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Alignment Aspects of OAM Signal Reception Using Rotman Lens Based Circular Array

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Abstract—This paper discusses orbital angular momentum (OAM) signal reception and alignment aspects using a Rotman lens based multimode circular patch antenna array. A 9-element planar circular array is connected to a 5 beam port Rotman lens which is capable of hosting 5 spatially orthogonal OAM modes namely \( l = 0, \pm 1 \) and \( \pm 2 \). The Rotman lens based circular array is paced at the receiver end when it is illuminated with OAM signals. It is shown that the OAM modes reception is separable at the Rotman lens stage, hence reducing the requirement of the OAM phase correction at the receiver’s signal processing block. It is also shown that a slight misalignment between transmitter and receiver circular arrays can substantially decrease the signal recovery chances for the transmitted data using the OAM modes \( l = \pm 1 \) and \( \pm 2 \). This feature can enhance physical layer security to the communication link using Rotman lens based multimode circular array.

Index Terms—5G, MIMO, beamformer, antenna, lens, array.

I. INTRODUCTION

Along with the optical fiber infrastructure at the communication back-haul, the wireless technology carries up to 50% of the global mobile traffic [1]. Since the primary wireless resource i.e. radio frequency spectrum is limited, disruptive techniques are now investigated to enhance the wireless spectral efficiency. Multimode radio transmission is one of such techniques. A multimode antenna array is capable of generating the magnitude and phase of the antenna elements in such a way that the radiated modes wavefront is spatially orthogonal to each other. Each spatially orthogonal wavefront corresponds to a separate mode. Orbital Angular Momentum (OAM) is an example of multimode radio transmission where modes are generally denoted by \( l \). In some recent studies, it is shown that a Rotman lens based circular array is capable of hosting multiple OAM modes [2, 3].

In an associated investigation [4], we have demonstrated that a single antenna receiver can be used to decode the information transmitted by a simplex OAM transmitter. In this study, our contribution is to investigate and highlight the consequences of using an OAM receiver to decode the transmitted OAM signal. Alignment between transmitter and receiver is not an issue for the case shown in [4], however, it plays an important role when OAM receiver is used to receive the transmitted signal, which we will discuss in this paper.

II. OAM TRANSMITTER AND RECEIVER

The OAM radio beams can be mathematically expressed in terms of \( l \)-order Bessel function at the frequency of operation with wavelength \( \lambda \) [5–7]. The radii of an \( l \)-mode OAM at the transmitter side is given by

\[
    r_i = \frac{X_l}{k \sin \theta},
\]

when \( X_l \) is the abscissa for the \( l \)-order Bessel function’s maximum value, \( k \) is the wave number, and is equal to \( 2\pi/\lambda \), while \( \theta \) is the beam divergence angle. OAM modes can be generated by a combination of a Rotman lens and a circular array, put together back-to-back like the one shown in Fig. 1 [3]. The signal transmitted via OAM modes can be written as

\[
    A_{ln}(d) = \frac{a^l N l^* e^{-jkd}}{d}
\]

where \( A_{ln}(d) \) is the signal propagation factor, \( N \) is the antenna element number, \( a^l \) is the OAM signal magnitude, \( i \) is the imaginary unit, and \( d \) is the wave path. General form of an
OAM beam generated by a planar circular array of the kind shown in Fig. 1(b) is given in [5] as

$$E_{in}(d, \theta_{in}, \phi, l_n) \approx A_{in} \cdot J_{l_n}(k R_n \sin \theta_{in}) e^{-j l_n \phi}$$  \hspace{1cm} (3)

where \( l_n \) is the mode number, \( n \) represents channels within a single OAM mode, \( \phi \) is the azimuthal angle when \( e^{-j l_n \phi} \) represents spiral phase along the angle \( \phi \) defining the periodic phase variation in OAM wavefront. \( J_l(.) \) represents the \( l \)-th order Bessel function. \( \theta_{in} \) is the beam divergence against \( l_n \)-th model.

Consider the same multimode circular array at the receiver end, it turns out to be a special case of multiple-input multiple-output (MIMO) system. When an OAM signal is received by multiple antenna elements, we will receive \( N \) signals, each corresponding to the \( n \)-th element of the array. The received signal at the Rotman lens’s output will be a merger of \( l \)-th OAM mode, which can be recovered by

$$R_{in} = \frac{1}{N} \sum_{n=1}^{N} r_n \alpha_n^* e^{j \Delta \theta_n} e^{j \phi(l_n, n)}$$ \hspace{1cm} (4)

where \( r_n \) is the \( n \)-th element received signal, \( \alpha_n^* \) is the amplitude compensation factor, \( \Delta \theta_n \) is the instantaneous phase difference on each antenna in the circular array as a result of phase spiral of the OAM wavefront, while the \( \phi(l_n, n) \) represents phase demultiplexing. Generally \( \Delta \theta_n \) can be calibrated at the receiver end by using a training sequence or a pilot signal. In our investigation, this compensation is physically handled in the Rotman lens body. Consider the case presented in Fig. 2 where an OAM wavefront against mode +1 hits the circular array, antenna element are excited in a circular sequential order. This means that each output of the antenna will have a linear phase ramp corresponding to the order of phase spiral of the received OAM signal.

To further elaborate this, let us compare the OAM mode 0 and +1 reception by the circular array. From the results shown in Fig. 3, it is evident that the magnitude of the received signal is substantially different between OAM modes 0 and +1. This is because the OAM mode +1 wavefront have a vortex along the circular array axis [3, 8]. If we compare the received signal phase at each array port of the Rotman lens for the two modes, we can observe two different phase ramps. These phase ramps makes an actual difference in the Rotman lens’s body where the received signal against OAM mode 0 diverges at the beam port 3 while the received signal against OAM mode +1 diverges at array port 2. This is evident from the field plots shown in Fig. 4.

Another note worthy observation is that when the transmitter and receiver circular arrays are not perfectly aligned, it becomes almost impossible to receive signal against OAM mode ±1 and ±2. To explain this further, let us now observe the phase result against the OAM mode +1 reception when the transmitter array is 15° misaligned (see phase plot in Fig. 3). The phase ramp in this case is identical to the phase ramp generated by the OAM mode 0 signal. This means that OAM mode +1 will not be able to converge at the beam port 2 as it should be, just because of a slight misalignment between the transmitter and the receiver. The bit error rate (BER) of the \( l \)-th OAM mode at the receiver from [9] can be found from

$$P_2^h = \frac{1}{N} \sum_{n=1}^{N} P_{k2}^h (\gamma_2^n),$$

and

$$P_{k2}^h (\gamma_2^n) \equiv \alpha Q \left( \sqrt{\beta \gamma_2^n} \right),$$

when \( \gamma_2^n \) is the signal-to-noise-ratio (SNR) while the \( \alpha \) and \( \beta \) depends upon the modulation scheme and approximations involved in the communication link. If the received signal strength at beam port 2 is extremely low as a result of misalignment, it will have a negative impact on \( P_{k2}^h \), eventually making it improbable to correctly decode the signal transmitted by OAM mode +1.

**III. CONCLUSION AND FUTURE DIRECTION**

In this study, we show that the simultaneous data stream can be transmitted and received using Rotman lens based multimode circular antenna array. A classical OAM radio enhances the system complexity due to communication overheads required to deal with \( \Delta \theta_n \) at the receiver end, we show...
a Rotman lens based circular array receiver is capable of reducing this complexity. As an added benefit, we can use the same array to develop physical layer secure communication link if the transmitter and the receiver circular arrays are perfectly aligned. The next stage of this investigation is to verify simultaneous data transmission over OAM mode 0, +1 and -1.

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