OAM Mode-Multiplexing Transmission System for High-Efficiency and High-Capacity Wireless Transmission

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Abstract

Microwave and millimeter-wave communication systems are used for mobile backhaul applications all over the world. The Beyond 5G and 6G applications, however, require a higher capacity of 50 Gbps or more, and this is difficult to achieve with conventional systems. This paper introduces the principles, features, challenges, and implementation methods of NEC's OAM mode-multiplexing transmission system, which is a communication method suitable for high-frequency bands capable of increasing efficiency and capacity and for utilizing wider bandwidths. In a real-time transmission experiment conducted in the sub-terahertz band to demonstrate the feasibility of this technology, NEC succeeded in the transmission of 256QAM/16 multiplexing (14.7 Gbps) over 100m by combining it with polarization multiplexing. Now we aim to increase this to 100 Gbps for commercial release of this technology.

Keywords

OAM, orbital angular momentum, UCA, spatial multiplexing transmission, frequency utilization efficiency, millimeter wave, sub-terahertz wave

1. Introduction

Microwave and millimeter-wave wireless communication systems are playing a significant role in building the world's mobile backhaul (MBH) networks, and NEC delivers these systems to telecommunications service providers worldwide under the brand name of PASOLINK.

Applications for Beyond 5G and 6G are currently under development around the world for MBH, and they require a high-capacity transmission that exceeds 50 Gbps. This is difficult to achieve using conventional wireless communication systems.

In this paper, we take a look at orbital angular momentum (OAM) mode-multiplexing radio transmission, which is one of the spatial multiplexing transmission techniques that can meet the demand for high-capacity transmission.

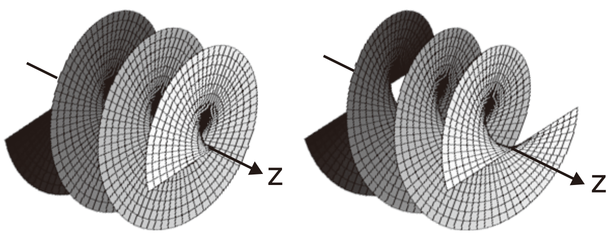
2. OAM Mode-Multiplex Radio Transmission

2.1 Principles and characteristics

OAM stands for orbital angular momentum, which is one of the physical quantities associated with electromagnetic waves. The number of OAM modes that are mutually orthogonal is infinite. If OAM can be utilized for multiplexing to transmit multiple independent signals at the same frequency, it can achieve both high-frequency utilization efficiency and high-capacity transmissions.

An OAM signal is represented by a mathematical expression in a cylindrical coordinate system using the Laguerre polynomial[1]. The topological charge ℓ (where ℓ is an integer) in the mathematical expression is represented as a mode.

There is an infinite number of modes, $\ell = 0, \pm 1, \pm 2,$



(a) mode 1 (b) mode 2

Fig. 1 Shapes of iso-phase front.

±3, and so on, which are mutually orthogonal. The ℓ = 0 mode represents a plane wave (Gaussian beam), which is used in conventional wireless communications. For modes other than ℓ = 0, the iso-phase front combines with an ℓ quantity of spiral surfaces (with a mutual phase difference of 2π/ ℓ rad), as shown in **Fig. 1**. The sign of the mode corresponds to the direction of rotation of the spiral (the Z-axis represents the direction of beam propagation). The iso-phase front is a characteristic of the OAM signal. The iso-phase front of a plane wave is a plane that appears at wavelength intervals.

Due to the orthogonality of OAM modes, the signal transmitted with mode + ℓ will have zero energy for receivers other than those with mode + ℓ when multiple modes are multiplexed and transmitted. In other words, it is theoretically possible to achieve infinite multiplexing because only the desired mode can be received without interference between modes.

Specifically, OAM mode-multiplexing signals are generated by modulating the sinusoidal wave of each OAM mode with the same frequency as the carrier, and this generates the modulated wave of each mode. By adding these modulated waves together, an OAM mode multiplexing signal is generated.

2.2 Challenges and countermeasures

On the other hand, there are fundamental challenges with OAM. When calculated using the aforementioned expression, the power density distributions of OAM signals at certain distances can be plotted in the form of rings, as shown in **Fig. 2**. This is because the phase rotates by an integer multiple of 2π radians on the beam axis in all modes other than mode 0, so the signals cancel each other out and the power becomes 0. The higher the order of the mode, the larger the radius of the rings where the power is maximized. The rings expand with the propagation distances as shown in **Fig. 3**. In other words, OAM signals have the tendency to spread as they propagate[2)].

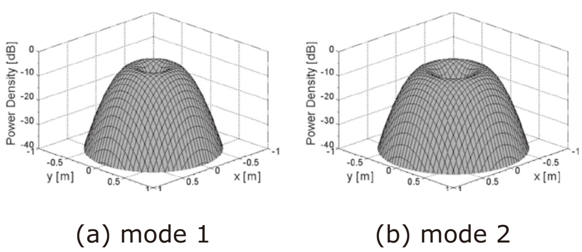


Fig. 2 Power density distribution.

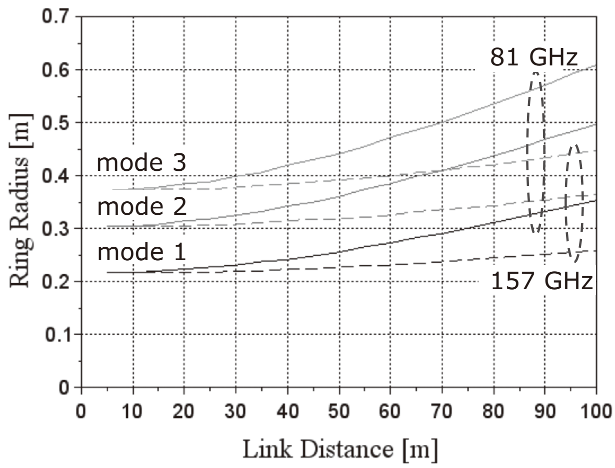


Fig. 3 Link distance versus ring radius.

The expansion of the ring radius resulting from this propagation is greater with higher order modes. When receiving transmissions with an antenna of the same diameter designed for bi-directional symmetrical communication, the higher the order of the mode is, the lower the reception level becomes as the propagation distance increases, thus making it impossible to achieve infinite multiplexing. Even when restricted to the use of lower order modes, the transmission distance is limited compared to communication using Gaussian beams. This is an issue when OAM signals are applied to wireless communications. As shown in Fig. 3, the expansion rate of the ring radius decreases with an increasing radio frequency (RF). Therefore, the use of higher frequency bands such as millimeter waves and sub-terahertz waves above 100 GHz is effective in expanding the transmission distance of OAM signals. The ability to use a wide bandwidth in such high-frequency bands is also advantageous for increasing the capacity of communication systems.

Another practical issue is that a slight misalignment between the beam axes of the transmitting and receiving antennas can result in inter-mode interference, and this results in degradation of the characteristics. Countermeasures against this are discussed in section 3.2.

2.3 Combination of polarization multiplexing and OAM mode multiplexing

OAM and polarization are independent of each other and can be used in combination with polarization multiplexing as in conventional systems. As a multiplexing technique, polarization multiplexing requires only a single pair of antennas so it is more economical than OAM mode-multiplexing. For this reason, OAM is used when it is necessary to increase the capacity beyond what polarization multiplexing can achieve. Combining N-mode multiplexing and polarization multiplexing can increase the capacity by 2N times, making it possible to achieve high-efficiency and high-capacity wireless communication.

3. Implementation Method

3.1 Antenna and phase shifting method

The configuration of the RF-independent digital signal processing (DSP) combined with a uniform circular array (UCA) antenna is explained in this section.

Because the power is concentrated in a ring shape, OAM can be approximated by using a UCA with elements arranged in a circle, and N elements can handle N modes.

The relationship between modes and elements in terms of OAM amplitude and phase can be expressed by discrete Fourier transform (DFT). So, assuming an N-element UCA is used, the DFT should be performed in the DSP. On the contrary, it needs to perform inverse discrete Fourier transform (IDFT) processing in DSP on the receiving side. The overall configuration is as shown in **Fig. 4**. Because the communication channel is orthogonalized by DFT/IDFT, it is possible to separate multiplexed signals regardless of the link distance.

A multiplex communication system that uses multiple antenna elements for transmission and reception to form multiple paths is called a spatial multiplex transmission system. OAM based on this configuration is also one such spatial multiplexing transmission method.

3.2 Adaptive control of signal processing on the receiving side

In practice, due to imperfections in the channel, including the equipment and axial misalignment, the orthogonalization of the communication path is not established with fixed coefficients, and the resulting inter-mode interference causes significant degradation of the performance. To compensate for this degradation, adaptive control of at least the signal processing on the receiver side is mandatory.

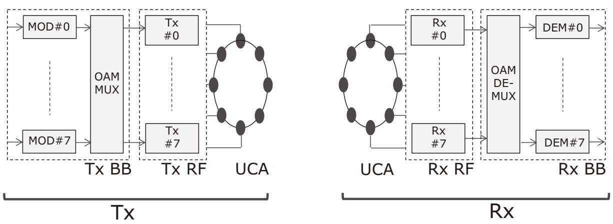


Fig. 4 DSP + UCA configuration (N = 8).

The same error signal and least mean square (LMS) algorithm used for equalizer (EQL) control to provide compensation for inter-symbol interference can also be applied to the adaptive control of the OAM mode de-multiplexing circuit.

Cross-polarization interference can be compensated for at the later stage of OAM mode separation, and receivers can be configured to support a combination of OAM and polarization multiplexing.

4. Features

4.1 Link budget calculation

With the condition of no axial misalignment, the received power of each mode can be determined only by calculating the power based on the phase difference caused by the path length difference between the transmitting and receiving UCA elements and the phase difference at the transmission output[3]. From this received power and the noise power of the receiver, the carrier-to-noise power ratio (CNR) can be calculated.

If the axis is misaligned, the CNR for each mode can be calculated by taking into account the effects of the radiation pattern of the antenna elements and the effect of adaptive control of the OAM separation process in the aforementioned calculation.

Table D-band prototype specifications.

Item	Specifications
UCA	4/8 element, Diameter: 0.62 m
Radio frequency	157.0 GHz
Baud rate	115.2 Mbaud
Modulation scheme	Single carrier from QPSK to 256QAM
OAM modes	0, ±1, ±2, ±3, 4 (8 modes in total)
Polarization	V/H
Error correction code	Reed-Solomon (255, 239)

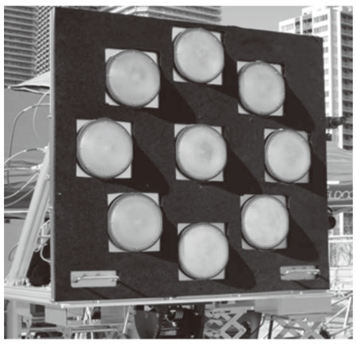


Photo D-band 8-element UCA.

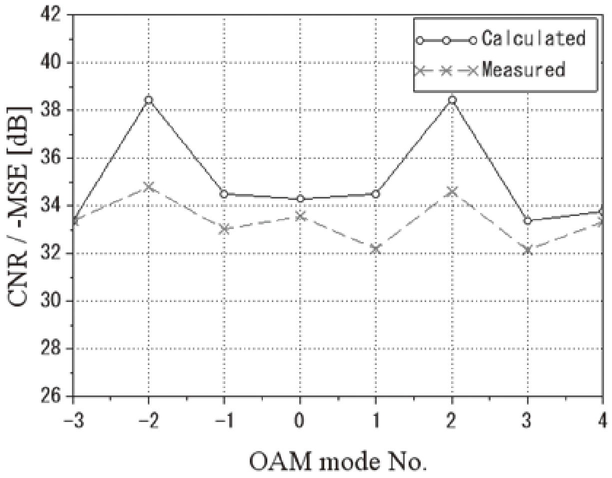


Fig. 5 MSE measured values/CNR calculated values by OAM mode.

4.2 Transmission experiment results in the D-band

Finally, the results of experiments using real-time transmissions in the D-band (130 to 174.8 GHz)[4] are introduced. The specifications and the external appearance of the UCA prototype are shown in **Table** and **Photo** respectively (the element in the center is for initial adjustments).

Fig. 5 shows a comparison between the measured values of the mean square errors (MSEs) of the received signals for each OAM mode at a distance of 100 m and the calculated CNRs derived from the link budget calculation.

A good result was obtained in this experiment. No bit errors were observed after transmitting a continuous 256QAM signal with 16 multiplexed channels for one hour (OAM8 x polarization 2). Because it is impossible to completely eliminate axial misalignment in actual measurement environments, this result is considered to be due to the effect of adaptive control of the OAM separation process. Comparing the measured MSE with the calculated CNR values, the measured MSE is close to the calculated values except for mode 2. The degradation of mode 2 is presumed to be due to axial misalignment on the transmission side, which cannot be completely compensated for on the receiving side. The frequency utilization efficiency of 82.7 bps/Hz is the highest level for fixed wireless systems in microwave and millimeter-wave bands.

5. Conclusion

In this paper, we introduced the OAM mode-multiplexing transmission method in the sub-THz band — from its principles, implementation means, and actual measurement results — as an approach to realize highly efficient high-capacity wireless transmission for Beyond 5G and 6G applications.

We are currently studying the commercialization of this method by further improving the tolerance of axial misalignment in transmissions and are aiming to achieve a capacity of 100 Gbps at a bandwidth of 1.25 GHz. If a wireless communication system capable of transmissions of 100 Gbps is developed, it can be expected to be used as an alternative to optical communications.

At NEC, we are committed to continuing to develop products that contribute to the advancement of the world’s wireless communication infrastructure.

6. Acknowledgments

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References

1) L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman: Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes, Physical Review A, vol. 45, no. 11, 1992
2) E. Sasaki, M. Hirabe, T. Maru, and N. Zein: Pragmatic OAM with polarization multiplexing transmission for future 5G ultra-high capacity radio, European Microwave Conference, October 2016
3) D. K. Nguyen et al.: Discussion about the link budget for electromagnetic wave with orbital angular momentum, The 8th European Conference on Antennas and Propagation (EuCAP 2014) proc, pp.1117–1121, 2014
4) NEC Press Release: NEC successfully demonstrates real-time digital OAM mode multiplexing transmission over 100m in the 150GHz-band for the first time, March 2020
https://www.nec.com/en/press/202003/global_20200310_01.html

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