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

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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

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- 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 rata 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 rata of 2.556 Gbps using 64QAM modulation and Turbo code with R = 8/9

MLD-based Signal Detection

Achieving Extremely High Data Rate

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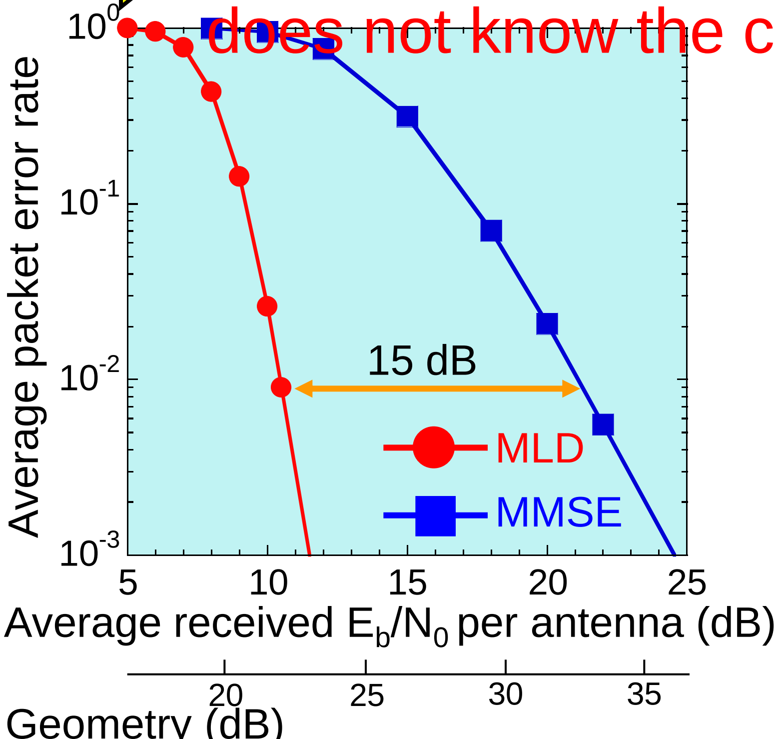
- Achievable performance of the OFDM MIMO multiplexing is largely dependent on the signal detection scheme.
  - Linear spatial filtering, successive interference canceller, and maximum likelihood detection (MLD)

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

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n} \quad \Rightarrow \quad \mathbf{s}_{ML} = \min_{\mathbf{s}_{candidate}} \left\| \mathbf{y} - \mathbf{H}\mathbf{s}_{candidate} \right\|^2$$

- 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) ➔ N_{search} = 65,536

Tree Search

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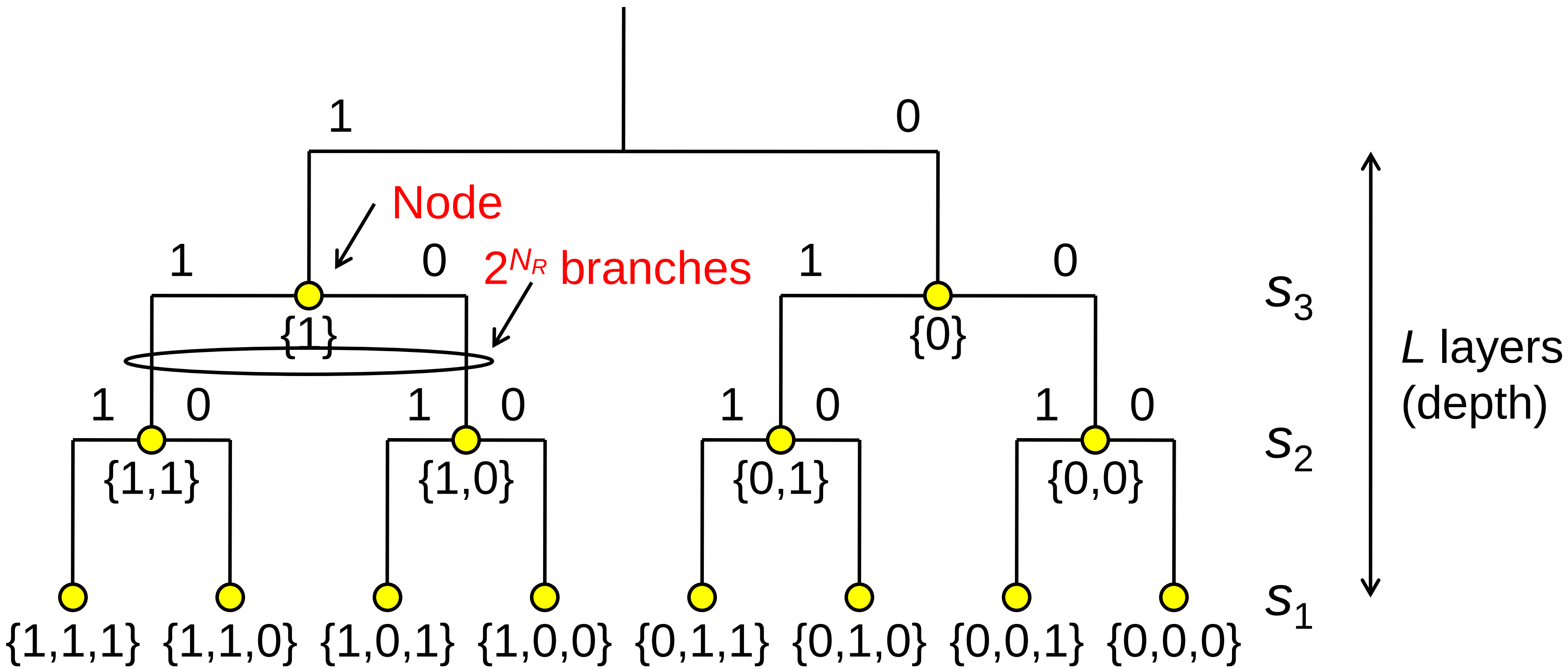
Finding ML is performed on a search tree.

- 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

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- 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**

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n} \quad \Rightarrow \quad \mathbf{z} = \mathbf{Q}^H \mathbf{y} = \mathbf{R}\mathbf{s} + \mathbf{Q}^H \mathbf{n}$$

$$\mathbf{H} \Rightarrow \mathbf{Q}\mathbf{R}$$

$$\therefore \mathbf{R}^H \mathbf{R} = \mathbf{H}^H \mathbf{H}$$

Contain all s_1, …, s_L ➔ used for evaluation of L-th layer's branches ⇨ (row z_1)

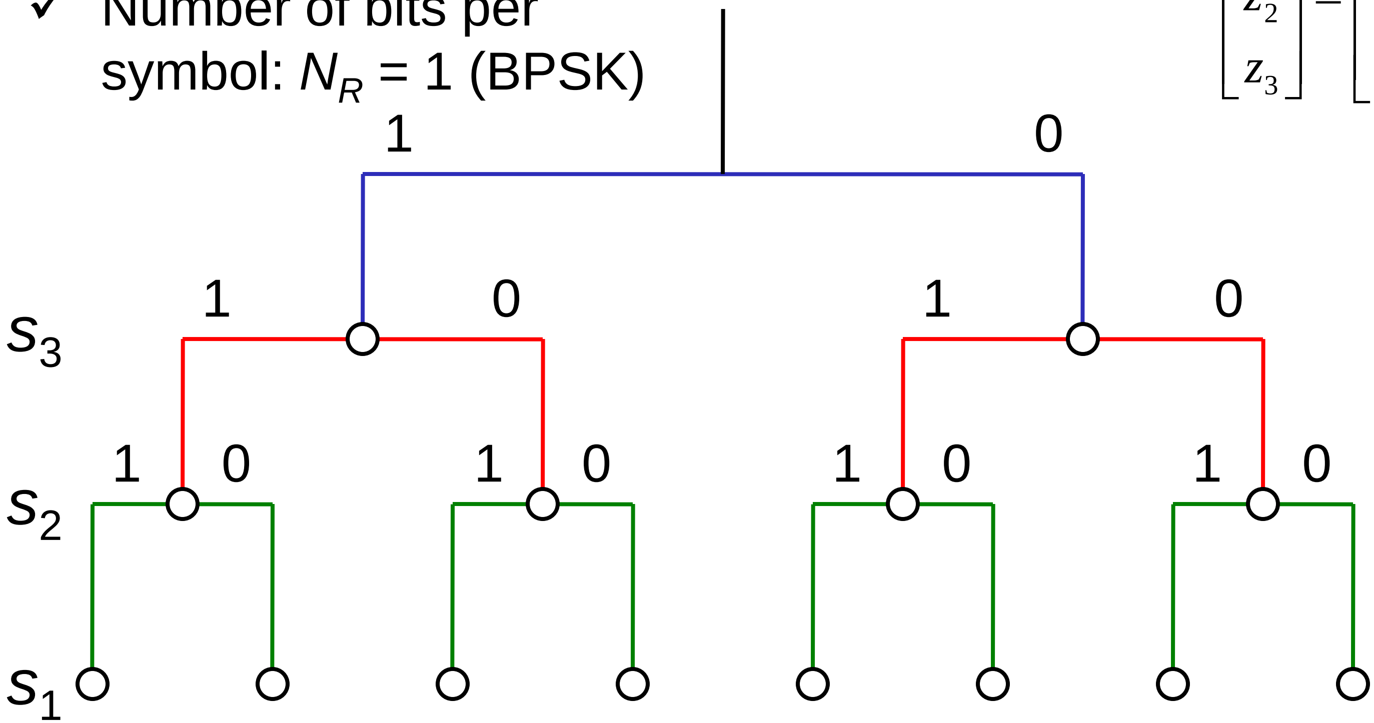
Contain s_L only ➔ used for evaluation of first layer's branches ⇨ (row z_L)

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

Tree Search Using Orthogonalized Signal

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

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



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

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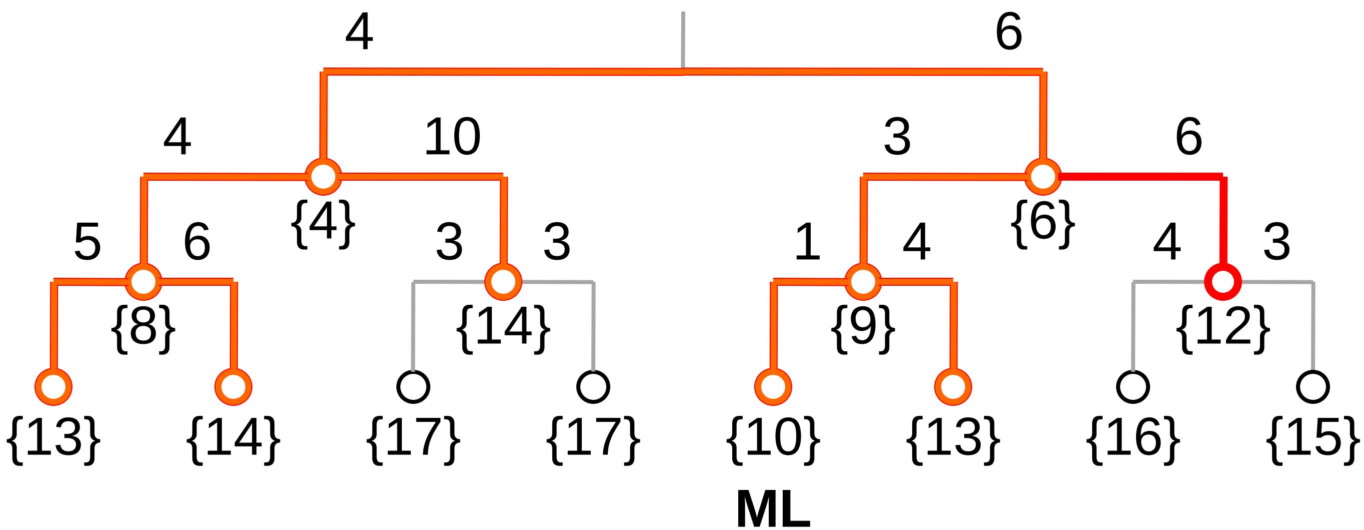
- Sphere detection prioritizes the search in vertical direction of the tree (depth first search).
  - Once some node has path metric below the threshold *C*, one of the succeeding branch is evaluated to calculate the path metric of the next node
  - If the path metric is larger than *C*, all the following 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

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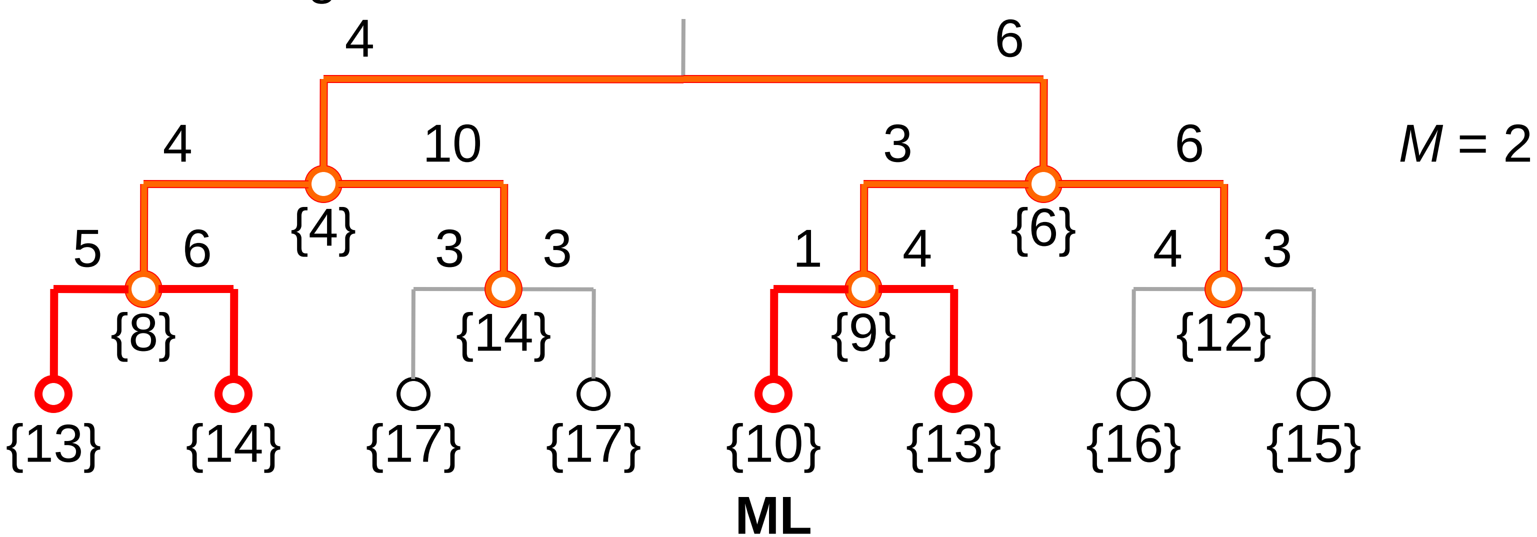
- M-algorithm prioritizes the search in horizontal direction of the tree (breadth first search).
  - The M-algorithm evaluates all branches belonging to the surviving nodes in the layer of interest.
  - By comparing all path metrics of the evaluated paths, M paths (nodes in the next layer) are selected.
  - 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

	Sphere detection	M-algorithm (QRM-MLD)
ML detection	Guaranteed	Not guaranteed
Required number of branch evaluations N_{search}	Approximately proportional to L^3 (not fixed)	Approximately $LM2^{N_R}$
Variation in complexity	Large variation	No variation
Parallel processing	Difficult	Relatively easy

Complexity Reduction in M-algorithm

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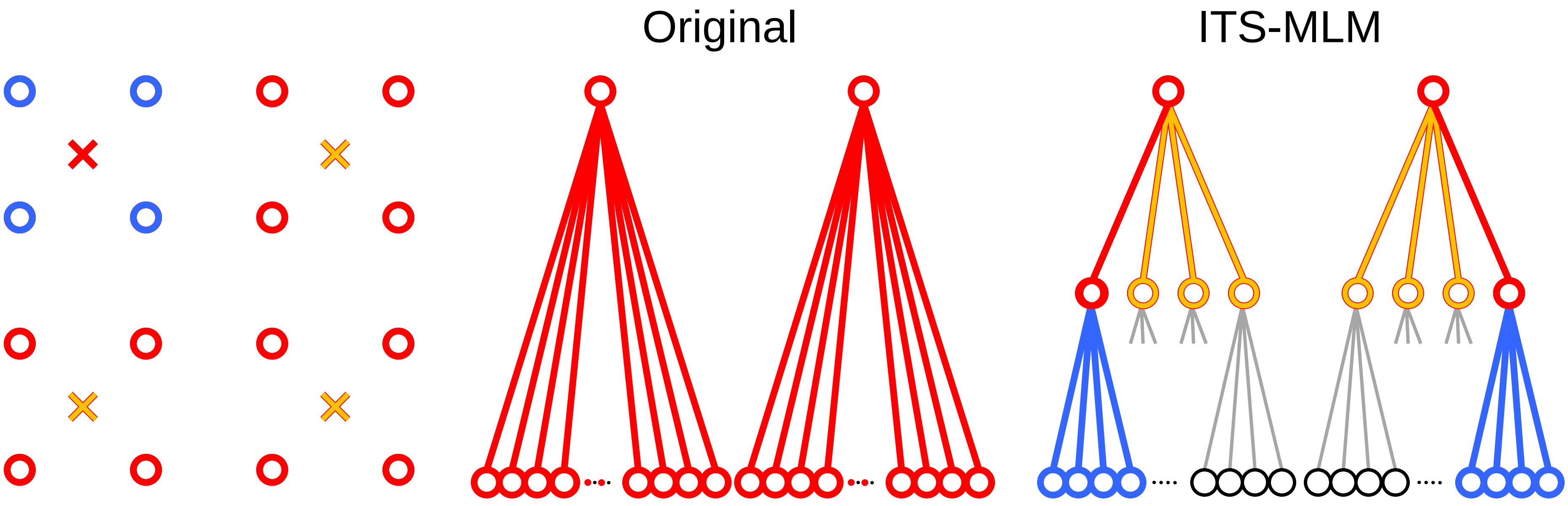
- When we consider the further reduction in the complexity of M-algorithm, there are two approaches.
  - Reduction in *M* value
  - Reduction in number of SED calculations per surviving node

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

- L: Number of stages (cannot be changed)
- 2^{N_R}: Number of SED calculations per surviving node
- M: 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

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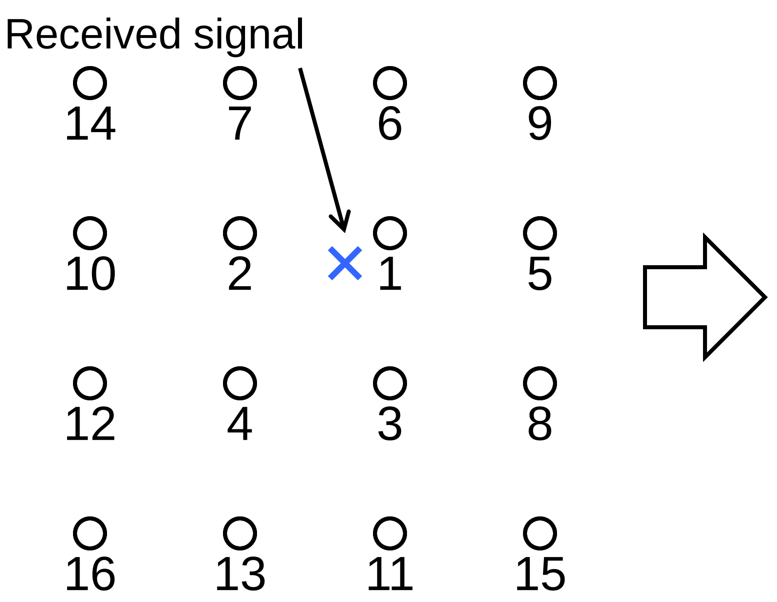
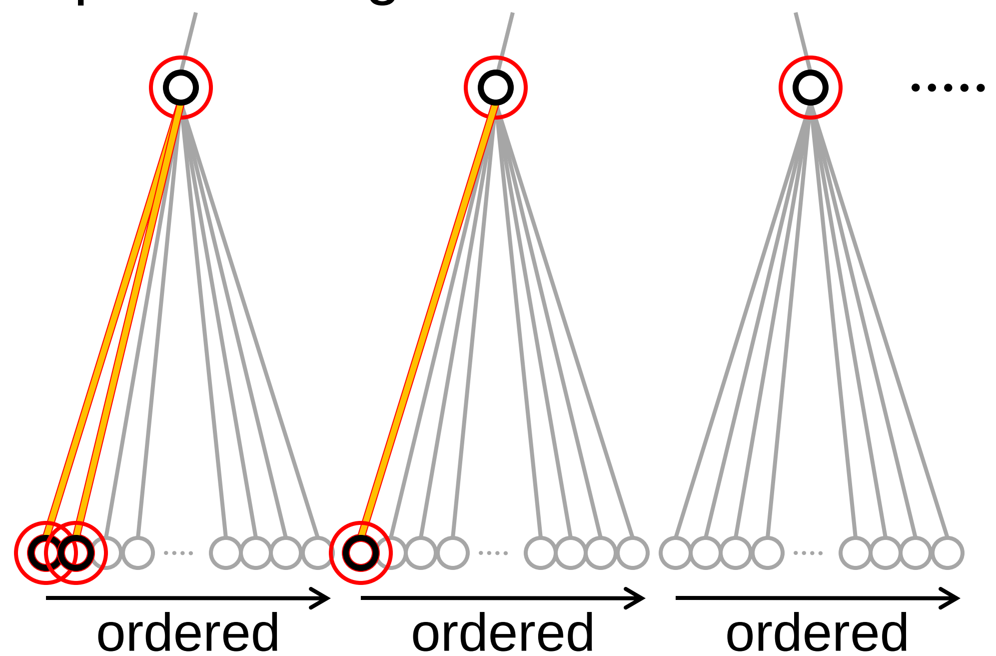
- ASESS (adaptive selection of surviving symbol candidates) performs selection of surviving node first and calculates SED for the selected node (path)
  - Selection of the surviving node is based on the branch ordering within a origin node and the maximum path metric derived from respective origin node



Branch ordering



Adaptive selection ➔ Only M SED calc. per stage

Quadrant Detection for Branch Ordering

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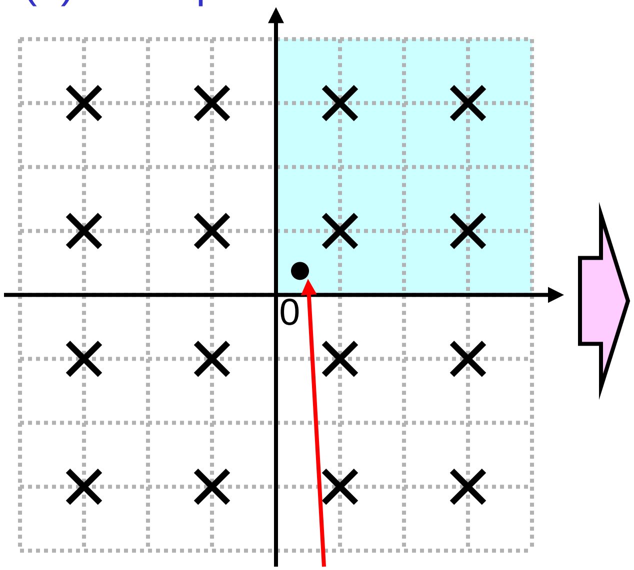
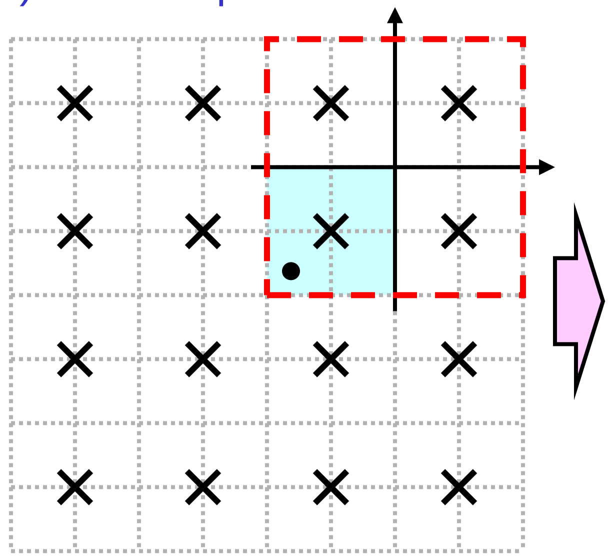
(1) First quadrant detection

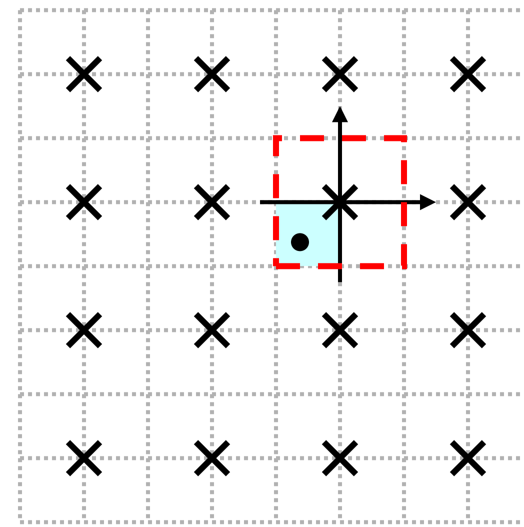


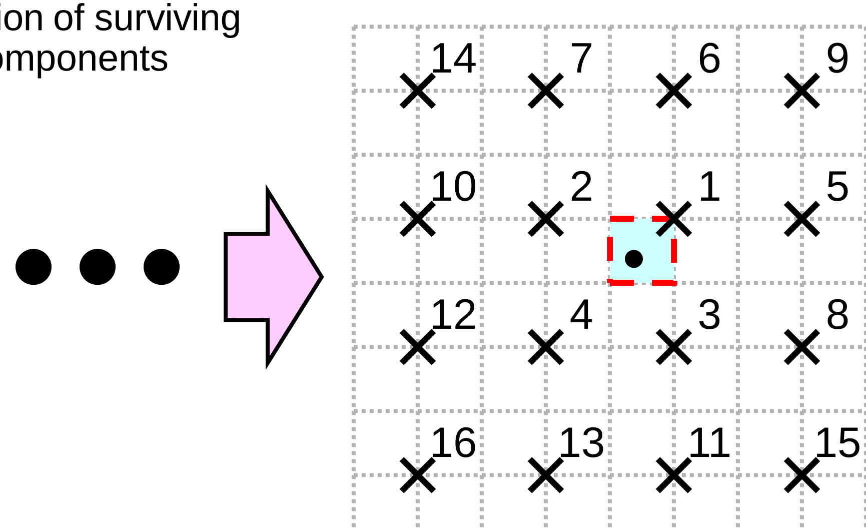
Received signal multiplied by $\mathbf{Q}^H$, z_m, after subtraction of surviving symbol replica components

(2) Second quadrant detection



(3) Third quadrant detection





(4) Branch ordering (symbol ranking) based on distance from detected quadrant

LLR Calc. in Complexity Reduced MLD

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- When we assume channel coding and soft-input decoding, LLR should be calculated from the MLD output.

LLR (assuming Max-log MAP approximation)

$$L_i = \min_{c_i=0} \left\| \mathbf{y} - \mathbf{H}\mathbf{s}_{c_i=0} \right\|^2 - \min_{c_i=1} \left\| \mathbf{y} - \mathbf{H}\mathbf{s}_{c_i=1} \right\|^2$$

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

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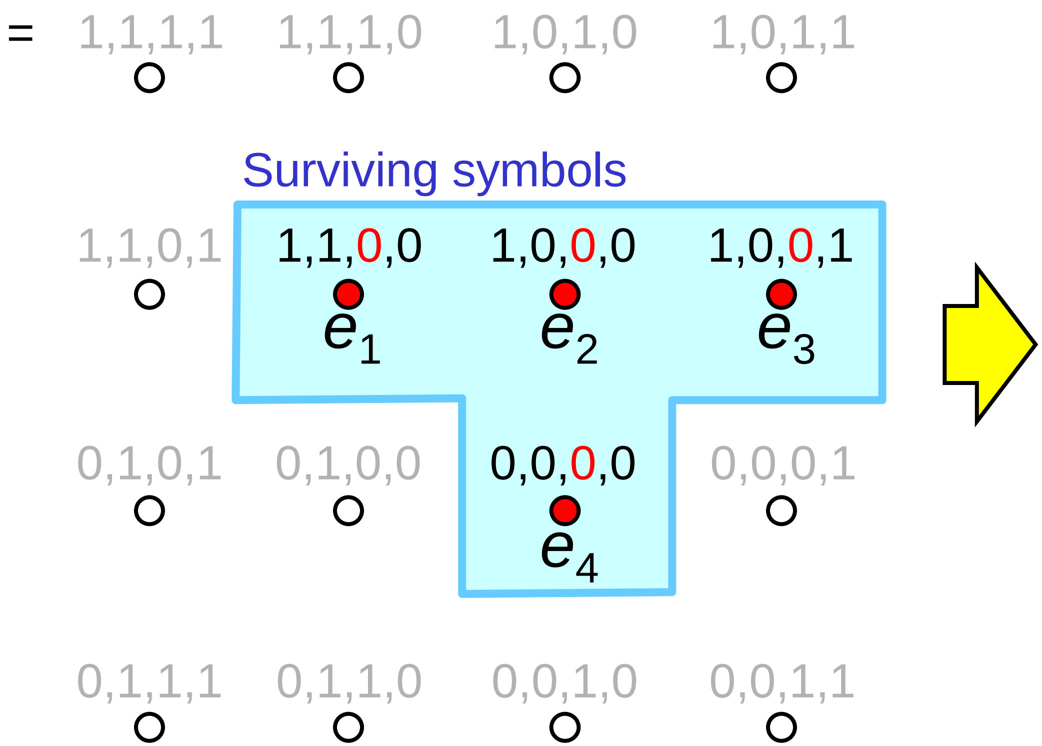
- Example

Bit #1, 2, 3, 4



e: path metric (accumulated SED)
(Assume $e_1 < e_2 < e_3 < e_4$)

LLR of 1st bit = $e_4 - e_1$

LLR of 2nd bit = $e_2 - e_1$

LLR of 4th bit = $e_1 - e_3$

LLR of 3rd 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

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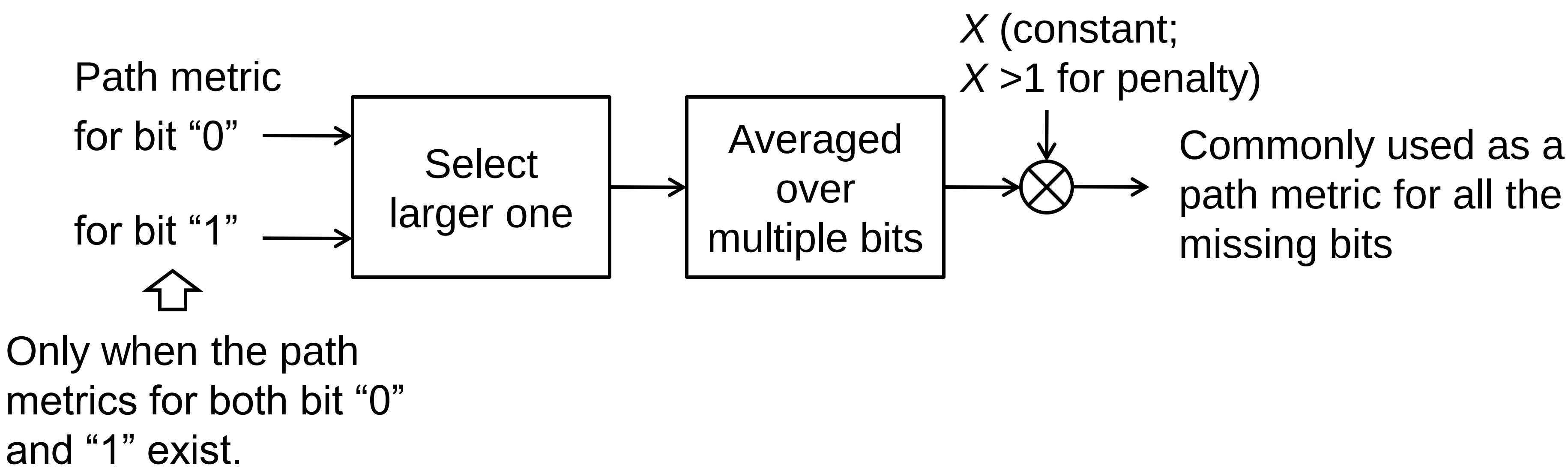
- Estimation of the path metric of the missing bits based on the averaging of the MLD output



Performance Example (1)

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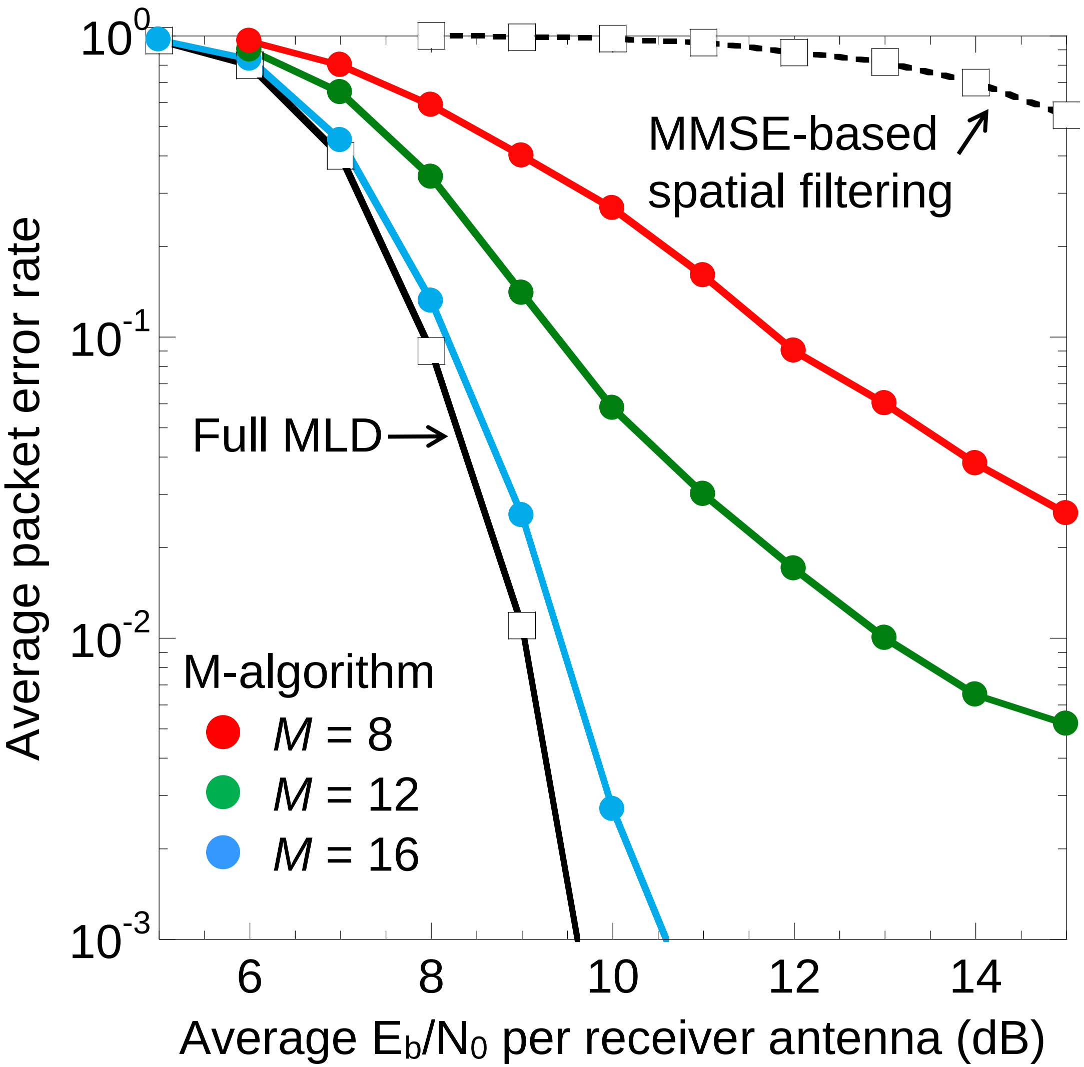
☐ Packet error rate with M-algorithm

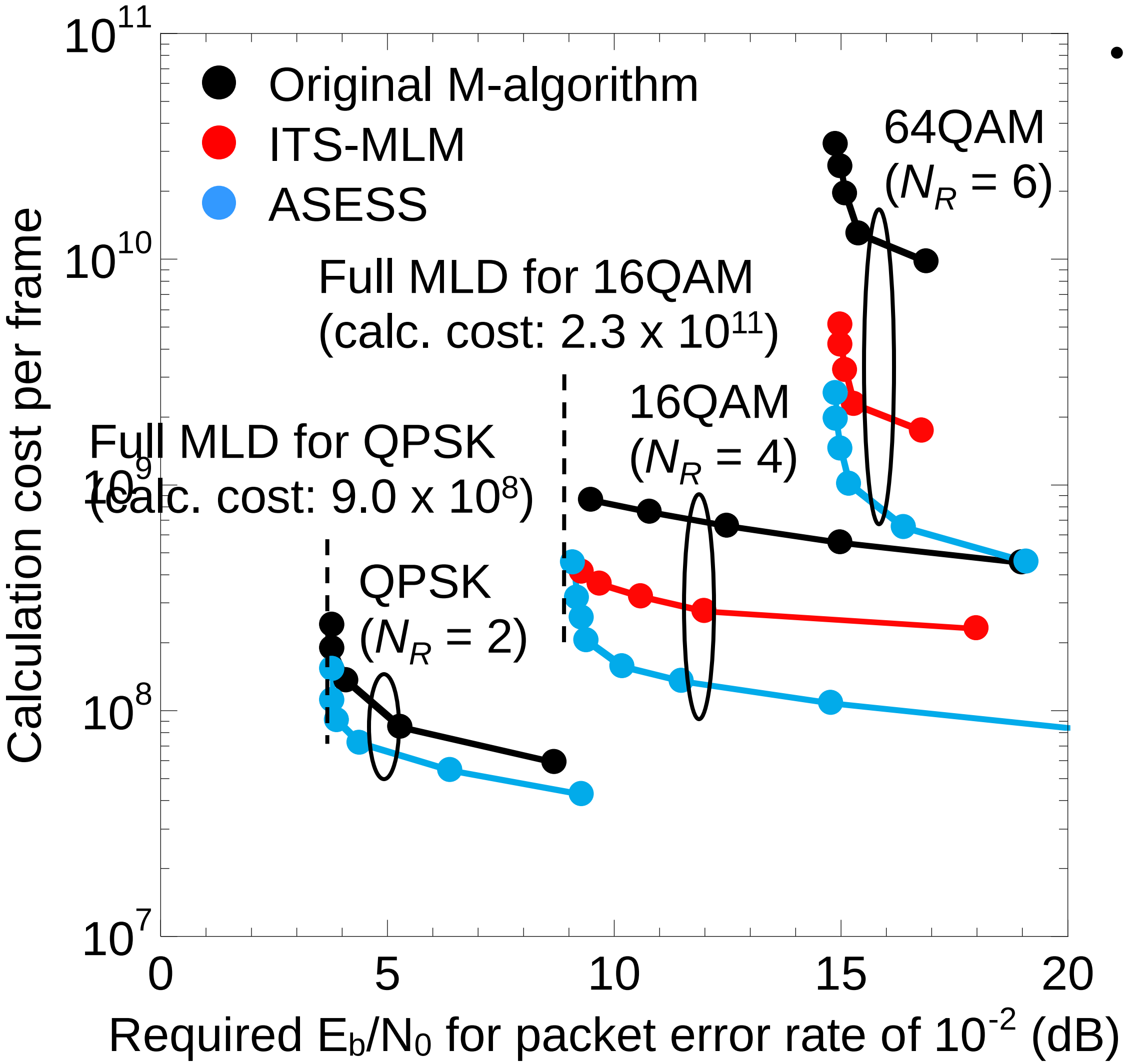


- Simulation conditions
  - ✓ 100-MHz bandwidth
  - ✓ $L = N_{tx} = N_{rx} = 4$
  - ✓ 16QAM modulation
  - ✓ Rate-8/9 Turbo code
  - ✓ Rms delay spread = 0.26 μs
- N_{search}

Full MLD	65,536
M = 16	784
M = 12	592
M = 8	400

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 μs

Investigation of Peak Frequency Efficiency of 50 Bit/Second/Hz

Investigation of Ultimate Freq. Efficiency

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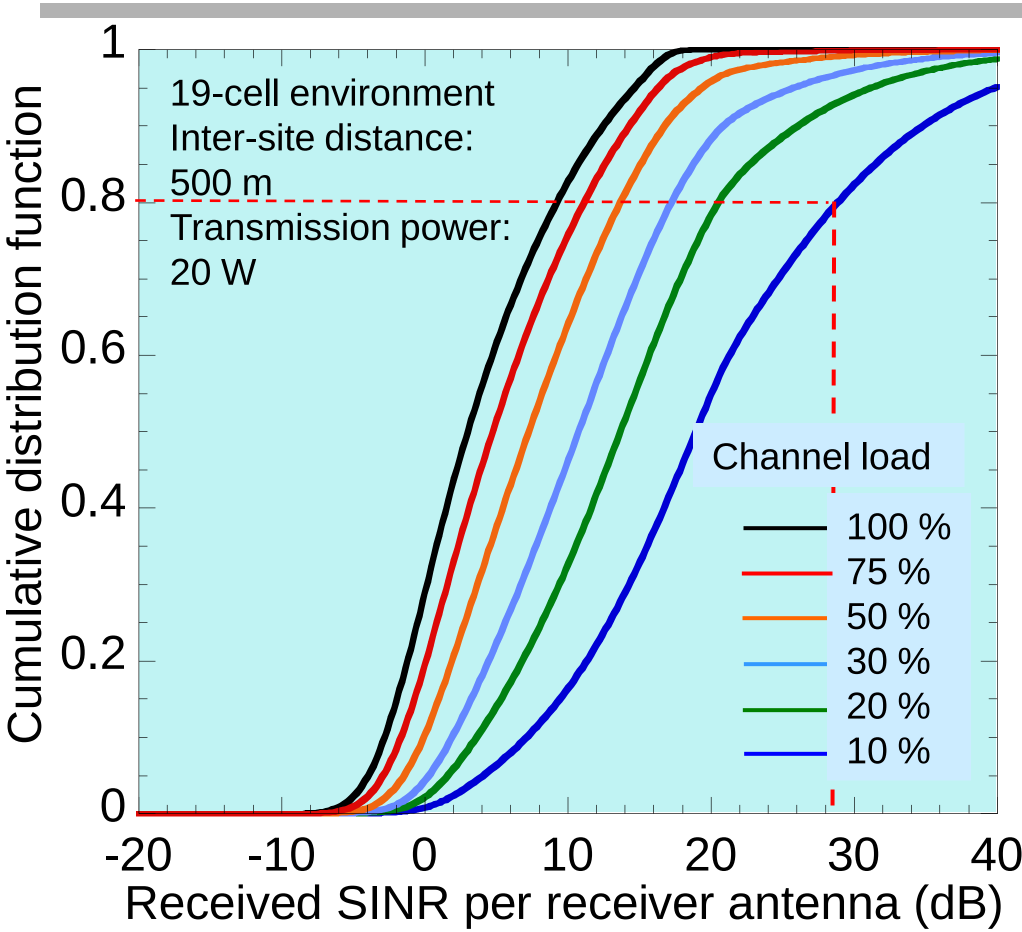

◆ In a multi-cell environment, the achievable peak data rate is determined based on received SINR near cell cite.

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)

SINR: Signal-to-interference plus noise power ratio
CDF: Cumulative distribution function

◆ 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

MMSE	1.2×10^{9}
Full MLD	5.0×10^{28}
Original QRM-MLD	4.4×10^{10}
QRM-MLD with ASESS	2.5×10^{9}

$1/(2 \times 10^{17})$

1/15

(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

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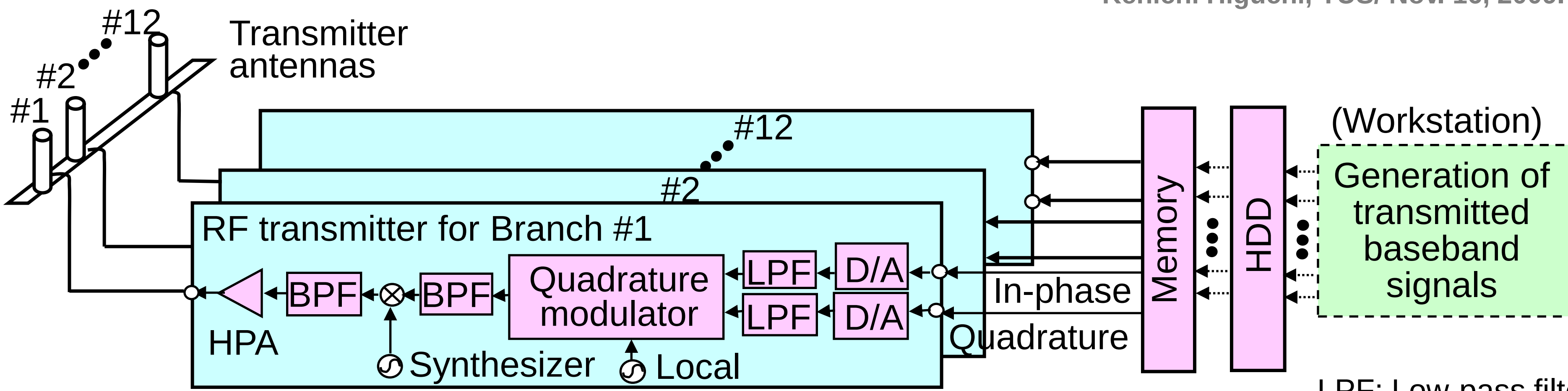
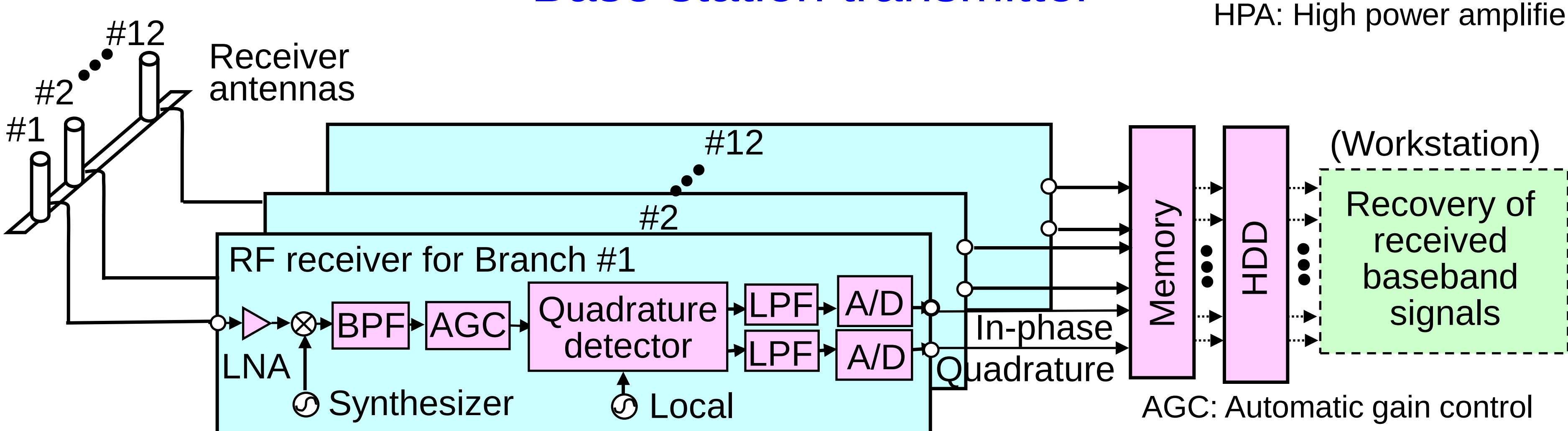


LPF: Low-pass filter
BPF: Band-pass filter
HPA: High power amplifier

Base station transmitter



AGC: Automatic gain control
LNA: Low noise amplifier

Mobile station receiver

Major Parameters for Field Experiments

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Radio access	OFDM
Carrier frequency	4.635 GHz
Channel bandwidth	101.4 MHz
Sub-frame length	0.5 ms
Number of sub-carriers	1536 (65.919 kHz subcarrier separation)
OFDM symbol duration	Effective data 15.170 μs + CP 2.067 μs (2048 + 279 samples)
Data modulation	64QAM
Channel coding / decoding	Turbo coding (R = 8/9, K = 4) / Max-Log-MAP decoding
Number of antennas	12-by-12 MIMO
Information bit rate	4.92 Gbps
OFDM symbol timing detection	Pilot symbol-based symbol timing detection
Channel estimation	Pilot symbol-based two-dimensional MMSE channel estimation
Signal detection	QRM-MLD with ASESS

Subframe Structure

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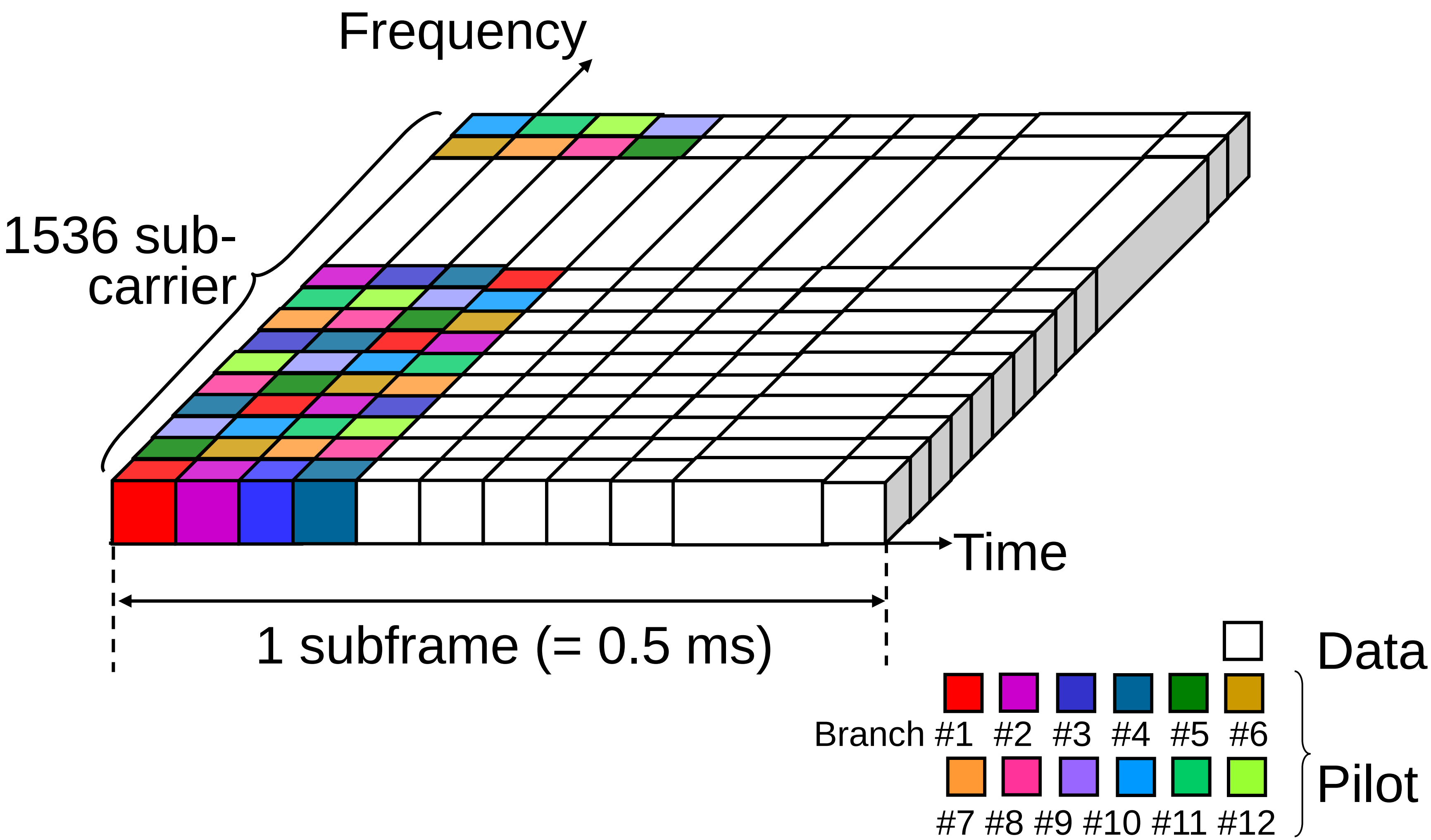

Summary

- 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