High-speed Downhole Transmission System and Its Synchronization Algorithm Based on Optical OFDM

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Abstract—To overcome the shortcomings of low transmission rate due to limited bandwidth in traditional wired transmission, this paper proposes a wireless downhole transmission system based on optical OFDM technique. This system is advantageous in both optical communications technique and OFDM technique. It has higher transmission rate. Furthermore, in order to overcome the defects of being sensitive to synchronization of OFDM systems, a frame synchronization algorithm based on superimposed training sequence is proposed. The mirror symmetry property of training sequence is used to shift intercept the received signals. The intercepted signals are mirror symmetrically superimposed, which cause frame synchronization objective function to accumulate more energy to synchronize. At the same time, it effectively avoids complex multiplication of long sequence. The simulation results show that good synchronization performance with low SNR is obtained and the proposed frame synchronization algorithm has lower mean square error.

Index Terms—Downhole Transmission, O-OFDM, Frame Synchronization, Superimposed Training Sequence

I. INTRODUCTION

The bad frequency response, limited bandwidth and low frequency efficiency of traditional heptcable lead to grave limitation to transmission rate. To increase downhole data transmission rate, Schlumberger uses Quadrature Amplitude Modulation (QAM) in downhole data acquisition system, which has a transmission rate up to 500(kbit/s). China Petroleum Group uses Coded Orthogonal Frequency Multiplexing (COFDM) to explore EILog downhole system, which realized a transmission rate of 430(kbit/s) in a 7(km) length-long cable[1]. However, with the development and usage of downhole apparatuses with high-resolution imaging, the low transmission rate of traditional cable cannot meet the requirement of large volume of data.

Optical Orthogonal Frequency Division Multiplexing (OFDM), which is a new optical modulation technique, has the advantages of both optical communication and OFDM modulation technique. It can effectively absorb dispersion in fiber and polarization mode dispersion. And build high-speed optical transport network. The transmission capacity is big and the cost is low. Therefore it catches wide attention [2]. To satisfy the urgent needs to develop full duplex downhole data transmission systems with high transmission rate and strong anti-interference, we build high-speed downhole transmission system based on Optical OFDM technique.

Due to the limited transmission rate of traditional cable, the present paper proposes a downhole system scheme based on Optical OFDM, and a frame synchronization algorithm of superimposed training sequence in time domain to overcome the defects of OFDM being sensitive to synchronization.

To over the defect of frame synchronization in O-OFDM systems, this paper proposes frame synchronization algorithm of superimposed training sequence in time domain on the basis of IM/DDO-OFDM multi-mode fiber systems,. Compared with the algorithm in document [3][4] in same simulation, the present method has higher synchronization accuracy and lower timing synchronization mean error. And it improves frequency efficiency.

II. EXPERIMENTAL DETAILS

A. *Optical OFDM System Based on Superimposed Sequence*

In the harsh downhole environment, the data in traditional heptcable are easy to be interfered, and the transmission rate is likely to be limited by the cable bandwidth. Therefore, it is necessary to build a high-speed downhole transmission system based on IM/DDO-OFDM combining optical fiber and OFDM techniques. The transmitted signals are uni-polar real signals. Usually, the signals are modulated into bi-polar complex singles through constellation mapping and Inverse Fast Fourier Transform (IFFT). Therefore, the uni-polar real signal suitable to O-OFDM system transmission is obtained by processing Hermitian Symmetry (HS) to signals after constellation mapping, then by IFFT to obtain bi-polar signals in time domain and then by clipping .

Fig. 1 displays the high-speed downhole transmission system scheme based on Optical OFDM. After HS, there are $N-2$ subcarriers carrying valid information (subcarrier 0 and *N/2* carrying zero information, sc.

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$S_m(0)=S_m(N/2)=0$). The later $N/2-1$ subcarriers carry the complex conjugation information after mapping. The data information on the *m-th* OFDM symbol can be expressed as:

$$S_m(k)=\left[0,S_m(1),S_m(1),\cdots,0,S_m^*(N/2-1),\right.\\\left.S_m^*(N/2-2),\cdots,S_m^*(1)\right] \quad (1)$$

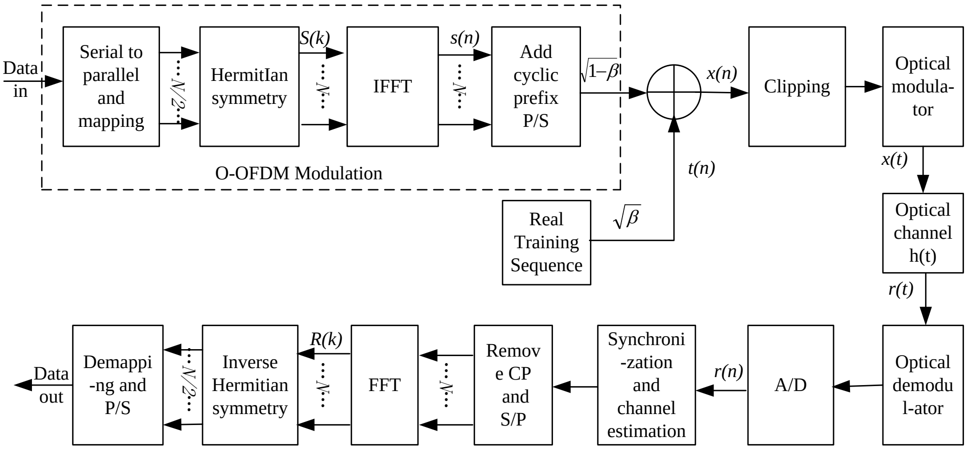

Fig. 1. High-speed downhole transmission system scheme based on optical OFDM

The downhole channel model is a multimode optical fiber channel model based on the pattern of the group time delay[5]. The model accurately reflects the dispersion, pattern time delay and differences of the model of the multimode optical fiber. The mathematical model of its unit impulse response function is expressed as:

$$h(n)=\sum_{i=0}^{M}\mu_i\exp(-\gamma_i)\delta(n-\tau_i)\,. \quad (2)$$

where, M indicates the number of transmission modular groups in a multimode fiber, μ_i represents the power distribution coefficient of the i^{th} transmission mode group when coupling enters the multimode fiber, γ_i is transmission attenuation coefficient, τ_i is time delay factor. Different time delays of model groups in multimode fiber will cause model dispersion during data transmission, which leads to inter-symbol interference in the course of data transmission. Convert Eq. (2) with FFT, we obtain the frequency response function of multimode optical fiber:

$$H(f)=\sum_{i=1}^{M}\mu_i\exp(-\gamma_i)\exp(-j2\pi f\tau_i) \quad (3)$$

$$\tau_i=\frac{l}{c/\bar{n}} \quad (4)$$

where, l is the transmission distance of the multimode optical fiber, c is light speed, $\bar{n}$ derives from $b=(\bar{n}-n_2)/(n_1-n_2)$, b stands for the normalized propagation constant, n_1 and n_2 are refractive indexes of multimode optical fiber core and cladding respectively.

The downhole transmission system based on Optical OFDM is brand-new. Compared with existing downhole transmission systems, it has below advantages:

- Higher transmission rate: the transmission system based on OFDM has a rate up to hundreds of Kbit/s, while traditional transmission only has a rate of dozens of bit/s.
- Higher frequency band efficiency: orthogonal subcarrier is adopted in OFDM system, so its frequency band efficiency is high. This overcomes the defect of low frequency band efficiency of traditional wired method and FSK modulation.
- Higher anti-interference performance: OFDM technique adopts cyclic prefix, so it can effectively overcome multipath effect interference. It adapts well to complex downhole transmission environment.

B. *Composition of Training Sequence*

Because the training sequence in documents [6]-[9] is a plural sequence, while uni-polar real signal is requested in IM/DD system. Therefore, the training sequence designed in the documents cannot be directly used in O-OFDM system. Below is the design method of uni-polar real training sequence.

Assume that the length of the training sequence to design is *N*. Uni-polar real training sequence is constructed according to the following steps:

Step1: designing a sequence *A* with good autocorrelation, the length of which is *L*, where $L \ll N$, $N=mL$;

Step2: processing IFFT with a length of *L* points of sequence *A* to generate sequence *B*;

Step3: taking the real part or imaginary part of *L* length of sequence *B* as sequence *C*;

Step4: transforming the bi-polar sequence *C* to uni-polar sequence *D* (set the negative signals as zero);

Step5: repeating *D m/*2 times to form sequence E, i.e. $E_{N/2}=\left[DD...D\right]$;

Step6: processing image transformation of original sequence E to obtain image sequence *F*;

Step7: combining *E* and *F* to form training sequence *T* with a length of *N*, sc. $T_N=\left[E_{N/2}\ F_{N/2}\right]$.

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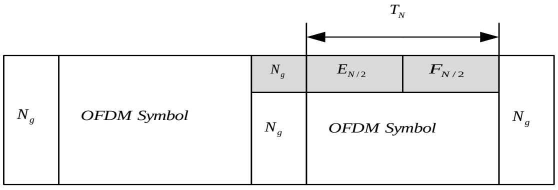

Fig. 2. The structure framework of training sequence being super-imposed on the OFDM symbol

Fig. 2 is the structure framework of training sequence being super-imposed on the OFDM symbol.

C. Frame Synchronization Method

Serial sequence synchronization lowers spectrum efficiency and information transmission efficiency. To resolve this defect, this paper proposes an O-OFDM frame synchronization method based on superimposed sequence. The design scheme is: linearly superimposing a designed training sequence with a complete OFDM symbol, and processing power distribution to the training sequence and the OFDM symbol, where the training sequence is allotted with weak energy. At the receiver end, the frame synchronization is obtained by correlating the local weak energy sequence to the received signal.

As is shown in Fig. 1, the downhole data are transformed into Optical OFDM signal and transmitted in multimode optical channel. At the receiver end, the signal *r(n)* after *A/D* transformation is written as:

$$\begin{aligned} r(n) &= x(n)\otimes h(n)+w(n) \\ &= (\sqrt{1-\beta}s(n)+\sqrt{\beta}t(n))\otimes h(n)+w(n) \end{aligned} \tag{5}$$

where ⊗ is cyclic convolution, *h(n)* is pulse response of optical fiber channel, *w(n)* is electronic domain Gauss white noise, *s(n)* is transmission data, *t(n)* is training sequence. The structure of the training sequence meets the image symmetry property of the E_N above. And β is power allocation factor, $\beta=\sigma_t^2/(\sigma_t^2+\sigma_s^2)$, where σ_t^2 is the training sequence and σ_s^2 is power of the transmission data.

In Eq.(1), the energy allotted to the training sequence is very weak. In order to get enough energy at the synchronization time and not to be interfered by other side lobes, the received signal *r(n)* is processed first. The received signal is intercepted by length *N*, and then Eq. (5) is used to transform and obtain a new received signal *z(n)*.

$$z(n)=r(n)+r(N-n+1)\,. \tag{6}$$

The new sequence has twice as much energy as that of the original sequence. It correlates to local training sequence *F* to obtain synchronization. The timing synchronization function can be expressed as:

$$\begin{aligned} Cor(n,d) &= \frac{1}{N\sqrt{\beta}}\sum_{n=0}^{N/2-1}\left[z(n+d)F(n)\right] \\ &= \frac{1}{N\sqrt{\beta}}\sum_{n=0}^{N/2-1}\left[(r(n+d)+r(N-n-d+1))\cdot F(n)\right] \end{aligned} \tag{7}$$

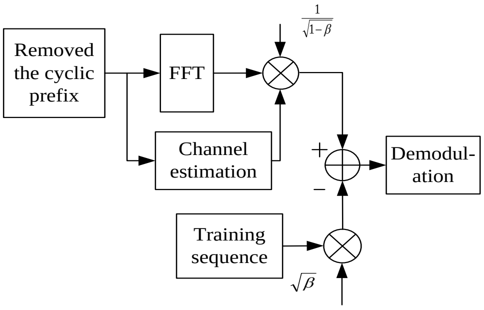

Fig. 3. The receiver model of separation

where *d* is an integer, which represents the relative slide location between the received signal sequences and the local sequences, and *N/2* is correlation length. The training sequences adopted in this paper have good auto-correlation and weak correlation. When *d* slides to synchronization location, frame synchronization function $Cor(n,d)$ reaches the maximum value. At other times, the function is random signals with low amplitude.

The preset threshold value T is adopted to simplify the receiver design. When the output of detector $Cor(n,d)$ meets Eq. (7), *d* arrives at frame synchronization location.

$$\left|Cor(n,d)\right|^2 > T\cdot P(n) \tag{8}$$

where $P(n)$ is the power of the received signals.

D. Separation of Training Sequence from Data Signal

The receiver model of the separation of training sequence and downhole data signals is illustrated in Fig. 3[10]:

After the time synchronization is achieved accurately, the cyclic prefix is removed. The time domain at receiver end is written as Eq. (5).

Assume the estimated values of time domain channel impulse response of the multimode optical fiber to be $\hat{h}(n)$, and $\hat{h}(n)$ is convoluted with the local training sequence *t(n)*, and then we derive the estimated values of the training sequence $\hat{t}(n)$ which can be written as:

$$\hat{t}(n)=t(n)\otimes\hat{h}(n) \tag{9}$$

The separated downhole data signal $s'(n)$ is the time domain signal at receiver end minus the estimated values of the training sequences. It is written as:

$$s'(n)=\frac{r(n)-\sqrt{\beta}\hat{t}(n)}{\sqrt{1-\beta}} \tag{10}$$

With the above methods, we can effectively separate training sequence from the downhole data signals, thus inhibiting the interference of superimposed training sequence with downhole data signals.

E. The Performance Analysis and Originality

In order to simplify the performance analysis, we assume that the transmitter data *s(n)* satisfies the independent identically distributed random process with mean being zero, that *w(n)* satisfies the additive white Gaussian noise which has a mean of zero and a variance of one, And that the training sequence, *d(n)* and *w(n)* are independent of each other. With certain signal to noise ratio, a position for the frame synchronization is θ.

Assume $R_{d=\theta}=\sum_{n=0}^{N/2-1}\left[(r(n+\theta)+r(N-n-\theta+1))F(n)\right]$, where the mean is $E\{r(n)\}=Nt(n)$, the variance is $D\{r(n)\}=\sigma_r^2$, Due to the symmetry characteristics, the information of training sequence included in received signal $z(n+d)$ after being processed approximates $2\sqrt{\beta}F(n)$. The detection probability that frame synchronization falls in the first half of the signal is expressed as:

$$\begin{aligned}P_r\left\{R_{d=\theta}\right\}&=P_r\left\{E\left[R_{d=\theta}\right]\le R_d\le E\left[R_{d=\theta}\right]+N/2\right\}\\&=\frac{1}{2}erfc\left(\frac{\psi_1}{\sqrt{2}\Lambda}\right)-\frac{1}{2}erfc\left(\frac{\psi_2}{\sqrt{2}\Lambda}\right)\end{aligned} \tag{11}$$

where:

$$\begin{aligned}\psi_1&=E\left(\sum_{n=0}^{N/2-1}z(n+\theta)F(n)\right)-u_{R_d}\\&=E\left(\sum_{n=0}^{N/2-1}z(n+\theta)F(n)\right)\\&\quad-N\sqrt{\beta}(\sigma_s^2+\sigma_t^2+\sigma_w^2)(N^2+N)-\sigma_t^2\end{aligned}$$

$$\begin{aligned}\psi_2&=E\left(\sum_{n=0}^{N/2-1}z(n+\theta)F(n)\right)+\frac{N}{2}-u_{R_d}\\&=E\left(\sum_{n=0}^{N/2-1}z(n+\theta)F(n)\right)+\frac{N}{2}\\&\quad-N\sqrt{\beta}(\sigma_s^2+\sigma_t^2+\sigma_w^2)(N^2+N)-\sigma_t^2\end{aligned}$$

$$\Lambda=\sqrt{N\cdot E\left(r^2(n)\right)\sigma_t^2-\left(E(R_{d=\theta})\right)^2}$$

where $E\left[R_{d=\theta}\right]$ indicates the mean of $R_{d=\theta}$, u_{R_d} stands for the mean of R_d, σ_w^2 is noise power, and the mean is zero. The mean of training sequence is *E(t(n))* and the variance is σ_t^2, the mean of *s(n)* is *E(s(n)),* the variance is σ_s^2.

Refer to the appendix for the detailed deduction.

The synchronization of Superimposed training sequence widely adopted in wireless OFDM systems to channel estimation, reduce the peak ratio and time and frequency synchronization,This is the first time to apply this theory in the optical fiber communication system . Compared With the existing IM/DDO-OFDM synchronization algorithm,this algorithm has following advantages: firstly, The long signal at the receiver is shift intercepted, mirror imaged and superimposed ,which effectively lowers the product times of the correlation operation with the local training sequences and reduces the complexity of calculation; secondly, a new method of training sequence is proposed. In the new training sequence, the original sequence is combined with mirror sequence. This greatly enhances the autocorrelation of the sequence and will help to judge synchronization.

III. SIMULATION ANALYSIS

Simulation parameters include: transmission data bit stream 10(Gbit/s), modulation method 16-QAM, and the number of system subcarriers 64, multimode fiber of 1310(nm) adopted in fiber link part, attenuation constant α=0.2(dB/km), chromatic dispersion effect 17(ps/nm km), the sensitivity of PIN photo-detector 1(A/W), and dark current 10(nA). The following simulation result is based on 10,000 Monte Carlo simulations.

A. Power Allocation Factor and BER Performance

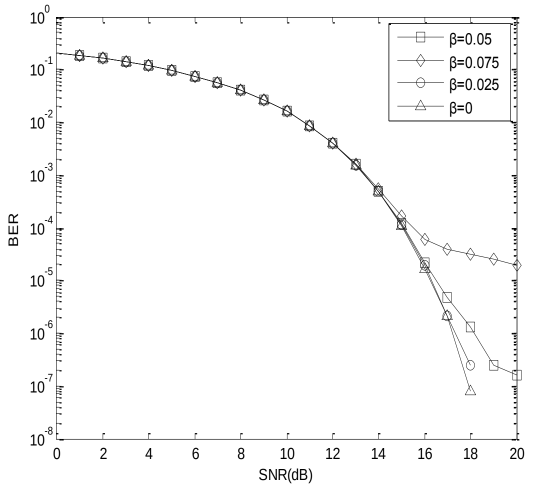

Fig. 4. Effect of power distribution factor to BER

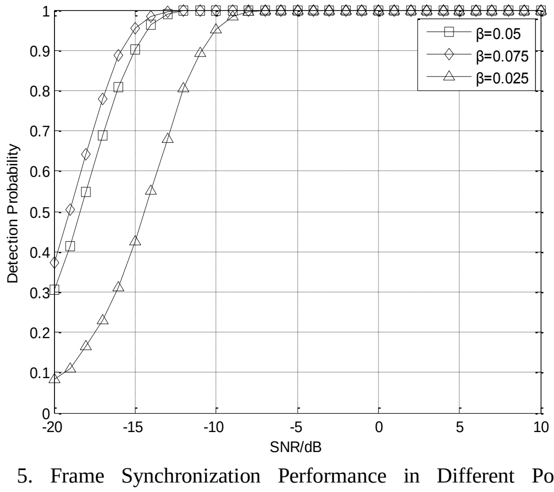

Fig. 5. Frame Synchronization Performance in Different Power Distribution Factor

In order to minimize the Bit Error Rate (*BER*) performance of the superimposed training sequence to system, and simultaneously to take the synchronization performance of the algorithm into account, this paper uses optimum power distribution factor. It is obtained by processing simulations with system *BER* performance with different *SNR*, and algorithm synchronization accuracy in different power distribution factor. As shown in Fig. 4 and Fig. 5, with the increases of power distribution factor, the energy superimposed on data OFDM symbols increases, which increases the energy value of object function. On the contrary, while the system *BER* performance worsens, the synchronization performance of the algorithm improves. To balance the two performances, this paper assumes a power distribution factor to be $\beta = 0.05$. The following simulations are based on this power distribution factor. It is necessary to illustrate that when BER performance of the system is simulated, superimposed training sequences serve as interference information. Hence in Fig. 4 extreme value does not exist.

B. Comparison between Synchronization Performances in Simulation

Fig. 6 shows the algorithm synchronization performance simulations in different transmission distances of chromatic dispersions of 17(ps/nm km) and 34(ps/nm km). In Fig. 6, *D* is chromatic dispersion, *L* is transmission distance. The longer the transmission distance is, the bigger optical energy consumption is, which worsens the algorithm synchronization performance. In the same transmission distance, different chromatic coefficients also affect the algorithm synchronization performance. The effect is that when chromatic dispersion increases, synchronization performance worsens. Therefore, the judgment is that in optical OFDM systems, chromatic dispersion of fibers and transmission distance will affect algorithm synchronization performance.

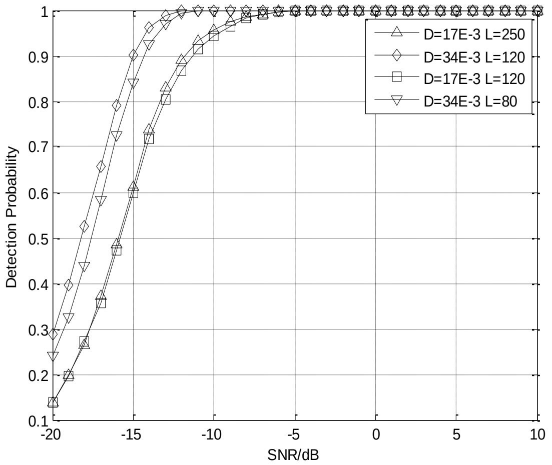

Fig. 6. Effect of chromatic dispersion and transmission distance to algorithm performance

To illustrate more superiority of the frame synchronization algorithm performance proposed in this paper, Fig. 7 shows the comparison on mean square error (MSE) among the algorithm proposed in this paper and the second and third timing algorithms in document [4]. It can be seen that because the composed training sequence has good autocorrelation, and received signal has been processed with simple shift interception and image superimposition, the correlation between the processed received signals and local training sequence is thus strengthened. Therefore, on MSE, the frame synchronization algorithm performance proposed in this paper is superior to algorithms in document [4].

In order to highlight the performance superiority of the frame synchronization algorithm proposed in this paper, Fig. 8 displays the simulation of the impact of different chromatic dispersions and transmission distances on the Mean Square Error (MSE) performance of the frame synchronization algorithm. It is obvious that as the signal-to-noise ratio increases the algorithm tends to be stable and converge rapidly. When the signal-to-noise ratio is greater than -2(dB), the algorithm performs stably. In case of long transmission distance and large dispersion, the algorithm will perform slightly less stably.

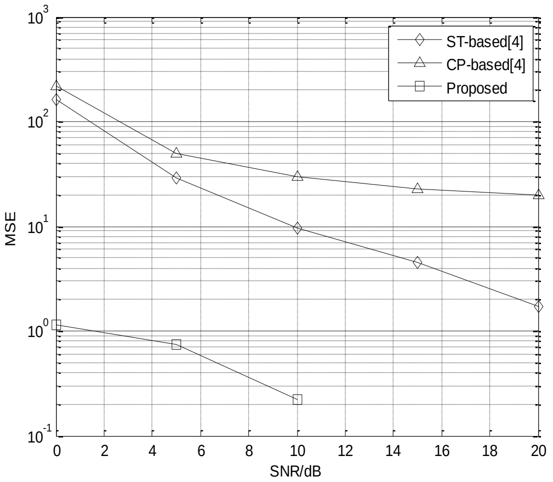

Fig. 7. Mean square error simulation of frame synchronization algorithm $\beta = 0.05$)

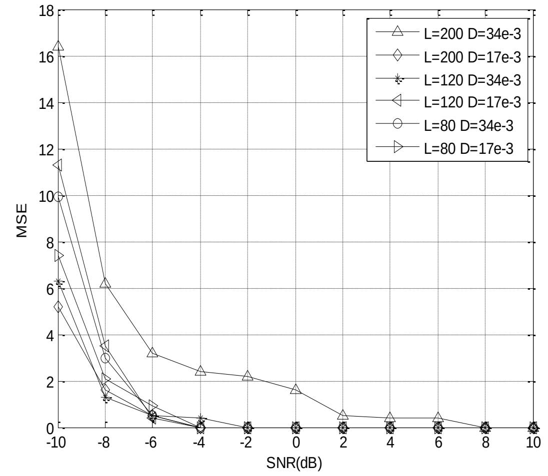

Fig. 8. The simulation of the impact of chromatic dispersion and transmission distance on the Mean Square Error (MSE) performance of the frame synchronization algorithm

C. Computational Complexity Comparison among Synchronization Algorithms

Document [4] adopted m sequence with a length of 512. In document [4], the algorithm 2 employed cumulative sum method with two loop nests, and the algorithm 3 used the method of computing mean value.

The method proposed in the paper adopts the sequence with a length of 256, and the image superimposition is conducted for received signal with length of 512. The multiplying of long sequences is transformed into that of short sequences, which reduces the uses of multiplier. Also the sequences used in the proposed algorithm are shorter than those in document [4]. Therefore, compared with the algorithm 2 and 3 in document [4], the synchronization algorithm in this paper has lower computational complexity.

IV. CONCLUSIONS

Due to the defects of conventional cable, the present paper proposes a high-speed downhole transmission system with superimposed training sequence based on Optical OFDM technique and its frame synchronization algorithm. Based on the special structure of superimposed training sequence, shift interception and mirror symmetry superimposition is carried out for received signals. By doing so, long sequences are shortened, and the computation of the synchronization algorithm is effectively simplified. Also processed received signal makes synchronization objective function accumulate more energy, hence better synchronization performance is obtained. By considering two factors: BER performance effect of system and synchronization performance of algorithm, this paper chooses $\beta = 0.05$ as the optimum power distribution factor. In the procedure of testing the performance of frame synchronization algorithm, the conclusion is that the bigger the chromatic dispersion is, the longer the transmission distance and the worse the synchronization performance is. In the end, to demonstrate the performance of the frame synchronization algorithm proposed in this paper, the comparison on MSE performance is carried with algorithms 2 and 3 in document [4]. The comparison result further illustrates the superiority of the present algorithm performance.

APPENDIX

In order to facilitate derivation analysis, we assume that noise power is σ_w^2, and the mean is zero. The mean of training sequence is *E(t(n))* and the variance is σ_t^2, the mean of *s(n)* is *E(s(n)),* the variance is σ_s^2. Impulse response *h(n)* of noise、training sequence、 transmitter data and optical fiber channel are mutual independence each other.

$$\begin{aligned}
E(R_{d=\theta}) &= E\left(\sum_{n=0}^{N/2-1}\left(z(n+\theta)\cdot F(n)\right)\right) \\
&= E\left(\sum_{n=0}^{N/2-1}\left(\left(r(n+\theta)+r(N-n-\theta+1)\right)\cdot F(n)\right)\right) \\
&= E\left(\sum_{n=0}^{N/2-1}\left(\left(r(n+\theta)+r(N-n-\theta+1)\right)\right)\right)\cdot E\left(F(n)\right) \\
&= N\cdot E\left(r(n)\right)\cdot E\left(F(n)\right) \\
&= E\left(r(n)\right)\cdot E\left(t(n)\right)
\end{aligned} \tag{A-1}$$

$$\begin{aligned}
\Lambda^2 = \mathrm{var}(R_{d=\theta}) &= E\left(R_{d=\theta}^2\right)-\left(E\left(R_{d=\theta}\right)\right)^2 \\
&= E\left(\left(\sum_{n=0}^{N/2-1}\left[r(n+\theta)+r(N-n-\theta+1)\right]F(n)\right)^2\right) \\
&\quad -\left(E\left(R_{d=\theta}\right)\right)^2 \\
&= E\left(\sum_{n=0}^{N/2-1}\left[r(n+\theta)+r(N-n-\theta+1)\right]\right)E\left(F^2(n)\right) \\
&\quad -\left(E\left(R_{d=\theta}\right)\right)^2 \\
&= \sum_{n=0}^{N/2-1}E\left[r(n+\theta)+r(N-n-\theta+1)\right]^2\sigma_t^2-\left(E\left(R_{d=\theta}\right)\right)^2 \\
&= N\cdot E\left(r^2(n)\right)\sigma_t^2-\left(E\left(R_{d=\theta}\right)\right)^2
\end{aligned} \tag{A-2}$$

The power of the received signal can be expressed as:

$$\begin{aligned}
E\left(r^2(n)\right) &= E\left(\left(x(n)\otimes h(n)+w(n)\right)^2\right) \\
&\quad -E^2\left(x(n)\otimes h(n)+w(n)\right) \\
&= E\left(\left(x(n)\otimes h(n)\right)^2\right)+E\left(\left(w(n)^2\right)\right) \\
&\quad +2E\left(\left(x(n)\otimes h(n)\right)w(n)\right) \\
&= E\left(\sum_{i=1}^{N-1}x^2(i)h^2(h-i)\right)+\sigma_w^2 \\
&= \sum_{i=1}^{N-1}E\left(x^2(i)h^2(n-i)\right)_N+\sigma_w^2 \\
&= NE\left(\sqrt{1-\beta}s(n)+\sqrt{\beta}t(n)\right)^2\cdot E\left(h^2(n-i)\right) \\
&\quad +\sigma_w^2 \\
&= N(1-\beta)E\left(s^2(n)\right)+\beta E\left(t^2(n)\right) \\
&\quad +2N\sqrt{\beta-\beta^2}E\left(s(n)\cdot t(n)\right)+\sigma_w^2 \\
&= N(1-\beta)\sigma_s^2+\beta\sigma_t^2 \\
&\quad +2N\sqrt{\beta-\beta^2}E\left(s(n)\cdot t(n)\right)+\sigma_w^2
\end{aligned} \tag{A-3}$$

The mean of the received signal can be expressed as:

$$\begin{aligned}
E\left(r(n)\right) &= E\left(x(n)\otimes h(n)+w(n)\right) \\
&= E\left(x(n)\otimes h(n)\right)+E\left(w(n)\right) \\
&= E\left(\sum_{m=0}^{N-1}\left(x(m)h(n-m)\right)_N\right) \\
&= NE\left(\left(x(m)h(n-m)\right)_N\right) \\
&= N\left(\sqrt{1-\beta}E\left(s(n)\right)+\sqrt{\beta}E\left(t(n)\right)\right)
\end{aligned} \tag{A-4}$$

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