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Experimental demonstration of low complexity hybrid FFE algorithm for strictly band-limited IM/DD system

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ABSTRACT

Feed forward equalizer (FFE) has been widely used in high-speed short-haul optical transmission. When system suffers from serious inter-symbol interference (ISI), i.e. low-cost transceiver induced narrow-bandwidth limitation, FFE with large number of taps is necessary, which significantly increases the computational complexity. In this paper, we proposed a hybrid FFE (H-FFE) algorithm with tap delay adjusted between T space and T/2 space. Enabled by the H-FFE and conventional T/2-spaced FFE algorithms, we demonstrated the intensity modulation and direct detection (IM/DD) transmission of 56, 70, and 80 Gbaud PAM4 signals over standard single mode fiber (SSMF) links up to 2, 1 km and 500 m employing the 18 GHz (3 dB) system bandwidth at C band. The experimental results indicate that the proposed H-FFE algorithm has the similar performance with the conventional T/2-spaced FFE algorithm. In addition, using the proposed H-FFE algorithm, the computational complexity is one third of that of the conventional T/2-spaced FFE algorithm.

1. Introduction

Most popular Internet applications including the Internet of Things (IoT), cloud computing and fifth-generation (5G) front-haul and back-haul transmissions have increased pressure on bandwidth limitation of existing high-speed short-haul optical communication [1]. Considering system cost, power consumption, footprint and latency, intensity modulation and direct detection (IM/DD) system remains the most viable solution for short-haul optical transmission [2–4]. To increase the capacity of IM/DD system, advanced modulation formats including pulse amplitude modulation (PAM) [5–9], discrete multi-tone (DMT) [10,11] and carrier-less amplitude and phase modulation (CAP) [12,13] have been widely used. Among these three advanced modulation formats, PAM4 is the most promising option to provide a high data rate with relatively low cost. In particular, the IEEE 400GbE P802.3bs task force has adopted PAM4 for data center interconnects [14]. In recent years, the digital signal processing (DSP) technology in the electrical domain has been used to overcome short-haul optical transmission impairments including component bandwidth limitations, impairments introduced by nonlinear modulation characteristics and chromatic dispersion (CD) in the fiber channel [15]. It is worth to note that the feed forward equalizer (FFE) is a promising candidate to compensate for various transceivers and channel impairments, especially for inter-symbol interference (ISI) [16–19]. For IM/DD system with limited bandwidth, low-cost electronic and optical devices and CD, serious ISI can be induced. In this way, FFE with large number of taps is needed, which increases the computational complexity, power consumption and latency of the system. Therefore, how to reduce the computational complexity of large taps FFE algorithms without degrading performance has become an urgent problem for the short-haul optical communications. There are ways to reduce the complexity. Frequency domain equalizer (FDE) can be employed instead of time domain equalizer (TDE) for linear FFE equalization, which can significantly reduce the complexity of linear FFE equalizer [20,21].

In this paper, we propose and experimentally demonstrate a low complexity hybrid FFE (H-FFE) algorithm, of which the tap delay is flexible by properly tuning the tap delay between T space and T/2 space. We successfully transmit 56, 70, and 80 Gbaud PAM4 signals over 2, 1 km and 500 m standard single mode fiber (SSMF) in a 3 dB bandwidth 18 GHz IM/DD system at C band. Considering the enormous computational complexity of T/2-spaced FFE with large number of taps, we use the H-FFE algorithm to omit several taps. The experimental results show that the BER is close to the floor when an appropriate ratio of T-spaced and T/2-spaced taps is used. Compared with the conventional T/2-spaced FFE algorithm, the computational complexity of the H-FFE algorithm can be effectively reduced by about 70% with similar transmission performance.

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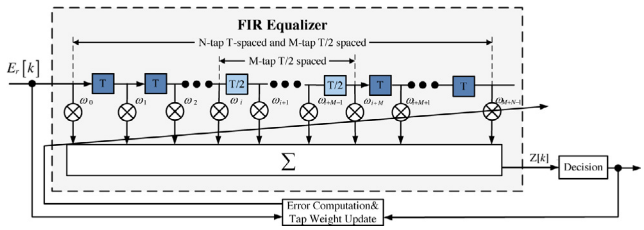

Fig. 1. Block diagram of the proposed H-FFE algorithm.

2. Theoretical analyses

A linear equalizer has played an important role in ISI compensation for high-speed short-haul optical transmission. This is due in large part to its simple structure and easy implement. However, hundreds of taps are needed for FFE if the signal suffers from serious ISI. Moreover, dominant ISI is caused by the adjacent symbols. According to this characteristic, a hybrid equalizer can be utilized to reduce the number of taps.

2.1. Principle of hybrid FFE (H-FFE)

When the IM/DD system suffers from serious ISI, ignoring the nonlinear distortions, at the receiver side, the original signal is distorted with severe pulse broadening, and the detected signal can be expressed as,

$$r(t) = \sum_{n=-\infty}^{\infty} a_n h(t - nT_s) + n(t) \tag{1}$$

where a_n is the original signal, $h(t)$ is the channel response of the system, $n(t)$ is the additive noise.

After ADC sampling, we can get the discrete signal expressed as,

$$r(kT_s + t_0) = a_k h(t_0) + \sum_{n \neq k} a_n h[(k-n)T_s + t_0] + n(kT_s + t_0) \tag{2}$$

where the first term represents the desired signal while the second term is the value of ISI, which is associate with the characteristic of transmission channel and transceiver components. The last term is the additive Gaussian noise at the kth sampling instant. And the dominant ISI existed in adjacent symbols. We use T/2-spaced FFE in adjacent symbols and T-spaced FFE in distant symbols to reduce the computational complexity.

Fig. 1 shows the block diagram of our proposed H-FFE algorithm, which is also referred to as tapped delay line, having an output given by,

$$z[k] = \sum_{j=0}^{i-1} \omega_j E_r((k-j)T) + \sum_{j=i}^{M+i} \omega_j E_r((k-j)\frac{T}{2}) + \sum_{j=i+M+1}^{N+M-1} \omega_j E_r((k-j)T) \tag{3}$$

where *z[k]* is the equalizer output, ω is the tap weight, N and M are the numbers of taps with tap spacing of T and T/2, respectively. The tap weights can be adaptively updated by the least-mean-square (LMS) algorithm.

2.2. Computational complexity

The computational complexity is one of the most attention issues for short-haul optical transmission. Here, the computational complexities of H-FFE algorithm mentioned above and conventional T/2-spaced FFE algorithm are analyzed in detail. The required number of mathematical operations including real multiplication (RM) and real addition (RA) is evaluated for every symbol.

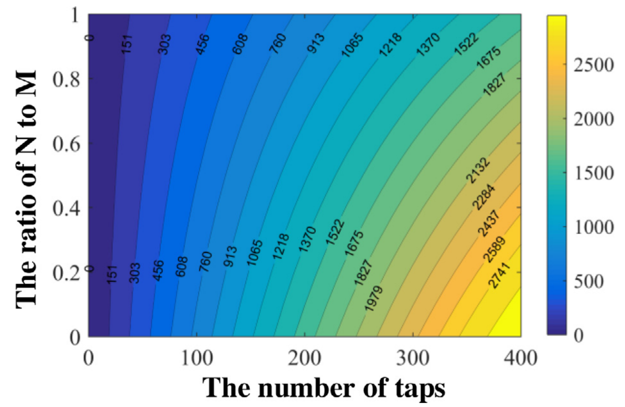

Fig. 2. The total number of the computational operations for each symbol as a function of the tap number for FFE algorithms with different tap ratio.

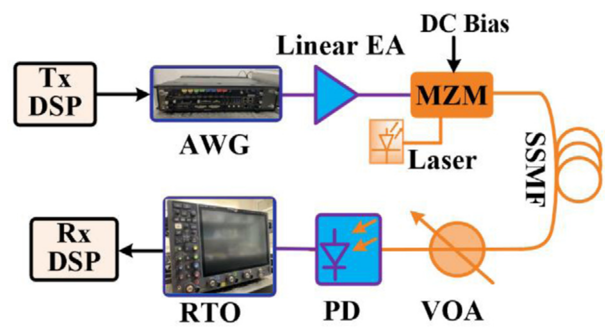

Fig. 3. Experimental setup of IM–DD system.

FFE is also referred to as finite impulse response (FIR) filter. For a static N-taps T-spaced FIR filter, it requires N RMs and *N-1* RAs for every output symbol. As for LMS based T-spaced FFE algorithm, the tap updating, error calculation and equalization are done every sample. Therefore, it requires *N+1* RMs and N RAs for every adaptive iteration. While for M-taps T/2-spaced FIR filter, which is operated at two samples per symbol, twice RMs and RAs of static T-spaced filter is necessary and the LMS based T/2-spaced FFE algorithm requires *2M+1* RMs and *2M* RAs for every adaptive iteration. The computational complexity of FFE with different taps is depicted in Fig. 2. The equipotential line represents the total number of the computational operations for every symbol, changing with the ratio of two type taps and the total number of taps. It can be seen that with the increase of the total number of taps, the effect of the FFE with more T-spaced taps on reducing the computational complexity is more obvious. When system suffers from serious ISI, in other word, when large number of taps are needed, the complexity can be effectively reduced by using our proposed H-FFE algorithm.

3. Experiment setup

The experimental setup of IM/DD transmission system is depicted in Fig. 3.

At the transmitter side, a pseudo random binary sequence (PRBS) with length of 2^{16}-1 is mapped into PAM4 format. DSP steps are employed to deal with the PAM4 signal, as shown in Fig. 5. After pre-emphasis, the PAM4 signal is uploaded into an arbitrary waveform generator (AWG) (Keysight M8196 A) operated at 92 GSa/s for digital-to-analog (D/A) conversion. Then a linear EA (SHF 807) is used to boost the electrical signal, which drives a Mach–Zehnder modulator (MZM) (FTM7937) with a C band ECL laser. The output optical signal is launched into SSMF. At the receiver side, a variable optical attenuator

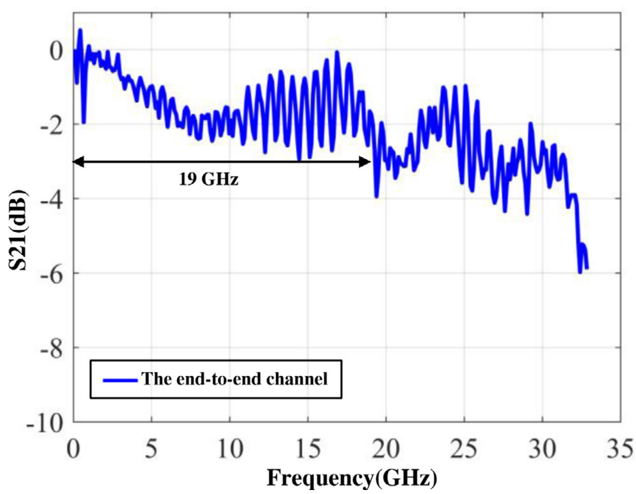

Fig. 4. The end-to-end frequency response of IM/DD system.

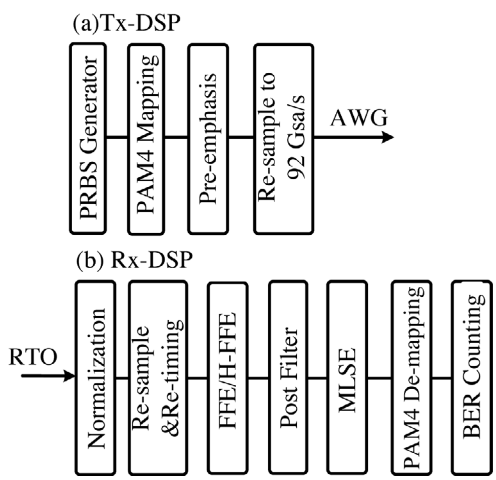

Fig. 5. The DSP blocks for PAM4 signal at the transmitter and the receiver.

(VOA) is placed after SSMF to adjust the received optical power (ROP). Then the signal is detected by a PD (FINRSAR XPDV2120ra) and captured by a real time oscilloscope (RTO) (UXR0334 A) operated at 128 GSa/s, with 33 GHz cutoff bandwidth. In addition, the end-to-end channel frequency response is measured, as shown in Fig. 4. It can be seen that 3 dB bandwidth of the system is about 19 GHz and the channel response is rugged, which is caused by the low-cost transceiver.

Fig. 5 shows the DSP procedures at the transmitter and the receiver side. At the transmitter DSP, pre-emphasis is used to compensate for linear impairments caused by the bandwidth limitation of the AWG, modulator and RTO. Thus, the signal to noise ratios (SNR) of the high frequency components can be increased. At the receiver side, after normalization and re-sample, digital square is used for timing recovery. Here, a T/2-spaced FFE and our proposed H-FFE algorithms are used to compensate for the bandwidth limitation and CD induced ISI. The coefficients of the FFE taps are adapted using training symbols aided LMS algorithm. As the linear equalizer is a full band response equalizer, the high frequency components of the enhanced in-band noise are also amplified, and this can be suppressed by the post filter, which also induced serious ISI. The maximum likelihood sequence estimation (MLSE) is used to eliminate the influence of ISI and the nonlinear distortions caused by the low-cost devices. Finally, the BER is measured by a bit error counter.

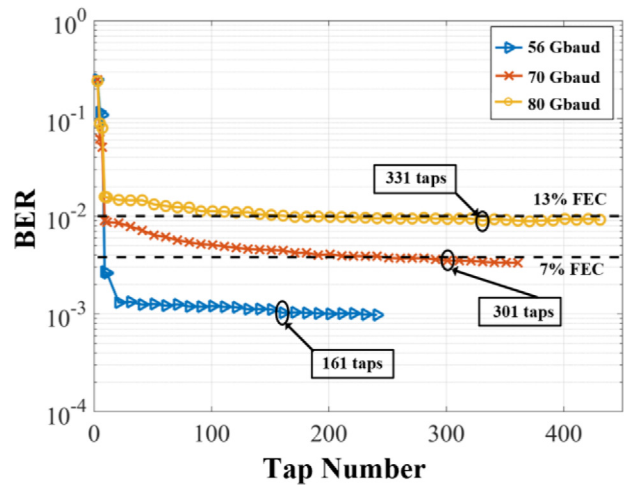

Fig. 6. BER as a function of tap number for 56, 70, and 80 Gbaud PAM4 signals using conventional T/2-spaced FFE algorithm at BTB transmission.

4. Results and discussion

The number of taps of FFE affects the performance and the complexity of the system. We first optimize the total tap number of the conventional T/2-spaced FFE algorithm in back to back (BTB) scenario.

The BER performance as a function of the number of taps for 56 Gbaud with a ROP of −4 dBm, 70 Gbaud with a ROP of −3 dBm and 80 Gbaud with a ROP of 3 dBm PAM4 signals at BTB scenario is shown in Fig. 6. More taps are needed for signals with higher baud rate, which has been more seriously influenced by the bandwidth limitation and CD induced ISI. It can be seen that with the conventional T/2-spaced FFE algorithm, the system performance can achieve optimum and keep stable by 161, 301, and 331 taps for 56, 70, and 80 Gbaud PAM4 signals, respectively. These results are used in the following experiment. According to the method of calculating computational complexities introduced in the principle part, large number of mathematical operations are needed for symbols with these three baud rates, which can increase the complexity, power consumption and latency of the system.

Our proposed H-FFE algorithm can be used to meet the data rate requirements in a complexity-effective manner. To find the optimal ratio of T-spaced taps and T/2-spaced taps, we keep the same ROPs as in Fig. 6 and fixed the equalizer length which has obtained in Fig. 6 for 56, 70, and 80 Gbaud PAM4 signals, respectively. By scanning the number of T/2-spaced taps, and using our proposed H-FFE algorithm, the BER performance versus the T/2-spaced tap number is shown in Fig. 7. It can be seen that H-FFE algorithm with 9, 11, and 15 T/2-spaced taps can keep relatively stable for these three baud rates (according to the numbers of T-spaced taps are 76, 145, and 158). In this way, the computational operations for each symbol can be reduced.

To obtain the optimal performance of the system, the conventional T/2-spaced FFE and the H-FFE configurations with taps mentioned above are investigated. Comparing the performance of the conventional T/2-spaced FFE with our proposed H-FFE algorithms, the variation of BER results as a function of ROP for the PAM4 signals at 56, 70, and 80 Gbaud are further measured, as shown in Fig. 8. A higher baud rate causes an obvious reduction on the maximum achievable distance, which is caused by the bandwidth limitation and CD. In the case of 56 Gbaud PAM4 signal shown in Fig. 8(a), for both optical BTB and 2 km transmission can reach BER at 3.8E−3 of 7% FEC threshold when receiver sensitivities are −5.2 dBm and −3 dBm, respectively. Using the corresponding H-FFE algorithm, similar performance can be observed. For the 70 Gbaud PAM4 signal as shown in Fig. 8(b), the transmission of 1 km can be achieved with −0.8 dBm receiver sensitivity at 7%

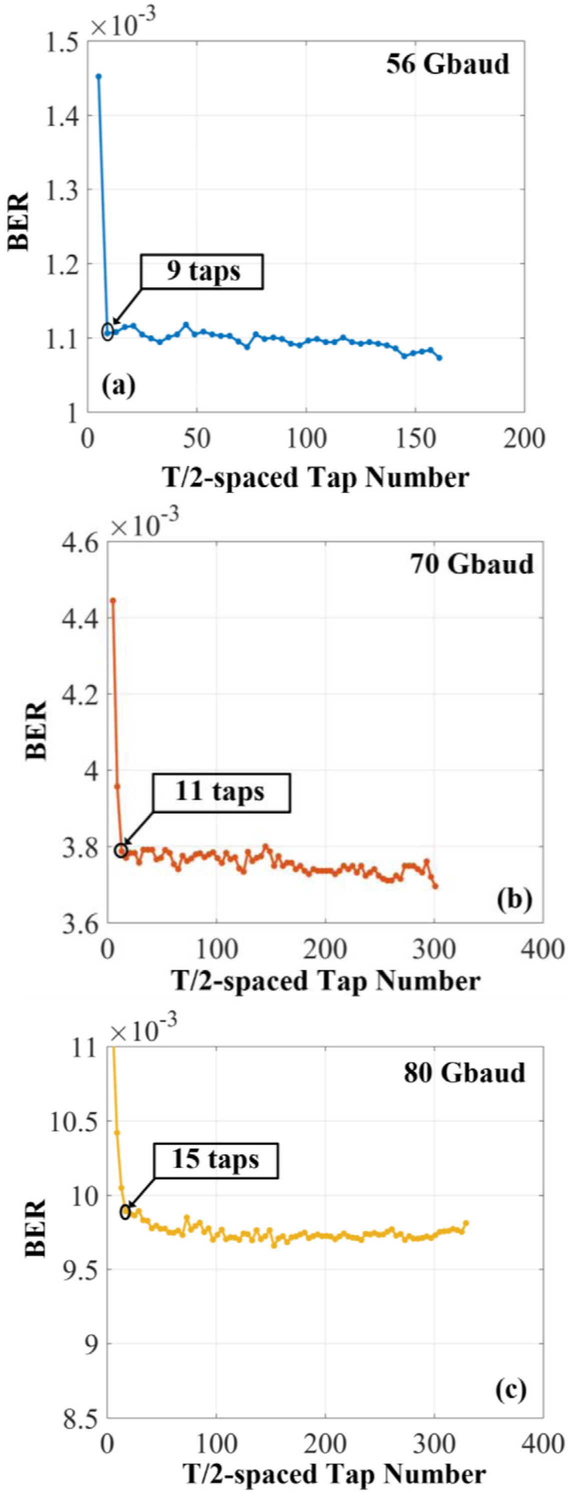

Fig. 7. BER as a function of T/2-spaced tap number for 56, 70, and 80 Gbaud PAM4 signals using H-FFE at BTB transmission.

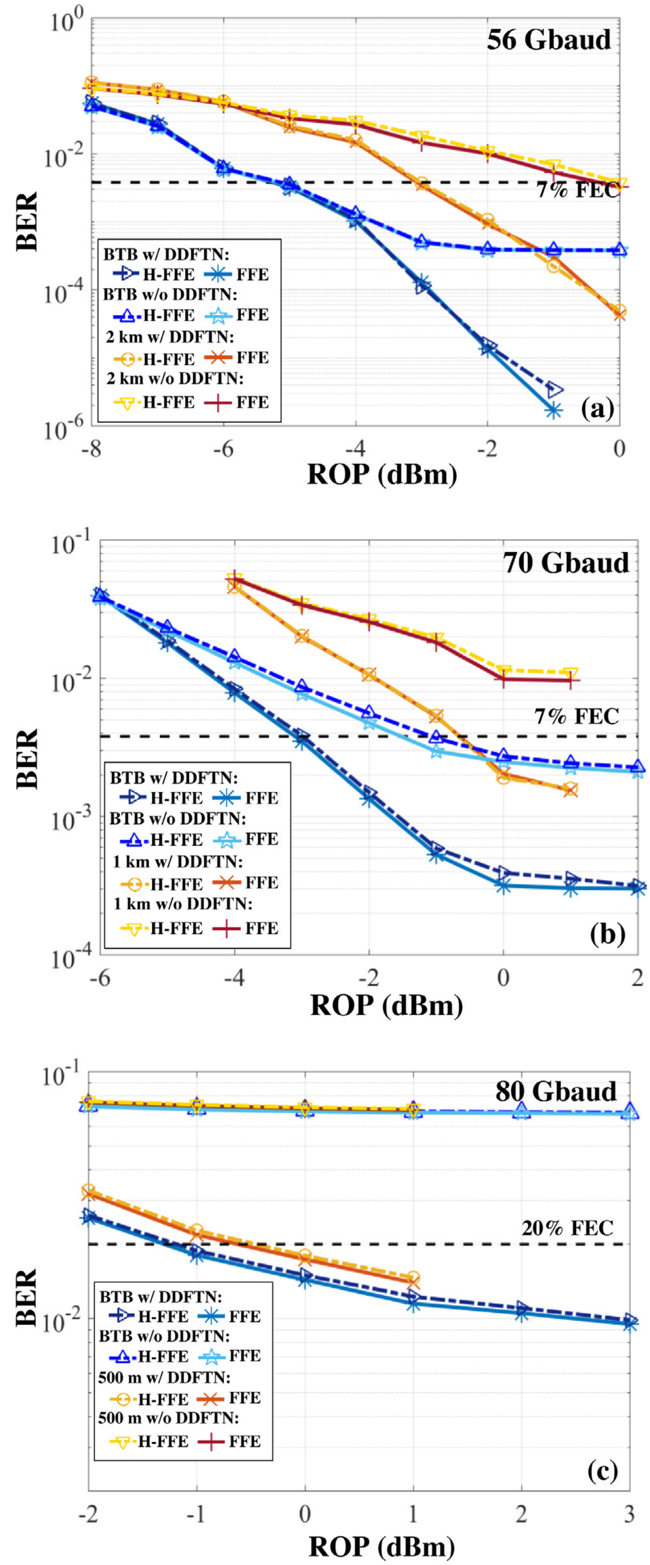

Fig. 8. BER performance versus ROP using conventional FFE and H-FFE algorithms for 56, 70, and 80 Gbaud PAM4 signal.

FEC threshold. The application of the H-FFE algorithm provides significantly computational complexity reduction with negligible sensitivity decreased. The performance for the 80 Gbaud PAM4 signal is further studied. Using the conventional T/2-spaced FFE algorithm, the receiver sensitivity at the BER of 1E-2 for BTB transmission is 2.8 dBm. For 500 m transmission, the 80 Gbaud PAM4 signal can reach BER at 2E-2 of 20% FEC threshold where the receiver sensitivity is −0.6 dBm. The proposed H-FFE algorithm is capable to achieve similar performance compared with the conventional FFE algorithm.

Finally, Table 1 summarizes the properties and computational complexities of 56, 70, and 80 Gbaud PAM4 systems with T/2-spaced FFE and our proposed H-FFE algorithms. In Table 1, the total concrete

Table 1
Properties and computational complexity of 56, 70, and 80 Gbaud PAM4 systems with T/2-spaced FFE and our proposed H-FFE algorithms.

Baud rate	H-FFE tap number (Number of operations per symbol)	T/2-spaced FFE tap number (Number of operations per symbol)	Complexity reduced
56 Gbaud	9 T/2-spaced and 76 T-spaced taps (375)	161 (1287)	71%
70 Gbaud	11 T/2-spaced and 145 T-spaced taps (667)	301 (2407)	72%
80 Gbaud	15 T/2-spaced and 158 T-spaced taps (751)	331 (2647)	72%

numbers of computational operations per symbol are counted based on Section 2.2. For 56 Gbaud PAM4 signal, 161-taps T/2-spaced FFE algorithm requires total 1287 operations, and the computational operations can be reduced to 375, owing to the H-FFE algorithm. In this case, about 71% (1-375/1287) computational complexity reduction can be achieved. Regarding the 70 and 80 Gbaud PAM4 signals with 301/331 taps T/2-spaced FFE algorithms, employing H-FFE algorithms, the receiver computational complexity can be reduced by 72%. Therefore, we concluded that our proposed H-FFE algorithm can be used to replace the conventional T/2-spaced FFE algorithm with the advantage of lower computational complexity.

5. Conclusion

In this paper, we experimentally studied the performance of 56, 70, and 80 Gbaud PAM4 signals using the conventional T/2-spaced FFE and our proposed H-FFE algorithms in IM/DD system. For 56 Gbaud PAM4 signal, H-FFE with 9 T/2-spaced taps and 76 T-spaced taps can be used to achieve 2 km transmission with -3 dBm receiver sensitivity. The receiver sensitivity of −0.8 dBm is observed for 70 Gbaud PAM4 signal transmission of 1 km at the 7% FEC threshold by using H-FFE with 11 T/2-spaced taps and 145 T-spaced taps. With 15 T/2-spaced taps and 158 T-spaced taps H-FFE, the receiver sensitivity of 80 Gbaud PAM4 signal below the 20% FEC threshold can be reached −0.6 dBm after transmission of 500 m. The results show the difference between the performance of FFE and H-FFE algorithms can be ignored. Furthermore, we also analyzed the computational complexity of these two equalizer algorithms. With similar performance our proposed H-FFE algorithm can reduce the computational operations for every symbol by about 70%, which can significantly reduce the computational complexity, power consumption and latency of the system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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