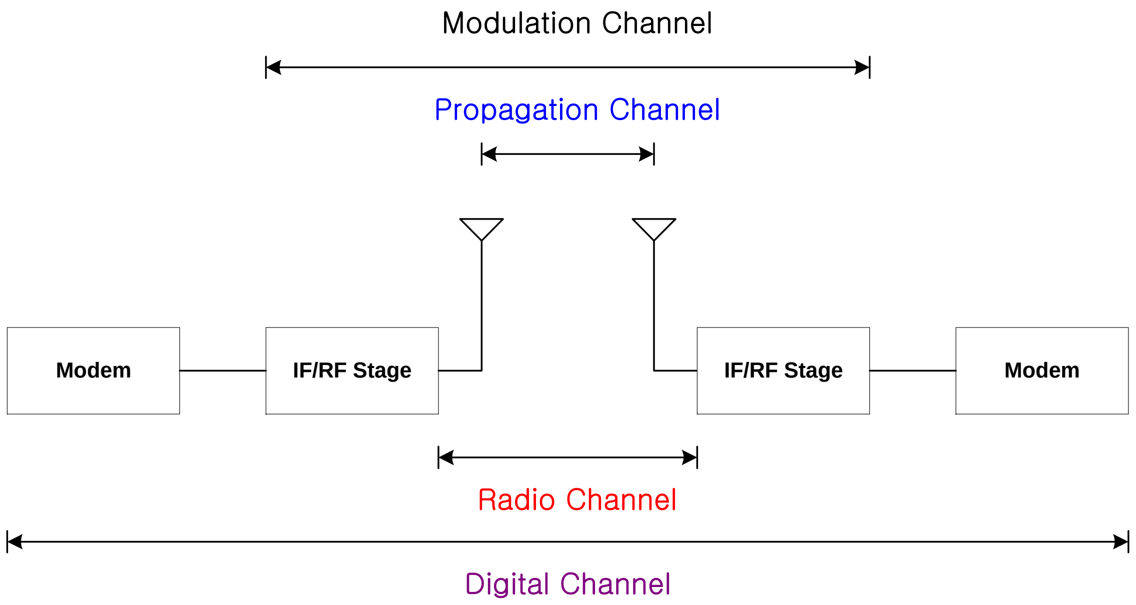
MIMO Wireless Channel

Radio Technology Laboratory
Seoul National University

Wireless Channel

- Radio channel
  - ✓ Antenna + Propagation Channel
  - ✓ Propagation loss of radio channel



Wireless Channel Models

✓ Empirical Model

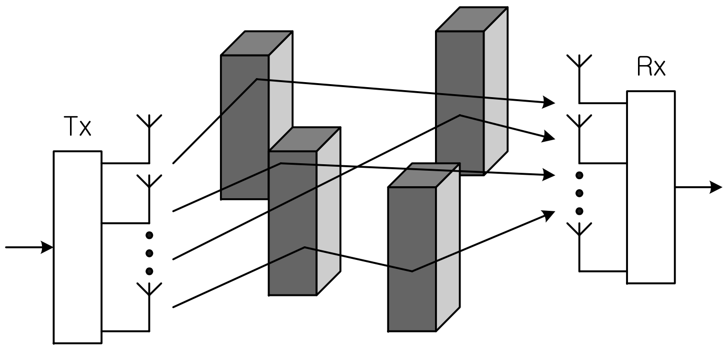
- Time domain channel measurement
- Frequency domain channel measurement

✓ Deterministic Model

- Ray-tracing
- FD-TD(Finite Difference - Time Domain)
- MoM (Method of Moment)

Concept of MIMO

- concept of MIMO system



- ✓ Multiple-transmitters and multiple-receivers
- ✓ Processing gain through the optimum combining
- ✓ Coding gain through the space time coding (STC)
- ✓ High spectral efficiency and extraordinarily large capacity

Wideband MIMO channel

- Wideband $n_T \times n_R$ MIMO channel
  - ✓ Wideband MIMO channel impulse response model from n_T-th transmit antenna to n_R-th receive antenna

$$h_{n_R,n_T}(t) = \sum_{k=1}^{N_{path}} \alpha_{n_R,n_T}(k)\delta\left(t - \tau_{n_R,n_T}(k)\right)$$

$\alpha_{n_R,n_T}(k)$: complex amplitude

$\tau_{n_R,n_T}(k)$: time delay

N_{path} : number of multipath

  - ✓ Frequency domain model

$$\mathbf{y}(f) = \mathbf{H}(f)\mathbf{x}(f) + \mathbf{v}(f)$$

$$h_{n_R,n_T}(f) = \sum_{k=1}^{N_{path}} \alpha_{n_R,n_T}(k) e^{-j2\pi f \tau_{n_R,n_T}(k)}$$

$$\mathbf{H}(f) = \begin{bmatrix} h_{1,1}(f) & h_{1,2}(f) & \cdots & h_{1,nT}(f) \\ h_{2,1}(f) & h_{2,2}(f) & \cdots & h_{2,nT}(f) \\ \vdots & \vdots & \ddots & \vdots \\ h_{nR,1}(f) & h_{nR,2}(f) & \cdots & h_{nR,nT}(f) \end{bmatrix}$$

Wideband MIMO channel

- Tapped delay line model

$$g(\tau) = \sum_{l=1}^{M} g_l \delta(\tau - \tau_l)$$

- ✓ Element : $j \in [1, \cdots, n_R]$, $k \in [1, \cdots, n_T]$
- ✓ g_l : channel response at delay τ
- ✓ $M = \max\{L_{jk}\}$, L_{jk} : excess delay
- ✓ $g_{jk,l}$: complex transmission coefficient between elements j and k at delay l
- ✓ Frequency domain representation : $G_f = FT(g_l)$, $f = 1, \cdots, F$
- ✓ Normalized matrix response

$$H = \frac{G}{\sqrt{\frac{\sum_{j=1}^{n_R} \sum_{k=1}^{n_T} \sum_{f=1}^{F} \left| G_{jk,f} \right|^2}{n_R n_T F}}}$$

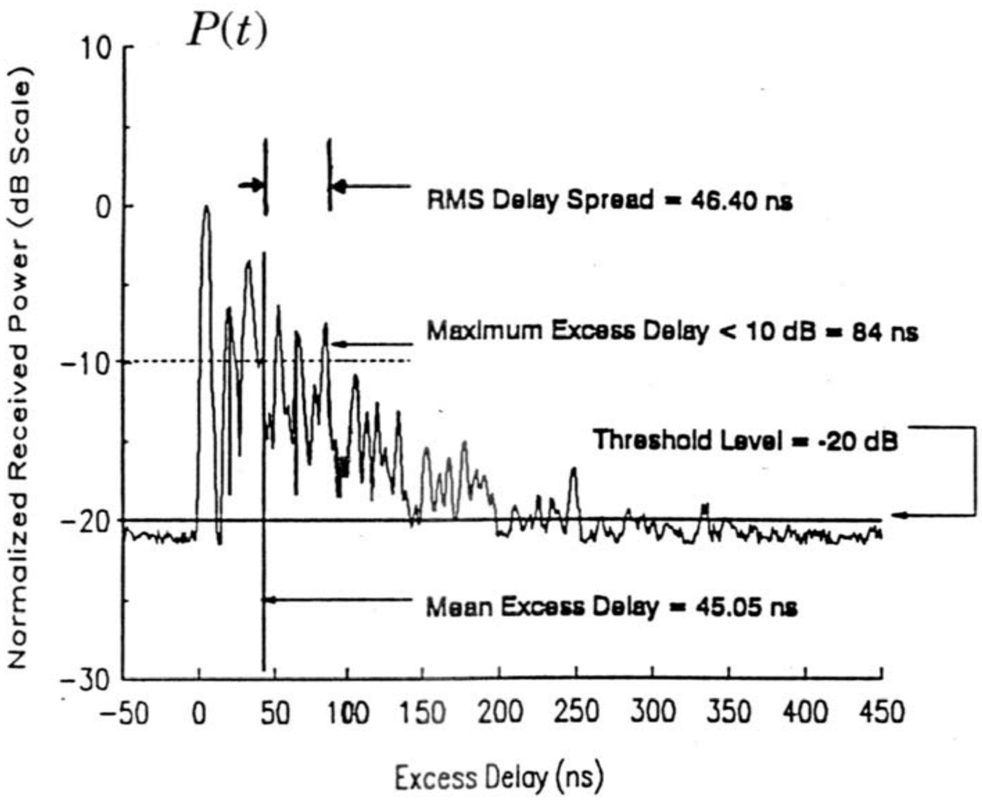
Wideband MIMO channel

- Extension of Shannon's capacity theorem
  - ✓ $$C = \log_2\left[\det\left(\mathbf{I}_{n_R} + \frac{\rho}{n_T}\mathbf{H}\mathbf{H}^\dagger\right)\right] \text{ (bits/s/Hz)}$$
    - n_R, n_T ; number of rx/tx elements, respectively
    - H ; the $n_R \times n_T$ normalized complex channel matrix
      (H_{ij} is the transfer fn. between tx element j and rx element i)
    - ρ ; the average signal to noise ratio (SNR) at each receiver branch
    - I ; the identity matrix
    - det ; the determinant function
    - † ; complex conjugate transpose
  - ✓ n×n Orthogonal channel matrix : $\mathbf{HH}^\dagger = \mathbf{I}_n$ (identity matrix)

    $C = n \cdot \log_2(1 + (\rho/n))$ → $C = \rho / \ln(2)$ as $n \to \infty$ at high SNR
  - ✓ Capacity of SISO channel : $C = \log_2(1+\rho)$

Channel Parameters

- Mean Excess Delay
  - ✓ $$\bar{\tau} = \frac{\int_0^\infty \tau P(\tau) d\tau}{\int_0^\infty P(\tau) d\tau}$$
    - τ : delay time
    - P(τ) : Received Power
- RMS Delay Spread
  - ✓ $$\sigma_\tau^2 = \frac{\int_0^\infty (\tau - \bar{\tau})^2 P(\tau) d\tau}{\int_0^\infty P(\tau) d\tau}$$
- Coherence Bandwidth
  - ✓ $f_0 \propto 1/\sigma_\tau$

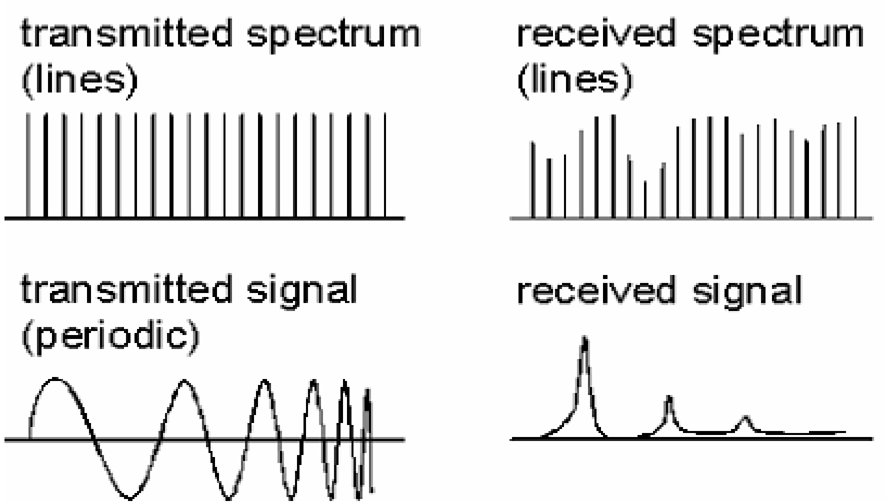


Channel measurement methods

- Traditional methods
  - Frequency sweep : vector network analyzer (VNA)
  - Direct RF pulse
- Alternative methods
  - Real time sampled sequences (RTS) method
  - Periodic test sequences
    - Band-limited multi-frequency signals for RTS
    - M-sequences for PN correlation
  - Medav RUSK vector channel sounder using RTS method
    - Almost all MIMO channel measurements
  - MIMO channel sounder using PN correlation method (Example)

MIMO Channel Measurement

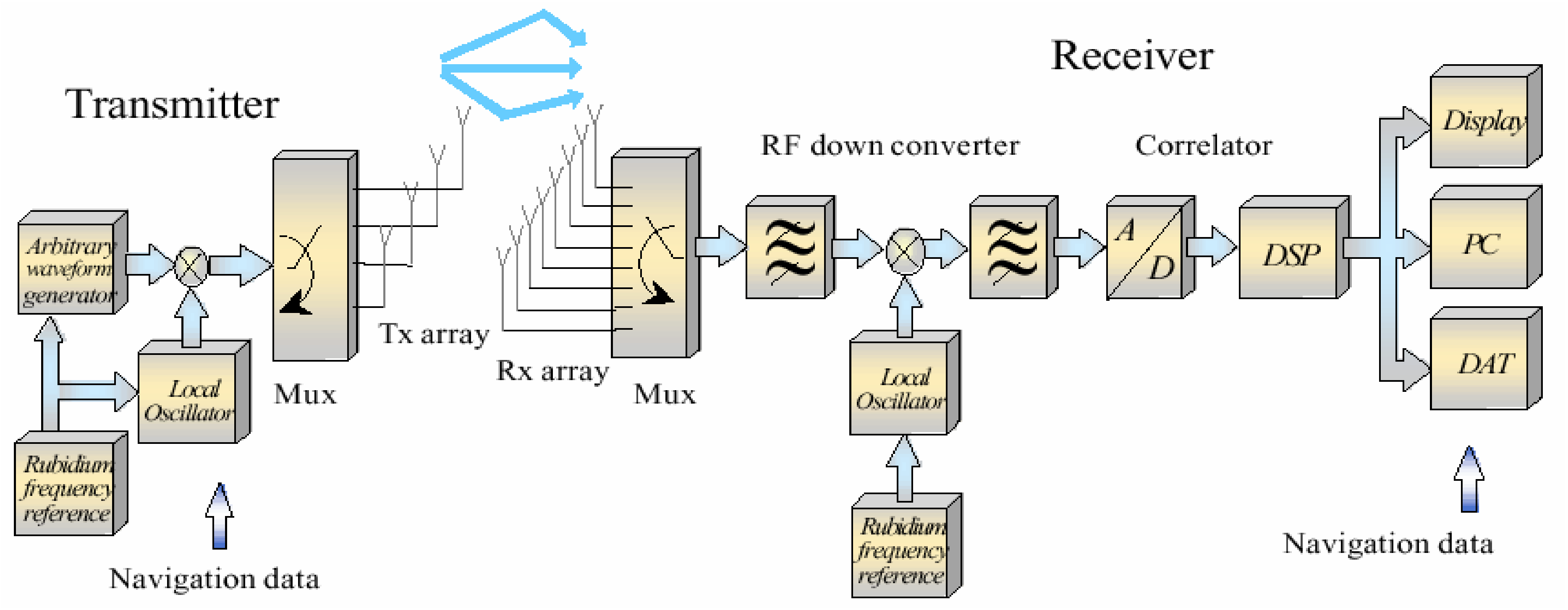
- Centre for communications Research – McNamara, Beach
  - ✓ Discrete Multi-Tone(DMT) technique



  - ✓ Specification
    - 120MHz BW centered at 5.2GHz
    - Frequency spacing 1.25MHz between adjacent tones
    - 8 transmitters and 8 receivers

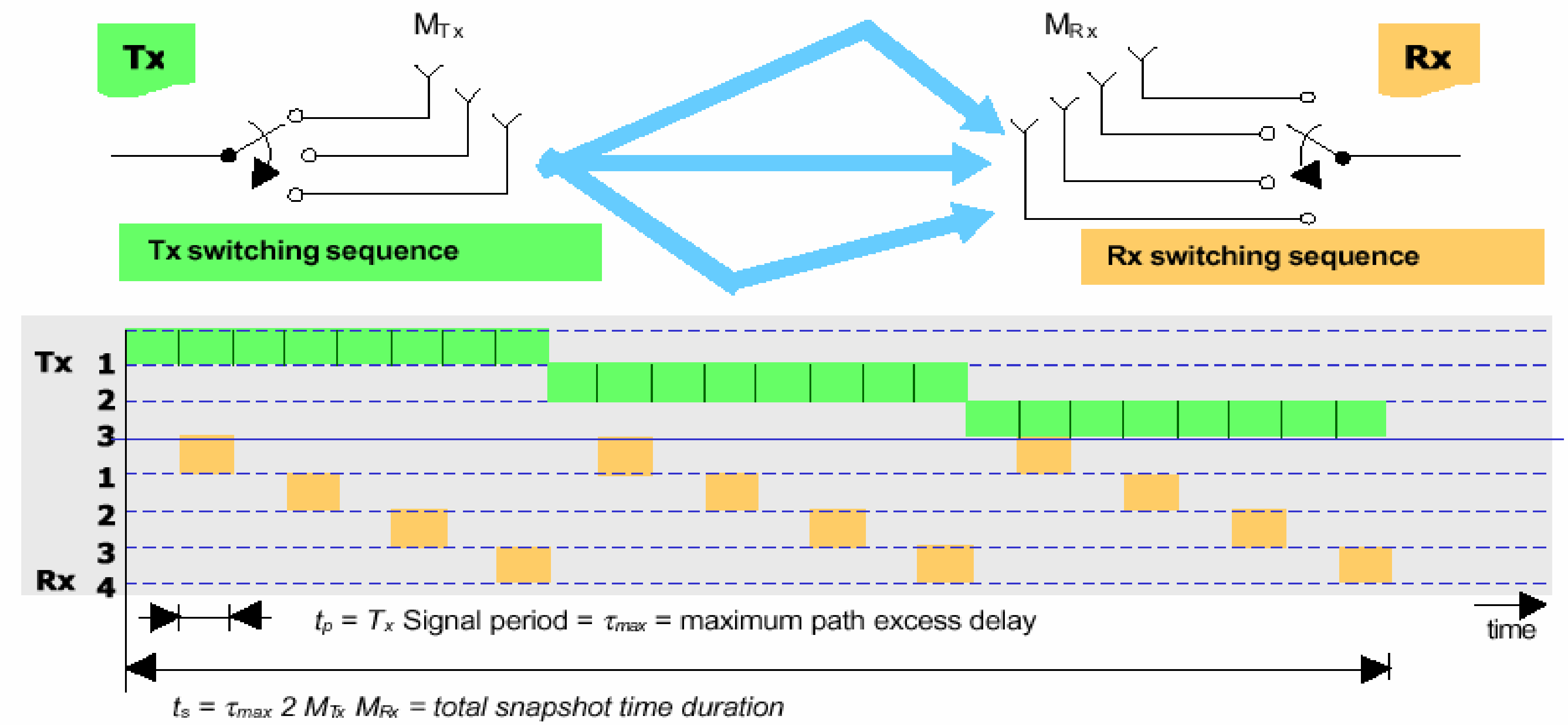
MIMO Channel Measurement

- Block diagram of the MIMO channel sounder
  - ✓ Medav RUSK BRI vector channel sounder



MIMO Channel Measurement

❖ Switching scheme



✓ $t_p = 0.8\mu s$, $t_s = 102.4\mu s$ for 8 transmit and 8 receive elements

PN Correlation Method

- Linear filter model for time-varying channel

$$h(t,\tau) = \sum_{n=0}^{N} \alpha_n(t)\left[\delta(\tau - \tau_n(t))\right]\exp\left[j(\omega_c t_n + \theta_n(t))\right]$$

- Channel impulse response measurement using PN correlation method
  - ✓ Impulse response of linear system

$$y(t) = \int_0^\infty h(\lambda)x(t-\lambda)d\lambda$$

  - ✓ Cross-correlation function

$$\Phi_{xy}(\tau) = \lim_{\tau\to\infty}\frac{1}{2T}\int_{-\tau}^{\tau} x(t)y(t+\tau)dt$$

$$= \int_0^\infty d\lambda\, h(\lambda)\lim_{\tau\to\infty}\frac{1}{2T}\int_{-\tau}^{\tau} x(t)x(t+\tau-\lambda)dt$$

PN Correlation Method

- Input auto-correlation function

$$\Phi_{xx}(\tau) = \lim_{\tau \to \infty} \frac{1}{2T} \int_{-\tau}^{\tau} x(t)x(t+\tau)dt$$

$$\therefore \quad \Phi_{xy}(\tau) = \int_0^{\infty} h(\lambda)\Phi_{xx}(\tau - \lambda)d\lambda$$

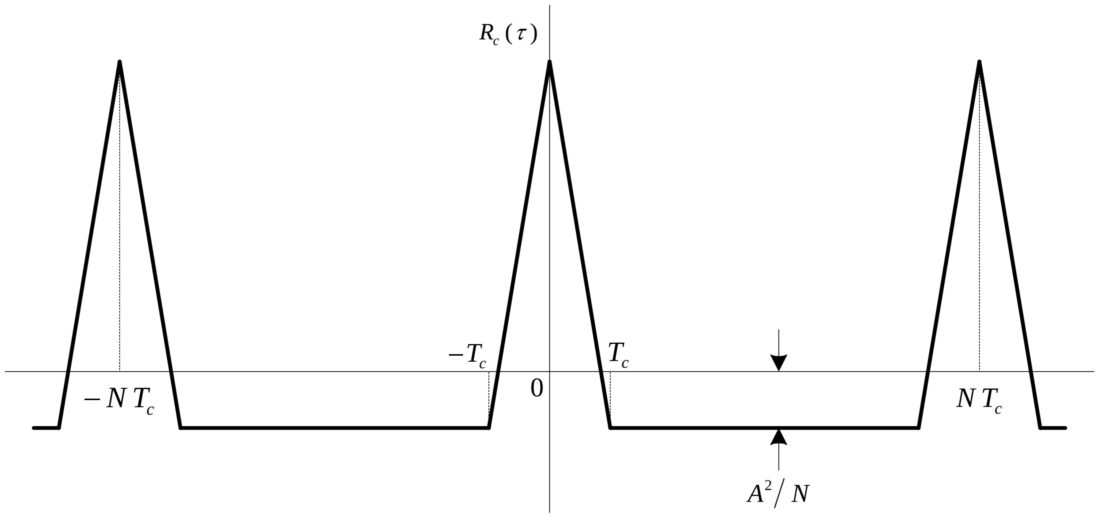
- If input auto-correlation function is delta function

$$\Phi_{xy}(\tau) = \int_0^{\infty} h(\lambda)\delta(\tau - \lambda)d\lambda$$

$$= h(\tau)$$

PN Correlation Method

- PN correlation method
  - ✓ Transmitted signal → PN-sequence
  - ✓ Received signal → Convolution of transmitted PN-sequence and channel impulse response
  - ✓ Cross-correlation of transmitted and received signal → Channel impulse response

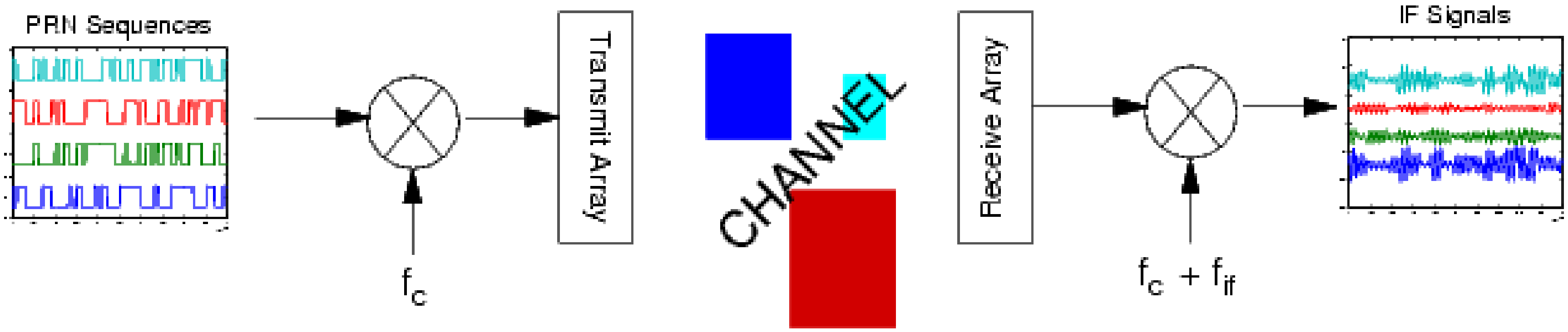


Autocorrelation of PN-sequence

MIMO Channel Measurement System

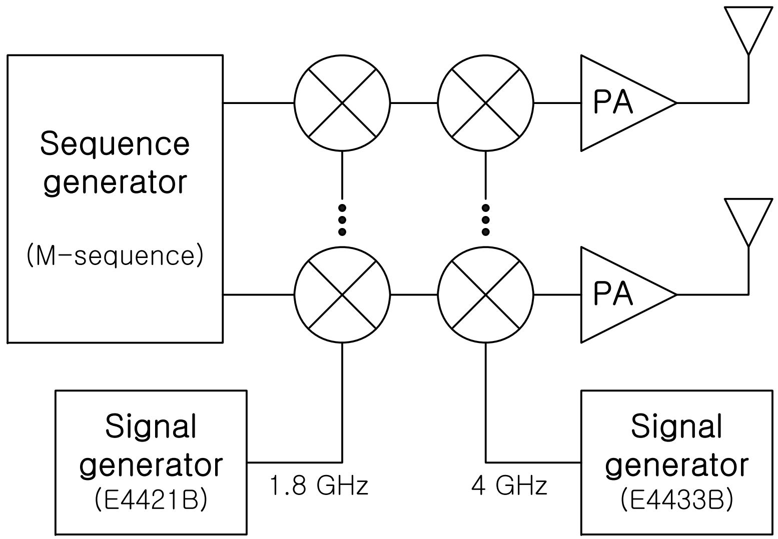
- Measurement Method
  - ✓ Transmitting shifted PN sequence for each antenna branch having orthogonal property
  - ✓ Enable to measure each channel simultaneously

Measurement Hardware



MIMO Channel Measurement System

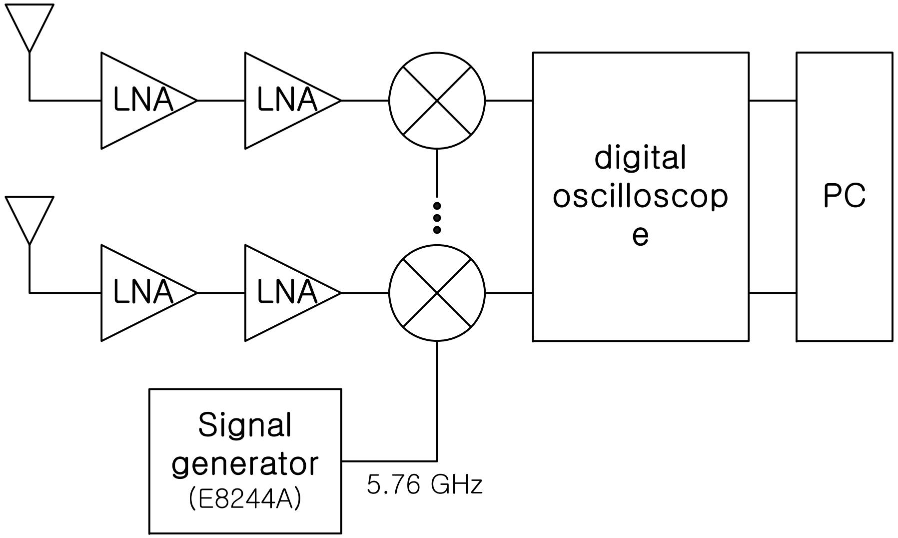
❖ Transmit System



- ✓ Transmit m-sequence
  - Length : 1023
  - Chip rate : 20MHz (variable up to 50MHz)
- ✓ Transmit power : 20 dBm
- ✓ Antenna : omni-directional, 4.6 dBi

MIMO Channel Measurement System

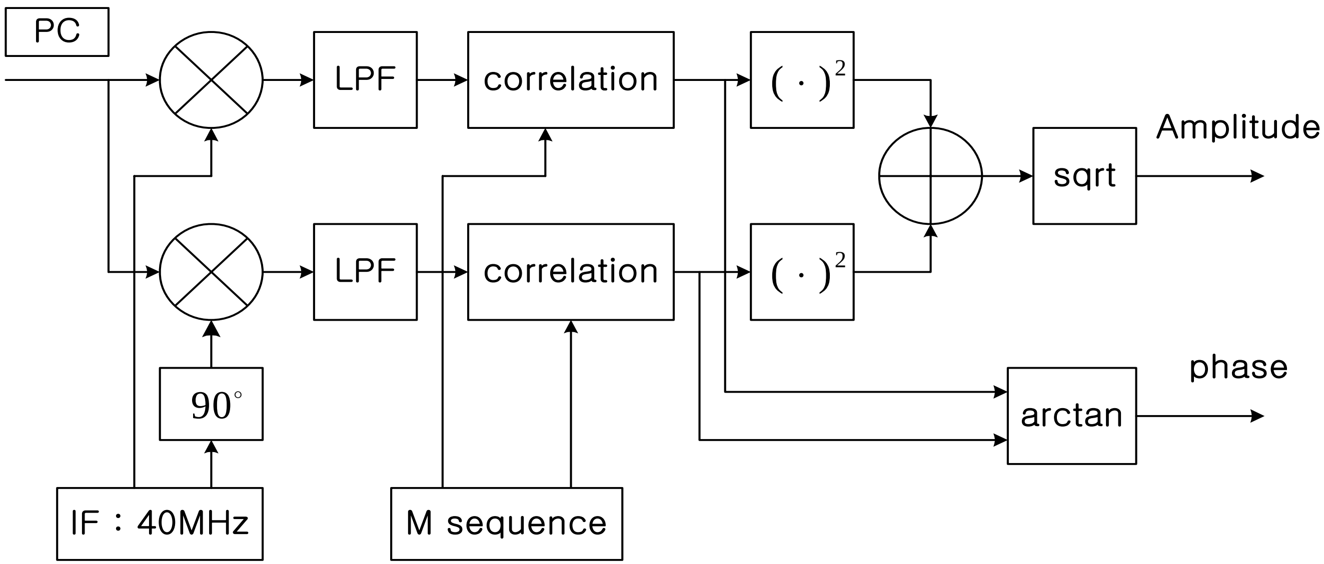
- Receive System



- ✓ Two 26dB-LNA for each channel
- ✓ IF frequency : 40 MHz
- ✓ Oscilloscope sampling rate : 250 MS/s
- ✓ Data saving to PC using GPIB interface

MIMO Channel Measurement System

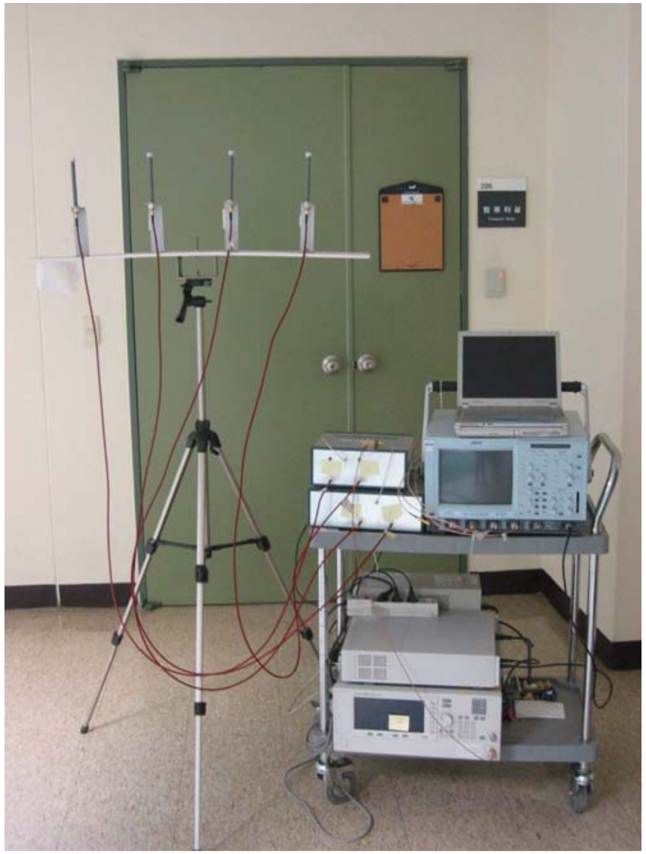
- Processing saved data



- ✓ Compute amplitude and phase of channel impulse response using I/Q demodulation
- ✓ Calibration measured data using back-to-back measurement

MIMO Channel Measurement System

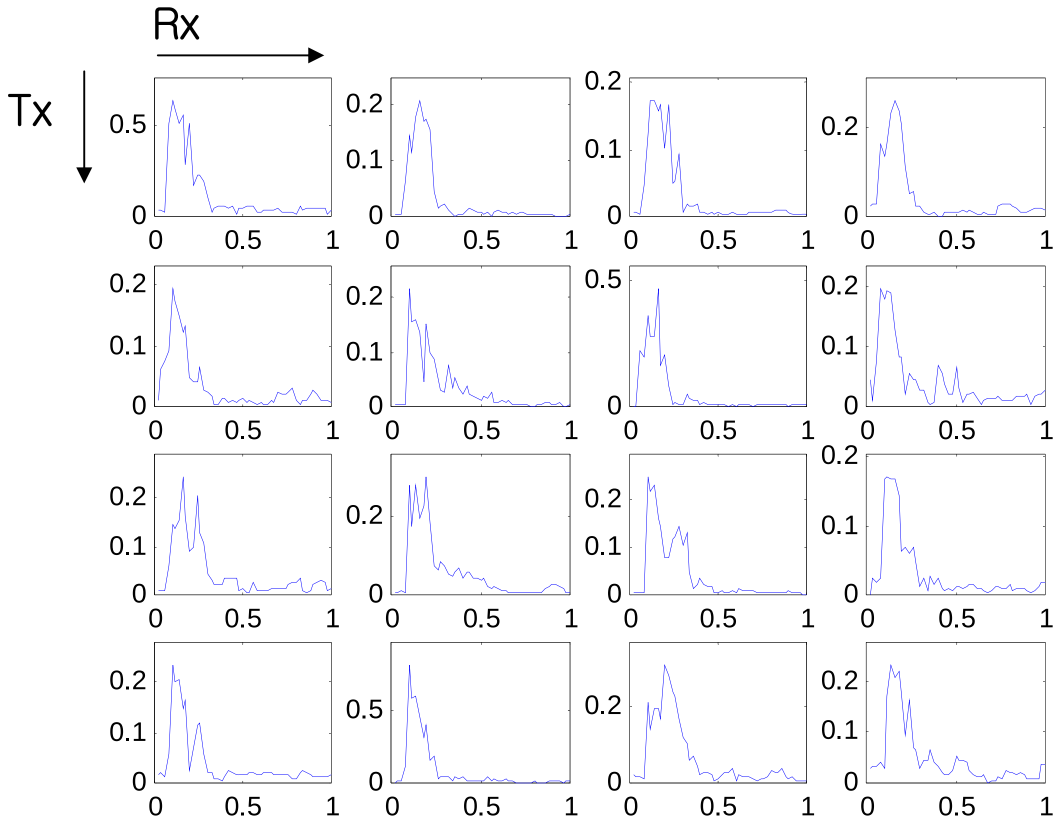
❖ Transmit System



❖ Receive System

Channel Impulse Response Example

- 4 × 4 Impulse Response

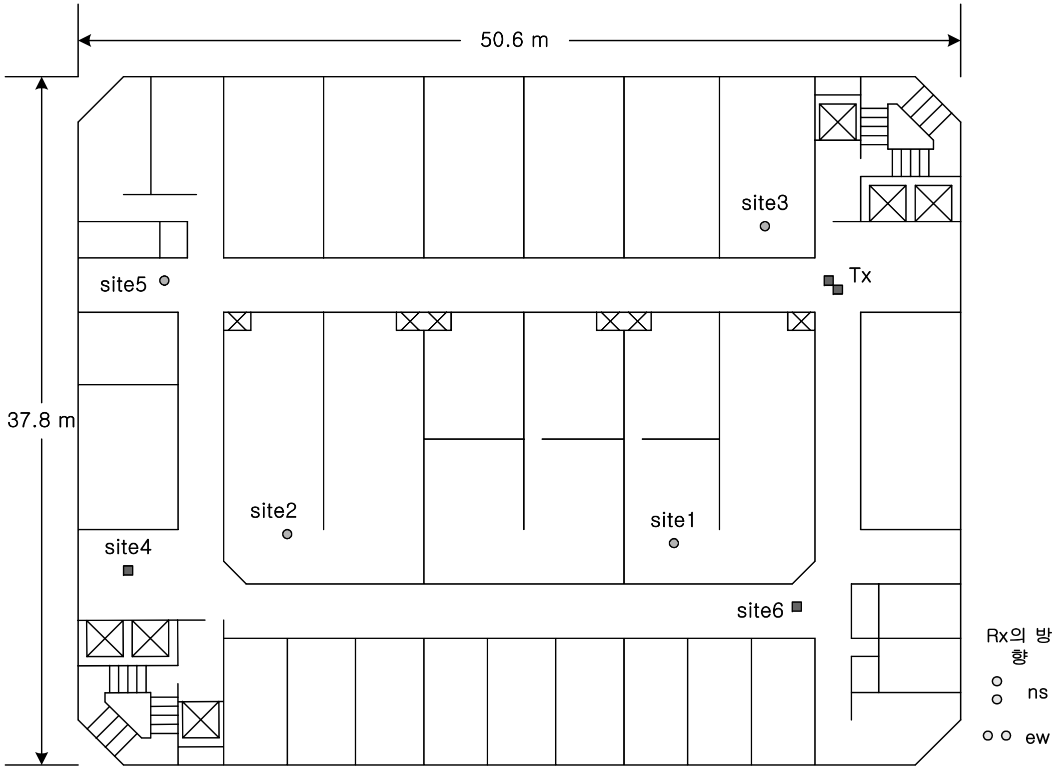


Measurements Environments

- Measurement point
  - Analysis as measurement environments
  - Path having obstacle or not
    - LOS , NLOS
  - Analysis as antenna element spacing
    - Every λ/2 step from λ/2 to 4 λ
  - Direction of receive antenna array
    - North-to-south, East-to-west
  - Transmit antenna element spacing : 1 λ, 4 λ
  - Antenna height : 1.6 m

Measurements Environments

❖ EERC (#301)

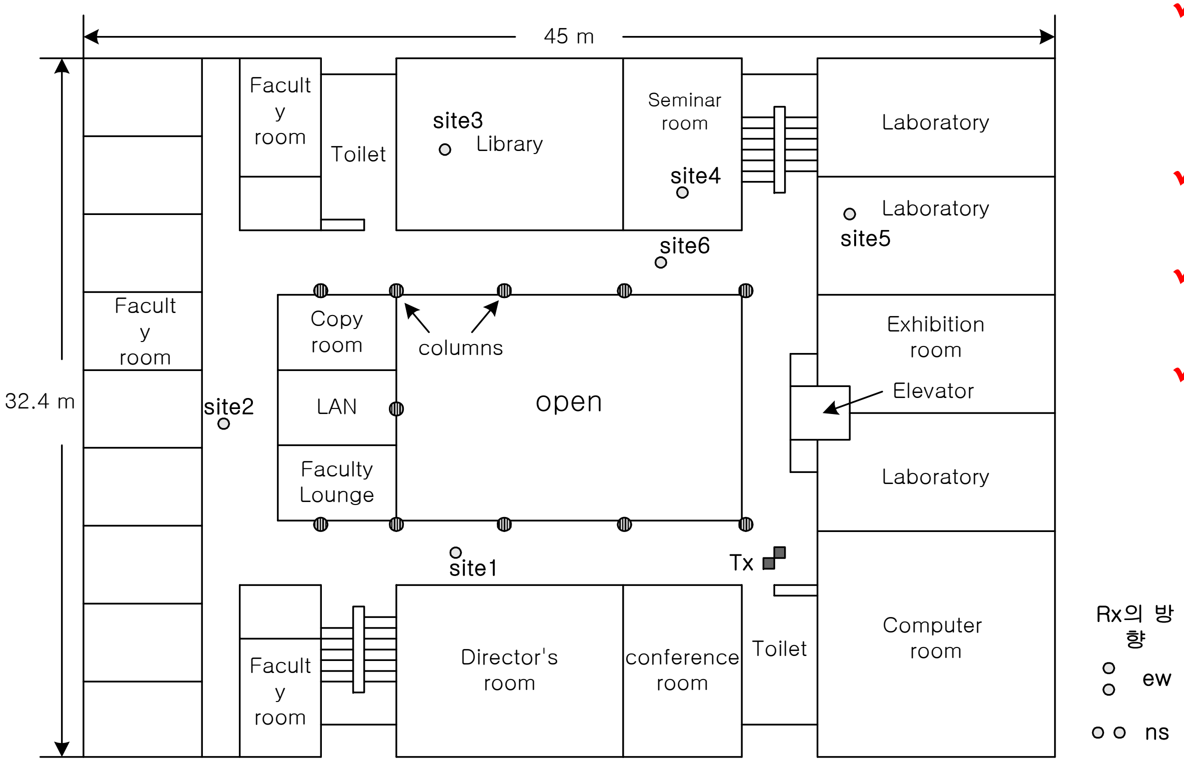


❖ Properties

- ✓ Some walls are made of metal, others are made of concrete
- ✓ Outer walls are coated with metallic film
- ✓ Measurements are carried out at 6th floor

Measurements Environments

❖ INMC

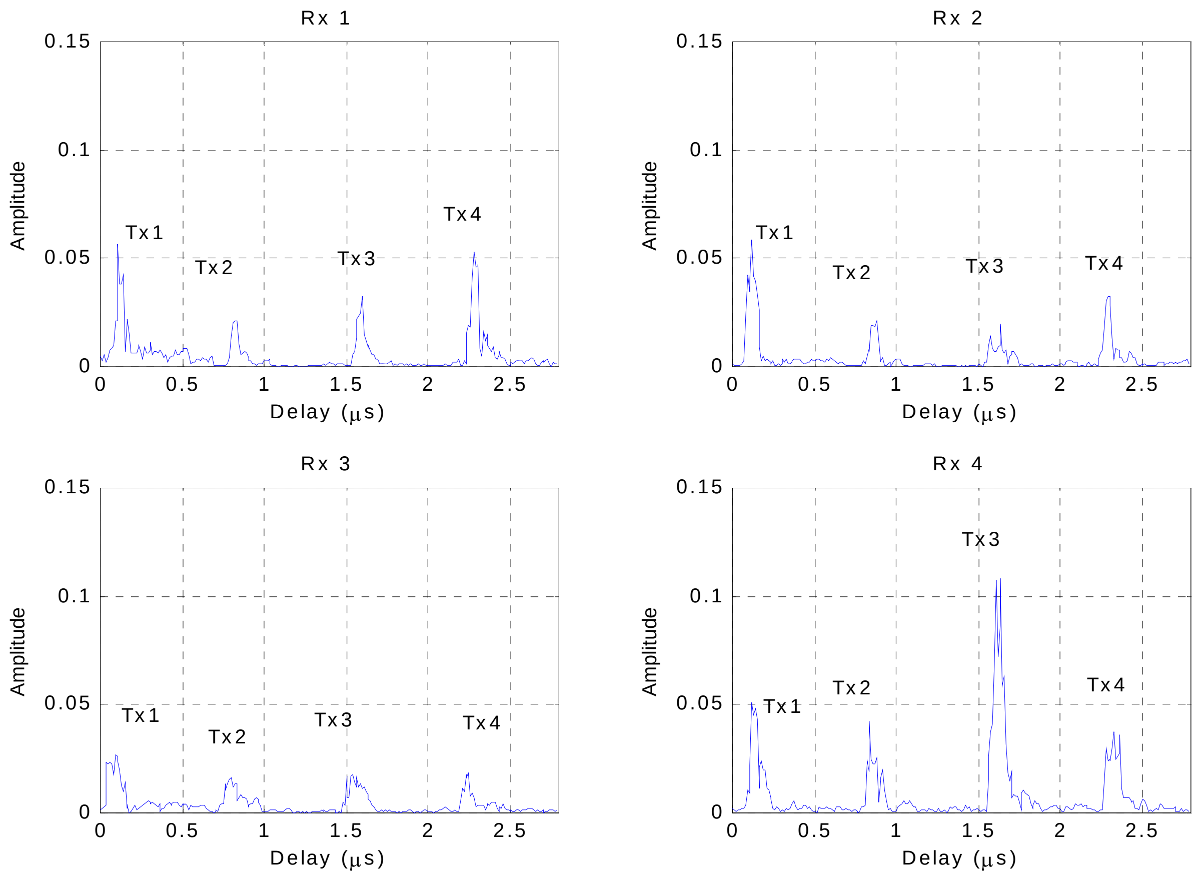


❖ Properties

- ✓ Walls are made of concrete, partition, and metal.
- ✓ All doors are made of metal
- ✓ There is Atrium at center
- ✓ Measurements are carried out at 2nd floor

Measurement Example : Snapshot

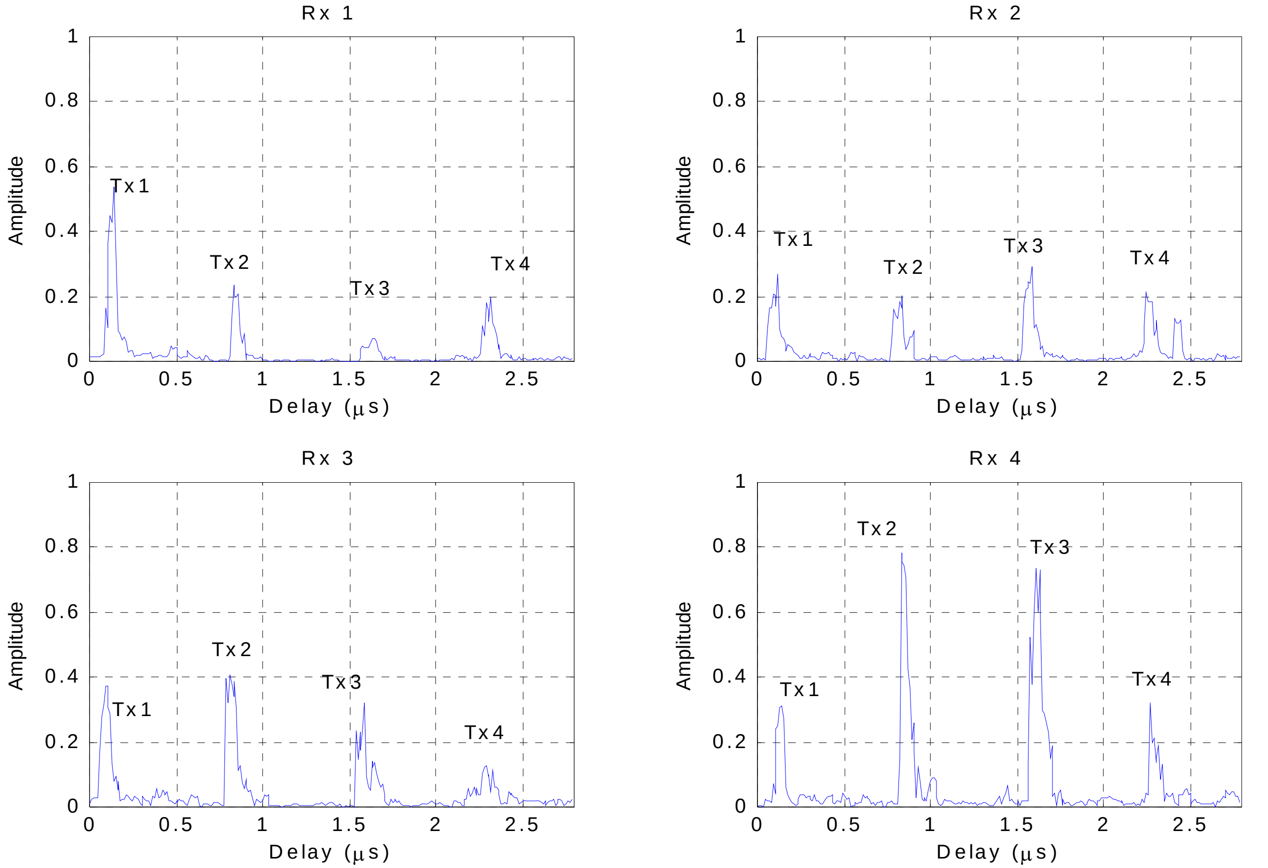
- EERC (site 5)



- Calibrate 50dB attenuation as 1.0

Measurement Example : Snapshot

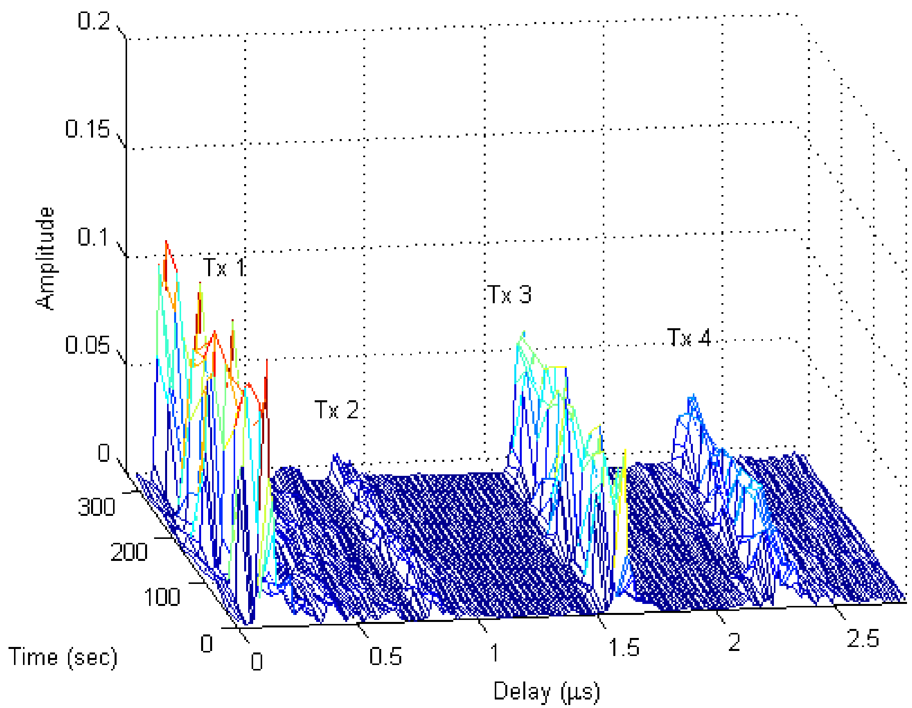
- INMC (site 1)



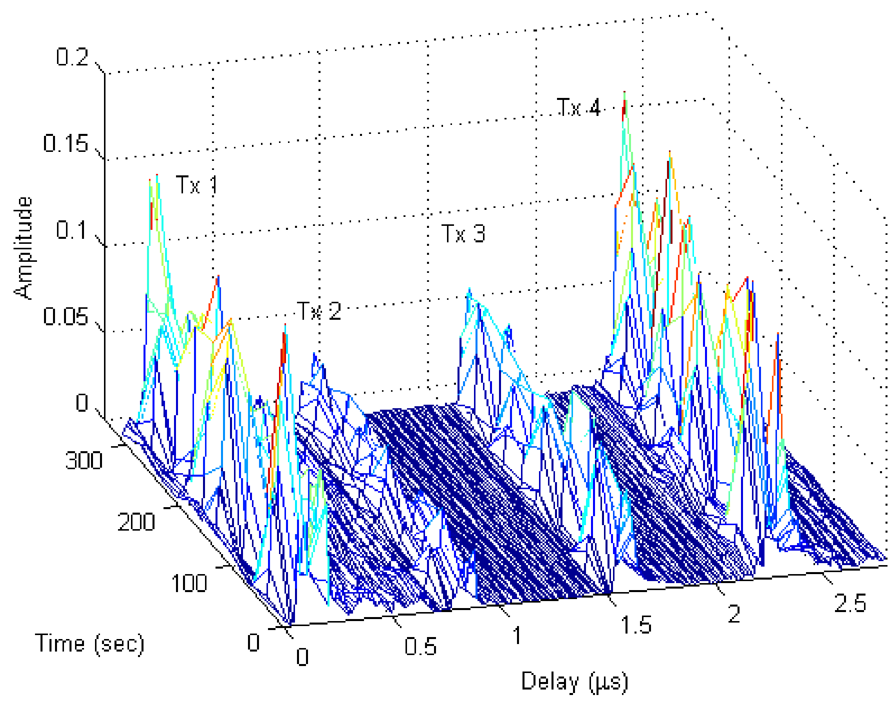
- Calibrate 50dB attenuation as 1.0

Measurement Example : Time Variation

- Time variation
  - ✓ Indoor LOS (EERC site 5)

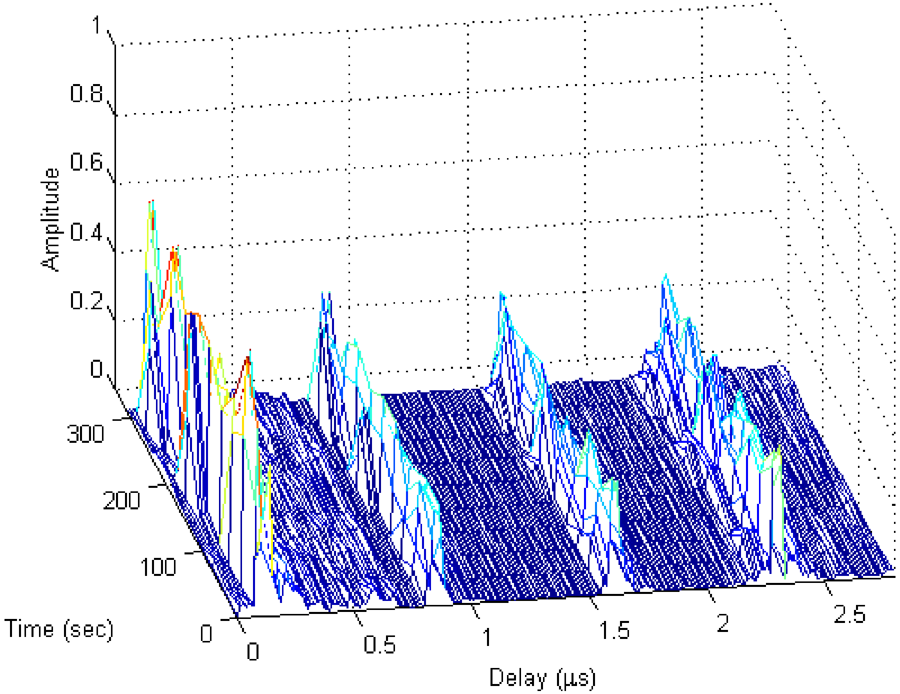


- Time variation
  - ✓ Indoor NLOS (EERC site 2)

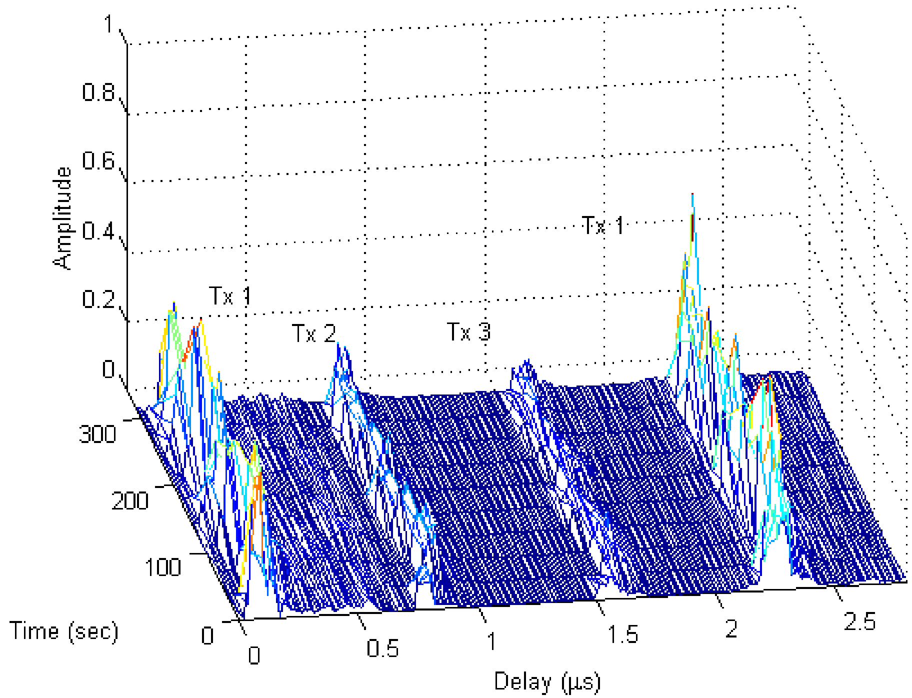


Measurement Example : Time Variation

- Time variation
  - ✓ Indoor LOS (INMC site 1)



- Time variation
  - ✓ Indoor NLOS (INMC site 2)



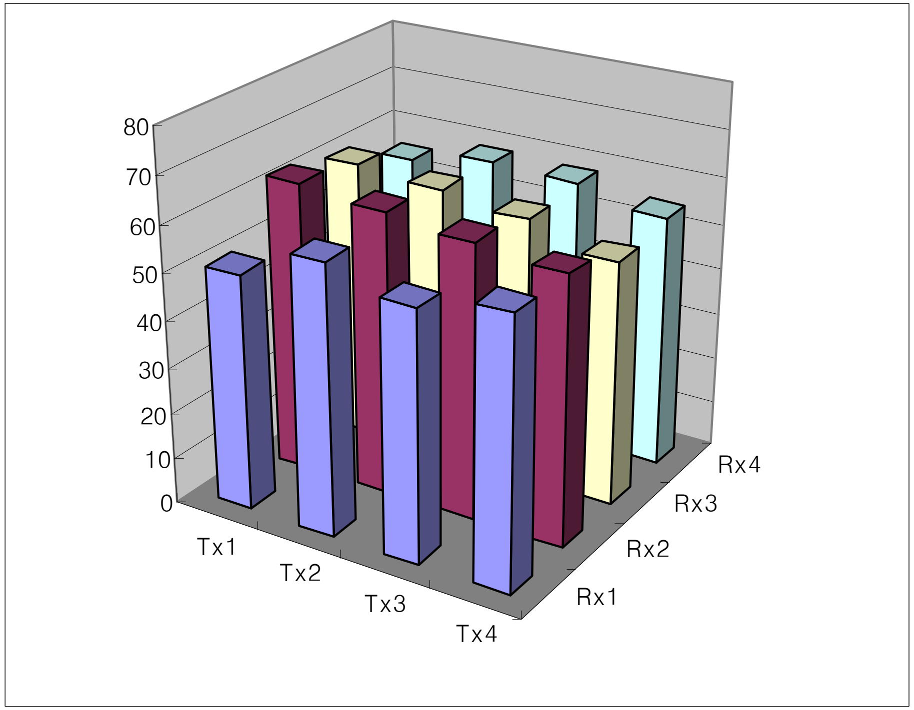
Path Loss Analysis

- Path loss
  - ✓ Path loss for each 4×4 wideband MIMO channel
  - ✓ Calculate path loss for each channel to sum multi-path power

- Average path loss
  - ✓ EERC (Bldg #301) : 64.1 dB
  - ✓ INMC (Bldg #132) : 64.8 dB

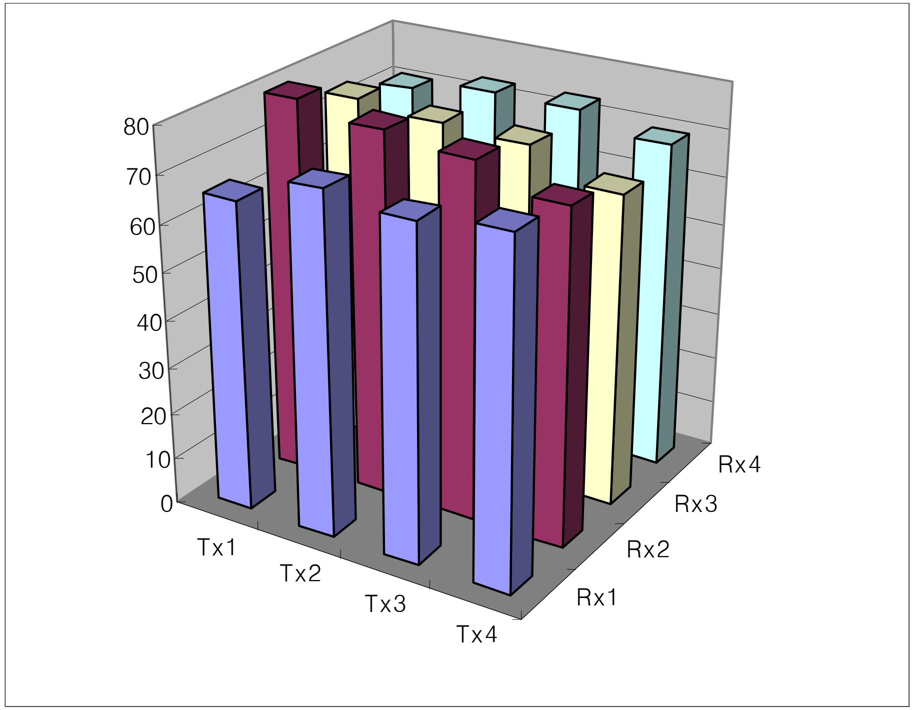
MIMO Channel Path Loss

❖ EERC LOS (site 6)



- ✓ Mean : 57.3 dB
- ✓ Standard Deviation : 3.20 dB

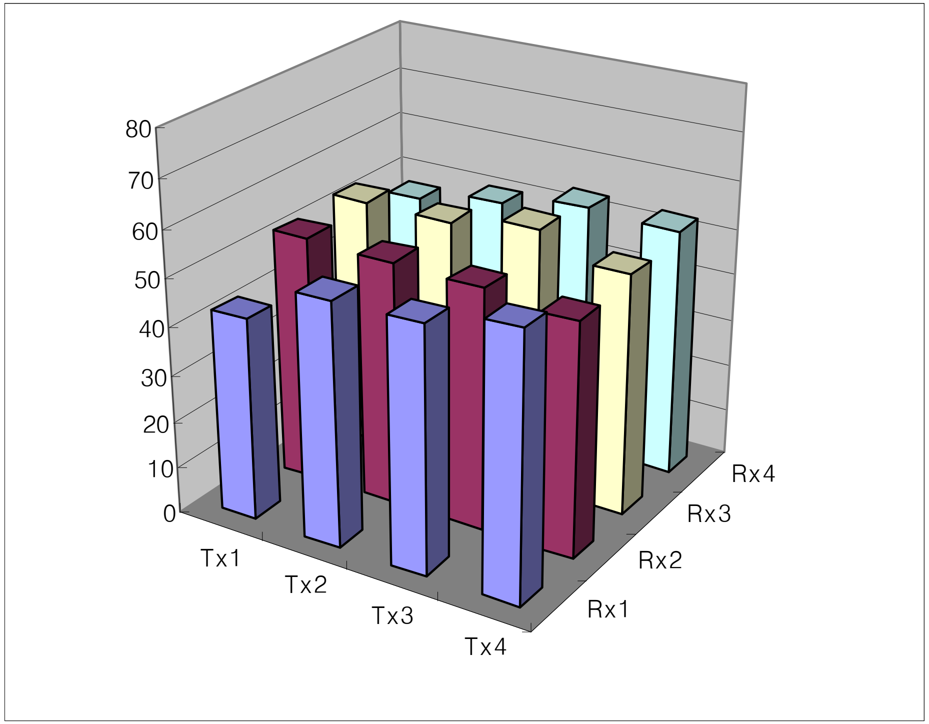
❖ EERC NLOS (site 4)



- ✓ Mean : 72.5 dB
- ✓ Standard Deviation : 3.61 dB

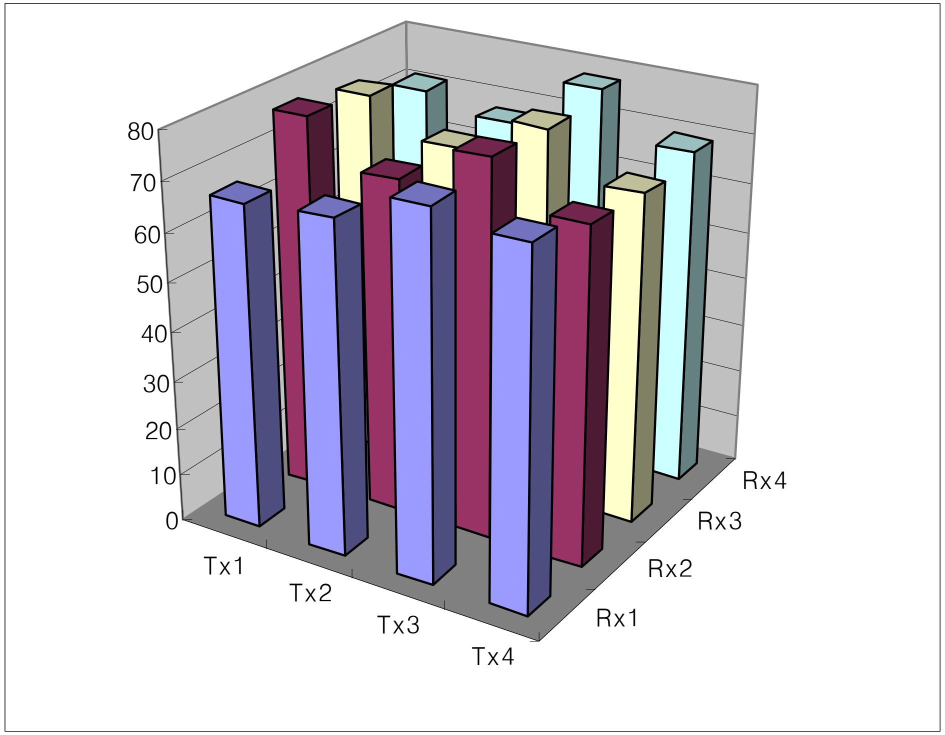
MIMO Channel Path Loss

❖INMC LOS (site 6)



- ✓ Mean : 51.5 dB
- ✓ Standard Deviation : 3.13 dB

❖ INMC NLOS (site 3)



- ✓ Mean : 71.9 dB
- ✓ Standard Deviation : 4.10 dB

Channel Parameter Analysis

❖ Channel Parameters

✓ Mean Excess Delay & RMS Delay Spread

	EERC (unit : μs)					
	Rx 1	Rx 2	Rx 3	Rx 4	Rx 5	Rx 6
MED	0.047	0.056	0.077	0.074	0.072	0.052
RMS	0.040	0.045	0.061	0.063	0.055	0.043

- A lot of multi-path due to metal walls
- Large rms delay spread for Los environments
- The distance between Tx and Rx affects rms delay spread and mean excess delay

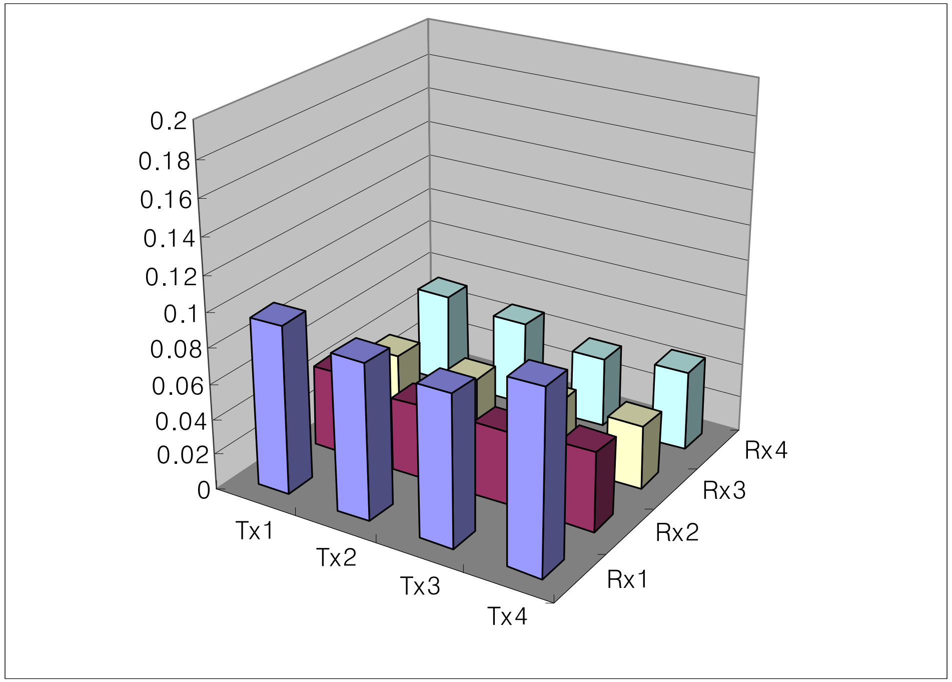
	INMC (unit : μs)					
	Rx 1	Rx 2	Rx 3	Rx 4	Rx 5	Rx 6
MED	0.062	0.053	0.070	0.143	0.137	0.183
RMS	0.041	0.043	0.050	0.084	0.095	0.094

- Building has atrium and is made of concrete
- The variation of rms delay spread and mean excess delay are large

- INMC average : MED 0.108 μs, RMS 0.067 μs
- EERC average : MED 0.63 μs, RMS 0.051 μs

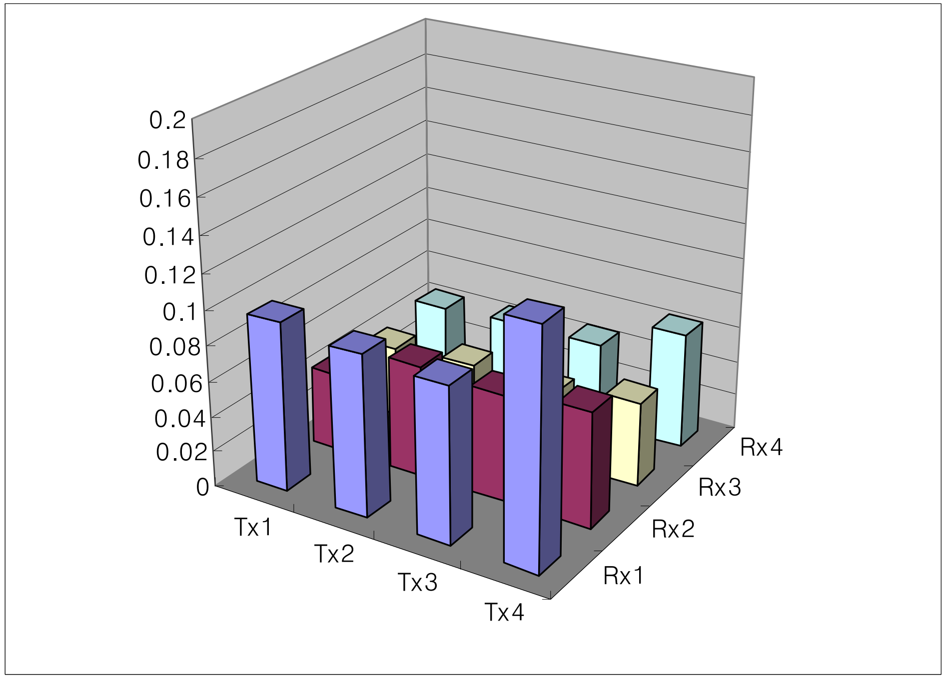
MIMO Channel : RMS Delay Spread

❖ EERC (LOS site 5)



- ✓ Mean : 0.055μs
- ✓ Standard Deviation : 0.023μs

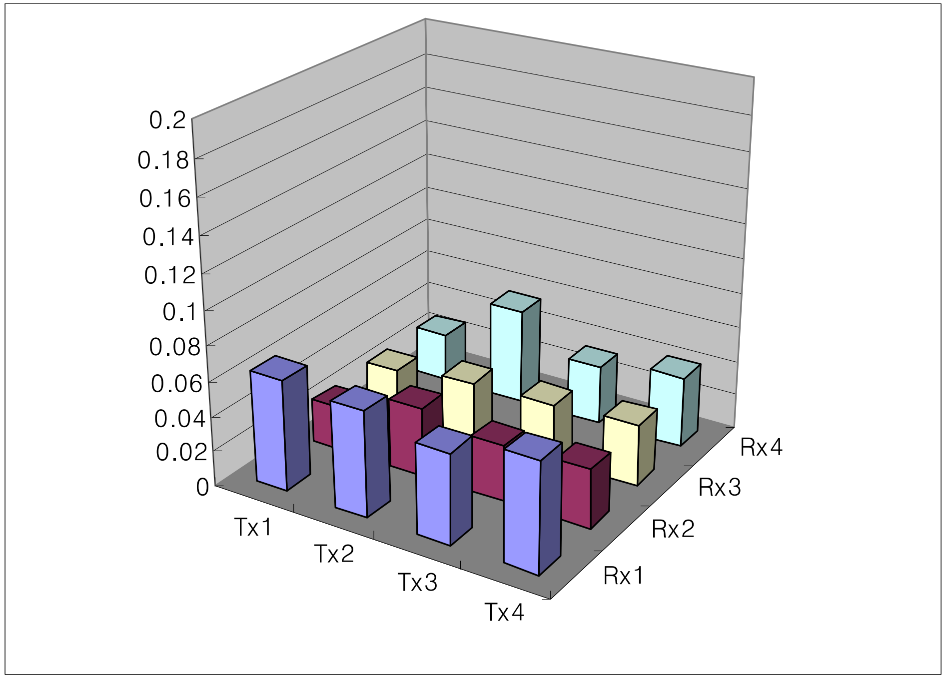
❖ EERC (NLOS site 4)



- ✓ Mean : 0.064μs
- ✓ Standard Deviation : 0.026μs

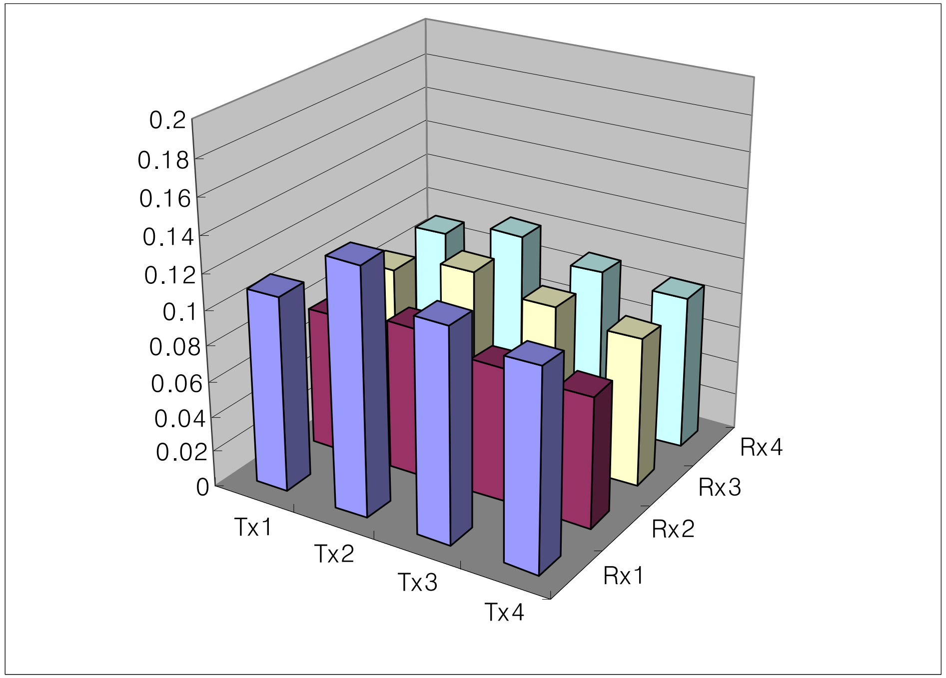
MIMO Channel : RMS Delay Spread

❖ INMC (LOS site)



✓ Mean : 0.041μs
✓ Standard Deviation : 0.013μs

❖ INMC (NLOS site)



✓ Mean : 0.095μs
✓ Standard Deviation : 0.017μs

Channel Correlation

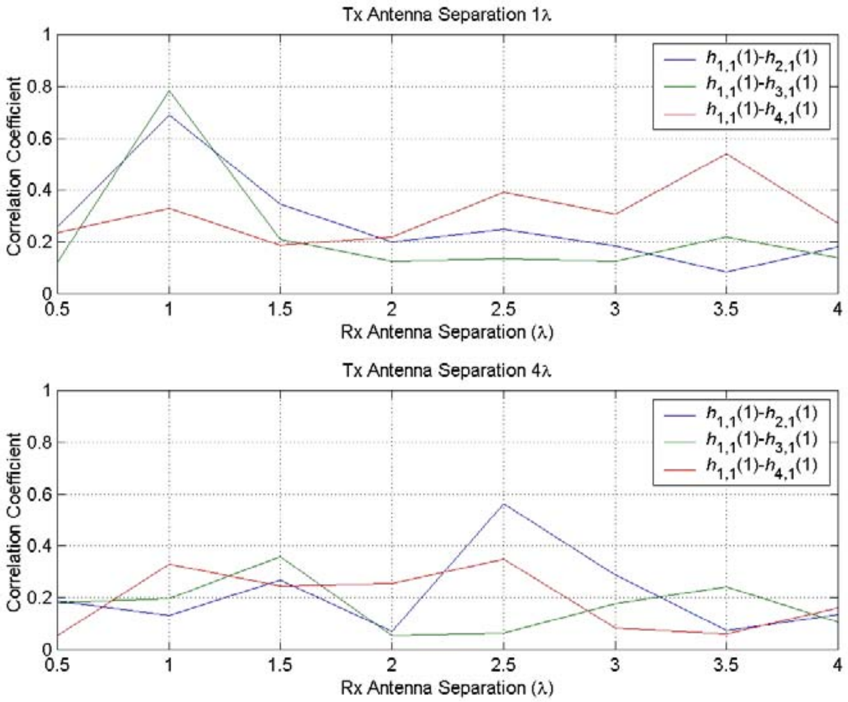
❖ Tx and Rx Correlation Coefficients

$$\rho\left(h_{i,j}(k), h_{n,m}(l)\right) = \frac{E\left[\left(h_{i,j}(k) - E\left[h_{i,j}(k)\right]\right)\left(h_{n,m}(l) - E\left[h_{n,m}(l)\right]\right)^{*}\right]}{\sqrt{E\left[\left|h_{i,j}(k) - E\left[h_{i,j}(k)\right]\right|^{2}\right] E\left[\left|h_{n,m}(l) - E\left[h_{n,m}(l)\right]\right|^{2}\right]}}$$

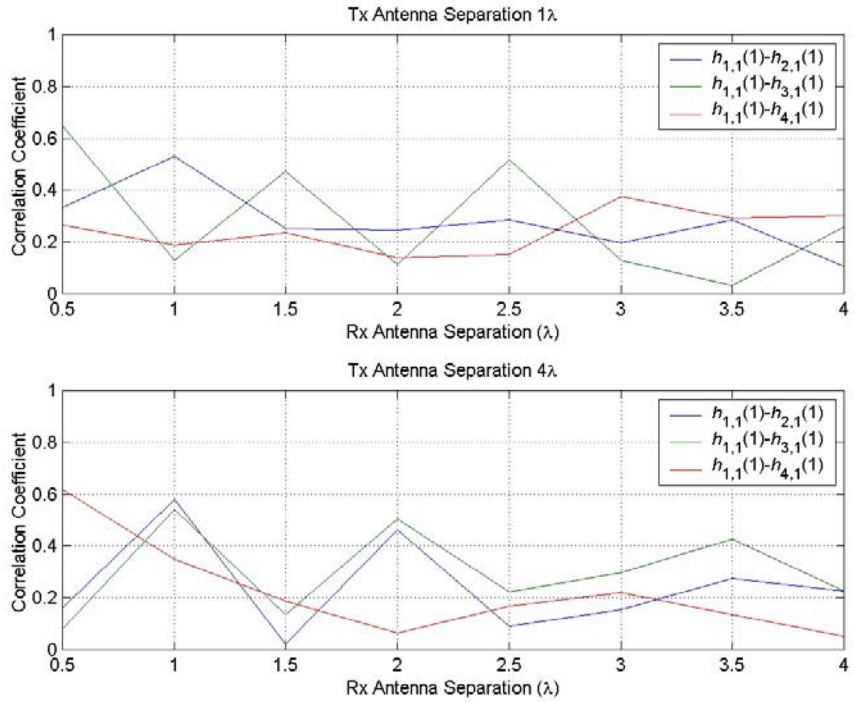
- ✓ $h_{i,j}(k)$
  - k-th multi-path from j-th transmitter antenna to i-th receiver antenna
- ✓ Tx correlation coefficient
  - Correlation of transmitted signals
  - Transmitter diversity
- ✓ Rx correlation coefficient
  - Correlation of received signals
  - Receiver diversity

Rx Correlation of 1st multi-path

- EERC (LOS site5)



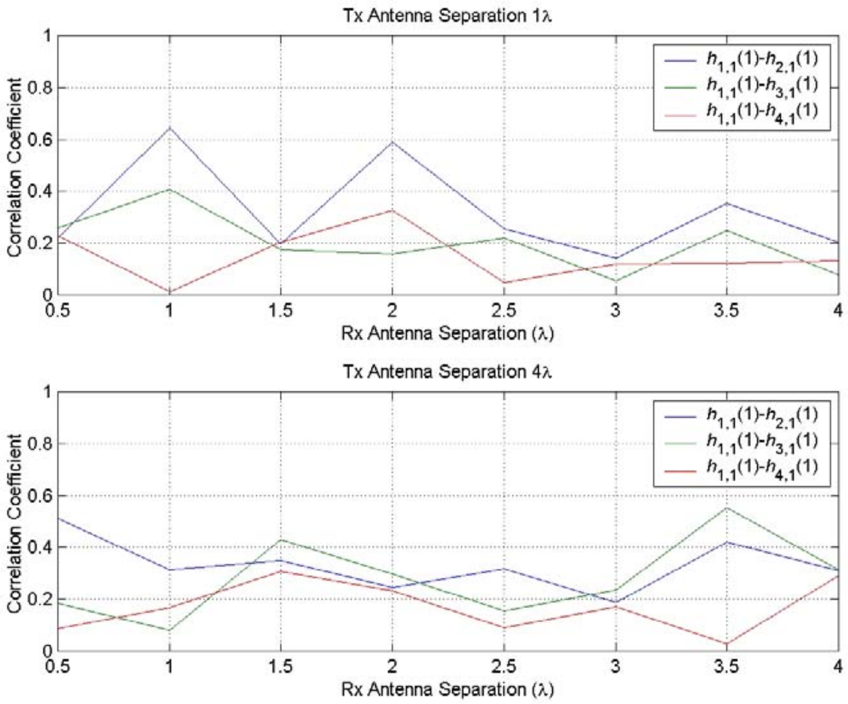
- INMC (LOS site1)



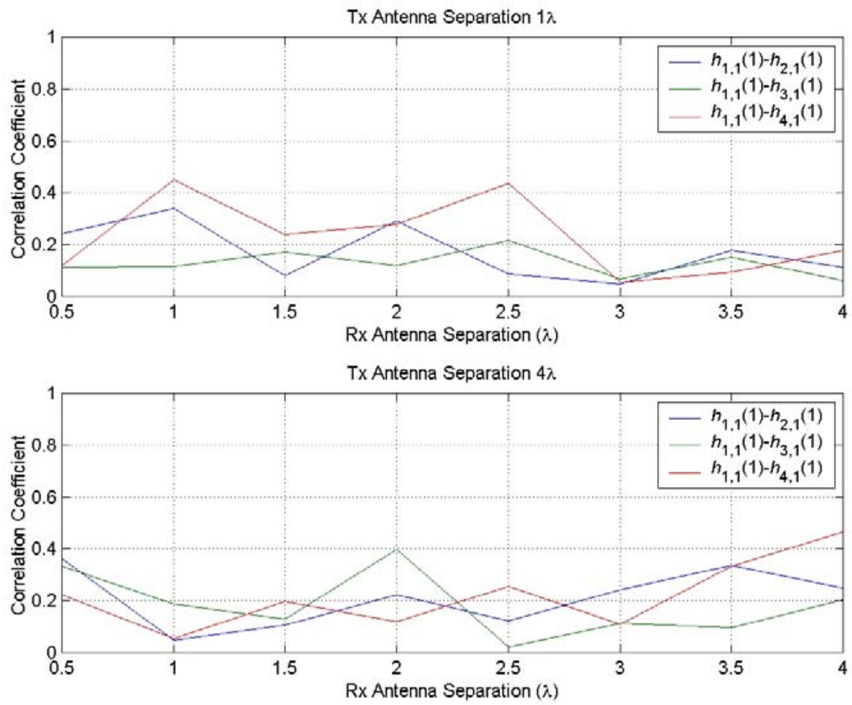
- For LOS case, the variation of correlation is large with receiver antenna separation

Rx Correlation of 1st multi-path

❖ EERC (NLOS site4)



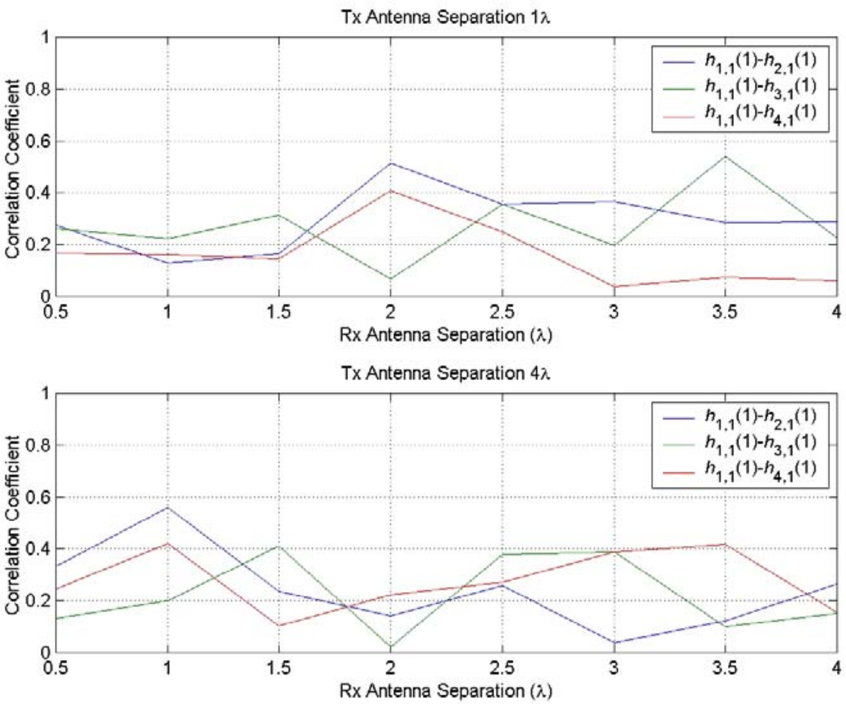
❖ EERC (NLOS site3)



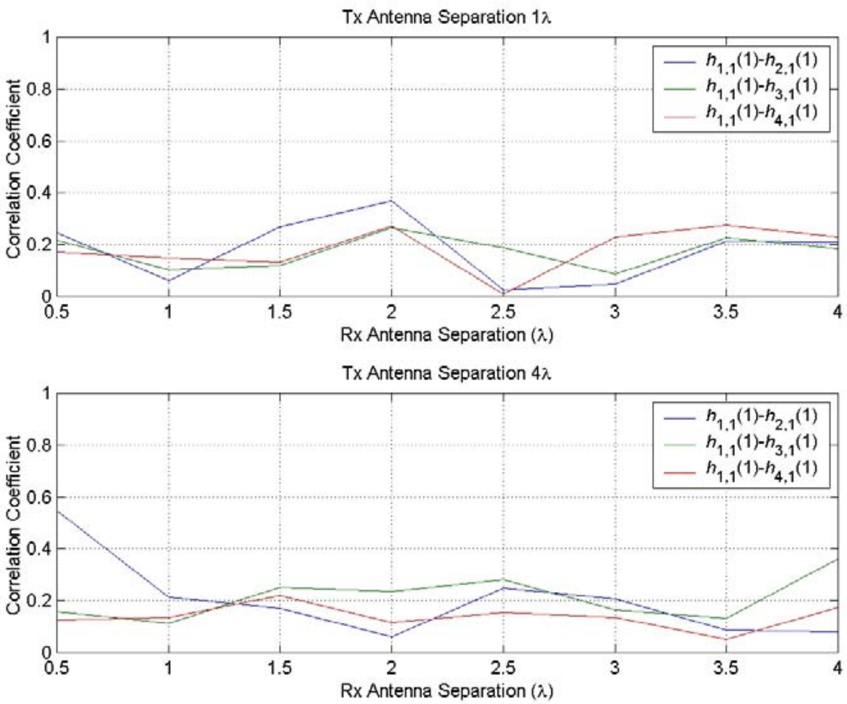
- For NLOS case, less variation than LOS case.
- Coefficients decrease as antenna separation increases

Rx Correlation of 1st multi-path

❖ INMC (NLOS site2)



❖ INMC (NLOS site3)



- For NLOS case, less variation than LOS case.
- Coefficients decrease as antenna separation increases

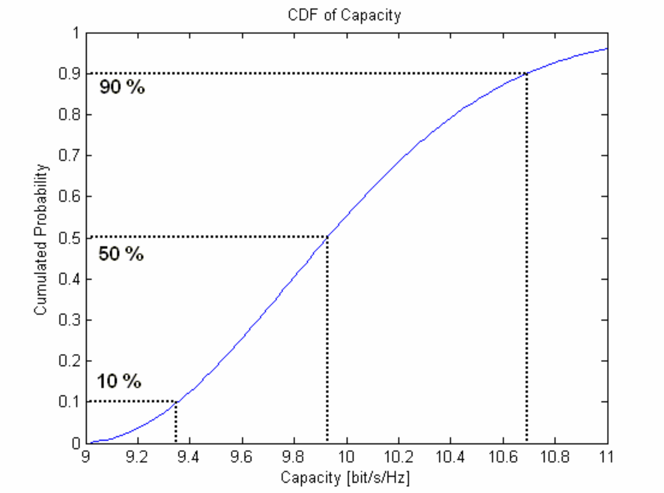
Channel Capacities

$$C = \log_2\left(\det\left[\mathbf{I}_{n_R} + \left(\frac{\rho}{n_T}\mathbf{H}\mathbf{H}^*\right)\right]\right)$$

ρ : Average received SNR

I_{n_R} : $n_R \times n_R$ identity

H : Channel matrix



✓ 1 λ separation

Measurement	EW			NS		
Position	10%	50%	90%	10%	50%	90%
Rx1	9.6	10.26	10.98	9.45	10.25	11.01
Rx2	9.83	10.45	10.94	9.96	10.57	11.18
Rx3	10.16	10.68	11.2	10.32	10.87	11.38
Rx4	10.2	10.73	11.31	10.41	10.91	11.47
Rx5	10.28	10.91	11.52	10.34	10.86	11.38
Rx6	9.61	10.31	10.88	9.45	10.32	11.04
Rx7	11.69	12.14	12.55	11.69	12.17	12.65

✓ 4 λ separation

Measurement	EW			NS		
Position	10%	50%	90%	10%	50%	90%
Rx1	9.89	10.47	11.11	10.01	10.6	11.11
Rx2	9.79	10.57	11.19	10.28	10.94	11.57
Rx3	10.29	10.9	11.42	9.93	10.73	11.33
Rx4	10.51	10.85	11.21	10.52	10.85	11.18
Rx5	10.54	10.86	11.18	10.61	10.92	11.23
Rx6	10.34	10.7	11.06	10.08	10.58	10.92
Rx7	10.63	10.94	11.41	11.79	12.24	12.65

Channel Capacities

✓ Tx 1 λ separation

Rx Separation	Rx1	Rx2	Rx3	Rx4	Rx5	Rx6	Rx7
0.5λ	10.1	10.3	10.7	11.1	10.5	10.3	12.0
1.0λ	10.1	10.3	10.7	10.9	10.5	10.2	12.0
1.5λ	10.6	10.3	10.6	10.9	11.0	10.5	12.1
2.0λ	10.5	10.5	10.7	10.9	11.1	10.3	12.1
2.5λ	10.7	10.7	11.0	10.7	11.1	10.4	12.2
3.0λ	9.9	10.4	10.7	10.5	10.9	10.2	12.2
3.5λ	10.0	10.9	11.0	10.9	10.9	10.3	12.2
4.0λ	10.2	10.5	10.8	10.8	11.1	9.9	12.2

✓ Tx 4 λ separation

Rx Separation	Rx1	Rx2	Rx3	Rx4	Rx5	Rx6	Rx7
0.5λ	10.5	10.4	10.3	10.9	10.8	10.3	11.7
1.0λ	10.5	10.7	10.7	10.8	10.8	10.6	10.8
1.5λ	10.6	10.8	11.0	10.9	10.9	10.5	11.1
2.0λ	10.7	10.9	11.0	10.8	10.9	10.7	10.9
2.5λ	10.4	10.4	11.2	10.9	10.9	10.7	10.8
3.0λ	10.4	11.1	10.7	10.9	11.0	10.7	11.1
3.5λ	10.5	10.6	10.7	10.9	10.9	10.7	11.2
4.0λ	10.6	10.9	10.7	10.7	10.9	10.7	10.9

Channel Capacities

- Available channel capacity is quite stable
- Variation with antenna separation is about 0.5 bps/Hz.