MIMO Technologies for Wireless Communications

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Agenda

- MIMO History
- MIMO Capacity Analysis
- MIMO Propagation
- MIMO Transmission
- RF Issues for MIMO
- Future Works and Conclusion

MIMO transmission

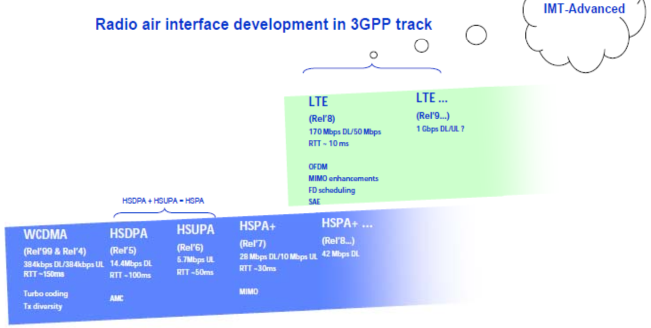
- Combination of Antenna Technology and Signal Processing for designing wireless channel
- Orthogonalization is an effective way for increase of channel capacity
- Time, Frequency(OFDM)

  ⇒ 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

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

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

TX Power

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

Bandwidth

Noise Power Density

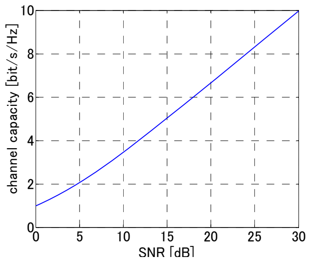
- Frequency Efficiency

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

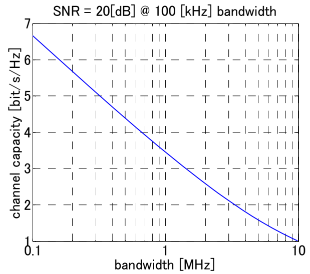
Noise Power

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)

$$C_{\mathrm{MIMO}}^{\mathrm{av}} = \mathrm{E}[C_{\mathrm{MIMO}}] = \int C_{\mathrm{MIMO}}(\mathbf{H}) \underbrace{f(\mathbf{H})}_{\text{Channel Matrix pdf}} d\mathbf{H}$$

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 $\#TX\text{ - }Ant$ m_r $\#RX\text{ - }Ant$

- 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.

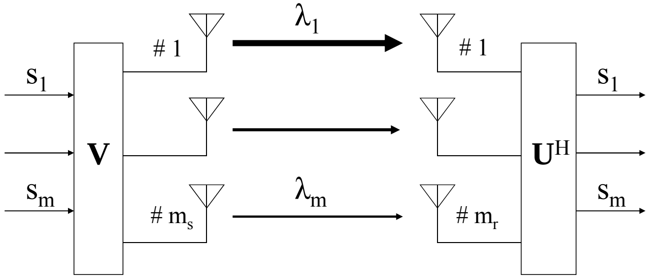
- Unitary Matrix **V** at TX conserves a total TX power.

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

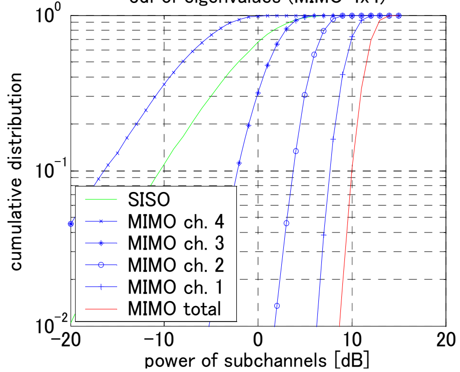
- Unitary Matrix $\mathbf{U}^\mathbf{H}$ at RX conserves a RX noise property.

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

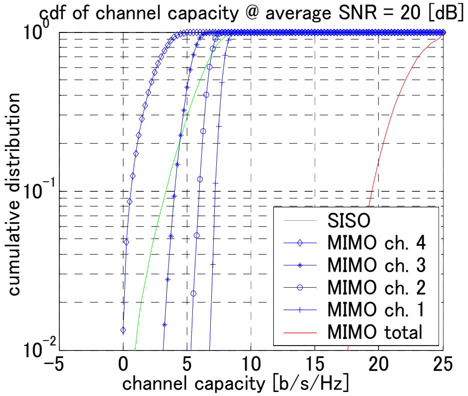
MIMO Eigen Mode System



Eigen-value Distribution for non correlation Channel



CDF of Channel Capacity



Water Pouring Algorithm

- Optimum TX Power Assignment

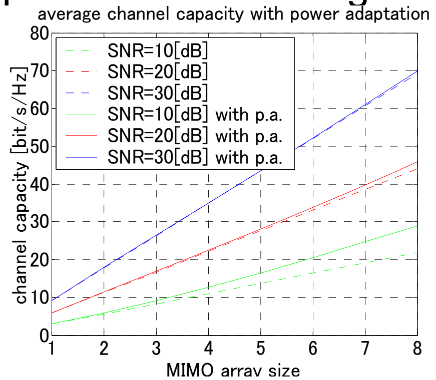
$$\sum_{i=1}^{m} P_i = P$$

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

- 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



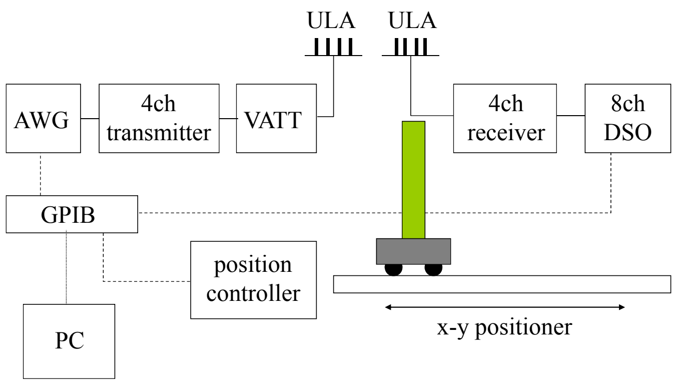
- MIMO Channel Capacity $\propto$ Antenna Size

cf. Adaptive Array $\propto$ log(Antenna Size)

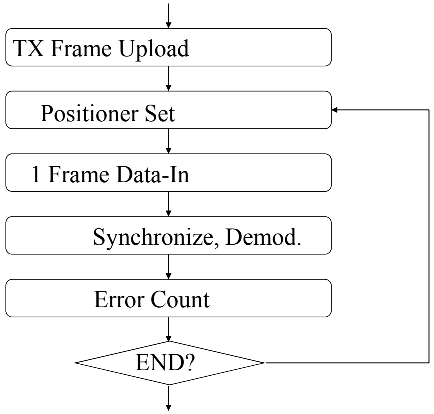
- MIMO Channel can be transformed to Eigen-mode sub-Channels

MIMO Propagation Measurement

Measurement Systems

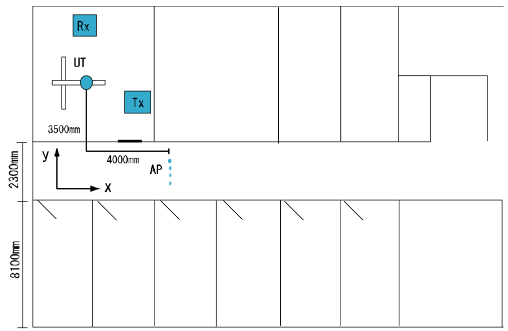


Procedure

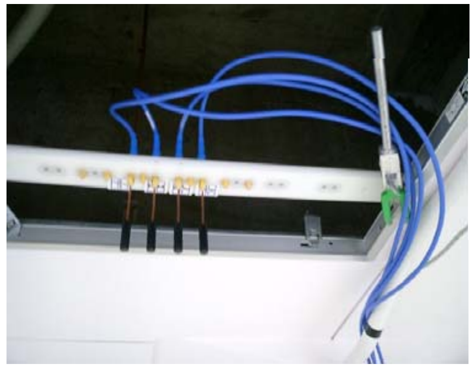


Center Freq.	5.2 [GHz]
TX Power	-13 [dBm/channel] → SNR = 15[dB]
Bandwidth	1875 [kHz]→125 [ksps] α=0.5
Modulation	QPSK / 16QAM
Frame	512 (31: Training, 480: Data)
Array	2 Sleeve Antenna with λ/ 2 sep.
Scheme	SISO / SM-ZF / STBC
# of Points	256 Points (30 [cm] 2[cm] Spacing)

Environment



TX Array Antenna



RX Array Antenna

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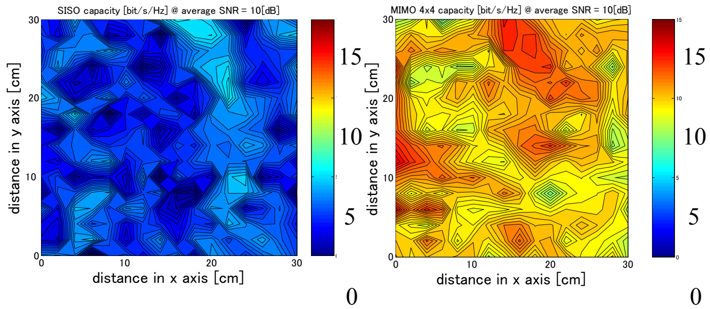
Channel Capacity Analysis

SISO Channel Capacity Distribution

MIMO Channel Capacity Distribution



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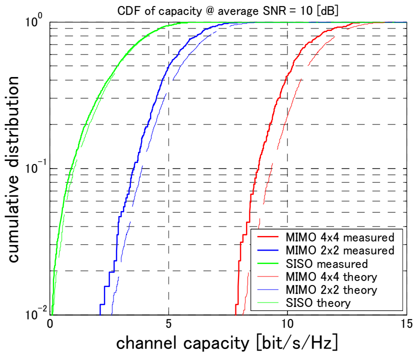
Channel Capacity Analysis



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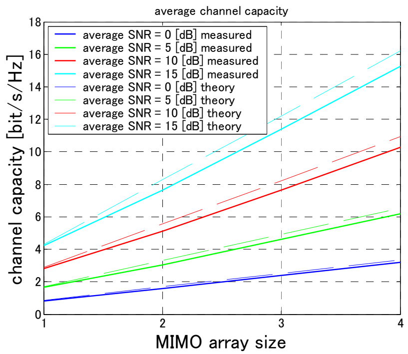
Channel Capacity



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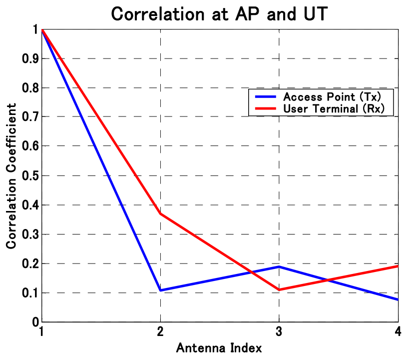
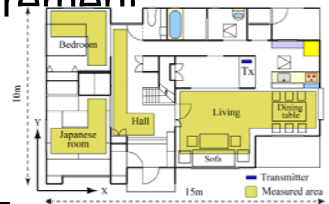
Correlation Characteristics

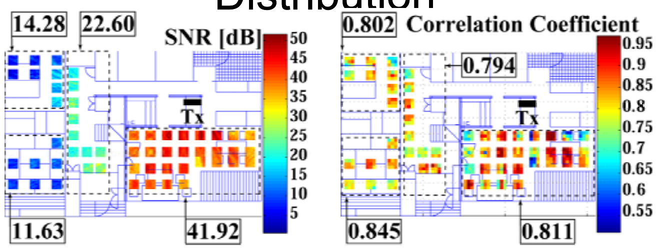


MIMO Propagation Measurement



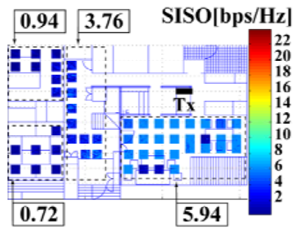
MIMO Configuration	4(Tx) x 4(Rx)
Antenna Configuration	ULA spacing half a wavelength
Central Frequency	5.06 GHz
Bandwidth	20 MHz
Signal	IEEE802.11a modified standard
Spatial Sample	50,993 (2cm step)

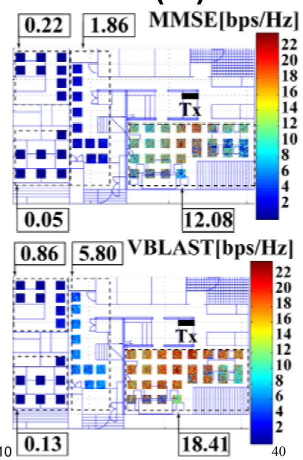
SNR & Spatial Correlation Distribution



- 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)

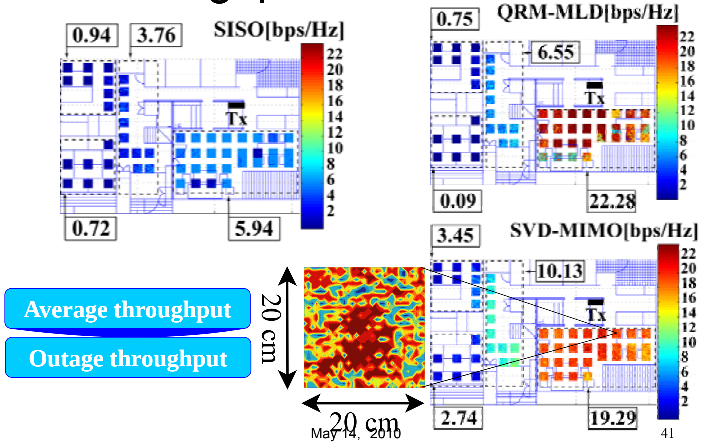




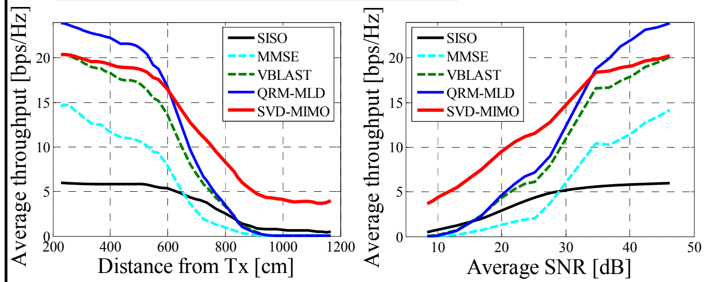
Results

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

Throughput Distribution (2)

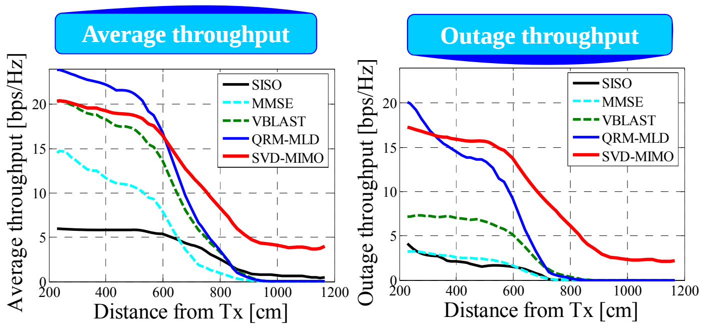


Average Throughput



- 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

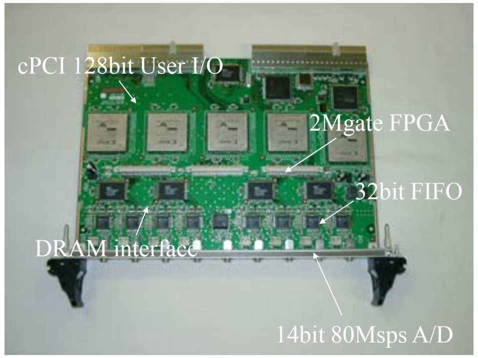


- Small different in average and outage performance of QRM-MLD and SVD-MIMO implies reliable schemes
- Large different in average and outage performance of MMSE implies the sensitiveness to channel variation

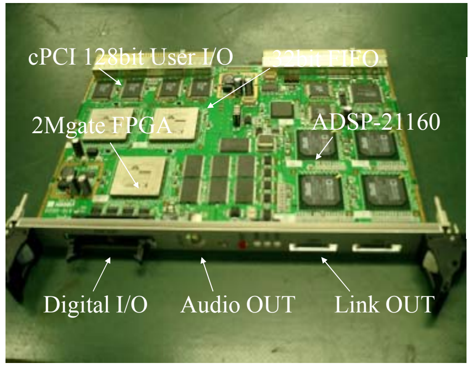
HW

- 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

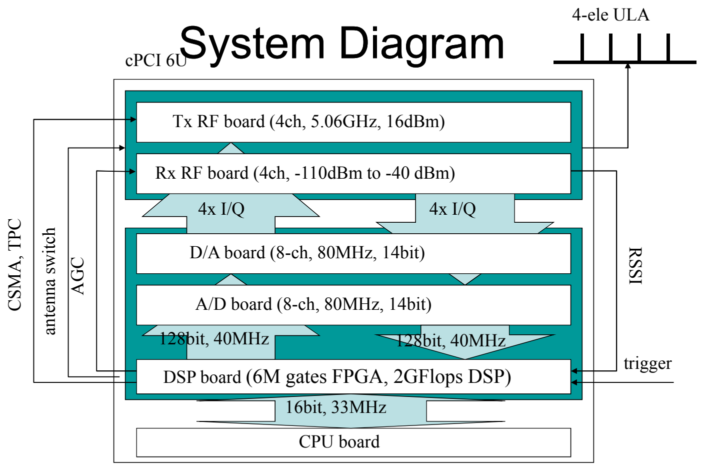
A/D

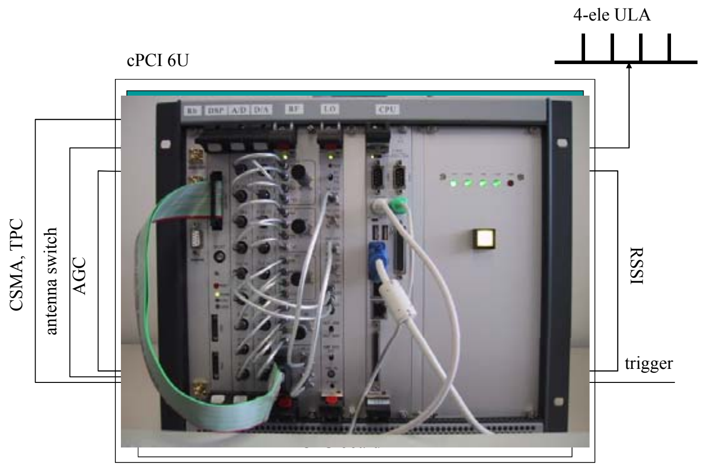


DSP



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 

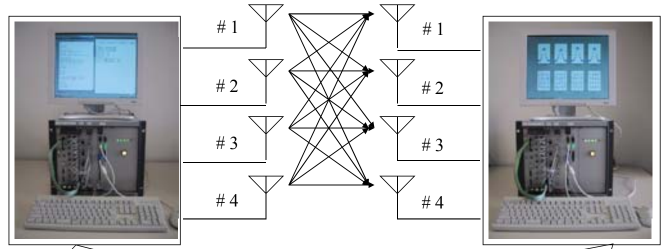
- ✓ AD = 14bit, 125Msps
- ✓ FIFO = 128kwords(32bit)
- ✓ FPGA = 2Mgates x 5 (IFFT, frame format)

➢ 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

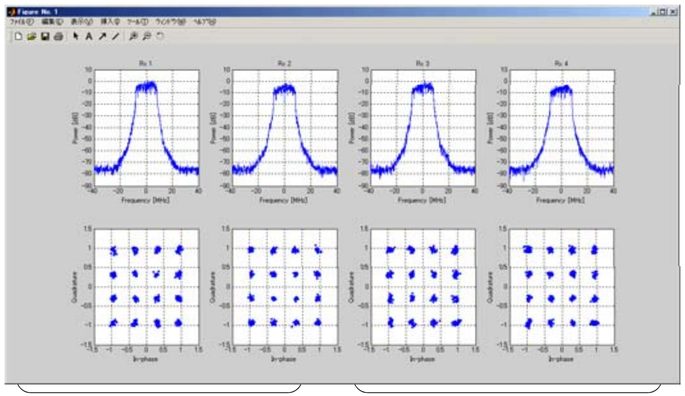
MIMO-OFDM Transmitter

MIMO-OFDM Receiver



- IEEE802.11a
- 48Subcarrier, Adaptive Mod.
- e.g. 16QAM x 4 = 192Mbps

- short preamble for Frame Sync.
- long preamble for Channel Meas.
- ZF Demod. → MATLAB GUI



Measurement Equipment

RF Module

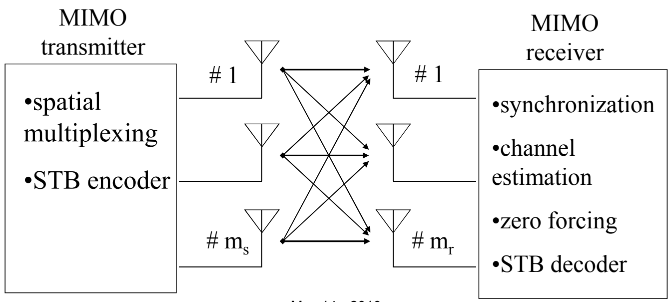
Center Frequency	4.8 [GHz]
TX Power	30 [dBm/channel]
Bandwidth	30 [MHz]
# of Channel	8
Transmission Scheme	Multi-tone (sounder), OFDM (802.11a, 4G)

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

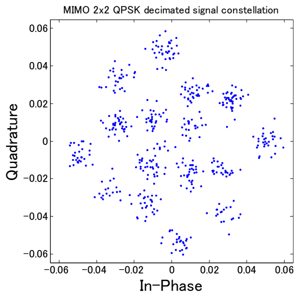
$$\mathbf{C} = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}$$

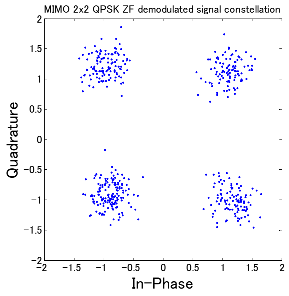
Features		
Diversity	:	$m_r \times m_s$
Rate	:	< 1

MIMO 2x2 QPSK Received Signal

Matched Filter Output

ZF Output

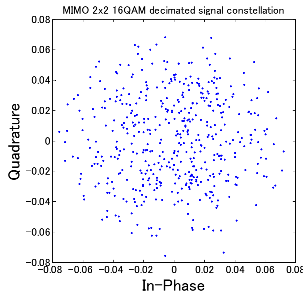


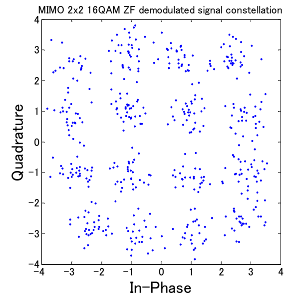


MIMO 2x2 16QAM Received Signals

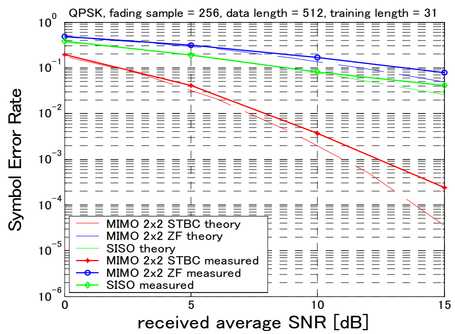
Matched Filter Output

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

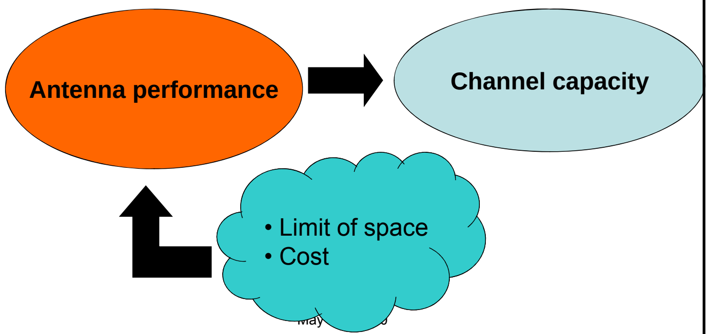
- Adaptive MIMO : Parasitic Array Antenna
- Multi-user MIMO : User diversity & Scheduling
- Virtual MIMO : Cooperative Base Station
- Differential Codebook : Low amount of CSI Feedback

Adaptive MIMO

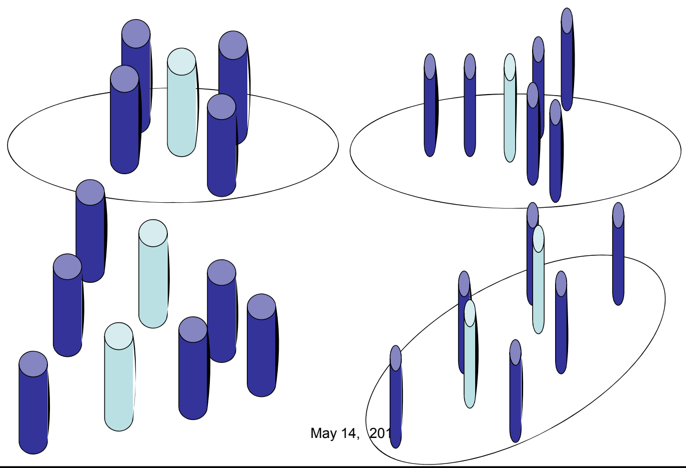
- Cross layer design between RF and BB
- Parasitic Antenna ＋ active antenna
- Control of “Re-radiation” from parasitic antenna

Background

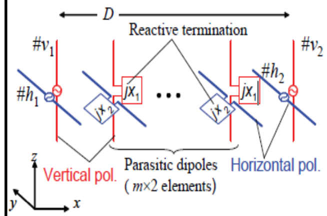
- MIMO from antenna point of view

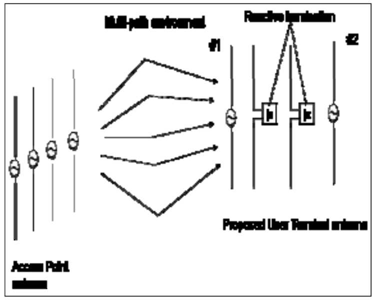


Antenna Patterns



Using Yagi-Uda Antenna in MIMO

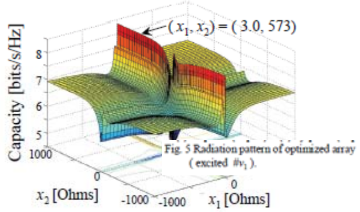




Antenna Configuration

Transmission Model

Performance



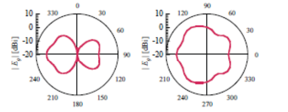
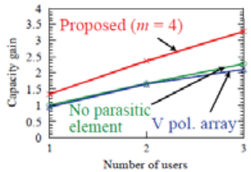


Fig. Radiation pattern of optimized array (excited #v1)



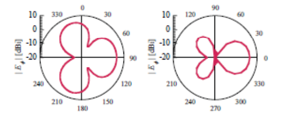
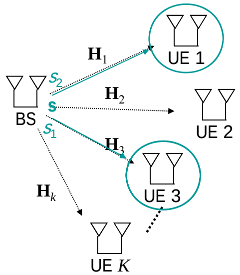


Fig. Radiation pattern of optimized array (excited #h1)

Multi-user Scheduling in MIMO

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

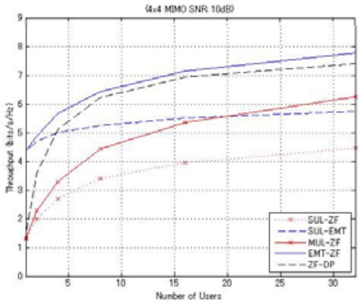
System Model



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)

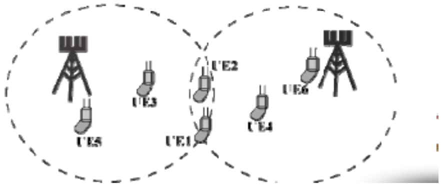


Cooperative Transmission

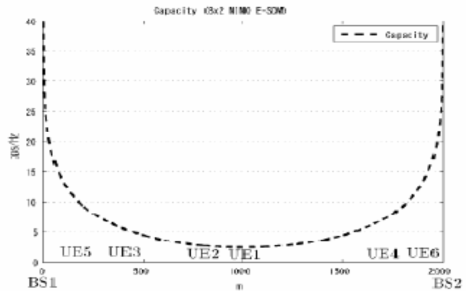
- Cooperative Transmission between Adjacent Base Stations ⇒ Virtual MIMO
- Improvement of Throughput at Cell-edge

System model

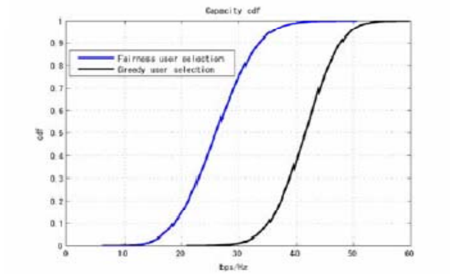
- 2 Base Stations with 4 Tx Antennas each
- 6 users with 2 Rx Antennas each
- Select 4 users



- **Path loss and Fading**



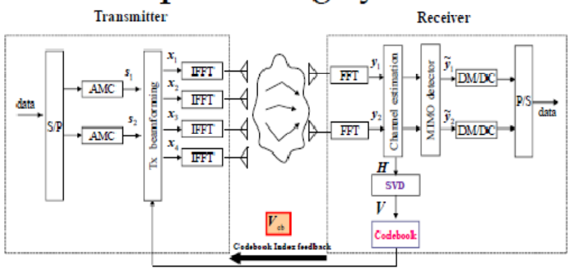
Fair or Greedy System Capacity



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

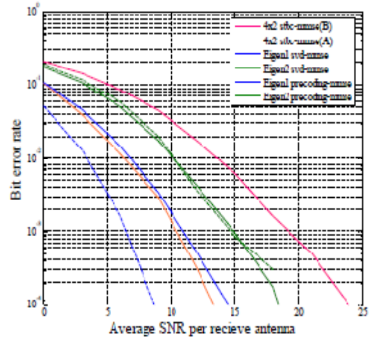
MIMO precoding system



$y = Hx + n$
$H = U\Sigma V^H$

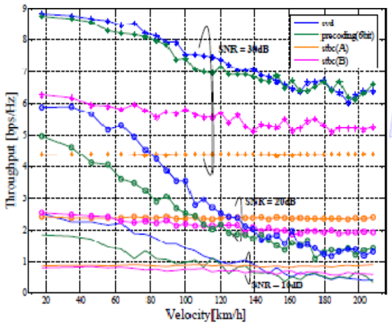
x : transmit signal
y : receive signal
H : channel matrix
s : original transmit signal
n : noise

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

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

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

Results (Differential codebook)

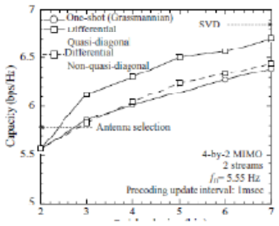


Fig4 : Capacity vs. Codebook size

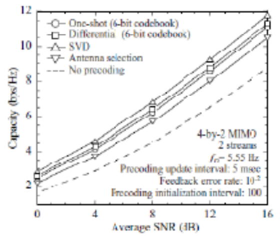


Fig 5 : Capacity vs. SNR(fc=5.55Hz)

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.