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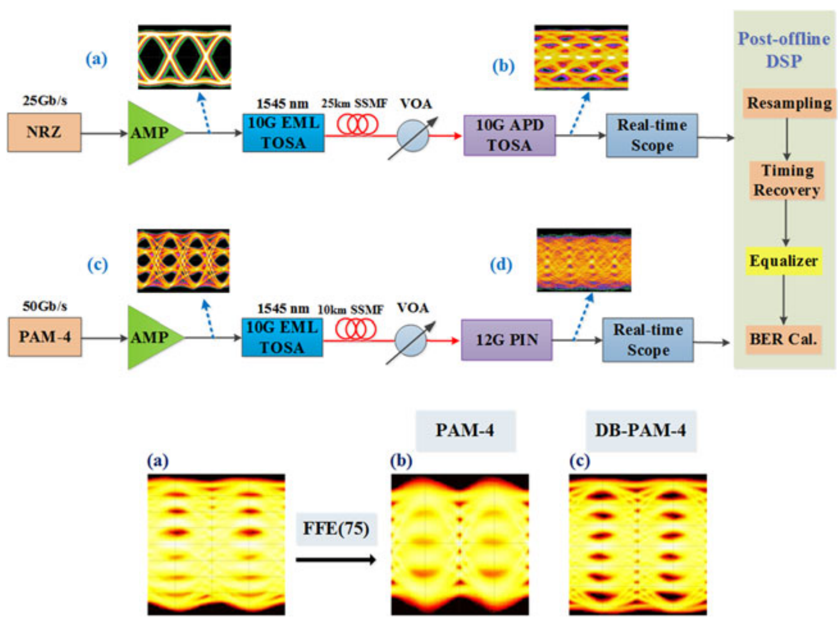

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Tingting Xu, Zhengxuan Li, Junjie Peng, Acai Tan, Yingxiong Song, Yingchun Li, Jian Chen, and Min Wang

Key Laboratory of Specialty Optics and Optical Access Networks, Shanghai Institute for Advanced Communication and Data Science, Shanghai University, Shanghai 200444, China

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Abstract: A simplified maximum likelihood sequence estimation (MLSE) based on Viterbi algorithm has been proposed. Experimental results show that compared with the conventional MLSE, the proposed algorithm saves the multiplication by 25% with no sensitivity penalty when the memory length of MLSE is 2 both in the 25 Gb/s nonreturn to zero and 50 Gb/s four-level pulse-amplitude modulation (PAM-4) transmission systems. In order to further reduce the number of multiplications in the 50 Gb/s PAM-4 transmission system, we use 75 taps of feed-forward equalization to equalize the received PAM-4 signal into duo-binary PAM-4 (DB-PAM-4) signal and then use MLSE with the memory length of 1 to decode, which improves the sensitivity performance by 1.8 dB and reduces the computing complexity by ∼98% compared with conventional MLSE (L = 4) method. As a result, a 10-km C-band transmission of 50 Gb/s PAM-4 signal is achieved using optical transceivers with a combined 3-dB bandwidth of ∼8 GHz, and only 107 multiplications are required by using our proposed simplified algorithm for equalization.

Index Terms: Maximum likelihood sequence estimation (MLSE), Viterbi algorithm, feed-forward equalization (FFE), four-level pulse-amplitude modulation (PAM-4).

1. Introduction

With the significant requirements of mobile front-haul network for the 5-th generation (5G) of mobile communication systems [1] and rapid growth of cloud computing, virtual reality, 4k/8k high-definition video and other high-bandwidth services, the optical access network capacity need to be increased urgently [2]. Over the past few decades, personal access network bandwidth increases at an average annual rate of about 1.5 times. Since 2015, IEEE is exploring the development direction of next generation Ethernet passive optical network (NG-EPON), hoping the optical access network transmission rate increased to 100 Gb/s in 3–5 years by stacking four wavelengths with 25 Gb/s modulation on each [3], [4]. So far, there have been many studies in this area. Optical duo-binary (ODB) [5], [6], electrical duo-binary (EDB) [7], [8], PAM-4 [8], [9] and NRZ [10], [11] modulation schemes are four main advanced modulation techniques which have been studied a lot to achieve 25 Gb/s per channel.

Limited bandwidth of the device, fiber dispersion and fiber nonlinearity [12], [13] will bring some inter-symbol interference (ISI) problems and limit the increasing of transmission rate and the distance. And these problems can be effectively solved by using digital equalizers. Therefore, in the new optical network with high data rate and low cost, there is a certain demand for the equalizers [14]. Recently maximum likelihood sequence estimation (MLSE) has drawn much attention because of its great advantage in eliminating ISI compared with other equalizers, such as FFE and decision feedback equalizers (DFE) [15]–[17]. However, its complexity increases exponentially with the increase of the memory length (L) which leads to an increase in the actual calculation cost. In order to save cost in practical applications, many methods have been adopted to shorten the memory length, such as using FFE [18] or Volterra filter [19] to remove the linear distortions and parts of the nonlinear distortions before MLSE in the system.

In this paper, we propose a simplified MLSE algorithm and apply this algorithm into the 25 Gbps NRZ and 50 Gbps PAM-4 transmission systems. The performances of the simplified MLSE with different memory lengths are analyzed and compared with the conventional MLSE. Experimental results show that compared with the conventional MLSE, the proposed algorithm saves the multiplication by $\frac{1}{L+2}$ with no sensitivity penalty both in the 25 Gb/s NRZ and 50 Gb/s PAM-4 transmission systems. Moreover, a new approach, which equalizes the received signal into a DB-PAM-4 signal, has been adopted to reduce the multiplications of MLSE to a greater degree in the 50 Gb/s PAM-4 transmission system. Experimental results show that we can obtain a performance gain of 1.8 dB with 6037 multiplications reduction utilizing the new approach compared with conventional MLSE (L = 4). As a result, 50-Gb/s transmission is realized using 10-G class devices and complexity-reduced DSP at the receiver, which provides a cost-efficient solution for future PON or short-reach interconnection systems.

2. Experimental Setup

We set up a 10-G optics based 25 Gb/s NRZ and 50 Gb/s PAM-4 transmission systems to evaluate the performances of equalizers. The pseudo random binary sequence (PRBS) data is generated by Arbitrary waveform generator (AWG) to send NRZ or PAM-4 signal at the transmitter side. The signal from the AWG is firstly amplified to a peak-to-peak voltage of 2 V, and then it drives a 10-G electro-absorption modulated laser based TOSA (10G EML TOSA) operating at 1545 nm. After 25-km standard single mode fiber (SSMF) transmission, a 10-G avalanche photodiode based ROSA (10G APD ROSA) converts the received optical signal to electrical signal for detection in the 25 Gb/s NRZ transmission system. Similarly, a 12-G PIN-TIA converts the received optical signal to electrical signal for detection after 10-km SSMF transmission in the 50 Gb/s PAM-4 transmission system. Besides, in order to imitate the optical splitter and measure the receiver sensitivity, we use a variable optical attenuator (VOA) to adjust the received optical power. The outputs of APD and PIN are sampled by DSO with the sampling rate of 80 GSa/s individually and the eye diagram of over 25-km and 10-km SSMF transmission are depicted as (b) and (d) in Fig. 1. Finally, the offline digital signal process is finished in Matlab, including resampling, timing recovery, equalizing and BER calculation modules.

3. Experimental Results

3.1 Simplified MLSE Principle and Experimental Verification

In the presence of ISI and covering $L+1$ interfering symbols, the MLSE criterion can be equivalent to a state estimation problem which can be equated to a discrete time channel with the equivalent coefficients $\{f_0, f_1, \cdots f_L\}$. At any observation time, its state is determined by the recent L inputs. The most commonly used algorithm in MLSE is the Viterbi algorithm where a memory modulation system can be modeled as several finite state machines represented by a trellis. Meanwhile, the sequence can be represented by the path of the trellis. In general, the trellis state is M^L for M-ary modulation where L is the memory length of MLSE. The maximum likelihood sequence

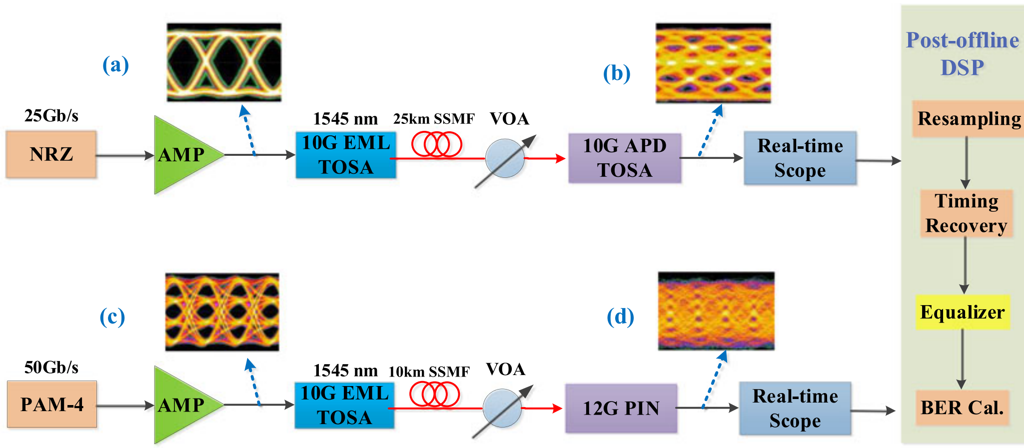

Fig. 1. Experimental setups for 25 Gb/s NRZ and 50 Gb/s PAM-4 transmission systems. Insets: (a) Electrical NRZ eye diagram at the input of EML; (b) Electrical eye diagram received by 10G APD over 25-km SSMF; (c) Electrical PAM-4 eye diagram at the input of EML; (d) Electrical eye diagram received by 12G PIN over 10-km SSMF.

detector (MLSD) which uses Viterbi decoding selects the most probable path through the trellis via measuring the received data sequence $\{y_m\}$ at the sampling instants = mT ($m = 1, 2, \cdots$) where T is the sampling period. Each node in the trellis both has M incoming paths and corresponding metrics. For M corresponding metrics which can also be called branch metric, the conventional MLSE selects one out of the M incoming paths as the most probable path based on the values of the metrics using squared Euclidean distance to the channel-output sequence. The Euclidean distance is denoted as:

$$C_k = (y_k - H * X)^2 = \left(y_k - \sum_{j=0}^{L} f_j I_{k-j}\right)^2 \tag{1}$$

Where y_k is the received data sequence, H is the channel response with the equivalent coefficients $\{f_0, f_1, \cdots f_L\}$, X is the branch data sequence $\{I_k, I_{k-1}, I_{k-2}, I_{k-3}, \cdots, I_{k-L}\}$. From Equation (1), each branch operation requires $L+2$ multiplications totally, where $L+1$ multiplications for H*X operation and 1 multiplication for a square operation. Therefore, MLSE requires $M^{L+1}(L+2)$ multiplications because of $M^L \cdot M$ branches at each sampling instant.

In this paper, we propose a simplified MLSE algorithm to reduce the computing complexity of conventional MLSE which uses the absolute value of the distance instead of the square of the distance in branch metric which can be expressed as follows:

$$C_k = |y_k - H * X| \tag{2}$$

If the channel estimation is accurate, the value of C_k only depends on the effect of noise on the received signal. If the noise has little effect, the difference between the calculation result of absolute value and the square value is very small. The simplified MLSE can reduce the number of multiplications from $M^{L+1}(L+2)$ to $M^{L+1}(L+1)$ in practical applications because of no square operation in each branch metric. The saving rate can be expressed as follows:

$$\text{SR} = \frac{M^{L+1}}{M^{L+1}(L+2)} = \frac{1}{L+2} \tag{3}$$

According to formula (3), we can easily find that the saving rate is only related to L. Thus the saving rate is 25% and 20% for L = 2 and L = 3 cases respectively.

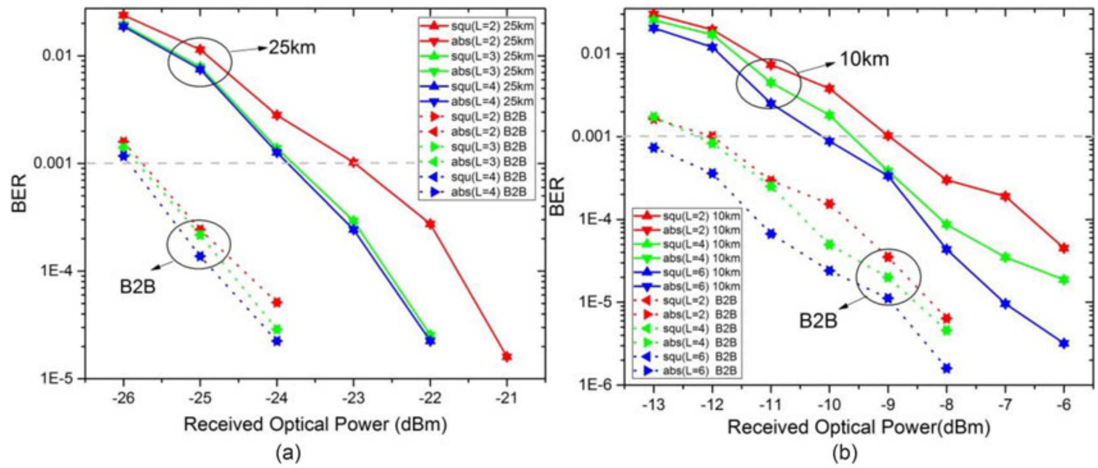

Fig. 2. Measured BER curves with different memory lengths (L) of MLSE using Euclidean distance (squ) and absolute distance (abs) in (a) 25 Gb/s NRZ transmission system over B2B and 25-km SSMF; and (b) 50 Gb/s PAM-4 over B2B and10-km SSMF. L: the memory length of MLSE.

We applied this algorithm in the 25 Gb/s NRZ and 50 Gb/s PAM-4 transmission systems. In order to make the channel estimation more accurately, we use 1000 symbols as the training sequence. The equalization performances of our proposed simplified MLSE using absolute distance (abs) and conventional MLSE using Euclidean distance (squ) are analyzed in Fig. 2. We can find that there is no sensitivity penalty in the proposed simplified MLSE. Compared with B2B case, the signal sensitivity degrades by ∼2.8 dB after 25-km transmission when L = 2 in the 25 Gb/s NRZ transmission system. And the sensitivity can be improved by ∼1 dB when L is increased to 3. Fig. 2(b) depicts the performance of different memory lengths (L) of conventional MLSE and simplified MLSE in the 50 Gb/s PAM-4 transmission system, the signal sensitivity is reduced by 2.7 dB over 10-km transmission in the case of L = 4. Although 0.5-dB sensitivity improvement is obtained when L is increased to 6, its computing complexity grows exponentially with the increase of the memory length. Thus L = 4 is preferred in 50 Gb/s PAM-4 over 10-km SSMF transmission system.

3.2 FFE Combined with MLSE in PAM-4 and DB-PAM-4 Decoding Methods

Considering the system performance, L = 4 is required for 50 Gb/s PAM-4 over 10-km transmission system. In this case, 6144 multiplications are needed for conventional MLSE algorithm. By using our proposed simplified MLSE, the number can be reduced by ∼16.7%, which is still a large amount of computations. To reduce the memory length (L) of MLSE, we use some simple equalizers such as FFE to remove parts of ISI of the signal. As squared timing recovery is performed before the equalization, the adaptive FFE used for pulse shaping is T-spaced instead of T/2-spaced. Recursive least square (RLS) algorithm is employed for tap-training. Fig. 3 shows the measured frequency responses of transceivers used in 25 Gb/s NRZ (EML + APD) and 50 Gb/s PAM-4 (EML + PIN) transmission systems. The 3-dB bandwidth of EML + APD and EML + PIN are both ∼8 GHz. But when the frequency is greater than 8 GHz, the frequency response of EML + APD drops rapidly. Thus the 10-dB bandwidth of EML + PIN is much better than that of EML + APD. The received PAM-4 eye diagrams in the B2B case with these two kinds of transceivers are also given in Fig. 3. Due to the more strict bandwidth limitation of APD, the degree of its eye opening is quite poor compared with PIN as inset (a) shows. Thus the memory length of the MLSE will be longer than that of the EML+PIN when using EML + APD as transceivers in 50 Gb/s PAM-4 transmission system, which results in an exponential increase in the complexity of the MLSE. Considering the computational complexity, we finally use a 12G-PIN as the receiver in the 50 Gb/s PAM-4 transmission system

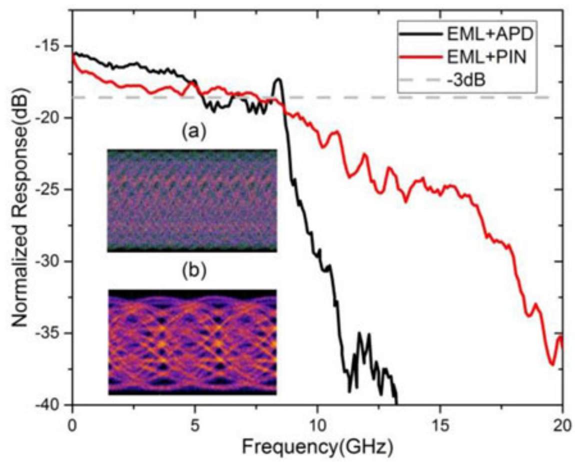

Fig. 3. Measured frequency responses of transceivers used in 25 Gb/s NRZ (EML+APD) and 50 Gb/s PAM-4 (EML+PIN) transmission systems. Insets: Received PAM-4 eye diagrams in the B2B case using transceivers (a) EML+APD; and (b) EML+PIN.

instead of a 10G-APD to further investigate the equalization performances over B2B and 10-km SSMF.

We consider two paths to equalize the received signal. One is to equalize the signal into the original transmitted PAM-4 signal, and the other is to equalize the signal into a DB-PAM-4 signal. As the signal is converted into to DB-PAM-4 format due to the limited bandwidth of the transceivers in our experiment, the dual-binary pulse shaping at the transmitter as in [19] is no longer required, and the non-ideal frequency response can be compensated by using adaptive equalization at the receiver. Then the signal after FFE is decoded using our proposed simplified MLSE. Note that for DB-PAM-4 decoding, the memory length of MLSE is 1 because the channel response H = [1 1] for the partial response signal. However, as the number of taps of FFE is not infinite, it cannot fully equalize the received signal to the ideal DB-PAM-4 signal, and H is trained to be [1.0042 0.9729] in our experiment.

3.2.1 PAM-4 Decoding Method

We firstly use FFE to equalize the signal into the original transmitted PAM-4 signal which reduces linear distortions such as chromatic dispersion during transmission. The memory length of following MLSE is set as 2. As the number of FFE taps increases, system performance improves as Fig. 4 shows. When the taps of FFE is 30, the signal sensitivity is ∼−6.6 dBm at the forward error correction (FEC) threshold (BER $= 1 \times 10^{-3}$). However, the signal sensitivity is increased to ∼−9.5 dBm when the FFE taps reaches 75, which is comparable with MLSE only with a memory length of 4. Compared with B2B case, the signal sensitivity degrades by ∼3.8 dB after 10-km transmission when the taps of FFE is 75. Further increasing the tap number of FFE provides no obvious sensitivity improvement as Fig. 4 shows.

3.2.2 DB-PAM-4 Decoding Method

Then we equalize the signal into a partial response signal with FFE and decode the signal using MLSE with L = 1. The system performance is shown in Fig. 5. The received optical power sensitivity is −10.6 dBm when using 30-tap FFE, which is ∼1.1-dB higher compared with 75-tap FFE combined with MLSE (L = 2). The sensitivity can be further improved ∼0.8 dB by increasing the taps of FFE to 75. The signal sensitivity degrades by ∼1.9 dB after 10-km transmission when the taps of FFE is 75 compared with B2B case. The eye diagrams of the FFE-equalized signal in PAM4 and DB-PAM4

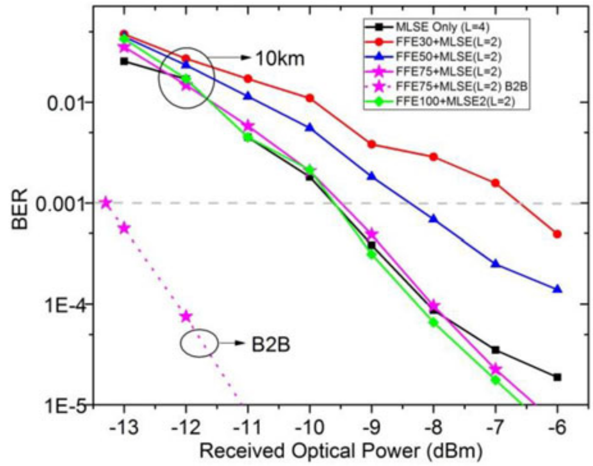

Fig. 4. Measured BER curves with different taps of FFE combined with MLSE (L = 2) in PAM-4 decoding method over B2B and 10-km SSMF. FFE30:30-tap FFE.

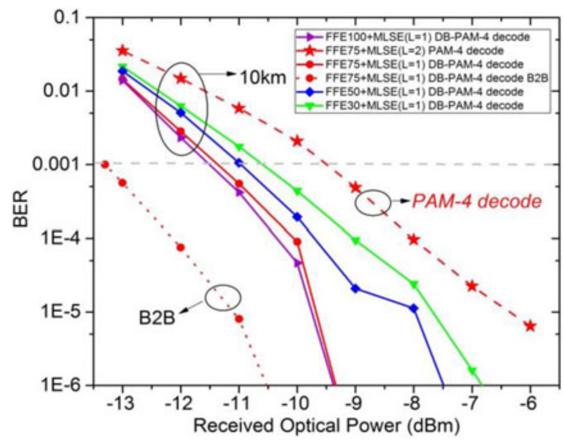

Fig. 5. Measured BER curves with different FFE taps with MLSE (L = 1) in DB-PAM-4 decoding method over B2B and 10-km SSMF.

formats are shown in Fig. 6. It can be seen that when the signal is equalized into a PAM-4 form, the eye opening is not very clear after 75-tap FFE equalizing as in Fig. 6(b). However, there is an obvious improvement when we use 75-tap FFE to equalize the signal into a DB-PAM-4 signal as Fig. 6(c) depicts. As a result, by using 75-tap FFE combined with MLSE (L = 1) based DB-PAM-4 decoding, a sensitivity of −11.4 dBm can be achieved, which is ∼1.9 dB higher than the PAM-4 decoding case.

3.3 Complexity Comparison

Table 1 concludes the comparison of different equalization methods on the number of multiplications and received signal sensitivity in 50 Gb/s PAM-4 transmission system. We give the calculation methods for the number of multiplications of different equalizers in Table 1, where N, M and L represent the number of FFE taps, M-ary modulation and the memory length of MLSE respectively. On the one hand, we compare all the equalization methods with the conventional MLSE (L = 4). Firstly, we can see that the use of our proposed simplified MLSE (L = 4) saves 1024 multiplications and has no received sensitivity loss. Secondly, in the case of 75-tap FFE combined with simplified MLSE in PAM-4 decoding method (L = 2), there is a reduction of 5877 multiplications with nearly

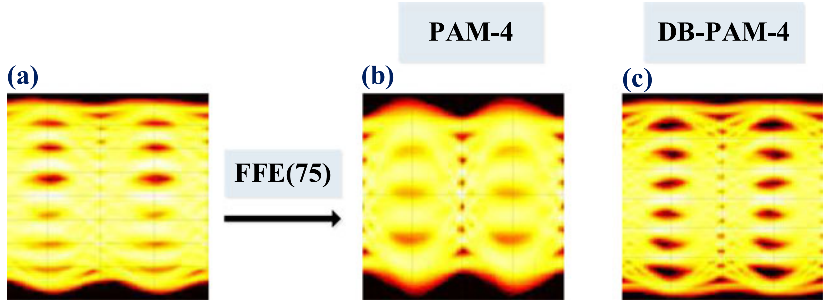

Fig. 6. Eye diagrams at −9 dBm received power in the 50 Gb/s PAM-4 transmission system. (a) without any equalization; (b) after 75-tap FFE before MLSE(L = 2) with PAM-4 decoding method; (c) 75-tap FFE before MLSE(L = 1) with DB-PAM-4 decoding method.

TABLE 1
Comparison of different equalization methods on the number of multiplications and received optical power sensitivity in 50 Gb/s PAM-4 transmission system

Equalization methods	Decoding methods	The number of multiplications	Signal sensitivity (dBm)
Conventional MLSE (L=4)	PAM-4	$M^{L+1}(L+2)$ 6144	-9.6
Simplified MLSE (L=4)	PAM-4	$M^{L+1}(L+1)$ 5120	-9.6
FFE75 + Conventional MLSE (L=2)	PAM-4	$N+M^{L+1}(L+2)$ 331	-9.5
FFE75 + Simplified MLSE (L=2)	PAM-4	$N+M^{L+1}(L+1)$ 267	-9.5
FFE75 + Conventional MLSE (L=1)	DB-PAM-4	$N+M^{L+1}(L+2)$ 123	-11.4
FFE75 + Simplified MLSE (L=1)	DB-PAM-4	$\boldsymbol{N+M^{L+1}(L+1)}$ **107**	**-11.4**

no received sensitivity loss. Finally, by using the DB-PAM-4 decoding method, the length of L is further reduced to 1, at this time, the number of multipliers can be minimized as the multiplications is greatly reduced by ∼98%. However, it still can obtain a 1.8-dB performance gain. On the other hand, we compare the equalization methods with the conventional MLSE (L = 2) combined with 75-tap FFE. With PAM-4 decoding method, our simplified MLSE combined with the same tap size of FFE saves the multiplications by ∼19%. It is worth mentioning that the multiplications of 75-tap FFE combined with simplified MLSE (L = 1) in DB-PAM-4 decoding method is reduced by ∼68%, which also brings 1.9-dB performance improvement compared with the conventional MLSE (L = 2) combined with 75-tap FFE.

4. Conclusion

In this paper, we have proposed a simplified MLSE algorithm and verified its feasibility in a 10-G optics based 25 Gb/s NRZ and 50 Gb/s PAM-4 transmission system. The simplified MLSE has no sensitivity penalty compared with conventional MLSE, while it reduces 25% and 20% multiplication operations for L = 2 and L = 3 cases respectively. In addition, we use 75-tap FFE to shorten the memory length of MLSE to 1 in DB-PAM-4 decoding method in 50 Gb/s PAM-4 transmission system, and it provides a performance gain of approximately 1.8 dB, reducing 6037 multiplications compared with conventional MLSE (L = 4). 1.9-dB sensitivity improvement and 160 multiplications can be saved compared with 75-tap FFE combined with simplified MLSE (L = 2) in PAM-4 decoding method. As a result, 50-Gb/s transmission is realized using 10-G class devices and complexity-reduced DSP at the receiver, providing a practical solution for future PON or short-reach interconnection systems.

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