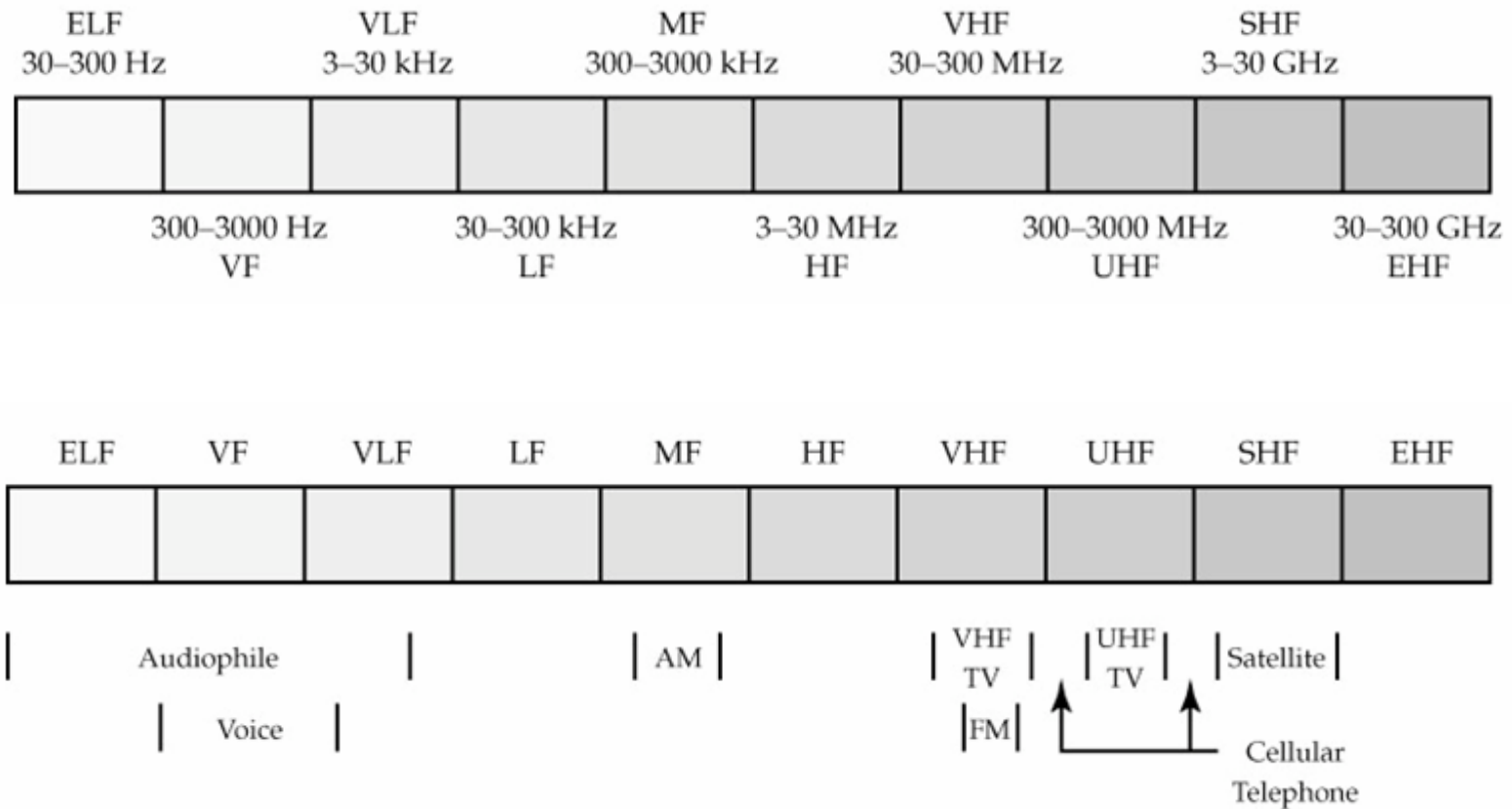


Lecture 2: Wireless Channel and Radio Propagation

Hung-Yu Wei
National Taiwan University

Basics of communications, capacity, and channels

Electromagnetic Spectrum



Frequency and Wavelength

- $c = \lambda f$
 - c: speed of light
 - λ : wavelength
 - f: frequency
- Example:
 - AM radio with frequency 1710 kHz
 - What's the wavelength? Ans: 175m
 - What's the period? Ans: 584 ns

dB

- Decibels

- $10 \log_{10} (x)$

- Power in decibels

- dB

- $Y \text{ dB} = 10 \log_{10} (x \text{ Watt})$

- Power ratio in decibels

- dB

- Power P1, P2 in Watt

- $10 \log_{10} (P1/P2)$

- Example:

- Input power 100W and output power 1W

- What's the power ratio in decibel? Ans: 20dB

dBm

- dBm
 - Reference power is 1 mW
 - $10 \log_{10} (\text{Watts}/10^{-3})$
 - Example:
 - $0 \text{ dB} = 30 \text{ dBm} = 1 \text{ Watt}$
- Summary
 - $P \text{ (dBW)} = 10 \log (P/1 \text{ Watt})$
 - $P \text{ (dBm)} = 10 \log (P/1 \text{ mWatt})$

Gain and Attenuation in dB or dBm

- Gain/attenuation in dB
 - $10 \log_{10} (\text{output power}/\text{input power})$
 - $\text{Gain(dB)} = \text{Pout(dB)} - \text{Pin(dB)}$
 - Gain: $\text{Pout} > \text{Pin}$
 - Attenuation $\text{Pout} < \text{Pin}$
- Gain/attenuation in dBm
 - $X(\text{dBm}) + Y(\text{dB}) = ??(\text{dB}) = ??(\text{dBm})$
 - $X(\text{dBm}) - Y(\text{dB}) = ??(\text{dB}) = ??(\text{dBm})$
 - Example:
 - Input power is 2dBm, system gain is 5dB
 - What's the output power? Ans: 7dBm
 - Notice: is it dB or dBm?

Wireless communication system

- Antenna gain
 - Transmitter antenna
 - Receiver antenna
- Wireless channel attenuation



- Questions: how do you represent the relationships between P_{tx} and P_{rx} ?
 - in dB
 - in Watt

Signal-to-Noise ratio

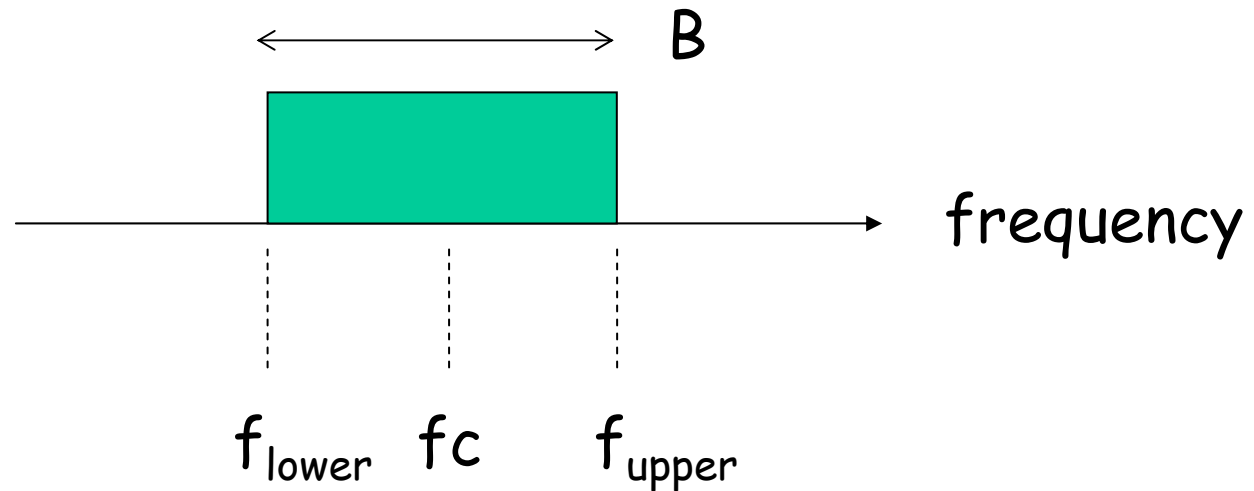
- S/N
 - $\text{SNR} = \text{signal power (Watt)} / \text{noise power (Watt)}$
 - Signal-to-Noise power ratio
 - Relate to the performance of communications systems
 - Bit-error probability
 - Shannon capacity
- SNR in dB
 - $S/N(\text{dB}) = 10 \log_{10} (\text{S/N power ratio})$
 - $10 \log_{10} (\text{signal power (Watt)} / \text{noise power (Watt)})$

Noise, Interference, SNR

- SNR
 - (signal power)/(noise power)
 - Noise: thermal noise
- SIR
 - Signal-to-Interference
 - Sometimes known as C/I (carrier-to-interference ratio)
 - (signal power)/(interference power)
 - Interference: signals from other simultaneous communications
- SINR
 - Signal-to-Interference-Plus-Noise ratio
 - (signal power)/(interference power+noise power)

Bandwidth

- $B = f_{\text{upper}} - f_{\text{lower}}$
- Carrier frequency: f_c
- Example:
 - 802.11 2.4GHz ISM band (channel 1)
 - $f_{\text{upper}} = 2434\text{MHz}$
 - $f_{\text{lower}} = 2412\text{MHz}$
 - $f_c = 2433\text{MHz}$
 - $B = 22\text{MHz}$



Shannon Capacity

- Theoretical (upper) bound of communication systems
- $C = B \cdot \log_2 (1 + S/N)$
 - C: capacity (bits/s)
 - B: bandwidth (Hz)
 - S/N: linear Signal-to-Noise ratio
- How to evaluate the performance of a communication scheme?
 - How close to Shannon bound?
 - Spectral efficiency
 - bit/s/Hz

Concepts Related to Channel Capacity

- Data rate
 - rate at which data can be communicated (bps)
- Bandwidth
 - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise
 - average level of noise over the communications path
- Error rate - rate at which errors occur
 - Error
 - transmit 1 and receive 0
 - transmit 0 and receive 1

Shannon Capacity Formula

- Equation: $C = B \log_2(1 + \text{SNR})$
- Represents theoretical maximum that can be achieved (in AWGN channel)
- In practice, only much lower rates achieved
 - Formula assumes white noise (thermal noise)
 - Impulse noise is not accounted for
 - Attenuation distortion or delay distortion not accounted for

Nyquist Bandwidth

- For binary signals (two voltage levels)
 - $C = 2B$
- With multilevel signaling
 - $C = 2B \log_2 M$
 - $M =$ number of discrete signal or voltage levels

Example of Nyquist and Shannon Formulations

- Spectrum of a channel between 3 MHz and 4 MHz ; $\text{SNR}_{\text{dB}} = 24 \text{ dB}$
 - What's the SNR value?

- Using Shannon's formula
 - What's the maximum capacity?

Example of Nyquist and Shannon Formulations

- Spectrum of a channel between 3 MHz and 4 MHz ; $\text{SNR}_{\text{dB}} = 24 \text{ dB}$

$$B = 4 \text{ MHz} - 3 \text{ MHz} = 1 \text{ MHz}$$

$$\text{SNR}_{\text{dB}} = 24 \text{ dB} = 10 \log_{10}(\text{SNR})$$

$$\text{SNR} = 251$$

- Using Shannon's formula

$$C = 10^6 \times \log_2(1 + 251) \approx 10^6 \times 8 = 8 \text{ Mbps}$$

Example of Nyquist and Shannon Formulations

- How many signaling levels are required in modulation?

Example of Nyquist and Shannon Formulations

- How many signaling levels are required?

$$C = 2B \log_2 M$$

$$8 \times 10^6 = 2 \times (10^6) \times \log_2 M$$

$$4 = \log_2 M$$

$$M = 16$$

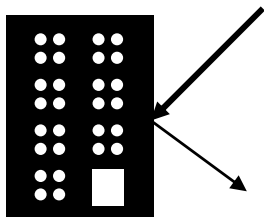
Radio propagation model

Physics: wave propagation

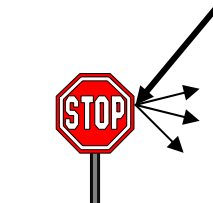
- Reflection - occurs when signal encounters a surface that is large relative to the wavelength of the signal
- Diffraction - occurs at the edge of an impenetrable body that is large compared to wavelength of radio wave
- Scattering - occurs when incoming signal hits an object whose size is in the order of the wavelength of the signal or less

Rf generally propagate according to 4 mechanisms

- **Reflection at large obstacles:** plane waves are incident on a surface with dimensions that are very large relative compared to the wavelength.
- **Scattering at small obstacles:** occurs when the plane waves are incident upon an object whose dimensions are on the order of a wavelength or less and causes energy to be redirected in many directions.
- **Diffraction at edges:** occurs according to Huygen's principle when there is an obstruction between the transmitter and receiver antennas, and secondary waves are generated behind the obstructing body. As the frequency gets higher, the *rf* wave will diffract less and start to behave like light.
- **Penetration:** In addition to diffraction, penetration of objects will allow *rf* reception when there is an obstruction(s) between the transmitter and receiver.



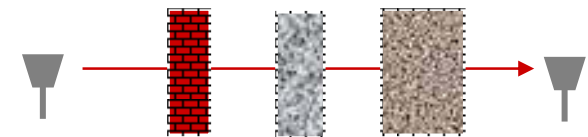
reflection



scattering

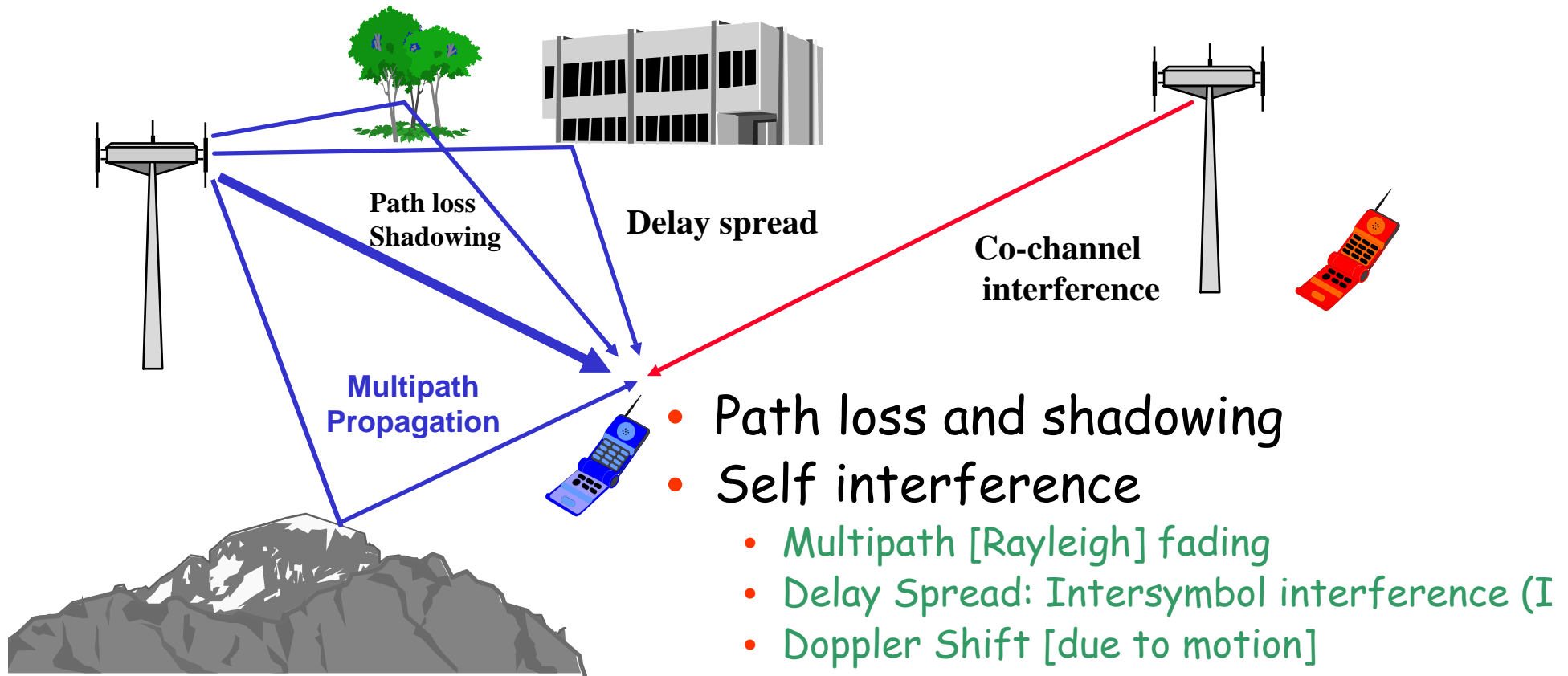


diffraction



penetration

Wireless Channel



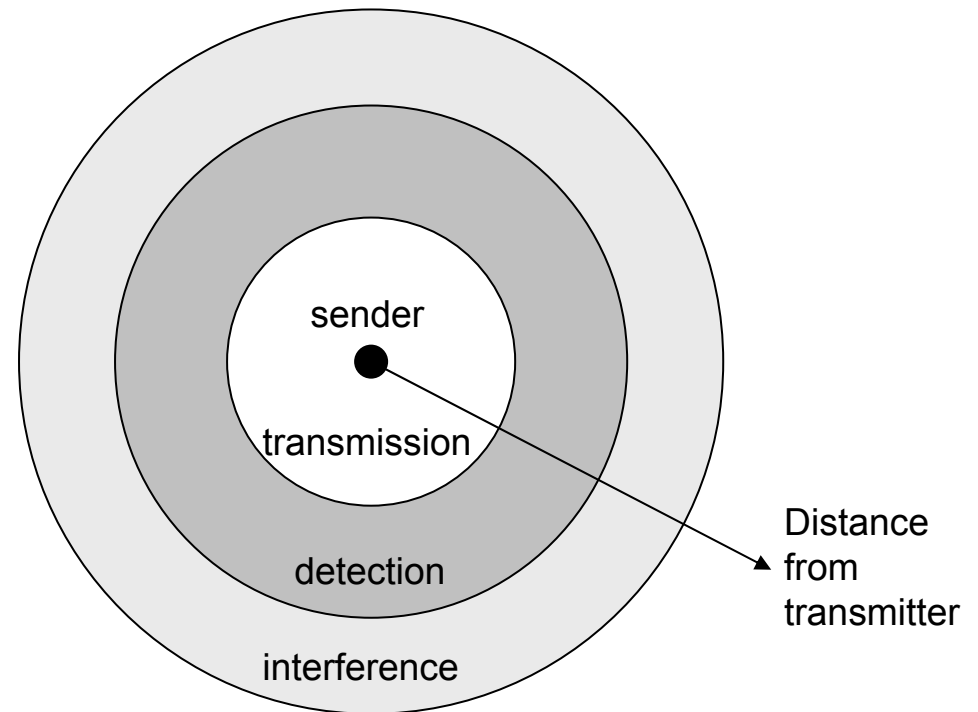
- Path loss and shadowing
- Self interference
 - Multipath [Rayleigh] fading
 - Delay Spread: Intersymbol interference (ISI)
 - Doppler Shift [due to motion]
- Noise (SNR)
- Other users
 - Co-channel interference (CCI)
 - Adjacent-channel interference (ACI)
- Time & Frequency synchronization

The Effects of Multipath Propagation

- Multiple copies of a signal may arrive at different phases
 - If phases add destructively, the signal level relative to noise declines, making detection more difficult
- Intersymbol interference (ISI)
 - One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit

Signal Propagation Ranges

- **Transmission range**
 - communication possible
 - low error rate
- **Detection range**
 - detection of the signal possible, but communication may not be possible due to high error rate
- **Interference range**
 - signal may not be detected
 - signal adds to the background noise



Radio Propagation Models

- Three components
 - Path-loss (long-term average)
 - Radio signal attenuation due to transmission over a certain distance
 - Depend on the distance
 - Shadowing (large time-scale variation)
 - Signal attenuation due to penetration of buildings and walls.
 - Log-normal distribution
 - Fading (small time-scale variation)
 - Due to multi-path transmission (reflection creates multiple radio paths)
 - Rayleigh distribution, Rician distribution

Radio Propagation Models

- Signal power at receiver
 - Path-loss $g(d)$
 - Log-normal shadowing $10^{\frac{x}{10}}$
 - Rayleigh fading α^2

$$P_R = \alpha^2 10^{\frac{x}{10}} g(d) P_T G_T G_R$$

Path-loss

- Path-loss

- Denoted as $g(d)$

$$\bar{P}_R = g(d)P_T G_T G_R$$

- Represent average values (local mean power of area within several meters)

$$g(d) \propto d^{-n}$$

- In general received signal strength is proportional to d^{-n}

- n : path-loss exponent
- k : constant
- $n=2 \sim 8$ in typical propagation scenarios
- $n=4$ is usually assumed in cellular system study

- Example: Free-space model

- $P_r = (P_t G_t G_r \lambda^2) / (16\pi^2 d^2) = (P_t G_t G_r) (\lambda / 4\pi d)^2$
- Proportional to d^{-2} (i.e. $n=2$)

Some more path-loss models

- Smooth transition model
- Two-ray-ground model
- Okumura-Hata model
- More models in telecom standard evaluation
 - E.g. 3GPP, IMT-2000, 802.16, EU WINNER project
 - Common ground to evaluate proposed schemes
 - Reflect the radio operation conditions (frequency, terminal speed, urban/rural)

Smooth transition model

- Improvement over simple distance-power relationship

- d^{-n}

$$g(d) = d^{-n_1} \left(1 + \frac{d}{b}\right)^{-n_2}$$

- Typically, n is smaller value in near-field and is a greater value in far-field

- Empirical measurement

$$g(d) = d^{-n_1} \quad 0 \leq d \leq b$$

- Two-stage transition model

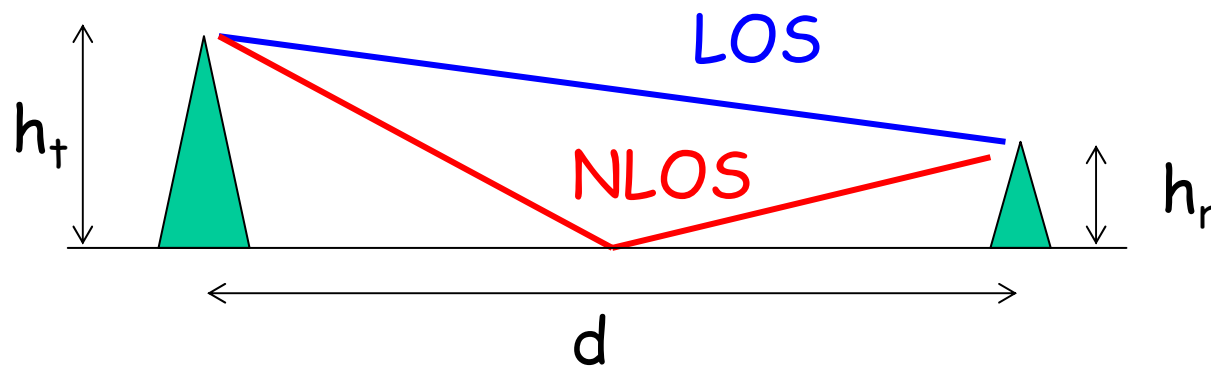
$$g(d) = d^{-n_1} (d/b)^{-n_2} \quad b \leq d$$

model	location	n1	n2	b(m)
Harley	Melbourne	1.5 to 2.5	3 to 5	150
Green	London	1.7 to 2.1	2 to 7	200-300
Pickholtz	Orlando	1.3	3.5	90

Two-ray model

- 2 radio paths
 - LOS(line-of-sight)
 - NLOS(non-line-of-sight)
 - Reflection from the ground
- Proof?
 - Sum the power of these 2 EM waves

$$g(d) = \frac{(h_t h_r)^2}{d^4}$$



Okumura-Hata model

- Model + measurement fit
- For macro-cellular network
 - Good fit for distance greater than 1km
 - 150-1500 MHz
- Practical use in cellular network planning
 - Extend by COST (European Cooperative for Scientific and Technical Research)
 - COST-231 model: suitable for urban microcells (1800-2000 MHz)

Hata Model for Mean Path Loss

- Early studies by Hata [IEEE Trans. On Vehicular Technology, Vol. 29 pp245-251, 1980] yielded empirical path loss models for urban, suburban, and rural (macrocellular) areas that are accurate to within 1dB for distances ranging from 1 to 20 km.
- The parameters used in the Hata equations and their range of validity are:
 - f_c = carrier frequency (MHz)
 - $150 < f_c < 1,500$ MHz
 - d = distance between base station and mobile (km)
 - $1 < d < 20$ km
 - h_b and h_m = base and mobile antenna heights (m)
 - $30 < h_b < 200\text{m}$, $1 < h_m < 10\text{m}$

Hata Model for Mean Path Loss –2

- Hata's equations for path loss are classified into three models

- **Typical Urban**

$$L_{urban} (dB) = 69.55 + 26.16 \log f_c + (44.9 - 6.55 \log h_b) \log d - 13.82 \log h_b - \alpha(h_m)$$

where $\alpha(h_m)$ = correction factor for mobile antenna heights and is given by

f is in MHz, h_b and h_m is in m, d is in km

- Large cities

$$\alpha(h_m) = 8.29[\log(1.54h_m)]^2 - 1.1 \quad f_c \leq 200 \text{ MHz}$$

$$= 3.2[\log(11.75h_m)]^2 - 4.97 \quad f_c \geq 400 \text{ MHz}$$

- Small and medium size cities

$$\alpha(h_m) = [1.1 \log(f_c) - 0.7]h_m - [1.56 \log(f_c) - 0.8]$$

- **Typical Suburban (note adding a negative number to the loss means a higher signal level)**

$$L_{suburban} (dB) = L_{urban} - 2 \left[\left(\log\left(\frac{f_c}{28}\right) \right) \right]^2 - 5.4$$

- **Rural** $L_{rural} (dB) = L_{urban} - 4.78[\log(f_c)]^2 + 18.33 \log(f_c) - 40.94 \text{ dB}$

COST-231 path-loss model

- Extend Hata model for PCS radio model in urban area

$$L(\text{dB}) = 46.3 + 33.9 \log f - 13.82 \log h_b - \alpha(h_m) + [44.9 - 6.55 \log h_b] \log d + C_M$$

where $\alpha(h_m)$ = correction factor for mobile antenna heights given in Hata model

f is in MHz, h_b and h_m is in m, d is in km

- Large cities

$$C_M = 0 \text{ dB}$$

- Small and medium size cities

$$C_M = 3 \text{ dB}$$

Shadowing

- Shadowing is also known as shadow fading
- Received signal strength fluctuation around the mean value
 - Due to radio signal blocking by buildings (outdoor), walls (indoor), and other obstacles.
- Large time-scale variation
 - Signal fluctuation is much slower than multipath fading

Log-normal distribution

- If logarithm of a variable x follows normal distribution, then x follows log-normal distribution
- Log-normal distribution for shadowing model
- P.d.f

$$f(x) = \frac{1}{\sqrt{2\pi\sigma x}} \exp\left(\frac{-(\ln x - \mu)}{2\sigma^2}\right)$$

Log-normal shadowing

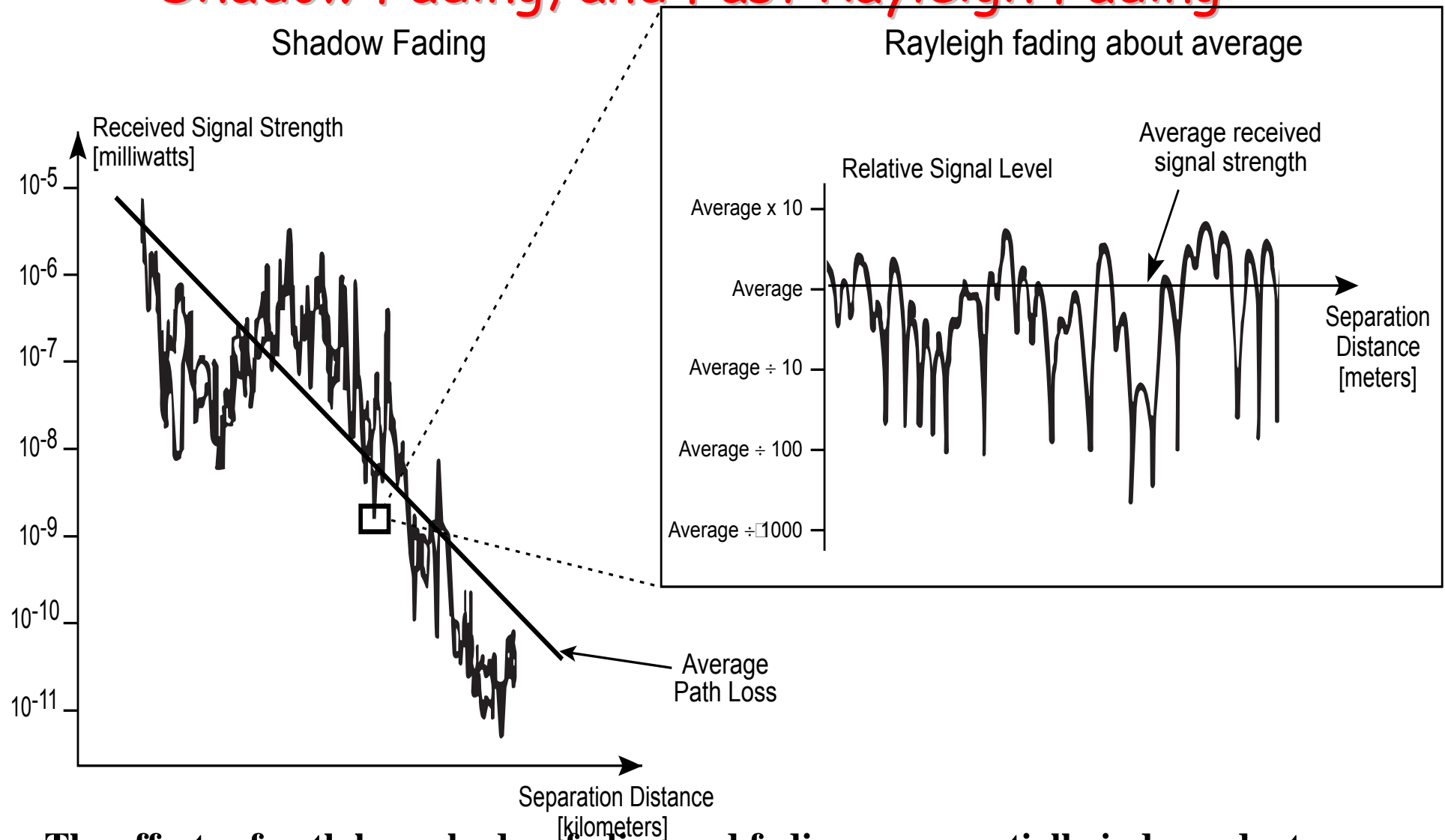
- Path loss component indicates the "expected" signal attenuation at distance d
 - The actual signal attenuation at d depends on the environment. This is modeled with shadowing effect.
- Statistical model for shadowing
 - Received mean power of the radio signal fluctuates about the area-mean power with a log-normal distribution
 - Log-normal distribution (in Watt)
 - Normal distribution if measured in dB
- x is a zero-mean Gaussian variable with standard deviation σ dB. Typically, $\sigma = 6 \sim 10$ dB

$$P_R = \alpha^2 10^{\frac{x}{10}} g(d) P_T G_T G_R$$

$$P_R(dB) = \bar{P}_R(dB) + S$$

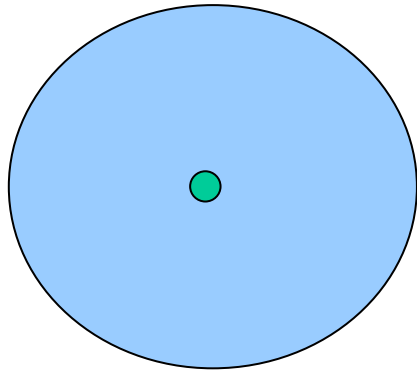
$$S \sim N(0, \sigma^2), \quad \sigma = 4 \sim 10 dB$$

Three-Part Propagation Model: Path Loss, Slow Shadow Fading, and Fast Rayleigh Fading

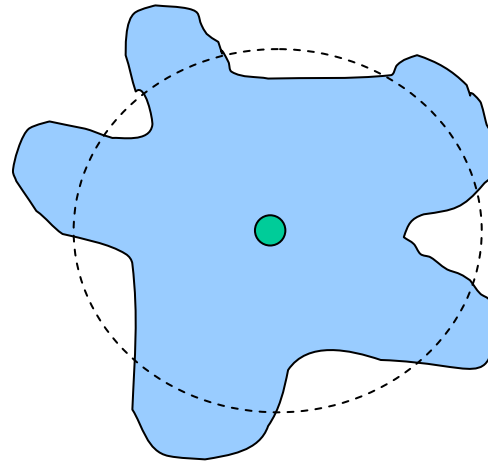


The effects of path loss, shadow fading and fading are essentially independent and multiplicative

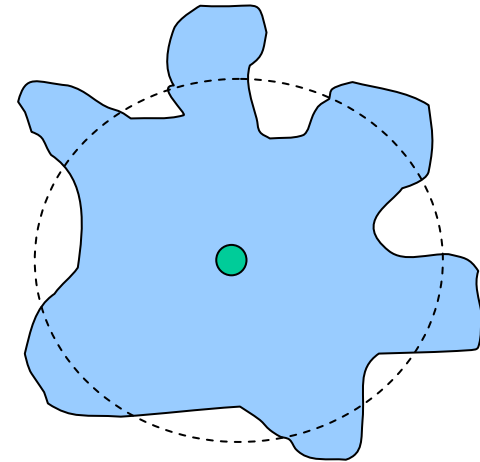
Transmission range



Ideal case



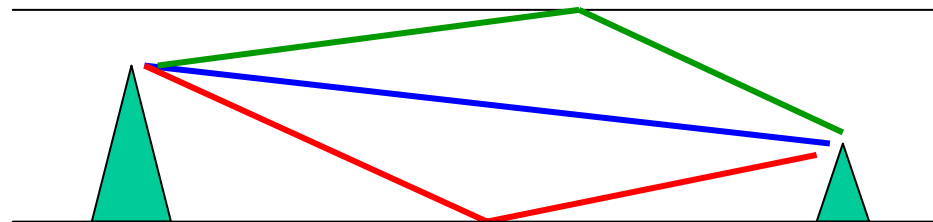
With shadowing



It might vary
with time

Multi-path fading

- Multiple radio propagation paths
 - Might include LOS path or not
 - Multiple copies of received signals
 - Different time delay
 - Different phase
 - Different amplitude
- More severe in urban area or indoor
- Characterized by
 - Rayleigh or Ricean distribution
 - Delay spread profile

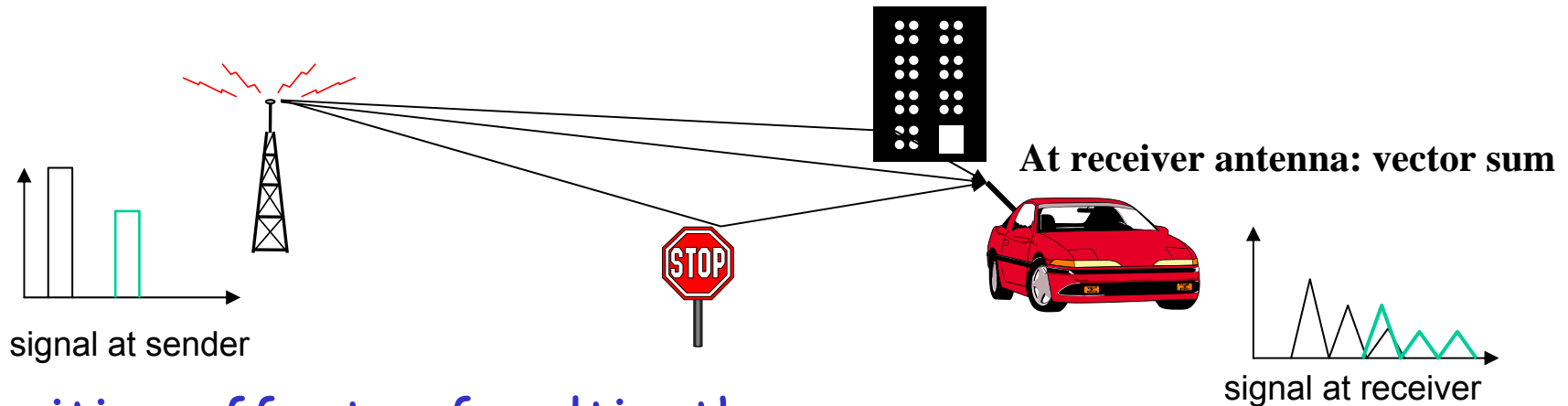


Effects of multi-path signals

- Multiple copies of a signal may arrive at different phases
 - If phases add destructively, the signal level relative to noise declines, making detection more difficult
- Intersymbol interference (ISI)
 - One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit

Multipath Propagation

- Signals can take many different paths between sender and receiver due to reflection, scattering, diffraction



- **Positive effects of multipath:**
 - Enables communication even when transmitter and receiver are not in LOS conditions - allows radio waves effectively to go through obstacles by getting around them, thereby increasing the radio coverage area
 - By proper processing of the multipath signals, with smart or adaptive antennas, you can substantially increase the usable received power
 - With multiple antennas you capture energy that would otherwise be absorbed by the atmosphere and you can compensate for fades --- since it is highly unlikely that a signal will experience severe fading at more than one antenna

Negative effects of small-scale fading

- Time dispersion or delay spread: signal is dispersed over time due signals coming over different paths of different lengths. This causes interference with “neighboring” symbols, this is referred to as **Inter Symbol Interference (ISI)**
- The signal reaches a receiver directly and phase shifted (due to reflections) as a distorted signal depending on the phases of the different paths; this is referred to as **Rayleigh fading**, due to the distribution of the fades. Rayleigh fading creates fast fluctuations of the received signal (**fast fading**).
- Random frequency modulation due to **Doppler frequency shifts** on the different paths. Doppler shift is caused by the relative velocity of the receiver to the transmitter, leads to a frequency variation of the received signal.

Delay spread and coherent bandwidth

- Reminder

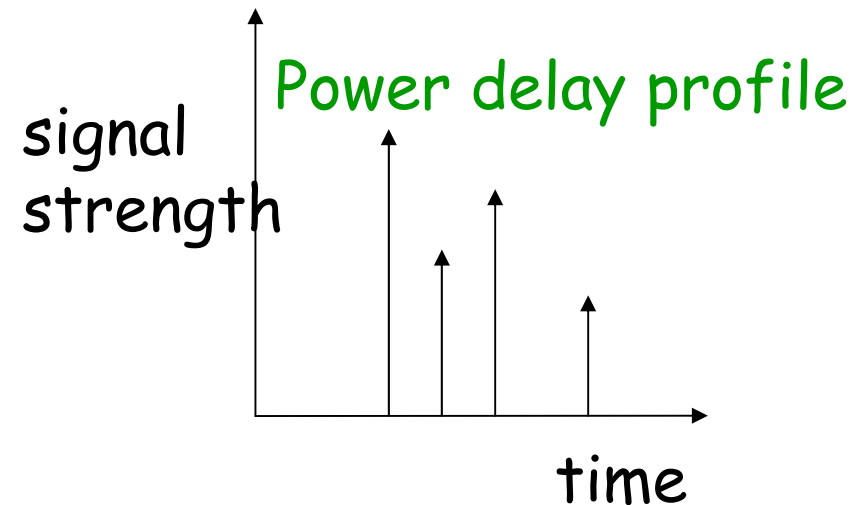
- duality property of signals in time-domain and frequency domain

- Time domain

- multi-path delay spread

- Frequency domain

- coherent bandwidth B_c
- Highly correlated signals among these frequency components



Power Delay Profile

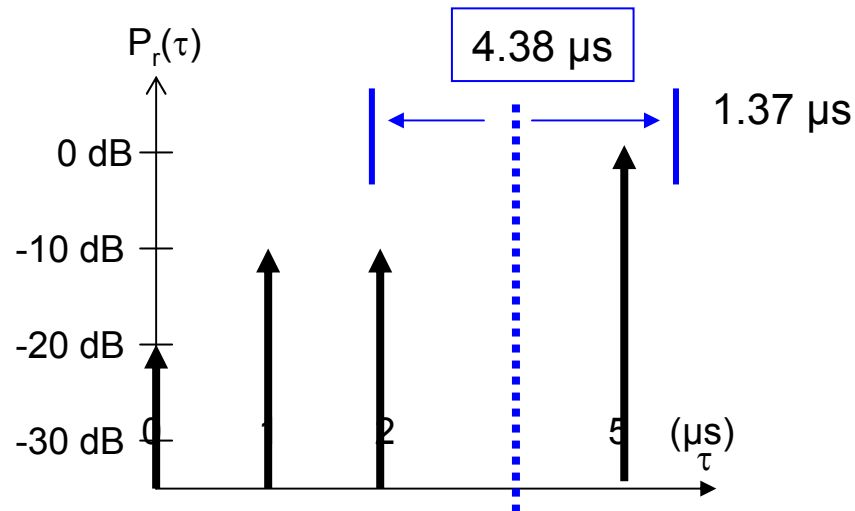
- In order to compare different multi-path channels, the time dispersive power profile is treated as an (non-normalized) pdf from which the following are computed

$$\text{Mean delay : } \bar{\tau} = \frac{\sum_k \alpha_k^2 \tau_k}{\sum_k \alpha_k^2}, \quad \text{Mean square delay : } \overline{\tau^2} = \frac{\sum_k \alpha_k^2 \tau_k^2}{\sum_k \alpha_k^2}$$

$$\text{The RMS Delay Spread : } \sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2} \quad (2.25)$$

- Typical values of *rms delay spread* are on the order of microseconds in outdoor mobile radio channels [GSM specifies a maximum delay less than $20 \mu s$] and on the order of nanoseconds in indoor radio channels

Example (Power delay profile)



Avg delay

$$\bar{\tau} = \frac{(1)(5) + (0.1)(1) + (0.1)(2) + (0.01)(0)}{[0.01 + 0.1 + 0.1 + 1]} = 4.38 \mu s$$

$$\bar{\tau}^2 = \frac{(1)(5)^2 + (0.1)(1)^2 + (0.1)(2)^2 + (0.01)(0)^2}{[0.01 + 0.1 + 0.1 + 1]} = 21.07 \mu s^2$$

$$\sigma_{\tau} = \sqrt{21.07 - (4.38)^2} = 1.37 \mu s \quad \longrightarrow \text{Delay spread}$$

Rayleigh fading

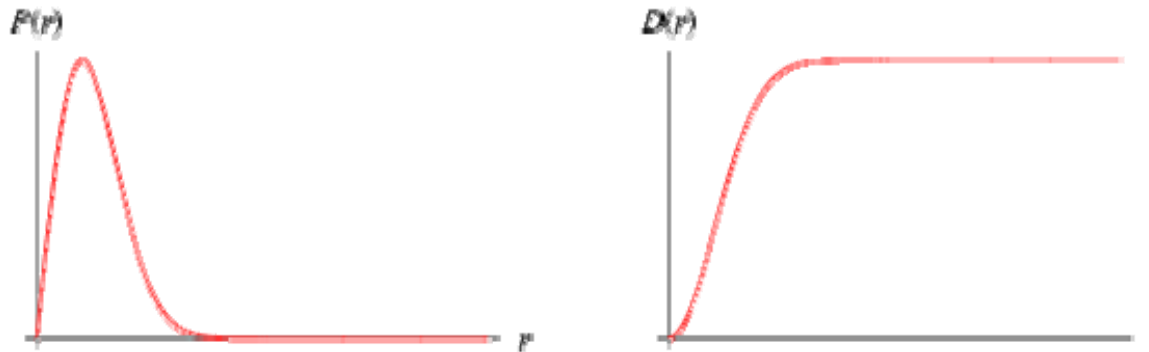
- "Amplitude" follows Rayleigh distribution

$$P_R = \alpha^2 10^{\frac{x}{10}} g(d) P_T G_T G_R$$

- How to derive it?

- Add several scaled and delayed versions of a sinusoid function

$$p_R(\alpha) = \frac{\alpha}{\sigma^2} e^{-\alpha^2 / 2\sigma^2}$$



Ricean Fading

- Some types of scattering environments have a **LOS** component (in addition to the scattered components) ---typically in microcellular and satellite systems. This dominant path may significantly decrease the depth of fading, and in this case $g_I(t)$ and $g_Q(t)$ are Gaussian random processes with non-zero means $m_I(t)$ and $m_Q(t)$. We can assume that these processes are uncorrelated and the random variables $g_I(t)$ and $g_Q(t)$ have the same variance, σ , then the received complex envelope has the Ricean distribution

$$p_r(x) = \frac{x}{\sigma^2} e^{-\frac{(x^2+s^2)}{2\sigma^2}} I_0\left(\frac{xs}{\sigma^2}\right) \quad x \geq 0$$

$$\text{where } s^2 = m_I^2(t) + m_Q^2(t)$$

and the zero order Bessel function of the first kind $I_0(x)$ is defined by

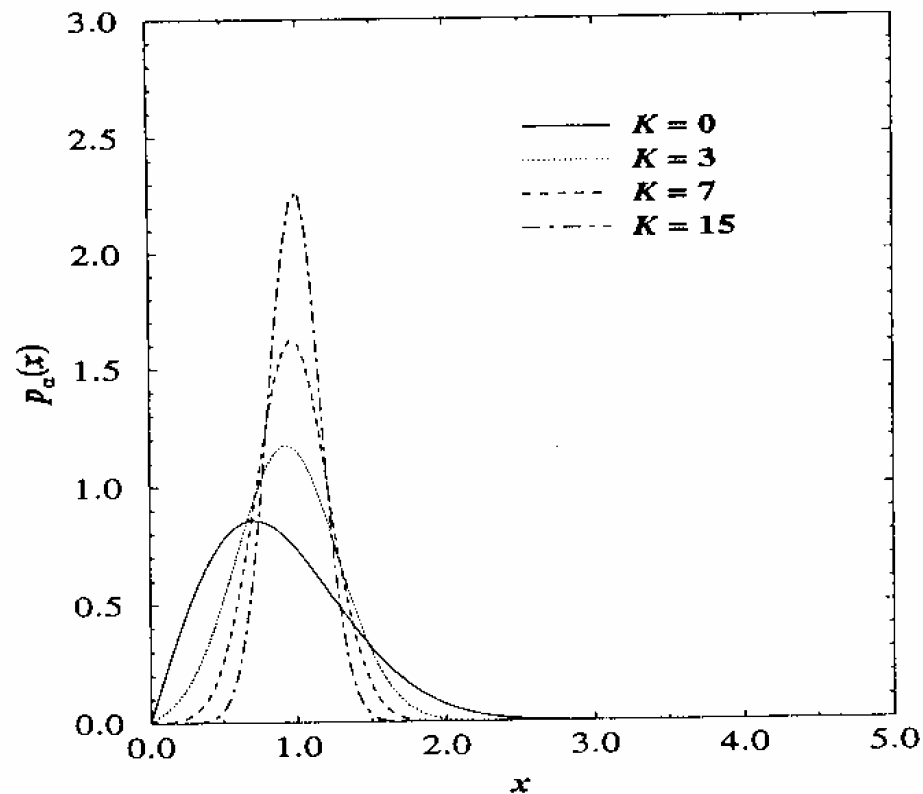
$$I_0(x) = \frac{1}{2\pi} \int_0^{2\pi} e^{-x \cos \theta} d\theta$$

- The **Rice factor**, K , is defined as the ratio of the specular (LoS) power to the scattered power

$$K = \frac{\text{power in the dominant (specular) path}}{\text{power in the scattered paths}} = \frac{s^2}{2\sigma^2}$$

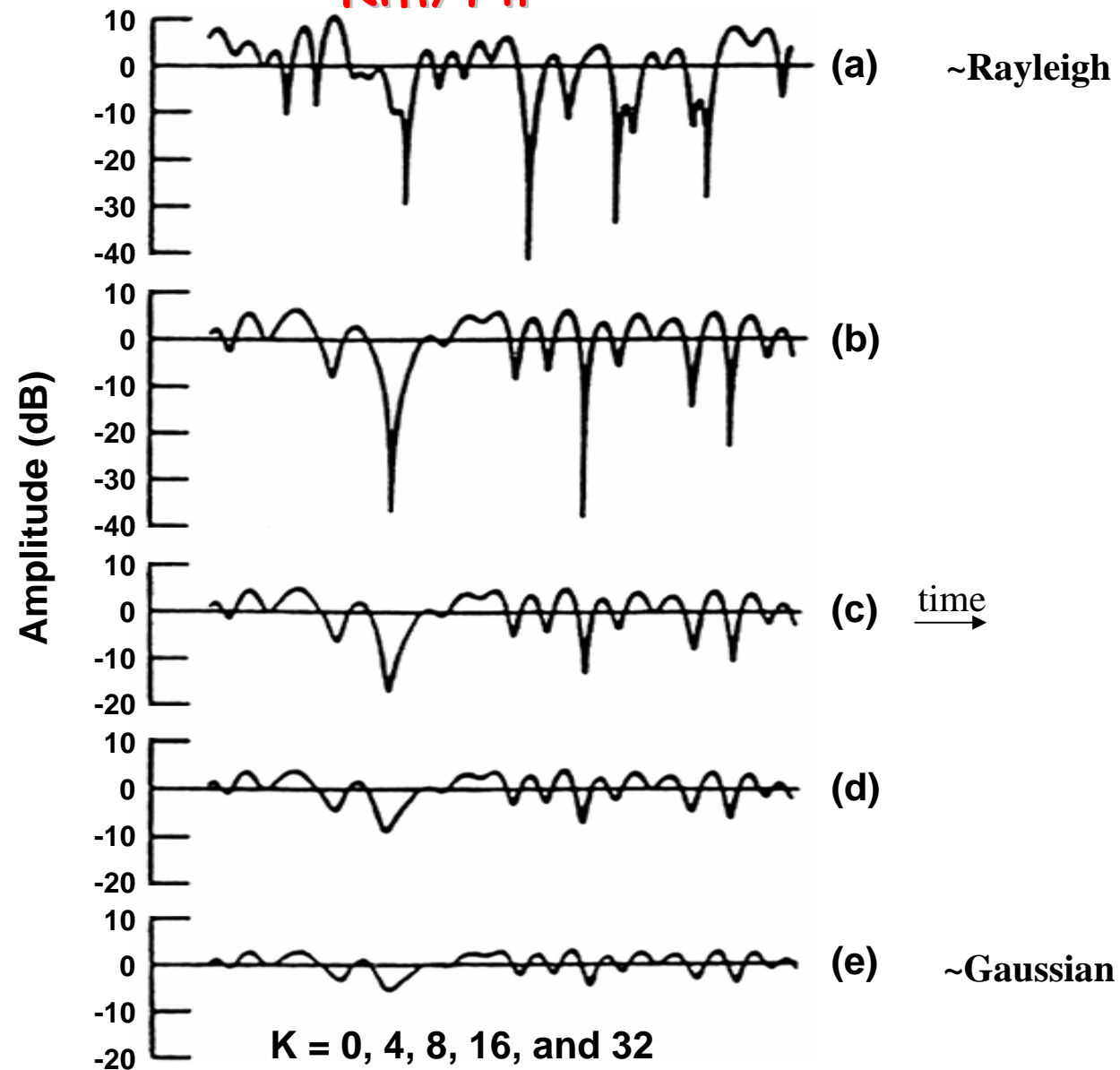
Ricean Fading

- When $K=0$, the channel exhibits Rayleigh fading and for $K \rightarrow \infty$ there is no fading and the channel is Gaussian.
- Most channels can be characterized as either Rayleigh, Rician, or Gaussian --- with Rician being the most general case --- the Rician pdf is shown below.



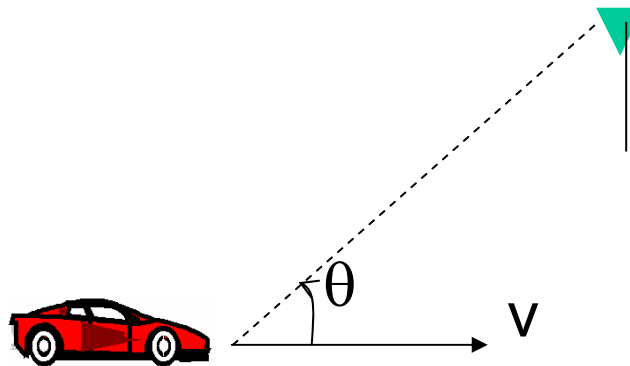
The Rice pdf for several values of K

Rician Fading Profiles for a Mobile at 90 Km/Hr



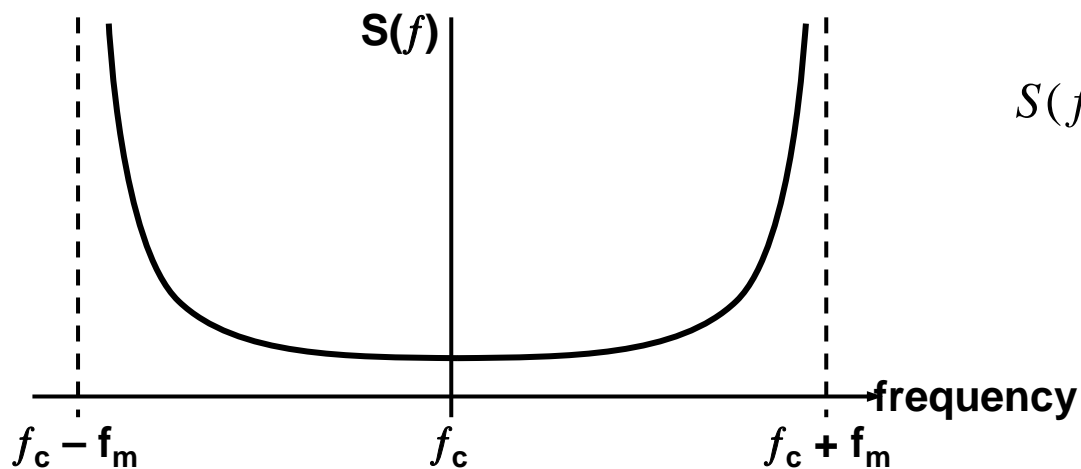
Doppler Shift

- The motion of the mobile introduces a *Doppler* (or frequency) *shift* into the incident plane wave and is given by
 - $f_D = f_m \cos \theta_n$ Hz
 - where $f_m = v/\lambda$ is the maximum Doppler shift that occurs when $\theta = 0$. Waves arriving from the direction of motion will experience a positive shift, while those arriving from the opposite direction will experience a negative shift.



Doppler Shift Spectrum

- For isotropic 2-dimensional scattering and isotropic scattering
- The power spectrum of the received signal is limited in range to f_m about the carrier frequency)



$$S(f) = \frac{A}{4\pi f_m} \frac{1}{\sqrt{1 - \left(\frac{f - f_c}{f_m}\right)^2}} \quad |f - f_c| \leq f_m$$

Effect of Doppler Shift

- Time-frequency duality
 - The Doppler effect produces **frequency dispersion** (an increase in the bandwidth occupancy)
 - This is equivalent to **time-selective fading** in the received signal
- Coherence Time
 - Doppler frequency shift (frequency domain) could be represented as coherence time (time domain) T_c
 - Represent the time duration that channel is stable
 - If symbol time is smaller than T_c , it is called **slow fading**. Otherwise it is **fast fading**.

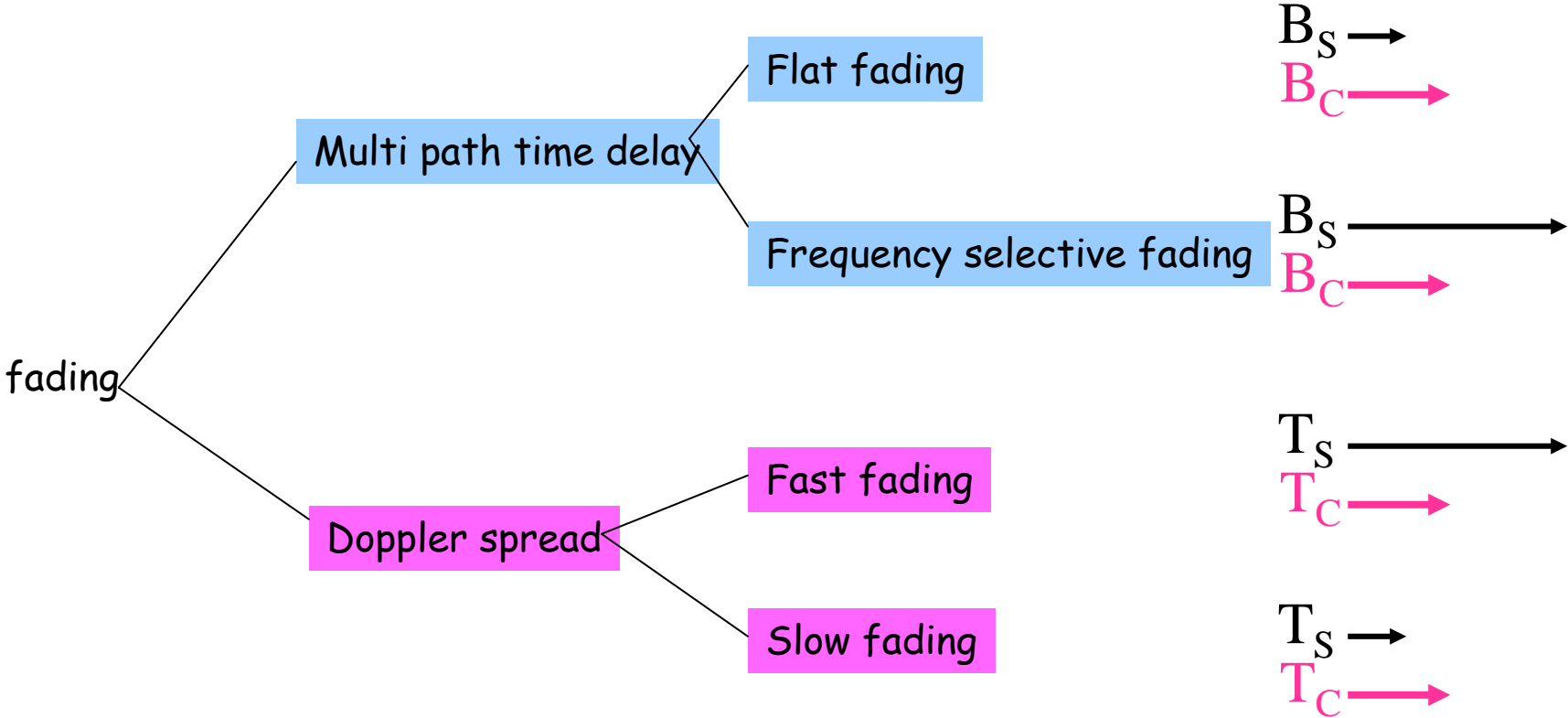
Mitigate Doppler shift

- If the baseband signal bandwidth is much greater than the maximum Doppler shift, then the effects of Doppler spread are negligible at the receiver.
 - To minimize the effect of Doppler, we should use as wide a baseband signal as feasible [e.g. spread spectrum]

Types of fading

- Summary: Fading (based on multipath time delay spread)
 - Signal is correlated or not (time)
 - Channel frequency response depends on frequency or not (frequency)
 - 1. Flat Fading
 - BW of signal $<$ BW of channel
 - Delay spread $<$ Symbol period
 - 2. Frequency Selective (non-flat) Fading
 - BW of signal $>$ BW of channel
 - Delay spread $>$ symbol period
- Summary: Fading (based on Doppler spread)
 - Channel varies faster or slower than signal symbol (time)
 - High or low frequency dispersion (frequency)
 - 1. Slow Fading
 - Low Doppler spread
 - Coherence time $>$ Symbol period
 - Channel variations slower than baseband signal variations
 - 2. Fast Fading
 - High Doppler spread
 - Coherence time $<$ symbol period (time selective fading)
 - Channel variations faster than baseband signal variations

Small scale fading



Summary of radio propagation and mitigations

- Shadowing
 - Problem: received signal strength
 - Mitigation:
 - increase transmit power
 - Reduce cell size
- Fast fading
 - Problem: error rate (BER, FER, PER)
 - Mitigation:
 - Interleaving
 - Error correction coding
 - Frequency hopping
 - Diversity techniques
- Delay spread
 - Problem: ISI and error rates
 - Mitigation:
 - Equalization
 - Spread spectrum
 - OFDM
 - Directional antenna

How to create propagation models?

- General ray-tracing method (simulation)
 - 3D building database with topography
 - Multiple ray-tracing with propagation effects (reflection, diffraction, LOS path, scattering, etc)
 - Might consider building material (steel, concrete, brick, etc)
- Empirical method
 - On-site measurement
 - Curve-fitting
 - Could be combined with ray-tracing method

Review question?

- In which case do you expect better propagation condition?
 - Indoor or outdoor
 - With LOS or NLOS
 - Fixed or mobile user

What's your propagation environment?

- Surroundings
 - Indoor, outdoor, street, open-area
- LOS or NLOS
 - Line-of-sight or not?
- Design choices?
 - Coding, modulation
 - Re-transmission (ARQ-Automatic Repeat-reQuest)
 - QoS requirement (at different layers)
 - Data rate requirement
 - BER (bit-error-rate)
 - FER (frame-error-rate)
 - Depend on BER and frame size

Diversity technique

- Diversity techniques improve the system performance with multi-path signals
 - Not just avoid multi-path condition, but take advantage of it
- Applicable in several aspects
 - Time diversity
 - Frequency diversity
 - Spatial diversity
- Examples
 - Linear combining
 - Sum of all received signals at each branch
 - Maximal-ratio combining
 - Weighted sum (weight is proportional to the received signal strength at each branch)

Types of Diversity used for Combating Multipath Fading

Type	Technique applied
Space	Receiving antennas sufficiently separated for independent fading.
Time	Send sequential time samples [interleaving]. Equalization
Frequency	Transmit using different carrier frequencies separated by frequencies greater than the coherence bandwidth for independent fading; or by wideband spread spectrum transmission.
Polarization	Transmit using two orthogonal polarizations for independent fading

Review: types of fading

- What are the definitions of the following terms?
 - Fast fading
 - Slow fading
 - Flat fading
 - Selective fading
 - Rayleigh fading
 - Rician fading

Cross-Layer Design and Optimization

Radio Propagation Model

- Understand wireless PHY property is the first step to conduct cross-layer design and engineering
 - Channel property affects communication system performance significantly
 - Cross-layer design could be optimized according to the radio propagation model
 - Indoor V.S. outdoor
 - LOS V.S. NLOS
 - Speed (static, low-speed, high-speed) → Doppler shift
 - Example: wireless communications over high-speed trains is challenging

Abstract Model

- Abstract model is helpful in cross-layer design
 - Sophisticated model could be too complex
 - Difficult to provide design insight
- Radio propagation model → channel state varies
 - Markov Chain model
 - Simple example: 2-state Markov chain
 - Good state and bad state
 - Gilbert/Elliot model