Channel Estimation and Channel Model for Orbital Angular Momentum in Wireless Communications

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***Abstract*—This report explores the use of Orbital Angular Momentum (OAM) in wireless communications, specifically focusing on channel estimation for different OAM modes. OAM offers a new dimension for multiplexing signals, providing orthogonal modes that can enhance spectrum efficiency and capacity. The report investigates the theoretical background of OAM, methods for generating and receiving OAM signals, and the challenges associated with implementing OAM in wireless networks. Simulation results using MATLAB are presented to analyze the phase profiles and channel estimation techniques for various OAM modes, demonstrating the potential and challenges of integrating OAM into future wireless communication systems.**

***Keywords*— Orbital Angular Momentum, OAM, wireless communications, channel estimation,**

I. Introduction

As wireless communication technologies evolve from 4G to 5G and beyond, there is a pressing need to handle exponentially increasing data traffic. Traditional resources such as frequency, time, and space have been extensively utilized, pushing the limits of technologies like time-division multiple access (TDMA) and frequency-division multiple access (FDMA). Orbital Angular Momentum (OAM) presents a novel approach by introducing a new dimension for multiplexing signals. Unlike conventional plane-electromagnetic (PE) waves, OAM waves possess a helical phase structure, allowing for multiple orthogonal modes that can be multiplexed to significantly enhance spectrum efficiency and capacity without additional frequency or time resources. This report investigates the theoretical foundations of OAM, its application in wireless communications, and the challenges faced in channel estimation for different OAM modes. Through MATLAB simulations, the report examines the phase profiles and channel estimation methods for various OAM modes, highlighting both the potential benefits and technical obstacles.

II. Theoretical Background of Orbital Angular Momentum

A. Orbital Angular Momentum

The transition from 4G to 5G and beyond is driven by the need to handle significantly higher data traffic, with the data rate expected to increase by 1000 times compared to 4G. Key technologies enhancing spectrum efficiency in 5G include massive MIMO, full-duplex transmission, and millimeter-wave (mmWave) frequencies. However, traditional methods like time-division and frequency-division multiple access are reaching their limits.

Orbital Angular Momentum (OAM) offers a new dimension for wireless communication. Unlike traditional plane-electromagnetic (PE) waves, electromagnetic (EM) waves have both linear and angular momentum. OAM, characterized by its helical phase, provides numerous orthogonal modes that can be multiplexed, potentially increasing capacity without relying on traditional resources.

Research has demonstrated the feasibility of OAM-based communication. For instance, experiments have shown successful transmission using different OAM modes at various frequencies. Combining MIMO with OAM can further enhance spectrum efficiency.

Despite these advancements, challenges remain. Antennas must support the generation and reception of multiple OAM modes, and OAM beams, which are divergent, need convergence for long-distance transmission. High frequencies like 70 GHz reduce divergence, improving signal-to-noise ratio (SNR).

OAM is defined by its rotational degree of freedom and can be described mathematically with a phase rotation factor. Different OAM modes are orthogonal and exhibit a spiral phase structure. Higher OAM modes have more complex phase changes and greater central hollowness, necessitating convergence for long-distance transmission.

In summary, while OAM shows promise for enhancing future wireless networks, significant technical challenges must be addressed to fully realize its potential.

B. What Is Orbital Angular Momentum

Orbital Angular Momentum (OAM) is a fundamental property of electromagnetic (EM) waves, describing their rotational characteristics and energy rotation. OAM can take both integer and non-integer values, with different modes represented by a phase rotation factor:

$$e^{j \cdot l \cdot \varphi}$$

Where:

$$j = \sqrt{-1}$$

And φ is azimuthal angle. Integer OAM modes are orthogonal to each other, and non-integer modes can be expressed as a sum of Fourier series of orthogonal OAM modes.

OAM waves have a spiral phase structure, rotating around the propagation direction, with the phase changing by 2πl after a full turn. Figure 1 to 2 illustrate the wavefront phases of OAM modes 0 to 3, showing increasing complexity and sharper phase changes as the mode index increases.

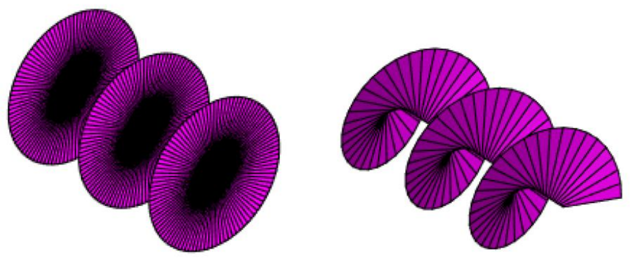

Figure 1 Wavefront of mode l = 0 and 1

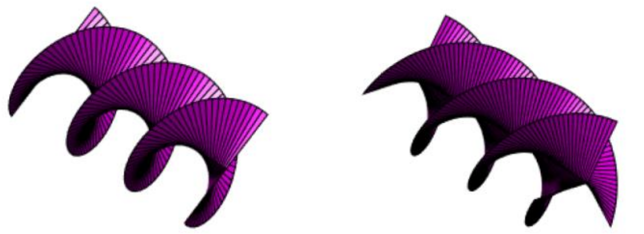

Figure 2 Wavefront of mode l = 2 and 3

C. Orbital Angular Momentum for Wireless Communication

The advantages and challenges of using Orbital Angular Momentum (OAM) in wireless communications and outlines the methods for generating, transmitting, and receiving OAM signals are at the following:

1) High Spectrum Efficiency

Different OAM modes are orthogonal to each other, allowing parallel transmission without interference, increasing spectrum efficiency without additional traditional resources. OAM can be combined with frequency, time, and code-domain resources for even greater efficiency.

2) More User Access

OAM enables mode division multiple access (MDMA), allowing users to access the network orthogonally using different OAM modes, reducing the need for non-orthogonal multiple access.

3) High Reliability for Anti-Jamming

OAM mode hopping can enhance anti-jamming capabilities, both in narrow and wide bands, providing a robust solution against crowded spectrum issues.

D. Antennas and Signal Transmission/Reception For Orbiral Angular Momentum Waves

OAM Waves Generation techniques are:

1) Spiral Phase Plate Antenna

Generates phase delay by varying antenna thickness or permittivity. It has low divergence and attenuation but can't generate multiple OAM modes simultaneously.

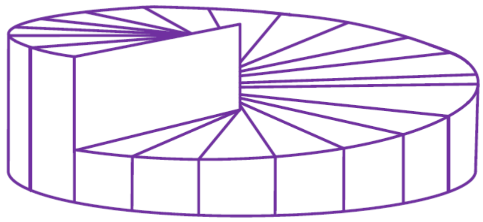

Figure 3 SPP Antenna

2) Uniform Circular Array Antenna

Generates multiple OAM modes with low profile and weight. However, the beams are divergent and hollow, requiring convergence techniques.

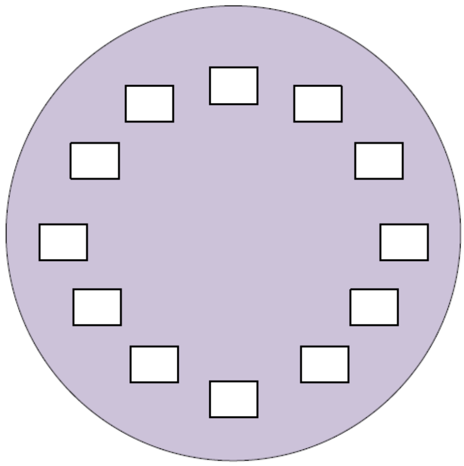

Figure 4 UCA Antenna

3) Metasurfaces

A metasurface is a thin, engineered material designed to manipulate electromagnetic waves by controlling their phase, amplitude, and polarization through an array of structured, sub-wavelength units.

Metasurfaces control wavefronts by phase shifts. They are low-cost and lightweight but difficult to control accurately for multiple OAM modes.

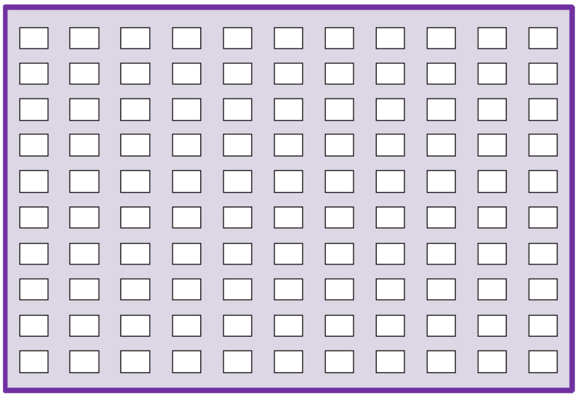

Figure 5 Metasurface Antenna

4) Radio Vortex Signal Transmission:

There are three main problems exist for OAM wave transmission at the following.

a) Transmitter Receiver Alignment

Proper alignment of transmitter and receiver is crucial to avoid phase turbulence and ensure accurate OAM mode detection.

b) Fading

Practical scenarios involve fading, requiring phase change estimation for each OAM mode.

c) Convergence

High-order OAM modes are divergent, reducing transmission distance and spectrum efficiency. Convergence techniques like parabolic and lens antennas are needed but come with size and attenuation trade-offs.

5) Radio Vortex Signal Reception:

The phase detection is the key to distinguish the order of different OAM Modes. The radio reception schemes for three antenna types are at the following.

a) SPP Antenna

Can only detect one OAM mode at a time by converting the OAM wave to a plane wave using conjugate phase multiplication.

b) UCA Antenna

Uses spatial FFT to detect multiple OAM modes, requiring alignment of transmit and receive antennas.

c) Other Methods

Include phase gradient method (PGM), direct torque measurement, and triangulation to detect OAM modes based on helical phase fronts.

E. OAM and FDMA Comparison

The source study involves a network with one macrocell using plane-electromagnetic (PE) waves and several small cells using OAM beams, demonstrating how OAM can prevent cross-layer and co-layer interference and significantly enhance spectrum efficiency.

From figure 6, it can be observed that the spectrum efficiency of networks using multiple OAM modes surpasses that of traditional FDMA, and this efficiency significantly improves as the number of OAM modes increases.

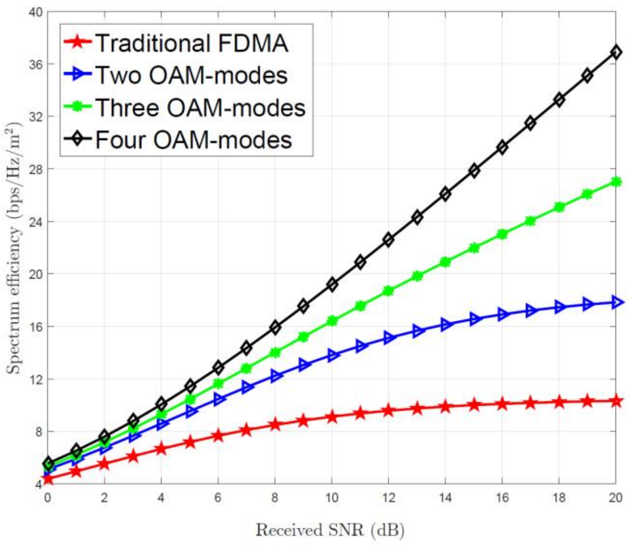

Figure 6 The spectrum efficiencies versus received SNR with different number of OAM-modes for multiple users access.

Figure 7 shows the spectrum efficiencies of traditional FDMA and various numbers of OAM modes in relation to user density in wireless networks. The spectrum efficiency rises as the user density increases.

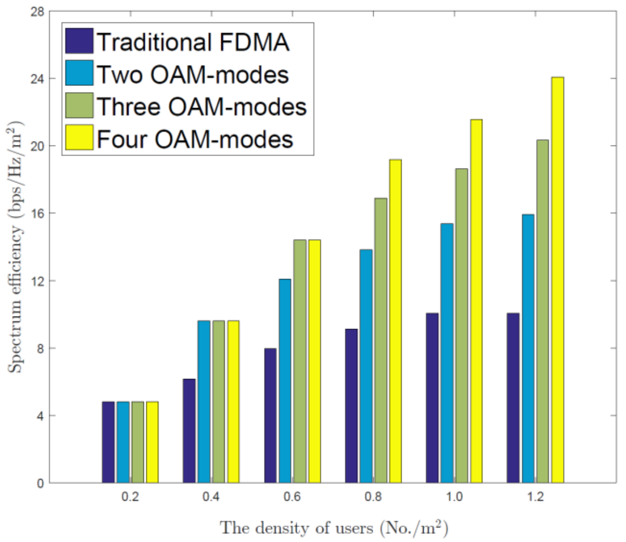

Figure 7 The spectrum efficiencies versus the density of users with different number of OAM-modes for multiple users access.

F. Challenges

1) Limited Number of Available OAM Modes

High-order OAM modes suffer severe attenuation, limiting their number. So, for high density small cells, it is very likely the number of available OAM Modes are not enough.

Solutions include converging OAM beams using parabolic or bifocal lens antennas and transforming UCAs into concentric UCAs to use more low-order modes.

2) Joint OAM-Mode and Frequency/Time Partition

When OAM modes are insufficient, combining them with frequency and time partitioning can be a solution to balance traffic and enhance spectrum efficiency. Developing integrated multi-channel medium access control (MAC) protocols that combine mode-division, frequency-division, and time-division multiple access.

3) Channel Estimation for Different OAM Modes

Channel estimation for OAM modes presents significant challenges due to the large number of channels and potential phase front changes during propagation, which can lead to loss of phase identification at the receiver.

This complexity makes it difficult to recover transmitted signals for multiple OAM modes. Currently, there are no robust solutions in this area. However, UCA antennas offer a promising approach, as their circular matrix structure simplifies channel estimation and may provide a breakthrough for OAM wireless communications.

III. Simulations For Channel Estimation for Different OAM Modes

For the simulations related to the Orbital Angular Momentum Waves, this paper focuses on *Challenge 3) Channel Estimation for Different OAM Modes*. From source article. Also, in this section, we conducted simulations using MATLAB to analyze the phase profiles of different OAM modes and their effects on the channel. The following describes the steps performed and the relevant mathematical formulas.

A. Uniform Circular Array Creation and OAM Modes

The first step involves defining the geometric parameters of a N-element Uniform Circular Array (UCA) antenna array.

The antenna elements are arranged in a circular configuration with equal spacing. The x and y coordinates of the antenna elements are calculated using the radius of the array:

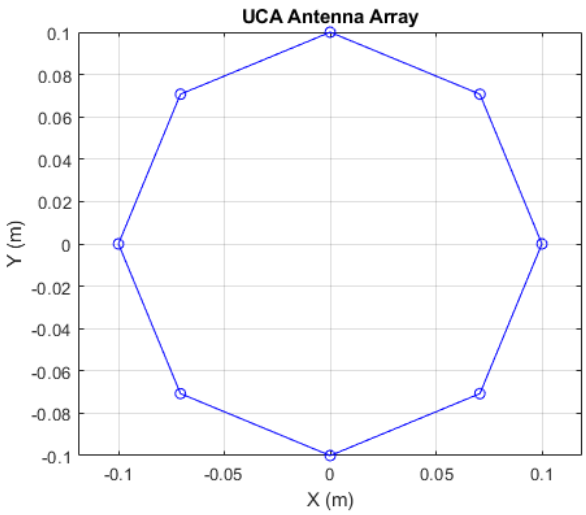

Figure 8 UCA Antenna Array for 8-elements

The OAM phase profile is calculated based on the angular positions of the antenna elements:

$$Wavenumber\ k = \frac{2\pi}{\lambda}$$

$$OAM\ Phase\ Profile = e^{jL\varphi}$$

This phase profile is computed for each antenna element, and a 3D plot of the phase angles is generated as following for mod $l = 1$.

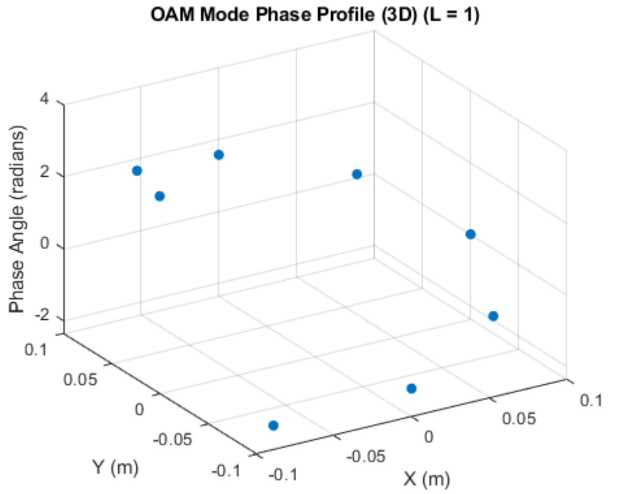

Figure 9 OAM Phase Profile for 8 element UCA antenna and l = 1

As an example of 32-element Uniform Circular Array (UCA) antenna array, mode $l = 1$ and $l = 2$ figures are below.

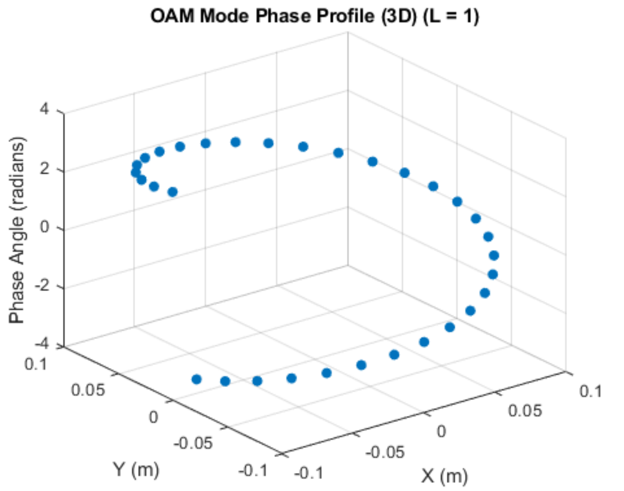

Figure 10 Phase Profile for 32 element UCA antenna and l = 1

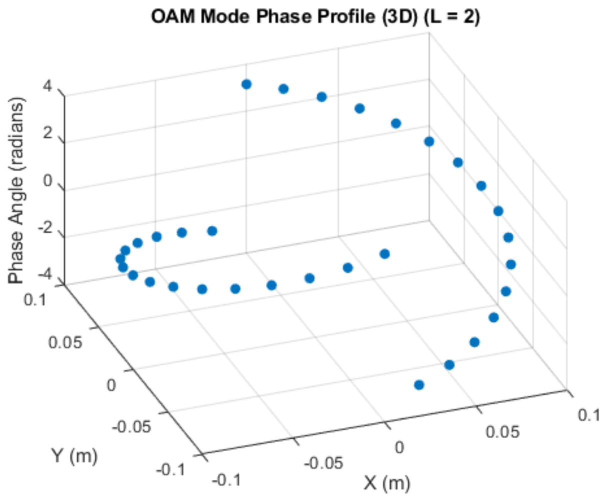

Figure 11 Phase Profile for 32 element UCA antenna and l = 2

B. *Transmission Transmission of OAM Signal Through AWGN Channel*

The OAM signal is transmitted through an AWGN channel with a specified SNR, which is chosen as

$$\frac{E_b}{E_0} = 6\ dB$$

The OAM symbols before and after AWGN channel can be seen at the figures below.

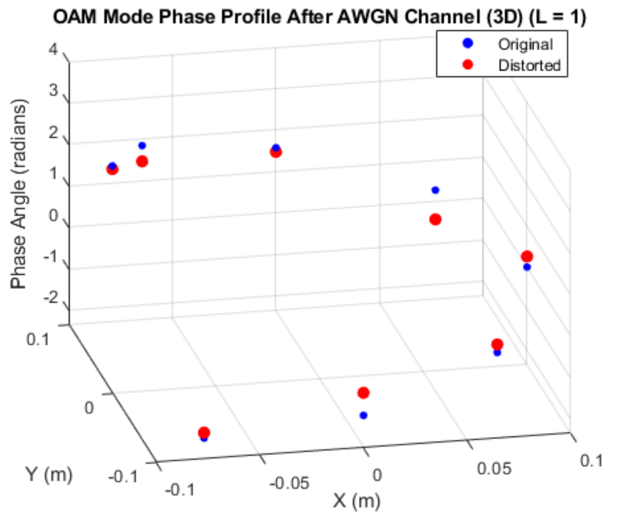

Figure 12 Noisy and Original OAM Phase Profile for 8 element UCA antenna and l = 1

Phase Distortion in OAM Phase Angle between Noisy and Original OAM Phase Profile for 8 element UCA antenna and l = 1. The calculation is:

$$Phase\ Error = Noisy\ OAM\ Signal\ Angel - OAM\ Signal\ Angel$$

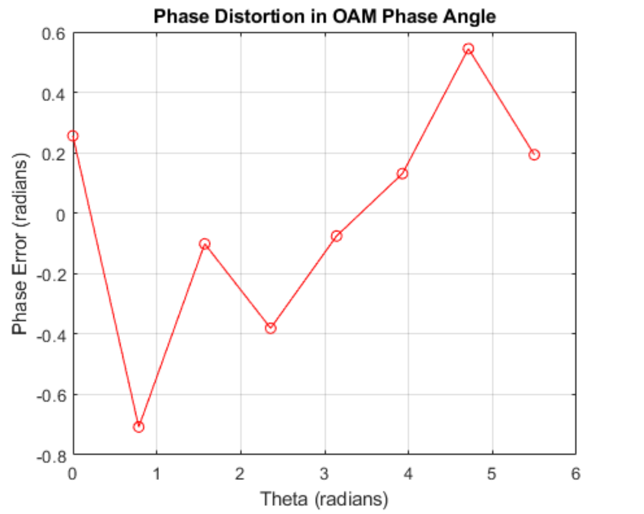

Figure 13 Phase Distortion in OAM Phase Angle between Noisy and Original OAM Phase Profile for 8 element UCA antenna and l = 1

To provide more example, noisy and original OAM Phase Profile for 32 element UCA antenna and l = 1 and 2 is below.

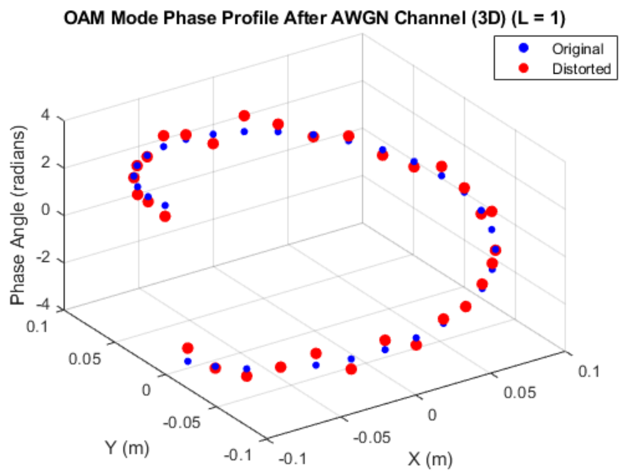

Figure 14 Noisy and Original OAM Phase Profile for 32 element UCA antenna and l = 1

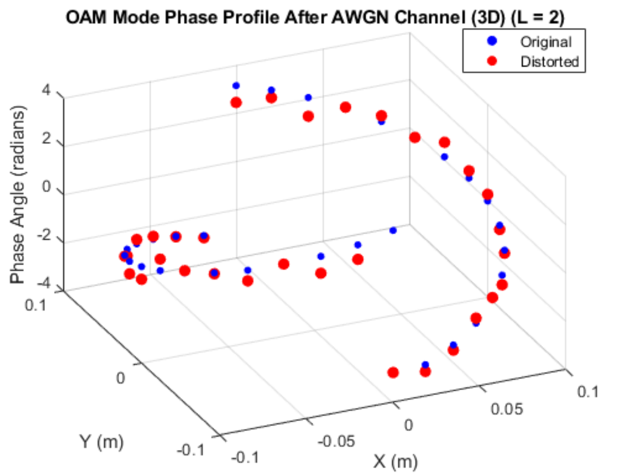

Figure 15 Noisy and Original OAM Phase Profile for 32 element UCA antenna and l = 2

C. *Calculation of the Channel Matrix*

The channel matrix H characterizes the signal propagation between antenna elements in the UCA. It is calculated using the distance d_{ij} between each pair of antenna elements:

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

The matrix H incorporates the phase shift due to propagation and the OAM phase profile:

$$H = e^{-jk \cdot d_{ij}} \cdot (OAM\ Signal \cdot Conjugate\ of\ OAM\ Sig.)$$

$$where\ wavenumber\ k\ is = \frac{2\pi}{\lambda}$$

The channel matrix is transmitted through an AWGN channel with a specified SNR

$$\frac{E_b}{E_0} = 10\ dB$$

This matrix models the complex gain and phase shift in the communication channel.

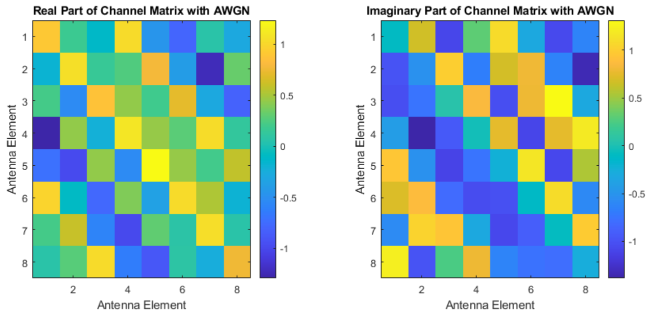

Figure 16 Channel Matrix

D. *LMS Channel Estimation Algorithm*

The LMS (Least Mean Squares) algorithm iteratively updates the estimated channel matrix H_{est} to minimize the error between the actual channel matrix H and H_{est}. The error matrix is:

$$Error\ Matrix = H - H_{est}$$

The update rule for H_{est} is:

$$H_{est} = H_{est} + \mu \cdot Error\ Matrix$$

where μ is the learning rate. This process is repeated for a number of iterations to refine the channel estimate and reduce the mean error. For the simulations, μ is choosed as 0.01 for 100 iterations. Estimated Channel Matrix is above.

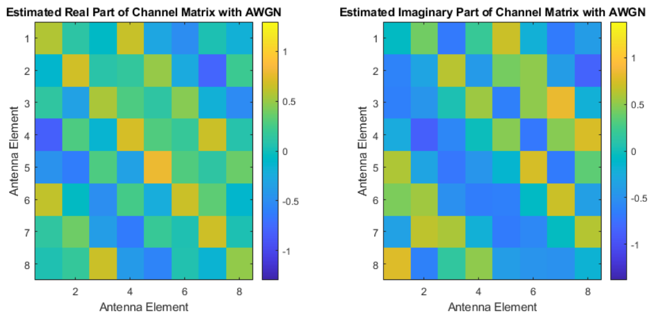

Figure 17 Estimated Channel Matrix for μ=0.01 and for 100 iterations,

The absolute difference between the actual and estimated channel matrices is calculated:

$$Mean\ Error = mean(|H - H_{est}|)$$

For our simulation, mean error with AWGN is 0.38043 for $\mu = 0.01$ and for 100 iterations,

For another example, mean error is 4.6528e-05 for $\mu = 0.01$ and for 1000 iterations.

IV. Conclusion

Orbital Angular Momentum (OAM) holds significant promise for revolutionizing wireless communications by providing a new dimension for multiplexing signals. The orthogonal nature of different OAM modes allows for increased spectrum efficiency and capacity, making it a valuable addition to future wireless networks. However, the implementation of OAM faces several challenges, including the need for specialized antennas to generate and receive multiple OAM modes, the convergence of divergent OAM beams for long-distance transmission, and the complexity of channel estimation for different OAM modes. The MATLAB simulations conducted in this report illustrate the potential of OAM in enhancing wireless communication systems, but also underscore the technical challenges that must be addressed. Continued research and development are essential to fully realize the benefits of OAM in future wireless communication technologies.

References

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