Note 1. Introduction to Wireless Communication Channel / MIMO Systems

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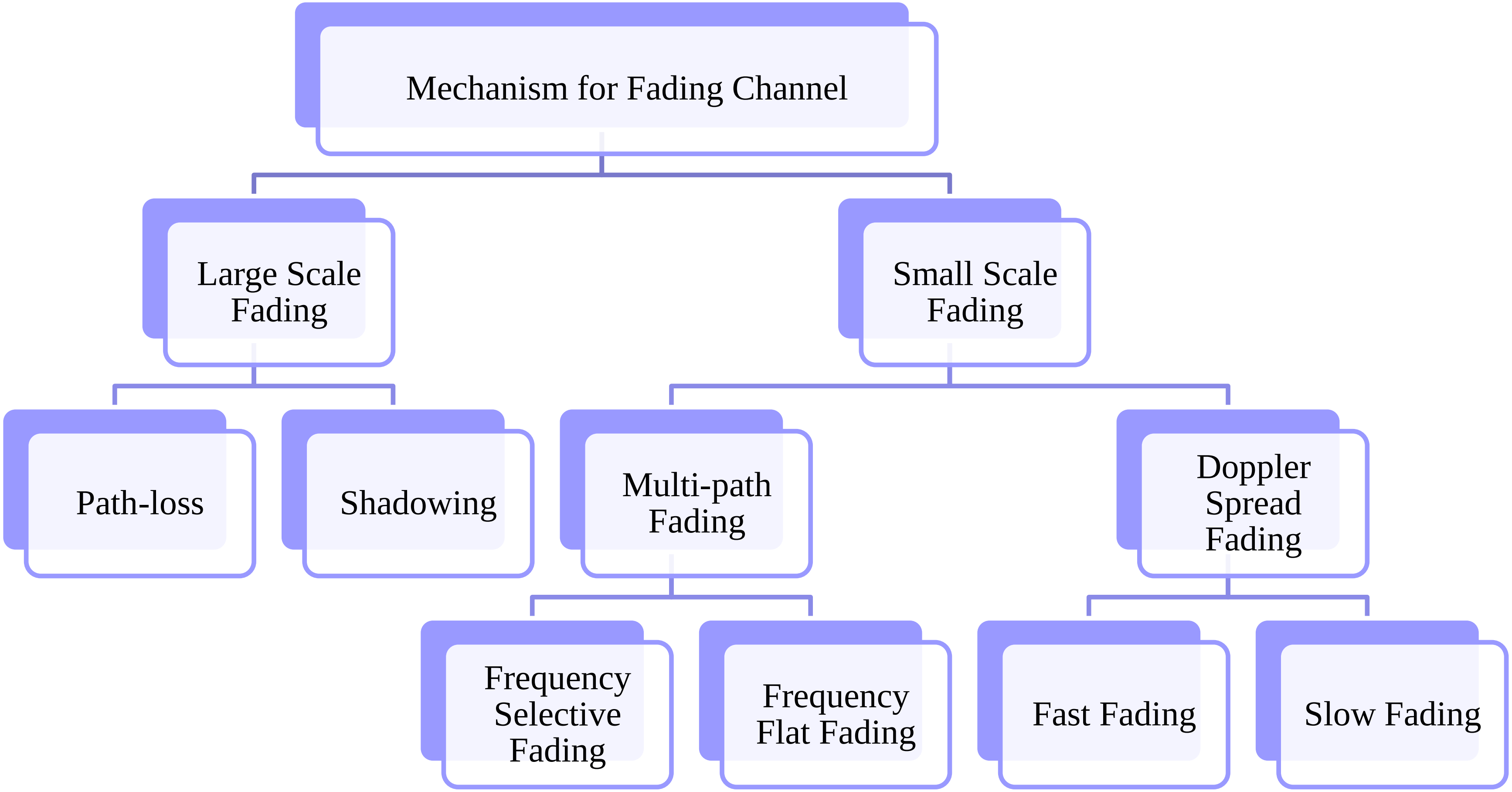
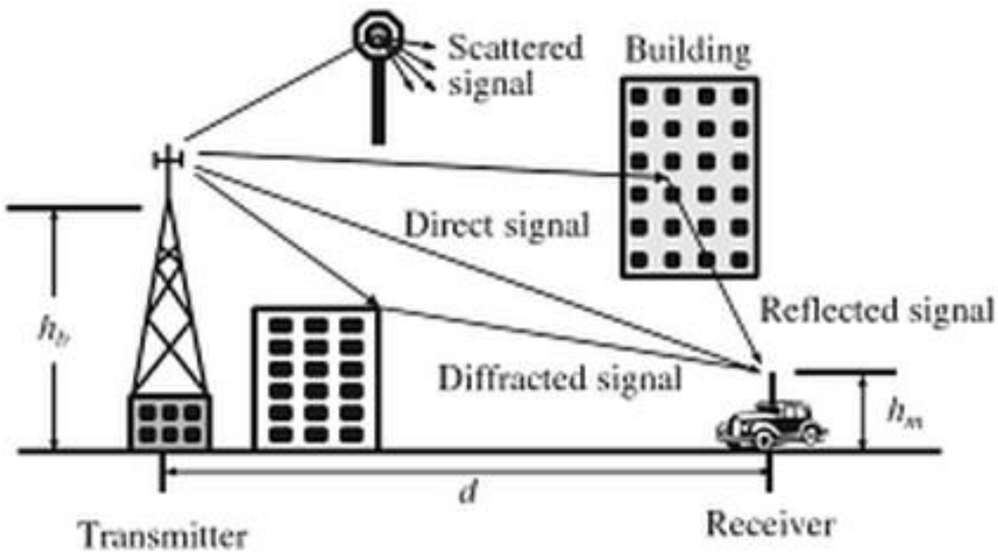
Introduction to Wireless Communication Channel / MIMO Systems

Wireless Channels (1/3)



Wireless Channels (2/3)

- Propagation mechanisms
  - Reflection: By an object that is larger as compared to the wavelength
  - Diffraction: Radio path between a transmitter and a receiver is obstructed by a surface with sharp irregular edges
  - Scattering: When objects are smaller than the wavelength of the propagating wave, incoming signal is scattered into several weaker outgoing signals



Wireless Channels (3/)

- Channel Impairments
  - Path loss is proportional to $1/r^{\alpha}$ (α is between 2 and 6) in wireless channel characteristics
  - Shadowing is caused by large obstructions between transmitter and receiver.
  - Small scale fading is mainly due to scattering of the signal by objects near transmitter.

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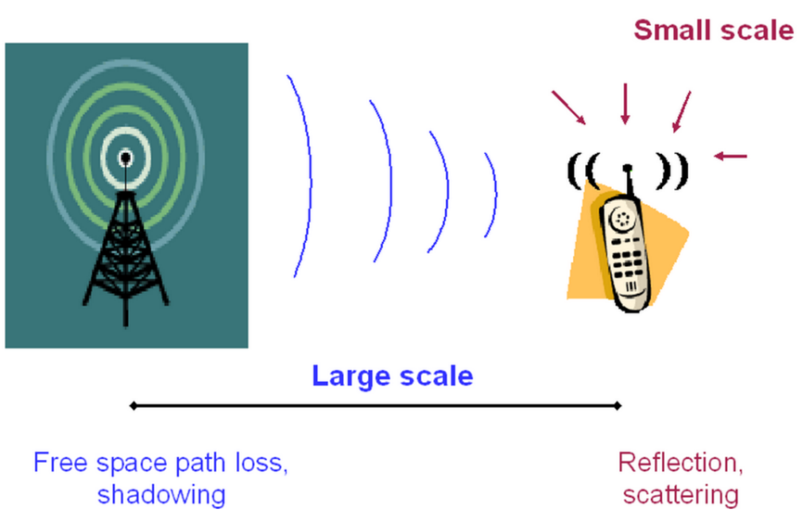
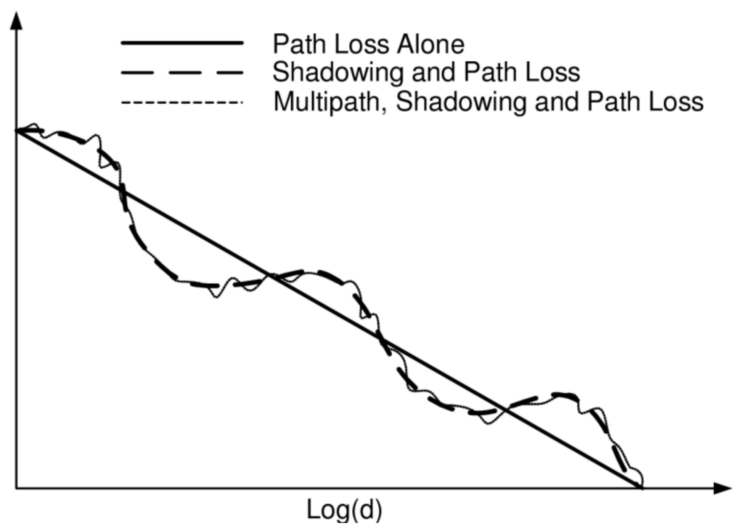




Large Scale Fading (1/3)

- Generalized Path-loss Model
  - Path-loss model for free space
    - Friis free space equation

$$P_r(d) = \frac{P_t \lambda^2}{(4\pi)^2 d^2}$$

P_t : Tx power, $P_r(d)$: Rx power according to d

d : Distance between Tx and Rx

$\lambda = c / f_c$, f_c : Carrier frequency

    - Path-loss model

$$PL_F(d)[dB] = 10\log\left(\frac{P_t}{P_r}\right) = -10\log\left(\frac{\lambda^2}{(4\pi)^2 d^2}\right)$$

  - Generalized path-loss model

$$PL(d)[dB] = PL_F(d_0) + 10n\log\left(\frac{d}{d_0}\right)$$

d_0 : Reference distance

n : Path-loss exponent

Large Scale Fading (2/3)

- Generalized Path-loss Model

$$PL(d)[dB] = PL_F(d_0) + 10n\log\left(\frac{d}{d_0}\right) \underset{\text{Linear scale}}{\Leftrightarrow} \underbrace{10^{\frac{PL_F(d_0)}{10}}}_{\text{constant}}\left(\frac{d}{d_0}\right)^n$$

d_0 : Reference distance

n : Path-loss exponent

  - Proportional to $1/d^n$ (n is between 2 and 6)
  - Reference distance d_0
    - Cellular system for large coverage (≥10km) : d_0 = 1km
    - Cellular system for small coverage (≤ 1km) : d_0 = 100m or 1m
  - Path-loss exponent n

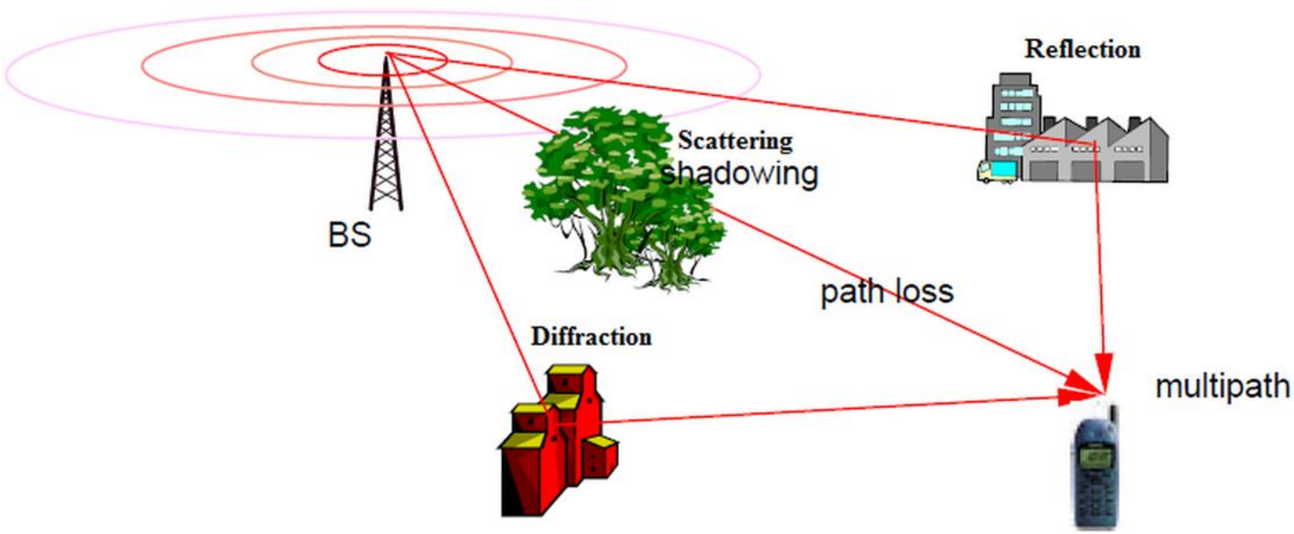
Environment	Path-loss Exponent (n)
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight (LOS)	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Large Scale Fading (3/3)

- Shadow Fading
  - Caused by large obstructions between transmitter and receiver
  - Even users are located in same distance from Tx, received signal may different because of each user's environment
  - In general, shadowing is modeled as log-normal Gaussian

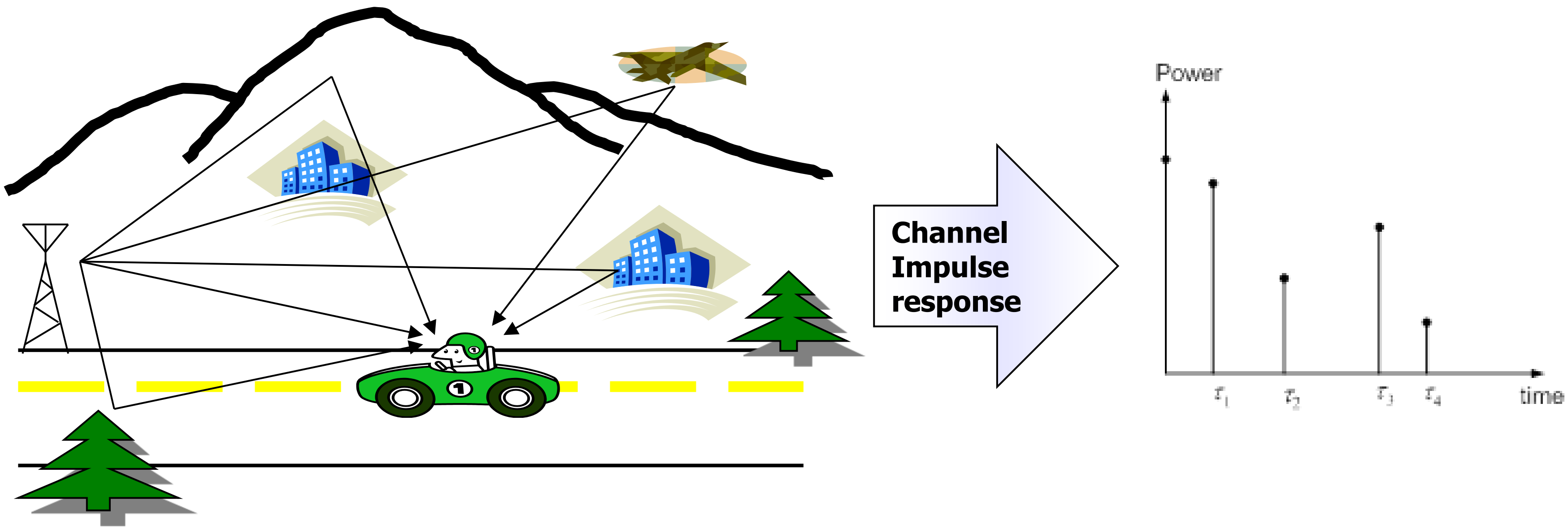
$$PL_{\text{Large-Scale}}(d)[dB] = PL_F(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_{shadow}$$

$$X_{shadow} \sim N\left(0, \sigma^2\right)$$



Small Scale Fading (1/7)

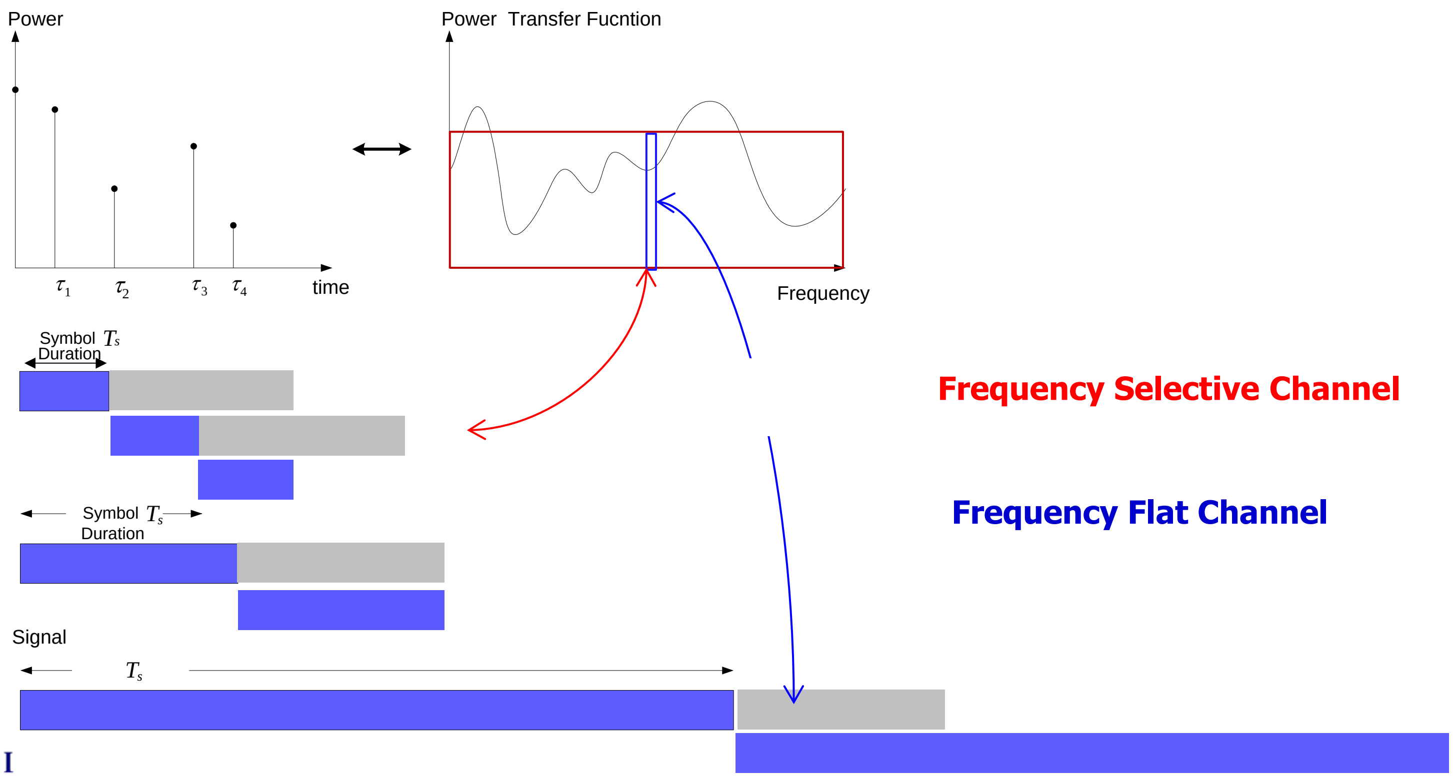
- Multi-path Fading
  - Signal reflection from scatters
  - Channel impulse response is composed of multi-taps with channel delay τ



  - The impact can be varied by the symbol duration

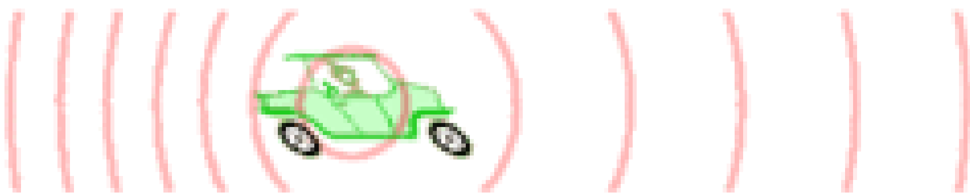
Small Scale Fading (2/7)

- Multi-path Fading
  - Symbol Duration & Channel delays
    - $T_s \leq \tau_4$: ISI (Inter-Symbol Interference) → Frequency selective
    - $T_s >> \tau_4$: Negligible ISI → Frequency flat
  - ISI gets severe as the symbol duration decreases (data rate increases)

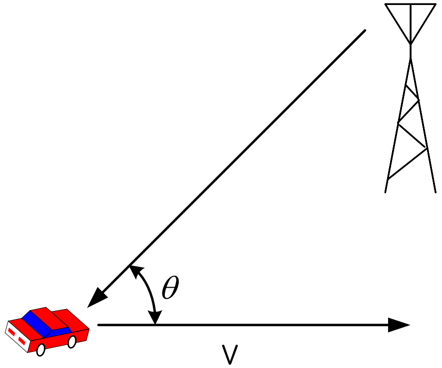


Small Scale Fading (3/7)

- Doppler Spread Fading
  - Doppler effect
    - Change of wavelength caused by motion of the source / the observer



  - In cellular communication systems
    - Change of frequency caused by motion of the RX(UE) when TX(BS) sends signal at f_0 frequency



$$\Delta f = \frac{v}{c} f_0 \Rightarrow \Delta f = \frac{v\cos\theta}{c} f_0$$

v : velocity of the receiver related to the source

UE: User Equipment

BS: Base Station

Small Scale Fading (4/7)

- Small-Scale fading based on Delay Spread and Doppler spread

Small-Scale Fading
(Based on multipath time delay spread)

Flat Fading
1. BW of signal < BW of channel
2. Delay spread < Symbol period

Frequency Selective Fading
1. BW of signal > BW of channel
2. Delay spread > Symbol period

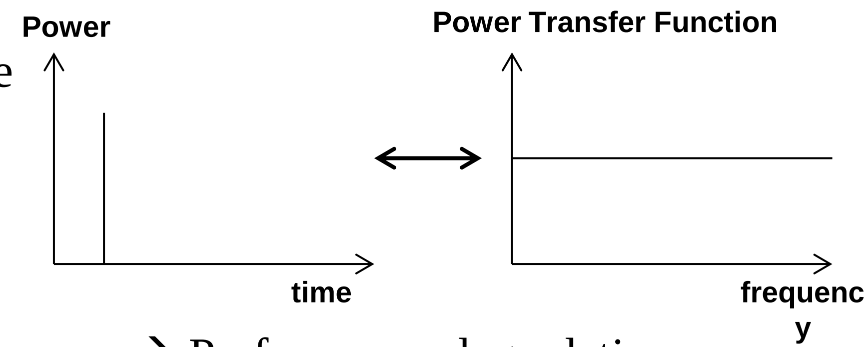
Small-Scale Fading
(Based on Doppler spread)

Fast Fading
1. High Doppler spread
2. Coherence time < Symbol period
3. Channel variations faster than base-band signal variations

Slow Fading
1. Low Doppler spread
2. Coherence time > Symbol period
3. Channel variations slower than baseband signal variations

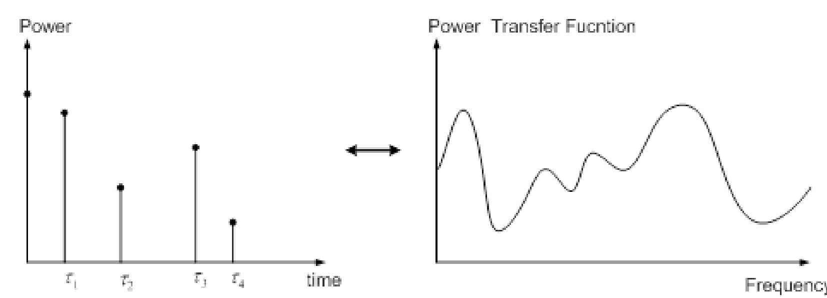
Small Scale Fading (5/7)

- Single-path Channel (Frequency Flat Channel)
  - Advantages
    - Inter-Symbol-Interference (ISI) free
    - Easy to decode (linear equalizer)
  - Disadvantages
    - No path (frequency) diversity gain
      - Power of single channel path is poor → Performance degradation



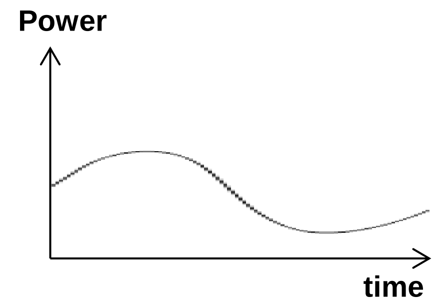
- Multi-path Channel (Frequency Selective Channel)
  - Advantages
    - Path (frequency) diversity
  - Disadvantages
    - High decoding complexity

    (Cannot decode by linear equalizer)
    - Linear equalizer → ISI problem → Performance degradation

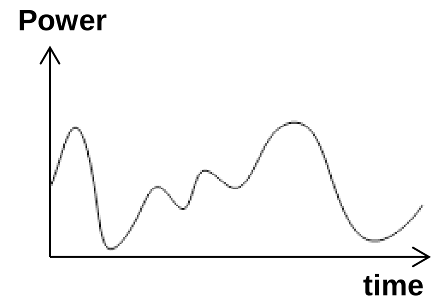


Small Scale Fading (6/7)

- Slow Fading Channel
  - Advantages
    - Easy to estimate channel
    - Estimated channel is useful for a long time
  - Disadvantages
    - No time diversity gain
      - Power of current channel is poor → Performance degradation



- Fast Fading Channel
  - Advantages
    - Time diversity
  - Disadvantages
    - Channel estimation should be performed frequently
    - Like adaptation failure, e.g., MCS (modulation & coding scheme) level selection

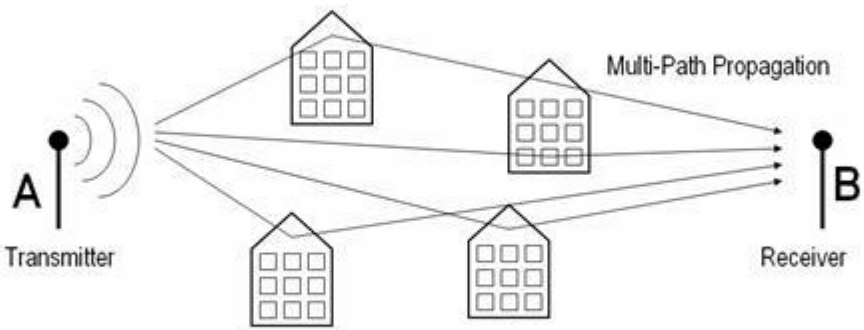


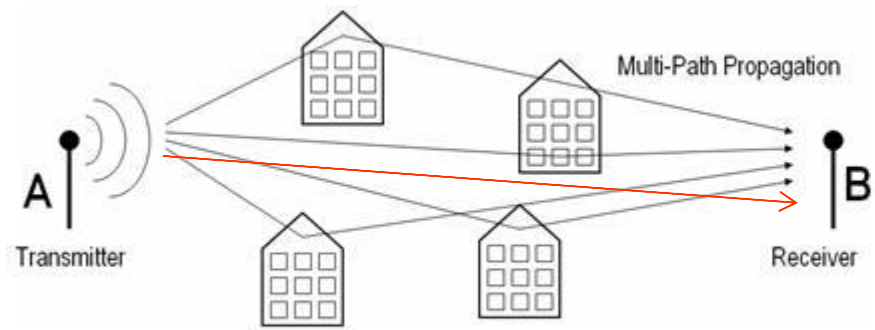
Small Scale Fading (7/7)

- Summary
  - Frequency Selectivity: Flat vs. Selective
    - Flat (Non-selective): ISI free
    - Selective: Path (Frequency) diversity
      - Path diversity: Rake receiver (CDMA)
      - Frequency diversity: Multicarrier system (OFDM)
    - Linear equalizer: Flat > Selective
    - No limitations on the receiver complexity: Selective > Flat
  - Time Selectivity: Slow vs. Fast
    - Slow: Channel estimation
    - Fast: Time Diversity
      - Coding scheme & Hybrid ARQ
    - Perfect channel estimation: Fast > Slow
    - Imperfect channel estimation: Slow ≥ Fast

Time-selective channels (1/3)

- Rayleigh fading channel vs. Rician fading channel
  - Rayleigh: Non-LOS
  - Rician: LOS





  - Rayleigh distribution PDF: $$p(x) = \frac{x}{\sigma^2} \exp(-x^2 / 2\sigma^2)$$
  - Rician distribution PDF: $$p(x) = \frac{x}{\sigma^2} \exp(-(x^2 + c^2) / 2\sigma^2) I_0 \left(\frac{xc}{\sigma^2} \right)$$

c^2 : Power of the LOS path

$2\sigma^2$: Power of the summation of scattering multi-paths

Time-selective channels (2/3)

- Rician K-Factor

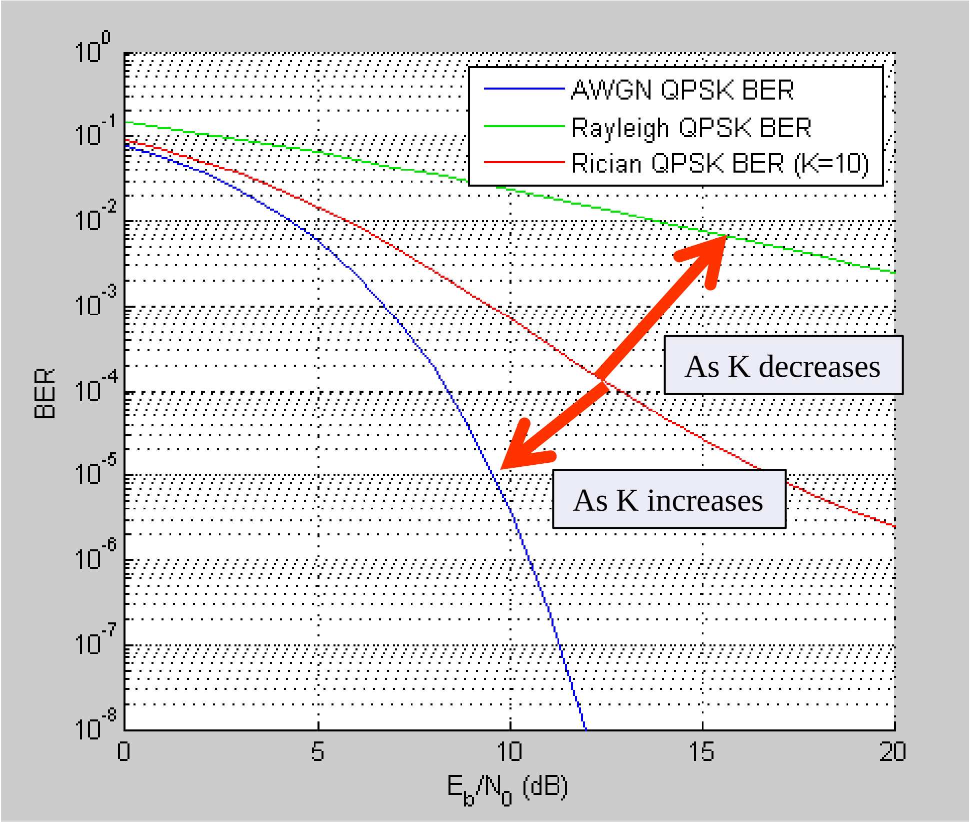
c^2 : Power of the LOS path

$2\sigma^2$: Power of the summation of scattering multi-paths

$$K = \frac{c^2}{2\sigma^2} : \text{ Rician K-factor}$$

- As K increases: LOS components dominate
  → Approaches AWGN

- As K decreases: NLOS components dominate
  → Approaches Rayleigh



Time-selective channels (3/3)

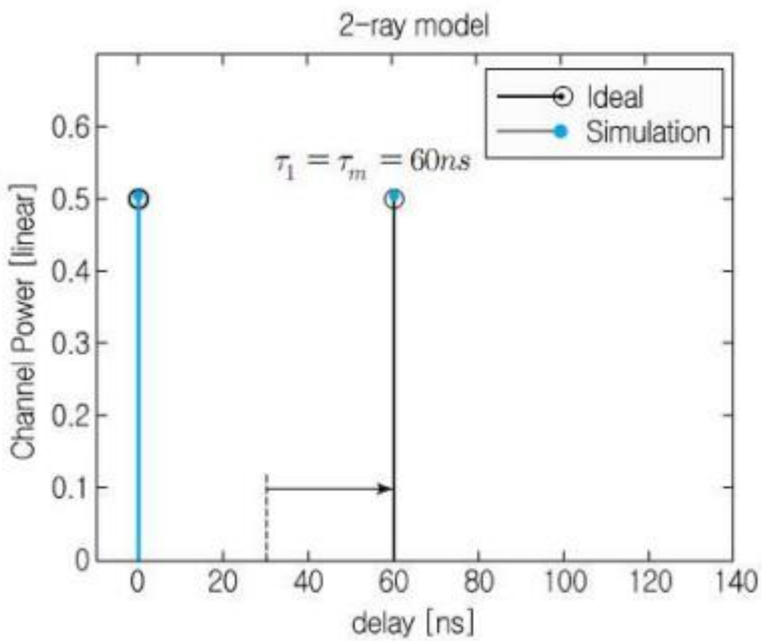
- Rician channels
  - K-factor: General model including Rayleigh channels
  - **Hard to analyze**
    - Without a specific goal, the assumption is quite limited in the paper

- Rayleigh channels
  - Easy to model and analyze
    - Square of the Rayleigh R.V. → Chi-Square distribution
  - Easy to generate
    - Simplest complex channel – independent Gaussian for real/imaginary parts
  - Jakes model – To generate the time-varying channel with mobile speed
    - Ex) Rayleigh channel when the mobile speed is 120km/h.
    - Clark/Gan model, FWGN model, Ray-based model

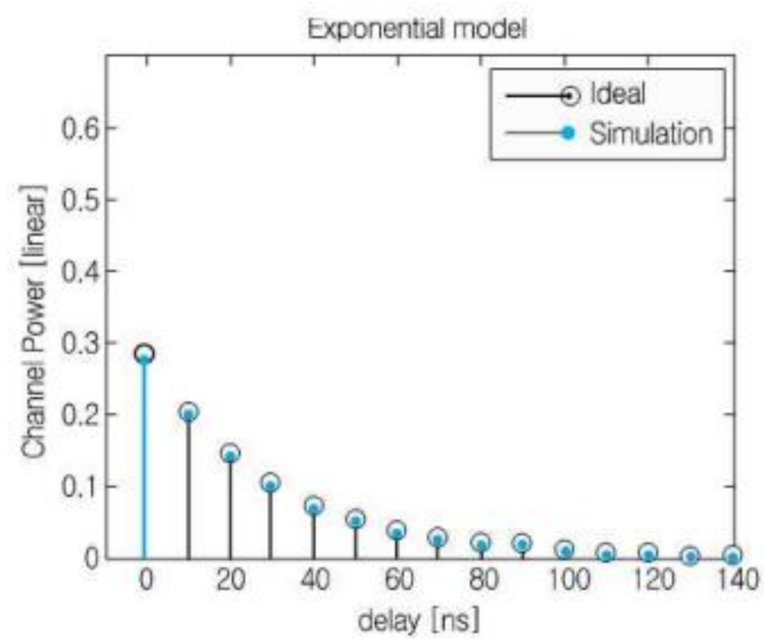
Frequency-selective channels (1/2)

- Uniform PDP vs. Exponential PDP
  - PDP: Power delay profile

- Uniform PDP (2-taps example)



- Exponential PDP



- Equal power for the entire taps
- Exponentially decayed power as the delay increases

Frequency-selective channels (2/2)

- ITU-R M.1225 Channel response model
  - Pedestrian channels (PED-A, PED-B)

Outdoor to indoor and pedestrian test environment tapped-delay-line parameters

Tap	Channel A		Channel B		Doppler spectrum
	Relative delay (ns)	Average power (dB)	Relative delay (ns)	Average power (dB)	
1	0	0	0	0	Classic
2	110	–9.7	200	–0.9	Classic
3	190	–19.2	800	–4.9	Classic
4	410	–22.8	1 200	–8.0	Classic
5	–	–	2 300	–7.8	Classic
6	–	–	3 700	–23.9	Classic

  - Vehicular channels (VEH-A, VEH-B)

Vehicular test environment, high antenna, tapped-delay-line parameters

Tap	Channel A		Channel B		Doppler spectrum
	Relative delay (ns)	Average power (dB)	Relative delay (ns)	Average power (dB)	
1	0	0.0	0	–2.5	Classic
2	310	–1.0	300	0	Classic
3	710	–9.0	8.900	–12.8	Classic
4	1 090	–10.0	12 900	–10.0	Classic
5	1 730	–15.0	17 100	–25.2	Classic
6	2 510	–20.0	20 000	–16.0	Classic

Channel generation for discrete simulations

- Example) Uniform PDP with 2 taps [0ms, 30ms], symbol duration: 20ms, Rayleigh
  - 1) Generate channels for the taps at a given transmission time slot

$$h_t(1) \sim Rayleigh \qquad h_t(2) \sim Rayleigh$$

  - 2) Normalize the channels with the corresponding power coefficients

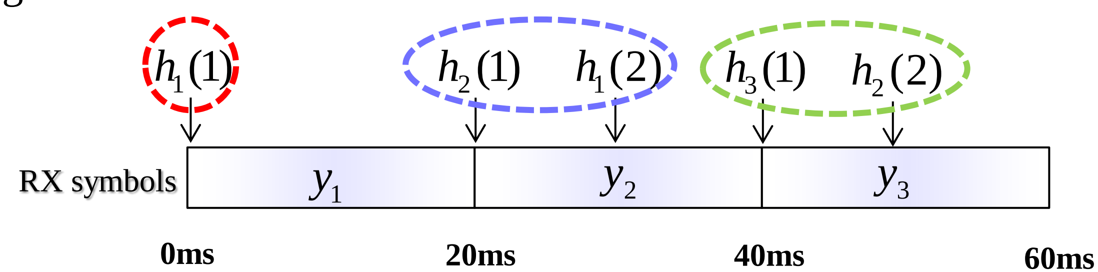
$$h_t(1) \leftarrow \frac{P_1 \cdot h_t(1)}{P_{total}} \qquad h_t(2) \leftarrow \frac{P_2 \cdot h_t(2)}{P_{total}}$$

$P_{total} = \sum_{l=1}^{L} P_l$: Total power

P_l : Power for the l-th tap

L: # of total taps

  - 3) Assign the location of each channel coefficient



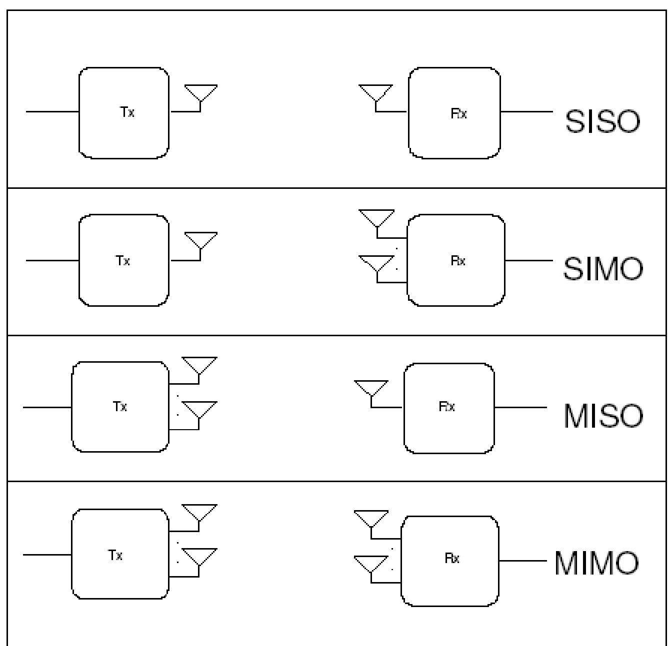
$$y_1 = h_1(1)x_1 + noise$$

$$y_2 = h_1(2)x_1 + h_2(1)x_2 + noise$$

$$y_3 = h_2(2)x_2 + h_3(1)x_3 + noise$$

Multiple Antenna Technologies (1/4)

- Space(Antenna) Domain
  - the final frontier (limitations on time-, frequency-, code-domain)
  - Space processing is interesting because it does not increase bandwidth
  - Utilization of *the "space(antenna) dimension"* along with the traditional time (or frequency) dimension *to improve the performance of wireless links*.



Single-Input Single-Output

Single-Input Multiple-Output

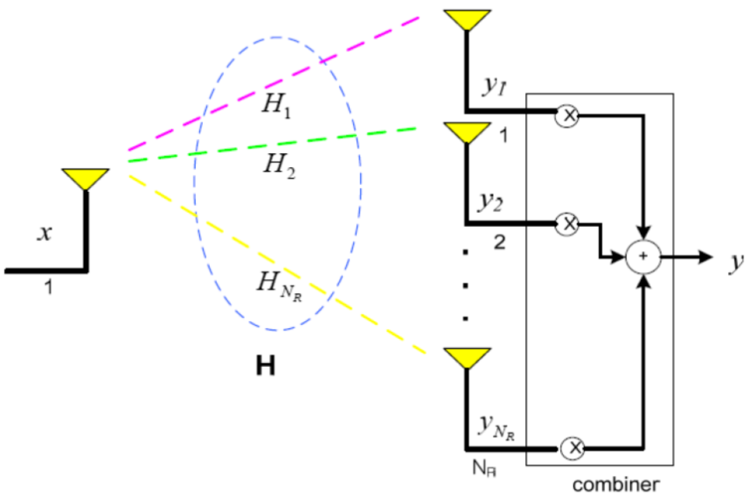
Multiple-Input Single-Output

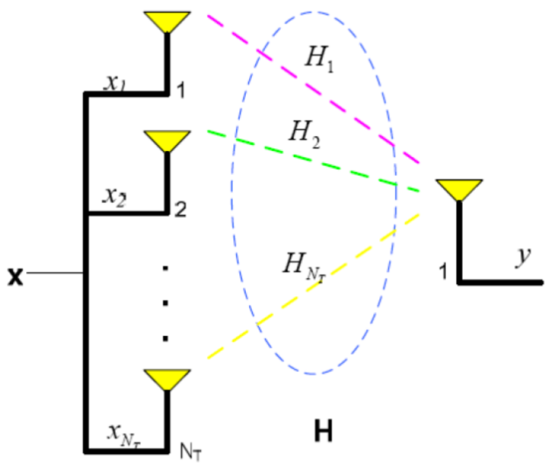
Multiple-Input Multiple-Output

Multiple Antenna Technologies (2/4)

- Single Input Multiple Output (SIMO)
  - A single transmit antenna and N_R receive antennas
  - Receive Spatial (Antenna) Diversity

- Multiple Input Single Output (MISO)
  - N_T transmit antennas and a single receive antenna
  - Transmit Spatial (Antenna) Diversity

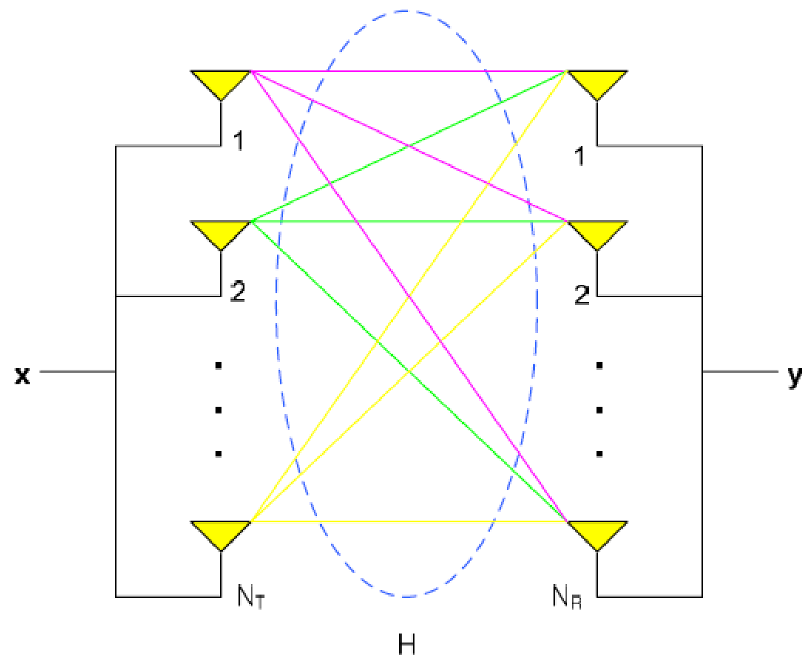




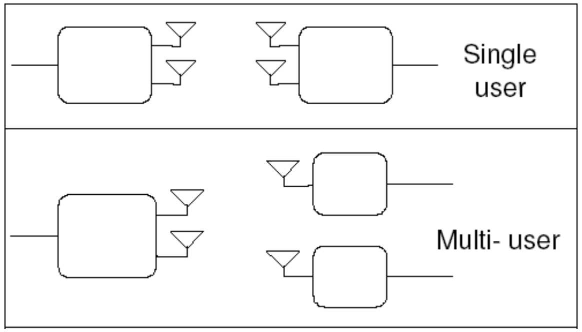
$$r = \mathbf{H}^T \mathbf{x} + n$$

Multiple Antenna Technologies (3/4)

- Multiple Input Multiple Output (MIMO)
  - N_T transmit antennas and N_R receive antennas
  - Diversity gain (Maximum) ~ $N_T N_R$
    Spatial Multiplexing (SM) gain (Maximum) ~ $\min(N_T, N_R)$
    - MIMO for reliability
    - MIMO for data rate

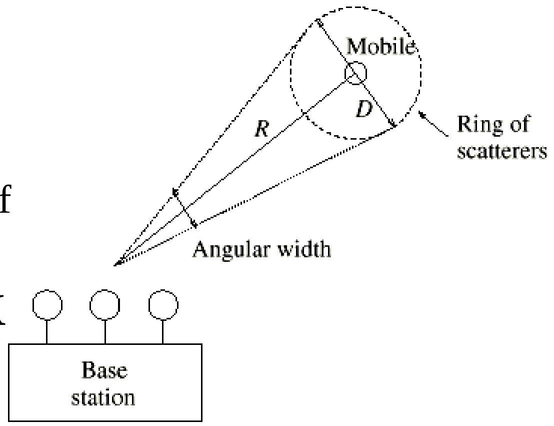


  - Single-User / Multi-User MIMO
    - # of users in a resource block
      - Frequency for example
    - Possibility of cooperation



Multiple Antenna Technologies (4/4)

- Doppler Spread – Time Selective Fading
  - For both single-antenna / multiple-antenna systems
  - Indicates correlation of channels for consecutive transmission time slots
- Delay Spread – Frequency Selective Fading
  - For both single-antenna / multiple-antenna systems
  - Indicates correlation of channels for consecutive subcarriers (OFDM cases)
- **Angle Spread – Space Selective Fading**
  - **For Multiple Antenna Systems**
    - Receiver side – spread in AOAs (angle of arrivals) of the multipath components at the receiver antenna array.
    - Transmitter side – spread in AODs (angle of departure) of the multipath that finally reach the receiver
  - **Indicates correlation of channels for consecutive TX (RX) antennas**



$\text{Mobile Range} = \frac{R}{D}$

Link-Level MIMO System Model (1/3)

- A basic MIMO System model equation
  - Frequency-Flat case

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

where

$$\begin{aligned}
&\mathbf{y} : N_R \times 1 \text{ receive signal vector} \\
&\mathbf{x} : N_T \times 1 \text{ transmit signal vector} \\
&\mathbf{n} : N_R \times 1 \text{ noise vector (usually AWGN)} \\
&\mathbf{H} : N_R \times N_T \text{ MIMO channel}
\end{aligned}$$

  - For link-level cases, the channel is typically modeled as complex Gaussian
    - Each element of $\mathbf{H}$ is i.i.d. complex Gaussian random variable.

  - Frequency-Selective case (L taps)

$$\mathbf{y}_k = \sum_{l=0}^{L-1} \mathbf{H}_k^{(l)} \mathbf{x}_{k-l} + \mathbf{n}_k,$$

Link-Level MIMO System Model (2/3)

- Block fading channel & Independent fading channel
  - Block fading channel (Simplest slow-fading channel)
    - For a given duration, the channel is remained as unchanged.

$$\mathbf{y}_1 = \mathbf{H}_1\mathbf{x}_1 + \mathbf{n}_1, \mathbf{y}_2 = \mathbf{H}_2\mathbf{x}_2 + \mathbf{n}_2, \cdots, \mathbf{y}_T = \mathbf{H}_T\mathbf{x}_T + \mathbf{n}_T$$

    - If $\mathbf{H}_1 = \mathbf{H}_2 = \cdots = \mathbf{H}_T$, then we can say "block fading channel".
  - Independent fading channel (Simplest fast-fading channel)
    - For a given duration, the channel is independently changed.

$$\mathbf{y}_1 = \mathbf{H}_1\mathbf{x}_1 + \mathbf{n}_1, \mathbf{y}_2 = \mathbf{H}_2\mathbf{x}_2 + \mathbf{n}_2, \cdots, \mathbf{y}_T = \mathbf{H}_T\mathbf{x}_T + \mathbf{n}_T$$

    - If the elements in the entire channel matrix are i.i.d., then we can say "independent fading channel".
  - For time-varying effects, each element of the channel matrix can experience "Doppler effects".

Link-Level MIMO System Model (3/3)

- Antenna(Spatial) correlation
  - There can be a correlation between the received signal gain and the angle of arrival of a signal
    - Usually happens with not-enough antenna spacings
  - If we consider the antenna correlation effects, the MIMO channel matrix can be rewritten as

$$\mathbf{H} = \mathbf{R}_R^{1/2}\mathbf{H}_w(\mathbf{R}_T^{1/2})^T$$

where

$\mathbf{H}_w$: i.i.d. complex Gaussian elements

$\mathbf{R}_T$: Transmit-antenna correlation matrix

$\mathbf{R}_R$: Receive-antenna correlation matrix

- The existence of the antenna correlations significantly degrades the performance of MIMO systems (not always, but most cases)

Channel considerations for research

- Frequency Flat channel
  - Used for the basic link-level simulation in time domain
    - Block-Fading channel (slow-fading channel) / Independent fading channels (fast-fading channel)
    - Time-varying channels with the carrier frequency & the mobile speed
- Frequency Selective channel
  - Used for the basic link-level simulation in freq. domain (OFDM)
    - Uniform PDP / Exponential PDP
    - ITU-R channel model
  - Block fading assumption: Time-varying is usually not considered
- Channel modeling in the specification (3GPP, SCM, 802.11n, ..)
  - System level simulation / performance evaluation of a system
- Other specific channel configuration (e.g., spatial correlation)
  - For the research (analysis/scheme) specialized for the channel
  - AWGN – basic environment (starts of research / ECC / modulation / ..)

Other Good Textbooks

- Introduction to Space-Time Wireless Communications, Cambridge University Press
  - A. Paulraj, R. Nabar, and D. Gore
  - General MIMO systems
- Fundamentals of Wireless communications, Cambridge University Press
  - D. Tse and P. Viswanath
  - Unified view on wireless communication systems (SISO / MIMO / OFDM)
- Adaptive and Iterative Signal Processing in Communications, Cambridge University Press
  - J. Choi
  - Receiver-side schemes (Channel estimation, equalization, soft-detection, ..)
- MIMO-OFDM Wireless Communications with MATLAB, Wiley, 2010
  - Y. Cho, J. Kim, W. Yang, and C. Kang
  - http://comm.cau.ac.kr/MIMO_OFDM/

Thank You!