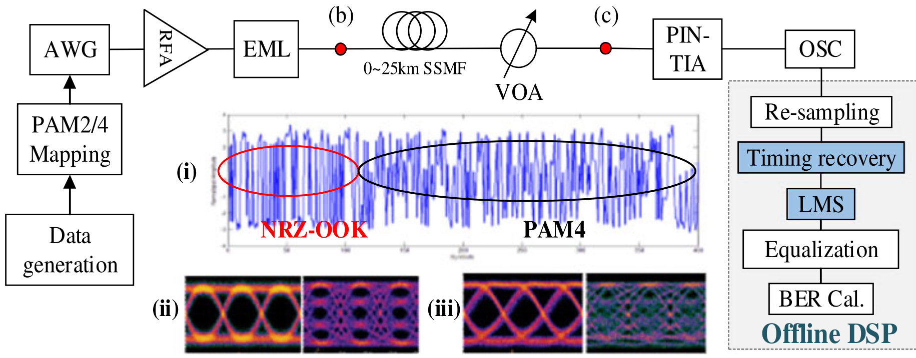


Fig. 1. Experimental setup. Insets: (a) proposed modulation mechanism; (b) measured eye-diagram of the modulated signal in OOK format and PAM4 format at 12.5 GS/s symbol rate in BtB and (c) 25 km transmission cases.

to eliminate the inter-symbol interference (ISI) for effective demodulation, including feed forward equalization (FFE), decision-feedback equalization (DFE), Volterra filtering, Winner filtering, maximum likelihood sequence estimation (MLSE), etc. [5]–[8]. Particularly, for uplink transmission in PON systems, adaptive equalization is required because the channel response varies from one burst packet to another. Besides, recovering the symbol timing from the distorted PAM4 signal accurately would be another issue to be considered.

In this paper, we propose an OOK-assisted adaptive equalization and symbol timing recovery (STR) scheme to facilitate the PAM4-signal processing. The data in each packet is divided into two sections with different length. The short part with a length of ∼1000 bits is mapped into OOK format as the header, and the remaining main part is mapped into PAM4 format. Experimental results show that similar training performance can be obtained by using OOK and PAM4 sequence, but the OOK-training has a faster convergence rate than the PAM4 training. For the symbol timing recovery, evaluation results show that compared with PAM4 format, a much lower timing jitter is obtained when using OOK for timing recovery. Moreover, as the OOK signal is more robust to both linear and nonlinear distortions, the data in the header can be successfully demodulated without equalization as long as the bit error rate (BER) is lower than 1×10^{-3}. In this case, the overhead can be reduced and the bandwidth efficiency is further increased.

2. Experimental Setup

We set up an experiment to verify the proposed modulation scheme as depicted in Fig. 1. Inset (a) illustrates the signal packet with data modulated in OOK format preceding the PAM4 modulation. The pseudo random binary sequence (PRBS) with a word length of $2^{15} - 1$ is generated offline using Matlab, then the PRBS sequence is repeated for 2 times to get a sequence with 65536 bits. During modulation, the first 2000 bits are mapped into OOK format, and the rest bits are mapped into PAM4 format. As shown in inset (a), the OOK-header is modulated with the same peak-to-peak voltage as PAM4 signal, by which the OOK-header would have higher tolerance to noise and distortions from the system. Note that 2000 symbols are used as the OOK-header in the experiment to make sure that the symbol length is enough for tap training and symbol timing recovery performance evaluation, and according to the experimental results, 800 symbols are sufficient. Then the data is loaded to an arbitrary waveform generator (AWG) for digital to analog conversion. The AWG has a bandwidth of 25 GHz and a sampling rate of 64 GS/s. The peak-to-peak voltage of the signal is boosted to ∼2 V by a radio frequency amplifier (RFA) before applied to the electro-absorption modulated laser (EML). The EML operates at 1543 nm with ∼2 dBm output power. At the receiving side, a PIN-TIA is used for signal detection. The measured combined frequency response of the transceivers is shown in Fig. 2. The 3-dB bandwidth is ∼9 GHz and the 10-dB bandwidth is ∼12 GHz. A variable optical attenuator follows the standard single mode fiber

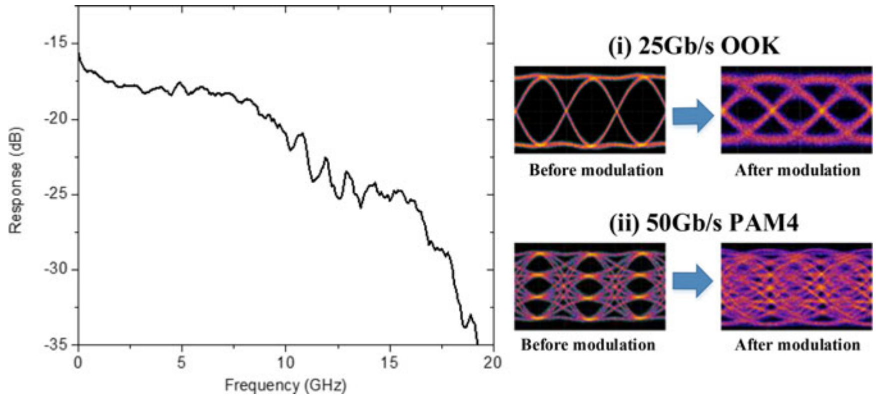


Fig. 2. Frequency response of the optical transceivers and eye diagram of (a) 25 Gb/s OOK and (b) 50 Gb/s PAM4 before and after modulation in BtB case.

(SSMF) for power control and sensitivity evaluation. The received signal is captured by a real-time oscilloscope with 80 GS/s sampling rate. Finally, off-line signal processing is performed, including data re-sampling, absolute-law based symbol timing recovery, least mean square (LMS) algorithm based tap adaption, signal equalization using DFE, and BER calculation.

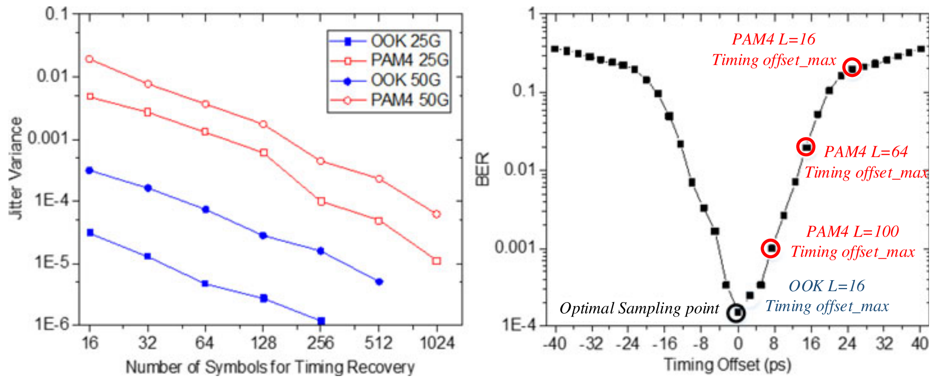
Two types of signal are evaluated, i.e., 25-km fiber chromatic dispersion distorted 25 Gb/s PAM4 signal and bandwidth limited 50 Gb/s PAM4 signal, representing the chromatic dispersion and bandwidth limitation-dominated transmission system respectively. Inset (b) in Fig. 1 shows the measured eye-diagram of the modulated signal in OOK format and PAM4 format at 12.5 GS/s symbol rate in back to back (BtB) case. After 25 km SSMF transmission, the signal is degraded by chromatic dispersion and the eye diagram is as inset (c) shows. For 50-Gb/s PAM4 modulation, the signal would be converted into 7-levels due to the bandwidth limitation, which is also named as duo-binary PAM4 format (DB-PAM4), as inset (b) in Fig. 2 shows. Note that although the frequency response of the transceivers is imperfect, we did not perform duobinary filtering during modulation/demodulation to avoid further bandwidth reduction, thereby enables direct detection of the OOK-signal. As a result, the 25-Gb/s OOK signal is also degraded by the limited bandwidth as inset (a) in Fig. 2 shows, but the eye diagram is still clearly open and can be decoded without equalization.

3. Experimental Results

3.1 OOK-Assisted Symbol Timing Recovery

As in other optical transmission systems, symbol timing recovery (STR) is required to enable effective signal detection in PAM4 systems. Several popular algorithms for STR has been studied, including absolute-law (AL), square-law (SL), and fourth-law (FL) functions [9], and those algorithms has been used for the off-line timing recovery of PAM-4 and NRZ signal [10]. We have verified that AL-STR is applicable for both ordinary PAM signal and partial response signal [11]. In this experiment, for 50-Gb/s PAM4 modulation, the signal will be converted into partial response signal by the bandwidth limited transceivers as Fig. 2 shows, therefore AL-STR is employed in our experiment for evaluation. The 80 GS/s sampling data is first resampled to 50-GS/s and 100-GS/s for 25- and 50-Gb/s PAM4 signal processing respectively, corresponding to 4 samples per symbol. Then the AL-STR algorithm is performed for symbol timing recovery. The normalized timing error $\hat{\epsilon}$ based on AL-STR algorithm can be represented as:

$$\hat{\epsilon} = -\frac{1}{2\pi}\left[arg\left(\sum_{k=mLN}^{(m+1)LN-1}\left|r\left(\frac{kT}{N}\right)\right|e^{-\frac{j2\pi k}{N}}\right)\right] \tag{1}$$



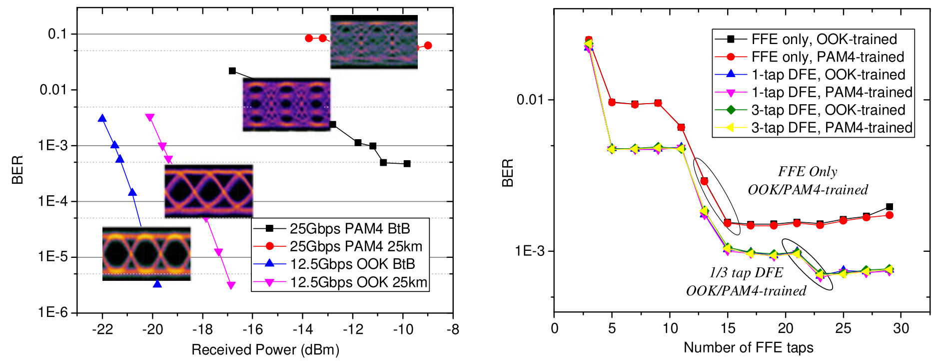
(a) (b)

Fig. 3. (a) Timing jitter variance as a function of symbol numbers for calculation (b) BER vs timing jitter for hard-detected 25 Gb/s PAM4 signal.

Where $r(\frac{kT}{N})$ is the received signal samples, and N is the number of samples per symbol, which is set as 4 in our experiment. The timing error $\hat{\epsilon}$ is calculated every section of L symbols with L $\times$ N sampling points. The OOK-header and PAM4 signal are used for timing recovery under L $=$ 16, 32,. . . 1024 cases respectively, and the variance of normalized timing error is shown in Fig. 3. Fig. 3(a) is evaluated using the data of 12.5G and 25G symbol rate in BtB case. As the timing accuracy is closely related with the symbol number used for calculation, the timing jitter increases when the length of L decreases. It can be seen from Fig. 3(a) that the timing accuracy obtained with the OOK-header is much higher than the PAM4 signal. Compared with PAM4 signal, the jitter variance can be reduced by two magnitudes when using OOK-header for symbol timing recovery. More than 512 PAM-4 symbols are required to obtain a similar timing accuracy with 16/32 OOK-symbols for 12.5G/25G symbol rate case respectively. It's well known that the timing offset reduces the signal to noise ratio and increases the BER during signal demodulation. Fig. 3(b) shows the relation between the BER and the timing jitter using the data sampled on −9.8 dBm received power with 12.5G symbol rate as an example. By using 16 OOK symbols for timing recovery, the maximal timing error is ∼2.5 ps, resulting in a negligible BER degradation compared with the optimal sampling time. Increasing the symbol length to 32, 64 and 100 can further decrease the timing offset. However, for 16 PAM4 symbol case, the maximal timing error is 25 ps, which degrades the BER to ∼0.2. When 100 PAM4 symbols are used, the maximal timing error is ∼7.5 ps, and the BER is still much higher than the 16-OOK symbol case. As a result, the symbol timing recovery can be realized using the OOK-header with a much shorter symbol length, verifying the benefit of the proposed modulation mechanism.

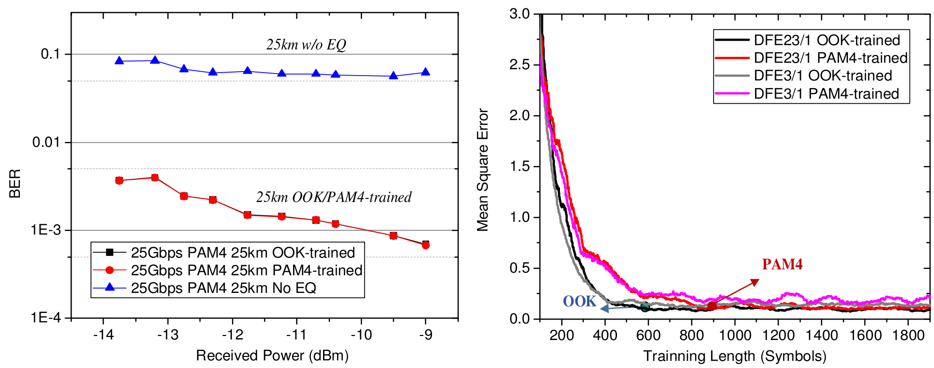
3.2 OOK-Assisted Channel Estimation & Tap Adaption

Secondly, we investigated the tap adaption performance of the OOK-header. For effective and fair equalization performance comparison, 64 OOK symbols are used for symbol timing recovery before equalization processing based on the discussions above. Similarly, two types of data rate are evaluated, i.e., 25-Gb/s and 50-Gb/s PAM4 modulation. For 25-Gb/s case, the signal distortion mainly comes from the chromatic dispersion during 25-km fiber transmission. Fig. 4(a) depicts the measured BER curves for the OOK header and the PAM4 signal for both BtB and 25-km SSMF transmission cases. The sensitivity at BER of 1×10^{-3} for OOK and PAM4 signal is ∼−21.5 dBm and −11 dBm respectively in BtB case. After 25-km transmission, the PAM4 signal is severely distorted as the inset shows, and a BER lower than 1×10^{-2} cannot be obtained. The OOK-signal is also degraded, but the eye diagram is still clearly open and can be correctly demodulated with a sensitivity of ∼−19.5 dBm. To eliminate the chromatic dispersion induced ISI, least mean square (LMS) based tap adaption followed by DFE equalization is performed. The OOK-header and PAM4



(a) (b)

Fig. 4. (a) Measured eye diagram and BER for OOK and PAM4 signal with 12.5G symbol rate in BtB and 25-km transmission cases; (b) BER versus tap number of DFE equalizer.



(a) (b)

Fig. 5. (a) Calculated BER curves of 25-km transmitted 25-Gb/s PAM4 signal after DFE23+1 equalization; (b) MSE versus number of training symbols.

signal are used as training sequence respectively. Firstly, the equalization performance of different feedback and feed-forward tap numbers are investigated. Fig. 4(b) shows the BER performance measured under different DFE and FFE tap number cases using the data sampled at -9 dBm received power as an example. It turns out that the tap adaption performance is almost the same for the OOK- and PAM4-trained cases, which can be verified from the overlapped BER curves in Fig. 4(b). A BER lower than 1×10^{-3} could not be obtained using only FFE equalization. However, when 1 feedback tap is added, the BER decreases obviously, as Fig. 4(b) shows. Further increase the feedback taps to 3, 5 or 7 does not make much improvement. Note that the BER might keep unchanged when the tap numbers are increased because the coefficients of some taps are very small. As a result, 23 FFE taps and 1 DFE tap decreases the BER to 7×10^{-4}.

Then we calculated the BER curve of the equalized 25-Gb/s PAM4 signal using DFE23+1, the results are shown in Fig. 5(a). After equalization, a sensitivity of -10 dBm at BER of 1×10^{-3} is achieved. The tap adaption performances of OOK- and PAM4-training are almost the same as Fig. 5(a) shows. Generally, to realize effective equalization, the training sequence is an already known sequence because the received signal could not be correctly decoded due to the distortion. Therefore, a fast convergence rate is preferred to avoid wasting bandwidth. Fig. 5(b) depicts the convergence of mean square error (MSE) versus training length using LMS algorithm. The convergence value is similar for OOK and PAM4 training, but the convergence rate is different. $\sim$600 symbols are required for training with OOK sequence but 900 symbols are required for PAM4-training. The convergence rate is compared for DFE23+1 and DFE3+1 cases, and similar results are obtained. Therefore, using OOK-header for tap adaption would be a good solution to decrease

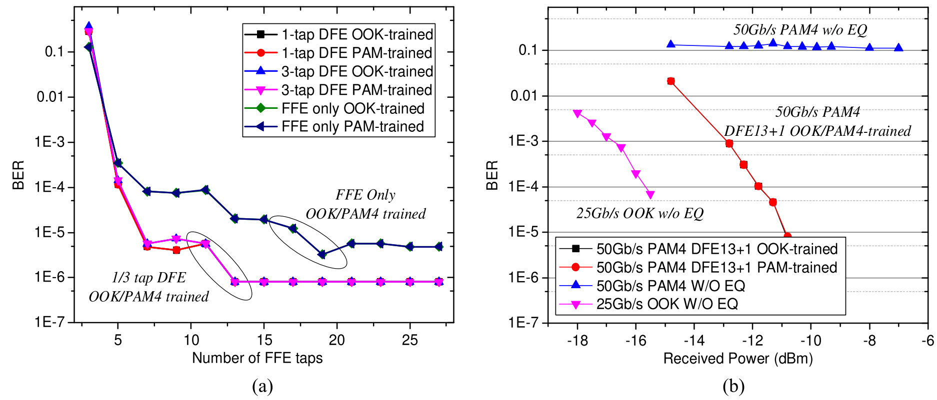


Fig. 6. (a) BER versus tap number of DFE equalizer for 50 Gb/s PAM4; (b) BER curves of 25Gb/s OOK and equalized 50 Gb/s PAM4 signal.

the overhead of PAM4 frame. Note that the BER of the OOK-sequence is much lower than 1×10^{-3}, therefore the training sequence can be correctly decoded from the received signal. In this case, it's not necessary to transmit already known sequences for training, i.e., the training sequence can be used to carry effective information. Conversely, the BER of the PAM4 signal is much higher, therefore the training sequence must be already known by the receiving side and could not be used for effective data modulation. In addition, the convergence rate of OOK signal is faster than PAM4 signal. Therefore, instead of decreasing the data rate, the bandwidth efficiency is improved by using OOK as training header.

The same evaluations are made for 50-Gb/s PAM4 case. As depicted in Fig. 2, the PAM4 signal will be converted into DB-PAM4 format due to the limited bandwidth of transceivers. The data could not be correctly decoded without equalization. As in 25-Gb/s PAM4 transmission case, LMS algorithm is used for tap adaption. The OOK-header and PAM4 signal are used as training sequence respectively. Taking the data sampled at -9.8 dBm received power for calculation, the BER versus feed-forward and feedback tap numbers in DFE equalizer is shown in Fig. 6(a). BER of 8×10^{-7} is obtained using 13-tap FFE and 1-tap DFE. The BER calculated using the taps trained by OOK and PAM4 sequences are overlapped, meaning that the training performance of OOK and PAM4 sequences are almost the same. Further increase the tap numbers makes negligible improvement. Therefore we take DFE13+1 for the following sensitivity evaluation. Fig. 6(b) shows the BER curves of the PAM4 signal and the OOK-header. Without equalization, the BER of the PAM4 signal is $\sim$0.1, but the OOK header can be successfully demodulated with a sensitivity of ~ -16.5 dBm at BER of 1×10^{-3}. After equalization, a sensitivity of ~ -13 dBm at BER of 1×10^{-3} is achieved for PAM4 signal. Similarly, the BER curves equalized with OOK-trained taps and PAM4-trained taps are overlapped, verifying the feasibility of using OOK as the frame header for tap adaption in bandwidth limited system.

Finally, we evaluated the convergence rate of the LMS based tap training. The MSE versus training length using OOK and PAM4 for tap training is depicted in Fig. 7. For DFE3+1, the convergence value is unstable and higher than the DFE13+1 case, corresponding to a weak equalization performance. For DFE 13+1 case, similar results are obtained as in Section 3–1. The convergence value is similar for OOK and PAM4-training case, but the convergence rate using OOK is faster than PAM4 sequence. $\sim$650 symbols are required for OOK-based training while 950 symbols are required for PAM4-training. According to the results above, the net rate can be obtained. Assuming that 10000 symbols are packaged as a packet and 7% hard decision forward error correction coding (HD-FEC) is used, the net rate is calculated to be 22.55 Gb/s and 21.15 Gb/s in OOK- and PAM4-assisted cases respectively for 25 Gb/s data rate case. For 50 Gb/s case, the net rate is 45 Gb/s and and 42 Gb/s for OOK- and PAM4-assisted cases respectively, verifying the benefit of using OOK sequence for tap adaption in a PAM4 transmission system.

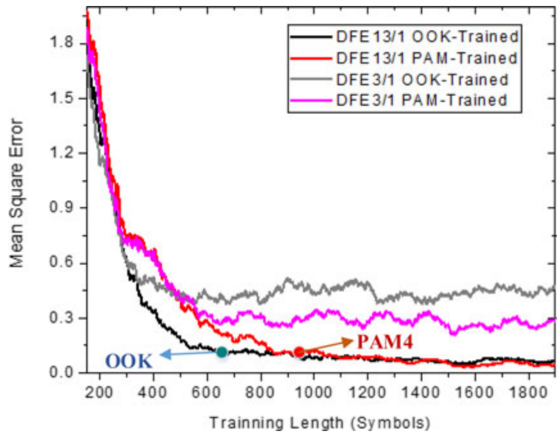


Fig. 7. MSE versus number of training symbols.

4. Conclusion

In this paper, we propose a combined OOK-PAM4 modulation mechanism to facilitate the PAM4 signal processing, where the OOK-header can realize efficient tap adaption and symbol timing recovery within a short symbol length. Compared with PAM4 signal, STR calculation with OOK sequence provides lower timing jitter by using much less symbols. Also, similar tap adaption performance can be realized by using OOK and PAM4 as training sequence, but the convergence rate using OOK is faster than using PAM-4 format. Experimental results show that the proposed OOK-based STR and tap adaption scheme is effective in assisting the digital processing of PAM4 signal distorted by chromatic dispersion and bandwidth limitation. Moreover, as the OOK-format has higher tolerance to fiber chromatic dispersion and device nonlinearity than the PAM4 format with the same symbol rate, the OOK sequence would be less distorted and the OOK-header can be used to carry data as long as the BER is lower than the FEC limit. As a result, by using OOK-sequence for tap adaption and timing recovery, the overhead for PAM4 modulation can be reduced and the bandwidth efficiency is increased.

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