

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

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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)

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Friis Formula

- TX antenna + Channel + RX antenna
- TX/RX antennas : Deterministics
Designable
- Channel : Stochastics Un-designable
- $G_t(\lambda/4\pi d)^2 G_r$
- G_t :TX antenna Gain G_r :RX antenna Gain
- $(\lambda/4\pi d)^2$: Free Space Loss

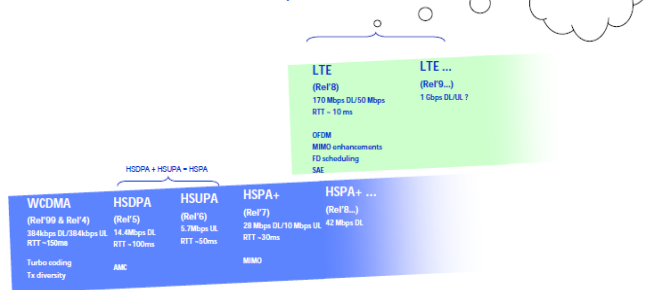
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Radio systems are evolving ...

Radio air interface development in 3GPP track



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MIMO History

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

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BLAST

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

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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

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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 : $1 \times N$ channel \Rightarrow Diversity
order : N
- TX side : $N \times 1$ channel \Rightarrow Diversity
order : N

Diversity Order

- For N i.i.d. Rayleigh channels

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

- MRC (Maximum SN-Ratio Combining)

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

- Optimum 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 P_e is
inversely proportional to n-th
power of the average SNR

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

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

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

TX Power (points to P)
Bandwidth (points to B)
Noise Power Density (points to N_0)

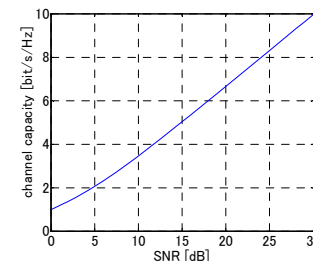
- Frequency Efficiency

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

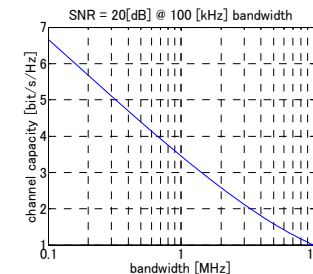
Noise Power (points to σ^2)

Frequency Efficiency

SNR



Bandwidth



MIMO Channel Capacity

- Equi-TX Power Case

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

- Fading Average (Ergodic Capacity)

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

Channel Matrix pdf

MIMO Channel Matrix Analysis

- MIMO Channel Degree
 $m = \min[m_s, m_r]$

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

- MIMO Channel Matrix Orthogonalization

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

- MIMO Channel Eigen Mode

$$\mathbf{\Sigma} = \text{diag}[\sqrt{\lambda_1}, \dots, \sqrt{\lambda_m}]$$

MIMO Channel Capacity Analysis

- Eigen Mode Channel

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

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

$$\mathbf{y}' = \mathbf{U}^H \mathbf{y} \quad \mathbf{s} = \mathbf{V} \mathbf{s}'$$

- Eigen Mode MIMO Channel Capacity

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

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

- Unitary Matrix \mathbf{V} at TX conserves a total TX power.

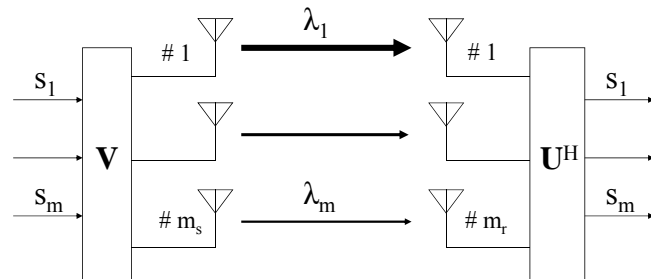
$$\mathbf{s} = \mathbf{V} \mathbf{s}' \quad |\mathbf{s}'|^2 = |\mathbf{s}|^2 \quad \mathbf{V}^H \mathbf{V} = \mathbf{I}$$

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

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

$$\mathbf{U}^H \mathbf{U} = \mathbf{I}$$

MIMO Eigen Mode System

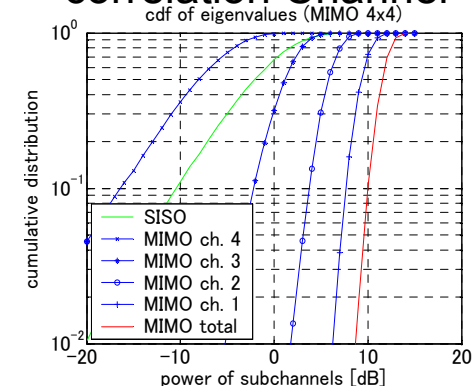


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Eigen-value Distribution for non correlation Channel

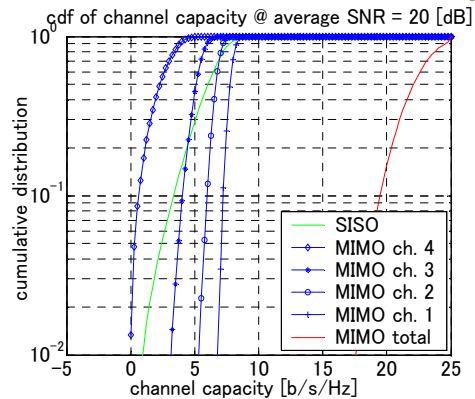


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CDF of Channel Capacity



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Water Pouring Algorithm

- Optimum TX Power Assignment

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

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

- Water Pouring Theorem

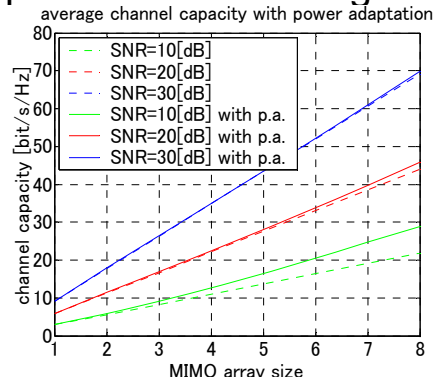
$$C_{\text{opt}} = \sum_{i=1}^m \left[\log_2 \left[\mu \frac{\lambda_i}{\sigma^2} \right] \right]^+$$

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Channel Capacity Improvement by Optimum Power Assignment



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□ MIMO Channel Capacity \propto Antenna Size

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

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

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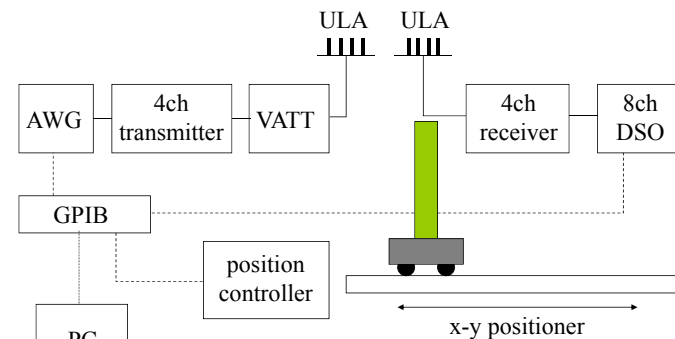
MIMO Propagation Measurement

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Measurement Systems

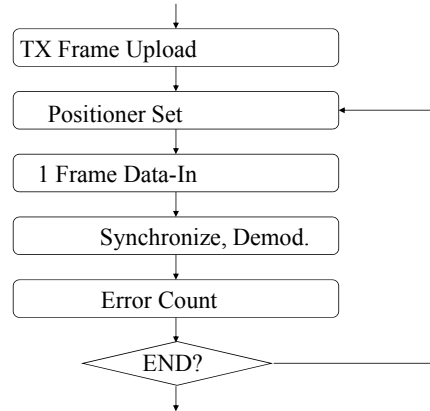


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Procedure



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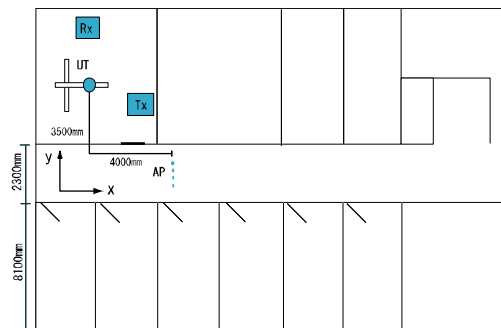
Center Freq.	5.2 [GHz]
TX Power	-13 [dBm/channel] → SNR = 15[dB]
Bandwidth	1875 [kHz] → 125 [ksps] $\alpha=0.5$
Modulation	QPSK / 16QAM
Frame	512 (31: Training, 480: Data)
Array	2 Sleeve Antenna with $\lambda/2$ sep.
Scheme	SISO / SM-ZF / STBC
# of Points	256 Points (30 [cm] 2[cm] Spacing)

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Environment



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TX Array Antenna



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RX Array Antenna



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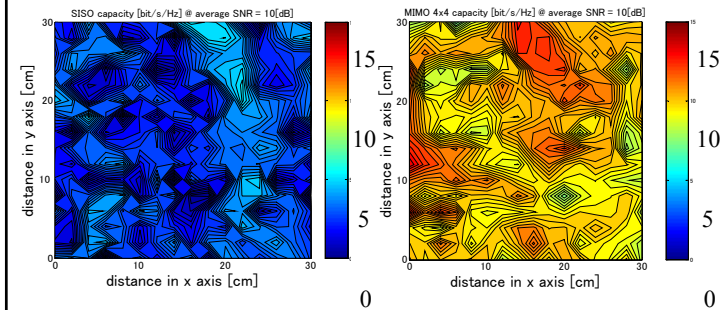
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Channel Capacity Analysis

SISO Channel Capacity Distribution

MIMO Channel Capacity Distribution

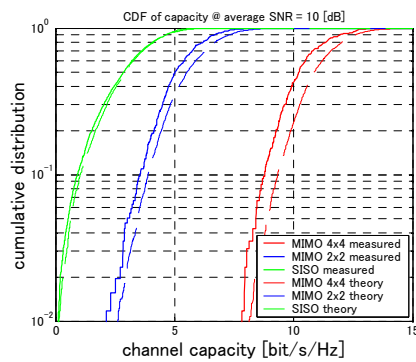


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Channel Capacity Analysis

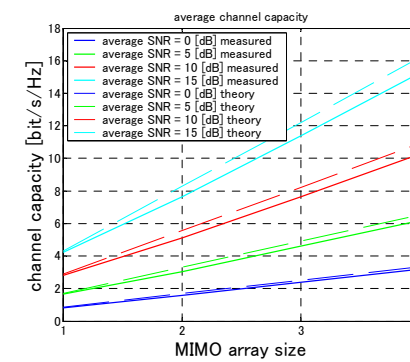


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Channel Capacity

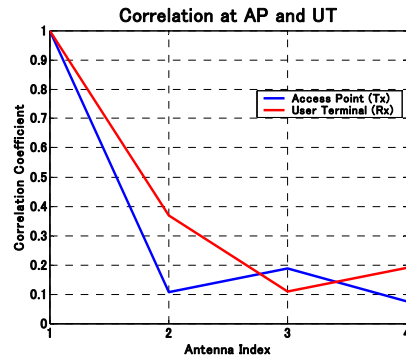


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Correlation Characteristics

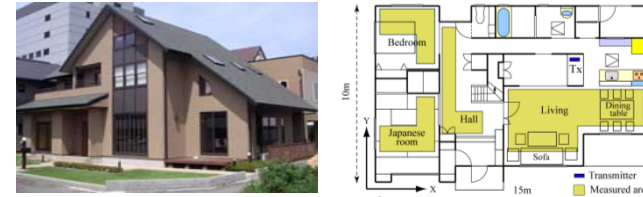


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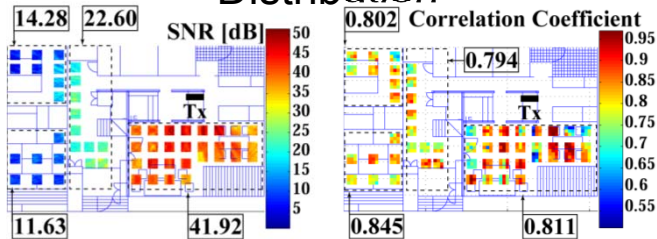
MIMO Propagation Measurement



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)

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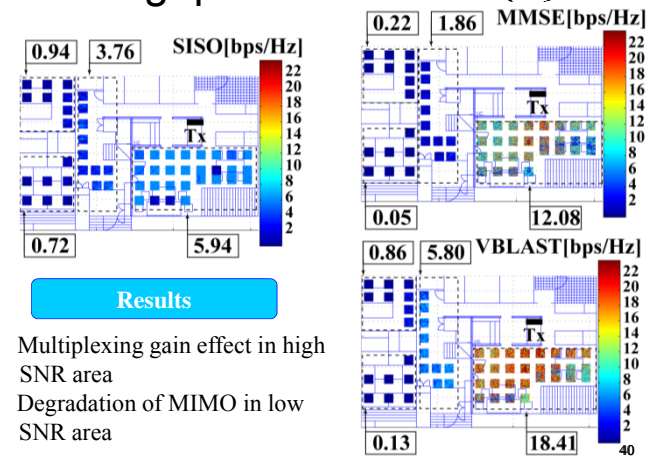
SNR & Spatial Correlation Distribution



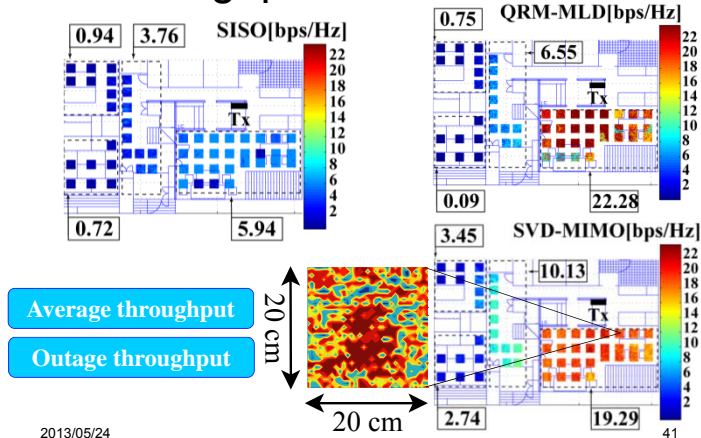
- SNR decreases as far from the Tx
 - Free space path loss
 - Shadowing
 - Penetration loss
- Spatial correlation is high even in NLOS environment
 - Wooden house is not a richly scattering environment

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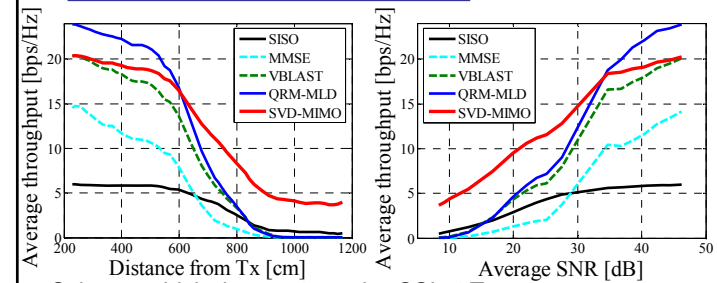
Throughput Distribution (1)



Throughput Distribution (2)

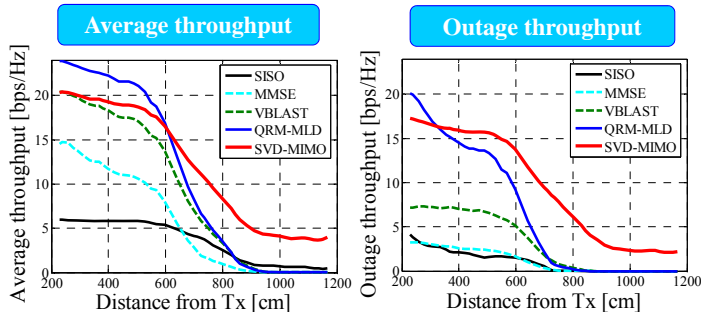


Average Throughput



- 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

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HW

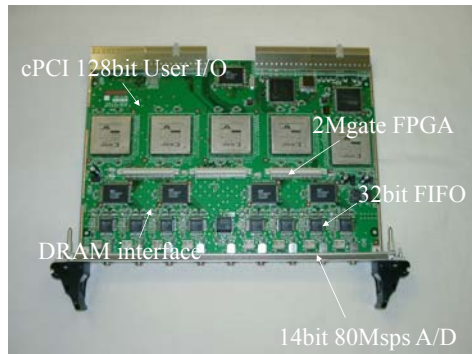
- cPCI 8 channel A/D
- cPCI 8 channel D/A
- cPCI FPGA-DSP
- cPCI 8 channel RF TX Unit
- cPCI 8 channel RF RX Unit

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A/D

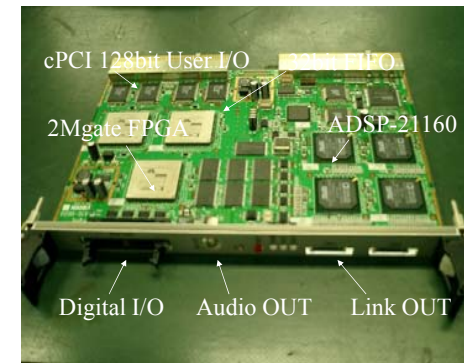


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DSP

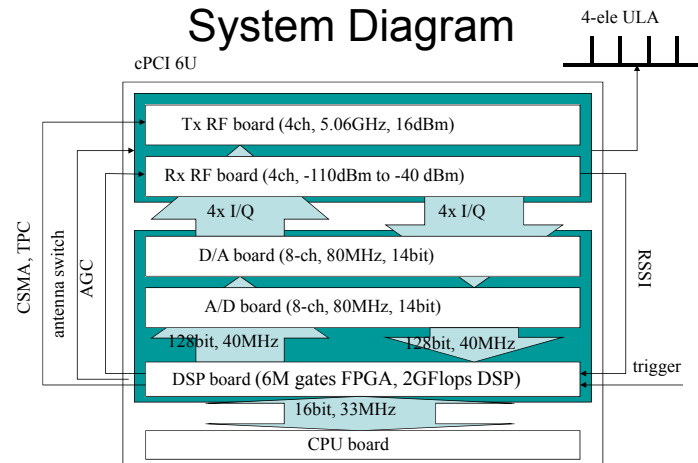


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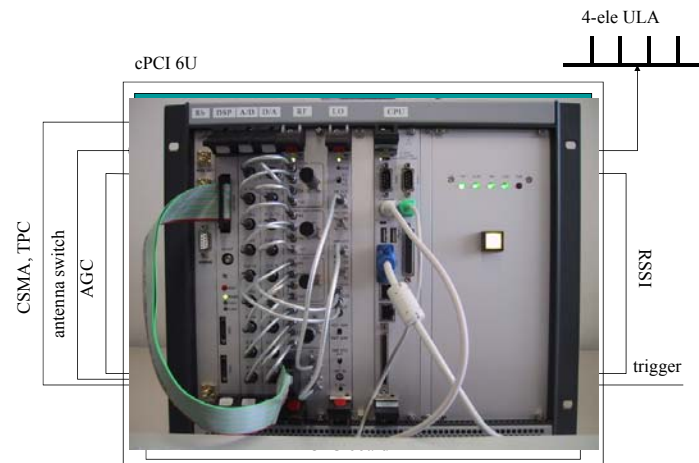
System Diagram



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Sub-systems

➤ RFBoard



- ✓ $F_c = 5.03 - 5.09\text{GHz}$
- ✓ $B = 20\text{MHz} \times 3 \text{ channel}$
- ✓ $P = 16\text{dBm/channel}$
- ✓ AGC = 70dB
- ✓ TPC = 50dB

➤ LocalBoard



- ✓ 1st Lo = 4470MHz
- ✓ 2nd Lo = 570MHz
- ✓ BB clock = 80MHz
- ✓ stability = 10^{-11}

➤ ADBoard



- ✓ AD = 14bit, 80Mps
- ✓ FIFO = 128kwords(32bit)
- ✓ FPGA = 2Mgates x 5 (frame synch, FFT)

➤ DABoard



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

➤ DSPBoard



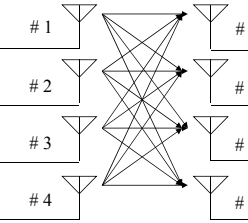
- ✓ FPGA = 200Mgates x 3 (channel estimation, demodulation, decode)
- ✓ DSP = 5MFlops x 4 (matrix inverse, etc.)
- ✓ CPU core = MicroBlaze (protocol, controller)
- ✓ API = C or MATLAB driver

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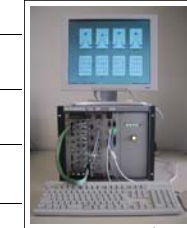
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MIMO-OFDM Transmitter



MIMO-OFDM Receiver



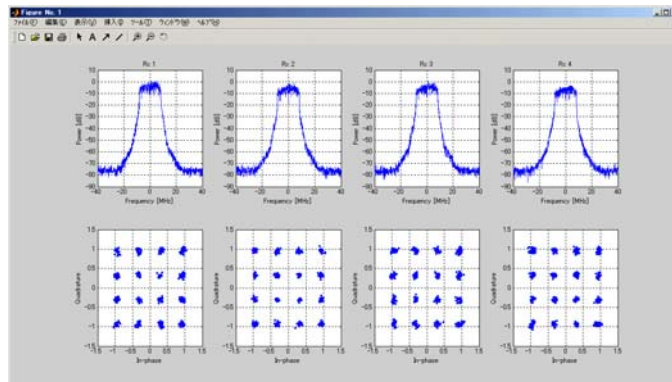
- IEEE802.11a
- 48Subcarrier, Adaptive Mod.
- e.g. 16QAM x 4 = 192Mbps

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

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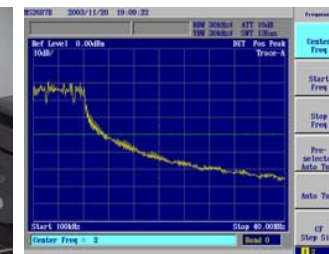


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Measurement Equipment



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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)

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MIMO Transmission

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

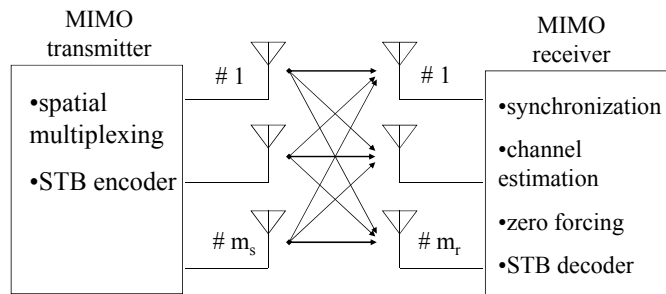
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MIMO Systems

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



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MIMO Data Transmission Analysis

Spatial Multiplexing - Zero Forcing

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

Features

$$\begin{array}{ll} \text{Diversity} & : m_r - m_s + 1 \\ \text{Rate} & : m_s \end{array}$$

Space Time Block Code

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

Features

$$\begin{array}{ll} \text{Diversity} & : m_r \times m_s \\ \text{Rate} & : < 1 \end{array}$$

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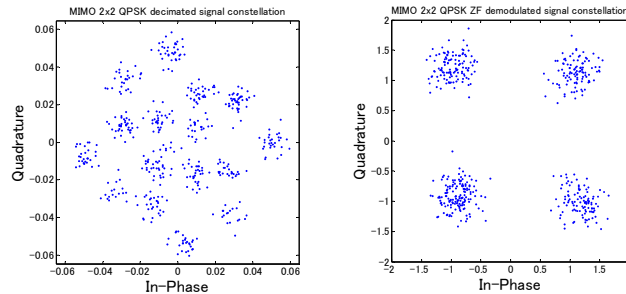
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MIMO 2x2 QPSK Received Signal

Matched Filter Output

ZF Output



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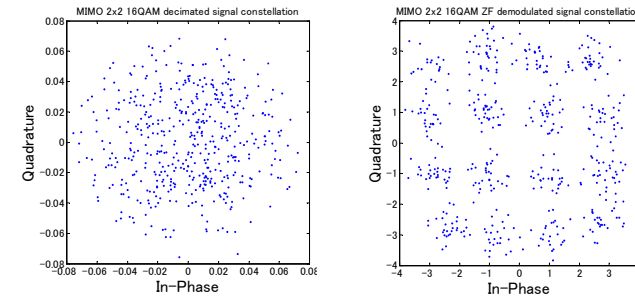
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MIMO 2x2 16QAM Received Signals

Matched Filter Output

ZF Output

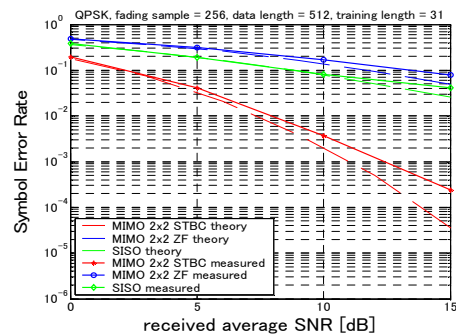


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Data Transmission Analysis (SER)



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RF Issues

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

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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

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Adaptive MIMO

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

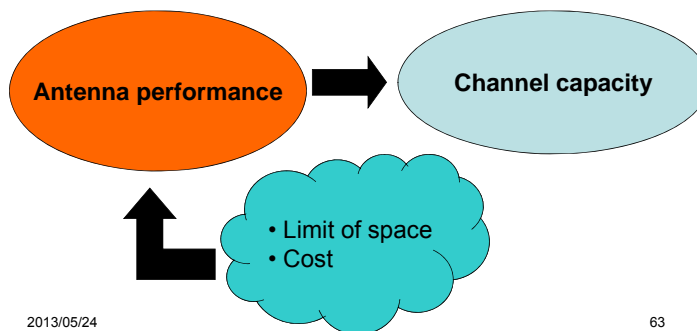
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Background

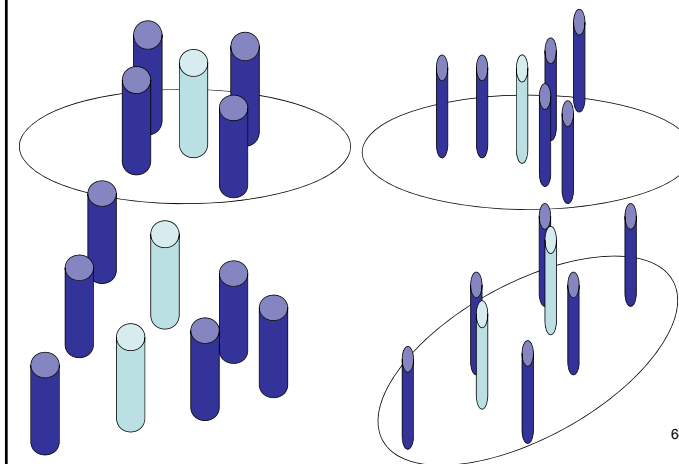
- MIMO from antenna point of view



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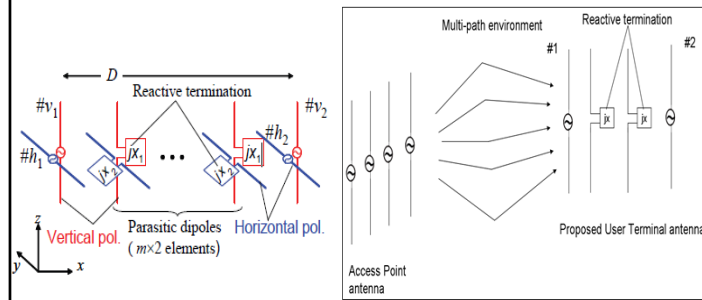
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Antenna Patterns



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Using Yagi-Uda Antenna in MIMO



Antenna Configuration

Transmission Model

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Performance

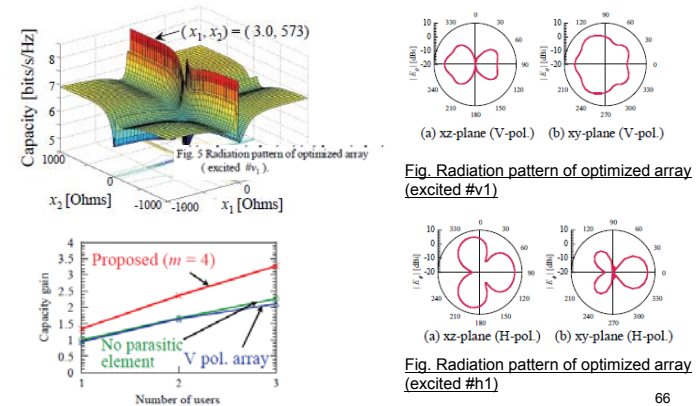


Fig. Radiation pattern of optimized array (excited $\#v_1$)

Fig. Radiation pattern of optimized array (excited $\#h_1$)

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Multi-user Scheduling in MIMO

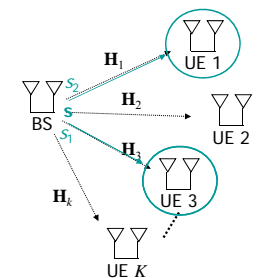
- MIMO \Rightarrow SDMA
- Multi-user Scheduling \Rightarrow "User diversity"
- Combination of SDMA & User Diversity

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System Model



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

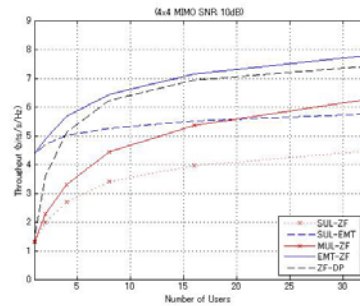
- Single user MIMO link
 - Only chooses one user in one time
- Multi-user MIMO link
 - Transmits to several users at the same time

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



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Cooperative Transmission

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

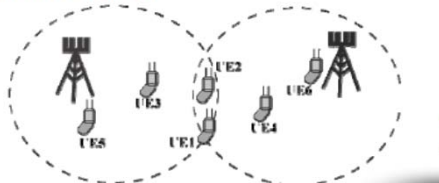
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System model

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

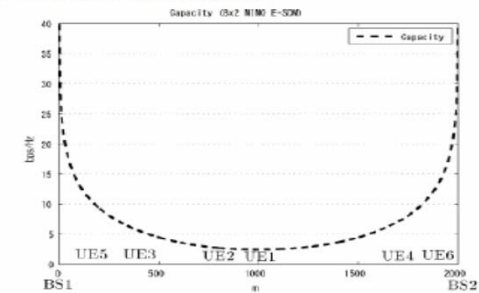


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Path loss and Fading

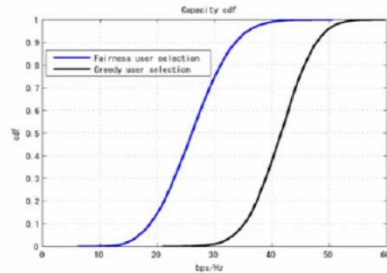


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● Fair or Greedy System Capacity



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Code Book for MIMO

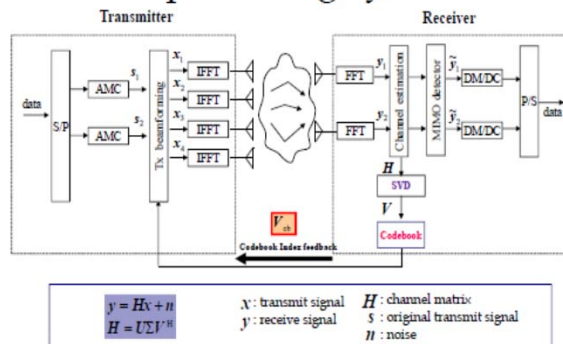
- TX and RX share the same code book for pre-coding unitary matrices
- An address in the code book is only feedback from RX to TX
- Haussholder transformation can be used for successive reduction of vector size

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MIMO precoding system

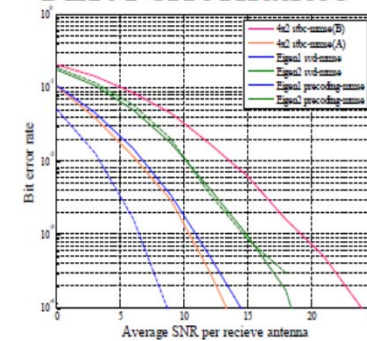


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BER Performance



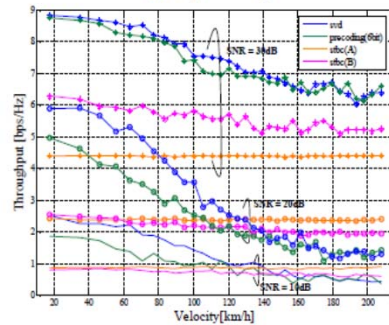
- The performance of two eigenmodes in closed-loop system is shown separately.
- The performance of eigen #1 is the best.

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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**

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

$$\{C_1, \dots, C_N\} = \{C_1 F_{k-1}, \dots, C_N F_{k-1}\}$$

Results (Differential codebook)

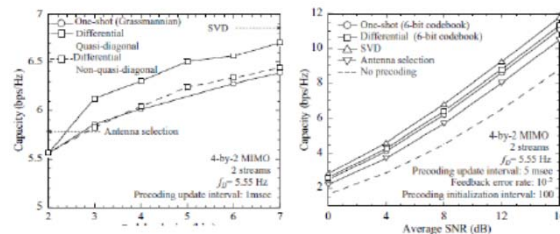


Fig 4: Capacity vs. Codebook size

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

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.**