Review of Research and Development on Antennas in Tohoku University

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Sendai, Japan
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  -Adaptive array antenna
  -Realistic simulation of MIMO

History of Tohoku University

- Tohoku University was founded in Sendai in 1907 as Tohoku Imperial University.
- It was the 3rd national university in Japan, and comprised of the College of Agriculture and College of Science.
Mr. Lu Xun (魯迅)

Famous foreign student from China (Qing). He stayed in Tohoku University.
First female student in national university in Japan

First female student Chika Kuroda with her teachers and classmates, 1913

Open door policy
Dr. A. Einstein visited Tohoku University on Dec. 3, 1922.
Dr. N. Bohr and his wife visited Tohoku University on May 2, 1937.
## Outline of Tohoku University

### Number of Faculties

<table>
<thead>
<tr>
<th>Position</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Professors</td>
<td>821</td>
</tr>
<tr>
<td>Associate Professors</td>
<td>638</td>
</tr>
<tr>
<td>Senior Assistant Professors</td>
<td>153</td>
</tr>
<tr>
<td>Assistant Professors</td>
<td>994</td>
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<tr>
<td>Research Associates</td>
<td>69</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>2,675</strong></td>
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</table>

### Number of Administrative and Technical Staff

<table>
<thead>
<tr>
<th>Category</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2,691</td>
</tr>
</tbody>
</table>

### Number of Students

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undergraduate</td>
<td>10,913</td>
</tr>
<tr>
<td>Graduate Master</td>
<td>4,155</td>
</tr>
<tr>
<td>Graduate Doctor</td>
<td>2,740</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>17,849</strong></td>
</tr>
</tbody>
</table>

- Number of Students/Number of Faculties = 6.67
10 undergraduate schools and 15 graduate schools

- Graduate School/Faculty of Arts and Letters
- Graduate School/Faculty of Education
- Graduate School/Faculty of Law
- Graduate School of Economics and Management/Faculty of Economics
- Graduate School/Faculty of Science
- Graduate School/School of Medicine
- Graduate School/School of Dentistry
- Graduate School/Faculty of Pharmaceutical Sciences
- Graduate School/School of Engineering
- Graduate School of Agricultural Sciences/Faculty of Agriculture
- Graduate School of International Cultural Studies
- Graduate School of Information Sciences
- Graduate School of Life Sciences
- Graduate School of Environmental Sciences
- Graduate School of Biomedical Engineering

5 Institutes

- Institute for Materials Research
- Institute of Development, Aging and Cancer
- Institute of Fluid Science
- Research Institute of Electrical Communication
- Institute of Multidisciplinary Research for Advanced Materials
The School of Engineering in Tohoku Imperial University was founded in 1919 with three departments:
- Mechanical Engineering,
- Electrical Engineering, and
- Applied Chemistry.
Departments of
- Electrical Communications in 1941
- Electronic Engineering in 1958
- Information Engineering in 1984
## Organization of School/Graduate School of Engineering

<table>
<thead>
<tr>
<th>School of Engineering (5 Departments)</th>
<th>Graduate School of Engineering (17 Departments)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Department of Mechanical and Aerospace Engineering</td>
<td>Department of Mechanical Systems and Design</td>
</tr>
<tr>
<td></td>
<td>Department of Nanomechanics</td>
</tr>
<tr>
<td></td>
<td>Department of Aerospace Engineering</td>
</tr>
<tr>
<td></td>
<td>Department of Quantum Science and Energy Engineering</td>
</tr>
<tr>
<td></td>
<td>Department of Bioengineering and Robotics</td>
</tr>
<tr>
<td>Department of Information and Intelligent Systems</td>
<td>Department of Electrical and Communication Engineering</td>
</tr>
<tr>
<td></td>
<td>Department of Electronic Engineering</td>
</tr>
<tr>
<td></td>
<td>Department of Applied Physics</td>
</tr>
<tr>
<td>Department of Applied Chemistry, Chemical Engineering and Biomolecular Engineering</td>
<td>Department of Applied Chemistry</td>
</tr>
<tr>
<td></td>
<td>Department of Chemical Engineering</td>
</tr>
<tr>
<td></td>
<td>Department of Biomolecular Engineering</td>
</tr>
<tr>
<td>Department of Materials Science and Engineering</td>
<td>Department of Metallurgy</td>
</tr>
<tr>
<td></td>
<td>Department of Materials Science</td>
</tr>
<tr>
<td></td>
<td>Department of Materials Processing</td>
</tr>
<tr>
<td>Department of Civil Engineering and Architecture</td>
<td>Department of Architecture and Building Science</td>
</tr>
<tr>
<td></td>
<td>Department of Civil and Environmental Engineering</td>
</tr>
<tr>
<td></td>
<td>Department of Management Science and Technology</td>
</tr>
</tbody>
</table>
ECEI Group

ECEI Group: Electrical Engineering
Communication Engineering
Electronic Engineering
Information Engineering

is composed of
1. Graduate School of Engineering
   Department of Electrical and Communication Engineering
   Department of Electronic Engineering
2. Graduate School of Information Sciences
   Department of Computer and Mathematical Sciences
   Department of System Information Science
   Department of Applied Information Sciences
3. Graduate School of Biomedical Engineering
4. Research Institute of Electrical Communication
5. New Industry Creation Hatchery Center (NICHe)
6. Cyberscience Center
ECEI Group

• Number of Faculties
  Professors: 70
  Associate Professors: 49
  Senior Assistant Professors: 1
  Assistant Professors: 59
  Research Associate: 1
  Total 180

One of the largest electronic and computer engineering complexes in the world.
Outstanding researches in ECEI Group

- Yagi-Uda antenna
  by Prof. H. Yagi and Prof. S. Uda
- Split-anode magnetron tube
  by Prof. K. Okabe
- Magnetic recording using AC biasing method
  by Prof. K. Nagai
- Pioneer research in electronics
  by Prof. Y. Watanabe
- Semiconductor science and optoelectronics
  by Prof. J. Nishizawa
- High density magnetic recording
  by Prof. S. Iwasaki
Mr. Koichi TANAKA, Nobel Laureate

1959  · Born in Toyama, Japan

1983  · Graduated from Department of Electrical Engineering, School of Engineering, Tohoku University

   · Researcher in Shimadzu Corporation

2002  · The Nobel Prize in Chemistry  2002

   “The development of methods for identification and structure analyses of biological macromolecules”

   · Honorary Doctor of Tohoku University
Yagi-Uda Antenna

• The first report describing methods to obtain a sharp beam by using parasitic elements was published by Uda of Tohoku University, Japan in 1925 [1].

• Details of the geometry of the Yagi-Uda antenna were reported by Yagi and Uda in 1926 [2].


Geometry of Yagi-Uda Antenna

Reflectors had already been used for directional antennas. Wave directing effects of director elements had not been reported.
Uda performed numerous experiments on antennas having many parasitic elements with varying their length and published eleven papers entitled “On the wireless beam of short electric waves” in Journal of IEE Japan in 1926-29.

Example of radiation pattern of multi-element Yagi-Uda antenna

\[ N_d = \text{Number of director elements} \]

\[ N_d = 6 \]

\[ N_d = 11 \]

\[ N_d = 14 \]

Example of radiation pattern of multi-element Yagi-Uda antenna

In 1927, Prof. Yagi visited the United States and lectured at several meetings on the experimental results of Yagi-Uda antenna and UHF generating split-anode magnetron tube invented by Okabe of Tohoku University.


IRE paper stimulated worldwide interests in UHF technology.

Yagi-Uda antennas were recognized as a useful antenna for VHF and UHF because of the simple but high gain property and were used for radar systems in Europe and America.

However, little attention was paid to the Yagi-Uda antenna in Japan for radars.
Invention of split-anode magnetron tube

- Albert W. Hull had first invented magnetron in 1921, but the generated power was low.
- Okabe in Tohoku University invented the split-anode magnetron tube, which can generate high power EM wave in VHF and UHF bands.

![Magnetron Diagram]

Kinjiro OKABE (1896-1984)

This is the first Milestone sent to the Asian region.
After the invention of Yagi-Uda antenna, Uda started research and development of transmitter and receiver in VHF frequency range.

Communication experiments at 65 MHz and 53 MHz

- Uda succeeded in communication experiments at 65 MHz and 53 MHz for a distance of about 50 km in 1931.
- These transmitters and receivers using Yagi-Uda antennas were put into police radiotelephone systems between main-land Japan and Sado island in 1933.
Communication experiments at 38 MHz

- Uda also succeeded in communication experiments at 38 MHz for a distance of about 30 km in 1932.
- These transmitters and receivers using the Yagi-Uda antennas were put into public services of radio wave telecommunication systems between Sakata City and Tobishima Island in 1933.
Development of UHF transmitter and receiver

Uda also performed the development of transmitter and receiver in the UHF frequency range.

Uda succeeded in a communication experiment at a distance of about 30km operating at 600 MHz in 1929, which was the world’s longest record in UHF radio communication.
Replicas of transmitters and receivers using Yagi-Uda antennas

600 MHz tranceiver 600 MHz receiver.
Duality of electromagnetic field

\[ \varepsilon, \mu \quad E_1, H_1 \quad S \quad E_2, H_2 \quad S_m \]

Structure #1

\[ \begin{cases} \mathbf{J}_0 = N \\ \mathbf{J}_{0m} = M \end{cases} \]

Electric current density

Magnetic current density

Structure #2

\[ \begin{cases} \mathbf{J}_{0m} = N \\ \mathbf{J}_0 = -\frac{1}{Z_0^2} M \end{cases} \]

Electric current density

Magnetic current density

\[ E_1 = Z_0^2 H_2 \\
H_1 = -E_2 \]

\[ Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 120\pi \quad [\Omega] \]
Babinet's principle

(a) Symmetric electric current sources

(b) Antisymmetric magnetic current sources

\[ E_1 = \pm Z_0^2 H_2, \quad H_1 = \mp E_2, \quad z > 0 \]
Booker’s relation

\[ Z_s = \frac{(Z_0/2)^2}{Z_d} \]

- \( Z_s \): Input impedance of slot antenna
- \( Z_d \): Input impedance of planar dipole antenna

\[ Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 120\pi \quad [\Omega] \]


Mushiake’s relation

Self-complementary antennas

• Mushiake in Tohoku University originated self-complementary structures and found that the input impedance of self-complementary antennas is constant independently of the frequency.


Self-complementary antennas are very interesting since there is an infinite variety of self-complementary structures.


\[ \tau = \frac{R_{n+1}}{R_n} : \text{Const.} \]

Self-complementary antenna having monopoles and notches.

Self-complementarity using log-periodically spaced notches and monopoles proposed by DuHamel

Modified self-complementary antennas

Planar self-complementary antenna radiates bi-directionally and a directional antenna was desired.

DuHamel tried to deform the structure by bending the planar antenna and obtained a modified self-complementary antenna called a “log-periodic antenna” having directional radiation pattern.


Main beam

Planar structure

Main beam

Wire structure

Log-periodic dipole array antenna

- Log-periodic antenna was further deformed to log-periodic dipole array (LPDA) antenna.
- LPDA antenna has been widely used for extremely wide frequency operation in communications and measurements, especially in EMC measurements.

Other papers related to self-complementary antennas


Small loop antenna

- Prior to the 1950’s, loop antennas were used in low frequency range as infinitesimal magnetic dipole.
- Maximum radiation occurs in the direction perpendicular to the axis of loop for the case of electrically small loop antenna.

\[ 2\pi b \ll \lambda \quad \lambda : \text{wavelength} \]
The characteristics of a loop antenna changes drastically in the high frequency range and more rigorous treatment was desired.


They also derived a compact solution in the first order approximation which is satisfactory for practical purposes [2].

One wavelength loop antenna

- Adachi found that a large loop antenna having a conducting wire of one wavelength has maximum radiation in the axial direction.
Loop array antennas

- Because of the high directivity, one wavelength loop antennas are used as elements in arrays such as the Yagi-Uda loop array antenna [1], [2] and the log-periodic loop array antenna [3].

Twin loop antennas

- Twin loop antenna is a type of antennas using one wavelength loop antennas, which have only one driving point but has high gain and wide bandwidth.
Twin loop antennas

- Four element (4L) twin loop antenna and six element (6L) twin loop antenna were also developed in Japan.
- 2L, 4L and 6L twin loop antennas located in front of conducting plane with a spacing of a quarter wavelength have been widely used for UHF TV broadcasting antennas in Japan.

Prof. Adachi was the supervisor of Mr. Koichi TANAKA (received the Nobel Prize in Chemistry 2002)
Current researches in Electromagnetic Wave Engineering Laboratory

Fundamental Studies

**EM wave Theory**
- Theoretical investigation of scattering and diffraction of EM wave.
- Numerical methods to analyze scattering and diffraction of EM wave (**MoM and FDTD**).
- Development of highly accurate EM simulators for antennas and EM wave.

**Measurement systems of antenna characteristics and EM Fields.**
- **Measurement of radiation characteristics of antennas.**
- Visualization of EM field.

Applications

**Antenna Engineering**
Development of antennas for
- Portable telephone.
- **Magnetic Resonance Imaging (MRI)**
- **Production and heating of RF plasma**
- **Long range RFID system**

**Adaptive array antennas**

**MIMO**

**Electromagnetic Compatibility (EMC)**
- Estimation of source location of undesired EM wave
- Suppression of undesired EM wave emission
MoM for planar and wire structures


Input impedance of planar inverted F-shaped antenna on conducting box
Folded array antenna used for plasma production

Fast measurement system of radiation characteristics of antennas

- 16 modulation probe elements.
- 0 to 168.75 degrees in elevation angle.
- Cross dipole antenna is used as probe.
- Horizontal and vertical dipoles are electrically switched.
- Local frequency of 20 MHz to 40 MHz for each probe.
- Wideband spectrum analyzer.

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>Received Power [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.05</td>
<td>-80</td>
</tr>
<tr>
<td>1.055</td>
<td>-60</td>
</tr>
<tr>
<td>1.06</td>
<td>-40</td>
</tr>
<tr>
<td>1.065</td>
<td>-20</td>
</tr>
<tr>
<td>1.07</td>
<td>0</td>
</tr>
<tr>
<td>1.075</td>
<td>20</td>
</tr>
</tbody>
</table>

Spectrum of received IF signal observed by real-time spectrum analyzer. 18 peaks of the spectrum correspond to the RF signal level excited on the 18 modulation probes.
Manufactured Measurement System

- Cross dipole element
- Isolation is more than 30 dB.
- Modulation circuit box.
## Summary of Measurement System

<table>
<thead>
<tr>
<th>Item</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of semicircular arch</td>
<td>1.03 m</td>
</tr>
<tr>
<td>Frequency range</td>
<td>800 - 1200 MHz</td>
</tr>
<tr>
<td>Frequency bandwidth</td>
<td>2 MHz</td>
</tr>
<tr>
<td>Total measurement time</td>
<td>16 sec.</td>
</tr>
<tr>
<td>Gain measurement repeatability</td>
<td>&lt; 0.3 dB</td>
</tr>
<tr>
<td>Polarization isolation</td>
<td>&gt; 30 dB</td>
</tr>
</tbody>
</table>
Measured 3-D Radiation Pattern

**Half wavelength dipole**
• Radiation efficiency is defined by a ratio of radiated power to incident power to the antenna.
• AUT is located in the vicinity of a rectangular container filled with a salt solution.
• Absorbed power in salt solution is a part of the antenna loss.
Measured Radiation Efficiency

Monopole antenna

f=1 GHz
1% salt solution (ε_r=77.8, σ=0.39 S/m)

Radiation Efficiency [%]

FDTD Analysis
Measurement

D [cm]

D [cm]
Measured Radiation Pattern

Inverted F-shaped antenna

- FDTD Analysis
- Measurement

f=1 GHz
1% salt solution (\(\varepsilon_r=77.8\), \(\sigma=0.39\) S/m)

Radiation Efficiency [%]

<table>
<thead>
<tr>
<th>D [cm]</th>
<th>Radiation Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
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<td>5</td>
<td>50</td>
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<td>80</td>
</tr>
<tr>
<td>9</td>
<td>90</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>

D [cm]
RFID tags are required to be compact, low price and long life without any maintenance.

Distance $r$ between the reader and the tag is limited because the received power at the tag from the reader is proportional to the $(\lambda/r)^2$, and the responding signal power at the reader from the tag is proportional to the $(\lambda/r)^4$.

**Background**

- 0.9 GHz band 10m
- 2.45 GHz band 4m
Passive RFID tag for a range longer than 20 m is proposed for tag systems at 900 MHz band 2.45 GHz band.

A high gain antenna and a rectifying circuit having high multiplying ratio are proposed to obtain long range passive RFID tag system.

Base station (reader)

\[ r > 20 \text{ m} \]


- High gain antenna
- Rectifying circuit having high multiplying ratio
Variable impedance $Z_v$ for modulation is connected to A and B.

Rectifying circuit for receiving power is also connected in parallel to A and B.

Structure of conventional passive RFID tag.

- Divided microstrip antenna is used for tag antenna.
- Two diodes are connected to A and B as variable impedance element for modulation.
- Rectifying circuit is connected to terminals B and C.

Structure of proposed passive RFID tag.
Received signal level

PIN diode: $R_s = 1 \, \Omega$, $C_0 = 2 \, \text{pF}$

**Fig. 4** Received signal level of reader antenna as a function of length of the tag antenna $L$. 

- 2.45 GHz, $z = 83 \, \lambda$
- $w = 0.053 \, \lambda$, $h = 0.02 \, \lambda$
Rectifying circuit

Tank circuit
Parallel resonance

Modified 3 stage Cockcroft-Walton circuit
Rectifying circuit

Frequency response of proposed rectifying circuit.

Input power = -10 dBm
Load resistance $R_L = 33 \, \text{kΩ}$.
Long range RFID Summary

- Passive RFID tags for a long reading range have been proposed.
- Divided microstrip antenna is used for tag antenna.
- Rectifying circuit boosting DC voltage composed of a tank circuit of a $\lambda/4$ short stub and modified Cockcroft-Walton circuit has been proposed.

<table>
<thead>
<tr>
<th>Frequency band</th>
<th>Tx power &amp; antenna gain</th>
<th>Standard specification</th>
<th>Reading range</th>
</tr>
</thead>
<tbody>
<tr>
<td>900MHz</td>
<td>1 W, 6 dBi</td>
<td>FCC 15.247 (U.S.A.)</td>
<td>30 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ARIB STD-T89 (Japan)</td>
<td></td>
</tr>
<tr>
<td>2.45 GHz</td>
<td>1 W, 6 dBi</td>
<td>FCC 15.247 (U.S.A.)</td>
<td>11 m</td>
</tr>
<tr>
<td></td>
<td>0.3 W, 20 dBi</td>
<td>RCR STD-1 (Japan)</td>
<td>30 m</td>
</tr>
</tbody>
</table>

Size of tags: 90 × 60 × 4 mm for 900 MHz band
               60 × 25 × 4 mm for 2.45 GHz band

- Estimation system of location of RFID-tag has been also presented.
Adaptive array antenna

Patch antenna elements of adaptive array antenna

Receiver using adaptive array antenna
Access Type: W-CDMA DPCH
Carrier Frequency: 2.4GHz
Bandwidth: 5MHz
Sampling Clock 3. 84MHz × 4
Number of Array Element: 4
Calibration: Blind automatic calibration
Experimental setup for evaluation of adaptive array antenna

Desired signal

Interference

Adaptive array antenna
Measured BER

Unechoic chamber

Indoor

4 monopole Adaptive Array Antenna

Single monopole

10dB

13dB
Adaptive array antenna combined with frequency domain equalizer

Prototype transceiver for wireless LAN

- Transmission system: Single carrier, Frequency domain equalizer, QPSK
- Baud rate: 20 Mbaud
- Frequency: 2.45 GHz
- Transmission rate: 17.78 Mbps
- Error correction: Encoding ratio: 1/2, Constraint length: 7, Viterbi
- Filter: 50% Root Nyquist Filter
Analysis model of wireless channel

Absorbing Boundary Conditions
Perfectly Matched Layer (PML) (Layers=8)

Receiving array antenna is moving to obtain statistical characteristics of the wireless channel

FDTD analysis has to be repeated for all the receiving points. ⇒ CPU time is huge and numerical calculation is impossible.

Hybrid Method combining FDTD method with MoM.
Hybrid method of FDTD method and MoM

Absorbing Boundary Conditions
Perfectly Matched Layer (PML)
(Layers=8)

FDTD is used to analyze transmitting antennas and propagation channel

Electric field at every Yee cell inside moving area is calculated by using FDTD

MoM is used to analyze received voltage

Sinusoidal function is used as basis function and weighting function

Required CPU time can be significantly reduced.
### Parameters for numerical simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitted power</td>
<td>Fixed regardless of $K$</td>
</tr>
<tr>
<td>Array Antenna</td>
<td>Vertical half wavelength dipole</td>
</tr>
<tr>
<td>Scatterers</td>
<td>Conducting Cubes with</td>
</tr>
<tr>
<td>Transmitting Antenna</td>
<td>Fixed $\frac{\lambda}{2} \times \frac{\lambda}{2} \times \frac{\lambda}{2}$</td>
</tr>
<tr>
<td>Receiving Antenna</td>
<td>Moving (in several wavelengths)</td>
</tr>
<tr>
<td>Power Allocation</td>
<td>Uniform</td>
</tr>
<tr>
<td>Modulation</td>
<td>BPSK</td>
</tr>
<tr>
<td>Carrier Frequency</td>
<td>1.5GHz</td>
</tr>
<tr>
<td>Number of Yee cells (FDTD)</td>
<td>301×701×150</td>
</tr>
<tr>
<td>Cell Size (FDTD)</td>
<td>1cm×1cm×1cm</td>
</tr>
<tr>
<td>Time Step (FDTD)</td>
<td>8192</td>
</tr>
</tbody>
</table>

Effect of number of scatterers $N_s$

- **Transmitter**
  - $N_t$
  - Number of scatterers $N_s$ is small.
  - Poor multipath environment, but large received signal

- **Total radiation power $P_r$**
  - $N_t$
  - $N_r$
  - $N_s$ is large.

- **Receiver**
  - $N_r$

- **Rich multipath environment, but small received signal**
Comparison of fixed and moving receiving antennas

Channel capacity versus received $E_b/N_0$

$N_t = N_r = 4$

$N_s$: number of scatterers

- Hybrid method yields average capacity and BER.
- CPU time of hybrid method for statistic evaluation is much shorter than that of FDTD (1:12,000).
Capacity and BER versus received $E_b/N_0$

$N_s$: number of scatterers

$N_t = N_r = 4$

- Capacity increases and BER decreases as number of scatterers increases.
Propagation loss increases as number of scatterers increases. 

Capacity decreases and BER increases.
A hybrid method combining FDTD method with MoM has been proposed for simulation of the MIMO wireless channel analysis.

Channel capacity and bit error rate have been analyzed using realistic antenna and propagation model.

The numerical results indicate that:
- both the effect of propagation channel and the antenna properties should be included in the analysis of MIMO.
- propagation loss due to scatterers should be incorporated.
Conclusion

ECEI Group of Tohoku University
- One of the largest electronic and computer engineering complexes in the world
- Outstanding researches have been achieved

Historical review of researches on antenna engineering
- Yagi-Uda Antenna
- Self-complementary antenna
- One wavelength loop antenna

Current researches in Electromagnetic Wave Engineering Laboratory
- Method of Moments (MoM)
- Finite Difference Time Domain (FDTD)
- Fast measurement system of radiation characteristics of antennas
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- Adaptive array antenna
- Realistic simulation of MIMO