Electromagnetic Wave with OAM and Its Potential Applications in IoT

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Abstract. As one of the hot techniques, the Internet of Things (IoT) is gradually penetrating all aspects of human life. The limitation of the spectrum resources has limited the development of the IoT, which forces us to look for new ways to increase the efficiency of the spectrum utilization. The Electromagnetic (EM) wave with orbital angular momentum (OAM), also called the EM vortex wave is a promising method to solve this problem. In this article, the basic theory of EM wave with OAM in radio frequency (RF) is introduced and the main techniques in the OAM radio beam, including the generation of the EM with OAM, the receive, the multiplexing based on OAM mode are summarized. Based on the main properties of EM wave with OAM in RF, the potential applications of EM vortex beam in the IoT are discussed.

Keywords: Orbital angular momentum · Vortex beam · IoT

1 Introduction

Since it was first introduced in 1999, the IoT has received a lot attention from all over the world and has been developed extensively in many areas [1]. The IoT has become the third tide of development after computers, the Internet and mobile communication networks. Communication technology enables the IoT to efficiently collect and exchange the perceived information data between different terminals, and realize the interworking and sharing of information resources, which is the key support for various application functions of the IoT. However, in a wireless communication system of IoT, there may be trillions of devices, which may congest the network because the limitation of the bandwidth. That may limit the development of the IoT and need novel techniques to overcome this problem.

Since wireless communication has spread to all aspects of our lives, there is always an increasing demand of new ways for using the existing spectrum

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efficiently. Various technologies such as the Orthogonal Frequency Division Multiplexing (OFDM) and the Code Division Multiple Access (CDMA) have been used to increase the efficiency of the available bandwidth [2], but they are still far from being sufficient. It has been known that the EM wave can carry both linear momentum and angular momentum [3]. When an EM wave has a helical phase-front, it has OAM [4]. The waves with OAM are also called 'vortex waves' and have been studied extensively in optical frequency [5–8] and have many applications in optics, for instance in optical manipulation [9], and microscopy [10]. However, the EM waves with OAM in RF is still quite new and a lot of their properties have not been clarified. One of the main researches on OAM in RF is how to using OAM modes in multiplexing in free-space communication. Theoretically, an EM wave can carry an infinite number of OAM modes on the same frequency, and each mode is orthogonal to each other [11]. Thus the multiplexing based on OAM modes can greatly increase the efficiency spectrum utilization in free space, while the EM waves with different OAM modes have a good anti-jamming ability due to the orthogonality of different OAM modes. In modern wireless communication systems, all the EM waves are plane waves, which means that their OAM modes are 0. Thus the EM waves carrying any OAM mode are orthogonal to the plane waves. Although the EM waves with OAM have not been studied extensively in wireless communications of RF, they were even paid less attention in the development of the IoT. Since their advantages over common EM waves, we believe that the EM waves with OAM will supply a quite new perspective in studying IoT and can support new ways to increase the efficiency of spectrum utilization for the IoT network.

In this article, we will first have a review of the main characteristics of the EM waves with OAM in RF and summarize the current key techniques in studying OAM in RF, then the potential applications of EM waves with OAM in the IoT will be discussed.

2 Basic Theory of OAM

As described in the standard electrodynamics literature, an EM wave will not only radiate energy (linear momentum) but also angular momentum (AM) into the far field [12]. The angular momentum of an EM wave is composed of two parts: the spin angular momentum (SAM) and OAM [13]. The SAM is associated with the photon spin which is manifested as circular polarization, and, in contrast, the OAM is shown as a result of a beam possessing helical phase fronts [14].

Let SAM be denoted by $\boldsymbol{S}$ and OAM be $\boldsymbol{L}$, then the total angular momentum of $\boldsymbol{J}$ can given by the sum [15]

$$\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}, \tag{1}$$

where,

$$\boldsymbol{L} = \varepsilon_0 \int \boldsymbol{Re}(\mathrm{i}\boldsymbol{E}^*(\widehat{\boldsymbol{L}} \cdot \boldsymbol{A}))\mathrm{d}V, \tag{2}$$

$$\boldsymbol{S} = \varepsilon_0 \int \boldsymbol{Re}(\boldsymbol{E}^* \times \boldsymbol{A})\mathrm{d}V, \tag{3}$$

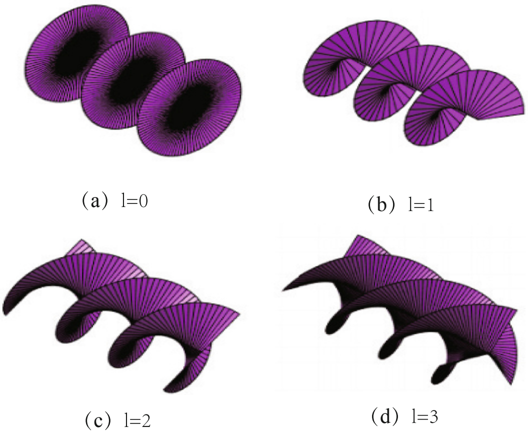
note the occurrence of the OAM operator $\widehat{\boldsymbol{L}} = -\mathrm{i}(r \times \nabla)$, $\boldsymbol{A}$ is the vector potential, $\boldsymbol{E}$ is the electric vector field, ε_0 is the vacuum permittivity.

OAM is one basic physical property of EM wave [16]. It describes the orbital property of an EM wave and supplies an rotational degree of freedom in EM field. The EM wave carrying OAM can be generated by an plane wave with one phase rotation factor $\exp(\mathrm{i}l\varphi)$, where l is the topological charge representing the state of OAM, and φ is the azimuthal angle. Because of the phase rotation factor, the wavefront phase or the phase-front has an spiral structure instead of a planar structure. The wavefront phase rotates around the beam propagation direction and the phase changes $2\pi l$ after a full turn.

The complex amplitude $U(r, \varphi)$ [17] of an electric field with OAM is a common EM wave with a phase rotation factor $\exp(\mathrm{i}l\varphi)$, which can be described as

$$U(r, \varphi) = A(r) \cdot \exp(\mathrm{i}l\varphi), \tag{4}$$

where r is the radial distance from the beam axis to the field point, and $A(r)$ represents the magnitude of the electromagnetic field. Figure 1 shows the phase structure distribution of four OAM radio waves with mode numbers 0, 1, 2, and 3 [18], where $l = 0$ represents the plane wave. It can be seen that if the topological charge of the OAM is different, the corresponding radiation mode is also different. As the topological charge l increases, the helicity of the wavefront for that EM waves become complicated, and the variation of the phase becomes more dramatic.


(a) l=0

(b) l=1

(c) l=2

(d) l=3

Fig. 1. The phase front structure of the EM vortex [18].

It is easy to demonstrate that the topological charge l can take any non-zero integer value, each value corresponds to an OAM mode, so the OAM modes have infinite states, and all these states are orthogonal to each other. Only two OAM modes with the same topological charge, i.e. two identical modes, have an inner product result of 1, and the OAM modes with different topological charge values has an inner product of 0. The OAM modes with different topological charge can be used as a series of channels, and theoretically such channels can be infinite, which means that using the OAM modes can greatly improve the transmission capacity and spectrum utilization. The orthogonality of the OAM modes also ensures that under ideal conditions, the crosstalk will not occur between channels, and the different modes can be easily separated at the receiving end to perform signal reading and processing. Therefore, the OAM technique can provide a potential solution for improving the transmission capacity and spectrum utilization of communication systems.

3 Techniques of OAM in RF

3.1 Generation

The EM waves carrying OAM can be generated in many different ways, and the most common methods include the array antenna method, the spiral phase plate (SPP) method, the helicoidal parabolic antenna method, etc. These methods allow the traditional plane wave to carry a spiral phase wavefront from different perspectives, thereby generating an OAM radio wave.

Array Antenna. The array antenna for generating the EM waves with OAM mainly have three forms: the uniform circular array (UCA) [15,19], the time-switched array [20] and the optical true time delay unit [21]. Among them, the UCA is the most widely used form, which is based on an unit antenna and is arranged with certain number in a special form. The array is evenly distributed around the center point (see Fig. 2). In an UCA, there are N antennas located equidistantly along the perimeter of the circle and phased with $\delta\phi = 2\pi l/N$ between two elements, where l denotes the mode of OAM (or the topological charge of waves with OAM). The phase difference between the first array element and the last element equals $2\pi l$. The mode of OAM generated by the antenna array is dependent on the total number of array elements N, i.e. they should satisfy this relation: $-N/2 < l_{max} < +N/2$. When $|l| \geq N/2$, the antenna array will not generate a pure spiral phase wavefront and OAM mode cannot be obtained.

Spiral Phase Plate. The SPP is one of the common devices generating OAM radio waves. In 1996, Turnbull explained how the beams carrying OAM arise from the SPP by using an optical model [22]. The SPP is a media disk with a spiral shape whose thickness varies with azimuthal angle (see Fig. 3). To generate an OAM radio wave with mode l, the phase of the EM field rotation should change by $2\pi l$. Assuming that number of discrete jumps is N, surface pitch is h, wavelength is λ, then the mode l is generated as shown in the following equation [23]:

$$l = \frac{2h}{\lambda}(\frac{N+1}{N}). \tag{5}$$

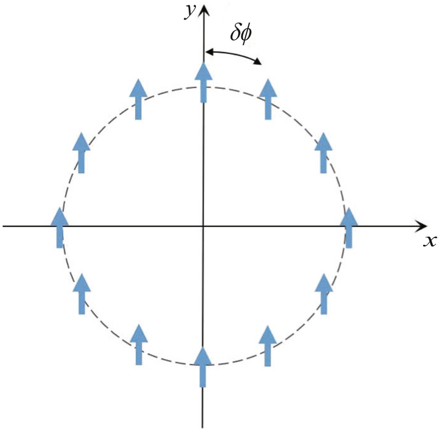


Fig. 2. Structure of circular array antenna [15].

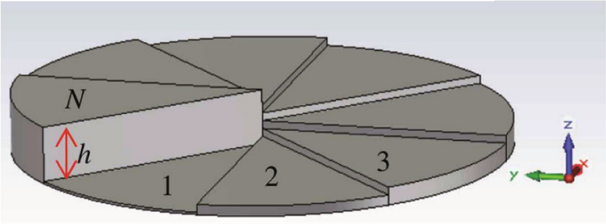


Fig. 3. Structure of SPP [23].

Helicoidal Parabolic Antenna. Using the helicoidal parabolic antenna is an early method of generating EM waves with OAM in RF. The first OAM wireless communication field experiment used a parabolic antenna as a reflective surface. The antenna was a 26 dBi commercial off-axis parabolic antenna, with diameter of 80 cm, which produced a vortex beam with $l = 1$ (see Fig. 4) [2]. Because the discontinuity of the phases in each element for the UCA and the SPP, the vortices generated in these two methods are not quite 'perfect', while the vortex beam produced in the helicoidal parabolic antenna usually has a very good helical shape. However the mode of OAM is hard to change in the helicoidal parabolic antenna, and it can be adjusted according to the need in the other two methods.

Fig. 4. Helicoidal parabolic antenna [2].

Other Methods. In addition to the more common methods of generating OAM described above, there are more and more other methods proposed these years, such as using the circular traveling-wave antenna [24], and the metasurface method [25–28].

Mathematical model of a circular traveling-wave antenna is shown in Fig. 5. It is a wire bent in a circle of radius a in the xOy plane, fed with a constant electric current amplitude I_0, which can ensure that the phase distribution on the ring is $\exp(\mathrm{i}l\varphi)$, where φ is the azimuthal angle. This current distribution means that the current phase increases $l \times 2\pi$ during one revolution.

In Fig. 6, an example of using metasurface for generating OAM modes is illustrated. The reflective metasurface is composed of a metasurface, a metallic ground plate, and an illuminating feed antenna. On the metasurface, there are some sub-wavelength elements without any power division transmission lines. The feed antenna spatially illuminates these elements that are designed to scatter the incident field to produce the reflective wave with a rotating phase front of $\exp(\mathrm{i}l\varphi)$ in the far-field zone.

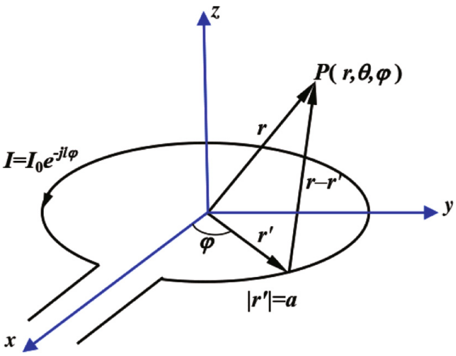


Fig. 5. Mathematical model of a circular traveling-wave antenna [24].

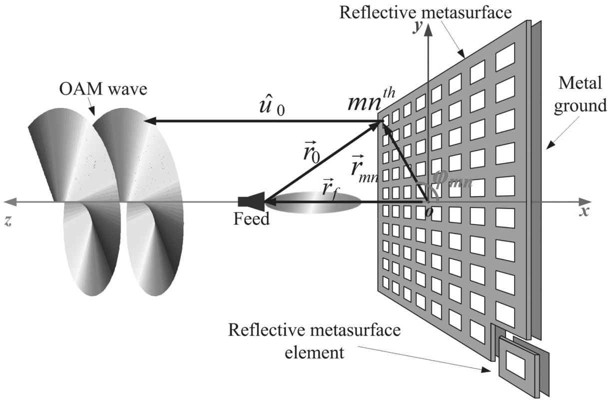


Fig. 6. Configuration of OAM generating reflective metasurface [25].

3.2 Receive

At the receiver, the phase detection is a key to distinguish the value of different OAM modes [29]. In this section we present two different methods for estimating the OAM of a radio wave.

Phase Gradient Method. An obvious feature of the OAM radio waves is that it has a spiral wavefront phase, so the phase gradient method uses phase differences at different receiving locations to identify different OAM modes. An approximation to the phase gradient would be to measure the phase difference between two points on a circle or a circle segment with the circle center on the beam axis [30]. As Fig. 7 shows, ϕ_1^{electric}, ϕ_2^{electric} are phase samples, β is the angle of the circle segment, then the estimated OAM mode can be calculated as

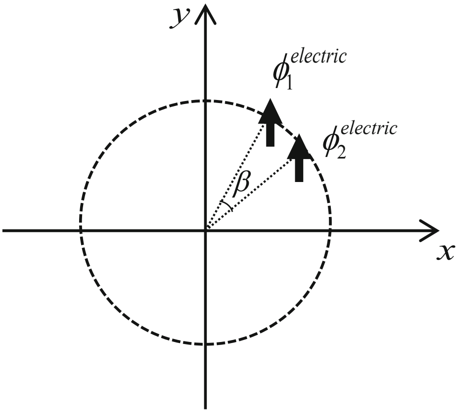


Fig. 7. Schematic of phase gradient method [30].

$$\frac{\phi_1^{\text{electric}} - \phi_2^{\text{electric}}}{\beta} = l. \tag{6}$$

Partial Aperture Sampling Receiving (PASR). The PASR method selects a part of the circle, $1/P$ as the receiving arc at the receiving end, and then uses M receiving antennas which are uniformly distributed on this arc for M-point signal sampling. The angular interval between the adjacent antennas is $2\pi/MP$ (see Fig. 8) [31]. The PASR method can correctly distinguish different modes, and the modes l_{n1} and l_{n2} need to satisfy the following two conditions:

(1) $|l_{n1} - l_{n2}| \bmod P = 0$,
(2) $|l_{n1} - l_{n2}| \bmod MP \neq 0$,

Although PASR has certain limits on the mode value, it solves the problem of excessive antenna aperture at the receiving end, simplifying the size of the receiving end.

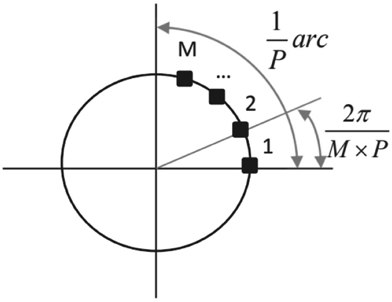


Fig. 8. Schematic of partial aperture sampling receiving [31].

3.3 Multiplexing

Without considering other factors, theoretically the number of OAM modes can be infinite. By using the orthogonality between the OAM radio waves with different modes and anti-interference characteristics, it is possible to transmit more information on the same carrier frequency without any interference, which greatly increase the rate of wireless communication and spectrum utilization [32]. For OAM radio waves in any two different OAM modes (l_1, l_2), the orthogonality equation can be expressed as:

$$\int_0^{2\pi} \exp[\mathrm{i}l_1\varphi_1]\exp^*[\mathrm{i}l_2\varphi_2]\mathrm{d}\varphi = \begin{cases} 2\pi & l_1 = l_2 \\ 0 & l_1 \neq l_2, \end{cases} \tag{7}$$

where * means complex conjugate. As it is shown in the Eq. (7), if the modes of the OAM radio waves are different, they are orthogonal to each other, which ensures that the EM waves carrying different OAM modes do not interfere with each other during propagation. In theory, the information carried by the OAM radio waves is proportional to the amount of the topological charges, which can increase the channel capacity.

3.4 Existing Problems

In the field of wireless communication, since the multipath effect has a large influence on the vortex waves, this limits the propagation distance of the EM waves with OAM, and makes the distance basically only for line-of-sight communication. In addition, the current methods of generating OAM commonly used generally has the problem of energy divergence, that is, when the transmitting end radiates the vortex wave outwardly by using a certain aperture antenna, the energy divergence angle is obtained on the premise of receiving the complete electromagnetic vortex information. The existence of the receiving antenna will increase with the increase of the transmission distance. Whether these problems can be effectively solved will be crucial for realizing vortex waves long-distance communication.

4 Potential Applications in the IoT

With the development of the IoT, the user types, scenarios, and scales of the communications industry have also undergone very big changes, highlighting the complexity and changes in the IoT [33]. The principle of the IoT is to use a combination of sensors and the Internet to create new technologies. During this period, the sensor generates massive data. However, due to the lack of spectrum resources, it is very hard to allocate large amounts of spectrum for transmitting these data, thus it is of great significance to apply OAM technology to the IoT. The possible applications of OAM in the IoT are discussed below.

4.1 Increasing Channel Capacity

Through the techniques of sensors, RF identification, and global positioning system, the IoT needs to collect data or process data in real time. The IoT collects all kinds of required information such as sound, light, heat, electricity, mechanics, chemistry, biology, location, etc. Through various types of possible network accesses, the IoT can realize the ubiquitous link between objects and objects, objects and people, and realize the goods and intelligent awareness, identification and management of processes. While during this period, a large amount of data will be generated, and the data generated by different access networks usually have the characteristics of large scale, multiple types, high speed, and complicated structure, which will affect the storage, processing and transmission of data. This problem can be solved by using the orthogonal properties of different modes of OAM. The radio beams carrying different OAM modes do not interfere with each other. Theoretically, the information carried by the OAM radio waves is proportional to the amount of topological charges, which makes it possible to multiply the channel capacity.

4.2 Potential Application Areas

The IoT can find its applications in almost every aspect of our daily life [34]. Below are some examples of applying OAM technique to IoT.

Wi-Fi Technology. Wi-Fi technology is a kind of near-field wireless communication technology, and also is a key technology in the IoT. Users connect Wi-Fi through different ways like mobile phones, laptops and other devices to achieve the purpose of browsing network information. The Wi-Fi transmission rate is from 1 Mb/s to 6.75 Gb/s [35]. However, if the amount of accessing users is too large, the transmission rate will be reduced sharply, which will strongly affect the user's communication experience. OAM can provide a novel multiple access method, like Mode Division Multiple Access (MDMA). The MDMA used the orthogonality property of the OAM modes instead of using the power domain to distinguish non-orthogonal multiple accesses for multiple users, thus it can be realized without consuming excessive frequency and time resources. With MDMA, different users can use different OAM modes to access the wireless network without interference.

Smart Agriculture. The effective combination of agricultural technology and IoT technology has greatly promoted the modernization of agriculture and realized the automation and intelligence of agriculture. At present, agriculture has used a large number of sensors in greenhouses and breeding ponds to obtain current temperature, humidity, PH, carbon dioxide concentration, etc. Through using these sensors, the data can be collected and sent to the management center of agricultural production through the communication system. The large amount of data generated during this period makes it difficult to transmit data efficiently. The orthogonality between different modes of OAM can solve this problem and effectively improve the transmission capacity.

Smart Logistics. The smart logistics is an important result of the application of IoT technology and meets the expectations and requirements of modern people. However, it is still in its early stage of development and a lot of problems need to be solved. The concept of smart logistics may refer to the intelligent supply chain, which contains various information about products and process indicators. All the parts in the smart logistics, such as product storage, delivery, distribution, and the construction of information management systems all are connected and processed through wireless sensing technology. A large amount of data will be generated during this period, and the transmission of this information can be achieved by OAM multiplexing technology, which will be helpful for developing the smart logistics.

5 Conclusion

In this article the EM waves with OAM and their potential applications are discussed. The basic theory including the physical meaning and the principle of the OAM of EM waves is explained firstly. The main techniques or methods of the generation, the receive and the OAM mode multiplexing for the OAM radio beams are analyzed. Through our analysis, one can find that applying the EM waves with OAM into the IoT may greatly improve the efficiency of the spectrum utilization, which will give a boost in the development of the IoT. Based on this theory, the potential applications of the OAM radio beams in the IoT, such as the Wi-Fi technology, smart agriculture and smart logistics are proposed. We believe that adopting the EM waves with OAM is a very promising way to greatly improve the utilization of the IoT, and the IoT with the technique of the OAM radio beams will have a very brilliant future.

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