Ray Tracing Analysis of Asymptotic Capacity Based on TCM

Minori Sasaki[1], Naoki Honma[1], Keisuke Konno[2], Qiang Chen[2], and Yoshitaka Tsunekawa[1]
[1]Graduate School of Engineering, Iwate University, 4-3-5, Ueda, Morioka, 020-8551, Japan
[2]Graduate School of Engineering, Tohoku University, 6-6-05, Aoba, Sendai, 980-8579, Japan

Abstract – **This paper proposes the evaluation of the multiple-input multiple-output (MIMO) channel capacity using the theory of characteristic modes (TCM) analysis. First, the mode directivity of the ground plate of a small terminal is analyzed by using TCM. MIMO propagation characteristics are evaluated using the ray tracing method. After that, the channel capacity is calculated using the MIMO propagation characteristics. The simulation revealed that the channel capacity is saturated with the increase in the number of modes.**

Index Terms — **MIMO, TCM, channel capacity**

1. Introduction

In recent years, a design of the compact MIMO terminal antennas that realizes a high channel capacity is required due to the demand for higher data-rate communication. However, the small MIMO terminal must have multiple antennas that are implemented in a narrow space, and this causes the capacity degradation due to the high spatial correlations among the elements. Hence, we need the design of MIMO antennas that achieve the higher performance even with a limited space and number of elements.

Recently, the theory of characteristic mode (TCM) is utilized to analyze the MIMO antenna performance [1], [2]. TCM has introduced new perspective in MIMO antenna analysis since this allows us to think the interaction between antenna and propagation characteristics theoretically.

In this paper, the asymptotic MIMO channel capacity is studied using both the ray tracing analysis and the TCM analysis of the current distribution of the ground plate of the small terminal. The channel capacity is evaluated by combining the TCM analysis results and the MIMO propagation characteristics calculated by the ray tracing method. Numerical analysis results show that the channel capacity is saturated with the increase in the number of modes.

2. Analysis Scheme of MIMO Channel Capacity

(1) Wire Grid Model

TCM is applied to the ground plate, which is assumed to be implemented in a small terminal in this study. The ground plate is analyzed by approximating it into the wire grid model [3], [4]. The wire grid model is composed of small dipole segments. The impedance matrix of the ground plate is calculated using the Method of Moments with these small dipole segments. In the wire grid model, it is necessary to consider the continuity of the current among the adjacent dipole segments.

TABLE 1
Parameters for analysis

Frequency		2.4 GHz
Wavelength λ		0.125 m
Noise power		-90 dBm
Walls	Number of reflection times	5~8
	Relative permittivity	6.76
	Loss tangent	0.0023
	Wall thickness	0.15 m
Tx	Antenna	Dipole antenna
	Number of elements m	2~20
	Element distance	$2\lambda/(m-1)$
	Transmission power	10 dBm
Rx	Antenna	Conducting plate
	Number of used modes	2~20
	Total number of modes	507

(2) TCM Analysis

TCM analysis in this study is based on the impedance matrix of wire grid model. The impedance matrix is composed of real part and an imaginary part, as defined below

$$\boldsymbol{Z} = \boldsymbol{R} + j\boldsymbol{X}. \qquad (1)$$

Characteristic mode is defined by the eigenvalue expressed as,

$$\boldsymbol{X}\boldsymbol{J}_n = \lambda_n \boldsymbol{R}\boldsymbol{J}_n \qquad (2)$$

where, $\boldsymbol{J}_n$ is n-th mode current. λ_n shows the imaginary part of the n-th eigenvalue [5]. From this equation, mode current of the ground plate is obtained by eigenvalue decomposition of this term. λ_n is a factor which corresponds to the reactively stored power of the antenna. The easily excitable mode current corresponds to the small λ_n. The ordering of the eigenvalue number is determined in an ascending manner. The n-th mode directivity is calculated from the mode current corresponding to the eigenvector of λ_n.

(3) Ray Tracing Method

MIMO propagation characteristics are obtained by using the mode directivity and the ray tracing method. In this study, the mode directivities are used as Rx antenna patterns. Here, the number of Tx antennas and the number of Rx mode is set to equal, and the aperture of the Tx array is set to be constant independently to the number of the antennas. The channel matrix $\boldsymbol{H}$ is expressed by

$$\boldsymbol{H} = \begin{pmatrix} h_{11} & \cdots & h_{1m} \\ \vdots & \ddots & \vdots \\ h_{m1} & \cdots & h_{mm} \end{pmatrix}, \qquad (3)$$

where m is the number of antennas to be used. The number of modes and the channel capacity are evaluated by using the $\boldsymbol{H}$.

3. Numerical Analysis

A. Simulation Conditions

Table 1 shows an analysis condition. In this study, the dipole antennas are used for Tx array. The operation frequency is set to 2.4 GHz. Rx antenna of the ground plate is divided into the small dipole segments, where the number of the segments is 507. Fig. 1 shows an overview of the analysis model. Analysis model assumes a room covered with concrete walls. In addition, there is no obstacle between Tx and Rx in this analysis model. Fig. 2 shows a top-view of the analysis model. The location of the Tx antennas are fixed in the position shown in this figure. Rx antenna is arranged at 23 m away from the Tx antennas. Tx has a liner array. The angular difference of Tx and Rx array is expressed by φ. The channel capacity is evaluated at each position by changing φ. The channel capacity is calculated by

$$C = \log_2 |\boldsymbol{I} + \frac{P_t}{\sigma^2} \boldsymbol{H}\boldsymbol{H}^H|, \qquad (4)$$

where, P_t is transmission power, and σ^2 is noise power.

B. Simulation Results

Fig. 3 shows the channel capacity versus number of used modes at each position. From this analysis result, it can be seen that the channel capacity fluctuates with the number of modes when the position of $\varphi = 0°$. It is believed that the Tx antennas element distance is affecting the channel capacity.

Fig. 4 shows the average channel capacity versus number of used modes. From this analysis result, the channel capacity is increased by an increase of the used modes. However, it can be seen that the increase in the channel capacity is gradually reduced with increase of the number of the modes. It is confirmed that the number of modes that affect the MIMO channel capacity is limited. Therefore, it is found that there is a limit in the number of available modes. In this model, it can be seen that the number of available mode is about eight.

4. Conclusion

This paper has reported the evaluation of MIMO channel capacity using TCM analysis. The mode directivity on the ground plate of the small terminal was analyzed by using TCM. Then, the channel matrix was obtained by using the ray tracing method. The numerical analysis showed the channel capacity is saturated with the increase in the number of modes. These analysis results indicate that the number of the available mode in this model is eight, and this is considered the maximum number of installable antennas is eight for this terminal size.

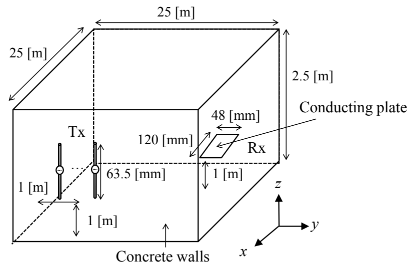

Fig. 1. Analysis model overview.

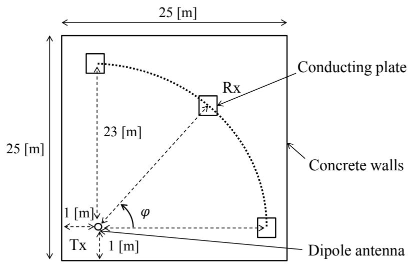

Fig. 2. Top view of analysis model.

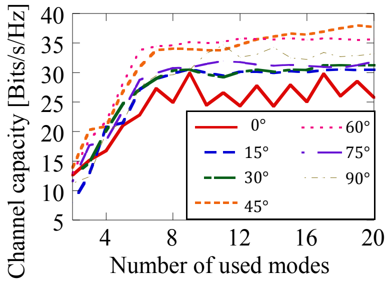

Fig. 3. Channel capacity versus number of used modes at each position.

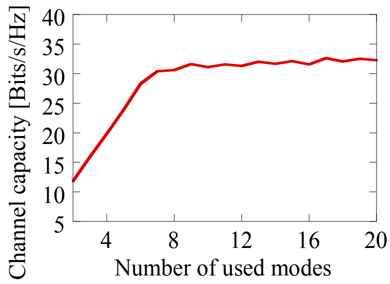

Fig. 4. Average channel capacity versus number of used modes.

References

[1] H. Li, Y. Tan, B. K. Lau, Z. Ying, and S. He, “Characteristic mode based tradeoff analysis of antenna-chassis interactions for multiple antenna terminals,” IEEE Trans. Antennas Propagat., vol.60, no.2, pp.490-502, Feb.2012.

[2] R. Martens, E. Safin, and D. Manteuffel, “Inductive and capacitive excitation of the characteristic modes of small terminals,” in Proc. Loughborough Antennas Propagat., Conf., Loughborough, U.K., pp.1-4 , Nov.2011.

[3] J. A. Richimond, “A wire-grid model of scattering by conducting bodies,” IEEE Trans. Antennas Propagat., vol.AP-14, no.6, pp.782-786, Nov. 1966.

[4] J. T. Mayhan, “Characteristic modes and wire grid modeling,” IEEE Trans. Antennas Propagat., vol.38, no.4 pp.457-469, April 1990.

[5] R. F. Harrington, and J. R. Maurz, “Theory of characteristic modes for conducting bodies,” IEEE Trans. Antenna & Propagat., vol.19, no. 5, pp. 622-628, Sept. 1971.