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Mitigation of crosstalk based on CSO-ICA in free space orbital angular momentum multiplexing systems

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ABSTRACT

Orbital angular momentum (OAM) multiplexing has caused a lot of concerns and researches in recent years because of its great spectral efficiency and many OAM systems in free space channel have been demonstrated. However, due to the existence of atmospheric turbulence, the power of OAM beams will diffuse to beams with neighboring topological charges and inter-mode crosstalk will emerge in these systems, resulting in the system nonavailability in severe cases. In this paper, we introduced independent component analysis (ICA), which is known as a popular method of signal separation, to mitigate inter-mode crosstalk effects; furthermore, aiming at the shortcomings of traditional ICA algorithm's fixed iteration speed, we proposed a joint algorithm, CSO-ICA, to improve the process of solving the separation matrix by taking advantage of fast convergence rate and high convergence precision of chicken swarm algorithm (CSO). We can get the optimal separation matrix by adjusting the step size according to the last iteration in CSO-ICA. Simulation results indicate that the proposed algorithm has a good performance in inter-mode crosstalk mitigation and the optical signal-to-noise ratio (OSNR) requirement of received signals (OAM + 2, OAM + 4, OAM + 6, OAM + 8) is reduced about 3.2 dB at bit error ratio (BER) of 3.8×10^{-3}. Meanwhile, the convergence speed is much faster than the traditional ICA algorithm by improving about an order of iteration times.

1. Introduction

The study of Allen et al. [1] indicates that the beams with phase factor have not only spin angular momentum (SAM), but also have orbital angular momentum (OAM) and each photon has an OAM of $l\hbar$, where l is the topological charge, it can be arbitrary integer values and OAM beams with different topological charges are orthogonal [2,3], $\hbar$ is Planck's constant. Since then, researches on OAM focus on optical wrenches [4], optical tweezers [5], quantum entanglement [6] and other fields. Gibson et al. [7] proposed the application of OAM in optical communication, and they demonstrated that OAM can be used to encoded data into beams to transmitted information. Taking advantage of this idea, Wang et al. [8] experimentally demonstrated a high-speed optical communication system based on OAM multiplexing, namely OAM multiplexing communication. In this system, they used four polarization-multiplexed OAM beams with $l = +4, +8, -8, +16$, each carrying a 16 quadrature amplitude modulation (16QAM) signal, to achieve a capacity of 1369.6 Gbit/s with a spectral efficiency of 25.6 bit/s/Hz. With the development of technology, free space link with the capacity of 100 Tbit/s is demonstrated by combining OAM multiplexing, polarization multiplexing and wavelength division multiplexing [9]. In order to improve the channel capacity continually, Wang et al. increased the multiplexing paths with high-order modulation [10], and realized the free space link with channel capacity of 1.036 Pbit/s and spectral efficiency of 112.6 bit/s/Hz. Because of its high spectral efficiency, OAM multiplexing has aroused widespread concern of researchers.

OAM multiplexing system will be disturbed by the medium [11], such as atmospheric turbulence. Due to the random refractive index, atmospheric turbulence results in scintillation [12], beam bending and drifting [13] and time-delay in receiver [14], which results that the power of OAM beams diffuse to beams with neighboring topological charges, that is inter-mode crosstalk. The existence of inter-mode crosstalk affects the performance of communication system seriously [15]. Anguita et al. [16] used Van Karman power spectrum to generate random phase screen to simulate the atmospheric turbulence, and analyzed crosstalk caused by atmospheric turbulence in OAM multiplexing system by numerical simulation. Rodenburg et al. [17] simulated the crosstalk caused by Kolmogorov turbulence in OAM multiplexing system. They used 11 different OAM modes in their experiments,

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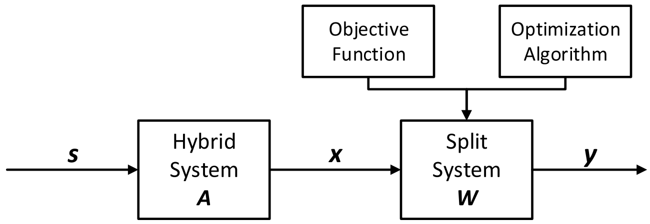

Fig. 1. Basic model of ICA.

and inter-mode crosstalk was introduced in all of the OAM modes. Experimental results show that mode purity is affected. Inter-mode crosstalk caused by atmospheric turbulence have a great impact upon the stability of OAM multiplexing system, for which crosstalk mitigation in free space OAM multiplexing system interference has aroused the interest of researchers. Some effective methods to suppress crosstalk have emerged, such as AO compensation [18,19], error correction encoding [20] and MIMO equalization [21].

In this paper, we propose a CSO-ICA algorithm to improve the process of solving the separation matrix taking advantage of fast convergence rate and high convergence precision of chicken swarm algorithm (CSO). Compared with methods mentioned above, CSO-ICA has several advantages, such as not requiring prior information of the signals, a fast speed of convergence and etc. This paper is organized as follows, firstly, we introduce the basic principle of the application of ICA in mixed signal separation, and then the CSO optimization method is given, next simulation of free space OAM multiplexing system with four OAM modes are performed by CSO-ICA algorithm, finally, simulation results are discussed and analyzed.

2. Principle

In this section, the principle of basic ICA is firstly depicted, and then basic model and application process of CSO-ICA algorithm are expounded in details, finally, the convergence curves depending on crosstalk index are given.

2.1. ICA algorithm

ICA is an algorithm to solve the blind source separation, which can separate the original signal from the mixed signal to achieve the extraction of the original information. The core idea of ICA is to construct an objective function based on the principle of statistic independence [22]. The observed signal is decomposed into several independent components by using the optimization algorithm, and then the signal separation is completed, that is ICA = objective function + optimization algorithm. The basic model is as shown in Fig. 1.

In Fig. 1, $\boldsymbol{s}=[s_1, s_2, \ldots, s_n]^{\mathrm{T}}$ is a n-dimensional statistically independent unknown source signal, $\boldsymbol{x}=[x_1, x_2, \ldots, x_m]^{\mathrm{T}}$ is an m-dimensional observed signal and $m \geq n$, $\boldsymbol{A}$ is an $m \times n$ hybrid matrix, then

$$\boldsymbol{x} = \boldsymbol{A}\boldsymbol{s} \tag{1}$$

The main purpose of ICA is to find a separation matrix $\boldsymbol{W}$, so that $\boldsymbol{y}=\boldsymbol{W}\boldsymbol{x}$. The separation matrix consists of objective function and optimization algorithm. We processed mixed signal with optimization algorithm, meanwhile, mixed signal is determined whether mixed signal is demultiplexed with the use of the observation function. If each component of $\boldsymbol{y}$ is independent, a certain component $\boldsymbol{y}_i$ of $\boldsymbol{y}$ is considered to be a component of $\boldsymbol{s}$, that is $s_j (i,\, j = 1, 2, \ldots, n)$.

Not all the hybrid signals are suitable for ICA algorithm. In order to guarantee the existence of the solution of the ICA model, the following constraint conditions need to be satisfied [23]:

(1) Source signals are statistically independent from each other;
(2) The number of received signals is not less than the number of source signals;
(3) At most one source signal obeys the Gauss distribution.

In free space OAM multiplexing system, due to the existence of atmospheric turbulence, the power of OAM beams will diffuse to beams with neighboring topological charges, resulting in inter-mode crosstalk, which affects the performance of the system. As a blind source separation algorithm, ICA can mitigate inter-mode crosstalk and separate source signals. Firstly, source signals are independently modulated to the optical signals in the system, that is to say, source signals are mutually independent. Then, for the OAM multiplexing system, the number of received signals equals to the number of source signals. Finally, the signals used to transmit information in the system are non-Gauss distribution. Thus, ICA is suitable for free space OAM multiplexing system.

In the ICA algorithm, objective function and optimize algorithm are two major components. The objective function is a measure of the degree of independence criterion, which mainly includes non-Gauss maximization, minimization of mutual information, maximum likelihood estimation and so on. In this paper, we use non-Gauss maximization as the measure of the degree of independence, and use negative entropy as the criteria for non-Gauss property. Generally speaking, the larger the negative entropy is, the greater the non-Gaussianity will be. On the other hand, optimization algorithm mainly includes fixed point iterative algorithm [24], gradient algorithm [25], Newton iteration algorithm [26], and so on. The convergence speed of optimization algorithms mentioned above are limited as they have fixed iteration speed, thus it leads to steady-state error imbalance and degrades the performance of ICA. Taking gradient algorithm for example, general iterative formula is as follows,

$$W(n+1) = W(n) + \eta(I - \varphi(y(n))y^T(n))W(n) \tag{2}$$

where η is iteration step, I is identity matrix, n is the number of iterations, $W(n)$ is the nth separation matrix, and $j[y(n)]$ is the nonlinear functions of $y(n)$. The nonlinear function used in this paper is $j[y(n)] = \log(y(n))$. It can be seen from the formula that iteration step is a fixed value, which needs to chosen appropriately according to the actual situation. In order to improve iteration speed, we use CSO as the optimization algorithm.

2.2. CSO-ICA

CSO is a new swarm intelligence optimization algorithm proposed by Meng et al. [27]. By simulating the hierarchy and foraging habits of chickens in nature (including roosters, hens and chicks), optimization problem is solved by making an analogy with swarm feeding. Compared with other swarm intelligence algorithms, CSO is excellent in convergence speed and convergence accuracy.

In CSO, the category of chickens is distinguished according to the fitness of chickens, the individuals with the highest fitness are roosters, chicks are the individuals with the lowest fitness, and the remaining individuals are hens. Roosters with higher fitness have a certain advantage over hens with higher fitness in foraging, that is to say, roosters have a wider foraging range than hens. Location update formulas of rooster are as follows:

$$W_{i,j}^{t+1} = W_{i,j}^{t} * (1 + Rand(0, \sigma^2)) \tag{3}$$

$$\sigma^2 = \begin{cases} 1, f_i \leq f_k \\ \exp\left(\dfrac{(f_k - f_i)}{|f_i + \varepsilon|}\right), \text{otherwise,} \end{cases} k \in [1, N], k \neq i \tag{4}$$

where $Rand$ $(0,\, \sigma^2)$ is Gaussian distribution function, k represents individual beside individual i, and f represents fitness of individual in a flock of roosters. $W_{i,j}^{t}$ represents the tth iteration of the element in the ith row, jth column of separation matrix.

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