# MIMO Technologies for Wireless Communications

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## Agenda





## MIMO transmission

- Combination of Antenna Technology and Signal Processing for designing wireless channel
- Orthogonalization is an effective way for increase of channel capacity
- Time, Frequency(OFDM)

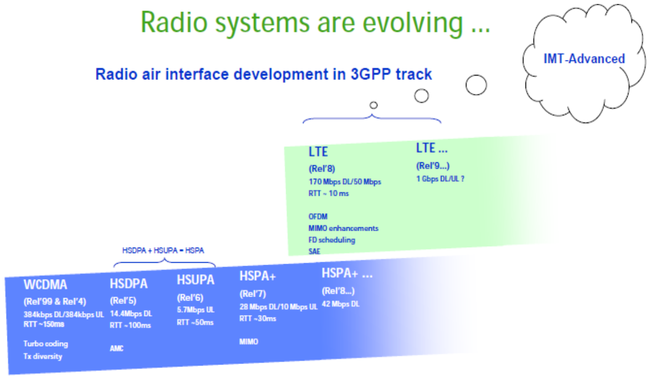
  ⇒ Space(MIMO)



## Friis Formula

- TX antenna＋Channel＋RX antenna
- TX/RX antennas : Deterministics Designable
- Channel : Stochastics Un-designable
- Gt(λ/4πd)^2Gr
- Gt:TX antenna Gain Gr:TX antenna Gain
- (λ/4πd)^2:Free Space Loss

## Radio systems are evolving ...






# MIMO History

- BLAST
- MUD (Multi user detection)
- Space-time Code
- TX Diversity
- Advanced PHS



# BLAST

- Sequential Zero-forcing for Multi-stream Detection
- Diversity can be obtained at later stage
- Bell Laboratory originally proposed



# MUD (Multi-User Detection)

- If # of RX antennas is $M_r$, then signals from $M_r$ users can be separated and detected simultaneously
- RX should know the channel responses for each user

# Space-Time Coding

- For 2 TX antennas Alamouti ST-Code
- 2 column vectors are orthogonal to each other
- TX does not need the channel responses
- Diversity order : 2

 for TX side

$$\mathbf{C} = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}$$



# Diversity

- RX side : 1 × N channel ⇒ Diversity order :N
- TX side : N × 1 channel ⇒ Diversity order : N



# Diversity Order

- For N i.i.d. Rayleigh channels

$$\mathbf{h} = (h_1, h_2, \cdots, h_n)^t$$

- MRC (Maximum SN-Ratio Combining)

$$\Gamma = \Gamma_1 + \Gamma_2 + \cdots + \Gamma_n$$

- Weight Vector

$$\mathbf{w} = \mathbf{h}^*$$



# MRC Synthesized Channel

- For each channel, pdf of SNR γ is exponential distribution
  Γ : average SNR

$$p(\gamma) = \exp(-\gamma / \Gamma) / \Gamma$$

- MRC synthesized channel's SNR becomes Gamma distribution
  cf. Nakagami-m distribution

$$p(\gamma) = \gamma^{n-1} \exp(-\gamma / \Gamma) / (\Gamma^n (n-1)!)$$

- Average Bit-error rate Pe is inversely proportional to n-th power of the average SNR

$$Pe = 1 / \{(\Gamma + 1)^n 2\} \cong 0.5 / \Gamma^n$$

# Advanced PHS

- Space Division Multiplexing
- “i-burst” (IEEE802.20) uses also SDMA



# Channel Coding Theorem

- For R<C , there exists a code such that an average error probability for any code word decreases exponentially with code length N [ Reliable Communication]
- For R>C an average error probability of code word approaches to unity exponentially by increasing N for any code [ No reliable communication]
- R : Data Rate C : Channel Capacity



# SISO Channel Capacity

- Channel Capacity

$$C_{\mathrm{SISO}} = B \log_2 [1 + \frac{P}{BN_0} |h|^2] \text{ [bit/s]}$$

TX Power ($P$), Bandwidth ($B$), Noise Power Density ($N_0$)

- Frequency Efficiency

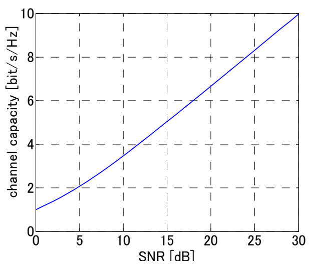
$$C_{\mathrm{SISO}} / B = \log_2 [1 + \frac{P}{\sigma^2} |h|^2] \text{ [bit/s/Hz]}$$

Noise Power ($\sigma^2$)

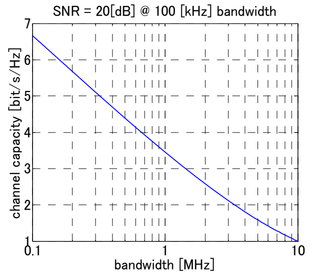


# Frequency Efficiency

SNR




Bandwidth



# MIMO Channel Capacity

- Equi-TX Power Case

$$C_{\mathrm{MIMO}} = \log_2[\det(\mathbf{I} + \frac{P}{\sigma^2 m_s}\mathbf{H}\mathbf{H}^H)] \quad \text{[bit/s/Hz]}$$

- Fading Average (Ergodic Capacity)

$$C_{\mathrm{MIMO}}^{\mathrm{av}} = \mathrm{E}[C_{\mathrm{MIMO}}] = \int C_{\mathrm{MIMO}}(\mathbf{H}) f(\mathbf{H}) d\mathbf{H}$$

Channel Matrix pdf



# MIMO Channel Matrix Analysis

- MIMO Channel Degree

$$m = \min[m_s, m_r]$$

$$m_s : \# TX\text{-}Ant \quad m_r : \# RX\text{-}Ant$$

- MIMO Channel Matrix Orthogonalization

$$\mathbf{H} = \mathbf{U}\Sigma\mathbf{V}^H$$

- MIMO Channel Eigen Mode

$$\Sigma = \mathrm{diag}[\sqrt{\lambda_1}, \cdots, \sqrt{\lambda_m}]$$



# MIMO Channel Capacity Analysis

- Eigen Mode Channel

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}$$

$$\mathbf{y}' = \Sigma\mathbf{s}' + \mathbf{n}'$$

RX Weight $m = \min[m_s, m_r]$ TX Weight

$m_s$ #TX-Ant $m_r$ #RX-Ant

- Eigen Mode MIMO Channel Capacity

$$C_{\mathrm{MIMO}} = \sum_{i=1}^{m} \log_2[1 + \frac{P}{\sigma^2 m_s}\lambda_i] \quad \text{[bit/s/Hz]}$$



MIMO channel can be reconstructed by Signal Processing at Base-band.

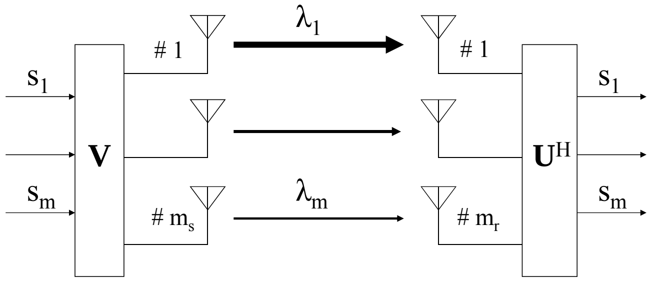
- Unitary Matrix **V** at TX conserves a total TX power.

$$\mathbf{s}' = \mathbf{V}\mathbf{s} \qquad |\mathbf{s}'|^2 = |\mathbf{s}|^2$$

- Unitary Matrix $\mathbf{U}^{\mathbf{H}}$ at RX conserves a RX noise property.

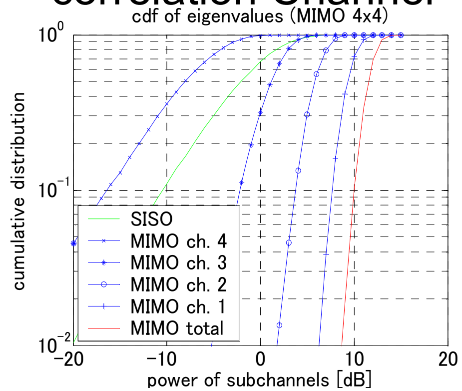
$$\mathbf{n}' = \mathbf{U}^H\mathbf{n} \qquad \overline{\mathbf{n}'\mathbf{n}'^H} = \overline{\mathbf{n}\mathbf{n}^H} = \sigma^2 \mathrm{I}$$

# MIMO Eigen Mode System



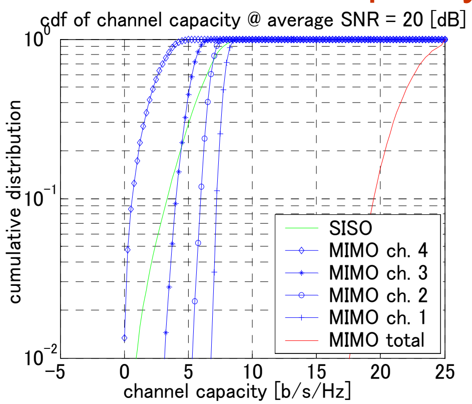



# Eigen-value Distribution for non correlation Channel






# CDF of Channel Capacity






# Water Pouring Algorithm

- Optimum TX Power Assignment

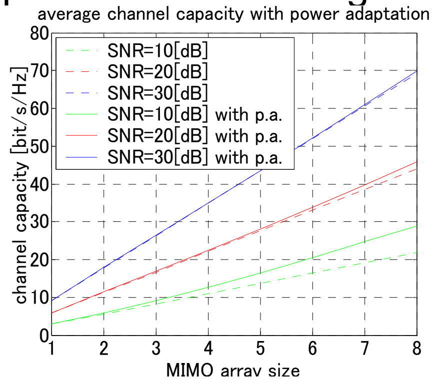
$$\sum_{i=1}^{m} P_i = P$$

$$C_{\mathrm{MIMO}} = \sum_{i=1}^{m} \log_2 [1 + \frac{P_i}{\sigma^2} \lambda_i]$$

- Water Pouring Theorem

$$C_{\mathrm{opt}} = \sum_{i=1}^{m} [\log_2 [\mu \frac{\lambda_i}{\sigma^2}]]^+$$

# Channel Capacity Improvement by Optimum Power Assignment






- MIMO Channel Capacity ∝ Antenna Size

cf. Adaptive Array ∝ log(Antenna Size)

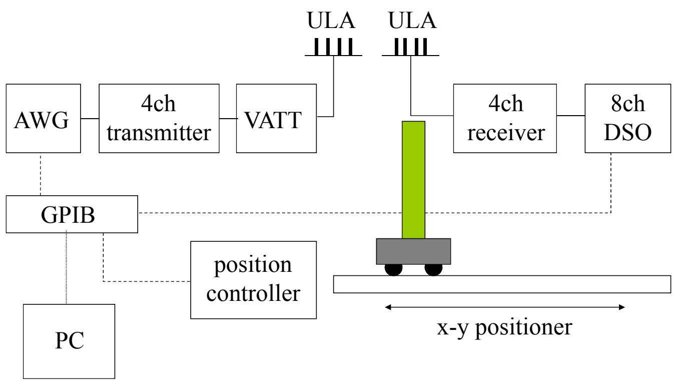
- MIMO Channel can be transformed to Eigen-mode sub-Channels



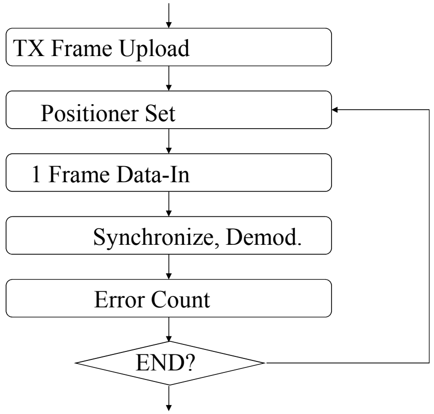
# MIMO Propagation Measurement



# Measurement Systems



# Procedure

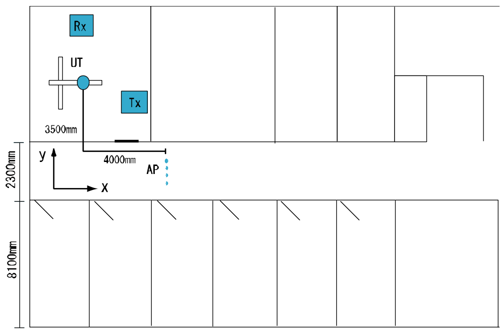





| | |
|---|---|
| Center Freq. | 5.2 [GHz] |
| TX Power | -13 [dBm/channel] → SNR = 15[dB] |
| Bandwidth | 1875 [kHz]→125 [ksps] α=0.5 |
| Modulation | QPSK / 16QAM |
| Frame | 512 (31: Training, 480: Data) |
| Array | 2 Sleeve Antenna with λ/ 2 sep. |
| Scheme | SISO / SM-ZF / STBC |
| # of Points | 256 Points (30 [cm] 2[cm] Spacing) |

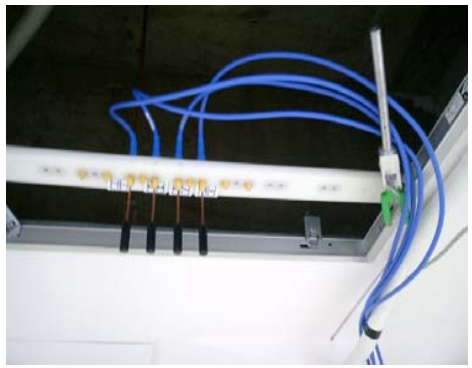


# Environment






# TX Array Antenna

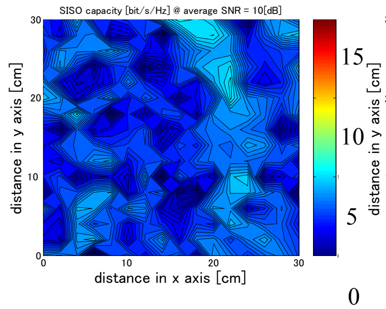


# RX Array Antenna

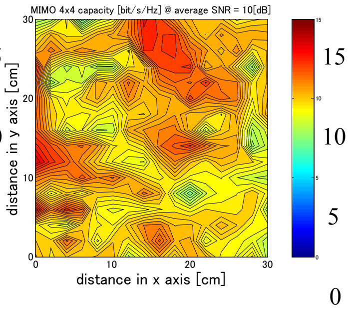


# Channel Capacity Analysis

SISO Channel Capacity Distribution

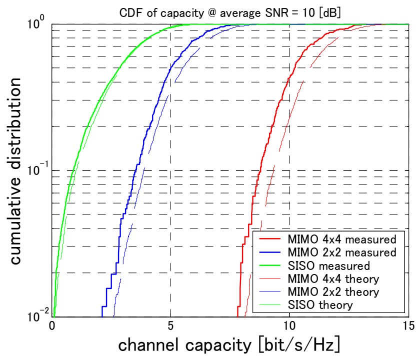



MIMO Channel Capacity Distribution



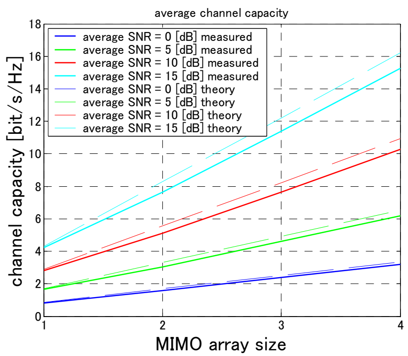



# Channel Capacity Analysis

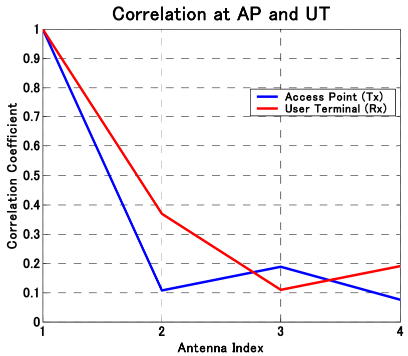





# Channel Capacity



# Correlation Characteristics



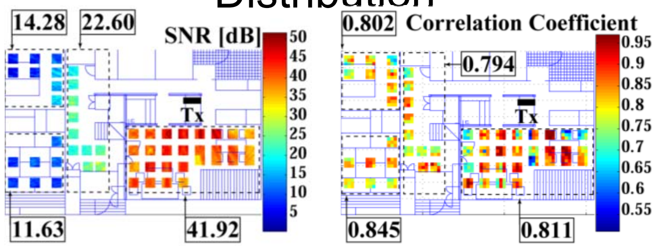



# MIMO Propagation Measurement


| | |
|---|---|
| MIMO Configuration | 4(Tx) x 4(Rx) |
| Antenna Configuration | ULA spacing half a wavelength |
| Central Frequency | 5.06 GHz |
| Bandwidth | 20 MHz |
| Signal | IEEE802.11a modified standard |
| Spatial Sample | 50,993 (2cm step) |



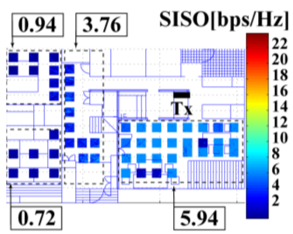
# SNR & Spatial Correlation Distribution

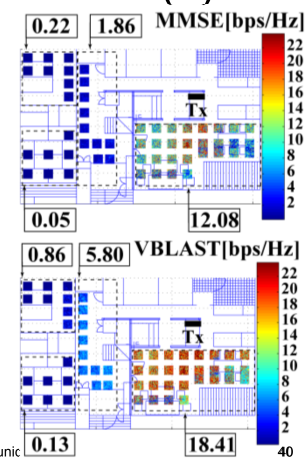



- SNR decreases as far from the Tx
  - Free space path loss
  - Shadowing
  - Penetration loss
- Spatial correlation is high even in NLOS environment
  - Wooden house is not a richly scattering environment



# Throughput Distribution (1)

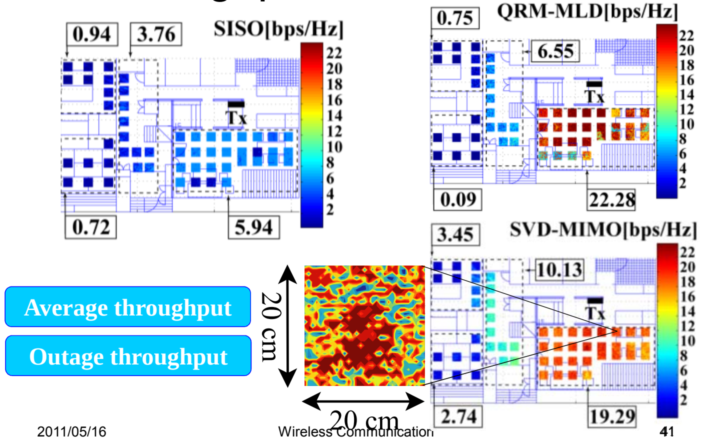



**Results**

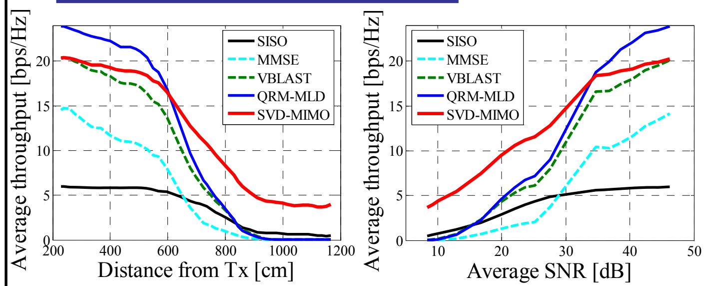
- Multiplexing gain effect in high SNR area
- Degradation of MIMO in low SNR area

# Throughput Distribution (2)





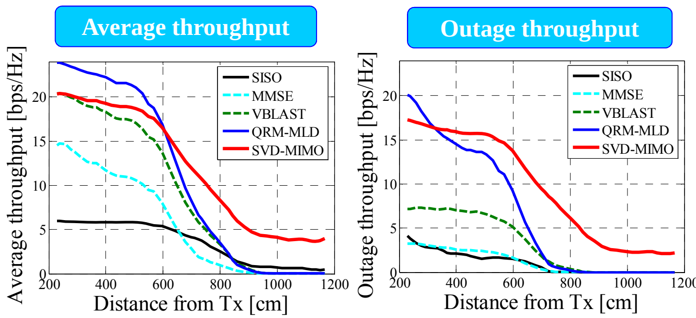

# Average Throughput




- Scheme which does not require CSI at Tx:
  - Throughput performance improvement of MIMO with high SNR
  - QRM-MLD shows best performance
  - Performance degradation of MMSE to SISO in low SNR area
- If CSI is available at Tx, SVD-MIMO is superior to the other schemes



# 1% Outage Throughput



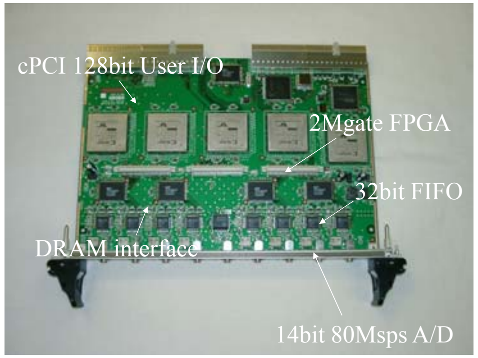

- Small different in average and outage performance of QRM-MLD and SVD-MIMO implies reliable schemes
- Large different in average and outage performance of MMSE implies the sensitiveness to channel variation



# HW

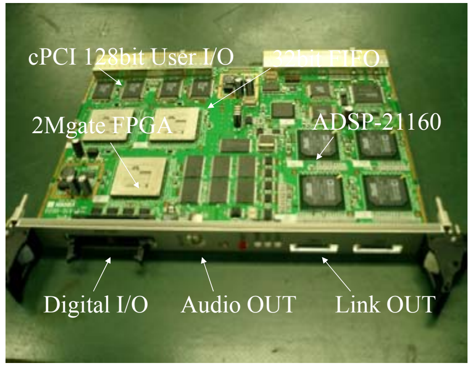
- cPCI 8 channel A/D
- cPCI 8 channel D/A
- cPCI FPGA・DSP
- cPCI 8 channel RF TX Unit
- cPCI 8 channel RF RX Unit

# A/D



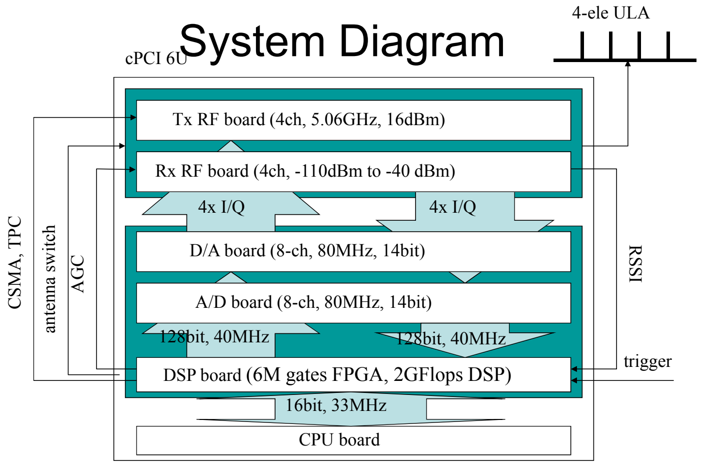



# DSP

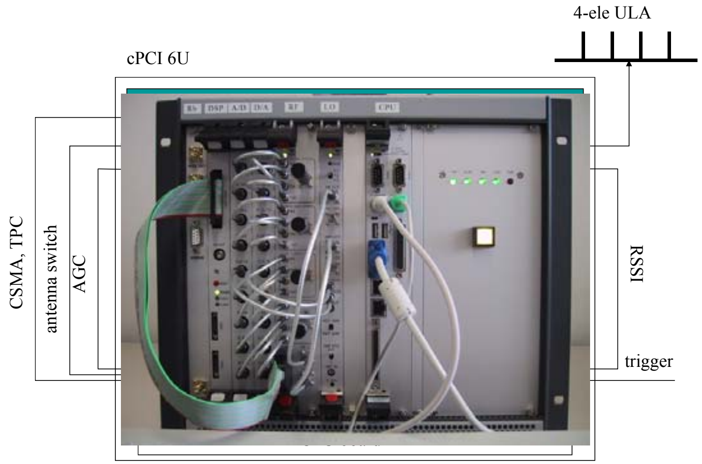





# System Diagram



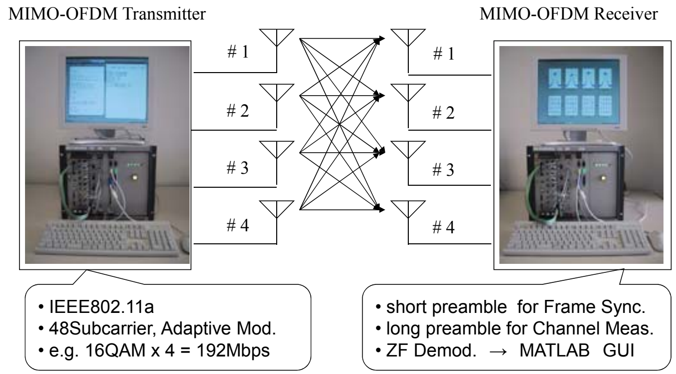


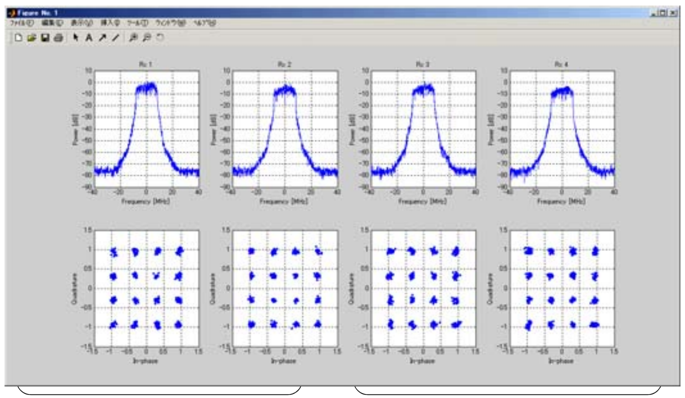
# Sub-systems

- RFBoard 
  - ✓ Fc = 5.03 – 5.09GHz
  - ✓ B = 20MHz x 3 channel
  - ✓ P = 16dBm/channel
  - ✓ AGC = 70dB
  - ✓ TPC = 50dB
- LocalBoard 
  - ✓ 1st Lo = 4470MHz
  - ✓ 2nd Lo = 570MHz
  - ✓ BB clock = 80MHz
  - ✓ stability = 10^-11
- ADBoard 
  - ✓ AD = 14bit, 80Msps
  - ✓ FIFO = 128kwords(32bit)
  - ✓ FPGA = 2Mgates x 5 (frame synch, FFT)
- DABoard 
  - ✓ AD = 14bit, 125Msps
  - ✓ FIFO = 128kwords(32bit)
  - ✓ FPGA = 2Mgates x 5 (IFFT, frame format)
- DSPBoard 
  - ✓ FPGA = 200Mgates x 3 (channel estimation, demodulation, decode)
  - ✓ DSP = 5MFlops x 4 (matrix inverse, etc.)
  - ✓ CPU core = MicroBlaze (protocol, controller)
  - ✓ API = C or MATLAB driver









# Measurement Equipment

# RF Module

| | |
|---|---|
| Center Frequency | 4.8 [GHz] |
| TX Power | 30 [dBm/channel] |
| Bandwidth | 30 [MHz] |
| # of Channel | 8 |
| Transmission Scheme | Multi-tone (sounder), OFDM (802.11a, 4G) |



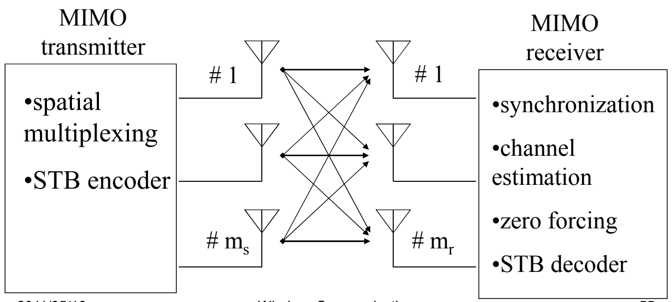
# MIMO Transmission

- Multi-data stream ⇒ High PAPR ( Peak to Average Power Ratio)
- Pre-coding reduces PAPR problem, however.
- Multi-data stream ⇒ Sensitive to Imbalance in I-Q MODEM



# MIMO Systems

- Multi-Input Multi-Output
- Same Frequency Band, Same Time






# MIMO Data Transmission Analysis

Spatial Multiplexing - Zero Forcing

$$\hat{\mathbf{s}} = \mathbf{H}^{-1}\mathbf{y}$$

Features

| | | |
|---|---|---|
| Diversity | : | $m_r - m_s + 1$ |
| Rate | : | $m_s$ |

Space Time Block Code

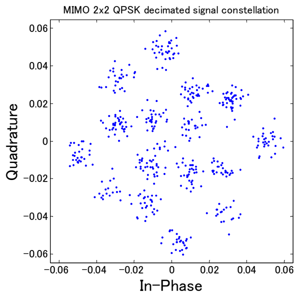
$$\mathbf{C} = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}$$

Features

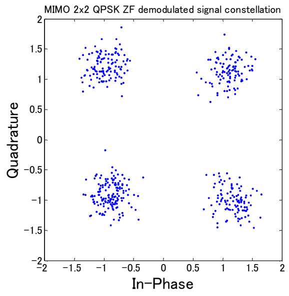
| | | |
|---|---|---|
| Diversity | : | $m_r \times m_s$ |
| Rate | : | $< 1$ |

# MIMO 2x2 QPSK Received Signal

Matched Filter Output



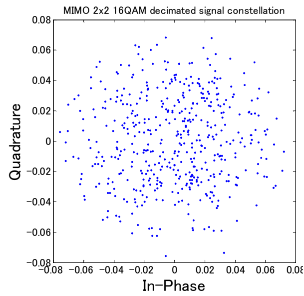

ZF Output



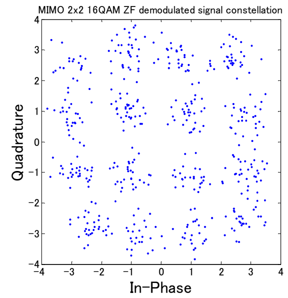



# MIMO 2x2 16QAM Received Signals

Matched Filter Output

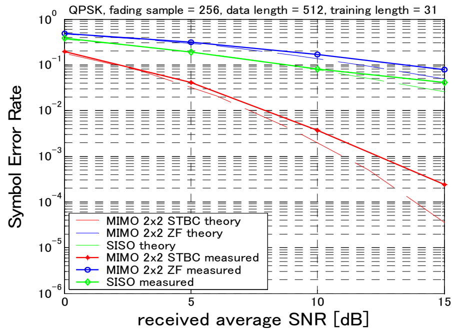



ZF Output






# Data Transmission Analysis (SER)






# RF Issues

- MIMO Duplexers
- MIMO Mixers
- Linearized PA for High PAPR
- Switched Diversity for RF Switch and Detectors

# Future Works

- Adaptive MIMO : Parasitic Array Antenna
- Multi-user MIMO : User diversity & Scheduling
- Virtual MIMO : Cooperative Base Station
- Differential Codebook : Low amount of CSI Feedback



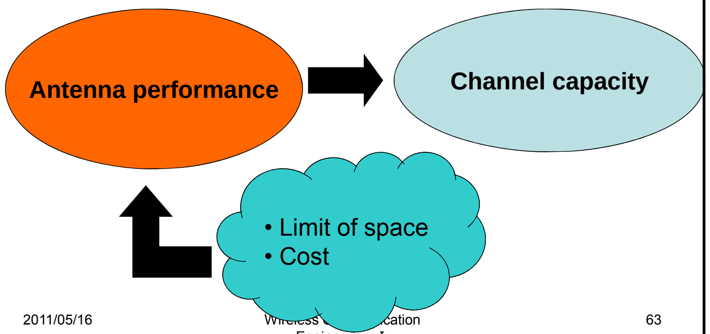
# Adaptive MIMO

- Cross layer design between RF and BB
- Parasitic Antenna ＋ active antenna
- Control of “Re-radiation” from parasitic antenna



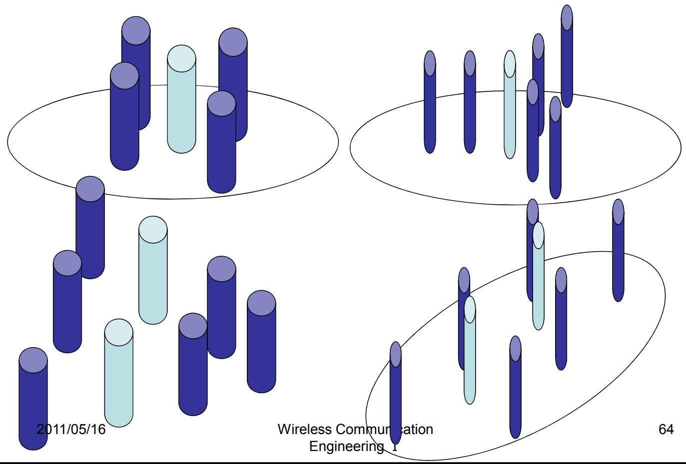
# Background

- MIMO from antenna point of view

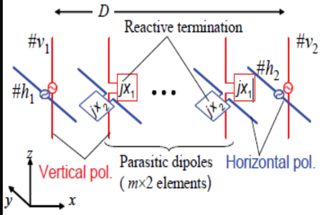


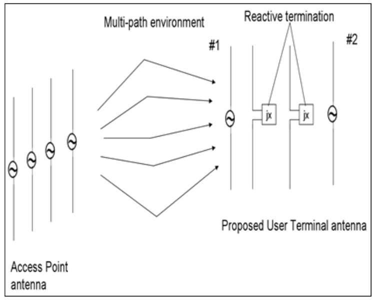



# Antenna Patterns



# Using Yagi-Uda Antenna in MIMO



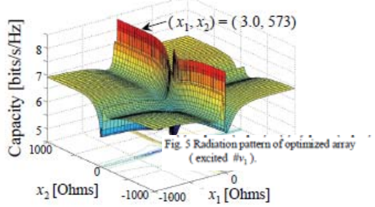



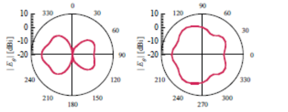

Antenna Configuration

Transmission Model



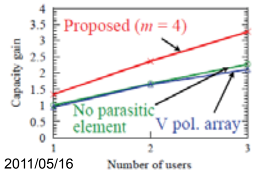
# Performance

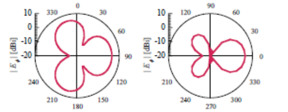


(a) xz-plane (V-pol.) (b) xy-plane (V-pol.)

Fig. Radiation pattern of optimized array (excited #v1)



(a) xz-plane (H-pol.) (b) xy-plane (H-pol.)

Fig. Radiation pattern of optimized array (excited #h1)

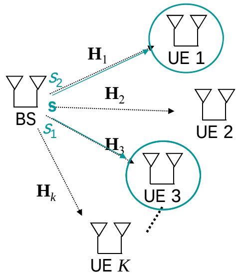


# Multi-user Scheduling in MIMO

- MIMO ⇒ SDMA
- Multi-user Scheduling ⇒ "User diversity"
- Combination of SDMA & User Diversity



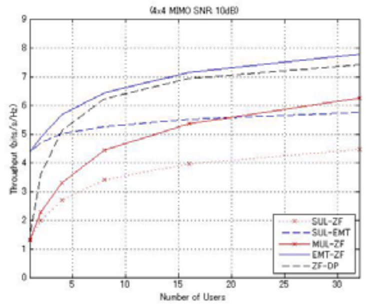
# System Model




Transmit antenna number of BS
= receive antenna number of each UE
= $m$

- Single user MIMO link
  - Only chooses one user in one time
- Multi-user MIMO link
  - Transmits to several users at the same time

# Simulation Result
(4x4 MIMO i.i.d. Rayleigh fading)





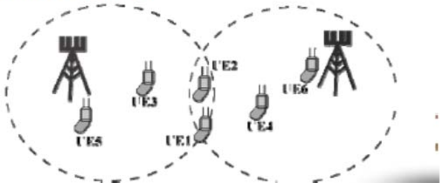

# Cooperative Transmission

- Cooperative Transmission between Adjacent Base Stations ⇒ Virtual MIMO
- Improvement of Throughput at Cell-edge



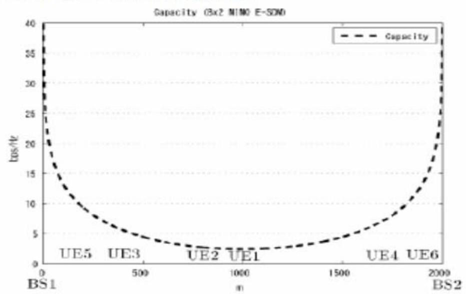
## System model

- 2 Base Stations with 4 Tx Antennas each
- 6 users with 2 Rx Antennas each
- Select 4 users

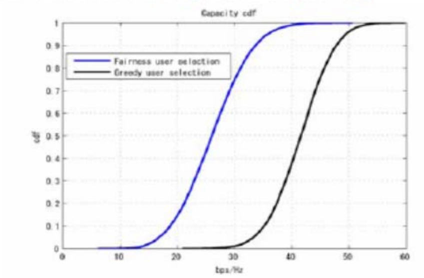





- **Path loss and Fading**



## Fair or Greedy System Capacity



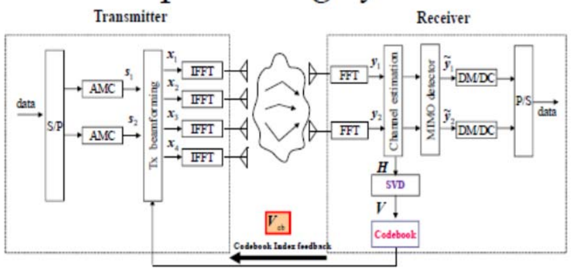



# Code Book for MIMO

- TX and RX share the same code book for pre-coding unitary matrices
- An address in the code book is only feedback from RX to TX
- Haussholder transformation can be used for successive reduction of vector size



# MIMO precoding system



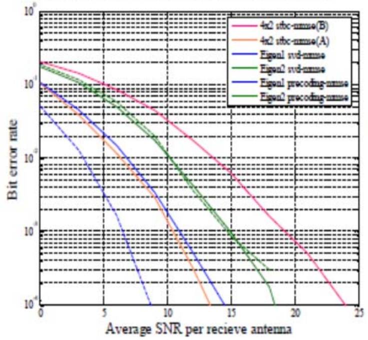

$y = Hx + n$

$H = U\Sigma V^H$

$x$ : transmit signal
$y$ : receive signal
$H$ : channel matrix
$s$ : original transmit signal
$n$ : noise

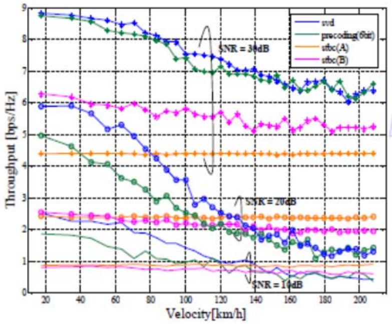


# BER Performance




- The performance of two eigenmodes in closed-loop system is shown separately.
- The performance of eigen #1 is the best.

# Throughput performance




- When SNR is 30dB, throughput performance of closed loop system is better open loop than throughput regardless of MS velocity.
- When SNR is 20dB or 10dB, throughput performance is different by MS velocity.



# Differential codebook

- The transmitter computes the precoding matrix by using the codebook matrix specified by the receiver and the previous precoding matrix

$$F_k = C_{m_{opt}} F_{k-1}$$

- The receiver selects the optimum precoding matrix which maximizes the capacity

$$m_{opt} = arg \max \log_2 \det\left( I_{N_r} + \frac{P}{\sigma 2 N_s} H_k C'_m C'^{H}_m H^{H}_k \right)$$

$$\{C'_1 \cdots C'_B\} = \{C_1 F_{k-1} \cdots C_B F_{k-1}\}$$



# Results (Differential codebook)

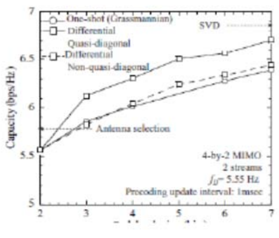



Fig4 : Capacity vs. Codebook size

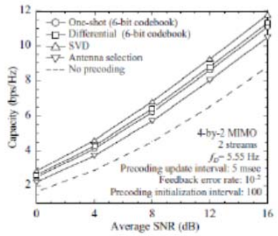



Fig 5 : Capacity vs. SNR(fD=5.55Hz)



# Conclusion

- MIMO is a key technology for future wireless communication system.
- Feedback of Channel State Information is a necessary task.
- Design of MIMO transceivers is a challenging theme for RF engineers and Antenna engineers
- Switched MIMO transceiver is a promising candidate for compact architecture.