Multi-core fiber channel equalization algorithm based on K nearest neighbor method

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Abstract. Aiming at the channel damage problems of multi-core fiber (Multi-core Fiber, MCF), the AKNN (Adapted K-Nearest Neighbor) algorithm is proposed. The MATLAB software was used to simulate the channel of the seven-core fiber, both the inter-core crosstalk (Crosstalk, XT) and nonlinear effects were considered. Then the KNN algorithm was adapted to equalize the damaged signal at the receiver. The simulation results show that the AKNN algorithm possesses better BER performance and lower OSNR requirements with the extension of transmission distance, compared to traditional KNN algorithm.

1 Introduction

With the rise of new services such as artificial intelligence, high-definition video and virtual reality, the network traffic increases sharply. As the main transmission technology of the network, optical fiber communication system needs to develop in the direction of large capacity and long distance. Light wave is the carrier of information transmission, and its physical multiplexing dimension includes five aspects, namely time, frequency, polarization, phase/amplitude and space [1-4]. At present, space division multiplexing (SDM), the spatial dimension in optical fiber communication system, has become a key technology to break through the capacity limitation of optical fiber communication system [5,6], which mainly realizes mode multiplexing and core number expansion in a single optical fiber. Generally, optical signal transmission in optical fiber channel will be affected by Gaussian noise, dispersion and nonlinear effects. However, multi-core optical fiber may bend or deform in the actual transmission process, resulting in crosstalk between different cores and affecting the communication quality.

Aiming at the problem of damage equalization in multi-core optical fiber communication system, this paper first models the channel of seven-core optical fiber transmission system, and introduces KNN algorithm to equalize the damage signal at the receiving end, then optimizes and improves the traditional KNN algorithm, proposes an adaptive KNN algorithm, and finally gives the simulation results and analysis.

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2 Seven core optical fiber transmission system

In the optical communication system transmitted by multi-core optical fiber, the transmission of optical signal in the core p of optical fiber generally follows the nonlinear Schrodinger equation (NLSE) [7,8]:

$$\frac{\partial A_p}{\partial z} = i\beta_{p0}A_p - \beta_{p1}\frac{\partial A_p}{\partial t} - \frac{i\beta_{p2}}{2}\frac{\partial^2 A_p}{\partial t^2} + \frac{i\gamma}{3}\sum_{lmn} f_{plmn}\left[\left(A_l^T A_m\right)A_l^* + 2\left(A_l^H A_m\right)A_l\right] + i\sum_m q_{mp}A_m \quad (1)$$

A_p is the signal strength in the core p, β_{p0} is the propagation constant of the core p, β_{p1} and β_{p2} are the first-order propagation constant and the second-order propagation constant respectively, γ is the nonlinear coefficients, l, m and n represent other cores. When the optical signal is transmitted in multi-core optical fiber, the nonlinear coupling coefficient f_{plmn} is:

$$f_{plmn} = A_{eff}\iint F_l F_m F_n^* F_p^* dxdy \quad (2)$$

F_m is the normalized mode field of the core and $\iint \left|F_m\left(x,y\right)\right|^2 dxdy = 1$, A_{eff} is the effective area of the mode field. Linear crosstalk term q_{mp} is that the optical signal in core p is crosstalk by other m cores. In multi-core optical fiber, in addition to the spontaneous crosstalk between different cores, the distortion or bending of multi-core optical fiber will also cause crosstalk between different cores. Figure 1 shows the seven-core optical fiber structure adopted, which adopts the same fiber core, that is, the signal in each fiber core is subject to the same interference. In terms of inter core crosstalk, it is designed that each fiber core is only subject to the crosstalk of adjacent cores, that is, cores 2-7 are only subject to the crosstalk of three adjacent cores. For example, core 2 will only have inter core crosstalk with core 3, core 7 and core 1, while core 1 will have inter core crosstalk with all other cores because it is in the middle. The channel matrix of inter core crosstalk of seven core optical fiber is as follows:

$$\begin{pmatrix} \boldsymbol{E}_1' \\ \boldsymbol{E}_2' \\ \boldsymbol{E}_3' \\ \boldsymbol{E}_4' \\ \boldsymbol{E}_5' \\ \boldsymbol{E}_6' \\ \boldsymbol{E}_7' \end{pmatrix} = \begin{pmatrix} I & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} & C_{17} \\ C_{12}^* & I & C_{23} & 0 & 0 & 0 & C_{27} \\ C_{13}^* & C_{23}^* & I & C_{34} & 0 & 0 & 0 \\ C_{14}^* & 0 & C_{34}^* & I & C_{45} & 0 & 0 \\ C_{15}^* & 0 & 0 & C_{45}^* & I & C_{56} & 0 \\ C_{16}^* & 0 & 0 & 0 & C_{56}^* & I & C_{67} \\ C_{17}^* & C_{27}^* & 0 & 0 & 0 & C_{67}^* & I \end{pmatrix} \begin{pmatrix} \boldsymbol{E}_1 \\ \boldsymbol{E}_2' \\ \boldsymbol{E}_3' \\ \boldsymbol{E}_4' \\ \boldsymbol{E}_5' \\ \boldsymbol{E}_6' \\ \boldsymbol{E}_7' \end{pmatrix} \quad (3)$$

$\boldsymbol{E}_1 \sim \boldsymbol{E}_7$ is the incident signal, $\boldsymbol{E}_1' \sim \boldsymbol{E}_7'$ is the signal after inter core crosstalk, C_{ij} is the crosstalk matrix between different cores, C_{ij}^* is the conjugate of C_{ij},

$$C_{ij} = \begin{bmatrix} h_{ij} & k_{ij} \\ p_{ij} & q_{ij} \end{bmatrix} \quad (4)$$

Each element in C_{ij} represents the crosstalk between the polarization of the optical signal transmitted in the two cores, which can be expressed as $x+iy$. If the polarization correlation is not considered, x and y follow the Gaussian distribution, then

$$x = y = n * \frac{nn}{2} * K^2 \tag{5}$$

K is the coupling coefficient between cores, n is the number of segments to add inter core crosstalk, nn is the number of randomly and uniformly distributed phase terms (In the process of optical fiber transmission, the non-uniformity of optical fiber structure and the bending in the process of use are random, so crosstalk is a random quantity with statistical characteristics).

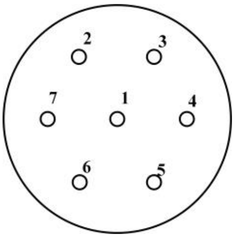

Fig. 1. Structure diagram of seven core optical fiber.

3 Multi-core fiber channel equalization scheme based on K-nearest neighbor method

3.1 KNN algorithm

The steps of KNN equalization of damaged 16QAM signal are follows[9,10]: 16QAM signal is composed of 16 constellation points, 16 constellation points are regarded as 16 clusters, and each cluster contains many constellation points. Each constellation point is two-dimensional in the constellation diagram, For a constellation point p, it can be expressed by its in-phase component $I(p)$ and orthogonal component $Q(p)$, In the KNN equalization process, a group of data is sent to the channel as training data. Training data $\{(p_1,l_1),(p_2,l_2),\dots,(p_N,l_N)\}$ are composed of N data points p_i with label $l_i \in L$, where label set $L=\{1,2,\dots,16\}$ represents 16 coordinates of 16QAM constellation, as shown in Figure 2 (a). The test data to be balanced has no label. In Fig. 2 (b), it can be seen that the test data point p_q is surrounded by four training data clusters "10", "11", "14" and "15". These numbers are labels pasted for the training data according to the constellation points. Then, it is necessary to calculate the European distance from the test data to each training data, the Euclidean distance between p_q and any training data point p_i is defined as:

$$d\left(p_q, p_i\right) = \sqrt{\left(I\left(p_q\right) - I\left(p_i\right)\right)^2 + \left(Q\left(p_q\right) - Q\left(p_i\right)\right)^2} \tag{6}$$

Then, the obtained Euclidean distance is arranged in the order from small to large, k nearest training data points are determined, and the set $N_k\left(p_q\right)$ composed of their indexes is obtained, KNN aims to provide a reasonable class label prediction function model f_{KNN} for the test data p_q of the location:

$$f_{KNN}\left(p_q\right)=\arg \max_{l\in L} \sum_{i\in N_k\left(p_q\right)} \varepsilon\left(l,l_i\right) \tag{7}$$

where $\varepsilon\left(l,l_i\right)=1$ if $l=l_i$, $\varepsilon\left(l,l_i\right)=0$ if $l\neq l_i$. Therefore, k labels corresponding to k nearest training data points can be obtained, and the label with the most frequent occurrence can be used as the prediction classification of the data point p_q. For example, as shown in Figure 2 (b): assuming k = 7, the seven nearest training data points are found for p_q, and their labels are {10, 10, 10, 11, 14, 14, 15}. The output result obtained according to f_{KNN} is "10", because most, that is, four out of seven data points have labels "10", p_q is classified as data with labels "10", and get the constellation points that should be judged.

Compared with other equalization algorithms, KNN algorithm is relatively simple. There is no data set in the training stage. There are classification and eigenvalues in advance. It can be directly processed after receiving new samples and used to identify different types of data. So it is particularly effective in processing two-dimensional signal data sets with large data set and low dimension.

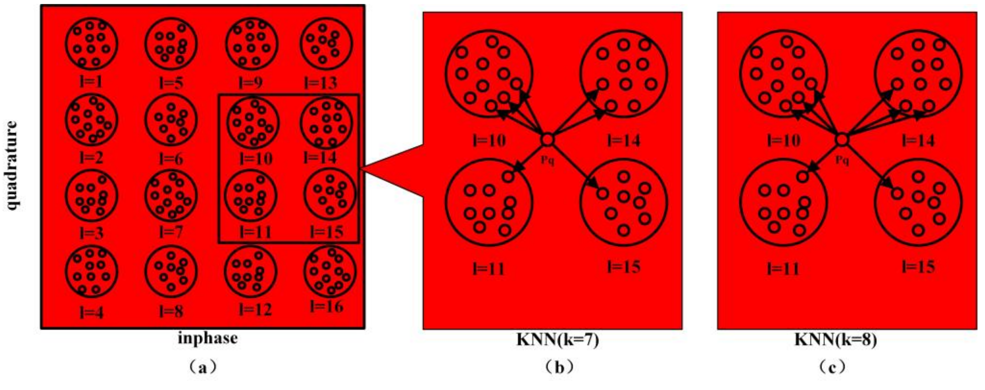

Fig. 2. Schematic diagram of KNN equalization 16QAM signal. (a) 16QAM signal constellation; (b) Classification of p_q when k=7; (c) Classification of p_q when k=8.

3.2 Construction of simulation system

The simulation model of seven core optical fiber transmission system is shown in Figure 3. At the transmitting end, the light source sent by the transmitting laser is modulated into 16QAM signal by two I/Q modulators driven by four-level pulse amplitude modulation electrical signals, and then sent seven channel multi-core multiplexer;, Signal transmit in fiber with a transmission power of 0dBm, a optical signal-to-noise ratio(OSNR) of 18dB, and a fiber attenuation of 0.2dB/km; The symbol rate of a single fiber core is set to 40Gbaud / s, so the total bit rate is 1.12Tbit/s. The transmission length of the optical fiber is divided into N spans, each span is 80km, n is set to 15, that is, the transmission distance is 1200km. An optical amplifier with amplification power of 16dB is set on each step to compensate the optical fiber attenuation; At the receiving end, the signal is separated into seven signals by demultiplexer, which are sent to the digital signal processing system for KNN equalization after filtering, coherent detection and photoelectric detection.

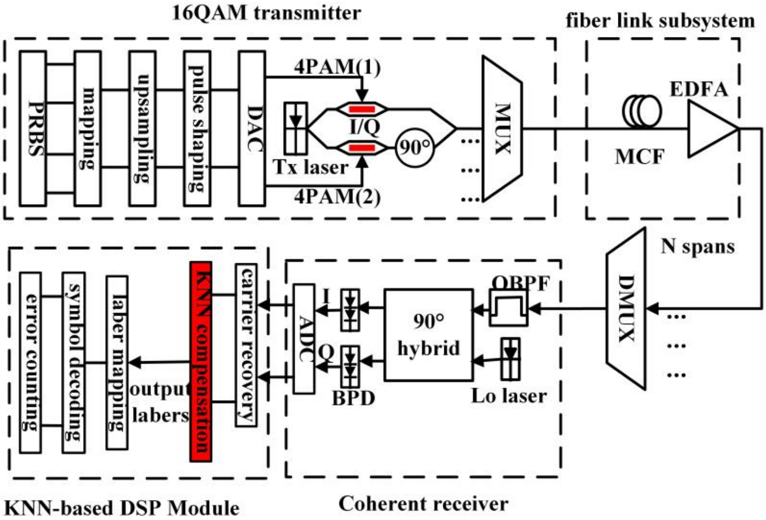

Fig. 3. Model diagram of 16QAM signal transmission through seven-core optical fiber.

4 Multi core fiber channel equalization scheme based on adaptive KNN algorithm

In the process of KNN equalization, the data is divided into two groups: one group of 5000 data points is used as training data, and the other group of 100000 data points is used as test data, so as to carry out KNN equalization at the receiving end. By changing the value of k parameter, the curve between k value and bit error rate is obtained:

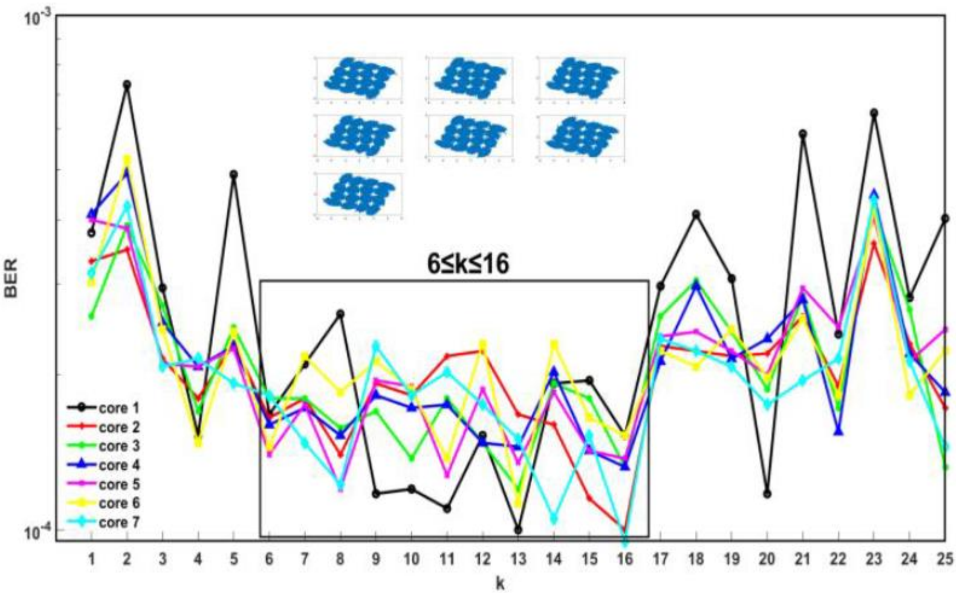

Fig. 4. Variation of BER with k value in seven-core fiber.

Figure 5 shows that when the value of K is small, the bit error rate performance is poor, because too few training data points are found for each test data point, which will make the algorithm performance unstable; When the value of K is large, a large number of irrelevant training data will be included in the set. These irrelevant data will interfere with the final classification results, resulting in the decline of bit error rate performance. In addition, it can be seen that the performance of KNN algorithm is relatively stable when $6 \leqslant k \leqslant 16$. Next, according to the bit error characteristics of multi-core fiber signal after KNN equalization, the KNN algorithm is improved.

In the KNN algorithm, because the traditional European algorithm is used, the contribution of each feature to the classification is the same, which obviously does not accord with the actual situation. The same weight makes the similarity calculation between feature vectors inaccurate, resulting in the impact on the classification accuracy. For example, in Figure 3 (c), when k = 8, the weights of label "10" and label "14" are the same, so it is easy to misjudge. To solve this problem, a multi-core fiber channel equalization method based on adaptive KNN algorithm is proposed. The specific steps are as follows:

(1) Send the optical signal into the built 16QAM signal seven core optical fiber transmission system to obtain a set of training data Tr and a set of test data Te, making k = 6. Firstly, cluster the original KNN algorithm.

(2) In the test data set Te, the set Te_1 of data points with multiple labels with the same weight after clustering by KNN algorithm is counted, and the remaining data points with only the label with the unique maximum weight after clustering by KNN algorithm are judged, and the judgment result is the constellation point represented by the unique maximum weight label.

(3) Update the value of k to make k plus 1. At this time, the training data set is still Tr, the test data set is updated to Te_1, and Te_1 is clustered by the second round of KNN algorithm.

(4) Update Te in step (2) to Te_1 and cycle steps (2) and (3) until all data points in the test data Te are judged. At this point, the adaptive KNN algorithm ends.

Compared with the original KNN algorithm, AKNN algorithm reduces the probability of misjudgment of the data points of the received signal. At the same time, because the value of k is guaranteed in the range of 6 ~ 16 in AKNN algorithm, the stability and reliability of the algorithm are also guaranteed.

5 Simulation result

In order to verify the equalization performance of AKNN algorithm in multi-core optical fiber communication system, Volterra series equalizer is used to compare with the channel (W / O) without any equalization method. Firstly, the transmission distance is guaranteed to be 15 steps, i.e. 2400km, and the relationship between bit error rate and optical signal-to-noise ratio of AKNN algorithm is obtained, as shown in Fig. 6 ~ Fig. 8, The bit error rate of multi-core optical fiber signal equalized by AKNN algorithm is lower than that of Volterra series equalizer. At the same time, it can be seen that in multi-core optical fiber, under the condition of ensuring that the bit error rate is 10^{-3}, the optical signal-to-noise ratio of core 1, core 3 and core 5 channels can be reduced by 1.1dB, 1.1dB and 1.2dB compared with the channel with Volterra equalizer. It is proved that the proposed AKNN algorithm can not only ensure the bit error rate performance of multi-core fiber channel, but also reduce the demand of optical signal-to-noise ratio.

Secondly, ensure that the optical signal-to-noise ratio is 18dB, and obtain the relationship between the bit error rate of AKNN algorithm and the transmission step size. As shown in Figures 9 to 11, when the transmission step size is less than 25, that is, the transmission distance is 1600km, the bit error rate performance of AKNN algorithm is not different from that of Volterra series equalizer, but after the transmission distance exceeds 1600km, the performance of Volterra series equalizer becomes worse and worse with the extension of distance, AKNN algorithm can still maintain relatively stable performance. When the channel bit error rate is maintained at 10^{-3}, after equalization by AKNN algorithm, the transmission distance of core 1, core 4 and core 6 channels can be increased by about 11, 10 and 13 steps, i.e. 880km, 800km and 1040km, compared with using Volterra series equalizer. It is proved that the proposed AKNN algorithm can greatly extend the transmission distance of multi-core fiber while ensuring the bit error rate performance of multi-core fiber channel.

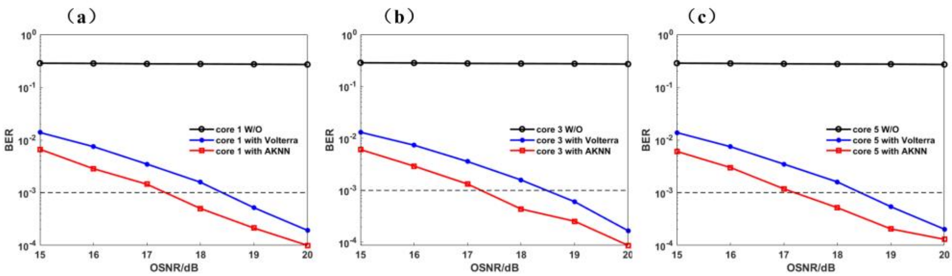

Fig. 5. (a) Relationship between BER and OSNR of core 1 equalized by AKNN algorithm; (b) Relationship between BER and OSNR of core 3 equalized by AKNN algorithm; (c) Relationship between BER and OSNR of core 5 equalized by AKNN algorithm

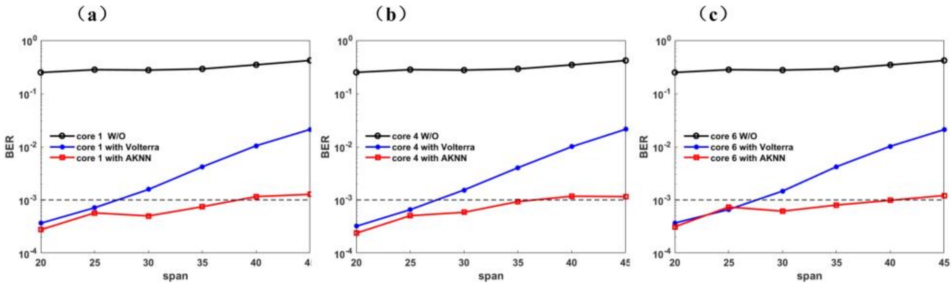

Fig. 6. (a) Relationship between BER and spans of core 1 equalized by AKNN algorithm; (b) Relationship between BER and spans of core 4 equalized by AKNN algorithm; (c) Relationship between BER and spans of core 6 equalized by AKNN algorithm.

6 Conclusion

A multi-core fiber channel equalization algorithm based on KNN is proposed. By introducing KNN algorithm into the damage equalization of multi-core optical fiber channel, the proposed scheme effectively reduces the damage of multi-core optical fiber channel caused by nonlinear effect, core crosstalk and other factors; According to the characteristics of KNN algorithm for multi-core optical fiber channel equalization, an improved AKNN algorithm is proposed. The application of this algorithm in multi-core optical fiber channel equalization can effectively reduce the demand for optical signal-to-noise ratio of multi-core optical fiber and greatly prolong the transmission distance of multi-core optical fiber. It is promising for large capacity and long-distance optical fiber transmission system.

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