Ray Tracing Analysis of Asymptotic Capacity Based on TCM

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Background

Cellular System throughput per terminal

Improvement of data communication speed

Transition of communication speed of the cellular mobile terminals

Wireless Communication Speed

- 2.4kbps (1993)
- 32kbps (1997)
- 384kbps (2001)
- 14Mbps (2006)
- 100Mbps (2009)
- 10~100Gbps (2020)

Year

Improvement

Base station

3G

4G

High channel capacity is required in small terminal
MIMO* channel capacity

*MIMO: Multiple Input Multiple Output

MIMO system

- Extends the data-rate of the wireless communication link

Problem

Increase of the number of the antenna elements

- The small MIMO terminal must have multiple antennas that are implemented in a narrow space

We need the design of MIMO antennas that achieve the higher performance even with the confined volume.

Diversity

SDM

Mutual coupling
TCM (Theory of Characteristic Mode) [1]

Analysis of the antenna mode current characteristic

Antenna mode

TCM with realistic channel may tell us the maximum number of the antennas on the handset chassis.

Conventional study using TCM

Study of the radiation efficiency improvement[2]

Study of the dual-band antenna design[3]

S-parameters

Frequency

Objective

Evaluation of the number of modes and the channel capacity

- Channel capacity evaluated using the mode directivity

Mode directivity

- Calculate the mode directivity from TCM

MIMO propagation characteristic

- Evaluation of the channel capacity

The interaction between mode directivities and propagation characteristic
Outline

- Background
- Analysis scheme of MIMO channel capacity
  - System model
  - Wire grid model
  - TCM analysis
  - Ray trace method
- Numerical analysis
- Conclusion
Analysis method and study model

- Ray tracing method analysis using mode directivity
- Evaluation of the number of used modes and channel capacity

Evaluation of the channel capacity with the various number of modes

\[ H = \begin{pmatrix} h_{11} & \cdots & h_{1m} \\ \vdots & \ddots & \vdots \\ h_{m1} & \cdots & h_{mm} \end{pmatrix} \]

Mode of easy excitation

Mode of not easy excitation
Wire grid approximation

Wire grid model

The ground plate is approximated into the small dipole segments

Method of Moment

Calculation of the impedance matrix among small dipole segments
Mode directivity

Derivation of the mode directivity

Eigenvalue of the impedance matrix $\nu_n = 1 + j\lambda_n$

$$XJ_n = \lambda_n R J_n$$

$\lambda_n$ \ldots Imaginary part of the n-th eigenvalue

Corresponding to stored power in the antenna

$(\lambda_1 < \lambda_2 < \cdots < \lambda_m)$

$J_n$ \ldots n-th mode current vector

Derivation of the mode directivity $D_{Ri}(\theta, \phi)$ of the ground plate

Wire grid approximation & TCM

Wire grid

Mode current

$$D_R(\theta, \phi) \times J = \begin{bmatrix} J_1 & \cdots & J_m \end{bmatrix}$$

$D_{R1}(\theta, \phi)$

$D_{Rm}(\theta, \phi)$
Ray tracing method analysis using the mode directivity

Evaluation of the MIMO propagation characteristics

\[ H = \begin{pmatrix} h_{11} & \cdots & h_{1m} \\ \vdots & \ddots & \vdots \\ h_{m1} & \cdots & h_{mm} \end{pmatrix} \]

\[ D_{Tj}(\theta, \phi) \]
Tx : j-th antenna directivity

\[ D_{Ri}(\theta, \phi) \]
Rx : i-th mode directivity

Concrete walls

Tx : Dipole antennas ↔ Rx : Mode directivities
Propagation channel

Analysis method of the propagation channel

Propagation channel $h_{ij}$

$$h_{ij} = \sum_{l=1}^{N} D_{Ri}(\theta_{Rl}, \phi_{Rl}) h_{ij} D_{Tj}(\theta_{Tl}, \phi_{Tl})$$

Rx : $l$-th path of $i$-th mode directivity
Tx : $l$-th path of $j$-th antenna directivity

* $V - V$ polarization  ** $H - V$ polarization

$$h_{ij} = \begin{pmatrix} h_{ij}^{(\theta,\theta)} & h_{ij}^{(\theta,\phi)} \\ h_{ij}^{(\phi,\theta)} & h_{ij}^{(\phi,\phi)} \end{pmatrix}$$

$V - H$ polarization  $H - H$ polarization

* Vertical , ** Horizontal

Evaluation of channel capacity from $H$

$$H = \begin{pmatrix} h_{11} & \cdots & h_{1m} \\ \vdots & \ddots & \vdots \\ h_{m1} & \cdots & h_{mm} \end{pmatrix}$$
Outline

- Background
- Analysis scheme of MIMO channel capacity
- Numerical analysis
  - Numerical analysis condition
  - Current distributions based on TCM
  - Evaluation of MIMO channel capacity
- Conclusion
Overview

The location of the Tx antennas are fixed.
Rx antenna is located at 23 m away from the Tx antennas.
Top of view analysis model (Ray tracing method)

Top of view

Positions at $\phi = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, 90^\circ$
### Numerical analysis condition

<table>
<thead>
<tr>
<th></th>
<th>Frequency</th>
<th>2.4 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength, $\lambda$</td>
<td></td>
<td>0.125 m</td>
</tr>
<tr>
<td>Noise power</td>
<td></td>
<td>$-90$ dBm</td>
</tr>
<tr>
<td>Walls (Concrete)</td>
<td>Number of reflection times</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Relative permittivity</td>
<td>6.76</td>
</tr>
<tr>
<td></td>
<td>Loss tangent</td>
<td>0.0023</td>
</tr>
<tr>
<td>Tx</td>
<td>Antenna</td>
<td>Dipole antenna</td>
</tr>
<tr>
<td></td>
<td>Number of elements, $m$</td>
<td>2~20</td>
</tr>
<tr>
<td></td>
<td>Element distance</td>
<td>$2\lambda/(m - 1)$</td>
</tr>
<tr>
<td></td>
<td>Transmission power</td>
<td>10 dBm</td>
</tr>
<tr>
<td>Rx</td>
<td>Antenna</td>
<td>Conducting plate</td>
</tr>
<tr>
<td></td>
<td>Number of used modes, $m$</td>
<td>2~20</td>
</tr>
<tr>
<td></td>
<td>Total number of modes</td>
<td>507</td>
</tr>
</tbody>
</table>

**Tx array aperture width is constant**
Frequency characteristics of the current distribution

Current distribution of the first mode

1.8 GHz

2.4 GHz

3.0 GHz

The first eigenvalue of TCM

\[ \lambda_1 = 0.727 \]

\[ \lambda_1 = -0.219 \]

\[ \lambda_1 = -0.017 \]
1st & 2nd \(xz - \) plane directivity \(E_{total}(\theta)\) and current distribution

- **1st mode**
  - Four peaks at the long side of the plate

- **2nd mode**
  - Two peaks at the long side of the plate

Strong current distribution at the long side of the plate
3rd & 4th \( xz - \) plane directivity \( E_{total}(\theta) \) and current distribution

- **3rd mode**
  - Two peaks at the short side of the plate

- **4th mode**
  - Four peaks at the both side of the plate

Current intensity is high at the edge of the ground plate
Channel capacity versus number of used modes at each position

Channel capacities with various directions of Rx

Channel capacity fluctuates at $\varphi = 0^\circ$

The saturation of capacity seen at each position
Average channel capacity versus number of used modes

Capacity averaged over the versus $\varphi$

MIMO channel capacity is saturated when the number of modes is greater than 8

The number of the antennas mountable on the rectangle chassis is up to 8
Outline

- Background
- Analysis scheme of MIMO channel capacity
- Numerical analysis
- Conclusion
Conclusion

Ray tracing analysis of asymptotic capacity based on TCM

- Current distributions on the ground plate
  - Current distribution changes depending on the frequency

- MIMO channel capacity evaluation using ray tracing method
  - The number of modes and the channel capacity are evaluated using a realistic channel

- MIMO channel capacity
  - The channel capacity is saturated when the number of modes $\geq 8$

TCM can predicts the number of the maximum antennas of the handset chassis before designing the realistic antennas