An approach for generating and detecting the signals with the given orbital angular momentum for wireless communication systems

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Abstract. The paper is devoted to the development of methods for increasing the efficiency of wireless communication channels via the usage of multiplexing by the orbital angular momentum (OAM). This wave property allows us to form an additional basis of orthogonal functions for the simultaneous independent transmission of several signals. In particular, we propose the uniform circular antenna array (UCA) operating in the 77 – 78.5 GHz frequency range designed to generate radio beams with various orders of the OAM without changing its configuration. The important points in the UCA’s design process were ensuring the minimum divergence of the beam during the propagation and obtaining the maximum gain. Regarding the OAM radio beams receiver, we propose a solution for detecting an OAM signal in case of misalignment between transmitting and receiving antennas. An antenna array consisting of two perpendicular dipoles is employed as a receiving device, providing the OAM signal reception from any direction. An important point of signal detection is the preservation of the information about the phase of the received signal. Finally, we demonstrate the simulation results of OAM signal transmission and reception.

1. Introduction
Currently, the global scientific community actively search for the new information technologies that will increase the efficiency of using the bandwidth of wireless communication channels. One of these directions is the use of the orbital angular momentum (OAM) of electromagnetic waves. OAM is a spiral dislocation of the electromagnetic wavefront defined by a phase factor \(e^{i\phi}\), where \(l\) is an integer specifying the OAM state. Radio waves with a non-zero OAM state provide an orthogonal basis of signals that can be used for new data multiplexing methods, along with conventional techniques. The secure communication channels and multiple access networks can be implemented based on radio waves with different OAM states. This will significantly reduce the utilization of the frequency resource in existing and future radio communication systems.

Unfortunately, OAM multiplexing technology is associated with the following difficulties. First, the transmitting and receiving antennas must satisfy the important requirement of generating and receiving mixed signals with a complex phase front. Second, the OAM electromagnetic waves divergence significantly limits the wireless distance. Thus, it requires the methods for controlling the radiation directivity. Third, it is very difficult to estimate the phase on the receiving side due to mismatching between transmitter and receiver and. That leads to significant signal attenuation.
Therefore, it is necessary to research the following three main challenges of wireless systems with OAM multiplexing: radio signal generation with a given OAM state, issues of OAM radio signal propagation in the wireless channel, and the OAM signal detection. A large number of studies confirm the efficiency of OAM signals application in the radio systems operating in the frequency range above 30 GHz [1 – 2]. So we will review the existing solutions for millimeter-wave band (W-band).

According to the first direction, the most common method for generating radio signals with the given OAM state is the use of spiral phase plates (SPP). SPP forms a required phase front as the signal passes through a system of multi-format holes [3]. The advantages of SPP are small OAM beam divergence and low attenuation. The SPP disadvantages – they are unworkable for low-frequency signal transmission and cannot provide the simultaneous generation of several different OAM states. The next approach is the application of uniform circular arrays (UCA) with the particular feeding system. Such a feeding system allows specifying the required phase shift for each radiator corresponding to the generation of the selected OAM state [4]. UCA provides to generate several different OAM modes and to shift the OAM state without changing the antenna configuration. The main disadvantage of UCA is a high divergence. Also, the radio wave energy is lost in the central radiation direction for high OAM states. Another solution is metasurfaces [5]. In this case, the OAM generation principle is similar to the SPP with the same disadvantages.

Different studies of the OAM radio signal propagation in free space mostly focus on the problem of OAM radio signal divergence in space. The divergence shortens the transmission distance and decreases the efficiency of spectrum utilization. Many researchers use highly directional parabolic antennas and focusing lenses to provide a high convergence of signals. This method allows effectively and simultaneously transmitting information with the different OAM orders [6]. Moreover, the possibility of saving the transmitted phase at the receiving side is another important task. During the OAM wave propagation, the signal phase acquires additional changes due to the channel characteristics in the millimeter-wave range. It is also necessary to take into account that small-scale and large-scale fading of the vortex signal. That effect usually occurs when propagating in free space and leads to the amplitude and phase change of the OAM radio signals.

There are only a few studies nowadays devoted to the OAM signal detecting task. Several approaches exist to correctly identify the signal phase. The application of SPP or metasurfaces makes it possible to detect only one OAM order since the plate is constructively calculated for a specific order [7]. Receiving based on antenna arrays has great advantages since it allows detecting several OAM orders. Although this method requires the precise alignment of the receiving and transmitting antennas. It’s based on the spatial fast Fourier transform (FFT) algorithm, which has the following property: after spatially sampling the sum is zero within the interval length except for the designed OAM-mode. The other detection methods include phase gradient analysis, angular momentum measurement, and triangulation.

Thus, in this paper, we solve the following actual scientific and technical tasks. The first one is the generation of a given OAM radio signal in terms of its minimum divergence during propagation. The initial data for this task is the maximum gain of the antenna array, the known transmission line length, and the possibility of controlling the orbital momentum. The second task is the detection of the OAM radio signal in terms of the transmitting and receiving antennas coaxiality offset. Another issue under the consideration is the reconstitution of the intensity distribution on the basis of partial information about the transmitted OAM radio signal.

We perform the design in the band of 77 – 78.5 GHz. Today W-band (75 – 110 GHz) is the most attractive and promising due to the absence of severe restrictions on the radiated power level. Also, its low workload compared to other radio frequency bands.
2. Transmitting antenna array for OAM generation

As it was mentioned above, the UCA application provides to generate and simultaneously emit different OAM modes without changing the transmitting antenna configuration. This advantage is not available for other approaches. Thus, the proposed design of the transmitting antenna focuses on finding the optimal shape and dimensions of UCA and its radiating elements. UCA’s elements utilize the microstrip line technology as the most common and proven technique for creating microwave devices [8].

The developed radiating element is presented in figure 1 (a), (b). The dimensions of the microstrip antenna are 5.14 mm × 2.5 mm, and it is matched to 50 Ohm impedance. The main radiating part has the shape of an octagon with a diameter of 2.2 mm. This dimension roughly corresponds to half the wavelength of radio emission in the W-band. The antenna is low profile and provides the UCA miniaturization. On the assumption of the operating frequency range, we chose Rogers RO TMM3 laminate and the connectors. Figure 1 (c) demonstrates the return loss $S_{11}$ of the proposed microstrip antenna, proving its matching in the band 76.5 – 79 GHz.

![Figure 1](image1.png)

**Figure 1.** The designed microstrip antenna: (a) front view; (b) back view; (c) $S_{11}$.

The UCA consists of eight microstrip antennas arranged in a circle with a distance of 1.50 from the circle center to the antenna center. The radiating elements orientation provides the ease of feeding. The element’s tops direct toward the circle center, and the feeding points locate on the outer UCA’s edge (figure 2 (a), (b)). The total size of the developed UCA without connectors is 14.28 mm × 14.30 mm.

![Figure 2](image2.png)

**Figure 2.** The designed UCA: (a) front view; (b) perspective view; (c) radiation pattern.
Figure 2 (c) presents the radiation pattern that has the maximum radiation oriented normal to the array plane with the realized gain of 7.24 dB. There are also 8 side lobes located above the radiating elements.

We propose UCA’s configuration providing the simultaneous generation of W-band radio waves with three different OAM states: +1, 0, -1. When the signal of uniform amplitude and phase shift equal to $\pi/4 + \pi$ feeds UCA’s radiating elements, UCA generates the OAM mode with $l = +1$ (figure 3 (a)). Phase shift equal to $-\pi/4$ implements the OAM mode with $l = -1$ (figure 3 (c)). In the case of the uniform phase shift of the input signal, we can obtain the zero OAM mode at the output of the UCA (figure 3 (b)). The results demonstrate the clear spiral phase front of the generated radio signal both in the near field and the far-field zone for the proposed UCA configuration.

![Figure 3](image1.png)

**Figure 3.** The E-field intensity and phase: (a) $l = +1$; (b) $l = 0$; (c) $l = -1$.

3. Analysis of the OAM radio waves divergence

To analyze the divergence of OAM radio waves at the receiver station we developed a simulation model in Matlab. The model takes into account the phase distribution of the longitudinal component of
the electromagnetic field, the distance between the transmitting antenna and the point of analysis, the radius of the transmitting antenna array, the size and number of radiating elements (dipole antennas).

During the simulation study, the following conclusions came to light. To reduce the OAM radio wave divergence while propagating in free space it is necessary to increase the radius of the transmitting UCA. This allows reducing the size of receiving antenna array consisting of two perpendicular dipoles for OAM signals and increasing the wireless transmission distance [9]. In the case of transmitting an OAM radio signal over a distance many times exceeding the wavelength, the OAM radio signal degrades dramatically. Thus, the OAM order can not be identified with a receiving antenna of limited resolution. As the radius of the transmitting antenna array decreases the wavefront lines with constant phase get shortened. That, in turn, indicates a high divergence of the OAM radio signal. Figure 4 represents the simulation results of OAM radio waves divergence for test antenna array based on 8 dipole antennas [10].

![Figure 4](image)

**Figure 4.** Wavefront lines with constant phase for different radius of transmitting antenna array:
(a) radius of antenna array – 5 cm (b); radius of antenna array – 1 cm.

Taking into account the conclusions above, we propose the second UCA’s configuration, designed to reduce the divergence of radio beams. The radius for placement of the UCA’s radiating elements increases to $2\lambda$. Figure 6 shows the front view and radiation pattern of the second UCA’s configuration. The dimensions of the refined UCA are 18.6 mm x 18.6 mm. Due to the rise of the spacing of the radiating elements, the antenna gain increases to a value of 8.71 dB.

![Figure 5](image)

**Figure 5.** The UCA’s configuration # 2: (a) front view; (b) radiation pattern.

Figure 6 shows a comparison of the radiated field in the near and far-field zone for the first ((a) – (b)) and second ((c) – (d)) UCA’s configurations when generating a radio wave with an OAM state.
$l = +1$. According to the analysis of the obtained data, the second proposed UCA’s configuration indeed demonstrates a decrease in the divergence of the OAM radio waves, which confirms the previously obtained conclusions.

**Figure 6.** The E-field intensity and phase for $l = +1$ at the distance: (a), (c) – 4; (b), (d) – 8.
4. Principles for OAM radio signals detection

At the next step of the research, we propose the principle for OAM signal detection. Figure 7 presents its scheme. For the phase front analysis of the received signal, we use a test antenna. The antenna moves in two directions in the vertical plane and captures the OAM states using a spectrum analyzer (SA) or a vector analyzer (VA). However, the alignment of the transmitting and receiving antennas of such a system under real conditions may be violated. Therefore we propose to develop a method for detecting the OAM signals in case of its deviation from the central propagation axis.

![Figure 7. The scheme for OAM radio signals detection principle.](image)

When identifying the order of the transmitted OAM signal at the receiving station, problems arise in the case of misalignment of the transmitting and receiving systems. When the coordinate system rotates, the OAM signal harmonics $e^{im\phi}$, $e^{i(m-1)\phi}$, $e^{i(m+1)\phi}$ are mixed. The utilization of vector spherical harmonics $Y_{l,m}(\theta,\phi)$ [11 – 14], which form a complete orthonormal set of rotationally invariant functions, provides avoiding this problem.

In this paper, we propose to use the model of the transmitting system specified by the spectral components of the multipole decomposition of the radiated electromagnetic field $\{a_{lm}\}$ [11 – 12]. In the case of misalignment of the transmitting and receiving systems the signal detection applies the correlation method. The transformation of vector spherical harmonics compensates the relative rotation determined by three Euler angles $\alpha, \beta, \gamma$ [13]:

$$\bar{Y}_{l,m}(\theta', \phi') = \sum_{k,l} D_{m,k}(\alpha, \beta, \gamma) \bar{Y}_{l,k}(\theta, \phi)$$  (1)

where $D_{m,k}(\alpha, \beta, \gamma)$ are Wigner functions.

The Wigner functions have a multiplicative structure in Euler angles:

$$D_{m,k}^{j}(\alpha, \beta, \gamma) = e^{im\alpha} d_{m,k}^{j}(\beta)e^{-ikj}$$  (2)

$$d_{m,k}^{j}(\beta) = \left[ (j+m)!(j-m)!(j+k)! \right]^{1/2} \sum_{s} (-1)^{s-k} \frac{\left( \cos \frac{\beta}{2} \right)^{2j+k-m-2s} \left( \sin \frac{\alpha}{2} \right)^{m-k+2s}}{(j+k-s)!(m-k+s)!(j-m-s)!}$$  (3)

The radiating system identification consists of determining the coefficients of the multipole decomposition $\{a_{lm}\}$ based on the compensatory rotation of the observation system determined by Euler angles. The angles of rotation compensate non-magnitude misalignment of detection and radiation. The maximization of the function determines the angles of rotation:
where \( \vec{E}(\theta, \phi) \) is vector field, \( \vec{Y}_{l,m}(\theta', \phi') \) is determined by (1).

It should be noted that the representation as mentioned above is simplified. For a more complete analysis, it is necessary to consider the monopole coefficients of the electric and magnetic type \( \{a_{lm}^E\} \) and \( \{a_{lm}^M\} \).

Based on the obtained expressions, we construct a simulation model in Matlab providing to analyze the phase distributions for OAM signals with state \( l = 2 \) (figure 8) if they deviate from the central axis of propagation by a certain degree.

In a simulation study, we assume that the signal propagates in a direct line of sight without multiple reflections with constant noise. The objective of the proposed method is to show that the non-coaxial reception of OAM signals is possible with additional signal processing at the receiving side. This model allows changing the wave incidence angle on the wavefront analysis plane. So, you can use the proposed correlation method for detecting OAM signals in case of incoherent reception. To estimate the efficiency of the proposed method, we conduct the simulation for different incidence angles. According to expression (4), we should determine the scalar product of the received signal and the reference signals with different OAM states to recover the OAM state of the received signal and restore its original structure.

![Figure 8](image)

**Figure 8.** Phase analysis for E-field component with \( l = 2 \) OAM order: a) 0°; b) 5°; c) 10°; d) 15°; e) 30°.

Figure 9 presents the obtained simulation data. Figure 9 (a) denotes the values of the correlation coefficient between the received and reference OAM radio beams for different values of the deviation angle from the central axis of propagation without additional processing of the received signal. Figure 9 (b) shows the correlation coefficients with the processing of the received signal by the proposed method. Figure 10 represents the result of the normalized scalar product of the received signal (OAM state \( l = 1 \)) with reference signals with different OAM states.

Simulation results show that if we receive some unknown phase distribution, the proposed method provides the determination possibility of the initial structure of the transmitted OAM signal by its complex amplitude. However, it should be noted that the inclination angle of the receiving plane is important, which determines the possibility of correct detection.
Figure 9. The correlation coefficient between the received and reference OAM signals: (a) without processing; (b) the received signal is processed with the proposed method.

Figure 10. The normalized scalar product of the received signal with reference signals of different OAM states in case of $l=1$ transmitted.

According to the simulation results, we can conclude that the proposed correlation method helps to increase the correlation coefficient of the transmitted signal with the reference one when there is non-coaxial reception. This ensures spatial coherent reception and allows to increase the detection efficiency of oblique OAM vortex signals.

5. Conclusions
In this paper, we consider three important tasks regarding wireless transmission based on the OAM radio signals application. The first task is the OAM signals generation with the possibility of OAM state control without changing the configuration of the transmitting antenna. The uniform circular array application, consisting of small microstrip antennas locating in the circle, solves this task. The developed UCA is small size, high gain, and allows generating three different states of OAM radio emission. While solving the second task, it is found that using a transmitting UCA of a larger radius provides to reduce the divergence of OAM radio emission. Based on this conclusion, we propose a second UCA’s configuration with an increased radius. The simulation results show a lower divergence of radio waves for this case. And finally, we present the detecting principles in case of misalignment of the transmitting and receiving antennas. The principle consists of the multipole decomposition of
the field which contains only partial information about the transmitted signal. In total the proposed solutions gains into the robust and fast implementation of OAM signals multiplexing which can dramatically increase the efficiency of modern and future wireless communication channels.

6. References

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**Acknowledgments**

This work was supported by the grant of Russian Science Foundation (RSF) (project No. 18-19-00123).