doi:10.3788/gzxb20164510.1006001

基于改进蝙蝠算法的 CO-OFDM 系统峰均比抑制技术

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摘 要:为了抑制相干光正交频分复用系统中的峰值平均功率比,采用蝙蝠算法优化系统子载波的相位.同时针对蝙蝠算法存在的易陷入局部最优和收敛精度不高的问题,对蝙蝠算法进行改进.在蝙蝠的速度更新公式中加入蝙蝠的自我学习部分,并引入惯性权值和学习因子,在保证算法收敛速度的同时尽可能提高算法的收敛精度,防止算法出现早熟收敛情况.采用改进算法对正交幅度调制、100 Gb/s 的相干光正交频分复用系统进行仿真实验,仿真结果表明,改进算法有较强的搜索能力和较高的搜索精度,使正交频分复用信号的峰值平均功率比降低了 5.48 dB,相对于蝙蝠算法降低了 0.52 dB,改进算法的峰值平均功率比抑制性能得到了进一步的提高.

关键词:正交频分复用;相干检测;峰值平均功率比;子载波相位;蝙蝠算法
中图分类号:TN913.7 **文献标识码**:A **文章编号**:1004-4213(2016)10-1006001-6

PAPR Reduction Method for CO-OFDM System Based on Improved Bat Algorithm

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Abstract: To reduce Peak to Average Power Ratio (PAPR) in CO-OFDM systems, bat algorithm was applied for optimizing the sub-carrier phase. Moreover, the algorithm was improved aiming at the problems that the bat algorithm is easy to fall into local optimum and has low convergence precision. In the velocity updating formula, the bat′s self study part, the inertia weight and learning factor were introduced to ensure the algorithm convergence speed and improve the convergence precision of the algorithm at the same time as much as possible, avoiding the occurrence of premature convergence. The simulation was carried out in a 100 Gb/s, 4QAM CO-OFDM system, and the simulation results show that the improved algorithm has been obviously improved in searching ability and accuracy. The PAPR can be reduced by about 5.48 dB and 0.52 dB compared with ones of the original OFDM and the BA-OFDM, respectively. The improved algorithm shows better effects on reducing PAPR.

Key words: Orthogonal Frequency Division Multiplexing (OFDM); Coherent detection; Peak To Average Power Ratio (PAPR); Sub-carrier phase; Bat algorithm
OCIS Codes: 060.4510; 060.2330; 060.1660

Foundation item: The Natural Science Foundation of Tianjin, China (No. 15JCYBJC17000), the Science Foundation for the Youth of Hebei Province, China (Nos. F2014202036, F2015202331), and the High-level Talents Program of Hebei Province, China (Nos. C2013001048, GCC2014011)
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Received: May. 17, 2016; **Accepted**: Aug. 15, 2016

0 Introduction

Orthogonal Frequency Division Multiplexing (OFDM) technology with its advantages of high spectrum efficiency, effective against intersymbol interference and resistance to multipath fading, has attracted wide attention in the field of optical fibers as one of multi-carrier transmission technology. However, high Peak Average Power Ratio[1-3] (PAPR) is a limit to OFDM systems since it can induce signal distorted and the nonlinear effect in fiber, thus reducing PAPR has become a research hotspot in recent years.

PAPR reduction method is roughly divided into three categories. Pre-distortion technology[4-5], which is simple to implement, but due to the nonlinear method applying to deal with the signal, it can cause the system Bit Error Rate (BER) performance to decline. The common methods are clipping method, *etc*. Coding class technology[6], the core idea is to encode the input signal to produce different block, then select words with smaller PAPR code values as transmission code word to carry the information of OFDM symbols, so as to avoid the emergence of the OFDM signal peak value. But with the increasing of the subcarrier, PAPR reduction performance will reduce gradually, so the technology is not applicable when the subcarrier number is large. The common methods are complementary and gray sequence coding, etc. Probability class technology[7-8], which focuses on reducing the probability of high PAPR. This method is to add different interference in OFDM symbol sequence code, and produce many different alternative signals, then choose the sequence with smaller PAPR to transmit. This method has nothing to do with modulation and the subcarrier number, so it is flexibly applied, but calculation of this method is complex and reducing effect is not ideal. The commonly used methods are selective mapping and partial transmit sequence. In conclusion, reducing the PAPR of OFDM signal from the perspective of seeking suitable phase optimization combination is an important choice. Phase optimization method[9-11] is to add appropriate phase perturbation on each sub-carrier phase so that each subcarrier cannot be the same at the same time in the time domain, thus reducing the occurrence of high PAPR fundamentally. In recent years, swarm intelligence optimization algorithms with its advantages of fast convergence rate and good robustness are applied in solving reducing PAPR problems. Some studies[12] proposed a method to optimize sub-carrier phase for PAPR reduction based on Simulated Annealing (SA) algorithm. This method requires high initial temperature, low cooling rate and end temperature, and enough times sampling under various temperatures, so optimization process is long, operation efficiency is low, and reducing PAPR performance is still not ideal. Some other studies[13-14] proposed a method to optimize sub-carrier phase for PAPR reduction based on Genetic Algorithm (GA). The method has more parameters and is difficult in programming. Parameters choosing directly affect the quality of the solution. This method is not real-time and flexibility in practical application, and it is still not ideal in reducing PAPR performance. Some other studies[15] proposed a method to optimize sub-carrier phase for PAPR reduction based on improved Bacterial Foraging Optimization Algorithm (BFOA). This method has more parameters and is difficult to implement. The efficiency of the algorithm is low and reducing PAPR effect is still not ideal.

In this paper, the Bat Algorithm (BA)[16-17] is proposed to optimize the sub-carrier phase to reduce PAPR. The improved algorithm is proposed aiming at the problem that the BA is easy to fall into local optimum and has low convergence precision.

1 CO-OFDM system

Fig. 1 shows the block diagram of CO-OFDM transmission system with the optimized sub-carrier phase by the BA. As shown in Fig. 1, the data stream was transformed to multiple low-speed data streams after serial-parallel conversion and then mapped; the low-speed data streams were modulated to the sub-carriers by an Inverse Fast Fourier Transform (IFFT); subsequently optimization of sub-carrier phase by the BA makes PAPR reduced; finally, after the parallel-serial conversion, adding a Cyclic Prefix (CP), D/A conversion processing, OFDM signal is generated. The OFDM signal generated after BA optimization is modulated to the optical domain from electric domain through Mach-Zehnder Modulator (MZM), and coupled to the fiber channel to be transmitted. At the receiving end, the optical domain signal is transformed to the electrical domain signal by the Photodiode (PD), then filtered, D/A conversed, and transformed to be the frequency domain signal by Fast Fourier Transform (FFT); the frequency domain signal is divided by corresponding phase factor, which makes it do phase-inversely-processed, and subsequently de-modulated; finally, the de-modulated parallel low-speed data stream is transformed to serial high-speed data stream and output.

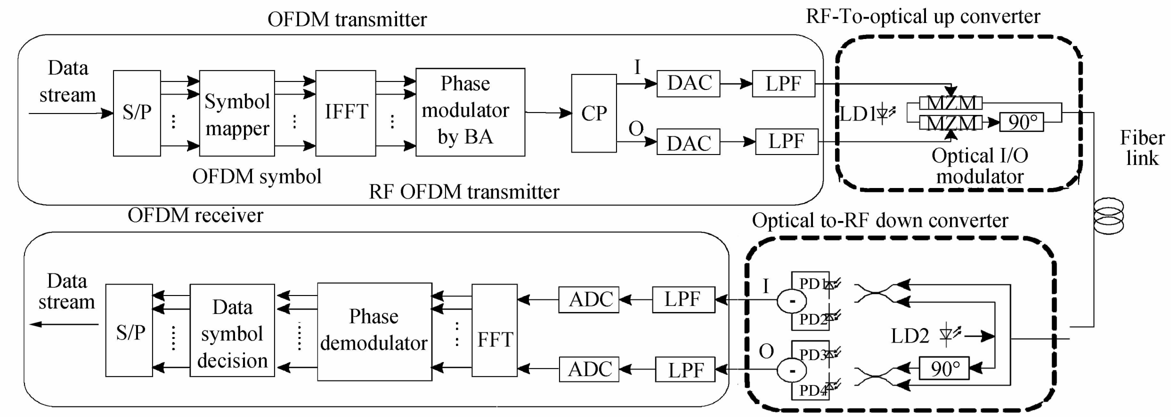

Fig. 1 The block diagram of CO-OFDM transmission

2 Bat algorithm and the proposed approach

BA is a global search intelligent algorithm. The algorithm is based on echo-location behavior of miniature bats and uses different pulse transmitting frequency and loudness to optimize and solve problems. With its simple model, fast convergence rate, potential parallelism and distributed characteristics, BA is applied to seek the optimal combination of phase on reducing PAPR.

In D-dimensional space, updating formula of velocity v_i^t and position x_i^t of the i-th bat at time step t as

$$\begin{cases} v_i^t = v_i^{t-1} + (x_i^{t-1} - x^*) f_i \\ x_i^t = x_i^{t-1} + v_i^t \\ f_i = f_{\min} + (f_{\max} - f_{\min})\beta \end{cases} \tag{1}$$

where v_i^t and v_i^{t-1} are velocities of the i-th bat at time step t and $t-1$, respectively. x_i^t and x_i^{t-1} are positions of the i-th bat at time step t and $t-1$, respectively. x^* is optimum solution of all bats. f_i is search pulse frequency of the i-th bat, $f_{\min}$ is the minimum of f_i, and $f_{\max}$ is the maximum, β is uniformly distributed random vector.

As for local search section, a solution is selected as optimum solution every time, new solution will be generated by random walking as

$$x_{\text{new}} = x_{\text{old}} + \varepsilon L d_t \tag{2}$$

where ε is a random number obeying uniformly distribution, $\varepsilon \in [-1, 1]$, Ld_t is the average loudness of all bats at time step t.

In order to reduce the emergence of high PAPR in OFDM systems, we introduce BA to optimize the phases of each subcarrier of OFDM signals. As a swarm intelligence optimization algorithm, BA is widely applied in the global optimization problem. In this algorithm, the bat location corresponds to the phase sequence formed by the phase angle of each sub-carrier. The location of each bat is chosen randomly in the range of $[0, 2\pi]$ and varies according to the increasing of iteration times. The space length of bat group corresponds to the number of sub-carriers in the OFDM systems. Fitness function is defined by PAPR directly, *i. e.* the ratio of maximum power point and the average power point in an OFDM signal, as

$$\text{fitness} = \text{PAPR} = 10\lg \frac{\max\{|d|^2\}}{\text{E}\{|d|\}^2} \tag{3}$$

where, $d = \text{IFFT}(D_m) \times e^{j\theta_m}$ is the time domain signal optimized phase, D_m is symbol sequence of Quadrature Amplitude Modulation (QAM) modulation, θ_m is the phase sequence and is selected in the range of $[0, 2\pi]$, $\max\{\cdot\}$ denotes maximum value, $\text{E}\{\cdot\}$ denotes average value.

Every bat searches in the solution space to follow the current best bat according to the best fitness function, until the maximum iteration time is reached. The output result is the best phase factor sequence.

Inertia weight w is used to control the influence of the previous speed on the current speed. Larger w can strengthen the bat algorithm global searching ability, and smaller w can strengthen the local search ability.

In traditional BA, w can be regarded as 1, so the method is lack of local search ability in the late iterations, therefore, for complex optimization problems, the search precision is not high. There is no bat's self study part in the velocity updating formula, i. e., the formula has nothing to do with the bat experience information. In this way, the flying speed depends more on the global optimal position of the bat population, falling into local optimal value more easily.

In the velocity updating formula, the bat's self study part, the inertia weight and learning factor are introduced to ensure the algorithm convergence speed and improve the convergence precision of the algorithm at the same time as much as possible, avoiding the occurrence of premature convergence. The velocity updating formula is as follows

$$v_i^t = w(t) \times v_i^{t-1} + (x_i^{t-1} - x^*) f_i +$$

$$(x_i^{t-1} - x_{ig})c \tag{4}$$

where, x_{ig} is the optimum solution of the i-th bat; c is the self learning factor. w is the inertia weight as

$$w = w_{\max} - (w_{\max} - w_{\min}) \times t / N_{\text{gen}} \tag{5}$$

$w_{\max}$ is the maximum of the inertia weights, $w_{\min}$ is the minimum of the inertia weight, t is the current iteration number, N_{gen} is the maximum number of iterations. The inertia weight determines particles inherited on the current speed. In the early, larger weights will lead to high speed for particles, which improves the global search ability of the algorithm. Later, smaller weights will enhance the improvement of algorithm local search ability, which is advantageous to control the convergence of the algorithm.

c is the self learning factor, which reflects the impact of the best flying position in memory of the i-th bat on flying speed, also called cognitive coefficient. Formula is as

$$c = c_{\min} + (c_{\max} - c_{\min}) \times \{1 - [a\cos[(-2 \times t / N_{\text{gen}}) + 1]] / \pi\} \tag{6}$$

where, $c_{\min}$ is the initial values of c, $c_{\max}$ is iteration end value of c, $a\cos(\cdot)$ denotes complementation cosine transform.

Asymmetric, arc cosine method is used to change c dynamically. In the early, bats can be spread into the search space by accelerating change speed of c, less influenced by the part of the social consciousness, to increase the diversity of bats. With the increasing of the number of iterations, the value of c declines to keep the speed of the bat, avoiding premature convergence. Individual extremum position can increase the variation of bat position, increasing the diversity of bats from a certain extent.

3 Simulation results and analysis

CO-OFDM system in this paper is built using VPI software, and the corresponding simulation parameters are set as follows. The data rate is 100 Gbit/s, the number of subcarriers is 512, QAM modulation is adopted, the length of CP is 64, and the number of bat is 50. A Continuous Wave (CW) laser is used as the light source with optical carrier frequency of 193.1 THz. The optical link consists of 4 spans of 100 km Single-Mode Fiber (SMF) with dispersion coefficient of 16 ps/(nm·km), nonlinearity coefficient of 2.6×10^{-20} m^2/W, valid area of 80 μm^2 and attenuation of 0.22 dB/km.

Fig. 2 shows the PAPR comparison chart, under the condition of 500 times iteration, 2 to 64 subcarriers with the Particle Swarm Optimization (PSO), BA and improved BA method. The son chart is the corresponding curve fitting. As can be seen from the figure, with the increasing of the subcarrier number, optimized signal PAPR value of three kinds of algorithms is approaching steady; and the improved BA method performs the best on the whole. With the improved BA method, PAPR reduction mean (2.461 7) and variance (0.218 1) are less than that BA (mean is 2.623 6, variance is 0.257 5). That is to say, the improved BA of reducing effect is better and more stable.

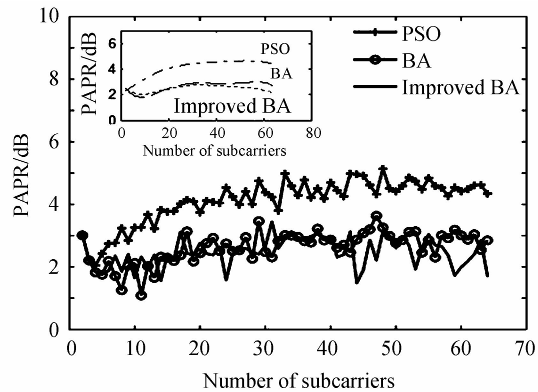

Fig. 2 PAPR versus the number of subcarriers for OFDM signals compared with some phasing schemes

Fig. 3 shows the Complementary Cumulative Distribution Function (CCDF) versus PAPR of the original OFDM signal, the BA-OFDM signal and the proposed improved BA-OFDM signal under the condition of 500 iterations and 64 sub-carriers. At the CCDF of 10^{-2}, the highest PAPR of the PSO-OFDM signal is about 4.85 dB, while about 3.63 dB, 3.11 dB with the BA method and improved BA method, respectively. The PAPR of PSO-OFDM is reduced by about 3.74 dB compared with that of the original OFDM. And the PAPR of the improved BA-OFDM signal is reduced by about 0.52 dB, 5.48 dB compared with that of the BA-OFDM and the original OFDM, respectively. The results indicate that the improved BA can furtherly reduce the PAPR values, i. e, it is superior to BA algorithm on the performance of reducing PAPR.

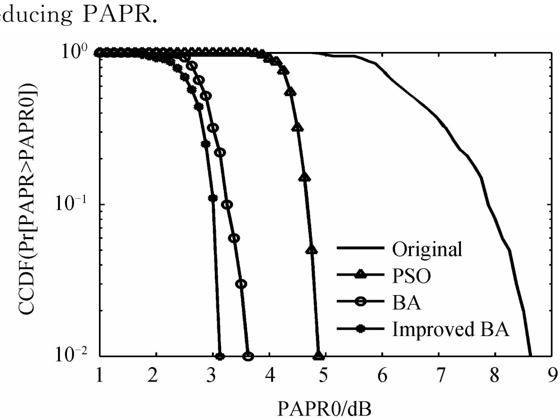

Fig. 3 CCDF curves of different techniques

Fig. 4 shows the signal constellation graph of original and improved BA optimized signal at the receiving end. As can be seen from the diagram, the constellation graph of the original OFDM signal is very divergent in Fig. 4 (a). The constellation graph of the improved BA-OFDM signal is obviously convergent in Fig. 4 (b). The results indicate that using improved BA alleviate nonlinear effect of the system.

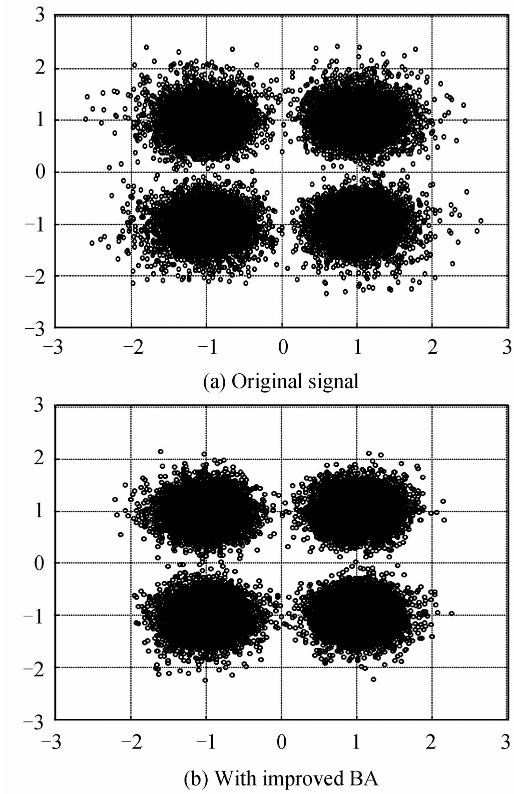

Fig. 4 Simulation signal constellation of different techniques at the receiving end

Fig. 5 shows the BER curves of the original OFDM signal, BA-OFDM signal and improved BA-OFDM signal for different fiber transmission distance. As can be seen from the diagram, the BER increases with the increasing of fiber transmission distance, but BER after BA and improved BA optimization is superior to original signal BER. And the BERs of both methods are almost the same.

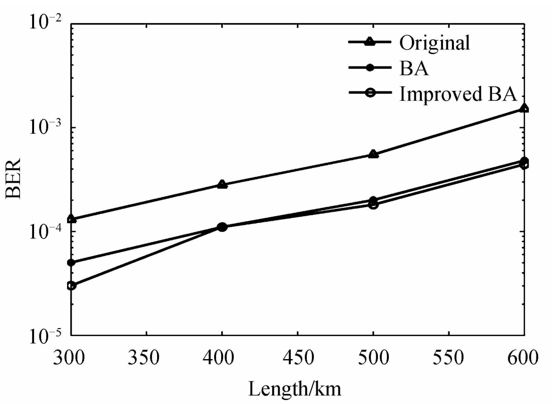

Fig. 5 BER performance

4 Computational complexity analysis

The substance of traditional Partial Transmit Sequence (PTS) algorithm is selecting suitable phase factor to reduce PAPR in OFDM system. The computational complexity of this algorithm is mainly reflected in calculation of complex multiplications and complex additions when performing IFFT.

As for swarm intelligence algorithm of phase optimized method, the computational complexity of it is mainly reflected in time complexity. Time complexity of swarm intelligence algorithm is proportional to swarm space length D and the number of individual S in swarm. Swarm space length D is decided by the number of subcarriers. Time complexity of BA of the main steps in one iteration is listed because improved BA has the same time complexity as BA. The result is shown in Table 1. Table 1 shows that BA algorithm for run time is $2S+6SD$.

Table 1 Time complexity of BA algorithms

BA algorithm steps	Complexity
Initializing position	SD
Calculating the fitness value	SD
Updating the best location	S
Selecting frequency	S
Calculating position	SD
Calculating velocity	SD
Updating location	SD
Calculating the fitness value	SD

5 Conclusion

A PAPR reduction method based on improved BA aiming at higher peak problems in the CO-OFDM system is proposed. The improved algorithm has been simulated and verified in MATLAB and VPI. As a results, the improved BA of reducing effect is better and more stable under the condition of 2 to 64 subcarriers with the PSO, BA and improved BA method; the PAPR of the improved BA-OFDM signal is reduced by about 0.52 dB, 5.48 dB compared with that of the BA-OFDM signal and the original OFDM signal, respectively at the CCDF of 10^{-2}; the constellation graph of the improved BA-OFDM signal is obviously convergent, in other words, using improved BA can alleviate nonlinear effect of the system; BER after BA and improved BA optimization is superior to original signal BER, and the BERs of both methods are almost the same. Therefore, it clearly reveals the algorithm can not only reduce the PAPR of the system, but improve the BER performance.

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