ABSTRACT Physical layer security is a cross research hotspot of information security and wireless communications. Recently, orbital angular momentum (OAM) technology has attracted widespread attention due to its potential of improving capacity and spectrum efficiency. However, there are few researches on system security based on OAM technology. In this work, we studied the security of the proposed OAM wiretap system by applying physical layer security theory to OAM communications. Firstly, we proposed a uniform circular array-based multi-mode OAM system and derived the secrecy capacity. Secondly, the phase profiles, channel capacity and received power of OAM beams are analyzed in terms of various system parameters in oblique scenarios at 30GHz. Thirdly, we discussed the security of the proposed OAM wiretap system. The results show that the system using vortex waves is superior to conventional communication systems using planar electromagnetic waves in terms of system security due to the inherent divergence and spiral phase structure of OAM beams. Moreover, we found that the distortion of OAM beams during transmission and the center shift at receiving end will occur and that system is more stable for high-mode OAM propagation in oblique scenarios. This work can provide an effective guidance for the research and application of OAM communications.

INDEX TERMS Wireless communication, physical layer security, orbital angular momentum, secrecy capacity, uniform circular array, multiplexing and demultiplexing.

I. INTRODUCTION
Orbital angular momentum (OAM), a physical property of electromagnetic waves discovered recently, has attracted widespread attention due to its potential of improving capacity and spectrum efficiency [1]–[3] and could be used as an alternative key technology of the 6th generation mobile networks. The crucial difference between vortex waves and plane electromagnetic waves is that the former carries a spiral phase factor \( \exp(i\ell \varphi) \), where \( \ell \) is an unbounded integer termed as OAM mode index satisfying \( \ell \in \{ 0, 1, \ldots, L - 1 \} \) with physical degree of freedom \( L \) equal to \( \min(N_t, N_r) \), and \( \varphi \) is the azimuthal angle [4].

Photon OAM originated [5] and developed in optics [6], [7] and was introduced in the low frequency radio field by B. thide until 2007 [8]. At present, OAM generation methods in wireless communications mainly include OAM antennas, metasurfaces and uniform circular arrays (UCA). OAM antenna, chiefly composed of an antenna and a spiral phase plate, can generate standard OAM beams and is often used in the study of propagation properties of OAM beams. In [9], a specular reflection model based on the OAM antennas was constructed and inter- and intra-channel crosstalk caused by multipath effect was studied. In [10], the effect of reflection and scattering on wave-front of OAM beams was analyzed on the basis of the uniform linear array constructed by OAM antennas. Meta-surface is an artificial periodic structure consisting of the units smaller than the carrier wavelength and generates...
OAM beams by controlling the shape and distribution of the units to adjust the beam phase. Due to the high cost and complicated structure, many researches on meta-surfaces usually focus on the optimization and improvement of the meta-surface itself [11], [12]. UCA, a typical method for generating OAM beams, can generate OAM beams with multiple modes flexibly and the relative theory is relatively mature [13], [14].

Millimeter wave (mmwave) has rich bandwidth resources compared with the low-frequency band. In mmwave band, antennas can be highly integrated, enabling large-scale antenna array feasible due to its shorter wavelength. With the growing requirements for large capacity, high-speed and low-latency services, the wireless communication frequency band will extend to mmwave. Furthermore, from the perspective of transmission, the combination of OAM technology and mmwave is expected to further improve the energy efficiency and increase the communication distance, and makes it easy to achieve a large-scale antenna array for improving higher channel capacity [15]–[17].

Security is a vital issue in communication system. Wireless signals are inevitably eavesdropped and interfered due to the broadcast nature of radio waves and the openness of channels [18]. The pioneering work on physical layer security in [19] considered the classical three-terminal network consisting of a transmitter (Alice), an intended receiver (Bob), and an eavesdropper (Eve) and it was shown that a source-destination pair can exchange perfectly secure messages with a positive rate as long as the desired receiver enjoys better channel conditions than the eavesdropper(s). In recent years, the physical-layer security of massive multiple-input multiple-output (MIMO) systems has been studied extensively by introducing artificial noise and interference signal into the transmitted signal to reduce the signal to interference noise ratio (SINR) [20], [21]. While in the case of OAM systems, the current research on the security of OAM systems focus on optics. In 2004, Gibson proposed that the information encoded as OAM states of a light beam is resistant to eavesdropping in the sense that any attempt to sample the beam away from its axis will be subject to an angular restriction and a lateral offset [7]. Sun et al. studied the physical-layer security of a line-of-sight (LoS) free-space optical (FSO) link using OAM multiplexing and demonstrated the OAM multiplexing technique provides higher security over a single-mode transmission channel in terms of the total secrecy capacity and the probability of achieving a secure communication under certain conditions [22]. Djordjevic et al. proposed using the hybrid FSO-THz technologies employing OAM modes can significantly improve the spectral efficiency and physical-layer security of both FSO and radio communications [23]. Reference [24] proposed an OAM-based multidimensional coded modulation and considered improving the physical-layer security of future wireless networks by using this underutilized degree of freedom. In [25], the eavesdropper outside the target region cannot observe distortion-free OAM beams according to the effective radiation range of OAM radio waves and thus is unable to recover the secret messages. Compared with the conventional secure transmission schemes with artificial noise, the proposed scheme can enhance the security of OAM system and achieve higher energy efficiency.

However, the security of OAM system in the radio communications needs further study. It is well known that the multimode OAM system performance is affected by crosstalk, transceiver array alignment problems, and multipath propagation [9], [26], [27] and the performance of LoS OAM system will deteriorate sharply when the transceiver is misaligned [28], [29]. Existing researches focus on the influence of a certain configuration parameter on OAM channel capacity. Studying the channel capacity under joint change of multiple influencing factors can make us more accurate in grasping the performance of OAM systems.

In this paper, we study the performance of OAM system in oblique scenarios and then analyze the security of OAM wiretap system. We summarize the contributions as follows:

- We proposed the UCA-based multi-mode OAM wiretap system and derived the secrecy capacity.
- We analyzed the security of OAM wiretap system regarding LoS OAM communications in oblique scenarios.

The structure of the rest paper is organized as follows: In section II, system models of LoS OAM system and wiretap system are introduced, the secrecy capacity of OAM wiretap system is derived. In section III, the phase structures and received power of OAM beams in oblique scenarios are discussed. Secrecy capacity and channel capacity jointly considering multiple parameters are simulated. Finally, conclusions are drawn in Section IV.

II. OAM SYSTEM MODELS AND SECRECY CAPACITY

In this section, we present the UCA-based multi-mode LoS OAM system in oblique scenarios and OAM wiretap system and then derive secrecy capacity of the proposed OAM wiretap system.

A. OAM LoS AND WIRETAP SYSTEM MODELS

Fig. 1 presents the UCA-based multi-mode OAM systems. Specifically, Fig. 1(a) shows the UCA-based LoS OAM system in oblique scenarios. UCAs fed by phase shift network (PSN) are used to generate and detect OAM beams with phase factor of \( \exp(\text{i} l \varphi) \). Note that the actually excited OAM modes would be negative and equal to \((l - N)\) for mode of \(|l| > N/2\) [30]. In Fig. 1(a), both the transmitter and receiver consist of a \(N\)-element UCA and a PSN. OAM beams with different modes are generated and multiplexed at the transmitter and then are received and detected at the receiver through free space transmission. Theoretically, the superimposed vortex waves can be completely separated at the receiver due to the orthogonality of OAM beams.

Fig. 1(b) shows the UCA-based OAM wiretap system comprising legitimate transmitter Alice and receiver Bob, and an eavesdropper Eve. All three terminals are composed of
a UCA and a PSN. Both Bob and Eve receive the signals from Alice through the legitimate channel $H_m$ and wiretap channel $H_w$, respectively. Alice and Bob are set to be coaxial and parallel to each other and Eve is located randomly around Bob.

**B. CHANNEL MODEL OF OAM SYSTEM**

In conventional MIMO system, the sub-channel transmission gain $h_{m,n}$ between the $m$-th receiving antenna and the $n$-th transmitting antenna of channel matrix $H \in \mathbb{C}^{N_t \times N_t}$ can be expressed as [30]

$$h_{m,n} = \beta \frac{\lambda}{2\pi d_{m,n}} \exp\left(-\frac{2\pi d_{m,n}}{\lambda}\right)$$

where $\beta$ contains all constants associated with antenna array configuration, $\lambda$ is the carrier wavelength. The transmission distance $d_{m,n}$ from the $n$-th ($1 \leq n \leq N_t$) transmitting antenna to the $m$-th ($1 \leq m \leq N_t$) receiving antenna is calculated as

$$d_{m,n} = \left[ (R_t \cdot \sin \varphi_1(n) \cdot \sin \theta_1 - R_t \cdot \sin \varphi_2(m) \cdot \sin \theta_2)^2 
+ (D - R_t \cdot \sin \varphi_1(n) \cdot \cos \theta_1 + R_t \cdot \sin \varphi_2(m) \cdot \cos \theta_2)^2 
+ (R_t \cdot \cos \varphi_1(n) - R_t \cdot \cos \varphi_2(m))^2 \right]^{\frac{1}{2}}$$

$$\varphi_1(n) = \frac{2\pi(n-1)}{N_t} + \varphi_{1,0}.$$  (2a)

$$\varphi_2(m) = \frac{2\pi(m-1)}{N_t} + \varphi_{2,0}.$$  (2b)

Detailed parameters and definitions are listed in Table 1.

When radiating $l$-mode OAM beam with modulation symbol $x_l$ and amplitude $A_l$, the $n$-th transmitting antenna should be fed with [30]

$$a_n^{(l)} = \frac{A_l}{\sqrt{N_t}} x_l e^{j\varphi(n)}$$

Because the OAM beams with different modes are transmitted simultaneously and independently, the total excitation of the $n$-th antenna is the linear superposition of excitation of each mode on the $n$-th antenna, therefore the $n$-th transmitting antenna should be fed with [30]

$$a_n = \sum_{l \in L} a_n^{(l)} = \sum_{l \in L} \frac{A_l}{\sqrt{N_t}} x_l e^{j\varphi(n)}$$

Then the transmitting signal vector $a$ can be denoted as

$$a = \frac{1}{\sqrt{N_t}} G A x$$

where $a \in \mathbb{C}^{N_t \times 1}$, $A \in \mathbb{C}^{L \times L}$ is magnitude matrix denoted as

$$A = \text{diag} \{ A_0, A_1, \ldots, A_{L-1} \}$$

in which $A \in \mathbb{C}^{L \times L}$ is modulated symbol vector denoted as $x = [x_0, x_1, \ldots, x_{L-1}]^T$, and $G = [g_{n,l}]_{N_t \times L}$ is modulation matrix and written as

$$G = \begin{bmatrix} e^{j\varphi_1(1)} & e^{j\varphi_1(2)} & \cdots & e^{j\varphi_1(L)} \\ e^{j\varphi_2(1)} & e^{j\varphi_2(2)} & \cdots & e^{j\varphi_2(L)} \\ \vdots & \vdots & \ddots & \vdots \\ e^{j\varphi_{N_t}(1)} & e^{j\varphi_{N_t}(2)} & \cdots & e^{j\varphi_{N_t}(L)} \end{bmatrix}_{N_t \times L}$$

Next the received signal can be expressed as

$$b = H a + n$$

where $n$ is AWGN matrix with zero mean and $\sigma^2$ variance, satisfying $E[n n^H] = \sigma^2 I_L$.

The signals over $N_t$ receiving antenna elements are demultiplexed in order to extract information from the received OAM beams. The output signal is expressed as

$$u = \frac{1}{\sqrt{N_t}} M b = \frac{1}{\sqrt{N_t N_r}} M H G A x + \frac{1}{\sqrt{N_t}} M n$$

Further, the output signals of legal receiver Bob and eavesdropper Eve are developed to

$$u_m = \frac{1}{\sqrt{N_t N_r}} M H_m G A x + \frac{1}{\sqrt{N_t}} M n$$

and

$$u_w = \frac{1}{\sqrt{N_t N_r}} M H_w G A x + \frac{1}{\sqrt{N_t}} M n$$
where $\mathbf{M} \in \mathbb{C}^{L \times N_t}$ is demodulation matrix and denoted as

$$
\mathbf{M} = \mathbf{G}^H = \begin{bmatrix}
e^{-j\psi(1)} & e^{-j\psi(2)} & \ldots & e^{-j\psi(N_t)} \\
e^{-j\psi(1)} & e^{-j\psi(2)} & \ldots & e^{-j\psi(N_t)} \\
\vdots & \vdots & \ddots & \vdots \\
e^{-j\psi(1)} & e^{-j\psi(2)} & \ldots & e^{-j\psi(N_t)}
\end{bmatrix}_{L \times N_t}
$$

And the channel matrix of multi-mode OAM system can be described as

$$
\mathbf{H}_{\text{OAM}} = \mathbf{MHG} = \begin{bmatrix}
h_{1,1} & \ldots & h_{1,L} \\
\vdots & \ddots & \vdots \\
h_{L,1} & \ldots & h_{L,L}
\end{bmatrix}_{L \times L}
$$

where the $i$-th diagonal element $h_{i,i}$ is the transmission gain of OAM channel with eigenmode $l_i$, $h_{i,j}$ ($i \neq j$) denotes the mode migration of the $l_i$-mode OAM channel to channels of other modes.

### C. SECRECY CAPACITY

In multi-mode OAM system, the channel capacity could be affected by both inter- and intra-channel crosstalk and noise, then the capacity measured by SINR is defined as [31]

$$
C = \sum_{i=1}^{L} \log_2(1 + \frac{P_i h_{i,i}^2}{\sum_{i \neq j=1}^{L} h_{i,j}^2 + \sigma^2}), \quad P_t = \frac{P}{L}
$$

where $P_i h_{i,i}^2$ is the received power of $l_i$-mode OAM beams and $\sum_{i \neq j=1}^{L} h_{i,j}^2$ is the sum of received power that $l_i$-mode OAM beams disperse to beams with other modes.

In the OAM wiretap system, it is possible for the eavesdropper Eve to intercept the OAM beams and obtain certain transmitting information without affecting the main legal channel communication between Alice and Bob. The wiretap power needs to be kept at a low value, otherwise it will inevitably cause the decline of the received power for the legitimate receiver and the transmission quality of the main channel. In order to evaluate the security of the proposed OAM system, we introduce the secrecy capacity defined by Wyner [19]. If the ratio of received power at the eavesdropper to the total received power is defined as $r_e$, the received power ratio of the legal receiver can be calculated as $(1 - r_e)$, that is the normalized total received power minus the eavesdropping power ratio. Therefore, although the main channel and the eavesdropping channel are spatially independent, the received power is mutually restricted. Hence, the main channel capacity $C_m$ and the wiretap capacity $C_w$ can be denoted as

$$
C_m = \sum_{i=1}^{L} \log_2(1 + \frac{(1 - r_e)P_i h_{i,i}^2}{\sum_{i \neq j=1}^{L} h_{i,j}^2 + \sigma^2}), \quad C_w = \sum_{i=1}^{L} \log_2(1 + \frac{r_e P_i h_{i,i}^2}{\sum_{i \neq j=1}^{L} h_{i,j}^2 + \sigma^2})
$$

respectively. The secrecy capacity $C_s$ is calculated as [19]

$$
C_s = C_m - C_w
$$

According to [22], the probabilistic metric for characterizing the security for the radio communications, which is also known as a probability of positive secrecy capacity, is defined as

$$
P_s^+ = \Pr(C_s > 0)
$$

### III. RESULTS AND DISCUSSIONS

In this section, numerical results are presented to evaluate the security of OAM wiretap system. Section III. A depicts the detailed phase profiles of single-mode, multiplexed and demultiplexed OAM beams in oblique scenarios. Section III. B evaluates the channel capacity considering tilt angle, transmission distance and array radii jointly. Section III. C presents the received power of OAM beams with different modes. Based on the analysis above, Section III. D analyzes the security of OAM wiretap system. In simulation, the number of elements of all three antenna arrays is set to 16, the carrier frequency to 30GHz. In this work, the antenna element is assumed as an ideal omnidirectional point source and the mutual coupling between antenna elements is ignored. Moreover, the transmission distance between the transmitter and receiver is set to $10\lambda$, so the delay between different paths is also ignored.

### A. THE PHASE PROFILES OF OAM BEAMS

For the multi-mode OAM system based on OAM antennas, each single-mode OAM beam is generated by single-mode OAM antenna. Although the phase distortion and mode migration could occur in transmission, the single-mode beam is independent of each other in the process of generation and reception and accurate demodulation can be achieved by phase compensation of single-mode OAM beam [27]. While in the case of multi-mode OAM systems, the beams with different modes are overlapped from the beginning of their generation. The phase structure of single-mode beam cannot be obtained separately and phase compensation cannot be achieved on the overlapped OAM beams, so it is needed to perform demodulation analysis of the multiplexed OAM beams for obtaining the transmission information.

Fig. 2 describes the phase profiles of single-mode, multiplexed and demultiplexed OAM beams at different tilt angles. As shown in Fig. 2(a) and (b), the phase wave-front of OAM beams with mode 1 and 3 at tilt angles $\theta_1$ of 90°, 85° and 80° are firstly simulated. It can be seen that the phase structures of OAM beams are distorted and the distortion of 3-mode OAM beam is more severe than that of 1-mode OAM beam. Secondly, the phase structures of multiplexed OAM beams
FIGURE 2. Phase profiles of single-mode, multiplexed and demultiplexed beams at different tilt angle $\theta_1$. (a) Single-mode OAM beam with $l = 1$; (b) Single-mode OAM beam with $l = 3$; (c) Multiplexed OAM beam with $l = \pm 1$ and $l = \pm 3$; (d) Demultiplexed OAM beam with $l = \pm 1$ and $l = \pm 3$; (e) Demultiplexed beams with $l = \pm 1$; (f) Demultiplexed beams with $l = \pm 3$. (Observation plane size: 0.3m × 0.3m).

with $\pm 1$ and $\pm 3$ are simulated as shown in Fig. 2(c). It is observed that the phase center of multiplexed beams is off the center of transmission axis. Thirdly, the multiplexed beams with $\pm 1$ and $\pm 3$ are demultiplexed as shown in Fig. 2(d). Beam center offset also occurs after demultiplexing and the more oblique the antenna arrays, the farther the center of phase profiles deviates. Hence the effect of tilt angle of array on transmission and demultiplexing of OAM beams can be reflected through the deviation of beam center. It is also found in Fig. 2(e) and (f) that the phase structure of 3-mode beam has less distortion than that of 1-mode beam after demultiplexing in oblique scenarios, which is because high-mode OAM beams have stronger divergence. It can be inferred that the system is more stable in oblique scenarios when transmitting high-mode OAM beams.

B. OAM CHANNEL CAPACITY

In the analysis of phase structure of OAM beams above, it is observed that the distortion of OAM beams during transmission and the center deviation at receiving end are obvious in misalignment cases. To figure out the performance of OAM system, we further perform a comprehensive comparative analysis of channel capacity by jointly considering different transmission distance, tilt angle and array radii.

Fig. 3 presents the capacity changing with tilt angle $\theta_1$, array radii $R$ ($R_l = R_t = R$) and transmission distance $D$ jointly. Fig. 3(a) shows the channel capacity when $\theta_1$ and $D$ change simultaneously at $R_l = R_t = 1\lambda$. It can be seen that the capacity is the highest no matter how $R$ changes when $\theta_1 = 90^\circ$ (i.e. the arrays are aligned and parallel strictly) and decreases as $D$ increases due to the energy attenuation of the OAM beams during transmission. Fig. 3(b) shows the channel capacity when two parameters $\theta_1$ and $R_t$ change simultaneously at $R_l = 1\lambda$ and $D = 10\lambda$. It can be seen that the capacity is the highest no matter how $R_t$ changes when $\theta_1 = 90^\circ$. The channel capacity shows a step-like variation and reaches its maximum when $R_t$ is $2\lambda$. This is because the divergence of OAM beams make the energy of the received signal dependent on the radius of the receiving array. What’s more, antenna arrays with smaller radii can achieve better system performance, which means the UCA-based OAM systems can be integrated to a smaller specification.

Fig. 3(c) illustrates the channel capacity in terms of radii $R$ and tilt angle $\theta_1$. It is observed that the capacity is very low in some angle ranges. The fluctuation degree of capacity in low-capacity area is different when the radius changes. The fluctuation of capacity may be caused by the interference effect of OAM waves when the array plane is oblique, which results in the change of the radiation field strength at the receiving plane. Although this brings challenges to OAM communications in oblique scenarios, it also reduces the possibility of eavesdropping in OAM-based communication systems to a certain extent.

C. RECEIVED POWER OF OAM BEAMS

Fig. 4 shows the received power of OAM beams with different modes. Fig. 4(a) illustrates the received power of OAM beams under different array radii. It can be seen that the received power of OAM beams with different modes differ sharply when $R_l = 1\lambda$. The received power of the five modes of $\pm 6, \pm 7$ and 8 are lower than $-120$dBm (the sensitivity of professional receivers can reach $-120$dBm) when $R_l = 1\lambda$. 


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while only mode 8 is lower than the receiver sensitivity of $-120$ dBm when $R_t$ is extended to $2\lambda$. When $R_t = 2\lambda$ ($R_f = 2\lambda$ and $R_r = 4\lambda$) and $R_t = 3\lambda$ ($R_f = 3\lambda$ and $R_r = 6\lambda$), the received power of all modes is higher than the receiver sensitivity and the difference of received power between different OAM modes is also reduced when $R_t$ is greater than $R_f$, which means that a larger receiving array radius is conductive to the reception of multi-mode and high-mode signals and is helpful to enhance the balance of receiver power of beams with different modes.

OAM beams with received power lower than receiver sensitivity cannot be received, which means the waste of transmitting power and the loss of carrier information, therefore, effective transmission modes can be set reasonably according to transmitting array radius and at the same time receiving arrays with different radii can be set at the receiving end to receive different modes.

Fig. 4(b) illustrates the received power of OAM beams under different array radii ($R_t = R_f$) and tilt angle $\theta_1$ ($90^\circ$ and $80^\circ$) at $N = 16$ and $D = 10\lambda$. It can be seen that the received power of OAM beams with different modes when $\theta_1 = 90^\circ$ is superior to that when $\theta_1 = 80^\circ$. Moreover, it can be observed that the decrease of the received power caused by the tilt of array plane is still within an acceptable range when the radii of array are large. This means that the influence of tilt angle on the received power in oblique scenarios can be ignored to some extent when the array radii are large.

**D. SECRECY CAPACITY**

Calculating and improving the secrecy capacity under multi-antenna technology is one of the core issues in physical layer security research. In wireless communication systems, randomly distributed eavesdroppers are likely to reduce legal received power.
FIGURE 5. Secrecy capacity $C_s$ and main channel capacity $C_m$ changing with $D_e$ at $R = 1\lambda$ under different wiretap power ratio $r_e$ of 0.1 - 0.5.

TABLE 2. Probability of achieving secure communication when $D_e$ is in the range of $5\lambda$-$15\lambda$.

| $r_e$ | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
|-------|-----|-----|-----|-----|-----|
| $P_s'$ | 100% | 98% | 82% | 66% | 50% |

TABLE 3. Probability of achieving secure communication when $\theta_e$ is in the range of $0^\circ$-$90^\circ$.

| $r_e$ | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 |
|-------|-----|-----|-----|-----|-----|
| OAM   | 100% | 95.6% | 89% | 86.8% | 84.46% |
| MIMO  | 100% |           |     |     |     |

FIGURE 6. Secrecy capacity $C_s$ changing with $\theta_e$ under different wiretap power ratio $r_e$ of 0.1 - 0.5 at $R = 1\lambda$ and $N = 16$. (a) $D_b = 5\lambda$; (b) $D_b = 10\lambda$.

Fig. 5 illustrates the secrecy capacity $C_s$ and main channel capacity $C_m$ changing with $D_e$ under different wiretap power ratio $r_e$ of 0.1 - 0.5 at $R_t = R_r = 1\lambda$ and $N = 16$. The red and blue lines represent the main channel capacity and secrecy capacity $C_s$ at different $r_e$, respectively. The difference between the main channel capacity and the secrecy capacity denotes the wiretap capacity $C_w$. It can be seen from Fig.5 that both $C_m$ and $C_s$ gradually decrease as $r_e$ increases, $C_s$ increases and $C_w$ decreases as $D_e$ increases. The probability of achieving secure communication when $D_e$ is in the range of $5\lambda$ - $15\lambda$ is shown in Table 2. The probability of secure communication remains above 50% with the change of wiretap power ratio.

Fig. 6 shows the secrecy capacity $C_s$ changing with $\theta_e$ under different $r_e$ of 0.1 - 0.5 at $D_b = 5\lambda$ and $10\lambda$, respectively. According to Fig. 6(a), the probability of achieving secure communication when $\theta_e$ is in the range of $0^\circ$ - $90^\circ$ is shown in Table 3. It can be seen that OAM system still has a secure communication probability of 84.6% compared with conventional MIMO system with a secure communication probability of 0.

In the conventional MIMO communication system using plane electromagnetic wave, because of the broadcast characteristics of wireless signal, the receiver (legal or illegal) at any position in free space can receive information from the transmitting end, thus the system security needs to be guaranteed by adding additional techniques like cooperative jamming technology. While in the case of OAM system, it can be seen from OAM phase profiles in Section III. A that, unlike the conventional electromagnetic wave with plane phase wave-front, vortex electromagnetic wave has a unique spiral phase structure and the phase structure will be damaged when the array is tilted, which makes it impossible for the eavesdropper at any position in free space to obtain the complete OAM beam and transmission information. The spiral phase structure of OAM beam will enable it to be widely used in high security communication scenario in the future.

In Fig. 6(b), the secrecy capacity in $0^\circ$ - $78^\circ$ ($90^\circ$ - $\alpha_{\min} = 78^\circ$) is valid when $D_b = D_e = 10\lambda$. It can be seen that the secrecy capacity is all positive when $r_e$ is less than and equal to 0.5 and it can be inferred that $C_s$ can hold positive when $D_e > D_b$ no matter how $\theta_e$ changes. In summary, system using directional vortex electromagnetic waves can achieve high-speed secure communication due to its unique spiral phase structure and natural orthogonality and is superior to conventional communication systems using planar electromagnetic waves in terms of system security when there are no any additional technical restrictions.

IV. CONCLUSION

In this paper, a UCA-based multi-mode OAM wiretap system has been studied in order to clarify the security of OAM.
technology. We have analyzed the phase structure of OAM beams in oblique scenarios, the capacity and received power of OAM beams, and the secrecy capacity of the system under different eavesdropping power and different eavesdropping positions. The results show that compared with conventional MIMO, communication system based on OAM has stronger anti-wiretap ability due to its inherent divergence and spiral phase structure. The research on the security of OAM system has both theoretical and practical significance for reducing the sensitivity of OAM technology to directions and enhancing the performance of OAM systems.

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