Wireless Optical OAM Communication Modulation and Demodulation

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Abstract. In recent years, orbital angular momentum (OAM) optical communication system has attracted much attention due to its larger channel capacity and stronger noise immunity. The light beam carrying OAM has infinite orthogonal characteristics and can make full use of spatial dimension, which provides a new idea for high-capacity communication. This paper outlines the basic theory of OAM and the development status of OAM optical communication, focusing on the modulation technology based on spatial light modulator (SLM) and the demodulation technology based on convolutional neural networks (CNN). Finally, the current challenges and future development trends of wireless optical OAM communication are discussed, being summarized and prospected to provide references for further research.

Keywords: Orbital Angular Momentum · Infinite Orthogonal Characteristics · Modulation · Demodulation

1 Introduction

The OAM exists in the vortex beam, which is a special beam that presents a spiral advance during transmission [1], and it has a spiral phase factor $e^{il\theta}$. The spatial distribution of the OAM is shown schematically in Fig. 1 [2].

Where, l represents the OAM mode (OAM mode or OAM topological charge value), which theoretically can be any integer and fraction. The vortex beams carrying different OAM modes have mutual orthogonal characteristics, providing a new multiplexing dimension for high-speed optical communication, which can realize high-capacity and high-spectral-efficiency information transmission.

With the continuous research on OAM multiplexing, it has been found that orbital angular momentum (OAM) in vortex beams offers a new degree of freedom and the potential to increase the capacity of free-space optical communication systems [3], providing a solution to the problem of channel capacity and spectrum resources in other areas.

The University of California team proposed and experimentally demonstrated a method using the orbital angular momentum (OAM) of acoustic vortex beams [4], which

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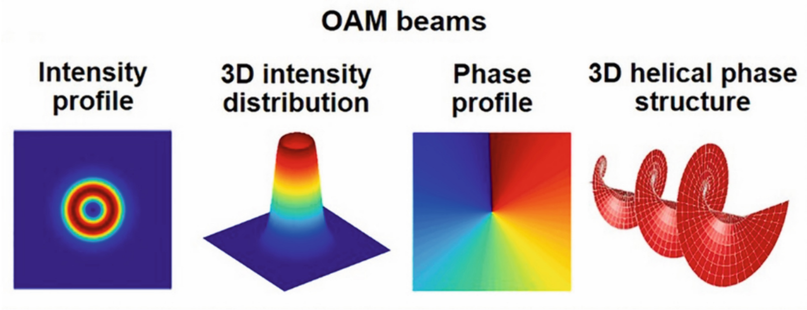

Fig. 1. Intensity distribution, 3D intensity distribution, phase distribution, 3D spiral phase distribution of OAM beam

enables multiplexing in a single beam of a transducer array, achieving high spectral efficiency acoustic communication of 8.0 ± 0.4 (bit/s)/Hz using a topological charge of -4 to 4, and is easy to combine with other modulation means, which has significant implications for underwater multiplexing communication systems. OAM can also be used for ultra-narrowband transmission, covert communication, etc. While the spectrum resources of traditional communication systems are becoming increasingly strained as the demand for transmission rates continues to increase, ultra-narrowband systems which introducing OAM do not use electric field strength resources but use OAM's variations to transmit information, having great potential in high spectral efficiency scenarios [5]. In addition, the information sequence carrying OAM mode's variation is not easily detected, and the OAM channel is not easily detected, thus achieving covert communication. Compared with the traditional covert transmission scheme, the covert transmission scheme introducing OAM mode's variation frees the spectrum resources occupied by the spreading codes and improves the effectiveness and reliability of the system [6].

2 OAM Modulation

OAM modulation refers to the encoding of data information by different vortex beams, which are used as separate carriers to deliver different data information, which's schemes typically include laser cavity outputs [7], helical phase plates [8], diffractive optics [9], metamaterials or supersurfaces [10], mode conversion [11], spatial light modulators(SLM) [12], etc.

Among them, laser cavity output belongs to OAM active generation scheme, which usually requires high pump optical power or specially designed components with relatively low efficiency, limited power generation, futhermore not easy to generate higher-order OAM modes. Spiral phase plates, diffractive optics, metamaterials or supersurfaces, and mode converters belong to OAM passive generation schemes, which are highly controllable, simple and flexible, however one device can usually generate only one OAM beam. In contrast, SLM can generate OAM beams through reconfigurable diffractive optics, which's the liquid crystal molecules can be programmed to dynamically change the incident beam and thus generate different OAM beams, having greater advantages in terms of efficiency, energy consumption, conversion speed and quality.

2.1 SLM-Based OAM Modulation

As early as 2004, Gibson et al. [12] of the University of Glasgow successfully used the OAM-SK mechanism to construct a 15 m experimental free space optical (FSO) communication link and to transmit and receive data. In this experiment, a collimated helium-neon laser is incident on a SLM, then continuously refreshing the hologram loaded on the SLM. As a result, the incident beam transmitting through free space is converted into an OAM beam with eight different OAM mode values.

Chunqing Gao's team [13] at Beijing University of Technology proposed a free-space one-to-many communication link based on OAM modulation, which converts Gaussian beams via SLM into four sets of time-varying OAM beams with different directions at the same time, realising multiple OAM encoding, with the transmitted four sets of signals captured and demodulated by four receivers respectively. In the same year, the team performed eight modes of OAM shift-keyed communication in free space above 10 m [14], obtaining time-varying OAM sequences for modulation by switching holograms, demodulating them at the receiver via Dammann gratings, and analysing them by image processing.

2.2 Optical OAM Holographic Encrypted Communication

Holography has been widely used in optical display, optical encryption and optical artificial intelligence, and orbital angular momentum (OAM) has been widely implemented as an independent degree of freedom in information encryption [2].

Ruffato et al. [15] provided the first reference for OAM holography by designing holograms with OAM beam phase singularities to encode and decode information by iterative Fourier transform. Although the spiral wave front of the OAM of light acts as an independent physical dimension, all OAM modes will diffract in the same way according to the Bragg diffraction formula, lacking the selectivity of the spiral mode index, and thus no information carrier is realized as holography in the OAM, therefore, conventional hologram designs lack OAM selectivity.

Ren et al. [16] of the University of Munich proposed a super-surface orbital angular momentum holography that provides strong orbital angular momentum selectivity using a meta-hologram consisting of GaN nanopillars with discrete spatial frequency distributions, laying the foundation for ultra-high capacity holography. Next year, the team designed to preserve OAM amplitude and phase information by discrete sampling in the spatial frequency transform [17], using different OAM The team has designed a system for extracting information through the Fourier transform using different OAM modes, with up to 200 multiplexed channels.

Fang et al. [18] of the Shanghai University designed a hologram with a discrete spatial frequency distribution, transferring the OAM characteristics from the incident spiral wavefront to each pixel of the reconstructed hologram, which allows the OAM to be used as an independent information carrier, and adding a spiral phase plate to further enhance the OAM selectivity, enabling ultra-high capacity holographic multiplexing and highly secure encrypted communications.

Zhou et al. [19] of the Beijing Institute of Technology proposed and demonstrated orbital angular momentum multiplexing of different polarisation channels for holographic encryption using birefringent hypersurfaces, where OAM-selective holographic information can only be reconstructed with precise topological charges and specific polarisation states, providing a higher level of security for holographic encryption by combining multiple polarisation channels with orbital angular momentum selectivity.

The above work achieves high-security encrypted communication by discrete sampling in spatial frequency transformation by encoding amplitude and phase information, and some scholars have also improved the security level of optical OAM holographic encryption by exploiting other information carried by the OAM beam.

Zhang et al. [20] of Soochow University used composite spiral modal index coding for the target image to verify the feasibility of composite OAM beams to provide a higher level of optical holographic encryption.

Li et al. [21] of Nanjing Normal University used the phase gradient factor of the vortex phase structure as an independent degree of freedom to encode the image and thus achieve encrypted communication.

Zhu et al. [22] of Shenzhen University distinguished different OAM modes in radial and angular directions to enhance holographic capability and fidelity, demonstrating ultra-fine fractional OAM holography with a topological charge resolution of 0.01 and 20-bit OAM encoding for holographic encryption.

2.3 High-Order OAM Modulation Format

The capacity of optical communication can be effectively enhanced by higher-order modulation of the amplitude, phase, frequency, time, polarization, and lateral spatial distribution of photons [23–25].

Bell Labs (USA) and Corning Optical Communications Laboratory (UK) [26] transmitted 4096-QAM advanced modulated signals in 200 km of optical fibre with a spectral efficiency of up to 19.77 bit/(s·Hz).

Zhu et al. [27] built a single-wavelength Tbit free-space communication system using intensity modulation direct detection technique. In this work, 12 OAM modes with two polarisation states were used for a total of 24 channels, each carrying a 30 Gbaud Nyquist PAM-4 signal, achieving a total transmission capacity of 1.44 Tbit/s at a single wavelength with a modulation efficiency of 48 bits/symbol.

Fu et al. [28] proposed an OAM-ASK-based data transmission scheme that modulates two independent dimensions, OAM mode and amplitude, separately. Assuming that the OAM mode and beam amplitude are used to characterise n-dimensional and m-dimensional symbols respectively, a total of log2mn bits of information can be generated when both dimensions are used simultaneously, and thus the scheme can use a smaller number of OAM modes to achieve higher-bit coding, effectively expanding the channel capacity.

Liang et al. [29] proposed an OAM-OFDM scheme of OAM multiplexing combined with orthogonal frequency division multiplexing (OFDM) to achieve high-capacity wireless communication in sparse multipath environments. The scheme proposes to compensate the phase difference caused by different path lengths to mitigate inter-mode interference in HODM communication and introduces a conventional water injection algorithm. Numerical results show that the OAM-OFDM scheme with the introduction of OAM mode largely improves the system communication capacity compared with the conventional OFDM scheme. Chen et al. [30] proposed a trellis coded modulation (TCM) based on the physical properties of OAM, which can be used for the optimization of OAM joint coded modulation. In order to break the channel capacity limitation of conventional quantum dense coding (QDC) under the condition of fixed quantum resources.

3 Machine Learning Based OAM Demodulation

In OAM optical communication systems, the high-quality extraction of information from the transmitted OAM beam at the receiver side is the key to ensure the communication quality of OAM optical systems. The conventional OAM demodulation scheme includes spiral phase plate (SPP) [8], the SPP is used to generate the inverse process of the OAM beam and convert the incident OAM beam into a Gaussian plane wave to complete the OAM beam demodulation; Diffractive optics, observing whether Gaussian bright spots appear on the corresponding diffraction stage can determine whether the corresponding OAM component [31]; Optical transformation, demodulate the diffraction stripe or diffraction spot to improve the OAM demodulation accuracy and expand the demodulation range of OAM mode values [32].

OAM, as one of the solutions to the wireless communication capacity problem, has received a lot of attention from scholars for its ability to maintain orthogonality between modes and significantly improve channel capacity without increasing the frequency band. In recent years, with the development of machine learning and its powerful learning capability, many scholars have introduced machine learning into OAM demodulation to further improve OAM identification accuracy.

In 2014, Krenn et al. of the University of Vienna first applied self-organizing map (SOM) neural network, one of the classical models of unsupervised learning in machine learning, to the field of OAM optical communication to achieve the task of demodulation of OAM beams [33]. In 2016, the team used a similar approach on the water surface between Canary islands conducted 143 km of experiments with a recognition error rate of 8.33% for OAM patterns [34].

In 2017, Doster et al. [35] introduced CNN into the field of OAM optical communication, using a spatial light modulator to simulate atmospheric turbulence, and used CNN to identify 5 bit OAM codes with a recognition rate of 99%, which is much higher than the demodulation accuracy of traditional demodulation schemes, making OAM beam demodulation scheme based on deep learning technology becomes a new research hotspot in the field of OAM optical communication. In the same year, Li et al. [36] designed a CNN-based multivariate adaptive demodulator and compared its performance with those based on K-nearest neighbor, plain Bayesian, and back-propagation artificial neural networks, etc. Simulation results showed that the error rate of the CNN-based demodulation scheme was only 0.86% even in a strong turbulent channel environment with a transmission distance of 1000 m, which was higher than those based on K-nearest neighbor, plain Bayesian, and back-propagation artificial neural networks. The error rate of the CNN-based demodulation scheme is only 0.86%, which is nearly 30% lower than that of the K-nearest neighbor, Bayesian, and back-propagation artificial neural network-based demodulation schemes. Based on this, the group continued to improve the number of layers of CNN structure in the subsequent work [37] to further realize the function of atmospheric turbulence detection with an accuracy of 95.2%. Jiang et al. [38] proposed a joint scheme of CNN and coherent demodulation based on the research of Li et al. This scheme uses coherent demodulation before CNN processing, i.e., interfering with the transmitted OAM beam with the local oscillation light, and then feeding the captured interferometric image into the CNN for subsequent classification processing. Their simulation results show that the scheme has a higher signal-to-noise ratio of the detected image and higher demodulation accuracy compared to the non-coherent system.

2021, Shimaa et al. [39] addressed the shortcomings of the OAM-SK-FSO mechanism and used two efficient deep learning techniques, convolutional recurrent neural network and 3D CNN, for decoding to improve the reliability and efficiency of video communication. In 2021, Li et al. [40] of Shanghai Jiao Tong University proposed an AT-detector-based multi-CNN (ATDM-CNN) demodulator, where the AT detector detects the AT intensity and then activates the AT-determined CNN-based demodulator to identify incident OAM patterns that can be further corrected in can significantly optimize the image data quality.

Our team extracted OAM features by gradient direction histogram and trained them using support vector machine, and also analyzed the ocean turbulence caused by different temperature and salinity by using the topological charge value of OAM to identify the classification labels, and the experimental results showed that the method still has high recognition accuracy under strong turbulence conditions [41]. There is also a paper of Sis. In the same year, we implemented the recognition of dual-mode OAM and single-mode OAM based on CNN model [42], which also has a high recognition rate under strong turbulence.

CNNs have been shown to be able to extract and recognize the intrinsic features of the input raw image using multilayer representation learning techniques with local connectivity and weight sharing, and they have also performed quite well in OAM beam demodulation [43]. Also, many scholars have taken an alternative approach to transform the OAM beam so that the OAM pattern before demodulation has more distinguishable features, resulting in a higher recognition rate of the neural network [44]. Table 1 shows the current status of the development of CNN-based OAM demodulation.

Table 1. The current status of the development of machine learning based OAM modification

Team	Implementation of algorithms	Beam type	Wavelength/Power	Distance/Environment	Recognition rate
Krenn [34]	SOM	Bimodal overlay twisted light	532 nm/60 mW	143 km/strong gas turbulence	91.67%
Doster [35]	CNN	Gaussian-tapered Bessel beam	633 nm/6 mW	$D(r)/r_0$=15	98.94%
Li [36]	CNN	8 model LG beams	633 mm	1 km/$C_n^2 = 1E - 14M^{-2/3}$	99.14%
Jiang [38]	Coherent-demodulation and CNN	8 model LG beams	633 mm	2 km/$C_n^2 = 1E - 15M^{-2/3}$	97.21%
Li [40]	ATDM-CNN	8 model LG beams	1550 nm	1 km/$C_n^2 = 1.12E - 13M^{-2/3}$	97.75%

where C_n^2 is the refractive index structure constant, $D(r)$ is the atmospheric refractive index structure function, and r_0 is the atmospheric coherence length.

4 Challenges and Prospects

Although OAM technology offers a new direction for high-capacity communications, there are currently many issues and challenges in the field of OAM optical communications that are waiting to be addressed by researchers. OAM optical communications has been proven to be able to transmit in the ocean and atmosphere [12, 46–49], but in real-world environments, OAM optical communications still faces many problems. In OAM optical communications, the divergence of the OAM beam during transmission can lead to energy loss due to incomplete identification of the OAM beam within the finite aperture [50], the truncation of the radial profile of the beam can also cause mode coupling problems [51], and the faster divergence of higher order OAM modes severely affects the communication distance of higher order OAM beams. In turbulent channels, the beam alignment problems of the transmitting and receiving devices are also worth investigating, which can be combined with machine learning and programmable devices to correct the OAM beam before distortion at the transmitter or receiver side [52, 53]. Phase distortion caused by complex channels can change the wavefront phase of the OAM beam and introduce inter-mode crosstalk [54], which can be mitigated by using devices such as digital micromirrors, multi-plane optical converters or SLM [55].

The interconnection between different scenarios requires a variety of OAM optical signal processing technologies, therefore, OAM optical communication networks have high requirements for OAM optical signal processing devices, and the varying degrees of OAM multiplexing in different environments lead to higher system costs. The key devices at the corresponding OAM optical signal processing nodes of the communication network should have good scalability and programmability. OAM is widely studied in the field of optical communication, but it also has broad application prospects in RF communication and acoustic communication, which will bring more possibilities for future communication [4, 56].

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