Joint Frequency and Time Domain Frame Synchronization for Short-Reach IM/DD Optical Fiber Transmission Systems

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***Abstract*—A low-complexity joint frequency and time domain frame synchronization method based on PAM4 training sequence is proposed for short-reach IM/DD systems. Compared with the traditional method, the results in 50 Gbit/s PAM4 transmission systems show the proposed method reduces the computational complexity by 97.09% without performance penalty.**

***Index Terms*—frame synchronization, PAM4, training sequence, computational complexity**

I. Introduction

Driven by the rapid growth of capacity in data center interconnects, technologies to equalize channel impairments have been extensively researched [1]. Usually, in practical link transmission, frame synchronization is a precondition for equalization [2]. For the received signal, to identify the start-of-frame through frame synchronization technology is necessary before equalization and decoding. Incorrect frame synchronization may affect the equalization performance of the signal [3]. Therefore, frame synchronization is a crucial task for successful data reception. The IEEE P802.3bs Task Force has started to standardize four-level pulse amplitude modulation (PAM4) as the modulation format for 400-GbE transmission [4].

Frame synchronization is used in many fields such as fiber optic transmission systems [5], visible light communication systems [6] and free-space optical communication systems [7]. In optical fiber transmission systems, frame synchronization methods can be mainly divided into two categories [8]–[10]. The first kind of frame synchronization is realized by constructing a training sequence as frame head of signal, and then calculating the correlation at the receiver side according to the structure of frame head. For example, in the classical Schmidl's method, two identical training sequences are designed as frame head [8]. Then the frame synchronization is achieved by calculating the timing metric function of the received signal and searching for the maximum value. However, the timing metric function obtained by this method is not always sharp enough, resulting in inaccurate synchronization information. Park's method modified it by employing a conjugated and symmetric training sequence structure to generate a sharp pulse-shaped timing metric curve [9]. The second kind method achieves frame synchronization by calculating the cross-correlation between the training sequence in transmitted signal and the received signal [10]. This method is mainly used in intensity modulation/direct detection (IM/DD) systems, which is named as the traditional method here. However, the traditional method requires traversing the whole frame of data to calculate the cross-correlation in sliding window, which leads to huge complexity in practice, especially for the received signal with long length.

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In this paper, we design a PAM4 training sequence to achieve low-complexity frame synchronization for short-reach IM/DD systems. The amplitude of the PAM4 training sequence on frequency spectrum is significantly higher than that of normal signal. Taking advantage of this property, coarse synchronization can be performed by searching for peaks in the frequency domain. Subsequently, fine synchronization is achieved by calculating the cross-correlation between a small part of received signal obtained from the coarse synchronization and the training sequence of transmitted signal. Introducing the PAM4 training sequence designed in this paper greatly reduces the data length of subsequent cross-correlation operations. Hence, the computational complexity is significantly reduced. The feasibility of the proposed method is demonstrated by simulating 50 Gbit/s PAM4 on back-to-back (BTB) and fiber link transmission in IM/DD systems. Compared with the traditional method, the computational complexity of the proposed method is reduced by 97.09% without any performance degradation.

II. Principle of Joint Synchronization in Frequency Domain and Time Domain

Synchronization algorithms usually rely on cyclic prefix or known training sequence [11]. Compared with the two, although the training sequence will increase the overhead, it has a better anti-interference effect on the intersymbol interference caused by delay. Therefore, synchronization methods based on training sequence are widely used [12], [13]. In this paper, a special PAM4 training sequence is designed, as shown in Fig. 1. It consists of four levels, which named 0, 1, 2 and 3 respectively here. The length of PAM4 training sequence is N, where each level is repeated n times.

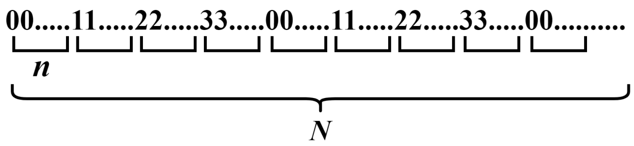

Fig. 1. Structure of the PAM4 training sequence.

Fig. 2 shows the spectrum of the PAM4 training sequence and normal PAM4 signal, where N are both 256, and n is set to 6 and 11 respectively. The selection about n will be discussed in more detail in section III. From the Fig. 2, it can be found that the designed PAM4 training sequence (red curve) shows obvious peaks on the spectrum, which is much larger than the amplitude of normal PAM4 signal (blue curve), regardless of the value of n. Based on this feature, a coarse synchronization method in frequency domain is proposed, that is, the approximate position of the frame head is determined by searching the peak of the spectrum.

The schematic of frequency domain synchronization is shown in Fig. 3. A frame of data in the received signal is divided into m segments, and the length of each segment is N. The Fast Fourier Transform (FFT) is performed on each segment separately, and then the spectrum peak A for each segment is found. In this way, m peaks are obtained. Assuming that A_k is the maximum of these peaks, then the position of the frame head is locked to the k^{th} segment. It should be noted that in the process of randomly splitting the received signal into equal segments, the PAM4 training sequence is likely to be split into two and mixed with the normal signal. In this case, the k^{th} segment contains only a part of the PAM4 training sequence. Therefore, to ensure that the frame head is fully covered, we select three-segment signal as the result of coarse synchronization in the frequency domain. That is the k^{th} segment and its left and right adjacent segments.

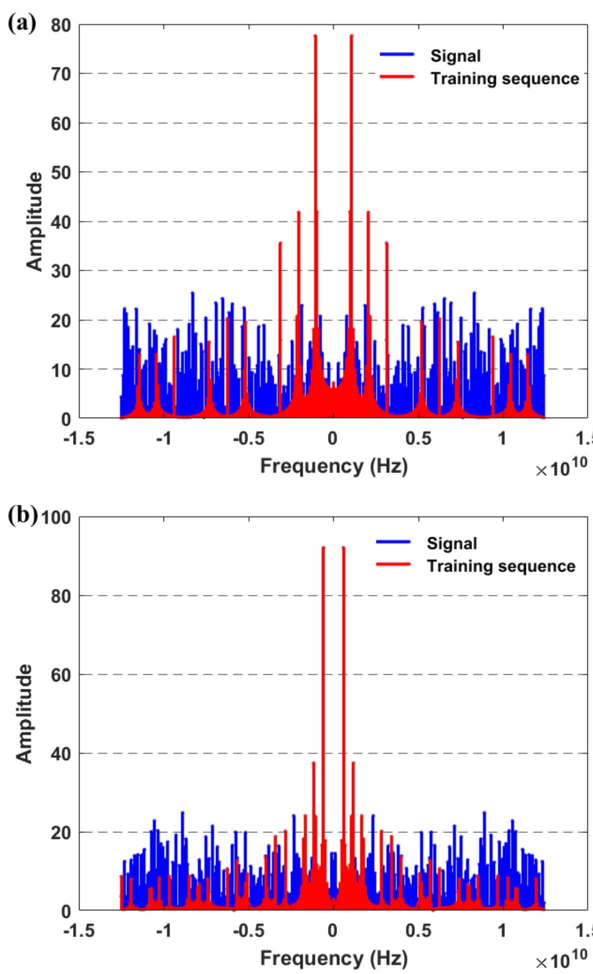

Fig. 2. The spectrum of the PAM4 training sequence and normal PAM4 signal corresponding to different n. (a) n=6; (b) n=11.

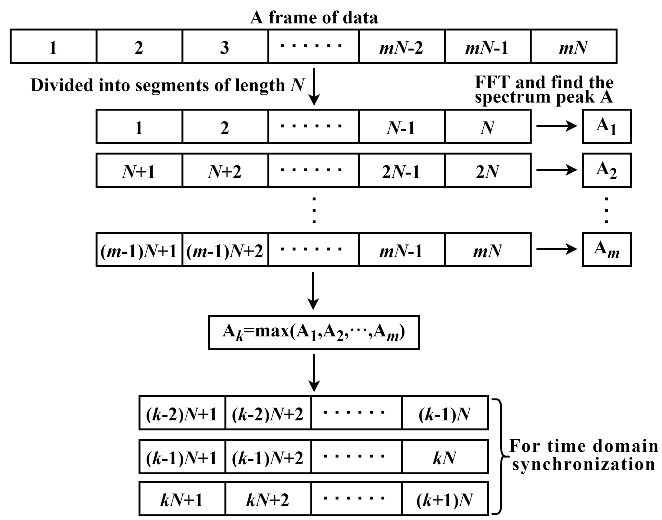

Fig. 3. Schematic of frequency domain synchronization.

After the coarse synchronization in frequency domain, time domain synchronization is operated by calculating the cross-correlation between above three-segment signal and PAM4 training sequence to achieve fine synchronization, as shown in Fig. 4. The PAM4 training sequence at transmitter is denoted as S with a length of N. The signal obtained after frequency domain synchronization is denoted as R with a length of $3N$. Take a sliding window of length N to calculate the cross-correlation between R and S. It can be expressed as:

$$\eta_p = \sum_{i=1}^{N} S_i \times R_{p+i-1} \tag{1}$$

where p is the starting of each sliding window. When the cross-correlation value reaches the maximum, it means that the similarity between R and S is the highest. Thus we can obtain:

$$P = \arg\max_{p} \{\eta_p\} \tag{2}$$

where P is the start-of-frame in the received signal. That is, the position of the frame head.

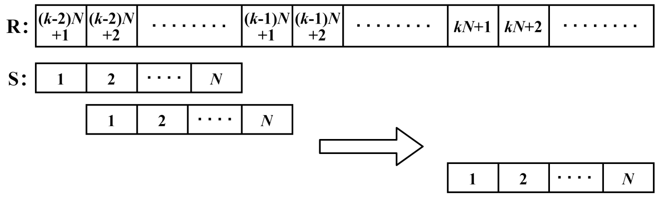

Fig. 4. Schematic of time domain synchronization.

The principle of time domain synchronization in the proposed method is similar to that of traditional method [10]. It is worth noting that the data length of the two methods for cross-correlation is different. For traditional method, R represents the whole frame of data in the received signal [14]. However, for time domain synchronization of the proposed method, R is only a small part of a frame of data, which will greatly reduce the computational complexity. The computational complexity will be discussed in section IV.

III. Simulation System Setup and Results Analysis

To demonstrate the validity of the proposed joint frame synchronization method, we set up a simulation platform for the 50 Gbit/s PAM4 system, as shown in Fig. 5. In the simulation, the starting of the received signal is the same as that of the transmitted signal. But in the experiment, since the transmitted signal is sent cyclically, the starting of the received signal we get is not always the start-of-frame in the transmitted signal. Considering this situation, the transmitted signal in the simulation is set to be composed of three parts, that is, payload, PAM4 training sequence and payload in order. A laser with a center frequency of 193.1 THz and a linewidth of 100 kHz is used to generate the continuous optical carrier. The electrical signal is modulated to optical domain by a 25-GHz Mach-Zehnder modulator (MZM). Then, an erbium-doped fiber amplifier (EDFA) is used to control the launch optical power. The chromatic dispersion (CD) of standard single-mode fiber (SSMF) is 17 ps/nm/km, the nonlinearity is 1.3 /W/km, and the fiber attenuation is 0.2 dB/km. After that, the amplified spontaneous emission (ASE) noise is added by "Set OSNR" module to adjust the optical signal-to-noise ratio (OSNR). At the receiver, a variable optical attenuator (VOA) is used to adjust the received optical power. The signal is detected by a 22-GHz photodiode (PD) to achieve photoelectric conversion. The filters in the system are used to simulate the bandwidth of MZM and PD, respectively.

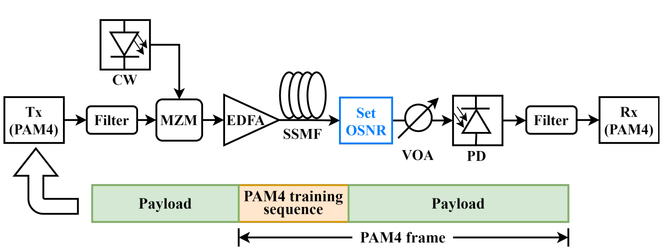

Fig. 5. Simulation setup of the 50 Gbit/s PAM4 system.

For frequency domain synchronization, the signal is divided into m segments. By comparing the peaks of each spectrum, the largest peak is found out to locate the approximate position of the frame head. Considering that the randomness of noise interference will affect the peak search, 100 seed numbers of ASE noise are traversed in the simulation to better evaluate the correct rate of synchronization.

A. Effect of Training Sequence Structure on Joint Frequency and Time Domain Synchronization

From Fig. 1, it can be noticed that the PAM4 training sequence structure is related to the value of n. Therefore, we investigate the effect of the n on the synchronization performance. The curve of the synchronization correct rate varies with the n is shown in Fig. 6. The length of PAM4 training sequence is 256, and the OSNRs are set to 8 dB, 10 dB and 12 dB, respectively. It can be observed that, the synchronization correct rate gradually increases with the increase of the n. However, the bigger n is not the better. When the n exceeds 11, the correct rate begins to decrease. For different OSNRs, the trend of the curve is similar. Under the condition of n=11, the synchronization correct rate is the highest. Therefore, the PAM4 training sequence at n=11 is the best choice for the synchronization method proposed in this paper, and the subsequent research is based on this structure.

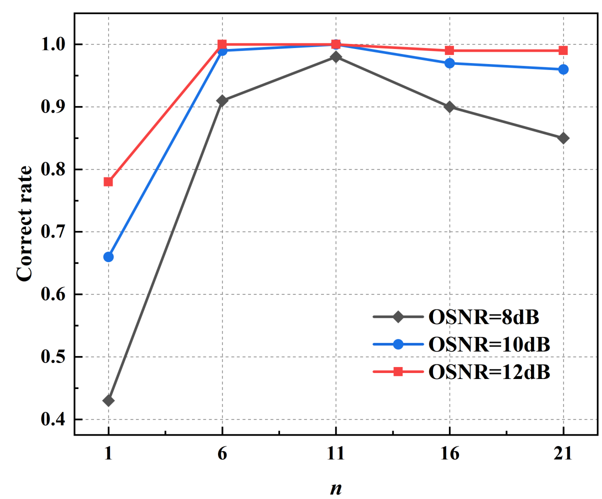

Fig. 6. Correct rate versus n with OSNR of 8 dB, 10 dB and 12 dB.

B. Effect of ASE Noise on Joint Frequency and Time Domain Synchronization

The Fig. 7 shows ASE noise effect on the synchronization correct rate when the N is 128, 256, and 512. It can be seen that for different PAM4 training sequence lengths, the synchronization performance improves with the increase of OSNR. When the OSNR corresponding to the N of 128, 256 and 512 is larger than 12 dB, 10 dB and 10 dB respectively, the correct rate can reach 100%, indicating that the synchronization of the proposed method in 100 samples with different ASE seed numbers is correct. In addition, with the increase of the N, the robustness of the proposed method to ASE noise is enhanced. This is because the spectrums corresponding to PAM4 training sequence with different length are different. The spectral peak of the PAM4 training sequence increases as the increase of the N, which makes it better distinguished from the peak of the normal signal. Thereby, the anti-noise ability of frequency domain synchronization is enhanced and the error probability is reduced. Although the synchronization performance of the proposed method can be improved by appropriately increasing the length of the PAM4 training sequence, it will also increase the system overhead and reduce the spectrum utilization. Therefore, the selection of the length of PAM4 training sequence requires a trade-off between synchronization performance and system efficiency.

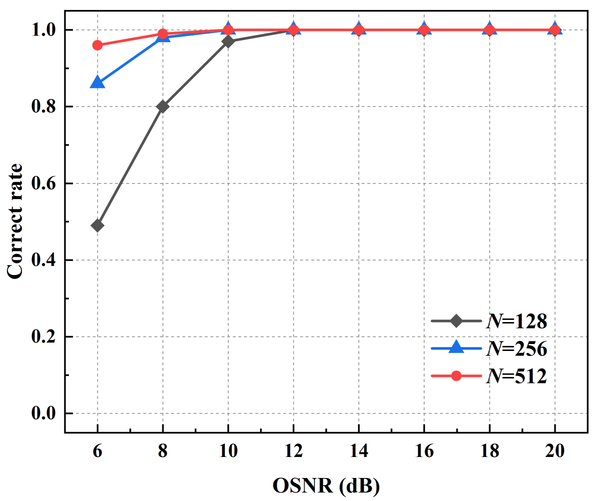

Fig. 7. Correct rate versus OSNR with the N of 128, 256 and 512.

In order to compare the performance of the proposed method with traditional method, the back-to-back (BTB), 10 km, 20 km and 30 km transmission systems have been researched respectively when the length of PAM4 training sequence is set to 256. The results are shown in Fig. 8. It can be found that the synchronization correct rate of different transmission distances increases with the increase of OSNR. For BTB transmission, the synchronization correct rate of both methods can reach 100% at the OSNR of 10 dB. When the transmission distance is 10 km, the correct rate can reach 100% at the OSNR of 12 dB. And when the transmission distance is 20 km and 30 km, the synchronization correct rate of both methods can be improved to 100% at the OSNR of 14 dB. These results verify the effectiveness of the proposed method. Meanwhile, the results obtained by the proposed method are basically consistent with the traditional method, showing that the both methods can achieve the same synchronization effect in the short-reach IM/DD optical fiber transmission systems.

IV. Computational Complexity Analysis

An efficient synchronization technology, in addition to having excellent performance, is also critical to achieve fast

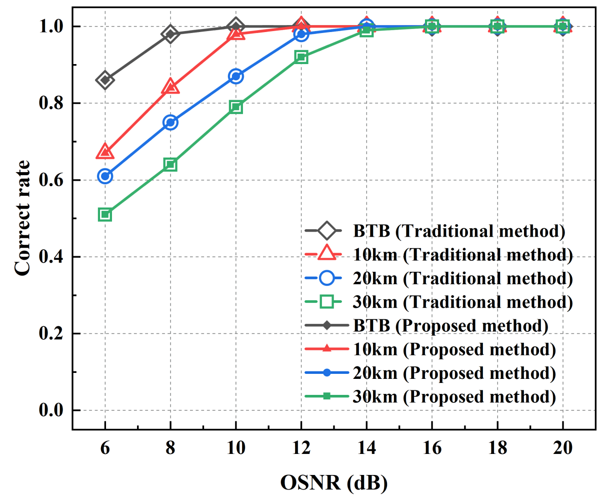

Fig. 8. Correct rate versus OSNR with the transmission distance of BTB, 10 km, 20 km and 30 km.

computations for practical applications [5]. Here, the computational complexity of our proposed method and the traditional method is analyze and compared. The computation can be mainly divided into multipliers, adders and comparators. For the traditional method, the PAM4 training sequence at transmitter needs to slide on a whole frame of data in received signal to calculate the cross-correlation. Therefore, $N \times M + 2M$ multipliers are required to calculate the cross-correlation and the absolute values, where N is the length of the PAM4 training sequence and M represents the length of a frame of data in the received signal. Furthermore, $(N-1) \times M$ adders and $M-1$ comparators are also required to identify the maximum cross-correlation value. For the proposed method, coarse synchronization in the frequency domain requires performing FFT on m segments of data with length of N separately and takes the absolute values to calculate the peak of the spectrum. This process requires $N/2 \times \log_2 N + 2N \times M/N$ multiplications and $(N-1) + (M/N-1)$ comparators. The fine synchronization of the proposed method only uses a small part of a frame of data to calculate the cross-correlation with the PAM4 training sequence at transmitter. It takes $N \times 3N + 2 \times 3N$ multiplications, $(N-1) \times 3N$ adders, and $3N-1$ comparators.

When M=131072 and N=256, the complexities of the traditional method and the proposed method are summarized in Table 1. The proportions of multipliers, adders and comparators required for the proposed method are only 2.91%, 0.59% and 1.17% of that for the traditional method, respectively. That is, the proposed method can reduce computational complexity by 97.09%. These results indicate that our proposed joint synchronization method can significantly reduce the computational complexity, without the synchronization performance penalty in comparison with the traditional method. The reason can be attributed to that the subsequent cross-correlation calculations are greatly reduced by the frequency domain synchronization in the proposed method. It is worth noting

TABLE I
COMPUTATIONAL COMPLEXITY COMPARISON

Synchronization Method	Category		
	Multipliers	***Adders***	***Comparators***
Traditional method	33816576	33423360	131071
Proposed method	984576	195840	1533
Proposed/Traditional	2.91%	0.59%	1.17%

that the above results are all calculated when the data length M is only 131072. In fact, the data length of one frame for synchronization is far more than this value [15], and then the advantage of the proposed method in terms of complexity will be more obvious. Therefore, the proposed method is desired for optical fiber communication systems that are sensitive to cost and delay.

V. CONCLUSION

In this paper, we propose a low-complexity joint frequency and time domain frame synchronization method based on PAM4 training sequence. The results of 50 Gbit/s PAM4 systems for both BTB and fiber link transmission showing that, compared with the traditional method, the proposed method can reduce computational complexity by 97.09% without performance penalty. We believe that the proposed method has a certain practicability in the short-reach IM/DD optical fiber transmission systems which are cost- and delay-sensitive.

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