Experiments on MIMO Multiplexing with Peak Frequency Efficiency of 50 Bps/Hz Using MLD Based Signal Detection for OFDM High-Speed Packet Access

Hidekazu Taoka
Radio Access Network Development Department
NTT DOCOMO, INC.
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DOCOMO’s Research Activities for 4G

- Oct. 2002: 100 Mbps in laboratory experiment
- May 2003: 100 Mbps in field experiment
- Aug. 2004: 1 Gbps in laboratory experiment
- May 2005: 1 Gbps in field experiment
- Dec. 2005: 2.5 Gbps in laboratory and field experiments
- **Dec. 2006**: 5 Gbps in laboratory and field experiments

<table>
<thead>
<tr>
<th>Mobility</th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate</td>
<td>100 Mbps (1 bps/Hz)</td>
<td>1 Gbps (10 bps/Hz)</td>
</tr>
</tbody>
</table>
Objective

Objective of this presentation
• Demonstrate ultimate spectrum efficiency of approximately 50 bit/sec/Hz (i.e., 5 Gbps using 100 MHz channel bandwidth) based on indoor and field experiments
Overview of 5Gbps (50 bps/Hz)
Experimental Configurations
Features of Experimental Configuration

(1) OFDM radio access with 100-MHz transmission bandwidth
(2) Efficient modulation and channel coding scheme
   • 64QAM modulation
   • Turbo code with coding rate of $R = 8/9$
   • Multiple codeword
(3) 12-by-12 MIMO multiplexing
(4) MLD-based signal detection
   • QRM-MLD\(^{[1]}\) with ASES\(^{[2]}\) (adaptive selection surviving symbol replica candidates based on maximum reliability)
   • LLR (log-likelihood ratio) generation appropriate to QRM-MLD


Overview of 5 Gbps Experiments

The MIMO transmitter and receiver comprise of RF transmitter / receiver, D/A(A/D) converter, and Data Storage (Memory and HDD)

Baseband signal processing is done offline (Radio channel performance is basically identical)
Structure of 12-by-12 MIMO Transceiver

Mobile station receiver

Base station transmitter

LNA: Low noise amplifier
AGC: Automatic gain control
LPF: Low-pass filter
BPF: Band-pass filter
HPA: High power amplifier
## Major Radio Parameters for RF Transceiver Part

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>4.635 GHz</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>101.4 MHz</td>
</tr>
<tr>
<td>Number of antennas</td>
<td>12-by-12 MIMO</td>
</tr>
<tr>
<td>Total transmission power</td>
<td>1.2 W (Indoor) / 20 W (Field)</td>
</tr>
<tr>
<td>Number of quantized bits at D/A (A/D) converters</td>
<td>14 bits (D/A) / 12 bits (A/D)</td>
</tr>
<tr>
<td>Sampling clock rate</td>
<td>270 Msample/sec</td>
</tr>
<tr>
<td>Memory per branch</td>
<td>9 GB (Transmitter) / 18 GB (Receiver)</td>
</tr>
<tr>
<td>Hard disk capacity</td>
<td>480 GB</td>
</tr>
</tbody>
</table>
Block Diagram of Baseband Signal Processing Part

BS signal processing part

From RF receiver circuitry

Symbol timing detector

CP deletion

Channel estimator

FFT

P/S

QRM-MLD using AESS

Deinterleaver

Turbo decoder

Recovered data

To RF transmitter circuitry

Orthogonal pilot

MS signal processing part

Turbo encoder

IFFT

Interleaver

MUX

S/P

Data modulator

Turbo encoder

S/P

Transmitted data

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## Major Radio Parameters for Baseband Signal Processing Part

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radio access</strong></td>
<td>OFDM</td>
</tr>
<tr>
<td>Sub-frame length</td>
<td>0.5 msec</td>
</tr>
<tr>
<td>Number of sub-carriers</td>
<td>1536 (65.919 kHz sub-carrier separation)</td>
</tr>
<tr>
<td>OFDM symbol duration</td>
<td>Effective data 15.170 $\mu$sec + CP 2.067 $\mu$sec</td>
</tr>
<tr>
<td>Channel coding / decoding</td>
<td>Turbo coding ($K = 4$) / Max-Log-MAP decoding</td>
</tr>
<tr>
<td>Symbol timing detection</td>
<td>Pilot signal-based symbol timing detection</td>
</tr>
<tr>
<td>Channel estimation</td>
<td>Two-dimensional MMSE channel estimation</td>
</tr>
<tr>
<td>Signal separation</td>
<td>QRM-MLD with ASESS</td>
</tr>
</tbody>
</table>
Subframe Structure

- **Frequency**
- **1536 sub-carrier**
- **1 subframe (= 0.5 msec)**
- **Time**
- **Data**
- **Pilot**
Indoor Experiments
(Laboratory Room)
Measurement Course in Indoor Experiments

Laboratory room of DOCOMO R&D center

<table>
<thead>
<tr>
<th>BS transmitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>✷ Total Tx power: 1.2W</td>
</tr>
<tr>
<td>✷ Antenna height: 2.5 m</td>
</tr>
<tr>
<td>✷ Antenna space: 10 cm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MS receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>✷ Average speed: 4 km/h</td>
</tr>
<tr>
<td>✷ Antenna height: 1.5 m</td>
</tr>
<tr>
<td>✷ Antenna space: 3.2-10 cm (adjustable)</td>
</tr>
</tbody>
</table>
Cumulative Distribution of Fading Correlation (Impact of Receiver Antenna Spacing)

- 12-by-12 MIMO Multiplexing
- Total Tx power: 1.2W
- Average speed: 4 km/h

- Fading correlation between receiver antennas is increased from 0.26 to 0.42 at 50% CDF when $d$ is reduced from 10 cm to 3.2 cm
- Fading correlation between transmitter antennas is comparable to that between receiver antennas.
Throughput Performance
(Impact of Receiver Antenna Spacing)

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- 12-by-12 MIMO Multiplexing
- 64QAM, $R = \frac{8}{9}$
  (Max: 4.915 Gbps)
- Average speed: 4 km/h

- Achieved 4.9 Gbps at received SNR of 28 dB when $d$ is 10 cm.
- Even when $d$ is 3.2 cm, the loss in the required received SNR is only 1 dB.
- Loss in the required average received SINR compared to simulation is 1 dB
- Quantization error in A/D
- Difference in the propagation channel
Field Experiments
(YRP District)
Views of BS Transmitter for 5 Gbps Experiments

Installation space of BS transmitter (Rooftop of R&D center)

- Power amplifier
- RF transmitter circuitry/memory
- HDD, PC control
- BS transmitter
Views of BS Antennas for 5 Gbps Experiments

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BS transmitter antennas for 5 Gbps experiments
- 12 branch cross-polarized antennas
- Antenna gain: 19 dBi/antenna
- 3 dB beam width: 90 degrees (horizontal), 5 degrees (azimuth)
- Polarization: linear polarization (vertical/horizontal)
- Antenna space: 30-70 cm (adjustable)
- Antenna height: 26 m
MS receiver antenna for 5Gbps experiments
- 12 branch cross-polarized antennas
- Antenna gain: 2 dBi/antenna
- Polarization: linear polarization (vertical/horizontal)
- Antenna space: 10-40 cm (adjustable)
- Antenna height: 3.5 m
Measurement Course in Field Experiments

Yokosuka Research Park (YRP) district
Yokosuka, Japan

BS transmitter (NTT DOCOMO R&D Center)
- Total Tx power: 20W
- 3-dB beamwidth: 90 degrees
- Antenna height: 26 m
- Antenna separation: 20-70 cm

MS receiver
- Average speed: 10 km/h
- Antenna height: 3.5 m
- Antenna separation: 10-40 cm
Time Variation of Measured Throughput

- 12-by-12 MIMO multiplexing
- 64QAM, $R = \frac{8}{9}$
  (Max: 4.915 Gbps)
- Average speed: 10 km/h

QRM-MLD with ASESS achieves over 4.9 Gbps throughput at 99% of the locations in the course
12-by-12 MIMO multiplexing
Total Tx power: 20W
Average speed: 10 km/h

- Fading correlation between receiver antennas is increased from 0.25 to 0.35 at 50% CDF when $d$ is reduced from 40 cm to 10 cm
- Fading correlation between transmit antennas is increased from 0.36 to 0.51 when $D$ is reduced from 70 cm to 20 cm
- Fading correlation between transmitter antennas is greater than that between receiver antennas
12-by-12 MIMO multiplexing
Total Tx power: 20W
Average speed: 10 km/h

- Singular value ratio is decreased by approximately 3 dB according to the reduction of receiver antenna space from 40 cm to 10 cm.
- Singular value ratio is decreased by approximately 4 dB according to the reduction of transmitter antenna space from 70 cm to 20 cm.
Throughput Performance
(Impact of Receiver Antenna Spacing)

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- Achieved 4.9 Gbps at received SNR of approximately 28 dB when $d$ is 40 cm.
- Even when $d$ is 10 cm, the loss in the required received SNR is only 0.5 dB.
- Loss in the required average received SINR compared to simulation is approximately 1 dB.

- 12-by-12 MIMO Multiplexing
- 64QAM, $R = 8/9$
  (Max: 4.915 Gbps)
- Average speed: 10 km/h

Throughput (Gbps)

Measured average total received SNR per receiver antenna (dB)

Throughput Performance (Impact of Receiver Antenna Spacing)

- $d = 10$ cm ($1.5\lambda$)
- $d = 20$ cm ($3.1\lambda$)
- $d = 40$ cm ($6.2\lambda$)

Simulation
Field experiments
Cumulative Distribution of Throughput (Impact of Receiver Antenna Spacing)

- 12-by-12 MIMO Multiplexing
- Total Tx power: 20W
- 64QAM, $R = 8/9$
  (Max: 4.915 Gbps)
- Average speed: 10 km/h

Throughput exceeding 4.9 Gbps is achieved at the location probability over 85% even when $d$ is 10 cm.

Course A → B
Average speed: 10 km/h
$D = 70$ cm
Cumulative Distribution of Throughput (Impact of Transmitter Antenna Spacing)

- 12-by-12 MIMO Multiplexing
- 64QAM, $R = 8/9$
  (Max: 4.915 Gbps)
- Average speed: 10 km/h

Achieved 4.9 Gbps at received SNR of approximately 30 dB when $D$ is 20 cm.
Cumulative Distribution of Throughput (Impact of Transmitter Antenna Spacing)

- 12-by-12 MIMO Multiplexing
- Total Tx power: 20W
- 64QAM, $R = 8/9$
  (Max: 4.915 Gbps)
- Average speed: 10 km/h

Throughput exceeding 4.9 Gbps is achieved at the location probability over 40% even when $D$ is 20 cm.
Cumulative Distribution of Throughput (Impact of Vehicular Speed)

- 12-by-12 MIMO Multiplexing
- 64QAM, $R = \frac{8}{9}$
  (Max: 4.915 Gbps)

According to the increase in UE speed, throughput performance is degraded.
Even when $v = 40$ km/h, 4.9 Gbps throughput is achieved at received SNR of 29.5 dB
Cumulative Distribution of Throughput (Impact of NLOS/LOS)

- 12-by-12 MIMO Multiplexing
- 64QAM, $R = 8/9$
  (Max: 4.915 Gbps)

In NLOS condition, the throughput performance is almost identical irrespective of measurement courses
In LOS condition, the throughput performance is degraded compared to the in NLOS condition

Average speed: 10 km/h
$D = 70$ cm, $d = 20$ cm

Measured average total received SNR per receiver antenna (dB)
Achieved approximately 50 bit/sec/Hz (i.e., 4.9 Gbps data transmission using 100-MHz bandwidth) at the maximum distance of 200 m between BS and MS using MLD-based signal detection.

Required average received SNR for achieving 4.9-Gbps throughput is approximately 28.5 dB ($D = 70$ cm, $d = 10$ cm), which is near the upper limit taking into account interference from surrounding cells in multi-cell environment.