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TOPICAL REVIEW

A Review of Orbital Angular Momentum Vortex Waves for the Next Generation Wireless Communications

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ABSTRACT The next-generation wireless technology that can fulfill such a demand, namely the fifth-generation (5G) technology, should provide 1000 times larger capacity. Moreover, sixth-generation (6G) communication, which represents a significant upgrade from the fifth-generation (5G) network and is anticipated to operate from 100 GHz to 3 THz band, will be required in the years after 2030 due to newly developed data-hungry applications and the greatly expanded wireless network. To meet the ever-growing demands of wireless carriers, an efficient wireless access method that can improve wireless area throughput without expanding bandwidth or cell size is required. Radio Frequency (RF) Orbital Angular Momentum vortex waves (which is now on referred to as OAM waves) to address the concerns mentioned above have attracted much attention in recent years. Due to their orthogonality, different OAM waves of different modes can be multiplexed in the same frequency channel, which can greatly increase the channel capacity. Using the orthogonal modes, a new type of multiple access scheme known as Mode Domain Multiple Access (MDMA) can be used by multiple users using the same frequency channel without additional resources such as frequency and time. As a result, the channel capacity for the next generation wireless communication systems can be enhanced as well as the overall spectrum efficiency can be improved. This review paper begins with an overview of the next generation communication such as 5G communication technology and beyond. This paper first briefly discusses the theory of OAM waves and several methods to generate OAM waves. Various different designs have also been analyzed for their ability to generate OAM waves and discussion on several restrictions and solutions to resolve. Open concerns and development trends are discussed for possible future RF OAM antenna upgrades. This study also proposes that for next generation wireless communication employing OAM, the typically used Uniform Circular Array (UCA) could be paired with the Multiple-Input-Multiple-Output (MIMO) system to improve performance in dense or urban areas for multiusers. In addition, the purity of OAM-modes needs to be considered for efficient utilization of the OAM system for future communications at the radio domain.

INDEX TERMS Orbital angular momentum (OAM) waves, uniform circular array antenna, 5G communication systems, antenna review paper, future wireless communication survey.

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I. INTRODUCTION

Advances in mobile communications have significantly impacted economic and social growth over the past few decades. There have been noteworthy improvements with every generation of communication technology in terms of data rate, channel capacity, advanced applications such as video call, real-time health monitoring and so on. Based on the survey [1], it all started in the 1980s with the first generation (1G) technology, which mainly employed analog signals for voice services. The data rate was up to 2.4 Kbps. However, the voice quality was poor owing to a lot of interference. A decade later, second generation (2G) technology was created to address the limitations of the first generation (1G) system. 2G is the digital version of the 1G system, which has a data rate of up to 64 Kbps. In addition to the voice services offered by the first generation, additional services such as short messaging service (SMS) were launched in this generation. The third-generation (3G) system, with a data rate of more than 384 Kbps, was based on Code Division Multiple Access (CDMA) and the Global System for Mobile Communication (GSM) and launched in the early 2000s. 3G provided multimedia messaging services and SMS and voice services. Later, 3G was upgraded to 3.5G, with data rates increasing to 2 Mbps. In the early 2010s, the fourth generation (4G) system was introduced with a data rate up to 100 Mbps. In addition to higher data rates, services such as video calls, online streaming, and online gaming were introduced by 4G. Nevertheless, frequency bands for 4G were expensive, and devices designed for 4G could only utilize the services provided by 4G [1], [2]. Frequency division multiple access (FDMA), Time division multiple access (TDMA), Code division multiple access (CDMA) and Orthogonal frequency division multiple access (OFDMA) are some multiple access methods used during the deployment of 1G to 4G.

The latest fifth-generation (5G) system should be 100 times faster than the previous 4G system with new services such as smart homes, smart cars, the Internet of Things, etc. As an outcome, 5G technology has risen to the top of the 2020 generation's demand list. The next generation of technology would enable high data rates, lower latency, additional capacity, and excellent quality of service. It is worth noting that the 5G technology will open up new possibilities to overcome existing development limitations. The advantages of deploying 5G wireless communication also include more secured communication, lower power consumption, and no harm to health [3], as illustrated in Figure 1 (a). Every year, the number of people who subscribe to mobile broadband systems increases substantially. People constantly seek faster internet connections, more appealing mobile phones, and rapid connectivity with others to share data [4]. As a result, wireless mobile devices and services have grown massively. There are interesting uses for Millimeter-Wave (mmWave) and THz systems that are projected to develop in 6G networks and beyond, in addition to the extremely high data rates. Applications in wireless cognition, sensing, imaging, wireless communication, and position location/THz navigation

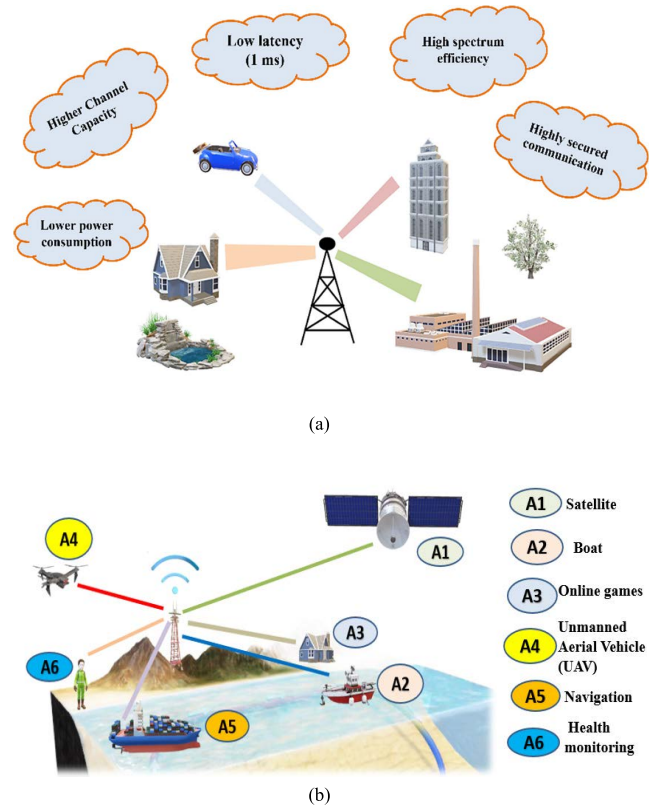


FIGURE 1. The evolution of different generations of technology (a) Advantages of 5G technology in cellular communication (b) Possible applications of 6G technology in 2030 and beyond.

are just a few of the important groups that these can be classed under positioning [5]. By 2030 and beyond, 5G communications would be insufficient due to the rapid development of new technologies including virtual reality, vehicle-to-X networks, unmanned aerial vehicle networks, mid-earth-orbit (MEO) and low-earth-orbit (LEO) satellite networks, and oceanic information networks as illustrated in Figure 1 (b). Although 6G's specifications, such as its frequency ranges and data rate requirements, are still being not decided, its implications have already been considered [6].

Mobile telecommunication providers are encountering an ever-increasing demand from new wireless applications for higher data rates, broader network capacity, high spectral efficiency, energy efficiency, and greater flexibility. Smartphone traffic is anticipated to expand tenfold between 2017 and 2022, while overall mobile traffic will increase eightfold [7]. From 2017 to 2022, Figure 2 depicts the growth in mobile data traffic and the number of connected devices [8]. By the end of 2022, cell phones will account for more than 90% of all traffic. With the abilities of earlier wireless generation systems, managing this huge quantity of mobile data traffic is difficult. With present technologies, 4G networks had almost reached the theoretical data rate limit and so are inadequate to handle the above-stated difficulties [9]. To solve the above issues and provide better services to the

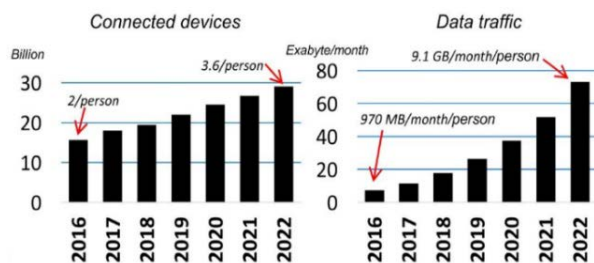


FIGURE 2. Global mobile data traffic and growth in connected devices from 2017 to 2022 [8].

trillions of wireless devices, researchers moved to a higher unused frequency spectrum to replace 4G with 5G. When compared to present 4G networks, 5G networks promise 10- to 100-times faster data rates with up to 10-times lower latencies. This achievable through more efficient radio technology (spectral efficiency) and more spectrum bandwidth (spectral capacity). In 2020, a report by Simon Kemp of KEPIOS analyzed and compared the share of web traffic by different devices. The report states that 53.3% of the web traffic is from mobile phones, while laptops/desktops, tablets, and other devices shared 44%, 2.7%, and 0.07%, respectively [10]. Later, in 2021, the same company reported a rise in mobile devices for sharing global web traffic [11]. The rise of mobile phone users for web access increased from 53.3% to 55.7%, while for laptops/desktops, it decreased from 44% to 41.4%. Therefore, future wireless communications such as 5G and 6G radio communication will be used more by mobile phone users than other devices, which means compact devices are more preferred and in high demand.

One potential way to utilize the future wireless communication systems is by using Orbital Angular Momentum Vortex waves instead of conventional plane waves. For the readers convenience, Orbital Angular Momentum Vortex waves is referred as OAM waves throughout this paper. There are infinitely many OAM-modes, and these modes are orthogonal to each other. This orthogonality can be exploited to multiplex different OAM-modes in the same channel, providing a new strategy to increase channel capacity and spectrum efficiency [12], [13]. In this view, utilizing OAM waves with the upcoming wireless communication system could potentially improve the services such as higher data rates, high spectrum efficiency, and highly secured communication. OAM waves have not been studied extensively for future wireless communication systems in the radio domain. OAM waves were significantly studied by focusing on optical communication for a long time [14], [15], [16]. Hence, in this paper, we present the different aspects of OAM waves, such as its background theory, how it differs from plane waves, its generation method, the advantages and limitations of OAM waves, how it differs from Multiple-input-multiple-output (MIMO) systems and the mode purity of OAM.

Review papers on OAM waves exist in the literature [17], [18], [19], [20]. Nevertheless, the authors in [17] focus on

the summarization of different methods to generate OAM waves and how to reduce the divergence of OAM waves. Meanwhile, in [18], the authors provide literature on the advantages of OAM waves and carried out a brief case study to compare OAM with FDMA scheme. [19] provides a comprehensive review of different methods to generate OAM waves only. Moreover, in [20], the authors did not cover OAM waves generation using dielectric resonator antenna (DRA), multiuser-OAM communication, OAM waves phase distribution measurement and factors that influence OAM mode purity. Dielectric Resonator Antenna (DRA) is compact in size and it has the potential to generate multiple OAM modes to increase the overall spectrum efficiency. Previous review papers published in [17], [18], [19], and [20] described the methods to generate OAM waves, its advantages and comparison with FDMA scheme in general. However, a detailed comparison, signal fading, contrast with MIMO, multiuser-OAM communication, phase distribution method and importance of mode purity are not covered by any other previous papers. Therefore, our work not only includes a comprehensive review of different methods of generating OAM waves and its advantages, but our work comprehensively compares the different methods, phase distribution measurement approach, mode purity and factors affecting it. This includes a detailed comparison with MIMO system, multiuser-OAM communication system and limitations of OAM waves which include details of multipath fading and Inter-Symbol-Interference (ISI) issues. The paper is organized as follows: Section II describes the basic theory and background information of OAM waves in the radio domain. Next, section III elaborates on the advantages of OAM waves and their utilization for 5G wireless communication systems. In addition, section IV summarizes the different methods to generate OAM waves in the radio waves domain. This section also includes a comparison between different methods. Moreover, a brief discussion is presented regarding the phase distribution measurement. Section V includes a discussion on the differences between OAM and MIMO systems. The importance of mode purity in array design is discussed in section VI. The challenges, limitations, and recommendations are discussed in section VII. Multiuser-OAM waves-based communication for practical scenarios is covered in section VIII. Lastly, the conclusion of this review paper is given in section IX.

II. OAM BACKGROUND AND ITS THEORY

Electromagnetic (EM) waves can carry both linear momentum and angular momentum. Angular momentum can be of two types, namely Spin Angular Momentum (SAM) and Orbital Angular Momentum (OAM) [17]. The OAM is related to the spatial phase distribution of the EM wave, and it was discovered by Allen *et al.* [21]. OAM is carried by an EM wave with the azimuthal phase distribution of $\exp(il\phi)$, and such an EM wave is termed an OAM wave. Here ϕ is the azimuthal angle and l is an integer, which is known as the topological charge. The presence of the phase

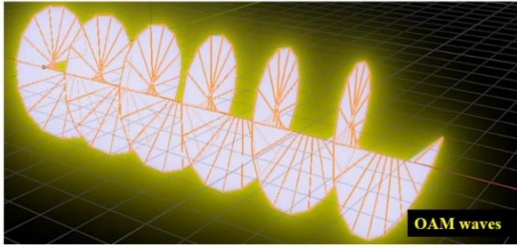


FIGURE 3. Helical wavefront of OAM waves.

distribution $\exp(il\phi)$ implies that on a plane perpendicular to the propagation axis, the phase of an OAM wave changes continuously by $2\pi l$ upon one full circle around the beam axis. In addition, an OAM wave exhibits a helical wavefront with l indicating the number of wavefront twists within one wavelength as shown in Figure 3.

The advantage of OAM over SAM is that, theoretically, OAM can provide an infinite number of states or modes since the mode number l are a limitless integer. Circularly polarized waves carry SAM with two orthogonal states, such as either Left-Hand Circular Polarization (LHCP) or Right-Hand Circular polarization (RHCP). Furthermore, the OAM modes are orthogonal [22], [23]. OAM waves with different values of l correspond to different OAM-modes, and they are orthogonal. This mode of orthogonality can be exploited to increase spectrum efficiency and channel capacity with more users using the same frequency without increasing the bandwidth [24], [25], [26]. For radio communication, the OAM wave research was first carried out in 2007 by Thide *et al.* at lower frequencies of the radio domain [27]. In 2012, Fabrizio Tamburini *et al.* conducted the first OAM-based radio communication according to real-world settings [28]. The authors performed experiment at the frequency of 2.414 GHz over 442 m between the transmitting and receiving antenna in Venice, Italy. Two orthogonal channels within the same frequency with fixed bandwidth was detected through this experiment. They concluded that OAM waves could increase the transmission channel capacity without additional resources such as bandwidth which could open up new opportunities for wireless communications systems and radio waves-oriented systems.

The topological charge l is a limitless integer, and OAM waves with different values of l are referred to as OAM modes or states. It can be shown that different OAM modes are orthogonal to each other. Owing to this orthogonality, different OAM-modes can be combined into the same frequency channel to enhance the point-to-point transmission rate [29]. As a result, the overall spectrum efficiency can increase. This concept is called OAM multiplexing. Moreover, the OAM multiplexing technique can generate multiple orthogonal channels under line-of-sight (LoS) conditions. Along with multiplexing different OAM channels, demultiplexing of orthogonal OAM-modes or channels can also be carried out. As shown in Figure 4, at the transmitting

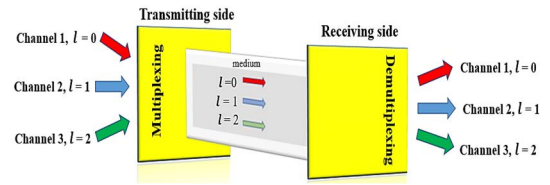


FIGURE 4. Multiplexing and Demultiplexing of OAM-modes.

side, the OAM waves can carry multiple OAM channels with different OAM-modes or topological charges, and these channels can be merged into a medium. OAM-modes with different topological charges can be separated at the receiving side using OAM demultiplexing technique. Hence, OAM waves carrying multiple OAM-modes can be demultiplexed to the original modes. This technique is very useful because it will save the usage of additional resources since radio frequency (RF) resources are limited [30]. Other than exploring new frequency bands, implementing MIMO, and advanced coding, OAM multiplexing has huge potential to meet the requirements of higher data rates.

III. POTENTIAL OF OAM WAVES FOR 5G WIRELESS COMMUNICATION SYSTEMS AND BEYOND

The orthogonality of OAM waves can be utilized for efficient and safe usage of 5G wireless communication systems. This section focuses mainly on spectrum efficiency, channel capacity, and secure communication, which are important aspects of future wireless communication systems. Since the specifications of 6G are yet to be decided, this section focuses more on 5G communication systems.

A. HIGH SPECTRUM EFFICIENCY

OAM-modes are orthogonal. Ideally, there will be no interference among the OAM-modes carrying the signal. Every mode has the potential to carry individual signals or data using the same frequency band, and these modes can be reused. As a result, multiple signals can be transmitted using the same frequency band without disruptions. The properties of OAM waves such as having orthogonal modes can be used to increase the spectrum efficiency without consuming conventional frequency, time, and power resources [18]. In addition, the OAM waves can also be jointly used with other resources such as time and frequency to increase the overall spectrum efficiency. As the number of users increases, devices are consuming more data. Due to limited bandwidth, the service might be slower, and the service providers might fail to meet users' demands. The authors in [18] also mentioned that until now, wireless communication is being built on the plane electromagnetic wave. In conventional wireless communication systems, transmitting and receiving data using the same frequency causes interference of signals among one another, which can be eliminated by using the OAM system due to its naturally orthogonal properties. As shown in Figure 5, the spectrum efficiency of conventional FDMA and a different

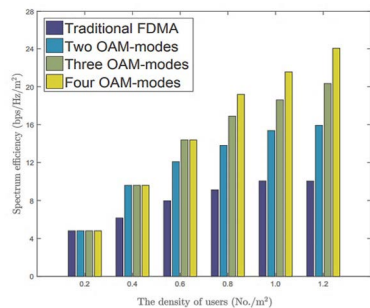


FIGURE 5. Comparison of OAM modes with FDMA system [18].

number of OAM-modes in wireless networks as a function of user density. We can also see that conventional FDMA's spectrum efficiency is lower than that of multiple OAM-modes. However, the spectrum efficiency of OAM mode with 1.0 users/m² is comparable to the spectrum efficiency of 1.2 users/m². When the number of users is high, the spectrum efficiency of four OAM-modes is substantially higher than that of two and three OAM-modes, since more users can be interference-free as the number of OAM-modes increases. As a result, while using wireless communications in wireless networks, it is beneficial to use OAM wave for interference avoidance, considerably increasing the spectrum efficiency of wireless networks.

B. CHANNEL CAPACITY

For more user access (channel capacity) in wireless communication systems, it is important to allow multiple users to simultaneously use the same frequency spectrum without causing degradation in the overall performance. Conventionally, to allow more users access, schemes such as FDMA, TDMA, and CDMA are used where plane electromagnetic waves are used [31]. However, narrow bandwidth issues in FDMA, improper synchronization between transmitter and receiver in TDMA, increased noise levels, and difficulty in recovering data from digital signals in CDMA are the major issues of the conventional methods [32], [33]. In [34], the authors have compared the performance of the Opportunity Driven Multiple Access (ODMA) system with a conventional CDMA system. The authors have observed that ODMA shows a capacity improvement over the non-relaying system and, in most cases, reduced transmission power. However, more radio resource is consumed to serve a transmission with ODMA, affecting the quality of service for other packet transmissions [35]. A new scheme called Mode Domain Multiple Access (MDMA) which uses OAM waves can be used to increase user access. MDMA allows multiple users to use the same frequency without consuming additional frequency or time resources [36]. OAM waves have spatial characteristics; hence, it provides a new degree of freedom to increase the channel capacity by allowing multiple users to access the frequency spectrum simultaneously. There are an infinite number of OAM-modes, and these modes can be assigned

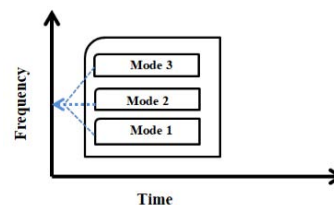


FIGURE 6. Mode Domain Multiple Access (MDMA) scheme.

to multiple users without affecting the overall performance, as shown in Figure 6. Hence, with MDMA scheme, multiple terminals can be connected, and large amounts of data can be exchanged simultaneously. Moreover, the authors compared the MDMA scheme with conventional MIMO system and it has been observed that the channel capacity is higher using MDMA method compared to MIMO specially when the signal to noise ratio (SNR) is lower [36]. Users expect to have a reliable and best performance wireless environment from deployment of 5G communication system however having lower SNR value tends to reduce channel capacity. One of the key features of 5G is to increase channel capacity, which can be achieved with help of MDMA scheme because compared to other schemes even at critical conditions such as high-level noise during signal transmission, MDMA still can maintain better channel capacity.

C. HIGHLY SECURED COMMUNICATION SYSTEM

A conventional communication system uses plane electromagnetic waves [37]. The transmitting characteristic of the wireless signal causes the receiver, whether it is legal or illegal in the free space, to receive the transmitted information. As a result, the information is not secure. Additional security techniques, such as cooperative jamming techniques, can overcome this issue [38]. In the case of OAM, the electromagnetic wave has a spiral phase structure. When the antenna is tilted or displaced, the phase changes, or maybe the phase gets damaged [39]. Furthermore, the alignment between the OAM transmitter and OAM receiver is very important because misalignment between them will prevent the receiver from receiving all the data. This feature of OAM waves can prevent any third party or illegal user from intercepting the data while transmitting it to the receiving side. To intercept the data, the third party has to be very close to the transmitting side, therefore the third party or illegal user would not risk being around the transmitting side. In conventional signal transmission, a third party or illegal user can intercept the data, even from a long distance. When it comes to OAM, third party user may not be able to collect the whole data properly as the main data can be converted into smaller data which individual modes can carry. Hence, the third-party user or illegal receivers cannot receive the complete OAM wave carrying the transmission information. In addition, OAM can be used for both narrow band and wideband frequency bands to improve the security system and anti-jamming system for future wireless

TABLE 1. Summary of previous works on generating OAM waves at Radio domain.

Ref. No	Frequency (GHz)	Method	Mode numbers	Total number of modes
[40]	18	SPP	1	1
[41]	28	SPP	-1,+1,-3 and +3	2 (each aperture)
[43]	18	Parabolic Reflector	+1	1
[44]	5.8 and 10	Parabolic Reflector	+1	1
[45]	1.550	UCA	-1 and +1	2
[46]	73.5	UCA	+1 and +3	2
[47]	2.73	UCA	-1,+1,-2,+2,-3 and +3	6
[48]	2.5	UCA	-1 and +1 (RHCP and LHCP)	4
[49]	2.4	UCA	-1,0 and +1	3
[51]	3.5	DRA	+1 and +2	2
[52]	13-20	DRA	1,2,3 and 4	4
[53]	17.77 and 20.38	DRA	-3 and -4	2
[54]	5.8	DRA	-1 and +1	2
[60]	5.2 and 10.5	Metasurface	+1 and +2	2
[61]	10	Metasurface	+1	1

TABLE 2. Advantages, disadvantages and applications of OAM based different types of antenna.

Ref. No	Method	Advantages	Disadvantages	Remarks
[40-41]	SPP	1. Purity of OAM mode is high. 2. Gain is high	1. It is not suitable for lower frequencies. 2. Limitation of generating multiple OAM modes. 3. Design flexibility is less. 4. Difficult to manufacture plates.	This method is suitable for applications where it involves high frequency such as optical communication systems.
[43-44]	Reflector parabolic	1.Design complexity is less. 2.Mode purity is high. 3. Divergence is less for higher OAM modes. 4.Gain and directivity is high.	1.Limitation of generating multiple OAM modes. 2.Design adaptability is less. 3.Aperture is very large in size. 4. Feeder blocks the signal	This method is suitable for radio astronomy and satellite communications where high gain and directivity is required regardless of aperture size.
[45-49]	UCA	1.Design complexity is medium. 2.Design flexibility is high. 3. Suitable for low, mid and high frequencies. 4.Design adaptability is high. 5. Multiple OAM modes can be generated. 6. Purity of OAM mode is moderate however it can be increased easily.	1.Possibility of mutual coupling. 2.Gain is low.	It can be used for radar system, mobile communications, indoor or outdoor communications as well as radio direction finding (RDF). Moreover, UCA can be implemented for low, mid and high frequency applications where multiple users are using the same network channel simultaneously.
[51-54]	DRA	1.Design complexity is low. 2.Multiple OAM modes can be generated.	1. Not suitable for high frequencies. 2. Aperture becomes large in size in high frequencies due to dielectric permittivity.	It is suitable for lower frequencies applications such as global positioning system (GPS).
[60-61]	Metasurface	1.Less divergence of OAM waves. 2.Multiple OAM modes can be generated.	1.Aperture is very large in size. 2.Design complexity is high. 3. Design adaptability is low.	It is suitable for 5G small base stations or 5G Picocells to meet high demand of channel capacity.

communication system [18]. To sum up, OAM waves can achieve high-speed secured communication because of its orthogonal characteristics. As a consequence, no additional technical resources are required for OAM waves in contrast to conventional communication system using plane electromagnetic waves. With 5G deployment, there should be huge exchanges of data from device to device. Hence, data security and safety is always a main concern, and OAM waves

have the potential to maintain a secured communication network.

IV. METHODS TO GENERATE OAM WAVES AND PHASE DISTRIBUTION MEASUREMENT

There are different methods for generating OAM waves, such as spiral phase plate (SPP), parabolic reflector antenna, Uniform circular array antenna, dielectric resonator antenna

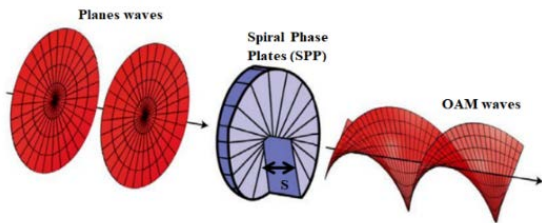


FIGURE 7. Conversion of a plane waves into an OAM waves through a SPP [42].

(DRA), and metasurfaces, as discussed in this section. Every method has its advantages and limitations. This section also includes a comparison between these methods and recommendations for the most suitable method considering the design complexity, size, flexibility, or adaptability.

A. SPIRAL PHASE PLATE (SPP)

A spiral phase plate (SPP) is a plate with a constant refractive index (n) and a thickness (s) that varies azimuthally, as shown in Figure 7. When a plane wave with a planar wavefront passes through the plate, it acquires an azimuthal phase factor $\exp(il\phi)$ and transforms into an OAM wave with a helical wavefront. In the SPP method, the plate's thickness, the plate's refractive index, and the azimuthal angle are important to generate a particular OAM beam at a specific frequency, as mentioned in [12].

Several studies have been conducted to generate OAM waves for radio frequency communication using the SPP method [40], [41]. The authors [40] proposed three different 3D-printed SPP designs to generate OAM mode 1 at 18 GHz. The three plates were of different designs and structures such as smoothly varying thickness, staircase structure, and flat with gradient refractive index. When the 3D-printed SPPs were combined with a 3D-printed dielectric lens, the OAM mode purity and beam divergence were significantly improved. A flat, moderately thin SPP with an azimuthally shifting graded index together with a dielectric lens produced the best overall OAM purity and minimized OAM beam divergence. At millimeter wave frequency, the authors in [41] generated two different channel states with four different OAM-modes, include $l = +1, -1, +3, -3$ using SPP method. The SPP was designed using high density polyethylene (HDME) material with a refractive index value of 1.51 as shown in Figure 8. To generate mode $+1$ and -1 , the height difference between the adjacent plate's step height were 2.07 cm while the height different was 6.21 mm to generate mode $+3$ and -3 . In addition, the authors conducted modal multiplexing at 28 GHz. The receiver easily distinguished the different OAM-modes without requiring any additional signal processing resources.

The literature review indicates that the SPP method is mostly used for higher frequencies, such as 18 GHz [40] and 28 GHz [41]. For future wireless communication system



FIGURE 8. SPP method measurement setup [41].

which includes the usage higher frequencies such as millimeter wave, the frequency is much lower than the suitable operating frequency to use the SPP method except for 28 GHz. In addition, it has been noticed in [41] that to generate different OAM-modes, the height difference required for mode ± 1 and mode ± 3 was different. Nevertheless, the SPP method is a simple method with less complexity. In addition, the purity of the OAM wave is higher when generated by SPP method. Moreover, the OAM divergence is small, therefore high gain can be achieved easily with low attenuation. Therefore, this method is a good option to generate OAM at higher frequencies if the overall size or dimension is not a big concern. As mentioned earlier, the plate thickness increases with the increase in mode number, which increases the overall volume of SPP. As a result, it cannot be used for modern miniaturized devices or applications which require a compact design. In addition, since it is a fixed design, it is very complex to generate multiple OAM-modes simultaneously, limiting applications practical world where more users will use the same frequency and higher channel capacity would be required. Lastly, the SPP method is basically for OAM waves at higher frequencies such as millimeter wave hence when it comes to lower frequency bands, this method of generating OAM beams is not recommended.

B. PARABOLIC REFLECTOR ANTENNA

Another way to generate OAM waves with the help of a reflecting system is by using a "parabolic reflector antenna". In this method, there is a feeder to generate incident wave which is plane EM wave and there are parabolic reflector plates to reflect the incident wave. The method works on the same principle as the SPP, where the propagated wave's phase variation depends on the azimuthal angle [19]. However, the main difference between the two methods is that, in the SPP, the introduction of the phase factor $\exp(il\phi)$ happens during the transmission process. In contrast, in the reflecting system method, the introduction of the phase factor takes places during reflection off the surface. Consequently, the two methods look similar where the height difference H_{max} along the roll angle is derived by [82]:

$$H_{max} = \frac{1}{2}l\lambda \quad (1)$$

Here l is the OAM mode, and λ is the working frequency.

The feeder generates uniformly directed plane waves toward the reflector in this method. Since the reflector is a conformal parabolic plate, where every plate has different heights azimuthally, the length of the generated wave traveled from the feeder to the reflector is different. Consequently, it causes a delay at the transmitting side, and it causes phase delay, which eventually forms OAM waves with helical wave fronts. A parabolic reflector antenna was used in order to generate an OAM waves with mode +1 at 18 GHz [43]. The authors used two reflector antennas: one is a normal parabolic reflector antenna and the other was azimuthally deformed Cassegrain sub-reflector antenna. The Cassegrain sub-reflector antenna was used because designing the main parabolic reflector antenna in a helicoid shape is very costly and inefficient. In addition, the gain obtained was 23.1 dB which is a major merit of this design. The authors generated a dual-band OAM mode with high gain in [44] at 5.8 GHz and 10 GHz. In this paper, the authors have designed an array of microstrip patch antennas where the substrate was Rogers 4350B with a permittivity value of 4.35 and thickness value of 0.5 mm. A total of 16 patch elements were used, where eight patch elements were for 5.8 GHz and eight patch elements were for 10 GHz. It has been found that the gain was 11 dB along with a decent helical phase distribution to represent OAM mode +1 at 5.8 GHz and 10 GHz. To further improve the gain of the antenna, the authors have used a parabolic reflector antenna. The authors were successful in improving the gain from 11 dB to 20.1 dB and 25.8 dB for 5.8 GHz and 10 GHz respectively. Furthermore, the use of parabolic reflector reduces the divergence of the OAM waves as well.

The advantage of this method is directionality, high gain, and high mode purity. However, drawbacks such as larger size and the difficulty in changing the OAM states make it an unsuitable option for devices where the size is limited and simultaneous signal transmission is required. In addition, placing the feeder in front of the reflector blocks the signal transmission in this method. Moreover, if the receiver is too far from the parabolic reflector antenna, less power will be received due to the divergence of OAM waves. Therefore, this method can be used for short-range indoor environments, which may also suffer from signal fading due to multipath. Hence, this method of generating OAM waves is not preferable for practical applications.

C. UNIFORM CIRCULAR ARRAY (UCA) ANTENNAS

One of the most popular methods to generate OAM waves is through the concept of the UCA antenna. A UCA antenna consists of identical antenna elements which are arranged uniformly in a circle. The elements are excited with power of the same amplitude, but different phases. To generate an OAM wave with mode l using a UCA with N elements, the phase difference between two adjacent elements has to be

$$\Delta\phi = \frac{2\pi l}{N} \quad (2)$$

It is this phase difference that plays a central role in the generation of OAM waves [45]. The required phase difference can be achieved with the help of a properly designed feeding network. The maximum mode number l_{max} that can be generated with a UCA is determined by the number of elements [27].

$$\frac{2\pi l}{N}. \quad (3)$$

The authors in [46] generated two modes +1 and -1 at 1.550 GHz suitable for global positioning system (GPS) applications. In this paper, a total of six identical patches were used and the substrate was ceramic with a permittivity value of 21.4 and thickness value of 4 mm. The OAM waves observed were 2 m away from the source with less divergence and zero side lobe. From this paper, the authors have suggested using an even number of patches since an odd number of patches will cause deformation of OAM waves, affecting the helical shape of the wavefront. In contrast to the lower frequency band, another experiment to generate OAM mode 1 and 3 using 8 and 12 dipole antennas, respectively, with FR408 substrate at 73.5 GHz was carried out in [47]. The phase distribution distorts as the mode number increases. In addition, from the 2D polar form of this paper, it has been noticed that for OAM mode 3, the divergence is more compared to OAM mode 1. However, as the number of radiating patches increases, the helical wavefront tends to be clearer and better in shape, as shown in Figures 9 (a) and (b) for modes 1 and 3 respectively.

In UCA, the radiating elements must be arranged in such a way that the spacing among the adjacent elements are at least 0.7λ to avoid mutual coupling. Generating multiple OAM-modes requires more radiating elements, increasing the overall antenna size. Moreover, the antenna tends to be bigger at lower frequencies. Several authors have implemented the concept of reconfigurable antenna to generate multiple OAM-modes at lower frequencies with simple and compact design to solve this issue. Le Kang *et al.* [48] designed an eight-element (radiator) array antenna to generate six OAM-modes from 2.33 – 2.73 GHz, as shown in Figure 10 (a). The overall radius of the array antenna was 60 mm and the substrate has a circular form with a permittivity value of 2.2 and thickness of 0.5 mm. The OAM modes can be switched just by tuning the dc voltages of the p-i-n diodes in the bias circuit. The authors [49] proposed a uniform circular array-based antenna with dual-mode and dual circular polarization reconfigurable technique to operate from 2.39 GHz to 2.64 GHz. The overall dimension of the way was $169 \times 169 \times 7 \text{ mm}^3$. In this particular work, the authors deployed four dual-fed elements. Each element is designed to carry out multi-functions such as polarization switching between left-hand circular polarization (LHCP) and right hand circular polarization (RHCP) and provides specific initial phases. By controlling the RF switches, the initial phases were shifted with an additional $+90^\circ$ or -90° to excite the elements and generate OAM mode +1 or -1

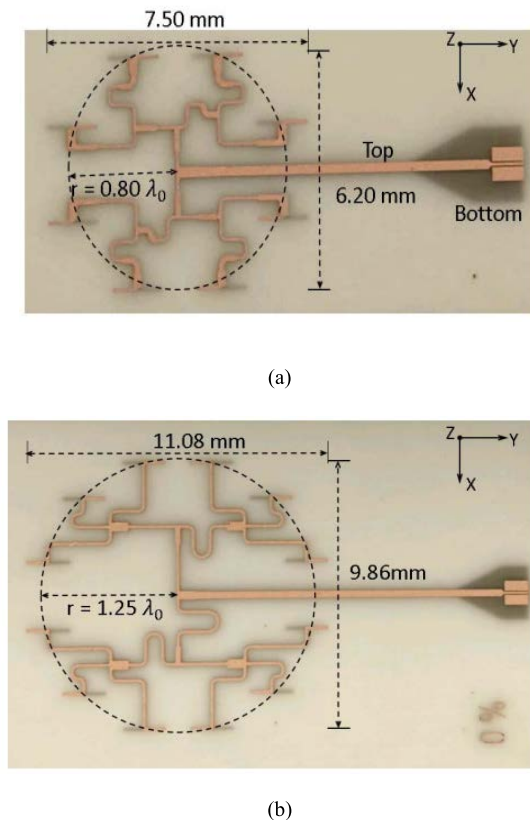


FIGURE 9. UCA method (a) 8-element dipole array [47] (b) 12-element dipole array [47].

along RHCP and LHCP. As shown in Figure 10 (b), an overall four states where state 1 and 3 are mode +1 and state 2 and 4 are mode -1 were achieved at 2.5 GHz, and these states can be changed by switching the bias voltage of the p-i-n diodes. The work in [50] designed a reconfigurable 2×2 rectangular array antenna to generate three OAM-modes -1, 0, and +1 at 2.4 GHz, as shown in Figure 10 (c). The authors used the principle of a switches-line phase shifter and switching delay line technology to control the microwave signal passing through the transmission lines of different lengths to achieve different phase states for multimode OAM. At 2.4 GHz, the antenna covered overall bandwidth of 170 MHz (2.38 GHz–2.55 GHz) for mode 0, while the antenna covered a bandwidth of 190 MHz (2.34 GHz–2.54 GHz) for mode ± 1 .

A uniform circular array antenna is a convenient and mature method of generating OAM waves since multiple modes of OAM waves can be generated with the flexibility to re-design and modify the design. In addition, this method provides the researchers with the flexibility to operate at lower bands, mid-bands, and higher bands. Moreover, the designs are simple, lightweight, and compact, which makes this method ahead of other methods, especially when overall size matters. In addition, multiple layers can also be designed within the same structure to generate different modes at a time. In addition, a technique such as a reconfigurable

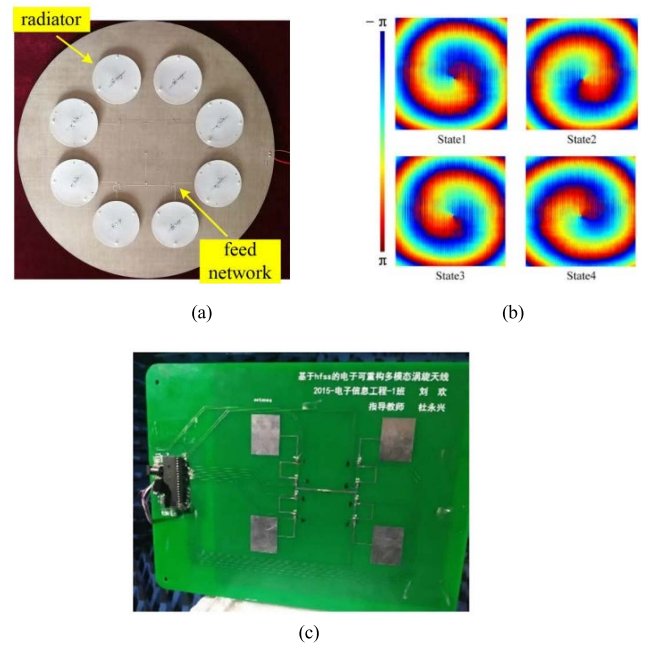


FIGURE 10. Multiple OAM modes (a) Eight-element radiator array antenna [47] (b) OAM states at RHCP and LHCP [48] (c) Reconfigurable 2×2 rectangular array antenna [49].

concept can be implemented easily with UCA to generate multiple OAM-modes while keeping the overall structure simple and compact. However, the feeding network is close to the radiating patches, such as antenna elements. Consequently, the feeding network's transmission signal and the antenna element's signal radiation could affect the OAM pattern. These problems arise when all the components are in one layer. Moreover, proper arrangement of patch elements around the array must be considered strongly since misalignment of patches will generate distorted spiral phase distribution.

D. DIELECTRIC RESONATOR ANTENNA (DRA)

As mentioned in [51], the DRAs have gained popularity in wireless applications because it is compact, low cost, high radiation efficiency, and flexible toward various feed lines. In contrast to the microstrip patch antenna, DRAs have less loss since it does not have any metallic surface such as radiating element. Instead, of it, there is a dielectric resonator made up of low-loss ceramic material. In recent years, researchers have carried out research to generate OAM waves using a DRA. Different types of DRAs, such as array [52], cylindrical [53], [54] and hemispherical [55] have been used to generate OAM waves.

The authors [52] designed a cylindrical DRA to generate two OAM-modes, namely mode 1 and mode 2 at 3.5 GHz. A total of eight slot coupled cylindrical DRAs with a dielectric constant value of 10.2 were arranged in the array. The obtained phase distribution of the resulting OAM waves is shown in Figure 11 (a). Using multiple ports for the feeding

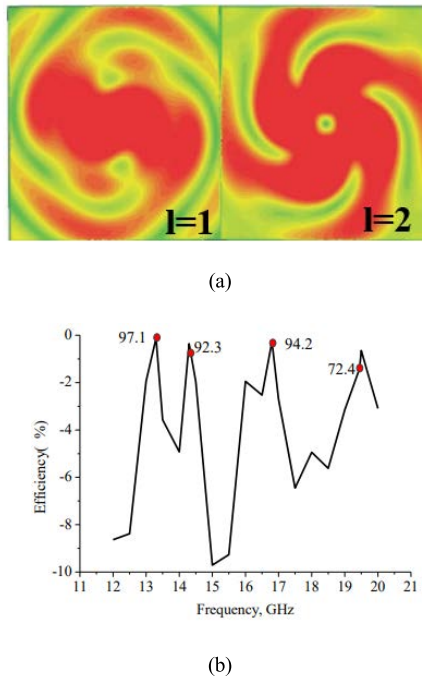


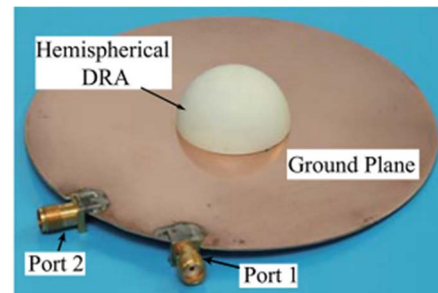
FIGURE 11. DRA method (a) Phase distribution of mode 1 and 2 [51] (b) Decreasing pattern of efficiency at high frequencies using higher modes [52].

network is not a convenient approach; hence, the Wilkinson power divider rule was used to design the feed line so that the elements receive equal power. Furthermore, two different feeding networks were designed to generate mode 1 with a phase difference of 45° and mode 2 with a phase difference of 90° . Another study in [53] designed a cylindrical DRA to generate separate different modes in multiple frequencies from 13 GHz to 20 GHz. The substrate used was Rogers with a permittivity value of 3.48, loss tangent of 0.0002, and thickness value of 1.6 mm. A total of four different frequencies were chosen to generate four different OAM-modes. Modes 1, 2 3 and 4 were generated at 13.3 GHz, 14.4 GHz, 16.8 GHz, and 19.45 GHz, respectively. The unique thing about this design is that a single cylindrical DRA was used to generate these four modes at four different frequencies. Regarding radiation efficiency, from the results of this paper, the efficiency decreases as the higher modes are generated in higher frequencies, as shown Figure 11 (b).

Yu Pan *et al.* [54] proposed a DRA to generate two OAM modes, namely mode -3 and -4 at 17.77 GHz and 20.38 GHz, respectively, as shown in Figure 12 (a), with an overall diameter of 12 mm. The proposed design is compact and inexpensive, and it can generate multiple OAM-modes at two different frequency bands. A hemispherical DRA was designed by Jian Ren and Kwok Wa Leung [55] as depicted in Figure 12 (b) and it generated OAM modes $+1$ and -1 at 5.8 GHz simultaneously. The DRA was made of Steatite-based composite material with a permittivity value of 7 and loss tangent value of less than 0.002. In addition,



(a)



(b)

FIGURE 12. Multiple OAM modes using DRA (a) Low cost compact DRA antenna [53] (b) Hemispherical dielectric resonator antenna [54].

the radius of the dielectric body was 13 mm, and the overall radius of the structure was 48 mm. Two slot-based feeding networks were designed to generate OAM-modes $+1$ and -1 . Two feeding networks with 90-degree phase differences were used to generate two opposite OAM-modes. Moreover, the proposed antenna not only generated two OAM-modes, but also covered a bandwidth of 300 MHz with efficiency above 80%. There was a small difference in gain between the two generated modes. For mode $+1$, the gain was 5.8 dBi, whereas for mode -1 the gain was 5.4 dBi.

From the above literature review, it can be observed that, DRAs offer a convenient method to generate OAM waves in different frequency ranges. Furthermore, DRAs have great adaptability to generate either single-mode, dual-mode, or multimode. Moreover, DRAs can be used to generate multiple modes in multiple frequency bands. Another feature of the DRA which keeps it ahead of other methods is its size. The DRA diameter size was 10 mm to generate dual OAM mode at 3.5 GHz [52]. Next, the DRA diameter was 12 mm to generate four modes in higher frequencies above 10 GHz [53] and two modes in two different bands [54]. Similarly, the DRA diameter was 13.5 mm to generate dual OAM-modes at 5.8 GHz [55]. Therefore, in terms of simple design, compact size, and great adaptability, DRA is a good candidate for generating OAM-modes. However, considering the 5G communication system where multiple signals should be transmitted and received from different

directions, DRAs have some limitations. From the above literature review, the OAM-modes were traveling in the same direction, which showed that the beam steering is impossible in DRA. Moreover, the dielectric constant of the material used in DRAs is also a major concern. Because the dielectric constant of DRAs is inversely proportional to the bandwidth [56], for a DRA antenna to operate at higher frequencies with wider bandwidth, substrate with lower dielectric must be used and vice versa. Moreover, increases in dielectric constant value decrease the DRA size.

E. METASURFACE

In recent years, metasurface has gained popularity to generate OAM beams due to its advantages such as ease of fabrication, free of complex feed network, lower weight, and designing different scales based on applications [57]. Moreover, the ability to shape a wavefront [58], polarization conversion [59], and control the radiation [60] has made metasurface one of the promising methods to engineer electromagnetic waves. As discussed in section II, phase and amplitude plays a very important in generating OAM waves. To generate OAM waves, the metasurface has to control the wavefront of electromagnetic waves by adjusting the phase of the incoming waves. Since metasurface can control different electromagnetic properties such as phase, amplitude, wavefront, and so on, extensive research has been carried out in recent times. One of the major parts of the metasurface method is the “unit cells.” It is important for the unit cell’s structure to achieve minimum 2π phase variation while maintaining the suitable phase. Consequently, incident waves or transmitting plane waves can be converted into OAM waves with a metasurface of full range phase modulation.

Chenji Ji *et al.* [61] generated two different OAM-modes at two different frequency bands using a single layer metasurface. In this work, the authors generated OAM mode +1 at 5.2 GHz and OAM mode +2 at 10.5 GHz. The proposed metasurface design consists of 41×41 metasurface cells and the overall dimension was $492 \text{ mm} \times 492 \text{ mm}$ as depicted in Figure 13. Additionally, both the patterns are made of $17 \mu\text{m}$ thick copper and the patterns were etched on F4B substrate with a permittivity value of 2.65 and thickness value of 3 mm. The purpose of the I-shape pattern was to construct the resonant phase cells. Moreover, to achieve different reflection phases, the geometrical structure of this pattern could be modified. The role of the rectangular pattern was to vary the phase shift change from 0 to 2π linearly. The authors have also observed that there is very little crosstalk between the two metallic patterns. The mode purity was 65% for mode 1 and 83% for mode 2.

In [62], the authors designed a metasurface with a gradient reflection phase of $200 \text{ mm} \times 200 \text{ mm}$ to generate OAM mode 1 at 10 GHz where the conversion of the plane wave into OAM waves was 80% efficient, as shown in Figure 14. A total of 400 metasurface units were designed and fabricated where each unit ($10 \text{ mm} \times 10 \text{ mm}$) is composed of a metallic patch and metallic ground layers. A dielectric spacer separated

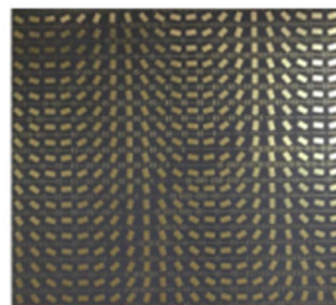


FIGURE 13. Metasurface with 41×41 metasurface cells [60].

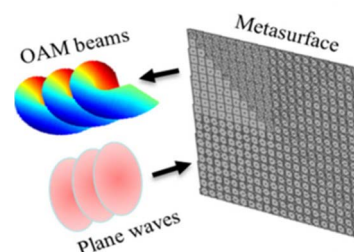


FIGURE 14. The concept of vortex beam generation using 400 metasurface units [62].

these two layers with a thickness value of 1.6 mm and a dielectric constant value of 2.65. Moreover, the metasurface is divided into eight regions, where every region has a different phase shift that depends on the patch layer size. This paper indicates that, as the patch layer size increases, the phase shift changes from a positive value to a negative value. When the patch layer size was 1.90 mm, the phase shift was 135° . For patch layer size 3.61 mm, 4.27 mm, and 4.76 mm, the phase shifts were 90° , -45° , and -135° , respectively. To generate mode 1 with eight different regions on the metasurface, the phase difference among the adjacent regions needs to be 45° . That is why every region had a difference of 45° . Consequently, when the plane waves incident the metasurface, the phase shift causes them to convert into OAM waves.

The literature review shows the essential feature of these designs is that they involve changing the structural parameters to fulfill the two-phase variation to generate the OAM waves. Undoubtedly, altering fewer parameters is better. Additionally, the generated OAM waves has a large divergence angle, which is a huge issue for long-distance transmission, which shall be addressed in the next sections. Generating OAM waves using metasurface is useful in reducing OAM waves’ divergence, especially at higher modes. However, there are several drawbacks to using metasurface to generate OAM waves. Firstly, the overall metasurface dimensions are too large such and $492 \text{ mm} \times 492 \text{ mm}$ [61]. Practically, such a big dimension is not desirable since most devices are compact these days. Next, the design complexity and the overall cost are very high in this design because it involves a lot of radiating patches such as 41×41 cells [61], and

400 metasurface units [62]. And lastly, an additional resource such as a horn antenna is required to transmit the incident waves, and this antenna is placed in front of the metasurface, which can block the reflected OAM waves. To implement multiple OAM beams in practical applications, it is important to simplify the design architecture further and minimize the antenna profile into a less complex integrated structure.

F. COMPARISON BETWEEN DIFFERENT OAM GENERATION METHODS

The summary of previous works on generating OAM waves at Radio domain and their advantages, disadvantages and possible applications are summarized in Table 1 and Table 2 respectively. The major focus of future generation wireless communication systems such as 5G and 6G is to increase the channel capacity, increase spectrum efficiency and allow more users in the wireless network efficiently. Hence, undoubtedly, it is important to have multiple modes where each mode can be used for individual channels in the frequency band. SPP and parabolic reflector antenna are unsuitable for utilizing OAM waves for future generation of communication systems since both the methods have limitations in generating multiple modes flexibly. The UCA, DRA, and metasurface can generate multiple modes in the same frequency band and different bands. It is very simple to design SPP and reflector parabolic antennas to generate OAM waves. The number of components needed in these methods is relatively low compared to UCA, DRA, and metasurface. A design becomes very complex when more components had to be integrated into one design. From the design adaptability perspective which mainly depends on the operating frequency wavelength, SPP and reflector parabolic antenna is suitable for higher frequencies. UCA, DRA and Metasurface methods can be used for a wide range of frequencies, such as lower bands to higher bands. As a 5G communication system has a lower band of 700 MHz, a mid-band of 3.5 GHz, and a high band of 28 GHz [63]. It is important for an OAM waves generation method to work efficiently in various frequency bands.

In UCA, the purity is relatively lower compared to DRA and Metasurface because of the alignment issue. If the transmitting and receiving UCA are not properly aligned, then the receiving UCA cannot receive the full wavefront of the OAM mode. Nevertheless, from future generation of wireless communication perspective, as depicted in Figure 15, the base stations need to serve multiple users in different directions. Consequently, UCA is preferable since the steering of beams can be controlled electronically by the controlling phase. In UCA, there is an option to modify the feedline to modify the phase and direction of the OAM waves. Changing the phase in azimuthal direction makes it possible to generate OAM waves, as mentioned in previous sections. In addition, changing the phase from left to right or right to left in steering direction shall generate OAM waves with a beam steering option. This beam steering flexibility is relatively simple for the UCA method compared to DRA and Metasurface.

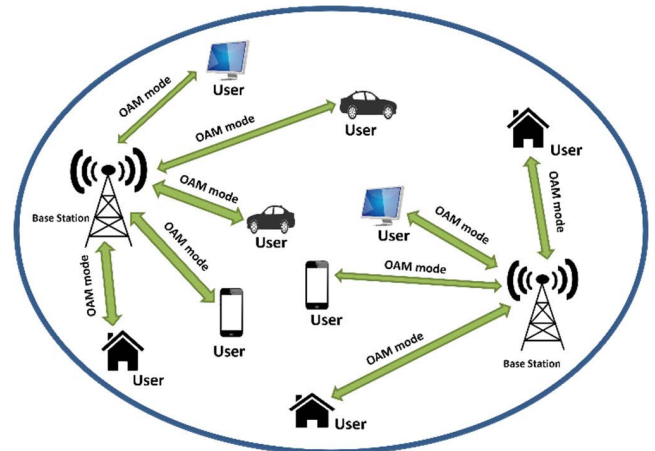


FIGURE 15. Multiple OAM-modes for multiple user.

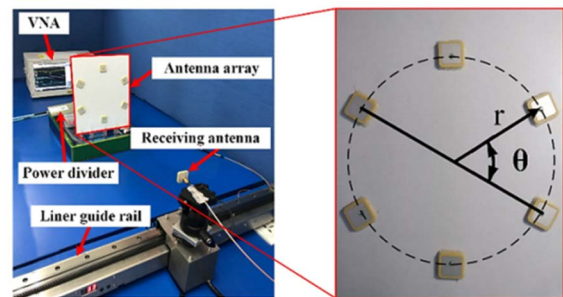


FIGURE 16. Setup using linear guide rail to measure OAM mode purity [46].

Moreover, the concept of reconfigurable to generate multiple OAM-modes while keeping the antenna size compact is a major advantage of UCA over other methods. As discussed in section I, the literature review shows that UCA is the most convenient method compared to other methods to generate OAM waves with compact and simple design.

G. PHASE DISTRIBUTION MEASUREMENT METHOD

The purity of a generated OAM waves can be evaluated from its phase distribution. One of the most convenient approaches to measure the phase distribution of an OAM waves is to use a receiving antenna mounted on a 2-axis linear guide rail. As shown in Figure 16, a 2-axis linear guide rail and a receiving antenna are used to scan the phase over a sampling plane that is perpendicular to the propagation of the radiation produced by the transmitting antenna. The positioning of the receiving antenna on the linear guide rail can be precisely controlled by a computer with a suitable step size. At every step point, the signal measured by the receiving antenna is sent to a Vector Network Analyzer to determine the phase, which is then stored in a file on a computer. The resultant 2D data can be used to plot the phase distribution and be analyzed to determine the purity of the OAM wave using Python, Matlab, etc.

V. OAM-BASED UCA VS, MIMO

There is a major relation between the OAM wireless communication system and Multiple-Input Multiple-Output

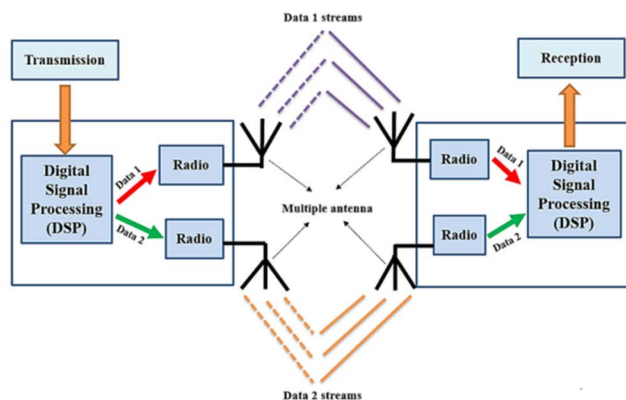


FIGURE 17. Data exchange using MIMO system.

(MIMO) based wireless communication system. Because both OAM and MIMO system follow spatial multiplexing concept. Moreover, the arrange of UCA based OAM and MIMO antenna design is very similar. Therefore, this section presented a short review of MIMO-based communication systems and compared them with OAM-based communication systems. Before comparing these two communication systems, it is important to know what MIMO is and how it works. Toward the end of this section, this paper's author's recommendations are presented.

A. MIMO CONCEPT

In MIMO, there are multiple antennas on the transmitting and receiving sides. The same data is transmitted as several data (streams) through multiple antennas while using a single radio channel [64]. As shown in Figure 17, a 2×2 MIMO system is designed where the main data (Data 1 and Data 2) splits into three multiple streams individually at the transmitting side, and these multiple streams recombine with each other the receiving side by another MIMO system. Nevertheless, the number of antennas on the transmitting and receiving sides is often equal. Using this method, the strength of the RF link can be increased [58]. It is very important to increase the strength of the RF link because this is the link that connects the antennas at the transmitting side and receiving side as shown in Figure 17. Moreover, the signal quality can be enhanced through the MIMO system. MIMO system is very important in urban areas where there are different objects such as buildings, walls, trees, cars, etc. Hence, the LoS is not clear in urban areas. Consequently, there is an increase in signal interference which affects the overall signal when received. In the MIMO system, the receiving antennas are designed so that it considers the environmental factors affecting the transmission of data. These antennas consider the time difference between reception signal, additional noise, multipath effect, etc. Furthermore, advantages such as higher data rate, spectral efficiency, less Bit Error Rate (BER), less fading, and wider cell coverage make the MIMO system a

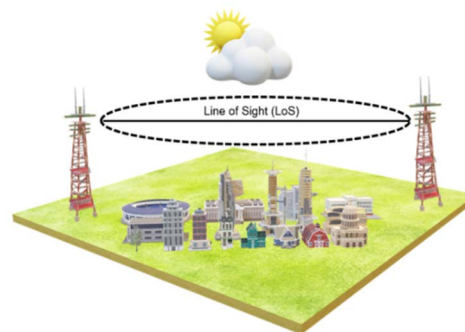


FIGURE 18. Line-of-sight (LoS) in an urban area.

potential candidate for a modern wireless communication system [65].

B. IS OAM BETTER THAN MIMO SYSTEM?

The difference between the OAM and MIMO systems is because of the arrangement of the radiating elements in the UCA, which is similar to the MIMO antenna. In UCA, multiple antennas are used to transmit signals, similar to the concept of the MIMO system. Hence, the authors compared the UCA-based OAM system with the conventional MIMO system. The authors in [66], [67] conducted numerical analysis and simulation to compare the OAM system and MIMO system in terms of channel capacity. However, the authors performed the research under certain conditions, such as antenna design was in the form of a UCA where the antennas are aligned properly at the transmitting and receiving sides with good Line of Sight (LoS) and high Signal to Noise ratio (SNR). LoS refers to the situation when two stations transmit and receive signals from each other while viewing each other directly without any obstacle in between, as shown in Figure 18.

The authors in [66] compared the UCA-based OAM system and the conventional MIMO system in direct propagation conditions. Different OAM-modes can be used to transmit different data, and these modes can be reused as well. This is very important when the frequency band is limited. Hence, different channels can be created within the same frequency band to increase spectrum efficiency. However, the helical wavefront of the OAM waves is very sensitive to the environment. In addition, there are issues such as fading, reflection, noise and so on that arises during transmitting signals. The OAM system does not need to consider these factors, while the MIMO system considers these factors and mitigates these issues. That is the reason that the OAM system is better during direct propagation only, whereas MIMO can be used for direct and indirect propagations undoubtedly. From Figure 19, even when the center distance between the array at the transmitting side and receiving side increases, the channel capacity of OAM is much greater than the conventional MIMO system. From the same graph, it can also be seen that

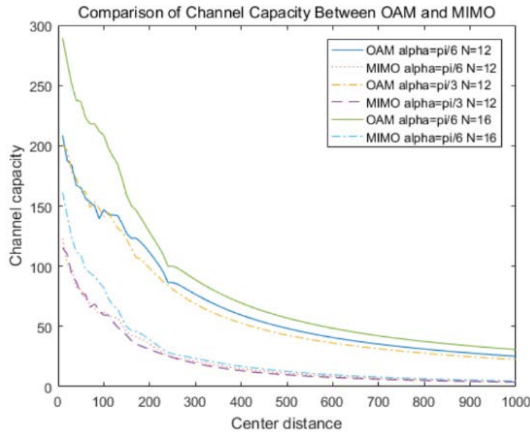


FIGURE 19. Comparison of channel capacity between OAM and MIMO [66].

an increasing number of antenna elements at the transmitting side and receiving side increases the channel capacity.

In [67], the authors have compared 4×4 and 4×8 MIMO systems with OAM mode 4. The authors mainly focused on the transmitting side of MIMO system hence the number of transmitting antennas is constant in both 4×4 and 4×8 designs. Furthermore, the authors also compared 8×8 MIMO system with OAM mode 8. In general, an 8×8 MIMO has greater subchannels compared to 4×4 MIMO. Similarly, OAM waves with 8 modes is better than OAM waves with 4 modes since having a higher number of available OAM mode increases the number of subchannels. Having more sub-channels can carry different signals in different carrier frequencies, leading to more data per second. In addition, at a higher Signal to Noise Ratio (SNR), OAM is more efficient than MIMO as it has more subchannels, as shown in Figure 20.

From the literature review, the comparison between the OAM and MIMO systems is tabulated in Table 3. OAM outperforms conventional MIMO systems in direct signal transmission using circular antenna arrays, and it can be used as a replacement to conventional MIMO systems. It is preferable to use OAM-modes for high capacity when the channel SNR is relatively high. For practical implementation of OAM waves for next generation of wireless communication system, multiple OAM modes must generate simultaneously to increase channel capacity. At the same time, compact devices are getting popular in recent years. People would prefer devices that provide higher channel capacity and higher data rate while it is easy for the user to carry it comfortably. Hence, we believe that designing an OAM antenna that can generate multiple OAM-modes while being compact will be one of the key matters for OAM-based 5G radio communications in the future. As tabulated in Table 3, both the systems have their own advantages and drawbacks. Nevertheless, if direct propagation or LoS is considered, OAM-based UCA is preferred above MIMO. Nevertheless, the OAM system and MIMO system concept can be combined to form a new OAM-MIMO system. The OAM system performs better in terms of channel

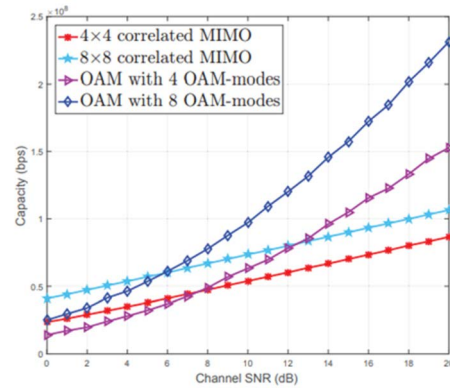


FIGURE 20. Comparison on Channel SNR and Capacity between MIMO and OAM [67].

TABLE 3. Comparison between OAM based UCA and MIMO.

Aspect	OAM based UCA	MIMO
Antenna size	Large	Medium
Design	Easy	Difficult
Line of Sight (LoS)	Required	Not required
Sensitivity	More	Less
Channel capacity (under LoS)	More	Less
Signal interference	No interference (orthogonal)	Severe interference

capacity under LoS conditions, and the MIMO system is very effective in urban areas where multipath takes place. Hence, the reconfigurable system can be implemented so that the antenna can operate both as an OAM system and MIMO system.

VI. OAM MODE PURITY

There are several methods to generate OAM waves, and the UCA array is the most prominent method of generating OAM-modes due to its flexibility. Generating OAM waves with mode purity is important to make sure the modes are orthogonal to one another; however, very little research has been carried out on the purity of generated OAM waves. Mode purity is a major aspect to measure the reliability of information transmission using OAM waves. Just having spiral phase distribution is not sufficient to utilize the intrinsic characteristics of OAM waves. Factors such as the number of elements, transmitting antenna size, observation plane size, and receiver size need to be considered to generate high purity OAM-modes [68]. Hence, this section overviews the factors and their importance in considering the OAM mode purity.

The authors in [68] also proved the importance of higher number of array elements in mode purity. If there are insufficient elements in the array to generate the desired OAM mode, then there is a possibility of ripples in the radiation pattern, as shown in Figure 21. The minimum number of elements needed to generate a specific mode can be found using the formula " $N \geq 2|l| + 1$ " where N is the number of array elements, and l is the mode number. The Figure 21 shows there is no radiation peak in the center for $N = 3$

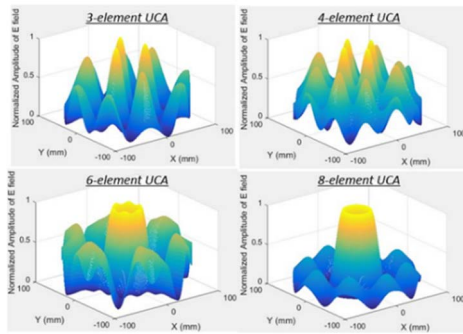


FIGURE 21. The effect of number antenna elements on mode purity [68].

and 4. There are lots of ripples in the radiation pattern. For $N = 6$ and 8, the amount of ripple has reduced, and there is a circular ring in the center of radiation peak. Moreover, if the amount of ripple is more, there will be more scattered surface waves in the design, which leads to distortion of the radiation pattern in the E-field [69]. Furthermore, if the number of elements in the array increases, the phase difference between the adjacent elements will be smaller, reducing the phase ambiguity effect. However, increasing the number of arrays will make the overall antenna size bigger with complex feedlines that are not desired as the overall design difficulty shall increase. Therefore, special attention needs to be paid during the simulation process to check how many elements are needed for a specific OAM mode to make sure the mode has high purity. The naturally orthogonal characteristics of OAM waves have great potential to increase the channel capacity by preventing interference in the channel. Hence, if the OAM is pure, then the actual strength of OAM can be utilized efficiently.

The next factor to be considered is the transmitting array antenna size and observation plane. In the case of transmitting array antenna size, decreasing the radius of the array increases mode purity; however, there is still an issue of mode divergence. In [68], the authors have concluded that a decrease in the radius of the array will reduce the mode divergence. The mode divergence issue is thoroughly discussed in the next section. There is a clash between mode purity and mode divergence. As depicted in Figure 22, when the radius increases, there is another deep curve: a side lobe. As the radius increases, the side lobe also increases, and it may interfere with other components. Hence, the purity decreases as well as the gain decreases. In addition, reducing the mode divergence by reducing the array radius helps in reducing multipath fading. Therefore, it is very important to design the array in such a way that it produces OAM waves with high purity as well as with less divergence. The receiving antenna size can be decided based on the size of the observation plane. However, to obtain OAM waves of high purity, it is important to make the receiving antenna smaller in size or at least the same size of the transmitting array antenna. If the observation plane is smaller in size, it will be able to detect the mode purity in a better way since it can concentrate at the center of the radiation pattern. The mode is high in purity at the

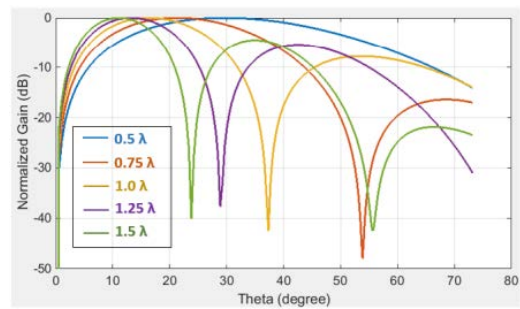


FIGURE 22. The effect of antenna radius on mode purity [68].

center of the radiation pattern. Nevertheless, due to the natural property of the non-zero value of OAM-modes, at the center of the radiation pattern, the power is low, but the mode is higher in purity. Therefore, a trade-off must be made between mode purity and radiation power. These are the major factors need to be considered while designing an OAM based antenna for wireless communication system.

VII. CHALLENGES AND LIMITATIONS OF OAM WAVES

The limitation of OAM waves is the availability of limited OAM-modes. During OAM wave propagation with higher modes, extreme attenuation takes place [70]. As a consequence, the number of OAM-modes is very limited. To increase channel capacity, undoubtedly, more OAM-modes are required. The transmission distance decreases as the OAM beams become more divergent with higher modes [71]. Moreover, the divergence also causes the spectrum efficiency of OAM-based communication systems to decrease. One of the methods to increase the availability of OAM-modes to increase the channel capacity is by converging the higher-order OAM-modes. However, converging the OAM waves is challenging for certain antenna structures.

To mitigate this issue, a parabolic antenna can be used to reduce the divergence of OAM waves without affecting the orthogonal characteristics of OAM waves [72]. The parabolic antenna helps the diverged OAM waves reform into converged OAM waves by keeping their orthogonal characteristics constant. Nevertheless, the size of the parabolic antennas is very large, which is not convenient for small and compact devices. For future generation wireless communications, small and handy devices are more in demand, so using a parabolic antenna to reduce divergence is not convenient. Another method to overcome the divergence issue is using an antenna with a bifocal lens [73]. The bifocal lens converges the diverged OAM waves with the concept of refraction. One major advantage of this method is that it can be used for any frequency of the radio spectrum. However, similar to parabolic antennas, these lenses are larger and must withstand a significant amount of attenuation. Alternatively, using a bigger antenna or using a higher frequency would reduce the beam divergence. However, use of bigger antenna is not practically desired since compact devices are getting popular now.

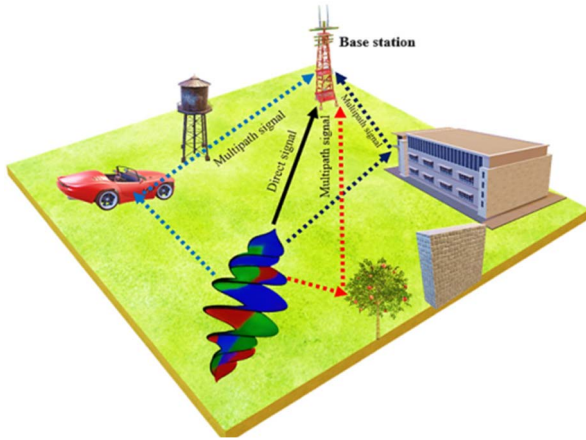


FIGURE 23. Multipath effect of OAM waves.

Multipath fading is another limitation of OAM beams with higher modes [74]. In general, multipath fading in wireless communication means “frequency attenuation” or loss of signal strength. Due to multipath, the OAM beams encounter “Frequency-selective fading.” In frequency-selective fading, the OAM beams undergo superposition where the multipath beams get destructive (out of phase = 180). It causes the bandwidth of the signal to be greater than the channel’s bandwidth. Hence, the channel becomes frequency-selective [75]. Multipath takes place in OAM beams since the divergence is more with higher modes of OAM beams. When transmitting antenna transmits OAM beams with higher modes, multipath causes the beams to travel to an undesired direction. The beams get reflected due to the surrounding objects such as buildings or cars, as shown in Figure 23. The original signal (transmitted signal) gets mixed with the reflected signal on the receiver side. As a result, there is a delay in the transmitted signal because the original signal gets divided into multiple signals with a delay and the received signal becomes distorted [76].

Frequency-selective fading not only causes a multipath fading effect to the transmitted signal and causes Inter-Symbol Interference (ISI), which causes signal distortion [76]. Consequently, OAM antennas are not convenient for long-distance transmission. Furthermore, the signal components at the receiver side encounter delay spread due to multipath. ISI takes place when the symbol time is less than the delay spread. Because of the long delay spread due to multipath signals, components carrying the next symbol are received before all components carrying the last symbol, resulting in ISI. In digital signals, the signals are represented by bits. Due to multipath fading, the bits collide with one another which are not desired. As a consequence, the BER increases and the signal quality degrades.

VIII. MULTIUSER-OAM COMMUNICATIONS FOR PRACTICAL SCENARIOS

Uniform Circular Array (UCA) is one of the most matured and suitable approaches to generate OAM waves as discussed

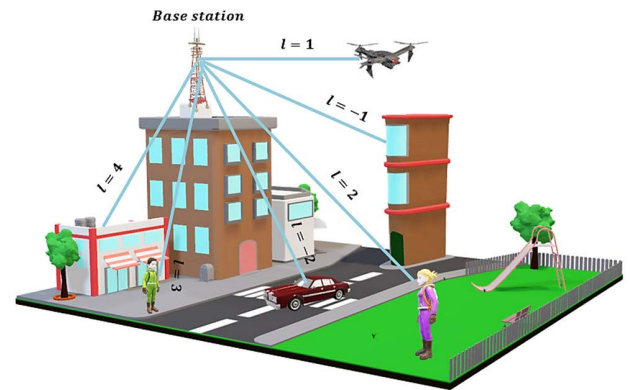


FIGURE 24. OAM waves based multiuser communication.

in section IV. However, it is mainly applicable when the transmitter and receiver are perfectly aligned to one another. However, maintaining the transmitters and receivers aligned with one another is unrealistic for wireless communications for multiuser communication systems. The efficient receiving for OAM waves wireless communications is affected if the transmitting and receiving UCAs are not aligned with one another. It is due to the phase of the received signal includes both the phase of the transmitting OAM-mode and the phase turbulence caused by unequal distance transmission at different locations of the receiver [77]. Furthermore, for practical implementation of OAM waves to increase the channel capacity and spectrum efficiency, an aperture should generate multiple OAM modes for multiuser usage as shown in Figure 24. Theoretically, OAM modes with different mode numbers are orthogonal to each other and each mode can carry data independently without interfering or cross talk with other modes. As explained in section II, multiplexing of OAM modes is important to increase spectrum efficiency. In fact, the total capacity and spectral efficiency of a communication system increases by a factor of number of transmitted OAM mode [78]. For instance, a communication system is three times more efficient if there are a total of three different OAM modes. However, from previous experiments on generating multiple OAM modes as discussed in section IV, it is been found that, as the OAM modes get higher in order, OAM waves tend to diverge more and loses energy hence it cannot transmit over a long distance. That is the reason that multiuser-OAM waves scheme is an important future study to be covered. As a consequence, researchers proposed different types of system architecture that combined OAM multiplexing scheme with traditional schemes such as spatial multiplexing and multiuser-multiple-input-multiple-output (MU-MIMO) scheme to mitigate the above mentioned issues to deploy OAM waves for practical scenarios.

To the best knowledge of the authors, the first multiuser-OAM waves scheme was proposed in [78] to provide system design flexibility and performance enhancement. In this paper, simulated channel capacity using different multiplexing schemes were validated experimentally and compared. These include pure MIMO multiplexing, pure OAM

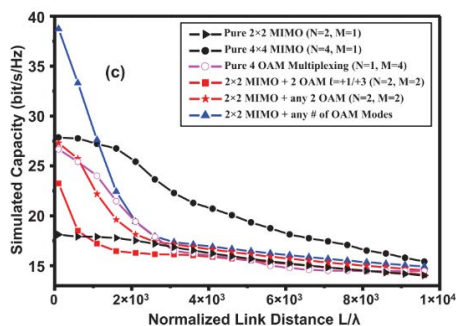


FIGURE 25. Comparison between pure OAM multiplexing scheme and MIMO+OAM scheme for multiuser [78].

multiplexing and OAM-MIMO joint multiplexing. It has been observed that, for a short distance, the channel capacity is much higher for OAM-MIMO joint multiplexing compared to pure MIMO multiplexing and pure OAM multiplexing. However, as the distance increases, the channel capacity of OAM-MIMO multiplexing is lower than pure MIMO multiplexing as demonstrated in Figure 25. This is due to the need of multiuser usage, where there should a greater number of available OAM modes. However, higher order of OAM modes diverges as the distance increases which results in lower channel capacity. Therefore, it is understood from this paper that, for multiuser usage, the use of OAM-MIMO joint multiplexing if the communication distance is shorter. Moreover, this paper performed computational analysis using SPP method of OAM waves communication, which is not an ideal way to deploy OAM waves for practical wireless communication system as discussed in Section IV.

Inspired by the work in [77], the authors in [79] proposed a new scheme to increase spectral efficiency for Multiuser-OAM communication compared to Multiuser-MIMO communication using Uniform Circular Array (UCA) model. From the proposed multiuser- OAM scheme in [79], it has been observed that the significantly fewer training symbols used in the Uniform Circular Array (UCA)-based downlink MU-OAM-MIMO system resulted in spectrum efficiencies that are nearly 30% higher than those of the downlink MU-MIMO system using standard channel estimation. As reported in [80], OAM waves suffers significantly from fading due to divergence of waves which takes place where high order OAM waves transmit data, degrading the overall system performance. Hence, to mitigate this issue for multiuser OAM waves-based communication, the authors proposed a new scheme called “OAM-based independent analog beam selection (OAM-IABS)”. They simulated an indoor scenario and it has been observed that OAM-IABS scheme performs the best to reduce inter-user interference when the users are more concentrated in orientation (transmitter and receivers are aligned parallel to each other). It was also reported that if the wavelength is more than 0.5λ , the interference of same order of OAM modes of two different apertures can be neglected.

F. Tamburini *et al.* in [81] carried out an experiment in a practical indoor setting where there were presence of multiple

reflection signals to prove the robustness of OAM waves multiplexing scheme. However, the setting was setup for point-to-point communication where the transmitter and receiver were at fixed points. The obtained results clearly demonstrate that OAM can be utilized to increase the transmission capacity of common devices and reuse the same frequency band effectively, assuring a high-quality and stable channel separation for a long period of time. To meet the ever-increasing demands for higher data rates by multiple users, OAM multiplexing can be combined with different modulation formats and different multiplexing techniques to achieve high-speed communication in multiple dimensions. Therefore, it can be said that there are certainly a limit of number of OAM modes that can be transmitted using one aperture to make sure efficiency transmission of data takes place. It is advised to use multiple apertures with a pre-processing system scheme of OAM multiplexing in combination with other schemes on the transmitting side. As a result, OAM modes will be received more efficiently.

IX. CONCLUSION

This survey is intended to provide a valuable framework for understanding current developments in Radio-Frequency (RF) OAM antenna design technologies, motivating further research to develop high-performance approaches for generating OAM waves. However, in this paper, a comprehensive review of future wireless communication such as 5G and 6G, different methods to generate OAM waves, and the advantages and limitations of OAM waves among different methods have been compared and analyzed. In addition, a discussion of the suitability of multiuser-OAM waves for next generation wireless communication system has been elaborated in this review paper. In this review, it is found from various studies that it is possible to multiplex a set of orthogonal OAM-modes on the same frequency channel to achieve high spectral efficiency. Undoubtedly, OAM waves are considered a potential candidate to meet the requirements of growing demands of bandwidth and higher data rates. Compared with different methods and by making the most of our expertise, it can be concluded that the UCA is the best candidate to generate OAM waves in lower frequency bands, mid-frequency bands, and high-frequency bands. UCA is the most matured approach due to its design adaptability, multimode performance, multi-beam steering, and 5G competency. Nevertheless, the tradeoff between antenna size, complexity, cost, bandwidth, and mode numbers requires understanding individual design concepts and applications. Moreover, in this review paper, particular attention has been devoted to the issues that still limit the application of OAM waves in practice, such as beam divergence, multipath effect, and ISI. This survey shows that the number of elements and receiving antenna size indeed plays a major role in generating high purity OAM-modes.

Currently, considering various aspects of the future wireless communication systems, future studies should include reducing the size of transmitters, receivers, multiplexers, and

demultiplexers. In addition, the efficiency of the performance of these components must be considered so that the OAM system can be compatible with the existing technologies. Furthermore, the beam divergence issue must be addressed. New solutions need to ensure higher-order modes do not undergo severe divergence to increase the transmission distance. Moreover, it is a major concern when it comes to the usage of OAM beams for 5G low and mid-band. As the frequency bands are lower, the wavelength is longer, which increases the divergence of OAM waves. This results in difficulty in recovering the modes at receiving side. Using a lens is one of the solutions; however, the lens size is large. Hence, compact components can be deployed on the transmitting side to focus the OAM waves in selected directions. It is noticed that, in this review paper, the effect of atmospheric turbulence is not highlighted. Atmospheric turbulence includes changes in air index as well as temperature, which influences the phase of the transmitting OAM waves. This turbulence leads to crosstalk and signal distortion and reduces the mode purity. Therefore, new systems at the receiving side need to ensure that the correct mode with the correct phase is recovered despite atmospheric turbulence. This review article shall assist researchers and designers of RF devices in considering of different factors when choosing an antenna for OAM waves based future wireless communication system in the radio domain. Despite the numerous challenges in applying OAM to future generation of radio communication systems, we remain confident that these challenges will be gradually overcome in the future, based on the research progress covered in this study.

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