Prototyping of 40 GHz Band Orbital Angular Momentum Multiplexing System and Evaluation of Field Wireless Transmission Experiments

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ABSTRACT
We are developing a spatial multiplexing technique based on orbital angular momentum (OAM) that is capable of 1 Tbit/s point-to-point wireless transmissions for the sixth generation mobile communication system. In this paper, we describe a demonstration of 100 Gbit/s wireless transmission over a range of 100 m that used OAM multiplexing of 15 streams with a 1.5 GHz bandwidth (39.5–41 GHz). The OAM modes of this system were generated using a Butler matrix that allows discrete Fourier transform (DFT) operations to be performed in analog circuits. We designed $8 \times 8$ Butler matrices to generate OAM modes by combining hybrid couplers and phase shifters. Since this Butler matrix was connected to 16 element antennas, two $8 \times 8$ Butler matrices were connected to make an $8 \times 16$ matrix. Furthermore, since these inputs were in 7 OAM mode, one port was terminated to create a $7 \times 16$ Butler matrix. It was confirmed that the mode isolation was more than 15 dB in the 1.5 GHz bandwidth. Next, we designed microstrip antennas for a horizontal and vertical polarization uniform circular array (UCA) to radiate the OAM modes. Then, we implemented radio frequency (RF) chains and digital signal processing, including single carrier-frequency domain equalization and adaptive modulation and coding. A transmission experiment conducted in a field line-of-sight environment showed that the system could transmit at 119.45 Gbit/s at a distance of 100 meters, thereby demonstrating the feasibility of wideband OAM transmission in the millimeter-wave band.

INDEX TERMS
Butler matrix, microstrip antenna, OAM multiplexing, orbital angular momentum (OAM), uniform circular array (UCA), 40 GHz.

I. INTRODUCTION
Wireless traffic continues to grow due to the spread of a wide variety of devices connected to wireless networks and the increasing amount of content transmitted over them. In order to accommodate the increase in wireless traffic, it is necessary to use more frequency bands and achieve higher spectral efficiency. The fifth generation (5G) mobile communication system has significantly increased the available bandwidth compared with the fourth generation (4G) by utilizing millimeter-wave (mmWave) bands with hundreds of MHz of bandwidth [1]. The sixth generation (6G) is expected in the 2030s and it will use even higher frequencies, including terahertz (THz) bands [2]. Mobile backhaul and fronthaul are also expected to increase in capacity through the use of wireless transmission, with capacities of around 1 Tbit/s. In this context, a number of demonstrations of high-capacity transmissions have been conducted: their reports are summarized in Fig. 1 [3], [14]. As shown in the figure, an experiment on 32 GHz transmission using the D band achieved a 1 Tbit/s wireless transmission over a distance of 3.1 m [3]. A 124.8 Gbit/s transmission over a distance of 104 m was also reported [4]. That experiment used the 339 GHz band and probabilistic-shaping 256QAM. In the mmWave band, long-distance and high-capacity transmissions on the order of hundreds of meters to kilometers have been reported.
including a 139 Gbit/s transmission over a distance of 1.5 km in the 73 GHz band [5]. As well, spatial multiplexing using multiple-input multiple-output (MIMO) has been tried as a way to increase the transmission capacity [15]. In particular, although MIMO with digital equalization is widely used [16], the computation size increases as the bandwidth and the number of multiplexes increase. Here, analog beamforming using analog circuits such as phase shifters and hybrid beamforming combining analog and digital circuits are promising ways of dealing with this problem. Especially in point-to-point (P2P) wireless communications, eigenmode transmission with fixed transmit/receive weights is possible using analog circuits, because the antenna layout and transmission paths are stable. This reduces the amount of digital signal processing. Uniform circular array (UCA) based orbital angular momentum (OAM) multiplexing transmission is a wireless transmission technology that has this advantage and it may be useful for P2P wireless transmissions.

OAM multiplexing is a type of spatial multiplexing that utilizes the twisting of electromagnetic (EM) waves: the wavefront phase of an EM wave with an OAM mode varies from 0 to $2\pi l$ ($l = 0, \pm 1, \pm 2, \pm 3, \ldots$). This phase rotation is called the “OAM mode”. OAM modes of integer order are spatially orthogonal, which allows multiplexing of different OAM modes. Several studies have been reported on OAM multiplexing for high-capacity wireless and free-space optical data transmission [17], [18], [19], [20], [21], [22], [23], [24]. The most basic way of generating OAM modes is using spiral phase plates (SPPs) that apply a spatial phase gradient to plane waves to generate OAM beams. OAM modes can be also generated by using metasurfaces to give a phase rotation [25]. Another way to generate OAM modes is to use a UCA [15]. Here, a distribution of OAM modes is created by radiating EM waves with different phases from each antenna element. Furthermore, by providing the antenna elements with radio frequency (RF) signals synthesized from multiple OAM modes, multiplexed OAM modes can be radiated from a single UCA.

Our development targets 1 Tbit/s P2P wireless transmissions with OAM multiplexing for 6G. So far, we have demonstrated OAM-MIMO multiplexing with four UCAs in the 28 GHz band, achieving a 200 Gbit/s transmission over a distance of 10 m [14]. This showed the applicability of OAM multiplexing for high-capacity transmissions. The study reported here is the next step, i.e., to confirm the feasibility of OAM multiplexing in a field environment. A 100 Gbit/s transmission over 100 m using OAM multiplexing in the 40 GHz band was conducted. To achieve this, we designed and fabricated a Butler matrix to generate and multiplex the OAM modes and a microstrip antenna for the UCA. We designed a transmitter and receiver for 40 GHz OAM multiplexing that included these components. We also implemented digital signal processing for 15 multiplexed streams and conducted simulations and transmission experiments in a field environment.

Section II describes the background and unique propagation characteristics of OAM multiplexing using a UCA. Section III describes the design, fabrication, and evaluation of the Butler matrix for generating and separating multiple OAM modes in the 40 GHz band. Section III also describes the design and fabrication of a microstrip antenna for the UCA and an evaluation of its gain. Furthermore, it describes a 40 GHz RF chain capable of a 100 m transmission, integration of the Butler matrix and antenna elements, and a prototype capable of 40 GHz OAM transmissions. The baseband signal processing is also described. Section IV reports the results of an implementation of an end-to-end wireless OAM transmission system, including the simulated data rates at the designed OAM multiplex transmitter and receiver and outdoor wireless data transmission experiments. Section V presents conclusions.

II. OAM MULTIPLEXING USING UNIFORM CIRCULAR ARRAY

The OAM beam-generation method using a UCA applies a constant phase gradient $\varphi = 2\pi nl/n$ ($l$ is the OAM mode, and $n$ is the number of antenna elements) to the antenna elements. Here, a simple approach is to use a phase shifter on each antenna element of the UCA. In this case, the number of phase shifters required is equal to the product of the mode and the number of antenna elements, which increases the circuit size. A more effective method to generate multiple OAM modes from a single UCA is to use a Butler matrix, which is an analog circuit that performs discrete Fourier transform (DFT) processing. When the Butler matrix $T_x$ UCA and $R_x$ UCA are coaxially located along the direction of propagation and the number of antennas is the same on both sides, the channel matrix $H$ is the following circulant matrix [26].

$$H = V_n \Sigma V_n^H,$$  \hfill (1)  

$$\Sigma = \begin{bmatrix} \Lambda_{l(1)} & & & O \\ & \Lambda_{l(2)} & & \\ & & \ddots & \\ O & & & \Lambda_{l(n)} \end{bmatrix}$$  \hfill (2)
where $N$, $L$, $d$, and $R$ denote the diameter of the antenna, the Rayleigh distance, that is, in the near field, each mode shows a characteristic large power attenuation at a specific distance. Beyond the Rayleigh distance, that is, in the far field, the power shows a constant attenuation characteristic for each mode. This attenuation is due to the beam divergence inherent in the OAM, which is proportional to the $(l+2)$ th power and increases as the mode increases. Therefore, to use the OAM as a P2P system, it is necessary to determine the appropriate antenna size according to the transmission distance and frequency to be used.

### III. RF DESIGN AND PROTOTYPING OF OAM MULTIPLEXING EQUIPMENT FOR 40 GHz BAND

#### A. BUTLER MATRIX

We designed $8 \times 8$ Butler matrices at 39.5–41 GHz that generate seven OAM modes ($-3$, $-2$, $-1$, $0$, $1$, $2$, and $3$) and perform the separation process, i.e., the DFT and inverse-DFT (IDFT) calculations. Since OAM modes are generated without digital processing, it is necessary for the Butler matrix to ensure high mode isolation to increase transmission capacity. A mode isolation of 15 dB or better would allow 4.5 bits/Hz/stream using channel coding. Our design uses 15 streams and a 1.5 GHz bandwidth to achieve 100 Gbit/s transmissions. In designing the Butler matrix, it is important to reduce the losses in the circuit. An $8 \times 8$ Butler matrix on one plane requires cross couplings at 18 intersections, as shown in Fig. 2. This cross-coupler degrades the phase and amplitude characteristics. To solve this problem, the Butler matrix is divided into two blocks and placed in two separate layers. This makes it possible to build a Butler matrix that does not require cross-couplers. As shown in Fig. 4,
the two layers are connected by through holes across the ground (GND) layer. Furthermore, we concatenated two $8 \times 8$ Butler matrices so that the output would have 16 ports, since the UCA has 16 antenna elements to obtain the array gain. As shown in Fig. 5, by shifting the phase of the input port of one of the Butler matrices, an $8 \times 16$ Butler matrix with 8 input ports and 16 output ports is realized. By terminating mode 4, which was not used, we finally obtained a $7 \times 16$ configuration. This simplifies the circuit configuration compared with a $16 \times 16$ Butler matrix.

Next, we designed and manufactured an $8 \times 8$ Butler matrix consisting of two layers on a transmission line. Fig. 6 shows the fabricated $8 \times 8$ Butler matrix. Its size is $45 \text{mm} \times 45 \text{mm}$. On each side, two ports are placed for easy connection to the UCA. We evaluated the mode isolation of a $7 \times 16$ Butler matrix composed of two of these $8 \times 8$ Butler matrices connected and terminated with the unused mode 4. The mode isolation was defined as the ratio of interference power to the desired mode power. The mode isolation characteristics are shown in Fig. 7. In the target band of 39.5 to 41 GHz, mode isolation better than 15 dB was obtained for all modes used.

This means that a transmission capacity of 100 Gbit/s can be achieved by using 15 streams with a bandwidth of 1.5 GHz.

**B. ANTENNA DESIGN**

We have designed a high-gain microstrip antenna element for UCA that can radiate both horizontal and vertical polarization in the 39.5 to 41 GHz band. Moreover, high-gain microstrip antennas for array antennas in the mmWave band exceeding 20 dBi have been reported [28]. In this study, we designed an antenna element that obtains a gain of 25 dBi. The size of the antenna element is $67 \text{mm} \times 67 \text{mm}$, which is large enough to place 32 elements ($16 \text{ elements} \times 2 \text{ polarizations}$) in a 120 cm diameter UCA. In addition, one element is placed at the center of the UCA to transmit mode 0, for a total of 33 elements.

First, we calculated the directivity gain in the horizontal (H) and vertical (V) planes of the antenna elements by using an EM wave simulator. The radiation patterns, i.e., the front directional directivity in the vertical and horizontal planes, are shown in Fig. 8. The red line shows the co-polarization and the blue line shows the cross-polarization. More than 30 dB of cross-polarization discrimination was obtained. Since this value is below the noise floor of the receiver used in the...
We fabricated microstrip antenna elements for the experiment and measured the gain in the frontal direction. The fabricated antenna element is shown in Fig. 9. Power was supplied from the center of the antenna element, and subminiature push-on mini (SMPM) connectors were used. Each antenna consisted of 16 elements for each polarization; thus, each antenna had 33 elements, including the single center element. Therefore, the total number of elements in the transmitter and receiver was 66. As shown in Table 1, the average gain of the antenna elements at 39.5, 40.25, and 41 GHz was 25.5 dB, 25.4 dB, and 25.6 dB, respectively. A flat gain was obtained for the frequency response in the 39.5−41 GHz band. We designed the transmitter and receiver RF chain for OAM multiplexing on the basis of the obtained antenna gain of 25 dBi.

### TABLE 1. Average antenna gain of 66 elements at the frequency of 39.5, 40.25, and 41 GHz.

| Frequency (GHz) | Average Gain (dBi) |
|----------------|--------------------|
| 39.5           | 25.5               |
| 40.25          | 25.4               |
| 41             | 25.6               |

In this section, we describe the prototype and baseband signal processing of the 40 GHz OAM multiplex transmitter (Tx) and receiver (Rx). The gain was designed such that the OAM mode could be transmitted over 100 m with a 25 dBi antenna. The 15-stream transmit signal was generated by an arbitrary waveform generator (AWG) and input at –3 dBm as a baseband IQ signal. The 1.5 GHz input signal was mixed with a bandpass filter at the IQ modulator and passed through a power amplifier. The amplified RF signal was radiated from the antenna with a power of +9 dBm. The received RF signal from the antenna element was gain-adjusted with a low noise amplifier (LNA) and then separated into individual mode signals with the Butler matrix. The gain was adjusted again with the driver amplifier and variable attenuator, and down-converted to signals in the 6.25 GHz to 7.75 GHz IF band with a mixer. The received signals were stored in a digital serial analyzer (DSA). The UCA was arranged in concentric circles with a diameter of 120 cm, with 16 antenna elements alternating between horizontal and vertical polarization. The polarization plane could be changed by rotating the antenna elements 90 degrees. A photograph and block diagram of the prototype are shown in Fig. 9 and 10.

Next, we implemented the baseband signal processing and experimented with the transceiver prototype. Low density parity check (LDPC) code and Bose-Chaudhuri-Hocquenghem (BCH) code were used for forward error correction (FEC). We used adaptive modulation and coding (AMC) to select the appropriate modulation and coding rates according to the received SNR. The channel was equalized by minimum mean square error (MMSE) based algorithm in...
The system specifications are summarized in Table 2.

### IV. DATA-RATE SIMULATION AND OUTDOOR TRANSMISSION EXPERIMENT

We conducted simulation and transmission experiments and performed an experimental evaluation and a theoretical analysis. The simulation was a data-rate simulation based on the prototype’s design and the outdoor transmission experiment using the fabricated devices covered a transmission distance of 100 m.

The data-rate simulation involved calculating a $7 \times 16$ OAM channel matrix based on (1) and (2) and the transmit power, antenna gain, noise figure, modulation rate, and coding rate shown in Table 2. The AMC was calculated with a 1 dB margin for SNR to account for estimation error in practical environments. The blue line in Fig. 11 shows the simulation results. Simulations were performed for distances up to 1000 m. The stair-case shape of the data rate is due to the quantization of the transmission capacity threshold by the AMC. BPSK modulation and a coding ratio of 1/2 are the minimum modulation rates in the AMC implementation. The SNR limit for error-free transmission at this modulation and coding rate is –4.7 dB. Under these conditions, mode $\pm 3$ can transmit up to 313 m and mode $\pm 2$ up to 583 m. Mode 0 and mode $\pm 1$ can transmit over 1000 m.

The outdoor wireless transmission experiment was conducted using the fabricated OAM Tx and Rx in a line-of-sight environment at 100 m, as shown in Fig. 12. The experimental parameters were the same as in the simulation (Table 2). Misalignment of the transmitter and receiver antennas affects the transmission capacity, so the antennas must be aligned correctly. We performed an alignment by placing the frequency domain. The signals were demodulated with offline signal processing. These offline digital-signal processings in the Tx and Rx were performed using MATLAB. The transmission capacity was evaluated in the error-free case. The system specifications are summarized in Table 2.

### TABLE 2. System specifications of OAM transmission simulation and experiment parameters.

| Parameters             | Values               | Parameters             | Values               |
|------------------------|----------------------|------------------------|----------------------|
| OAM modes              | $-3, -2, -1, 0, 1, 2, 3$ | Frequency             | 39.5–41 GHz          |
| Polarization           | V/H                  | Baud rate              | 1.5 Gbaud            |
| Diameter of UCA        | 120 cm               | FFT size / CP size     | 1024 / 16 symbols    |
| Num. of antennas       | 16 elements/pol. & center | FEC (Outer/Inner)    | BCH/LDPC             |
| Antenna gain           | 25 dBn/element       | Equalization           | SC-FDE/MMSE          |
| Output power           | 3 dBm                | Modulation (prepared)  | BPSK–1024QAM         |
| Noise figure           | 14.4 dB              | Coding rate (prepared) | 1/2, 3/5, 2/3, 3/4, 4/5, 5/6, 8/9, 9/10 |
targeting lasers at the four corners of the transmitter and receiver and adjusting the horizontal and elevation angles, as shown in Fig. 13. Error-free transmissions at 119.45 Gbit/s were achieved using channel coding. The total number of streams was 15, and each stream was transmitted at 64QAM, and the corresponding transmission rates were from 6.0 to 9.6 Gbit/s. The bandwidth was 1.5 GHz, resulting in a spectral efficiency of 79.6 bit/s/Hz. The transmission rates of the field experiment are compared with the simulation in Fig. 11. The results are close to those of the simulation, confirming that the prototype performed as designed.

V. CONCLUSION

Our goal is to develop a means of P2P high-capacity wireless transmission for the 6G era. In this study, we showed the feasibility of 100 Gbit/s transmissions with OAM multiplexing at a distance of 100 m in a field environment. We designed and fabricated the Tx and Rx for operation in the 40 GHz band with seven OAM modes, two polarizations, and a center antenna to transmit 15 streams. We determined the antenna size to be 120 cm in diameter from the link budget for each mode and designed Butler matrices and microstrip antennas. In OAM multiplexing with a UCA using a Butler matrix, by placing the transmitter and receiver on opposite sides of the central axis, the channel matrix becomes a circular one by the use of analog circuits. This property can be used to reduce the number of RF chains from the number of antenna elements normally required to transmit the number of modes. We fabricated a 7 × 16 Butler matrix using two 8 × 8 Butler matrices that could multiplex seven OAM modes (−3, −2, −1, 0, 1, 2, 3) from a 16-element UCA. Transmissions were evaluated with mode separation, which represents orthogonality between OAM modes, and the results showed that more than 15 dB of isolation was obtained for each mode in the 39.5−41 GHz band. The fabricated a microstrip antenna element for the UCA had an antenna gain of 25 dBi. Finally, we designed a 40 GHz RF chain and it integrated with the Butler matrix and antenna elements to make a prototype OAM-multiplexed Tx and Rx. The Tx and Rx were capable of transmitting 15 streams, with the center antenna transmitting vertical polarized OAM mode 0, and UCAs with alternating horizontal and vertical polarization antenna elements multiplexing and transmitting 7 OAM modes each. Transmission experiments on these devices and the implemented baseband signal processing were conducted in an outdoor environment. A transmission capacity of 119.45 Gbit/s was achieved at 100 m. This result demonstrates the practicality of wireless transmissions exceeding 100 Gbit/s by using OAM multiplexing in an outdoor environment.

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