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Research Status and Prospects of Orbital Angular Momentum Technology in Wireless Communication

Feng Zheng[1, 2, *], Yijian Chen[3, 4], Siwei Ji[1, 2], and Gaoming Duan[1, 2]

Abstract—It becomes more and more challenging to satisfy the long-term demand of transmission capacity in wireless networks if we limit our research within the frame of traditional electromagnetic wave characteristics (e.g., frequency, amplitude, phase and polarization). The potential of orbital angular momentum (OAM) for unleashing new capacity in the severely congested spectrum of commercial communication systems is generating great interest in wireless communication field. The OAM vortex wave/beam has different topological charges, which are orthogonal to each other. It provides a new way for multiplexing in wireless communications. Electromagnetic wave or synthetic beam carrying OAM has a spiral wavefront phase structure, which may provide a new degree of freedom or better orthogonality in spatial domain. In this paper, we introduce the fundamental theory of OAM. Then, OAM generation and reception methods are equally demonstrated. Furthermore, we present the latest development of OAM in wireless communication. We further discuss the controversial topic "whether OAM provides a new degree of freedom" and illustrate our views on the relationship between OAM and MIMO. Finally, we suggest some open research directions of OAM.

1. INTRODUCTION

Although wireless communication technology has reached a new height, it always uses the linear momentum (LM) of electromagnetic radiation to carry information in the form of signal amplitude, phase and frequency. Even utilizing multiple technologies in transmission and reception for spatial multiplexing does not break the limits of linear momentum. On the basis of these conventional multiplexing schemes which utilizes degrees of freedom in time, frequency and space domains, some leading-edge researches are exploring the use of novel angular momentum technologies to expand the modulation dimension of wireless communication or to enhance the existing communication efficiency.

Electromagnetic radiation can concurrently carry linear momentum and angular momentum according to the classic electrodynamics theory. Angular momentum can be divided into two types: spin angular momentum (SAM) which describes quantum spin and orbital angular momentum (OAM) which describes a spiral phase structure. There are distinct differences between communication technologies using angular momentum and the one based on linear momentum. In Table 1, OAM modulation uses OAM modes to carry information, and LM modulation carries information with frequency, phase, and amplitude.

OAM was found theoretically by Allen et al. [1] that some types of beams possess OAM of $l\hbar$ per photon until 1992 firstly. They confirmed that there were an infinite number of discrete orthogonal OAM modes. Therefore, OAM-based wireless communication can transmit an infinite amount of information

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[*] Corresponding author: Feng Zheng (zhengfeng@bupt.edu.cn).

[1] Bejjing Key Laboratory of Network System Architecture and Convergence, Beijing University of Posts and Telecommunications, Bejing 100876, China. [2] Beijing Laboratory of Advanced Information Networks, Beijing University of Posts and Telecommunications, Beijing 100876, China. [3] ZTE Corporation, Shenzhen 518055, China. [4] State Key Laboratory of Mobile Network and Mobile Multimedia Technology, Shenzhen 518055, China.

Table 1. Differences between OAM and LM modulation.

Modulation methods	Specificities	Advantages	Disadvantages
OAM modulation	Use OAM modes to carry information.	High-capacity communication in theory and high spectrum efficiency.	Complex methods of generation and reception. High requirements of antenna topology. Not suitable for long distance communication.
LM modulation	Carry information with frequency, phase and amplitude.	Mature technology, low cost.	The modulation resources have threshold, low spectrum efficiency.

in the same frequency band. OAM is formed by microscopic particles moving in a circle along the propagation direction, which is related to the spatial distribution of particles. It is macroscopically represented as a vortex beam carrying the wavefront phase factor $\exp(jl\varphi)$ (where "l" determines the number of OAM modes, and "φ" represents emission phase angle) [2, 3].

Vortex electromagnetic wave has already been applied to nanotechnology [4], quantum experiment [5] and radar imaging [6, 7]. In recent years, using OAM-based electromagnetic waves to transmit information in wireless communication has attracted increasing attention, and its potential to enhance spectral efficiency has been widely explored. In 2011, scientists used different modes of vortex electromagnetic waves to conduct wireless communication at the same frequency and achieved success for the first time. As a new wireless communication technology, OAM was hailed as a revolutionary innovation by Nature [8, 9]. Given its excellent performance, many researchers consider OAM as the core technology for the next generation of wireless communication.

The rest of this paper is organized as follows. In Section 2, the basic principles of OAM-based multiplexing are introduced. Current main generation and reception methods of OAM beams are summarized in Section 3. In Section 4, the latest development and some research status in OAM wireless communication are combed. In Section 5, the relationship between OAM and MIMO is addressed. In Section 6, the future development trends of OAM technology in communication are examined. Conclusions are drawn in Section 7.

2. BASIC PROPERTIES OF OAM BEAM

Consider a cylindrical coordinate system, as shown in Fig. 1(a). ρ, φ, and z represent radial distance, azimuth, and height, respectively.

The conversion between the cylindrical coordinate system and rectangular coordinate system is $x = r\cos\varphi$, $y = r\sin\varphi$, $z = z$. Assuming that z is a fixed value, the electric field can be described as

$$E_l(r,\varphi) = A(r)\exp(jl\varphi) \tag{1}$$

$A(r)$ is an amplitude function, and it is characterised by the Bessel function of the first kind, as shown in Fig. 1(b).

Different OAM modes correspond to different values of l. Rotational speed of the spiral is proportional to the absolute value of l. For a case that l is non-zero, a significant feature of OAM is that the phase distribution of the electromagnetic wave shows a spiral rise along the propagation direction. Fig. 2 shows the wavefront for OAM waves with different modes.

The electromagnetic wave carrying OAM has the following basic properties:

(i) In theory, l can take any discrete value. Generally, we use integer order. Non-integer can also be expanded to the superposition of integer ordered by Fourier series;

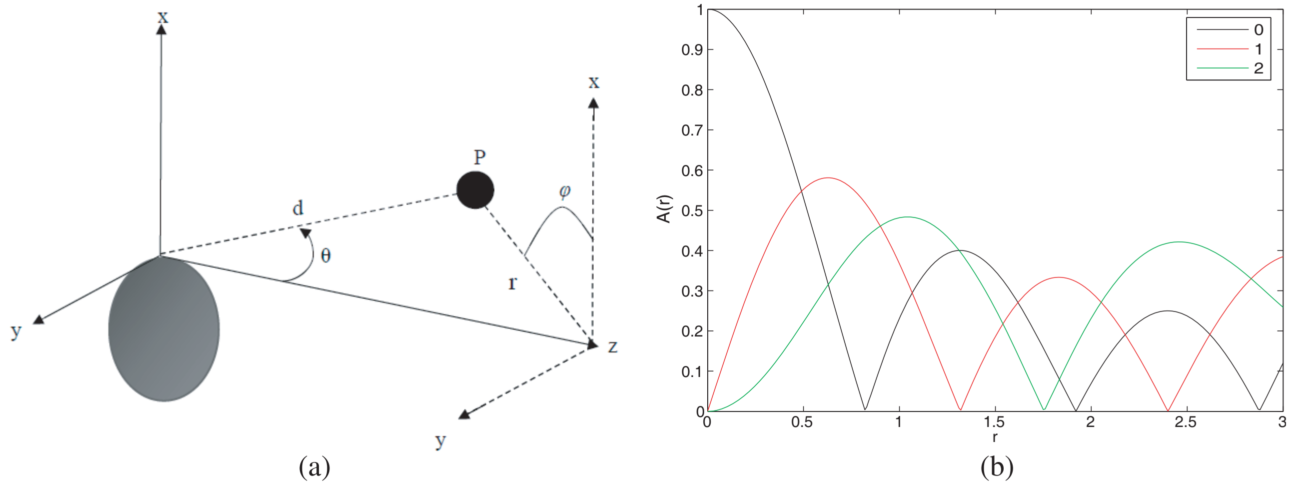
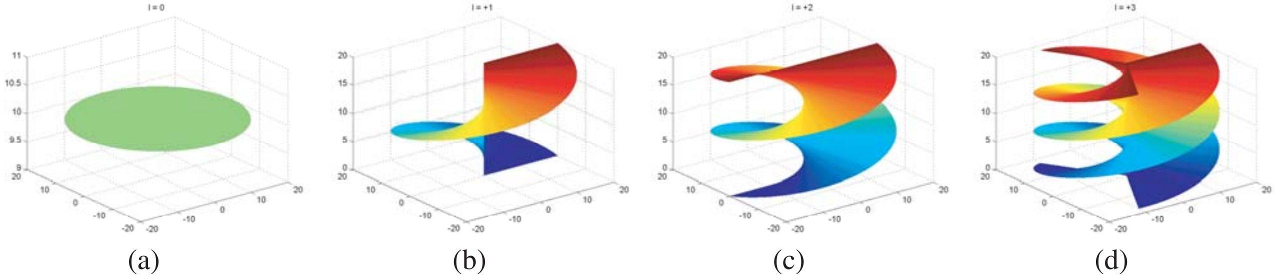


Figure 1. (a) Cylindrical coordinate system (ρ, φ, z). (b) Amplitude function of different modes.



(a) (b) (c) (d)

Figure 2. Phase wave fronts of vortex beams with different OAM models. (a) $l = 0$. (b) $l = +1$. (c) $l = +2$. (d) $l = +3$.

(ii) Define the pure OAM basis function as $\varphi_{\mathrm{m}} = \exp(il\varphi)$, $l = 0, \pm 1, \pm 2, \ldots$. For the vortex electromagnetic waves of two different modes l_1, l_1, there is

$$\frac{1}{2\pi} \int_0^{2\pi} e^{il_1\varphi} \cdot e^{il_2\varphi} d\varphi = \begin{cases} 1 & \text{if} \quad l_1 \neq l_2 \\ 0 & \text{if} \quad l_1 = l_2 \end{cases} \tag{2}$$

This orthogonality ensures that the overlapped eigenmodes in different spaces and times cannot interfere with each other under the same carrier frequency and the same polarization state, so that different information streams can be transmitted simultaneously without additional frequency bandwidth.

(iii) Electromagnetic waves carrying OAM are with two main characteristics: the spiral phase front and the intensity distribution of annular shape, as shown in Fig. 3. The field intensity of the central area of the vortex beam is 0, so called the null zone or dark zone. The energy is mainly distributed in annular area centered around the beam propagation axis;

(iv) When the propagation distance increases, the beam gradually diverges, and the radius of the ring region expands, showing a gradually expanding hollow cone, as shown in Fig. 4;

(v) Divergence angle of the vortex beam grows along with OAM modes.

The orthogonality of different OAM modes makes it possible to achieve multiplexed transmission, which greatly increases transmission rate and spectral efficiency. This is the biggest concern of OAM electromagnetic waves in the field of communication currently. It is also an important research direction of future wireless communication, especially in large-scale wireless relay transmission.

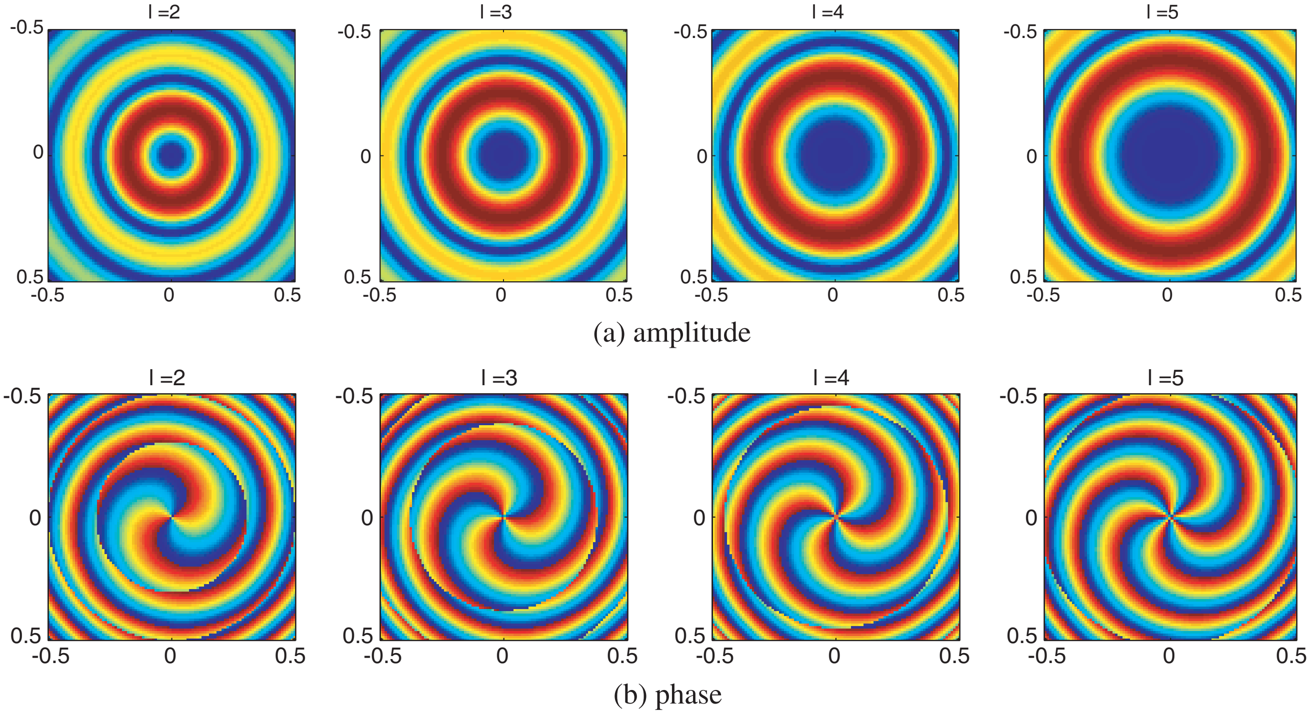


Figure 3. The OAM modes vary from $l = 2$ to $l = 5$. (a) The field intensity distribution of different OAM modes. The color coding is from weakness (blue) to strength(red). (b) Phase profile of different OAM modes(from the perspective of propagation axis). The color coding is from 0° (blue) to 360° (red).

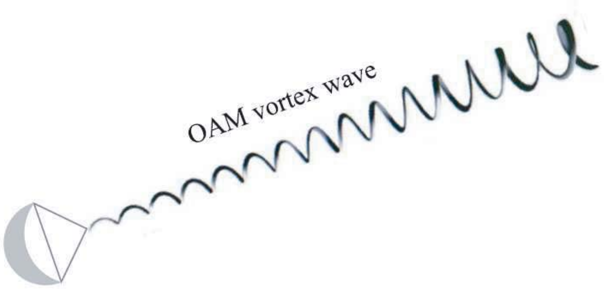


Figure 4. OAM vortex waves.

3. GENERATION AND RECEPTION OF OAM BEAM

3.1. The Generation of OAM

How to obtain various OAM modes is an important issue in practical application. Table 2 lists several common ways to generate OAM, and Fig. 5 shows some antennas of different generation methods. The following also focuses on using some new technologies to generate OAM, such as metasurfaces.

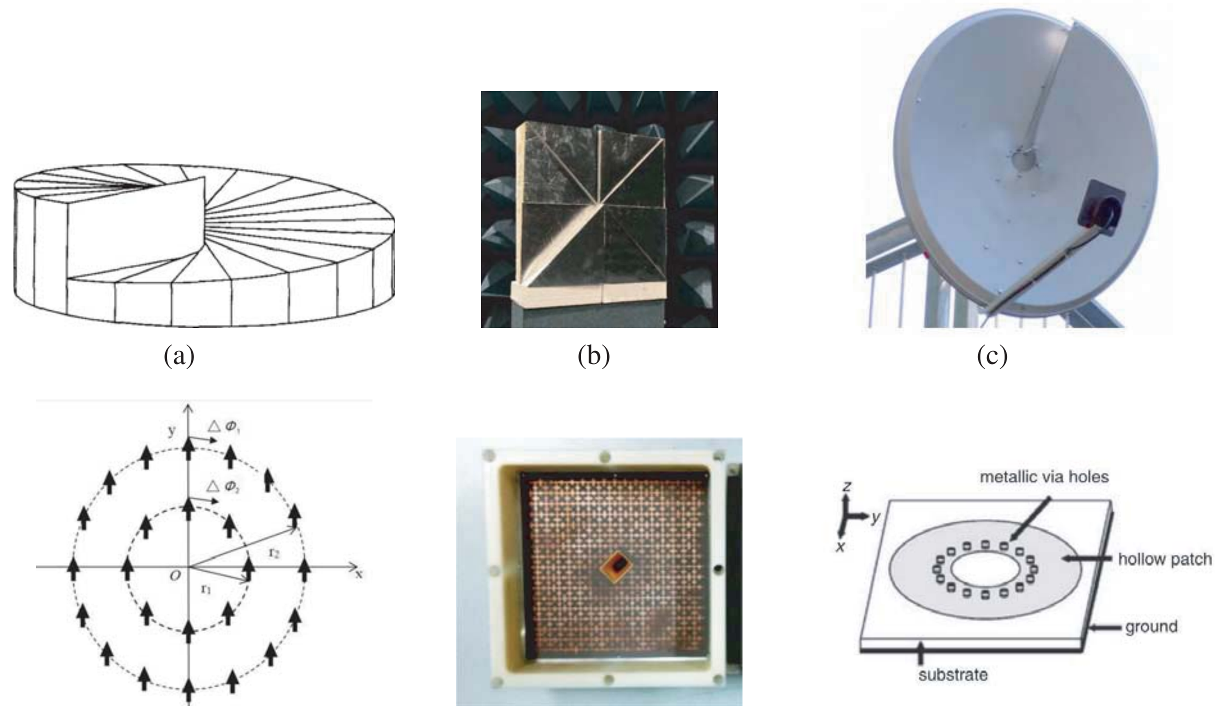
3.1.1. Common Ways to Generate OAM

3.1.2. Using Metasurfaces to Generate OAM

Recent developments in metasurfaces also expedite powerful and convenient design routes for OAM generation. Metasurfaces are composed of man-made subwavelength scatterers with varying geometry

Table 2. The difference between different OAM generation schemes.

Type	Principle	Advantages	Disadvantages	Application area
Spiral Phase Plate (SPP) [10]	Plane waves passing through circular dielectric plates with varying thickness or dielectric constant will cause phase delay. There are two devices: (1) a dielectric plate with spirally increased thickness; (2) a porous phase plate. In practice, a multi-step phase plate is also used to approximate.	Simple, low cost.	(1) Only be used in high-frequency to light wave band. (2) Can only generate OAM wave with a single mode. (3) It is hard to process the axis part when the mode number of OAM is high. (4) Large divergence angle with high model	Optical communications wireless communications
Wave-guided resonance antenna [11]	There are more schemes, such as line-wave resonance antenna, medium resonant antenna and so on.	Small size. Easy to integrate.	Short transmission distance. Lack of practicality.	Wireless communications
Reflection/ Transmission Array [12]	Irradiate the reflection /transmission surface composed of periodic unit with the feed source to form an OAM wave.	No need for complex feed network.	The design of element on reflective/transmissive surface is complex.	Wireless communications
Stepped-Reflector [13]	There is a phase step between each stair. When the beam is incident, the reflected wave is no longer a plane wave due to this special step-like structure. It becomes a vortex electromagnetic wave with twisted wavefront.	Simple structure.	Can only produce OAM waves with a single mode and hard to miniaturize.	
Rotating Parabolic Antenna [14]	Transform the parabolic reflector into a structure with a spiral lift.	Retain the advantages of parabolic antenna. No phase control required and carry strong direction of beam.	Can only generate OAwaves with a single mod Large volume.	Wireless communications
Array Antenna [15]	Utilize UCA to generate OAM. Each adjacent array elements adopt excitation feed with equal amplitude and $2\pi l/N$ phase difference.	Mature theory. Can generate OAM wave with multiple modes.	The feeding structure is complex. A large number of antenna units are needed to generate high-order OAM mode, which has a large beam divergence angle. The phase error of the elements leads to the wavefront jitter and the increase of main lobe width.	Wireless communications



(a) (b) (c)

(d) (e) (f)

Figure 5. Devices or antennas corresponding to different generation methods. (a) Spiral phase plate. (b) Stepped-reflector. (c) Rotating parabolic antenna. (d) Uniform circular antenna. (e) OAM reflectarray antenna. (f) Wave-guided resonance antenna.

and orientation. Metasurfaces locally alter the wave properties by the abrupt phase change at the scatterers. By varying the geometry or orientation, scatterers can cover a total 2π phase shift range so that arbitrary beam forming can be achieved. Metasurfaces can be easily fabricated with printed circuit board (PCB) etching process, and it does not need complex external feed-networks, which brings advantages such as small mass, low profile, and low manufacturing cost. Generally, they fall into two categories: independent and dependent on the wave polarization.

In the first category, in addition to the use of antenna array and spiral phase plate, $\exp(jl\varphi)$ can be generated based on the abrupt phase shift at scatterers on a metasurface, thus generating different OAM modes, as shown in Fig. 6. However, the phase and magnitude profiles on most metasurfaces are often fixed, which means that only one specific OAM beam can be generated once the metasurface is fabricated [16, 17]. It seriously restricts the generation of OAM in the real-world wireless communication. Recently, programmable metasurfaces are proposed to overcome the difficulties faced by conventional metasurfaces [18–20]. In [19], a reconfigurable OAM generator based on a 1-bit programmable metasurface was proposed. However, the main lobe loss (2 dB) of this method could not be ignored due to the use of a very low level of phase quantization. [20] explored an inexpensive 2-bit programmable coding metasurface working at around 3.2 GHz, which could be used to generate high-order OAM beams in a reprogrammable way. Based on the designed metasurface, OAM EM beams with electronic vortex centers and topological charges of $l = 0, \pm 1, \pm 2, \pm 3, \pm 4, \pm 5$ and ± 6 could be generated. In addition, Yu et al. utilized subwavelength reflective metasurfaces [21] to flexibly generate the vortex waves with different OAM mode numbers in 2016. On this basis, they designed an electromagnetic metasurface which could simultaneously generate multiple radio OAM beams in different directions [22], improving the previous experiments. Their experiments paved a way to generate the OAM vortex waves for radio and microwave wireless communication applications. In the same year, Xu et al. demonstrated a simple design to generate OAM beams by using metasurface with gradient reflection phase which was equally divided into eight regions instead of the spiral arrangement and each part was packed with the

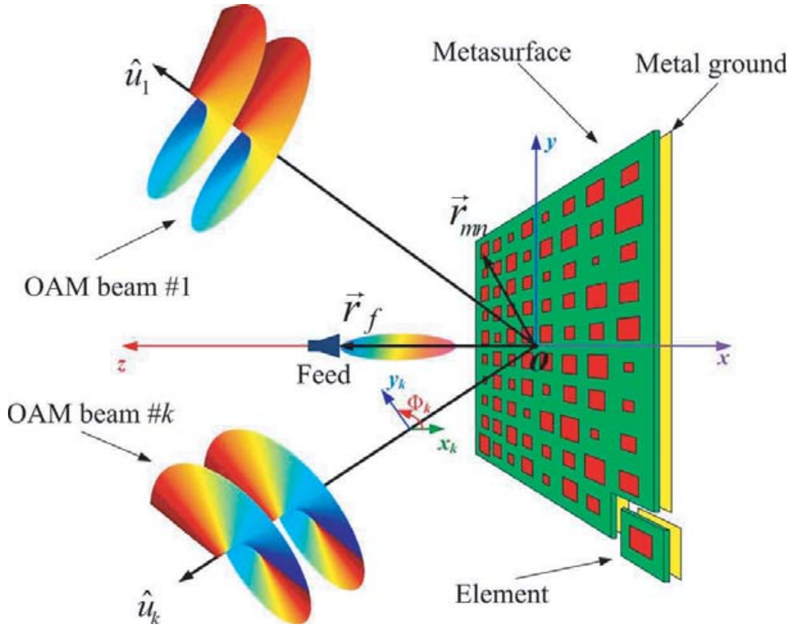


Figure 6. Configuration of OAM-generating reflective metasurface.

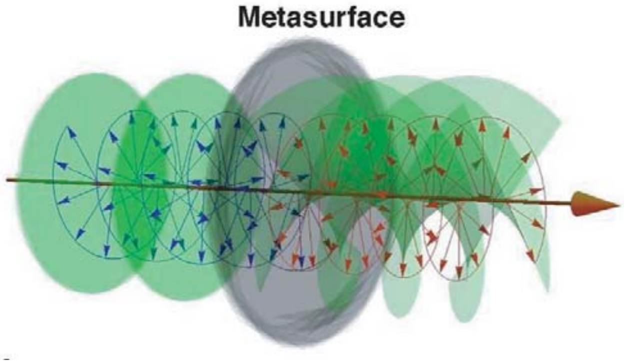


Figure 7. Schematic of the working principle of a spin-orbit converter. A left circularly polarized beam with plane wavefront is turned into a right circularly polarized helical mode.

identical metasurface units in microwave band [23]. This kind of metasurface is similar to a reflection array. In 2020, Guo et al. [24] designed a novel reflective metasurface to dynamically generate OAM with different modes in radio frequency domain. The reflective metasurface had the advantages of small size, low profile, mode reconfiguration and frequency-adjustable characteristics, which had great importance in future wireless communications system.

The second scheme is based on the coupling characteristics of SAM, which transforms SAM into OAM beams with different modes by metasurfaces. This process occurs in inhomogeneous and anisotropic media, realizing the characteristics of q-board [25]. According to the momentum conservation law and Pancharatnam-Berry phase concept [26], the SAM could be converted to OAM, as shown in Fig. 7. This effect requires a retardation of π between two orthogonal linear polarizations and the incidence of circularly polarized wave. The metasurfaces that can transform SAM and OAM are known as geometric-phase metasurfaces [27]. The handness of the produced OAM depends on the incident SAM. In 2014, Karimi et al. proposed and proved that plasmonic metasurface realized spin-to-orbit coupling in the visible region [28]. In 2016, Chen et al. [29] proposed composite perfect electric conductor (PEC)-perfect magnetic conductor (PMC) metasurfaces to convert the LCP (RCP) plane wave with zero OAM to the RCP (LCP) helical EM wave with desired OAM at microwave regime. The conversion efficiency can nearly reach 100%. After that, they put forward quasi-continuous metasurfaces [30] and ultrathin complementary metasurface [31], which provided great convenience for the generation of OAM with high quality and high transmission efficiency. In 2018, Guan et al. introduced the shared-aperture concept into metasurfaces for generating OAM vortex beams with different modes. This polarization-controlled shared-aperture metasurface achieved higher aperture efficiency than the conventional shared-aperture schemes [32]. In addition, metasurfaces are also used for OAM detection [33]. Such discoveries attract more and more researchers.

3.1.3. Other Generation Methods

In addition to the above methods, there have been some new OAM generation methods in recent years [34–36]. According to the concept of spatial transformation, [34] presented an all-dielectric microwave device that was capable of generating OAM electromagnetic waves with mode +1 in the reflection state. Importantly, because of the use of nonresonant metamaterial structures, the device possessed a substantial broad operational bandwidth. The authors in [35] analyzed current wave modes of the patch antenna by using the characteristic mode theory (CMT) and realized the third-order OAM radio wave by using the ring patch antenna. [36] proposed a transmit array antenna (TAA) with a small-scale circular phased array antenna (PAA) feed to generate OAM radio beams. This kind of antenna combines the advantages of PAA and lens antenna and is becoming the competitive candidate of high-gain array antenna. Recently, Ming and Shi [37] designed a water antenna to generate the OAM wave with the tunable modes in a frequency band. The use of the water as a superstrate reduced the degree of divergence of the OAM wave, which provided a feasible way for the OAM based wireless communication applications. OAM generation can also be combined with 3D technology. The authors in [38] used 3D-printed micro scale spiral phase plates to generate OAM beams. Meanwhile, the authors in [39] proposed a new OAM mode-reconfigurable discrete dielectric lens (DDL) antenna operating at 300 GHz. DDL [40, 41] is an appealing antenna structure for THz applications due to simpler feed network, smaller shape, and lower dielectric loss than SPP. With the compatibility of DDL and 3D (3-D) printing technology, rapid prototyping and cost reduction can be achieved.

3.2. The Reception of OAM

The main methods of receiving OAM include single-point receiving method, all airspace coaxial receiving method, and partial receiving method.

(i) Single-point receiving method
The single-point receiving method is also known as the far-field single-point approximation method, which achieves the detection of OAM modes by detecting the amplitude components of the electric and magnetic fields on the three coordinate axes [42, 43]. For example, we can receive the x component of the electric field and the y component of the magnetic field (z is the direction of the propagation axis) at a point on the RF vortex beams to complete the detection of the OAM modes, as shown in Fig. 8. However, this method is the result of far-field approximation. Only when the divergence angle of the OAM electromagnetic beam is small and the polarization direction of the receiving point is exactly the same as the polarization direction of the OAM wave, a better approximation effect can be achieved. In addition, because this method uses the amplitude of the electric field intensity and magnetic field intensity, the detection performance is greatly affected by noise.

(ii) All airspace coaxial receiving method
The receiving end receives the entire ring beam energy from space using a receiving antenna whose mode is opposite to the OAM mode of transmitter. The transmitted RF vortex wave is phase-compensated by the receiving antenna and becomes a regular plane electromagnetic wave. Since the radii of toroidal beams of RF vortex wave in different modes increase with the number of modes, the conventional electromagnetic wave which is phase-compensated can be separated by the method of space-division. This receiving method is learnt from optical OAM. However, due to the divergence of the RF vortex beams, the required size of the receiving antenna in the all airspace increases with the transmission distance, which cannot be achieved in practice. Therefore,

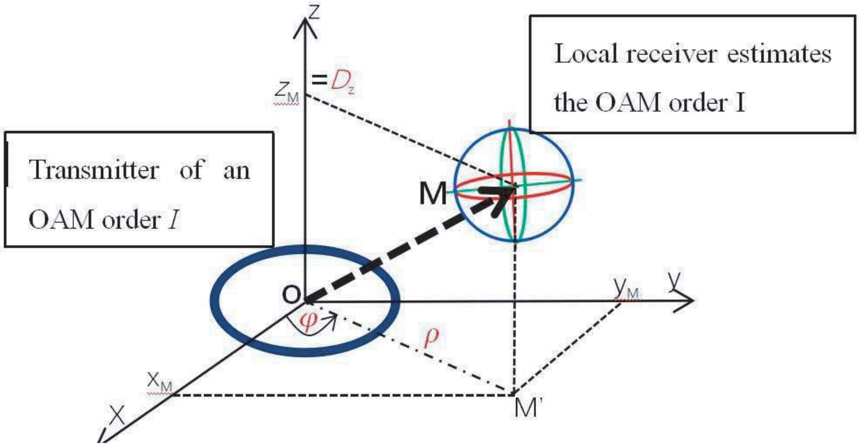


Figure 8. Principle of single-point receiving method.

this receiving method is only suitable for short-distance point-to-point reception. In addition, the diffraction module of electromagnetic wave is used to perform coordinate transformation on the received signal in the all airspace, which can transform the different OAM modes to the different momentum modes in the transverse direction.

In 2014, Yan et al. [44] used the all airspace reception method to multiplex eight signals at 28 GHz (4 OAM modes and each mode has 2 polarizations) with communication distance of 2.5 m. Its transmission rate could reach 32 Gbps and spectrum efficiency was 16 bit/s/Hz.

(iii) Partial receiving method

Because the phase of the RF vortex wave is linearly distributed on the ring beam, there is a phase difference between any two points on the ring beam. The phase differences generated by RF vortex waves with different modes are different. When the antenna spacing is fixed, the phase difference between the antennas is proportional to the OAM modes. Therefore, we can arrange an arc antenna array uniformly on partial ring beams to receive signals, perform a Fourier transform on received signals to detect different phase differences, and then to detect and separate different OAM modes. However, this partial receiving method is sampling a part of the ring beams, and the number of OAM modes that can be detected and separated are limited by the number of receiving antennas and the size of the arc segment formed by the antenna array. Besides, the size of arc segment of the antenna array required to detect the same number of OAM modes increases linearly with the transmission distance. It is worth mentioning that a simplified case of the partial receiving method is the phase gradient algorithm (PGA) [45–47]. In phase gradient algorithm, at the receiving end, we place two antennas on a ring beam perpendicular to the propagation axis to detect and distinguish different OAM modes of electromagnetic waves by the phase difference between the antennas.

(iv) Other receiving methods

There have been many other receiving and detecting methods of OAM in recent years. In 2017, Zhang and Ma reported an OAM mode detection method based on digitally rotating a virtual antenna [48]. It means that different OAM modes were identified by measuring the corresponding rotating Doppler shift. In 2019, Yao et al. proposed a new method to effectively measure OAM properties of long-distance transmission [49]. By rotating the OAM wave antenna and fixing the plane wave antenna as a reference, properties of OAM wavefront in terms of phase and amplitude could be measured. They conducted experiments in Qingdao, China to verify OAM phase properties for long-distance transmission. The experimental results showed that the vortex phase properties of OAM kept well after long-distance transmission. Their works offered more options and possibilities to utilize OAM properties in the real environment, especially in long-distance transmission. In addition, the neural network method has been used to distinguish OAM modes in [50] and [51]. The authors in [50] proposed a deep neural network approach, which could distinguish 110 kinds of OAM modes at the same time, and the classification error rate was less than 30%. Meanwhile, the

authors in [51] used convolutional neural networks (CNN) to differentiate 32 OAM modes with more than 99% accuracy under high levels of turbulence. However, the performance of these solutions was significantly reduced due to a large number of OAM modes and high levels of turbulence.
In 2020, Rostami et al. proposed a new method to decode OAM modes by combining the effective machine learning tools from persistence homology and CNN [52]. Simulation results showed that the method was superior to CNN in classification accuracy by 10% in presence of severe atmospheric turbulence and a large number of OAM modes.

How to detect OAM beams effectively has always been one of the major concerns of researchers. However, in the study of a better detection algorithm, we need to pay attention to two aspects: one is to minimize the power consumption of detection algorithm; the other is not to destroy the orthogonality. Besides, it is quite necessary to consider the actual antenna size and spacing.

4. DEVELOPMENT OF OAM IN WIRELESS COMMUNICATION

4.1. The Latest Research of OAM

OAM technology was first applied to optical communication. Compared with optical communication, the generation and application of radio frequency (RF) OAM are more difficult. Because of the divergence of RF-OAM beams, it is difficult for long-distance transmission. In 2011, Tamburini et al. [53] achieved the RF-OAM generation and measurement at 2.4 GHz using Yagi antenna with 7 arrays with a distance of 442 m in Venice Lake firstly. This experiment shows that using RF-OAM can achieve multiple transmissions at the same frequency, which greatly improves the communication rate. In addition, based on the mode selection scheme, [54] proposed an analog OAM transmission method based on dual-circular polarization (CP) in 2019, which could improve OAM transmission rate. Therefore, OAM can improve transmission rate and bandwidth utilization no matter from theory or experiment.

Antenna is an important part of a communication system. The OAM beam generated by traditional antenna has some disadvantages such as large divergence angle and inflexible mode generation. How to improve the existing antenna to produce more perfect OAM beams has been one of the hot researches. Since 2013, Zhejiang University has published a number of papers on OAM antennas and has developed a variety of original small-sized, high-performance RF-OAM antennas, including circular traveling wave antennas [55], substrate integrated waveguide antennas [56], dielectric resonant antennas [57], and metal ring resonator slot antennas [58]. In recent years, this research team has proposed a new concept of two-dimensional planar spiral OAM beam (PSOAM) [59] and proposed a partial aperture receiving scheme [60]. PSOAM is a new OAM carrier wave, which propagates along the transverse plane. Therefore, it overcomes the divergence inconsistency of different OAM modes. One team in Shanghai Jiao Tong University made significant contributions in the field of OAM coaxial multi-mode transmitting antennas [61–63]. The team proposed a design method about reflective surface antennas based on vortex wave feeds. This method could generate four-OAM-mode beams and achieve the same divergence angles of high-order as of low-order mode, which provided great help for long-range coaxial reception.

There are two different methods to make use of the orthogonality between OAM beams with different modes. In the first method, N different OAM modes can be encoded into N different data symbols representing $0, 1, \ldots, N-1$, and the OAM mode sequence sent by the transmitter represents the data information. At the receiving end, the data can be decoded by detecting the received OAM modes. The second method is to use various OAM beams with different modes as carriers for different data streams. OAM beams in different modes can be spatially multiplexed and demultiplexed, thereby providing independent data carriers as a multiplexing method. In an ideal situation, the orthogonality of the OAM beams can be maintained during transmission, thereby separating and recovering the required data channels at the receiving end. From 2016 to 2019, Xidian University had conducted a lot of researches in the field of OAM modulation, coding and long distance communication [64–67]. They combined OAM modulation with MIMO to achieve high spectral efficiency [66]. In order to further decrease the beam divergence angle, this team proposed a special OAM sequence scheme [67], which solved the problem of the divergence angle of the OAM beam using a method similar to beam forming.

The authors in [68, 69] studied OAM channel capacity and proposed an OAM-based spatial modulation (OAM-SM) transmission scheme. They analyzed energy efficiency, reception complexity and average bit error rate (BER) performance. In terms of energy efficiency, they compared it with OAM-based MIMO millimeter-wave communication systems. The OAM-SM scheme has the ability to resist path loss attenuation and is suitable for long-distance transmission.

The Avionics Laboratory of Tsinghua University studied the method of mapping the OAM domain to the second frequency domain. In December 2016, they completed the world's first 27.5 km long-distance RF vortex wave transmission experiment [70, 71] and proposed a joint OAM coding and modulation method [72]. They also combined OAM dimension to establish Euclid space [73]. In 2018, this laboratory also successively accomplished the 30.6 km long-distance, 4-mode index modulation OAM transmission from the Ming tombs reservoir to Tsinghua University, and the 172 km long-distance OAM partial phase receiving experiment. They laid a key theoretical and technical foundation for the future long-distance RF vortex wave spatial transmission experiment (100 km to 400,000 km).

The Ministry of the Interior and Communications(MIC), Japan, commissioned Nippon Electronic Company (NEC), Nippon Telegraph and Telephone Corporation (NTT) and other units to jointly promote the advancement of OAM in 5G and B5G engineering. In December 2018, NEC successfully demonstrated an OAM mode multiplexing experiment (using 256 QAM modulation and 8-mode OAM multiplexing) over 40 meters in the 80 GHz frequency band for the first time, which was mainly targeted at point-to-point applications. NTT successfully demonstrated the experiment of 11-channel OAM modes multiplexing technology in 2018 and 2019, and achieved a transmission rate of 100 Gbps at a transmission distance of 10 meters [74, 75].

In 2019, the Korean Academy of Sciences applied OAM to 6G mobile communications for future wireless communication applications. Meanwhile, they formulated national key topics on OAM quantum state transmission which will last until 2026.

In May 2019, the Ministry of Industry and Information Technology, China, held a seminar on 6G. The orbital angular momentum was decided to be one of the six key technologies of 6G in this conference. The meeting also included it in the national key research plan for the next three years and established the corresponding OAM technical task force.

4.2. Combination of OAM and New Technologies

With its excellent characteristics in reducing the correlation of single user channel, the combination of OAM and other technologies has become a new research direction. In 2017, Yuan et al. demonstrated the feasibility of OAM-MIMO in some Near Field Communication (NFC) scenarios [76]. One year later, Hirano also found that when the radius of UCA increased, the performance of OAM-MIMO improved [77]. Wang et al. derived the capacity of the OAM-MIMO communication system based on the proposed OAM wireless channel model in 2017. At the same time, they studied the effect of some system parameters (such as lager interval of OAM mode and antenna spacing) on the capacity of the OAM-MIMO communication system [68]. Simulation results showed that the channel capacity of the system increased with the increase of OAM state interval and antenna spacing. In 2019, Chen et al. proposed a constant envelope OAM (CE-OAM) system with appropriate modulation coefficient [78], which was superior to the traditional OAM system in peak-to-average power ratio (PAPR) and bit error rate (BER) performances.

Additional experimental studies revealed the possibility of improving the spectrum efficiency. Cheng et al. proposed the OAM-embedded-MIMO (OEM) communication framework to obtain the multiplicative spectrum-efficiency-gain (SE-gain) for joint OAM and massive-MIMO-based mmWave wireless communications [66]. The results illustrated that the scale was larger than traditional massive MIMO-based mmWave communications. The OEM mmWave communications could significantly improve spectral efficiency. In order to maximize the spectral efficiency of OAM-based MIMO system, in 2018, [79] presented a reused multi-OAM-mode multiplexing vortex radio (RMMVR) MIMO system, which is based on fractal UCAs.

Some existing academic researches have proved that OAM is compatible with the traditional OFDM and can achieve extremely high capacity in wireless communications [80–82]. However, these researches mainly focused on experimentally verifying the feasibility of joint OAM and OFDM, but lacked the theoretical analysis of OAM signals transmission and decomposition. Similarly, they assumed that the

OAM-based wireless channel model in sparse multipath environments was known and that there was no inter-mode interference caused by reflection paths. On the basis of previous research, Liang et al. built an OAM-based wireless channel model in a sparse multipath environment including a LOS path and several reflection paths, which obtained high capacity while resisting multipath interference [83].

The prospects of OAM mode-groups(MGs) in MIMO system, low interception communication system, and spatial field digital modulation system [84] have been explored. [85] proposed a plane spiral OAM (PSOAM) MG based MIMO communication system, which regarded PSOAM MG as an independent transmitting antenna. The simulated results showed that the scheme could increase the channel capacity, which meant that PSOAM MGs could not only improve the signal-to-noise ratio (SNR) of system but also decreased the spatial correlation of sub-channels. After that, [86] proposed a partial slotted curved waveguide leaky-wave antenna which could generate OAM MG with high equivalent OAM order $l_e = \pm 40$ at 60 GHz. The OAM MG showed a high gain beam with a helical phase distribution. This method may bring new applications to the next generation communication and radar system.

5. RELATIONSHIP BETWEEN OAM AND MIMO

The development of wireless communication technology based on OAM faced great controversy after 2012 when Tamburini et al. finished the outdoor experiment, mainly focusing on two issues: Does OAM provide a new dimension? What is the relationship between OAM and MIMO? This has led to a lot of discussion among physics and communication scholars.

Tamburini et al. finished the indoor [13] and outdoor [53] experiments of OAM wireless communication based on the same frequency. They argued that the new radio technology allowed an unlimited use of wireless channels on the same frequency, and it was a new degree of freedom. This caused a great sensation and controversy. Tamagnone et al. [87] immediately responded that OAM was not a new dimension but a special implementation of MIMO. They pointed out that the OAM technology allowed the decoding of two signals in line-of-sight (LOS) conditions because of the large separation between the receiving antennas, which placed the transmit antennas in the near-field Fresnel region of the receiving 'array'. This large separation between the receiving antennas also severely limited the practical applications of the technology.

Therefore, a discussion on OAM and MIMO technologies was carried out. First of all, Tamburini et al. and Tamagnone et al. published articles in the New Journal of Physics to comment and answer each other's opinions, respectively [88, 89]. Tamburini et al. emphasized in [88] that EM angular momentum (a pseudovector of dimension length × mass × velocity) was a unique and basic physical observation data carried in the electromagnetic field. MIMO was a multi-port engineering technique to improve the carrying capacity based on EM linear momentum (an ordinary vector of dimension mass × velocity). It indicated that the OAM radio was independent of MIMO radio. [89] also explained the difference in the maximum information carried by each photon between OAM technology and MIMO technology theoretically. However, it was emphasized in [1] that any system with multiple antennas at the transmitting (Tx) and receiving (Rx) ends could be regarded as MIMO and described by channel matrix H. Under the definition of generalized MIMO, OAM technology was just one of the special implementations.

As for the question of whether OAM provides a new degree of freedom, OAM can be divided into two categories. One is called quantum OAM (q-OAM), and the other is called synthetic OAM (s-OAM), as shown in Table 3. Due to the limitation of antenna technology, most of the OAM discussed in wireless communication at present belongs to s-OAM, which is a spatial vortex beam synthesized by multiple electromagnetic waves with different phases in space. Although a set of electromagnetic waves can be synthesized in a variety of vortex states, corresponding to different OAM modes, from the quantum characteristics of a single electromagnetic wave, all electromagnetic waves around the axis rotation are in the same state of quantum rotation. Since s-OAM relies on the electromagnetic waves emitted by multiple electromagnetic units to synthesize the beams, we can consider it as a beamforming. From the perspective of quantum science, when the q-OAM electromagnetic waves are transmitted, OAMs with different modes have been obtained without feeding phase difference. Moreover, for different modes of q-OAM waves, the micro-particles have different rotation states around the axis. There is relatively little progress in the application of q-OAM in communications, mainly because it is very difficult to

Table 3. The relationship between OAM and MIMO.

	Subclass	Relationship with MIMO
OAM	q-OAM	Independent of MIMO, a new dimension
	s-OAM	A subset of MIMO, a special form, corresponding to the vortex beamforming

generate and isolate electromagnetic waves with different quantum spin states. q-OAM is mainly carried out by physicists for some theoretical research, which cannot be used in engineering in a short time. Therefore, q-OAM will not be discussed in this paper.

In theory, MIMO is a general technique for dealing with direction/space and beam form. It does not specify the signal form and antenna usage, nor does it show the method of spatial sampling according to channel characteristics. Therefore, OAM is an application form of MIMO, because it also uses space resources in the traditional sense. However, the current spatial sampling uses a geometric beam, so it can only efficiently distinguish the signals in the spatial direction rather than in the beam form. OAM no longer needs to use a large number of unrelated paths for spatial reuse. Even in a line-of-sight environment, OAM can also host multi-path data through a large number of OAM modes. It realizes spatial multiplexing with high degrees of freedom and reduces the complexity of receiver detection.

Under the premise that the size of the receiving antenna is limited, OAM will not exceed the capacity limit of MIMO of the same antenna specification, nor will it increase the maximum freedom of a given channel. It means that MIMO and OAM have the same theoretical performance upper bound. Moreover, the wireless communication based on OAM will not increase the channel capacity in the communication link [90]. This conclusion is consistent with that of Edfors and Johansson [91]. They proposed that communication over different OAM modes sub-channels is a subset of MIMO solutions. Finally, in 2015, Oldoni et al. [92] compared the communication system based on OAM with the MIMO system and reached a consensus: the essential difference between OAM and MIMO is the complexity of signal processing. The OAM here is actually the s-OAM defined by us. Since then, the relationship between the OAM and MIMO has basically been determined, i.e., the OAM is a special implementation of MIMO.

However, the latest research suggests that there is a special circumstance. [93] revealed that UCA-based OAM could not be considered as a special case of MIMO any longer in keyhole channels and could provide additional degree of freedom (DOF) in keyhole channel. This physical phenomenon provides a promising way to overcome the keyhole effect for traditional multi-antenna wireless communications.

Although s-OAM cannot break through the capacity upper bound of generalized MIMO, in the case of sparse multipath channels, the rank (degree of freedom) of LOS-MIMO channel matrix is far less than the number of antennas. Traditional MIMO technique based on directional beam performs poorly in distinguishing spatial resources for different transport layers in this scenario. In the future, with the development of immersion services such as AR/VR, it will be a trend for single user to reuse more layers to improve capacity. It seems more advantageous than traditional methods to divide space resources according to different OAM modes corresponding to vortex beams. The orthogonal basis formed by them can significantly reduce the mutual correlation between sub-channels and increase the freedom of spatial multiplexing, and thus greatly improve the communication rate.

6. FUTURE RESEARCH DIRECTIONS OF OAM

The characteristic of the vortex wave is that the beam has a divergent shape as a whole. The center of beam is concave, and the energy is 0 when OAM mode is non-zero. The entire beam presents a hollow inverted cone. When the mode number begins to increase, the null area of the beam gradually expands. And the beam divergence becomes more and more severe. As the transmission distance increases, the radius of the beam will also become larger. This has contributed great disturbance to the reception of electromagnetic waves and has become one of the important factors restricting the further development and popularization of vortex electromagnetic waves. Due to the divergence of the main lobe of the non-zero mode signal in the OAM signal, the configuration problems of the receiving and transmitting antennas affect the overall performance. The main undesirable factors in OAM transmission also include center misalignment of the transmitting and receiving antennas and the long transmission distance.

OAM is still in the exploration stage in the field of wireless communications. We believe that future research trends should mainly focus on the following aspects:

(i) OAM transmission under non-ideal conditions
The OAM communication system needs axial alignment of the transmitting and receiving antennas. When an axial deflection occurs between the transceivers, the receiver will generate mode crosstalk, which will increase the bit error rate and reduce system performance. There are many non-ideal states in wireless communication, especially mobile communication, including non-coaxial and non-line-of-sight. This is the key to solve the problem of application for vortex electromagnetic waves in mobile communications. Non-ideal conditions will destroy the orthogonality of the OAM modes, leading to the loss of some of the excellent features. And these non-ideal conditions will invalidate the receiving methods of vortex wave because most of the current receiving methods are based on ideal conditions.
Thus some scholars have proposed solutions for some non-ideal conditions at present. In 2018, Chen et al. proposed an efficient transmit/receive beam steering approach to circumvent the large performance degradation in not only non-parallel case, but also off-axis and other general misalignment cases [94]. There are many non-ideal conditions in practical applications which need to be addressed. Some compensation solutions can only solve minor off-axis and non-parallel problems, which are more suitable for point-to-point application scenarios. For typical scenarios of mobile communications, large off-axis exists, and the terminal may also rotate and move quickly.

(ii) Suppression or elimination of OAM divergence angle
The existing OAM reception and detection methods use a large-diameter antenna (or antenna array) to receive the entire beam. With the increase of transmission distance, the divergence angle of the vortex electromagnetic wave becomes larger, which requires the size of receiving antenna to become even larger. This receiving method becomes extremely difficult when transmitting over long distances, and the antenna size is almost unacceptable. On the other hand, the deployment of large-diameter at the receiving end also limits its application scenarios in wireless communications. Some progress has been made in the suppression of divergence angle in optical communication, which is a step further for OAM in RF communications [95, 96]. At present, scholars have also proposed some solutions to solve the divergence problem in OAM wireless communication systems, such as partial wavefront detection algorithm. Although this algorithm can increase the communication distance, it will destroy the orthogonality of the OAM modes. In addition, the generation method of OAM beams propagating along a transverse plane was also proposed, which was validated by full-wave simulation [97]. Therefore, how to greatly suppress or even eliminate the energy divergence angle and solve the OAM transmission problems in the far field is worthy of further exploration.

(iii) Research on antenna topology of OAM-MIMO
Traditional MIMO technology emphasizes maximizing the performance potential of given classic antenna topologies, such as uniform linear array (ULA) and UCA. However, due to different application scenarios, we consider different factors when designing the antenna structure. Under the conditions of different size restrictions, communication frequencies, and transmission distances, how to design the antenna topology to obtain the optimal performance has not been fully studied in traditional MIMO. Some scholars have made some progress in this respect. In 2018, Zhang et al. analyzed the transmission and reception characteristics based on the theoretical formula of the radiation field [43]. By calculating the upper and lower boundaries of multiple OAM wave function formulas and analyzing the amplitude and phase of multiple optimal receiving positions, the common receiving sampling area of multi-mode OAM waves was determined.
There are significant differences in communication performance between different antenna topologies. How to find the optimal antenna topology in different application scenarios will be the focus of future research.

(iv) Selection of OAM modes
The orthogonality of different modes in OAM provides a new modulation method for transmitting information. Therefore, how to use different modes to modulate and process signals has become the focus of researchers. In addition to directly transmitting information similar to traditional

communication, different modes in RF vortex waves can also be used in new application scenarios such as index modulation and secrecy transmission. Whether it is partial phase surface reception or virtual rotation reception, the number of available OAM modes is limited (less than the number of transmitting antennas), and the gain caused by directly using different modes to transmit information is limited, too. By modulating the OAM mode combinations, spectral efficiency can be significantly improved, where the mode combinations correspond to independent channels for information transmission

(v) OAM application scenarios
At present, there are many methods for generating vortex electromagnetic waves in different modes, such as SPP and UCA. Different generation methods have different complexity, cost, and the required number of antennas. There are also differences in their performance. The OAM-MIMO system has multiple application scenarios. Service objects, the number of people receiving service, and the standard requirements for communication are different for different application scenarios. Therefore, it is also worth studying the choice of different OAM implementation methods for different scenarios.

7. CONCLUSION

The huge demand for transmission capacity may lead to bottleneck of bandwidth in communication system. Applying OAM to communication has been seen as a key solution to the foreseeable capacity crunch. OAM has been successfully used in optical communications and has very good application prospects in wireless communications. At present, the research and practical application of OAM communication are still in early stages. Because of the enormous potential of this technology, many universities and research institutions in the world have continually explored and advanced in this field, and have conducted a number of research progresses in radar, communications, optics, quantum, and other fields. With the introduction of OAM, there is no need to use a high number of unrelated paths for spatial multiplexing in wireless communication. Even in a LOS environment, this technology can also host multiple data through a large number of OAM modes to achieve a high degree of freedom in spatial multiplexing transmission. OAM can improve the capacity of microwave wireless return link and point-to-point communication and meet the needs of ultra-high speed data transmission for single user of short distance (such as virtual reality scene), which the traditional MIMO technology cannot offer. In addition, we can make use of the orthogonality between OAM modes to eliminate all kinds of interferences, such as inter-cell interference, uplink and downlink interference, and full-duplex transceiver self-interference, providing more technological means for interference elimination and having good application prospects.

We hope that such works will attract more attention from academic and industry groups to promote corresponding research activities, and in particular, to make useful suggestions for improving spectral efficiency.

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