Orbital Angular Momentum (OAM) in Wireless Communication: Applications and Challenges Towards 6G

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***Abstract*—In this survey, we explore the pivotal role of Orbital Angular Momentum (OAM) within the framework of wireless communication, with a special emphasis on its prospective contributions to sixth-generation (6G) systems. Guided by the International Telecommunication Union Radiocommunication Sector Working Party 5D (ITU-R WP 5D), the International Mobile Telecommunications 2030 (IMT-2030) recommendations for 6G have been initiated, addressing the immediate concerns of spectrum congestion and soaring data rates. This paper not only underscores the potential of OAM in boosting spectral efficiency but also delineates the imminent challenges spanning its generation, transmission, and reception in future wireless communication systems.**

***Index Terms*—Orbital Angular Momentum (OAM), Wireless Communication, 6G, Terahertz (THz) Band**

I. Introduction

The IMT-2030, known as 6G communication, marks a monumental milestone in the evolution of mobile telecommunications. This draft recommendation was formulated through the collaborative efforts of ITU-R WP 5D and was unveiled during the 44th conference in Geneva on June 22, 2023. As outlined in Fig. 1, six pivotal usage scenarios have been identified for IMT-2030 [1]. While 6G promises ultra-high-speed data rates, it is confronted with the challenge of spectrum congestion in current transmission technologies. This has driven the exploration of innovative approaches and untapped resources to address these issues. The 6 key usage scenarios in IMT-2030 can be regarded as extensions of the 4 primary usage scenarios in IMT-2020.

Among the notable solutions in these days, multiplexing technology stands out for its potential to overcome single-channel transmission constraints. Particularly, the communication via OAM emerges as a promising strategy. This approach leverages OAM as an orthogonal modal foundation for space-division multiplexing. ITU-R reports categorize OAM as a "Multiple physical dimension transmission" trend [1]. Its application in wireless communication designates it as a formidable candidate in the pursuit of 6G development.

Electromagnetic waves inherently possess both linear and angular momentum. A pivotal discovery by Allen *et al.* in 1992 revealed that Laguerre-Gaussian beams not only carry spin angular momentum but also have the capability to convey OAM [2]. Succeeding research has consistently introduced that

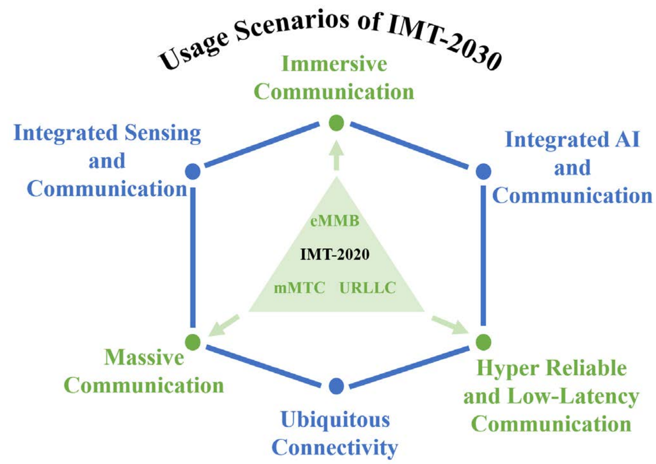

Fig. 1. The usage scenarios of 6G in IMT-2030.

electromagnetic waves of various frequencies, encompassing X-rays [3] and millimeter waves [4], can similarly carry OAM.

These vortex electromagnetic waves, characterized by helical phase wavefronts, exhibit diverse OAM modes [5]. Each OAM mode is defined by an integer parameter known as the 'mode number', influencing both rotational behavior and phase front morphology. The mode number corresponds to a unique helical phase front, varying in shape and quantity with changes in mode number. Theoretically, OAM can offer an infinite range of orthogonal modes, akin to amplitude, frequency, and polarization degrees of freedom, crucial for information encoding. The orthogonal property of OAM waves facilitates efficient multiplexing and demultiplexing during transmission and reception [6], enabling concurrent transmission of independent information streams on the same frequency bands [6] for substantial spectral efficiency enhancement.

Furthermore, the relationship between OAM multiplexing and multiple-input multiple-output (MIMO) technologies has been a topic of active research issues [7, 8, 9]. MIMO technology is primarily concerned with harnessing spatial diversity through the utilization of multiple antennas for concurrent transmission and reception. Conversely, OAM mode division multiplexing capitalizes on phase diversity to enable the concurrent transmission and reception of distinct, independent data streams within a shared frequency spectrum. Notably, in practical settings, OAM multiplexing often surpasses conventional MIMO, especially within the THz band [10]. In this domain, due to prevalent scattering losses, traditional MIMO faces challenges with weak multipath propagation. In contrast, OAM multiplexing capitalizes on line-of-sight (LOS) propagation, solidifying its stance as an optimal spatial multiplexing solution. Integrating OAM multiplexing with traditional MIMO augments the degrees of freedom [9], resulting in enhanced wireless channel capacities.

For the future 6G, wireless communication through OAM emerges as a pioneering force of innovation. With its distinct attributes, OAM promises unparalleled potential for shaping the landscape of future communication systems. This survey offers a comprehensive exploration of various facets of OAM-based wireless communication. Section II highlights the dynamic role of diverse OAM modes in enhancing communication speed. Section III explores challenges and potential solutions related to the integration of OAM into 6G systems. This section systematically addresses three pivotal stages: generation, transmission, and reception. Section IV provides an outlook on potential advancements and integrations of OAM for future wireless communications. Section V concludes this survey.

II. Main OAM Applications in Wireless Communication

IMT-2030 envisages a future where a spectrum of frequency bands, spanning from Sub-1 GHz to sub-THz, is used. Notably, while OAM is a foundational attribute of electromagnetic waves across all frequencies, extensive researches in wireless communication focused on the sub-terahertz frequency band. There are extensive evidences of OAM's efficacy, as a series of experimentally validated instances have consistently showcased its high performance.

- In 2014, Yongxiong *et al.* [6] made a significant achievement by realizing a 16 Gbps link on a 28 GHz communication channel. This achievement was facilitated by MIMO processing of 2 OAM modes on two spatially distinct transmitter/receiver antenna apertures utilizing Spiral Phase Plates (SPP). Here, the two modes functioned as two orthogonal wireless channels, both carrying 16-QAM signals at identical carrier frequencies. Interestingly, this research validated that OAM multiplexing can coexist with traditional spatial multiplexing when paired with MIMO processing.
- In 2016, Yan *et al.* [11] demonstrated 32 Gbps, on 60 GHz band using a pair of antennas with SPP to generate and receive OAM waves. The transmission distance was 2.5 meters. They used two OAM modes combined with two polarizations (vertical and horizontal polarization) to multiplex four channels. Each channel carries a 16-QAM signals. Results of the analysis showed that OAM multiplexing communication operating at a high millimeter-wave frequency is likely to reduce the power loss of the OAM beams, increase the distance of the link, and reduce the size of the transmitter and receiver, particularly for the OAM channels with large OAM numbers.
- In 2017, Weite *et al.* [9] used a pair of easily realized Cassegrain reflector antennas capable of multiplexing/demultiplexing four orthogonal OAM modes to realize four channels to transmit simultaneously at a microwave frequency of 10 GHz. The result showed a multiplexed microwave communication experiment with the transmission distance of 10 meters using four OAM modes is carried out to quadruple the spectral efficiency while retaining a very low receiver computational complexity compared with the traditional MIMO.
- In 2019, Dandan *et al.* [12] proposed a system using patch antenna arrays, in which two OAM modes are carried at 2.4 GHz. In the experiment, they tested the isolation between two OAM-mode channels. Video signals were transmitted using the two different modes, validating that the system can transmit two signals simultaneously in the same frequency range.
- In 2021, the OAM communication system based on the uniform circular array (UCA) was demonstrated by Nippon Telegraph and Telephone (NTT) at the 28 GHz band and realized over 200 Gbps data rate, which is a remarkable result on this band [13]. The antenna gain was over 11 isotropic radiator and could transmit OAM signals 10 meters away. They also used the different polarizations to combine multiplex in order to maximize the transmission capacity. In their experiments, a total of 65 antenna elements were used, allowing for the simultaneous transmission of 21 channels. Among these channels, there were 4 streams modulated by 16-QAM, 12 streams using 64-QAM modulation, and 5 streams utilizing 256-QAM modulation.
- In 2023, Hang *et al.* [14] proposed an OAM wireless communication system based on a transmissive metasurface working on THz band. It multiplexed two OAM modes and achieved the data transmission of 10 Gbps at 100 GHz. Two OAM modes were employed as two OAM channels to transmit two independent communication signals with ON–OFF Keying (OOK) modulation and a data rate of 10 Gbps is achieved at a transmission distance of 300 millimeters which is 100 times the wavelength of THz electromagnetic waves.

All aforementioned advancements indicates the potential of a space-division multiplexing technique rooted in the orthogonality of modes. Termed as OAM modes division multiplexing (OAM-MD), this technique is depicted in Fig. 2. At the transmitting side, OAM waves are loaded with multiple OAM channels, each distinguished by unique OAM mode. Consequently, OAM-MD becomes a promising multiplexing technology to improve spectrum utilization and increase transmission channel capacity in future 6G networks.

Furthermore, OAM-based multiple access schemes, notably OAM multiple division multiple access (OAM-MDMA) [15], have been proposed as promising solutions for managing user

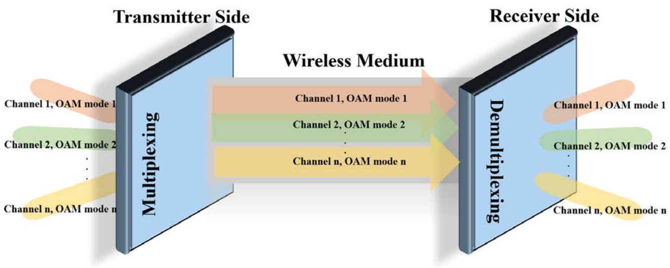

Fig. 2. OAM-MD: multiplexing and demultiplexing of OAM modes.

density. The premise involves utilizing distinct OAM waves for macro and micro cells to reduce interference. As a result, the spectrum efficiency of wireless networks can be significantly increased to meet the demand of tremendous data traffic of future 6G networks.

OAM's integration into wireless communication is also accompanied with the following advantages:

- **Simplified Mode Detection**: OAM communication leverages a unique set of orthogonal spatial modes. Specifically, these are spatially aligned waves infused with OAM, each possessing distinct mode numbers. The process of OAM-MD is streamlined through OAM-antennas paired with a phase-shift network. These passive devices bypass the need for digital signal processing. As a result, there is a marked reduction in computational complexity.
- **Increased Spectral Efficiency**: The adoption of OAM modes leads to significant improvements in spectral efficiency. The inherent orthogonality of OAM modes allows for the simultaneous transmission of multiple data streams over a single frequency, optimizing spectrum utilization. Furthermore, integrating mode-domain resources with other domains such as polarization, frequency, time, or code [13] has the potential to further enhance spectrum efficiency in wireless communications.
- **Infinite Modes Potential**: One of OAM's standout features is its theoretically infinite modal capacity [5]. This opens up a plethora of opportunities in wireless communication. Given the boundless nature of OAM modes, it represents a rich, largely unexplored phenomena for communication innovations.
- **Fortified Security Paradigm**: OAM introduces a fresh dimension in secure communication [10]. Transmitting and receiving OAM waves necessitate specialized antennas and a precise alignment between the sender's and receiver's orientations. Given the challenges in detecting OAM by third-party antennas, channels based on OAM are less vulnerable to unauthorized interception, ensuring a layer of covert security.

III. Current Challenges in OAM Wireless Communications

OAM electromagnetic waves have signaled transformative advancements in wireless communication. These waves, while promising, come coupled with intricate challenges, especially in their generation, transmission, and reception.

TABLE I
Characteristics and Limitations of the Common Types of Antennas Generating OAM Waves.

Method	Features	Limitations
UCA	A convenient and mature method with multiple OAM modes [13]. Flexibility to operate at different frequency band [17].	Need to be jointly used with converging schemes to combat signal attenuation during propagation [16].
SPP	Small divergence and low attenuation. Used for higher frequencies, such as 18 GHz [18], 28 GHz [6] and 60 GHz [11].	Not suitable for lower frequencies and cannot generate multiple OAM modes [18].
PRA	Directionality, high gain, and high mode purity [9].	Larger size and difficulty in changing OAM states [10].
Meta-surface	Ease of fabrication and free of complex feed network [14]. Useful in reducing divergence, especially at higher modes.	Design adaptability is low. An additional resource such as a horn antenna is required to transmit the incident waves [19].
DRA	Low design complexity. Multiple OAM modes can be generated. Suitable for low frequencies, such as 3.5 GHz [20] and 10 GHz [21].	Not suitable for high frequencies. Aperture becomes larger in size at higher frequencies [10].

A. Current Challenges in the Generation of OAM Waves for Wireless Communication

OAM waves, in contrast to traditional plane electromagnetic waves, have a distinctive phase rotation factor. Several antenna types, including UCA, SPP, Parabolic Reflector Antenna (PRA), Metasurface, and Dielectric Resonator Antenna (DRA), are recognized for their ability to generate these radio vortex signals. Table I provides a detailed overview of the characteristics and limitations associated with each of these antennas.

As the evolution of the next generation wireless communication systems may continuously require enhanced channel capacity, spectrum efficiency, and user accommodation, the ability to access multiple modes within a single frequency band becomes paramount. The limited flexibility of SPP and RPA antennas, especially in generating a spectrum of modes, renders them less viable for future systems. Moreover, the ambition to attain data rates beyond gigabits or even terabits per second necessitates pushing frequencies towards the millimeter-wave and THz bands. Yet, challenges arise: UCAs, for instance, demand intricate feed networks for vortex wave generation, becoming especially complex and loss-prone in sub-terahertz bands. At this moment, the essential focus is on designing innovative wideband, high-efficiency OAM multiplexing antennas customized for these communication scenarios.

B. Current Challenges in the Transmission of OAM Waves for Wireless Communication

The instinctive divergence property of OAM vortex waves is a bottleneck that hinders the application of radio OAM communications. OAM electromagnetic waves exhibit unique propagation characteristics distinct from those of traditional plane waves. These waves propagate in a spiral fashion, tracing their forward direction, which inevitably results in a certain divergence during propagation [5]. The divergence seems to intensify with the increasing order of the OAM mode. This divergence subsequently shortens the transmission distance and limits the spectral efficiency of OAM-centric wireless communication. Consequently, the channel capacity reduces due to these divergent OAM beams. Hence, an imminent need arises to make these beams converge, thereby harnessing the potential of all OAM modes.

Fig. 3 provides a visual aid to enhance our understanding. Different phase fronts in the condition of the divergence and without divergence are visually distinct due to varying positions and line thicknesses. These elements move in a captivating helical pattern along the time axis, while the propagation distance strengthens over time, revealing a noticeable divergence in the wave pattern. The 'l' symbol in the diagram represents the order of the Orbital Angular Momentum (OAM) mode. As this value increases, we observe a more pronounced divergence, highlighting the connection between mode order and divergence.

Though parabolic and lens antennas can adeptly produce convergent beams [9] [10], their considerable sizes are the obstacles to the demands of portable wireless communication. Consequently, there is an urgent demand for efficient antenna designs that can coax OAM beams into convergence without distorting the intrinsic wavefront phase of the OAM mode.

Beyond the antenna design, there is an alternative solution by designing signal processing algorithms. For instance, the virtual rotation antennas, which entail partial phase-plane reception at the receiver's end, have demonstrated promise in extending transmission distances [22]. In specific application scenarios, it may be necessary to comprehensively consider both antenna design and signal processing algorithm to achieve optimal OAM wave transmission effects in combating divergence.

Understanding the channel characteristics of OAM waves is also a crucial challenge during transmissions. While channel measurements play a pivotal role in the pursuit of understanding the characteristics [15], empirical findings pertaining to channel measurements of OAM waves are still limited. Atmospheric factors like turbulence [18], rain, and fog, coupled with the heightened beam divergence of higher-order modes, could significantly influence OAM multiplexing.

Recent studies show that these multipath channels can disrupt the inherent orthogonality of spiral phase planes, thereby introducing inter-modal interference and reducing channel capacity. Yang *et al.* [23] ventured into this territory, undertaking channel measurements for short-range indoor OAM communication at the 30 GHz frequency. Their findings emphasize the significant influence exerted by strategically positioning receivers and minimizing divergence angles for the short-range OAM wave communication.

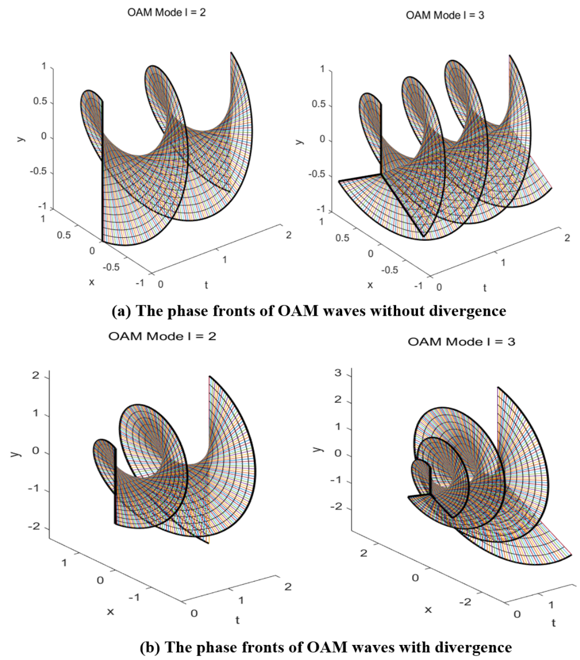

Fig. 3. Visualizing divergence characteristics of OAM modes in the transmission of electromagnetic waves.

C. Current Challenges in the Reception of OAM Waves for Wireless Communication

The UCA currently stands as the front-runner for both the generation and reception of OAM electromagnetic waves [18]. In direct line-of-sight communication scenarios, systems based on UCA requires precise alignment of both the transmitting and receiving arrays. Even a slight misalignment could result in significant energy losses and inter-modal interference, thereby diminishing the overall efficacy of the OAM system [16].

An innovative solution was proposed to combat this alignment problem, based on the dynamic adjustment of the transmitting and receiving beam directions [23]. This method has notably improved the performance in single-mode OAM communication systems. In addition, another proposition was made wherein the receiving antenna's alignment is harmonized with the incident beam's angle [24] while this requires accurate Angle of Arrival (AoA) estimation. Their newly-minted multi-mode OAM receiver, a combination of beam steering and diagonal amplitude detection, ensures impeccable alignment with OAM channels while maintaining operational simplicity. Nonetheless, the estimation of angles through the Bessel function approximation in the received signal does exhibit certain limitations, particularly with regard to its accuracy.

In the OAM domain, channel estimation at the receiver remains a complicated issue. Although OAM waves are often used for short-distance communication, their deployment indoors necessitates a thorough understanding of multipath effects [23]. Modifications in the phase front of the OAM mode during propagation can diminish the receiver's capacity for phase recognition, thereby, indicating the pivotal importance of accurate channel estimation. Therefore, ensuring channel estimation efficiency is critical, not just to preserve phase coherence but also to offset any fading-induced anomalies [24]. The strategic use of orthogonal OAM modes for concurrent data transmission intensifies these complexities, especially when multiple OAM modes are adopted to meet rising data demands.

IV. Future Prospects of OAM Waves in Wireless Communication

OAM waves, despite of technological and practical challenges in future wireless communication, are still a promising option to meet ever increasing data rate.

- **Technological Advancements and Refinements**: At present, extensive researches have been peroformed on novel antenna designs [10], signal processing algorithms [24], and channel estimation methodologies [23] tailored for OAM.
- **Integration and Interoperability**: Future iterations of OAM systems might necessitate coexistence with the current communication frameworks [16] . This poses inherent challenges to system designers but concurrently furnishes opportunities to integrate OAM wave techniques with other techniques, such as quantum communications [13] or millimeter-wave transmissions [20].
- **Broadening Application Horizons**: While current applications focus on OAM waves to short-distance communications [23], technological advancements may accelerate their applications into arenas like long-haul transmissions [9], submarine communications[25], or aerial links [14] .
- **Standardization and Commercialization**: The broad-scale deployment of OAM waves in wireless communications demands the formulation of industry standards and protocols. As the technology matures and undergoes rigorous validation, a proliferation of OAM-centric products and solutions entering the commercial market is expected.

In conclusion, the paradigm of OAM wave-based wireless communication offers a landscape full of challenges and rich with opportunities. With sustained technological evolution and intensified research endeavors, OAM waves might very well spearhead revolutionary shifts in next-generation wireless communications.

V. Conclusion

The integration of OAM modes offers innovative solutions to the challenges presented by 6G communication systems. The capability of OAM waves to transmit multiple independent information streams simultaneously on a single frequency band presents a compelling enhancement to spectral efficiency. While certain challenges persist in the generation, transmission, and reception stages of OAM electromagnetic waves, its transformative potential in reshaping the landscape of wireless communication cannot be overlooked.

Acknowledgement

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