Realization of Peak Frequency Efficiency of 50 Bit/Second/Hz Using OFDM MIMO Multiplexing with MLD Based Signal Detection

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Experiments on Peak Data Rate for Future 4G Broadband Radio Access
4G Broadband Radio Access Network (IMT-Advanced)

- Will provide high-speed data services such as high-density video/broadcast services and large-size data download at low cost
- IP-based radio access networks (RANs) satisfy the following technical requirements
  - Very low latency (connection and transmission delays)
  - High user data rates and high capacity
  - Wide coverage area
  - Precise QoS control (QoS: Delay, residual packet error rate, etc.)
  - Low network cost
  - Complementally use with 3G system and backward compatibility with existing legacy systems

Flexible packet-based access with high efficiency and affinity to IP-based core networks
Target Peak Data Rates for IMT-Advanced

- Target peak data rate is one of the most important requirements in radio access systems.

- Targets data rates specified in standardization or forum
  - **ITU-R Recommendation M.1645**
    - Peak data rate of 100 Mbps in new mobile access under high mobility
    - Peak data rate of 1 Gbps in new nomadic/local area wireless access under low mobility
  - **IST-2003-507581 in WINNER**
    - (D7.1 v1.0 System Requirements (2004.07.16))
      - Peak spectral efficiency in connected sites of 10 b/s/Hz/site in wide area deployments for heavy traffic loads
      - Peak spectral efficiency in isolated (non-contiguous) sites of 25 b/s/Hz/site
Series of Experiments for IMT-Advanced

- Experimental demonstrations of target peak data rates for IMT-Advanced by NTT DOCOMO
  - **May 2003**: Achieved 100-Mbps transmission in field experiments at the speed of 30 km/h in downtown Yokosuka
    - Peak data rate of 135 (300) Mbps using 16QAM (64QAM) modulation and Turbo code with $R = 1/2 \ (3/4)$
  - **Aug. 2004**: Achieved 1-Gbps transmission with 4-by-4 MIMO multiplexing in laboratory experiments using fading simulators (10 b/s/Hz)
  - **May 2005**: Achieved 1-Gbps transmission in field experiments at the speed of 30 km/h in downtown Yokosuka
    - Peak data rate of 1.028 Gbps using 16QAM modulation and Turbo code with $R = 8/9$
  - **Dec. 2005**: Achieved 2.5-Gbps transmission with 6-by-6 MIMO multiplexing in field experiments at the speed of 10 - 30 km/h in YRP district (25 b/s/Hz)
    - Peak data rate of 2.556 Gbps using 64QAM modulation and Turbo code with $R = 8/9$
MLD-based Signal Detection
Achieving Extremely High Data Rate

Achievable performance of the OFDM MIMO multiplexing is largely dependent on the signal detection scheme.

- Linear spatial filtering, successive interference canceller, and maximum likelihood detection (MLD)

MLD achieves the best transmission performance due to the largest diversity, especially when the transmitter does not know the channel information.

- OFDM (100-MHz bandwidth)
- 1.048 Gbps
- 4 x 4 MIMO multiplexing
- 16QAM
- Turbo coding rate, $R = 8/9$
- 6 paths, r.m.s. delay spread = 0.26 µs, $f_D = 20$ Hz

There is no application environment in cellular systems if we employ MMSE filtering (maximum Geometry is approx. 25 dB)
Problem in MLD

- MLD finds the ML symbol vector that achieves

\[ y = Hs + n \quad \rightarrow \quad s_{ML} = \min_{s_{candidate}} \| y - Hs_{candidate} \|^2 \]

- Major drawback of the MLD is its prohibitive computational complexity.
  - Exponentially increased according to an increase in the number of bits per layer and the number of transmitter antenna branches (layers)

Number of squared Euclidian distance (SEDs) calculations

\[ N_{search} = 2^{LN_R} \]

- \( L \): Number of layers
- \( N_R \): Number of bits per symbol

Example: \( L = 4 \) and \( N_R = 4 \) (16QAM) \( \Rightarrow \) \( N_{search} = 65,536 \)
Finding ML is performed on a search tree.

- Example
  - Number of layers: \( L = 3 \)
  - Number of bits per symbol: \( N_R = 1 \) (BPSK)

There are \( 2^{LN_R} \) paths to be searched for finding the ML.
Orthogonalization of Transmitted Signal

Original received signal \( y = Hs + n \) does not allow for evaluation of each branch of the search tree.

Orthogonalization of the received signal vector based on QR decomposition on \( H \)

\[
y = Hs + n \quad \longrightarrow \quad z = Q^H y = Rs + Q^H n
\]

\( H \Rightarrow QR \)

\[
\begin{align*}
R^H R &= H^H H \\
\end{align*}
\]

Contain all \( s_1, \ldots, s_L \) \( \Rightarrow \) used for evaluation of \( L \)-th layer’s branches

\[
\begin{bmatrix}
z_1 \\
z_2 \\
\vdots \\
z_L
\end{bmatrix} =
\begin{bmatrix}
r_{1,1} & r_{1,2} & \cdots & r_{1,L} \\
0 & r_{2,2} & \cdots & r_{2,L} \\
0 & 0 & \cdots & r_{L-1,L-1} & r_{L-1,L} \\
0 & 0 & 0 & \cdots & r_{L,L}
\end{bmatrix}
\begin{bmatrix}
s_1 \\
s_2 \\
\vdots \\
s_L
\end{bmatrix} +
\begin{bmatrix}
n'_1 \\
n'_2 \\
\vdots \\
n'_L
\end{bmatrix}
\]

Contain \( s_L \) only \( \Rightarrow \) used for evaluation of first layer’s branches
Tree Search Using Orthogonalized Signal

- Example
  - Number of layers: \( L = 3 \)
  - Number of bits per symbol: \( N_R = 1 \) (BPSK)

```
\[
\begin{align*}
    z_1 &= \begin{bmatrix} r_{1,1} & r_{1,2} & r_{1,3} \end{bmatrix} s_1 + \begin{bmatrix} n'_1 \end{bmatrix} \\
    z_2 &= \begin{bmatrix} 0 & r_{2,2} & r_{2,3} \end{bmatrix} s_2 + \begin{bmatrix} n'_2 \end{bmatrix} \\
    z_3 &= \begin{bmatrix} 0 & 0 & r_{3,3} \end{bmatrix} s_3 + \begin{bmatrix} n'_3 \end{bmatrix}
\end{align*}
\]
```

1\(^{st}\) layer: evaluated by using \( z_3 \)

2\(^{nd}\) layer: evaluated by using \( z_2 \)

3\(^{rd}\) layer: evaluated by using \( z_1 \)

Branch metric is measured by the squared Euclidian distance (SED) and path metric is the sum of branch metrics.

There are various computationally efficient tree search to find the ML symbol vector (node).
Sphere Detection

- Sphere detection prioritizes the search in vertical direction of the tree (depth first search).
  - Once some node has path metric below the threshold $C$, one of the succeeding branch is evaluated to calculate the path metric of the next node.
  - If the path metric is larger than $C$, all the following nodes are discarded from the search list and the search restarts from the node which has not been evaluated yet.

Initial $C$ is 15.

$C$ is updated to 13.

$C$ is updated to 10.
M-algorithm prioritizes the search in horizontal direction of the tree (breadth first search).

- The M-algorithm evaluates all branches belonging to the surviving nodes in the layer of interest.
- By comparing all path metrics of the evaluated paths, M paths (nodes in the next layer) are selected.
- Then, the search moves to the next layer and the branches leaving from the selected $M$ nodes are evaluated. This process is repeated $L$ stages.
## Comparison

<table>
<thead>
<tr>
<th></th>
<th>Sphere detection</th>
<th>M-algorithm (QRM-MLD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML detection</td>
<td>Guaranteed</td>
<td>Not guaranteed</td>
</tr>
<tr>
<td>Required number of branch evaluations (N_{search})</td>
<td>Approximately proportional to (L^3) (not fixed)</td>
<td>Approximately (LM^{2N_R})</td>
</tr>
<tr>
<td>Variation in complexity</td>
<td>Large variation</td>
<td>No variation</td>
</tr>
<tr>
<td>Parallel processing</td>
<td>Difficult</td>
<td>Relatively easy</td>
</tr>
</tbody>
</table>
When we consider the further reduction in the complexity of M-algorithm, there are two approaches.

- Reduction in $M$ value
- Reduction in number of SED calculations per surviving node

$N_{search} \sim L \times M \times 2^{N_R}$

- Number of stages (cannot be changed)
- Number of SED calculations per surviving node
- Number of surviving nodes (symbol candidates)

$M$ should be as small as possible while maintaining the required error rate.
ITS-MLM

- ITS-MLM (iterative tree search with multi-level bit mapping) reduces the number of SED calculations per surviving node by utilizing the multi-level QAM signal structure
  - One layer is divided into multiple hierarchical sublayers.
  - Selection of surviving nodes sublayer by sublayer
ASESS (adaptive selection of surviving symbol candidates) performs selection of surviving node first and calculates SED for the selected node (path)

- Selection of the surviving node is based on the branch ordering within a origin node and the maximum path metric derived from respective origin node.
Quadrant Detection for Branch Ordering

(1) First quadrant detection

Received signal multiplied by $Q^H$, $z_m$, after subtraction of surviving symbol replica components

(2) Second quadrant detection

(3) Third quadrant detection

(4) Branch ordering (symbol ranking) based on distance from detected quadrant
When we assume channel coding and soft-input decoding, LLR should be calculated from the MLD output.

\[ L_i = \min_{c_i=0} \| y - Hs_{c_i=0} \|^2 - \min_{c_i=1} \| y - Hs_{c_i=1} \|^2 \]

Path metric (full length)

We need the path metric not only of the ML symbol candidate but also of the symbol candidates that represent each of the opposite bits to the ML.

However, with complexity reduced MLD, some of the path metrics for calculating LLR may not be provided from the MLD output.

- Since the complexity reduced MLD does not evaluate all paths.
LLR Calc. in Complexity Reduced MLD

• Example

Bits #1, 2, 3, 4

\[
\begin{array}{cccc}
1,1,1,1 & 1,1,1,0 & 1,0,1,0 & 1,0,1,1 \\
\end{array}
\]

Surviving symbols

\[
\begin{array}{cccc}
1,1,0,1 & 1,1,0,0 & 1,0,0,0 & 1,0,0,1 \\
\end{array}
\]

\[
\begin{array}{cccc}
0,1,0,1 & 0,1,0,0 & 0,0,0,0 & 0,0,0,1 \\
\end{array}
\]

\[
\begin{array}{cccc}
0,1,1,1 & 0,1,1,0 & 0,0,1,0 & 0,0,1,1 \\
\end{array}
\]

e: path metric (accumulated SED)  
(\text{Assume } e_1 < e_2 < e_3 < e_4)

LLR of 1\textsuperscript{st} bit = e_4 - e_1

LLR of 2\textsuperscript{nd} bit = e_2 - e_1

LLR of 4\textsuperscript{th} bit = e_1 - e_3

LLR of 3\textsuperscript{rd} bit: 
Cannot be calculated since there is no surviving symbol representing third bit = “1”.

We need additional estimation for the metrics of the missing bits.
Simple Averaging-based Method

- Estimation of the path metric of the missing bits based on the averaging of the MLD output

Path metric for bit “0” → Select larger one → Averaged over multiple bits → $X$ (constant; $X > 1$ for penalty)

Commonly used as a path metric for all the missing bits

Only when the path metrics for both bit “0” and “1” exist.
Performance Example (1)

Packet error rate with M-algorithm

- Simulation conditions
  - 100-MHz bandwidth
  - $L = N_{tx} = N_{rx} = 4$
  - 16QAM modulation
  - Rate-8/9 Turbo code
  - Rms delay spread = 0.26 μs

- $N_{search}$

<table>
<thead>
<tr>
<th></th>
<th>Full MLD</th>
<th>$M = 16$</th>
<th>$M = 12$</th>
<th>$M = 8$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>65,536</td>
<td>784</td>
<td>592</td>
<td>400</td>
</tr>
</tbody>
</table>

M-algorithm

- $M = 8$
- $M = 12$
- $M = 16$
Performance Example (2)

Comparison of various M-algorithm based detections

- Simulation conditions
  - 100-MHz bandwidth
  - 0.5-ms frame
  - $L = N_{tx} = N_{rx} = 4$
  - Rate-8/9 Turbo code
  - Rms delay spread = 0.26 $\mu$s

![Graph showing comparison of various M-algorithm based detections and calculation cost per frame vs. required $E_b/N_0$ for packet error rate of $10^{-2}$ (dB).](image-url)
Investigation of Peak Frequency Efficiency of 50 Bit/Second/Hz
In a multi-cell environment, the achievable peak data rate is determined based on received SINR near cell cite.

Received SINR at 80% CDF is 30 dB when channel load is 10%.

Spectrum efficiency of 50 b/s/Hz is near the upper limit (assuming MLD-based detection)

Research objective
Demonstrate ultimate spectrum efficiency of approximately 50 b/s/Hz (i.e., 5 Gbps using 100 MHz channel bandwidth) based on field experiments
Features of Experimental Configuration

◆ OFDM radio access with 100-MHz transmission bandwidth
◆ Efficient modulation and channel coding scheme
  • 64QAM data modulation
  • Turbo code with coding rate of $R = 8/9$
◆ 12-by-12 MIMO multiplexing
◆ MLD-based signal detection
  • QRM-MLD with ASESS
  • LLR generation appropriate for QRM-MLD

◆ Calculation cost for all sub-carriers per frame

<table>
<thead>
<tr>
<th>Method</th>
<th>Calculation Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMSE</td>
<td>$1.2 \times 10^9$</td>
</tr>
<tr>
<td>Full MLD</td>
<td>$5.0 \times 10^{28}$</td>
</tr>
<tr>
<td>Original QRM-MLD</td>
<td>$4.4 \times 10^{10}$</td>
</tr>
<tr>
<td>QRM-MLD with ASESS</td>
<td>$2.5 \times 10^9$</td>
</tr>
</tbody>
</table>

(NOTE) Calculation cost per operation for real multiplication, real addition, comparison, bit-shift, and table lookup are set to 10, 1, 1, 0, and 6, respectively.
Structure of 12-by-12 MIMO Transceiver

Kenichi Higuchi, TUS/ Nov. 16, 2009.

Base station transmitter

Mobile station receiver

1. Transmitter antennae
2. Receiver antennae

RF transmitter for Branch #1
- BPF
- Quadrature modulator
- HPA
- Synthesizer
- Local

RF receiver for Branch #1
- BPF
- AGC
- Quadrature detector
- LNA
- Synthesizer
- Local

In-phase Quadrature
- LPF
- D/A
- Memory
- HDD

Generation of transmitted baseband signals
- LPF: Low-pass filter
- BPF: Band-pass filter
- HPA: High power amplifier

Recovery of received baseband signals
- AGC: Automatic gain control
- LNA: Low noise amplifier

LNA: Low noise amplifier
AGC: Automatic gain control
BPF: Band-pass filter
HPA: High power amplifier
LPF: Low-pass filter
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio access</td>
<td>OFDM</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>4.635 GHz</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>101.4 MHz</td>
</tr>
<tr>
<td>Sub-frame length</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>Number of sub-carriers</td>
<td>1536 (65.919 kHz subcarrier separation)</td>
</tr>
<tr>
<td>OFDM symbol duration</td>
<td>Effective data 15.170 μs + CP 2.067 μs (2048 + 279 samples)</td>
</tr>
<tr>
<td>Data modulation</td>
<td>64QAM</td>
</tr>
<tr>
<td>Channel coding / decoding</td>
<td>Turbo coding ($R = 8/9, K = 4$) / Max-Log-MAP decoding</td>
</tr>
<tr>
<td>Number of antennas</td>
<td>12-by-12 MIMO</td>
</tr>
<tr>
<td>Information bit rate</td>
<td>4.92 Gbps</td>
</tr>
<tr>
<td>OFDM symbol timing detection</td>
<td>Pilot symbol-based symbol timing detection</td>
</tr>
<tr>
<td>Channel estimation</td>
<td>Pilot symbol-based two-dimensional MMSE channel estimation</td>
</tr>
<tr>
<td>Signal detection</td>
<td>QRM-MLD with ALESS</td>
</tr>
</tbody>
</table>
Subframe Structure

1 subframe (= 0.5 ms)

1536 sub-carrier

Frequency

Data

Branch #1  #2  #3  #4  #5  #6
#7  #8  #9  #10  #11  #12

Pilot
Realization of Peak Frequency Efficiency of 50 b/s/Hz Using OFDM MIMO Multiplexing with MLD Based Signal Detection

- Targeting to achieve the peak rate at the SINR of 30 dB, which corresponds to the 80% outage probability in cellular system assuming 10% channel load
- MIMO configuration is 12-by-12 antennas with 64QAM data modulation and Rate-8/9 Turbo code
- The use of MLD is essential for achieving 50 b/s/Hz at SINR of 30 dB
- Complexity reduced MLD (QRM-MLD with ASESS) and LLR calculation method for complexity reduced MLD are investigated