Dual Polarized UCA-based OAM Multi-mode Transmission with Inter-mode Spreading

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Abstract—This paper presents a multi-mode transmission technique that can increase the T-R distance of UCA OAM systems. The proposed technique uses dual polarized UCA antennas to increase the number of simultaneously transmittable modes at a specific T-R distance by exploiting the two basis of the polarized dipole antenna elements, and further extends the reaching distance of the multi-mode signals by using the inter-mode spreading between the OAM modes belonging to the same polarization domain. Simulation results show that the proposed scheme improves the T-R distances by at least 2 times as much as the conventional scheme in transmitting the same number of OAM modes with the same symbol error rate, and also that the proposed technique can transmit twice as many modes as the conventional method with the SNR loss of less than 3 dB at the same T-R distance.

I. INTRODUCTION

Orbital angular momentum (OAM) is one of the momentum of all electromagnetic waves together with linear momentum and spin angular momentum (SAM), which can be conserved up to a long distance by the momentum conservation law [1]-[3]. There are growing interests in this technology in the field of millimeter wave [4]-[6] as it was found that theoretically an infinite number of OAM modes can be transferred without interference even in line-of-sight (LoS) environments.

The first radio frequency OAM experiment was performed by the research staffs in Padova University in Italy [7] where two OAM modes generated by a spiral phase plate (SPP) antenna and a Yagi antenna were successfully received at the distance of 442 meters in 2.4 GHz band, and recently the uniform circular array (UCA) based OAM technique has also drawn attention as it was proved by a wireless simulation [2] and mathematical analysis [3] that the OAM signal with an arbitrary OAM mode can be generated by use of an UCA antenna.

The analytical study on the UCA OAM in [8], however, has shown that the OAM modes can be detected without significant error only at the distance of closer than the Rayleigh distance of a UCA antenna even though the UCA antenna can generate multiple OAM modes as much as the number of UCA antenna elements, and raised an important question on the feasibility of the UCA OAM technique for radio communications which requires transmit-receive (T-R) distance much longer than the Rayleigh distance. Hence, developing techniques to overcome this limitation of the UCA OAM is still remaining as an important problem.

In this paper, we present an OAM multi-mode transmission technique that can increase the T-R distance of UCA OAM systems. In this method, by transmitting $N_{\text{mod}}$ modes for each of two polarized UCAs, it reduces the interference between the modes transmitted through the UCAs with mutually different polarization characteristics, and by transmitting $N_{\text{mod}}/2$ modes of low orders of each polarized UCA, it extends the T-R distance where all OAM modes can be successfully decoded.

The remainder of this paper is organized as follows. Section II describes the system model used in the study. The proposed technique is presented in Section III. In Section IV, the advantages of the proposed technique is demonstrated through computer simulations. Finally, Section V contains the conclusion.

II. SYSTEM MODEL

The system model considered in this paper is as follows.

A. System Structure

Fig. 1 represents the system model of the dual polarized UCA OAM (DP-UCA OAM) system considered in this paper. The transmitter of the DP-UCA OAM system consists of OAM modulators and UCA antennas. The receiver consists of UCA antennas, OAM demodulators, and a symbol detector. In case of UCA antennas, there are two UCA antennas of vertically polarized (V-pol) UCA and horizontally polarized (H-pol) UCA at the transmitter side and two UCA antennas of V-pol UCA and H-pol UCA at the receiver side.

Through this system, $2N$ signals are transmitted from the transmitter and received through the channel and then decoded by the receiver. Among the $2N$ transmission signals, $N$ signals $\{s_1^v, s_2^v, \ldots, s_N^v\}$ are OAM-modulated by a V-OAM modulator and then transmitted through a V-pol UCA having a radius of $R_{TX}$ and composed of $M$ V-pol elements, and the remaining $N$ signals $\{s_1^h, s_2^h, \ldots, s_N^h\}$ are OAM-modulated by a H-OAM modulator and then transmitted through a H-pol UCA having the same radius of $R_{TX}$ and composed of $M$ H-pol elements. $M$ should not be smaller than $N$.

The signals received at the V-pol receive UCA and
the H-pol receive UCA are demodulated by the V-OAM demodulator and the H-OAM demodulator, respectively, and then detected by the symbol detector.

B. Channel Model

Define the LoS channel between the transmitting UCA and the receiving UCA with the same radiation pattern as \( H \in \mathbb{C}^{K \times M} \), and the \((k,m)\)-th element of \( H \) as \( h_{k,m} \). Here, \( K \) and \( M \) denote the elements of the receive UCA and the transmit UCA, respectively. Then, \( h_{k,m} \) which is the channel response between the the receive antenna element \( k \) and the transmit antenna element \( m \) can be represented by

\[
h_{k,m} = G_{k,m} \alpha_{k,m} \tag{1}
\]

where \( \alpha_{k,m} \) is the gain/phase displacement of the transmitted signal caused by the distance between the transmit UCA element \( m \) and the receive UCA element \( k \), denoted by \( d_{k,m} \) and \( G_{k,m} \) is the parameter that reflects the wave transfer characteristics experienced by the signal associated with the propagation path \( p(k,m) \) due to the radiation patterns of the transmit antenna \( m \) and the receive antenna \( k \) as well as the cross polarization characteristics of the propagation path itself. In a free space LoS environment, we have

\[
\alpha_{k,m} = \frac{\lambda}{4\pi d_{k,m}} \exp \left\{ -j \frac{2\pi d_{k,m}}{\lambda} \right\}.
\]

If we write \( G_{k,m} \) as a sum of the mean and deviation for all combinations of \((k,m)\) as \( G_{k,m} = \mu + \varepsilon_{k,m} \), (1) can be rewritten as

\[
h_{k,m} = \mu \alpha_{k,m} + \varepsilon_{k,m} \alpha_{k,m} \tag{2}
\]

and we get

\[
H = \mu A + D \tag{3}
\]

where \( D \) is the remainder defined by \( H - \mu A \). Since \( A \) is a circulant matrix and \( D \) can be decomposed as a sum of a circulant component \( (D_c) \) and a non-circulant component \( (E) \) as \( D = D_c + E \), (3) can be rewritten as a function of \( N \)-point DFT matrix \( Q \) and a diagonal matrix \( \Delta \) as

\[
H = Q_{RX} \Delta Q_{TX}^H + E. \tag{4}
\]

III. DUAL POLARIZATION UCA OAM TECHNIQUE

The details of the DP-UCA OAM technique are described as follows.

A. Signal Model

Define the transmitted signals from the V-pol UCA and the H-pol UCAs as \( x_v = [x_{v1}, x_{v2}, \ldots, x_{vM}]^T \) and \( x_h = [x_{h1}, x_{h2}, \ldots, x_{hM}]^T \), respectively, and the received signals at the V-pol receive UCA and H-pol receive UCA as \( y_v = [y_{v1}, y_{v2}, \ldots, y_{vK}]^T \) and \( y_h = [y_{h1}, y_{h2}, \ldots, y_{hK}]^T \), respectively. Then, the aggregated received signal vector can be written as

\[
y = Hx + n \tag{5}
\]

where \( y = [y_v^T, y_h^T]^T, x = [x_v^T, x_h^T]^T \), \( n = [n_v^T, n_h^T]^T \), and

\[
H = \begin{bmatrix} H_{v,v} & H_{v,h} \\ H_{h,v} & H_{h,h} \end{bmatrix}. \tag{6}
\]

In (6), \( H_{v,v}, H_{v,h}, H_{h,v} \), and \( H_{h,h} \) are \( K \times M \) matrices that represent the 4 subchannels between V/H-pol receive UCAs and V/H-pol transmit UCAs, in which the first superscript represents the polarization of the receive UCA and the second superscript represents that of the transmit UCA.

B. Transmission and reception

The method to transmit signals through dual polarized UCA channel \( H \) and to decode the transmitted symbols from the received signals is derived as follows.

The received signal in (5) can be decomposed as

\[
\begin{bmatrix} y_v \\ y_h \end{bmatrix} = \begin{bmatrix} H_{v,v} & 0 \\ 0 & H_{h,h} \end{bmatrix} \begin{bmatrix} x_v \\ x_h \end{bmatrix} + \begin{bmatrix} n_v \\ n_h \end{bmatrix} \tag{7}
\]

where the first term in the right hand side represents the received signal through the co-polarization channels, \( H_{v,v} \) and \( H_{h,h} \) and the second term represents the received signal through the cross-polarization channels, \( H_{v,h} \) and \( H_{h,v} \).

Since, from (4), we have

\[
H_{v,v} = Q_{RX}^\dagger \Delta_{v,v} Q_{TX}^H + E_{v,v} \tag{8}
\]

and

\[
H_{h,h} = Q_{RX}^\dagger \Delta_{h,h} Q_{TX}^H + E_{h,h}, \tag{9}
\]

the received signal in (7) can be rewritten as

\[
\begin{bmatrix} y_v \\ y_h \end{bmatrix} = \begin{bmatrix} Q_{RX}^\dagger \Delta_{v,v} Q_{TX}^H & 0 \\ 0 & Q_{RX}^\dagger \Delta_{h,h} Q_{TX}^H \end{bmatrix} \times \begin{bmatrix} x_v \\ x_h \end{bmatrix} + \begin{bmatrix} w_v \\ w_h \end{bmatrix} \tag{10}
\]

where

\[
w_v = n_v + E_{v,v} x_v + H_{v,h} x_h \tag{11}
\]

\[
w_h = n_h + E_{h,h} x_h + H_{h,v} x_v. \tag{12}
\]
Now, let the transmitted signal vector through the V-pol UCA and the H-pol UCA be written as

\[
\begin{bmatrix}
x_v \\
x_h \\
\end{bmatrix} = \begin{bmatrix}
Q^v_{TX}(S_v) & 0 \\
0 & Q^h_{TX}(S_h) \\
\end{bmatrix}
\begin{bmatrix}
s_v \\
s_h \\
\end{bmatrix}
\]

(13)

and let

\[
\begin{bmatrix}
z_v \\
z_h \\
\end{bmatrix} = \begin{bmatrix}
Q^v_{RX}H(S_v) & 0 \\
0 & Q^h_{RX}H(S_h) \\
\end{bmatrix}
\begin{bmatrix}
y_v \\
y_h \\
\end{bmatrix}
\]

(14)

where \(S_v\) and \(S_h\) are the sets of column indices of \(Q^v_{TX}\) and \(Q^h_{TX}\) to be used for signal transmissions at the V-pol UCA and H-pol transmit UCA, respectively, and \(Q(S)\) is the submatrix of \(Q\) consisting of the column set \(S\). Then, using (10) and (13) in (14), we get

\[
\begin{bmatrix}
z_v \\
z_h \\
\end{bmatrix} = \begin{bmatrix}
\Delta^v_{mod} & 0 \\
0 & \Delta^h_{mod} \\
\end{bmatrix}
\begin{bmatrix}
s_v \\
s_h \\
\end{bmatrix} + \begin{bmatrix}
Q^v_{RX}H(S_v)w_v \\
Q^h_{RX}H(S_h)w_h \\
\end{bmatrix}
\]

(15)

where

\[
\Delta^v_{mod} = Q^v_{RX}H(S_v)Q^v_{RX}\Delta^v_{v, v}Q^v_{TX}H(S_v)
\]

and

\[
\Delta^h_{mod} = Q^h_{RX}H(S_h)Q^h_{RX}\Delta^h_{h, h}Q^h_{TX}H(S_h)
\]

are the submatrices of \(\Delta^v_{v, v}\) and \(\Delta^h_{h, h}\) composed of the rows and columns of \(\Delta^v_{v, v}\) and \(\Delta^h_{h, h}\) corresponding to \(S_v\) and \(S_h\), respectively.

Consequently, when the power of cross-polarization channels \(H_{v, h}\) and \(H_{h, v}\) plus the power by the non-uniform antenna radiation patterns are negligible, \(w_v\) and \(w_h\) in (11) and (12) become equal to \(n_v\) and \(n_h\) respectively, and hence (15) indicates that \(|S_v| + |S_h|\) parallel independent channels can be constructed by the use of the DFT precoders at the transmitter, \(Q^v_{TX}(S_v)\) and \(Q^h_{TX}(S_h)\) and the inverse DFT processors at the receiver, \(Q^v_{RX}H(S_v)\) and \(Q^h_{RX}H(S_h)\) without the need for channel information feedback and inter-channel interference cancellation.

The detection rule for this DP-UCA OAM system can be derived as follows. Define \(F\) and \(W\) as

\[
F = \begin{bmatrix}
Q^v_{TX}(S_v) & 0 \\
0 & Q^h_{TX}(S_h) \\
\end{bmatrix}
\]

(16)

\[
W = \begin{bmatrix}
Q^v_{RX}(S_v) & 0 \\
0 & Q^h_{RX}(S_h) \\
\end{bmatrix}
\]

(17)

Then, using (13) in (5), we get

\[
y = HFs + n
\]

which can be used in (14) to get

\[
z = WHF + WHn.
\]

Accordingly, the transmitter and receiver structure for the DP-UCA OAM can be expressed as shown in Fig. 2, and thus, the least squares detector for the transmitted symbols through V-pol and H-pol UCAs can be expressed by

\[
\hat{s} = \arg\min_{\hat{s}} \|z - WHF\hat{s}\|^2
\]

(18)

which reduces to

\[
\hat{s}_v = \arg\min_{\hat{s}_v} \|z_v - \Delta^v_{mod}s_v\|^2
\]

(19)

\[
\hat{s}_h = \arg\min_{\hat{s}_h} \|z_h - \Delta^h_{mod}s_h\|^2
\]

(20)

when the power of cross-polarization channels \(H_{v, h}\) and \(H_{h, v}\) plus the power by the non-uniform antenna radiation patterns are sufficiently small.

C. Inter-mode spreading (IMS)

Since, in the detection rule of (19), the elements of the diagonal matrix \(\Delta_{mod}\) generally have different values, the detection error performance of the elements of \(s_v\) becomes also different for each element; the same is true for the signal transmitted via the H-pol UCA. Like this, having different error performance for each symbol worsens the aggregate error performance of the entire symbols.

In order to improve this problem, we propose the system structure as shown in Fig. 3 which is based on inter-mode spreading. In the figure, \(P_v\) and \(P_h\) are the \(m\)-by-\(m\) unitary matrices in which all elements have non-zero values like the DFT matrix, and \(m\) is the number of elements of \(s_v\) and \(s_h\). In this scheme, the two spreading matrices, \(P_v\) and \(P_h\), are used to ensure that \(N_{mod}\) symbols transmitted via V-pol UCA share the same channel and the same is true for the \(N_{mod}\) symbols transmitted via H-pol UCA. In this case, (13) is changed to

\[
\begin{bmatrix}
x_v \\
x_h \\
\end{bmatrix} = \begin{bmatrix}
Q^v_{TX}(S_v) & 0 \\
0 & Q^h_{TX}(S_h) \\
\end{bmatrix}
\begin{bmatrix}
P_v & 0 \\
0 & P_h \\
\end{bmatrix}
\begin{bmatrix}
s_v \\
s_h \\
\end{bmatrix}
\]

(21)

and the least squares detector for the transmitted symbols is expressed by

\[
\hat{s} = \arg\min_{\hat{s}} \|z - WHF\hat{s}\|^2
\]

(22)
Fig. 4. Spectral efficiency vs. T-R distance. Rayleigh distance ($d_R$) is 1,800 m.

where

$$P = \begin{bmatrix} P_v & 0 \\ 0 & P_h \end{bmatrix},$$  \hspace{1cm} (23)$$

IV. SIMULATION RESULTS

In this section, the validity of the proposed dual polarized UCA OAM technique is analyzed through computer simulation.

A. System Parameters

For the simulation, half-wavelength dipole UCA antennas with the carrier frequency of 5 GHz were used. The mathematical expressions for the V-pol and H-pol radiation patterns of the half-wavelength dipole antenna are expressed as

$$B^v(\theta, \phi) = c (\cos \theta \cos \phi \sin \alpha - \sin \theta \cos \alpha) \frac{\cos \frac{\phi}{M}}{1 - \cos \phi},$$

$$B^h(\theta, \phi) = c \sin \phi \sin \alpha \frac{\cos \frac{\phi}{M}}{1 - \cos \phi},$$

where $\zeta = \sin \theta \cos \phi \sin \alpha + \cos \theta \cos \alpha$, $c$ is a proportional constant, $\alpha$ denotes the slant from the z-axis in the vertical z-x plane [10]. All transmit and receive UCAs that have been used for the simulation have the same number of V-pol and H-pol antenna elements which is 8, and their radii were 30 $\lambda$. In order to investigate the interference effect between different polarization domains, dipole elements with the slant of 0° and 90° were used for V-pol and H-pol antennas, respectively, though it is more desirable to use slot antennas for the generation of cross-polarized radiation patterns orthogonal to dipole antennas.

B. Performance of DP-UCA OAM without inter-mode spreading

Fig. 4 shows the achievable spectral efficiency with the T-R distance that can be obtained under the condition of SNR = 20 dB at the T-R distance of 500 m. In the figure, the spectral efficiency of the UCA OAM system has its maximum at the Rayleigh distance $d_R$, and we can see that it decreases monotonically with the T-R distance increasing over the Rayleigh distance. On the other hand, the spectral efficiency of DP-UCA OAM has the maximum value at the T-R distance of $2d_R$ and decreases by about 11.7 bps/Hz when the T-R distance changes from $2d_R$ to $10d_R$. It is relatively low rate of decrease by less than 0.55 times compared to the case of conventional UCA OAM in which the spectral efficiency decreases by 21.2 bps/Hz under the same condition. This means that the DP-UCA OAM scheme improves the effective T-R distance by more than 2 times compared to the conventional UCA OAM scheme.

Fig. 5 is the plot of the change in symbol error rate (SER) depending on the SNR. In the figure, it is observed that the single-polarized UCA OAM scheme exhibits an error floor with the SNR, while the DP-UCA OAM shows a tendency of 1/100-fold decrease in SER when the SNR increases by 10 dB.

C. Impact of inter-mode spreading

Fig. 6 shows the impact of the inter-mode spreading OAM technique that allows a set of OAM modes to experience the same channel. In this figure, it can be seen that the SNR gain over 1 dB can be obtained through the inter-mode spreading OAM technique in the high SNR region.

Fig. 7 is the simulation results for the change of SER with the SNR when transmitting three modes in case of UCA OAM and 6 modes in case of DP-UCA OAM. In the figure, it is observed that the additional SNR required for the DP-UCA OAM to transmit and receive six OAM modes at the distance of 500 m is only about 3 dB compared to the single polarized UCA OAM scheme to transmit 3 modes at the same T-R distance.

For $M = 8$, the Rayleigh distance is expressed as $d_R = (2R_{TX})^2/(2\lambda)$ [8].
V. CONCLUSION

In this paper, we have presented a method that can increase the T-R distance of UCA OAM systems by exploiting the two basis of the polarized dipole antenna elements, and verified the advantages of the proposed technique over the conventional UCA OAM scheme through computer simulation where the theoretical radiation patterns of the half-wavelength dipole antennas are applied and then by comparing a set of performance measures with the SNR and T-R distance. Computer simulation results show that the proposed dual polarized UCA OAM scheme improves the T-R distances by at least 2 times as much as the conventional scheme in transmitting the same number of OAM modes with the same symbol error rate, and also that the proposed technique can transmit twice as many modes as the conventional method with the SNR loss of less than 3 dB at the same T-R distance. Further research works include the determination of optimal UCA radius and transmit power control for UCA OAM mode signals.

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