Lecture 2: Wireless PHY and Radio Propagation Model

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Review and More Overview

What is special about "wireless"?

- Wireless channel
  - Electromagnetic
  - Channel variation → **Radio propagation model**
  - Signal power attenuation → **Radio propagation model**
  - Sharing wireless medium
- What will happen if we apply the same wired-line networking protocol in wireless environments?

What is special about "mobile"?

- User mobility → where are you now?!
  - Mobility management
  - Handoff
- Tradeoffs
  - Precision of user location
    - Time to find your exact location
  - Signaling overhead
    - Cost of updating your location
  - Power consumption
    - Updating your location consumes battery power

How do you categorize technologies?

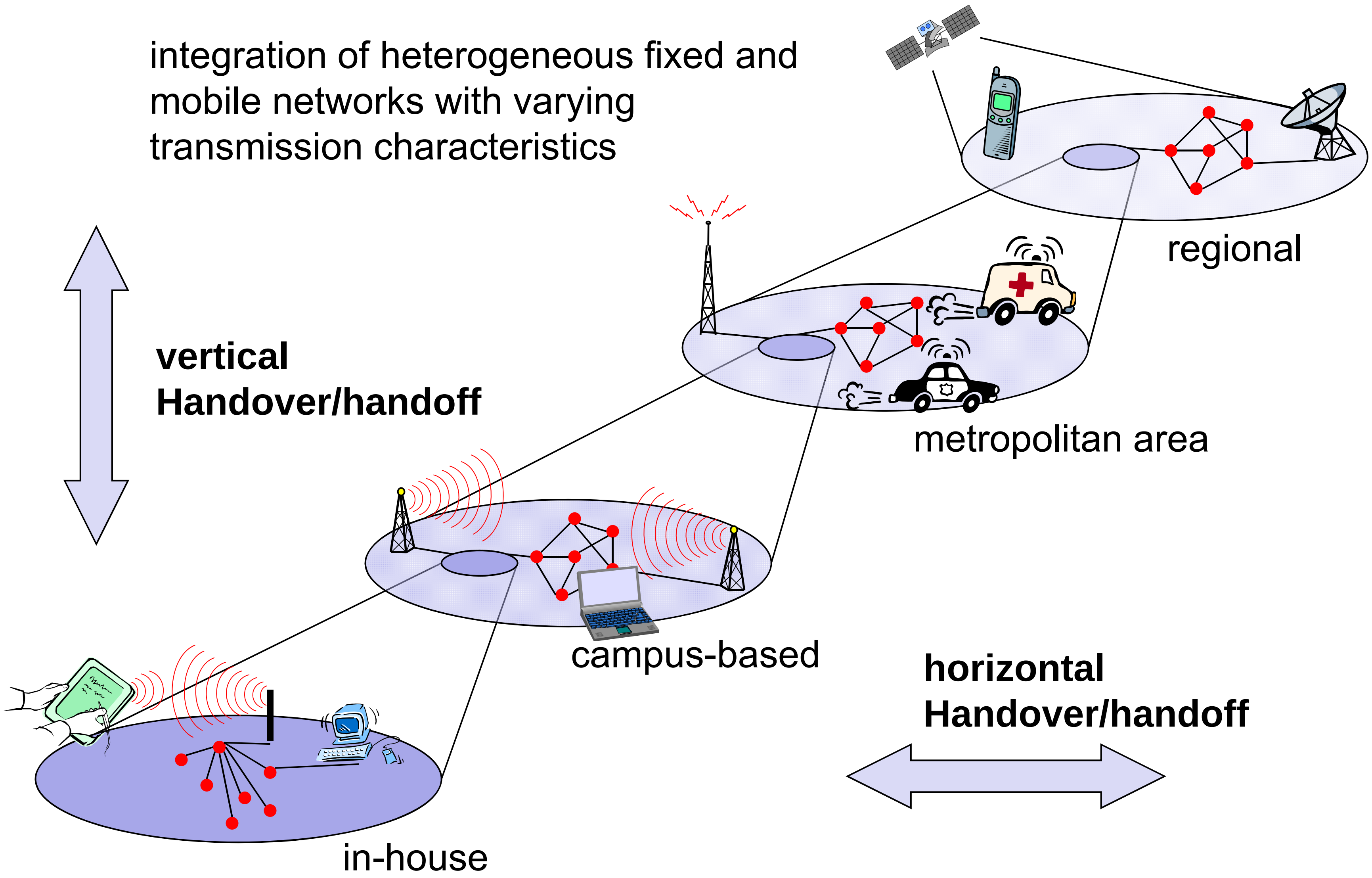
- Mobility - speed
  - Static, pedestrian, vehicular, high-speed rail
- Range
  - 1m, 10m, 100m, 1km, 10km, satellite
- Radio environment
  - Open space or Obstacles on transmission path
- Design goal
  - Low power v.s. high throughput

Two campaigns of networks

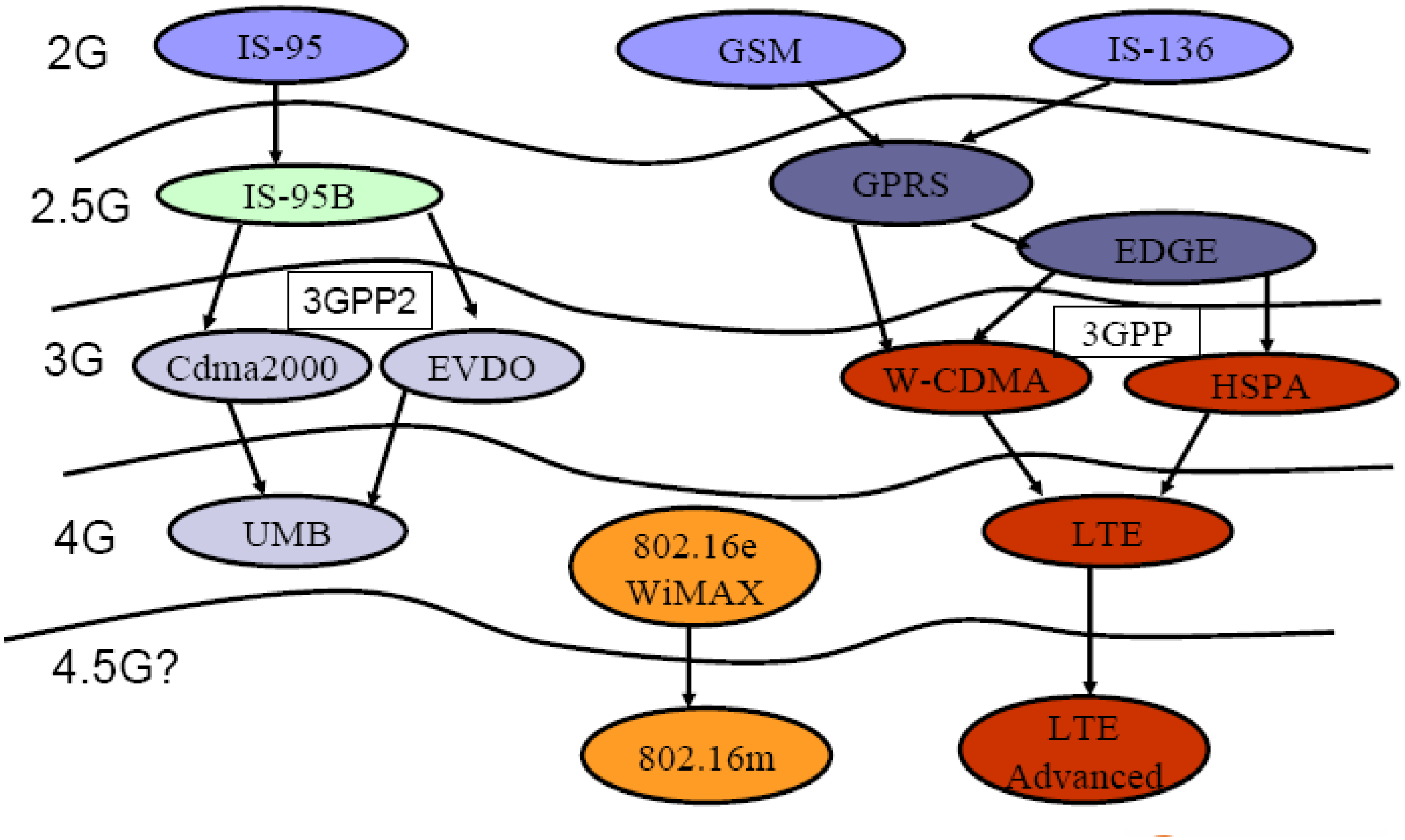
- Computer network (Internet)
  - TCP, IP, HTTP, IEEE 802.11
  - Standardization: IETF (Internet Engineering Task Force)
    - Internet drafts, RFC documents, Internet standards
- Telecommunications networks (telephony networks)
  - PSTN (your wireline telephony network)
  - SS7 (signaling network of PSTN)
  - Extend to GSM, 3G wireless telephony networks
  - Standardization: UMTS, 3GPP, 3GPP2
- Future trends
  - Confluence of these two types of networks
  - The boundary becomes more blurry

Overlay Networks

integration of heterogeneous fixed and mobile networks with varying transmission characteristics



Cellular Network Evolution



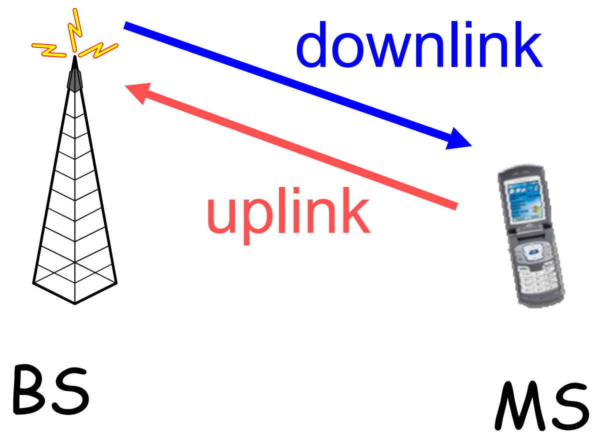
Standards

- IETF
  - TCP, IP, Mobile IP, HTTP, SIP
- 3GPP
  - UMTS, HSDPA, HSUPA, LTE (Long Term Evolution)
- 3GPP2
  - Cdma2000, Ultra Mobile Broadband (UMB)
- IEEE 802 (PHY/MAC)
  - 802.11 WLAN (wireless local area network)
  - 802.15 WPAN (wireless personal area network)
  - 802.16 WMAN (wireless metropolitan area network)
  - 802.20 (mobile wireless broadband access)
  - 802.21 (handoff over heterogeneous networks)
- ITU

Basics of communications, capacity, and channels

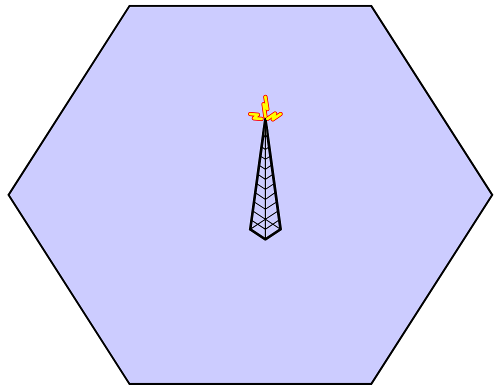
Terminologies: BS & MS

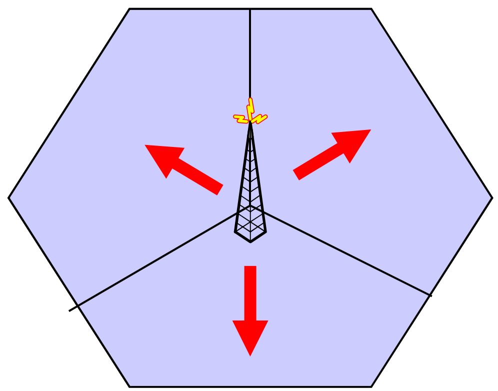
- Base station (BS)
  - Access point (AP)
- Mobile station (MS)
  - SS (Subscriber station)
  - MT (mobile terminal)
  - MN (mobile node)
- Downlink
  - Forward link
  - BS→MS
- Uplink
  - Reverse link
  - MS→BS



Terminologies: cell and sector

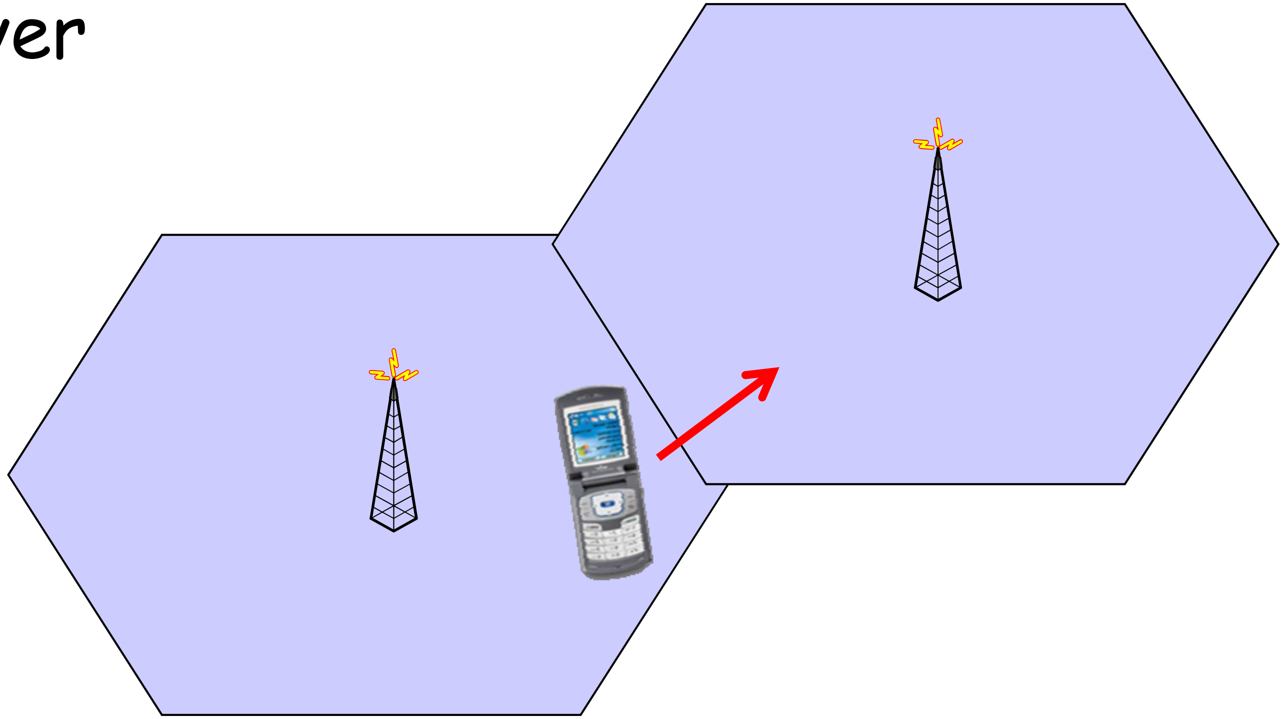
- Cell
  - Coverage area of a BS
- Sector
  - Partial area of a cell that is served by a directional antenna



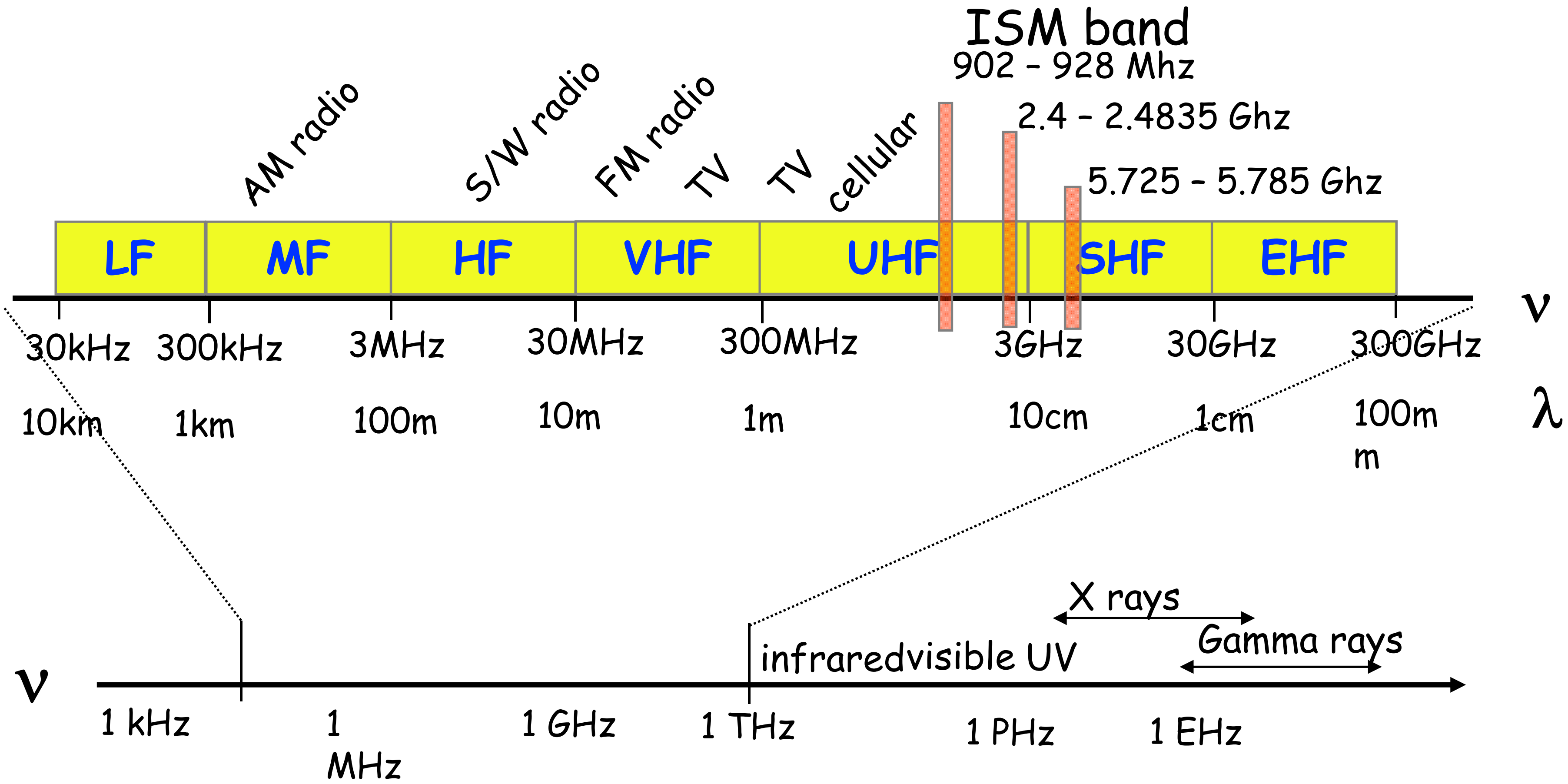


Terminology: handoff

- Handoff
  - MS changes serving BS due to movement or radio channel variation
  - handover



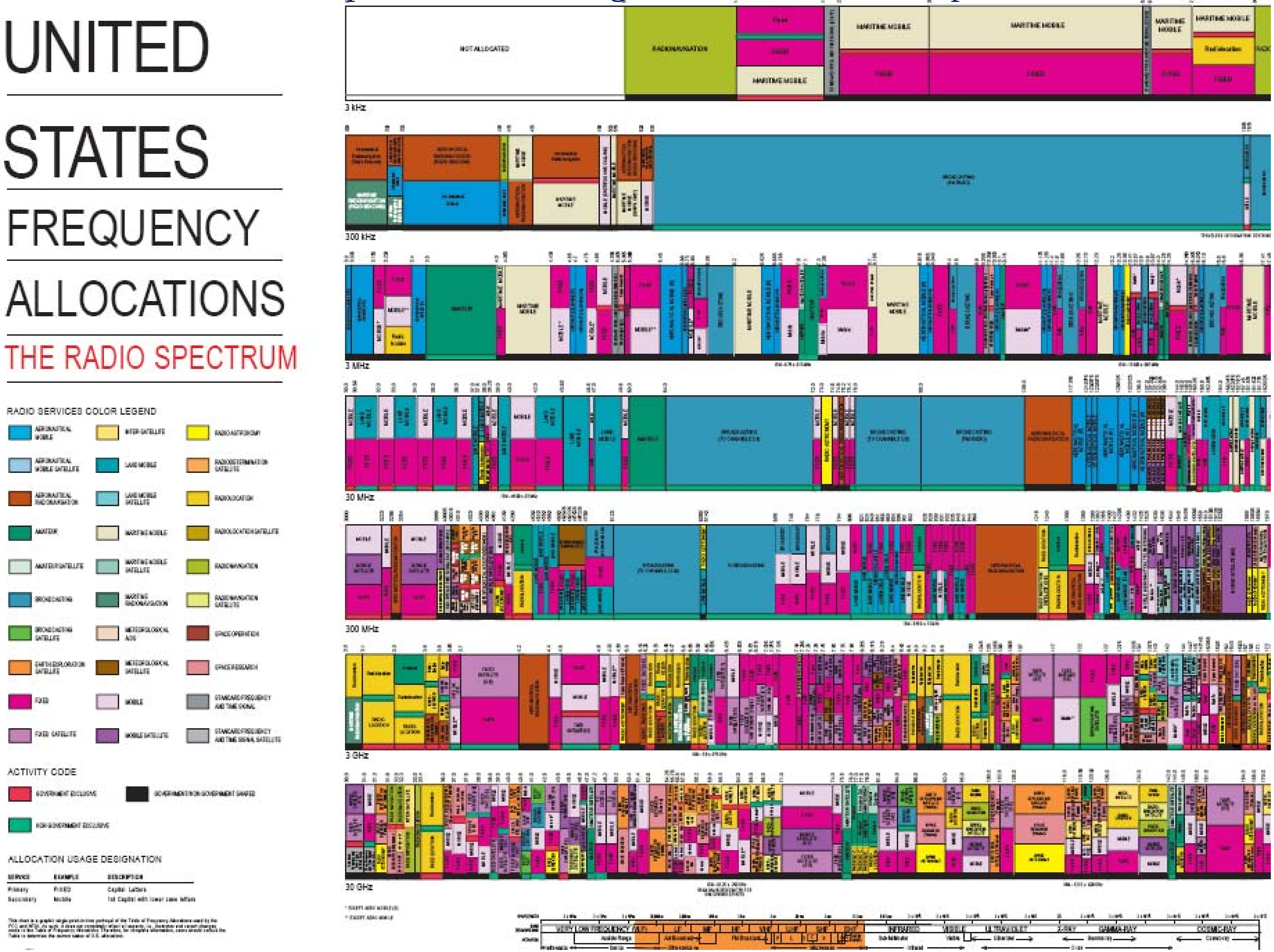
Radio Spectrum



Wireless Spectrum Regulation

- Wireless spectrum is regulated by governments
  - Regulation has significant impact on technology advancement and business development
  - Who should use the spectrum? How should it be used?
  - Auction for licenses (e.g. 3G license)
- Organization
  - NCC (Taiwan)
  - FCC (USA)

http://www.ntia.doc.gov/osmhome/allochrt.pdf



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

Gain and Attenuation in dB or dBm

- Gain/attenuation in dB
  - $10 \log_{10}$ (output power/input power)
    - Gain(dB)=Pout(dB)-Pin(dB)
  - Gain: Pout > Pin
  - Attenuation Pout<Pin
- Gain/attenuation in dBm
  - X(dBm)+Y(dB) =??(dB)=??(dBm)
  - X(dBm)-Y(dB) =??(dB)=??(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

$$P_{tx} \longrightarrow \boxed{G_{ant,tx}} \longrightarrow \boxed{G_{channel}} \longrightarrow \boxed{G_{ant,rx}} \longrightarrow P_{rx}$$

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

Signal-to-Noise ratio

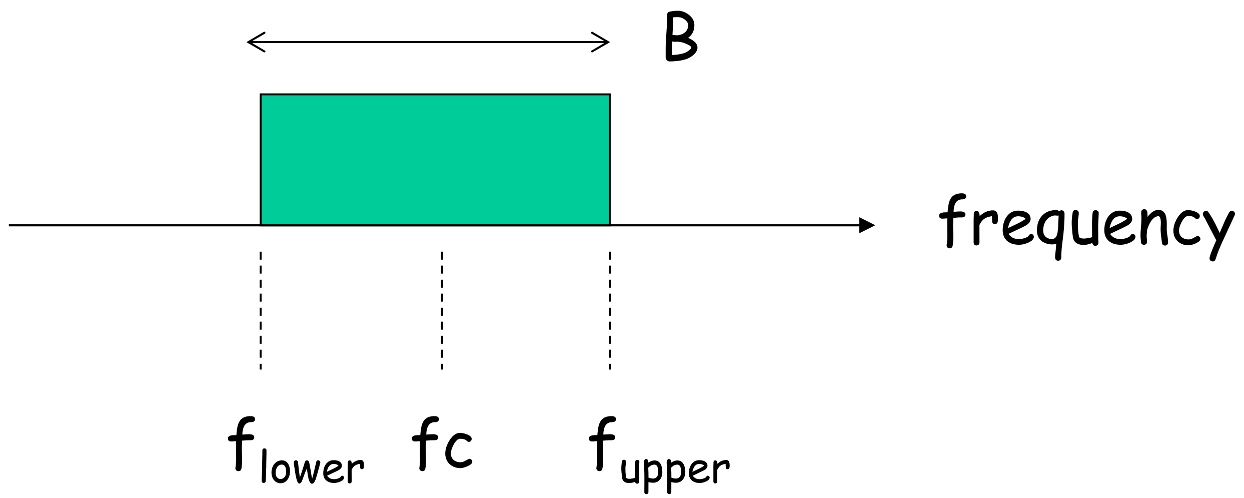
- S/N
  - SNR= signal power(Watt)/noise power(Watt)
  - Signal-to-Noise power ratio
  - Relate to the performance of communications systems
    - Bit-error probability
    - Shannon capacity
- SNR in dB
  - S/N(dB)= 10 $\log_{10}$ (S/N power ratio)
  - 10 $\log_{10}$ (signal power(Watt)/noise power(Watt))

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

- $B=f_{upper}-f_{lower}$
- Carrier frequency: fc
- Example:
  - 802.11 2.4GHz ISM band (channel 1)
    - f_{upper}=2434 MHz
    - f_{lower}=2412 MHz
    - fc=2423 MHz
    - B=22 MHz



Thermal Noise

- Thermal noise power
  - $N=kT_NB$
  - N: power in Watt
  - k: Boltzman's constant= 1.38*10^-23
  - T_N: temperature (degree Kelvin)
  - B: bandwidth of channel (Hz)

Bit Energy to Noise Ratio

- Eb/N_0
  - Energy per bit over the noise power spectral density
  - Related to SNR power ratio
  - Independent of bandwidth

Relate Eb/N_0 to SNR

- SNR=S/N (Watt/Watt)
- $Eb=St_b$
  - Eb: energy per bit (J)
  - S: signal power (carrier power) (W)
  - t_b: duration of a bit (s)
- $Eb/N_0=(S/N_0)*t_b = (S/N_0)*(1/f_b)$
- $N_0=N/B$
  - N: total noise power (W)
  - B: bandwidth (Hz)
- $Eb/N_0=(S/N)(B/f_b)$

S/N (or Eb/N_0)

- To compare systems, generally they should have the same transmitted S/N (or Eb/N_0)
- The S/N (or Eb/N_0) at the input to the receiver will determine the system performance

Example

- Find the Eb/N_0 for a system operating at 2Mbps in a bandwidth of 1MHz. The carrier power is 0.1pW. The system noise temperature is 120K.
- Ans:
  - $Eb/N_0=(S/N)*(B/f_b)$
  - (S/N)=(0.1*10^-12)/{(1.38*10^-23)(120)(1*10^6)}
  - (B/f_b)=(1*10^6)/(2*10^6)
  - Eb/N_0=30.2
  - Eb/N_0(dB)=14.8dB

Capture model

- $SNR_{received} \geq SNR_{threshold}$
  - Minimum SNR requirement, given a target bit-error-rate (or frame-error-rate)

Shannon Capacity

- Theoretical (upper) bound of communication systems
- $C=B*\log_2(1+S/N)$
  - 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: $$C = B\log_2\left(1+\mathrm{SNR}\right)$$
- 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
    - Additive
    - White
    - Gaussian
    - Noise

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 ; SNR_{dB} = 24 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 ; SNR_{dB} = 24 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?

$$C = 2B\log_2 M$$

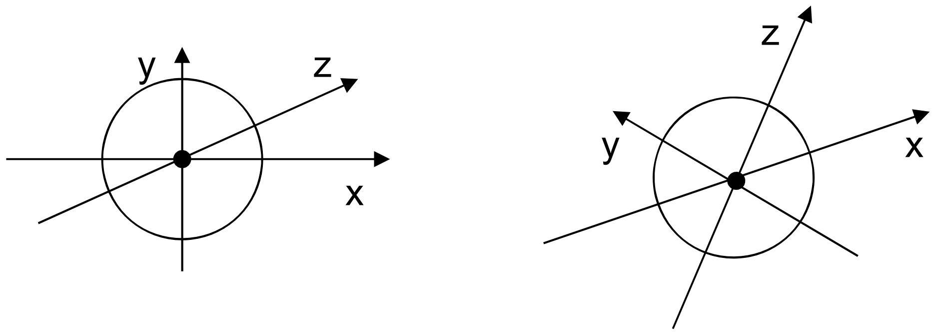
$$8\times10^6 = 2\times\left(10^6\right)\times\log_2 M$$

$$4 = \log_2 M$$

$$M = 16$$

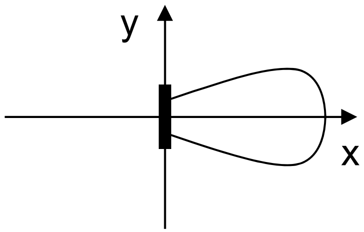
Antennas: isotropic radiator

- Isotropic radiator: equal radiation in all directions
  - only a theoretical reference antenna
- Real antennas always have directive effects (vertically and/or horizontally)
- Radiation pattern: measurement of radiation around an antenna

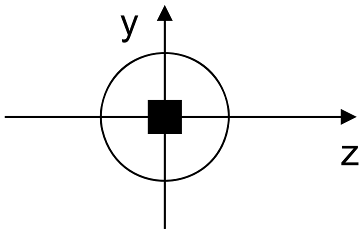


ideal isotropic radiator

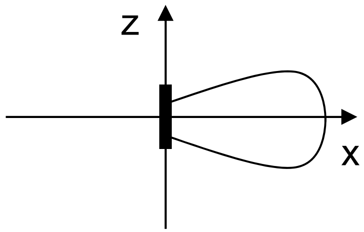
Antennas: directed and sectorized



side view (xy-plane)

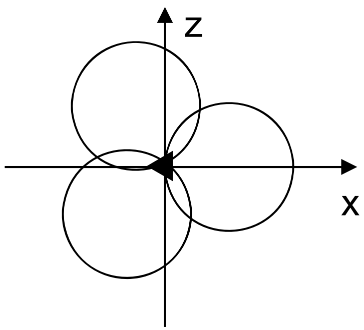


side view (yz-plane)

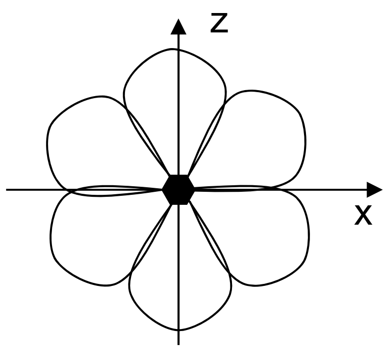


top view (xz-plane)

directed antenna



top view, 3 sector



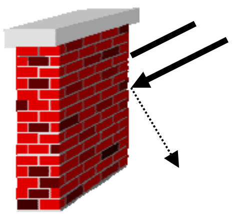
top view, 6 sector

sectorized antenna

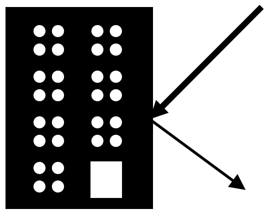
Radio propagation model

Signal propagation

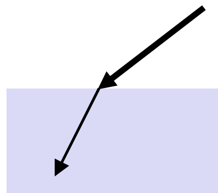
- Propagation in free space always like light (straight line)
- Receiving power proportional to $1/d^2$ in free-space
- Receiving power additionally influenced by
- fading (frequency dependent)
- shadowing
- reflection at large obstacles
- refraction depending on the density of a medium
- scattering at small obstacles
- diffraction at edges



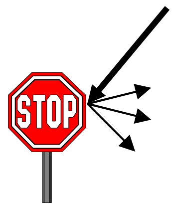
shadowing



reflection



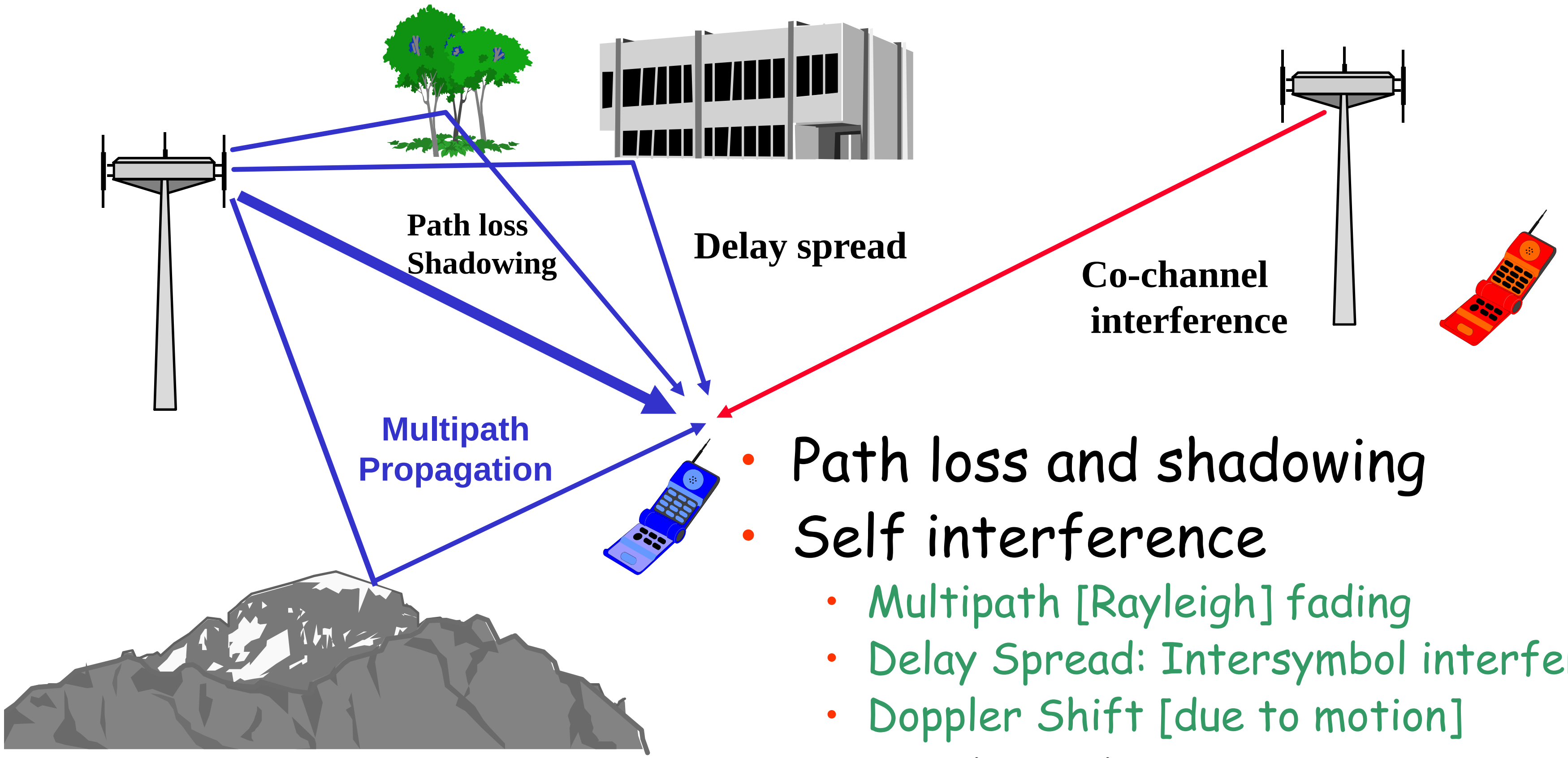
refraction



scattering

diffraction

Wireless Channel



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

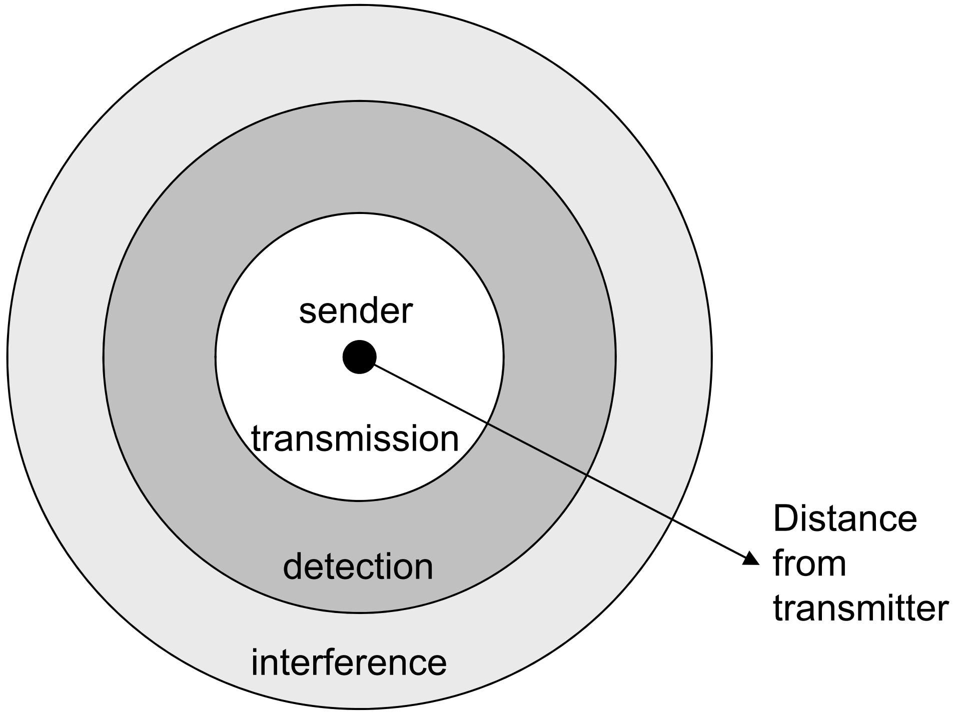
The Effects of Multipath Propagation

- 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

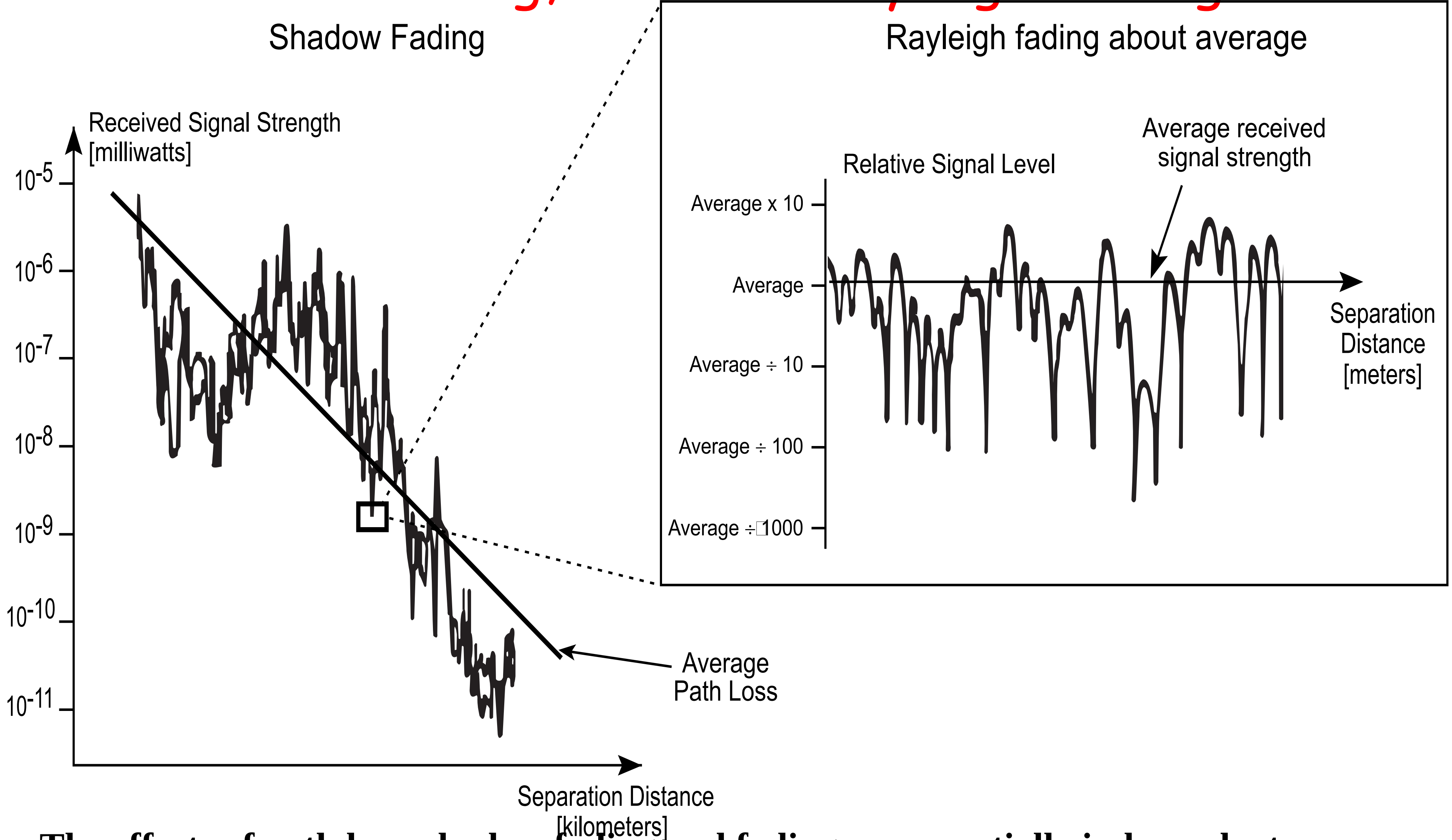
    due to high error rate
- Interference range
  - signal may not be detected
  - signal adds to the background noise



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

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

Radio Propagation Models

- Signal power at receiver: 3 components
  - 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)
  - Represent average values (local mean power of area within several meters)

$$\overline{P_R} = g(d) P_T G_T G_R$$

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

- In general received signal strength is proportional to d^{-n}
  - n: path-loss exponent
  - k: constant
  - n=2 ~ 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

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

  - d^{-n}
  - Typically, n is smaller value in near-field and is a greater value in far-field
  - Empirical measurement

$$g(d) = d^{-n_1} \qquad 0 \le d \le b$$

- Two-stage transition model

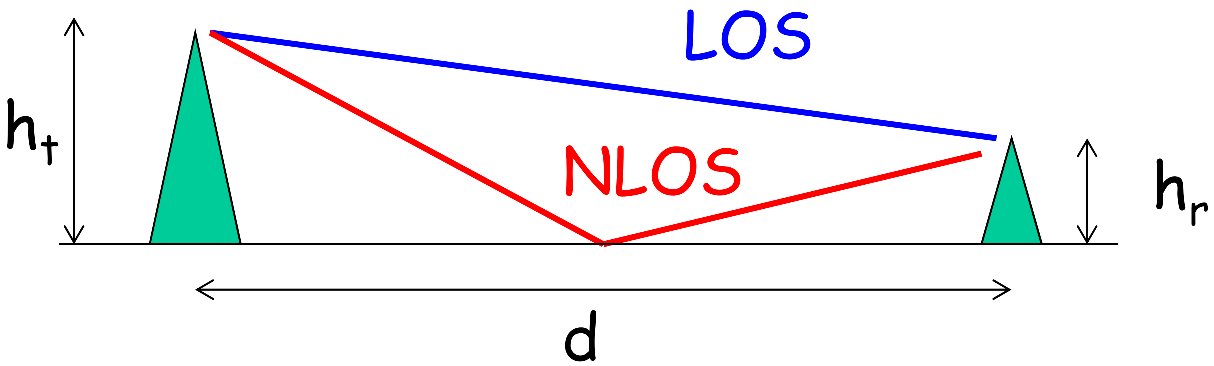
$$g(d) = d^{-n_1}(d/b)^{-n_2} \qquad b \le d$$

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
Pickhlotz	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)

COST-231 path-loss model

- Extend Hata model for PCS radio model in urban area

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

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

  $C_M = 0\,dB$

- Small and medium size cities

  $C_M = 3\,dB$

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 multi-path 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

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

Log-normal shadowing

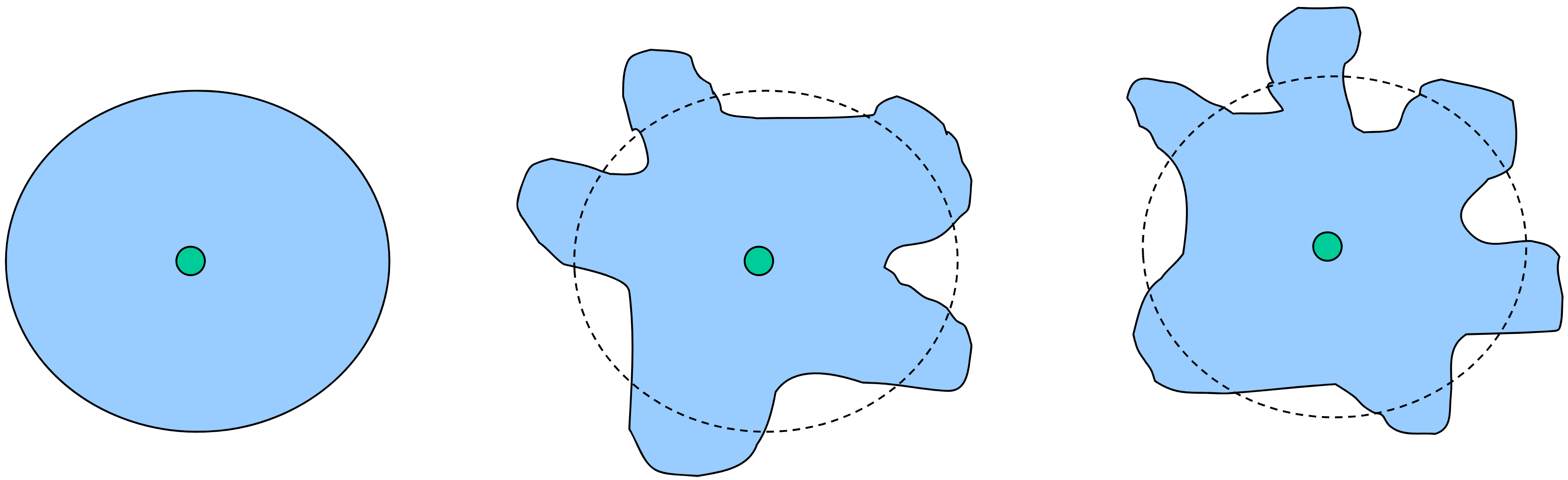
- Path loss component indicates the "expected" signal attenuation at distance *d*
  - The actual signal attenuation at *d* depends on the environment. This is modeled with shadowing effect.
- Statistical model for shadowing
  - Received mean power of the radio signal fluctuates about the area-mean power 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, σ = 6~10 dB

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

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

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

Transmission range



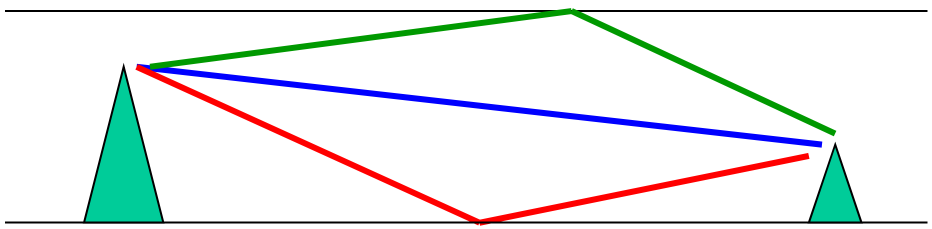
Ideal case

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 Rician distribution
  - Delay spread profile

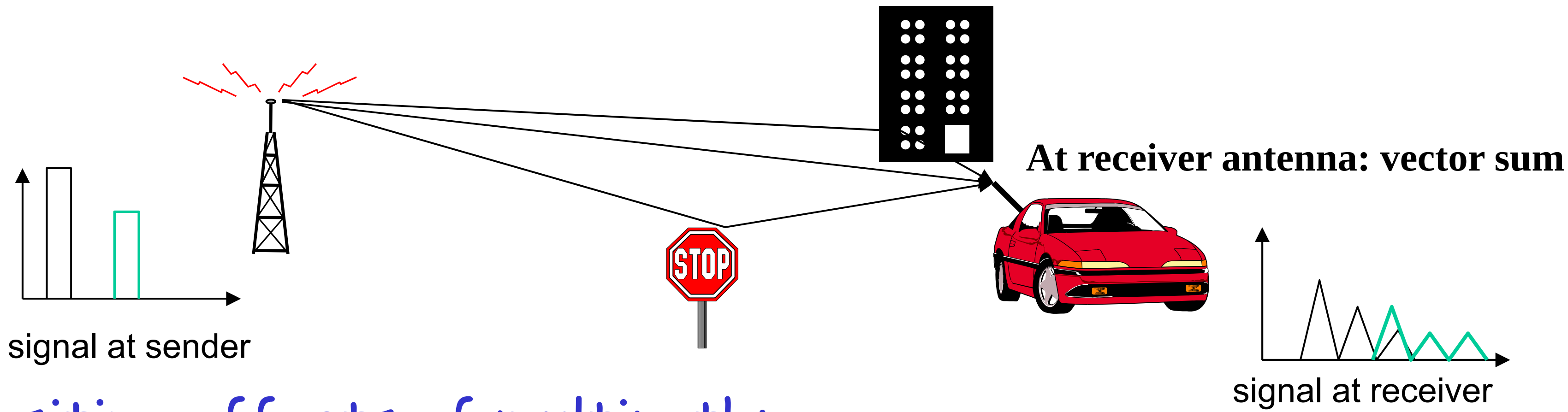


Effects of multi-path signals

- 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



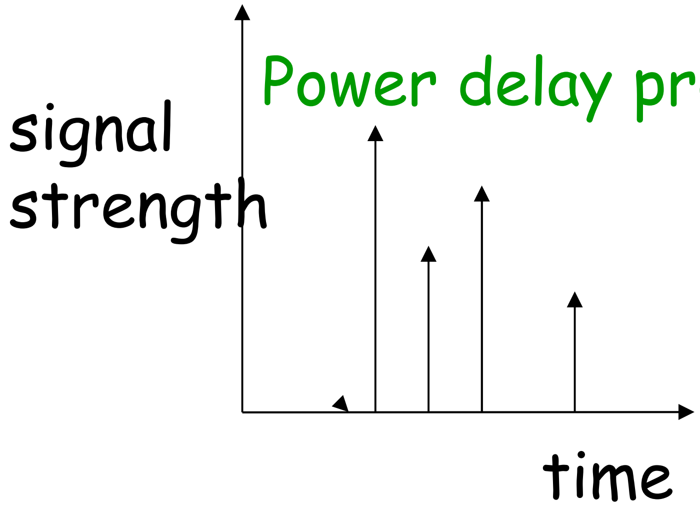
- Positive effects of multipath:
  - Enables communication even when transmitter and receiver are not in LOS conditions - allows radio waves effectively to go through obstacles by getting around them, thereby increasing the radio coverage area
  - By proper processing of the multipath signals, with smart 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.
- 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

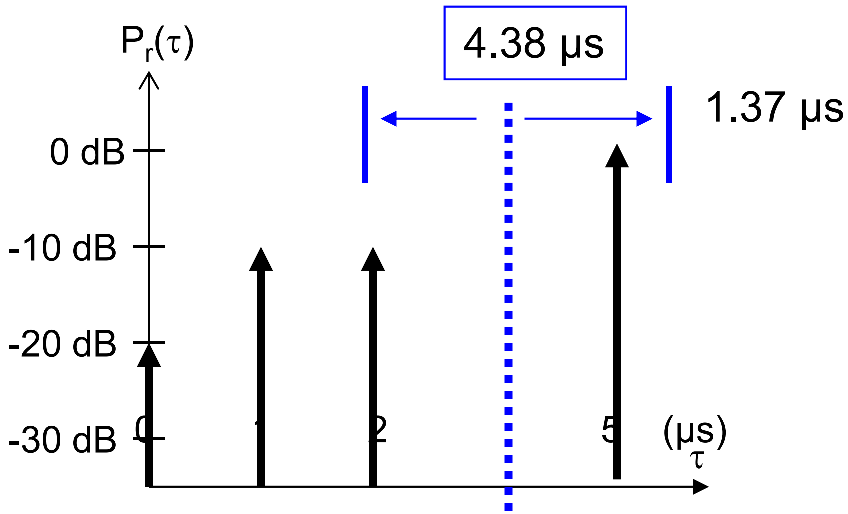
- In order to compare different multi-path channels, the time dispersive power profile is treated as an (non-normalized) pdf from which the following are computed

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

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

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

Example (Power delay profile)



Avg delay

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

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

$$\sigma_\tau = \sqrt{21.07-(4.38)^2} = 1.37\mu s$$

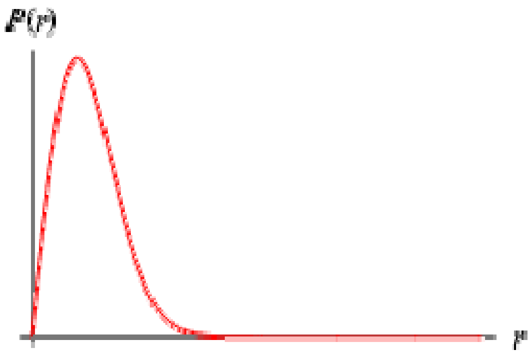
Delay spread

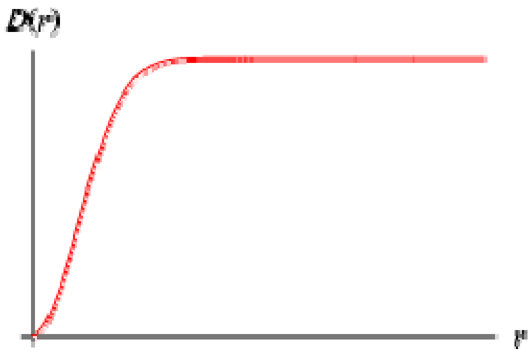
Rayleigh fading

- "Amplitude" follows Rayleigh distribution
- How to derive it?
  - Add several scaled and delayed versions of a sinusoid function

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

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





Rician Fading

- Some types of scattering environments have a **LOS (ling-of-sight)** component
  - In addition to the NLOS scattered components
  - LOS dominant path may significantly decrease the depth of fading

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

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

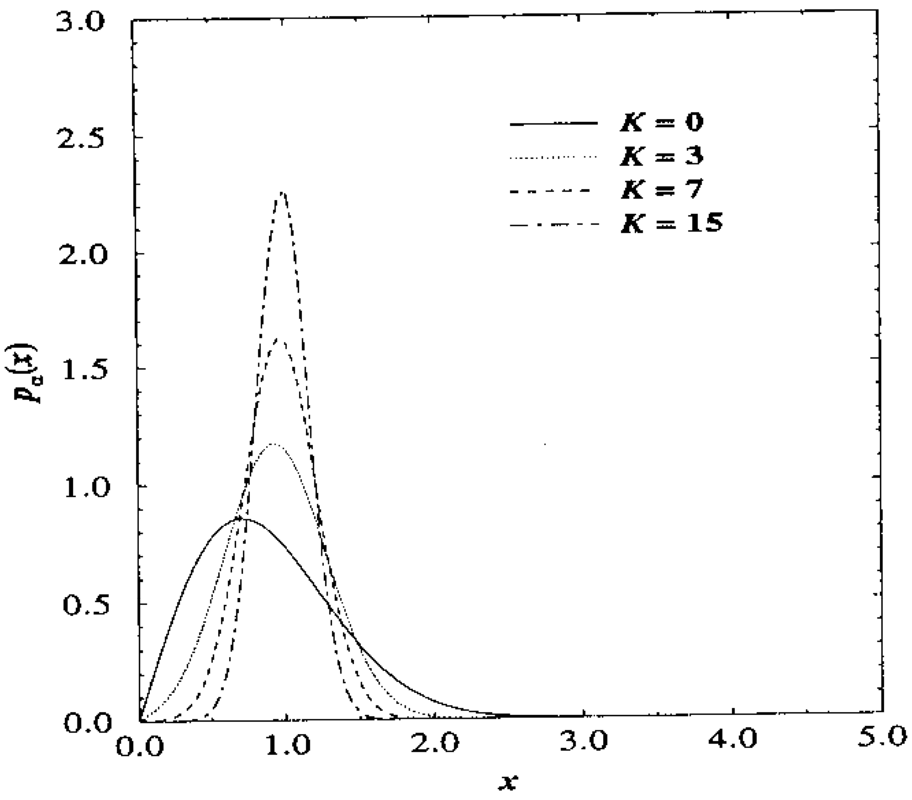
$$I_0(x) = \frac{1}{2\pi} \int_0^{2\pi} e^{-x\cos\theta} d\theta$$

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

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

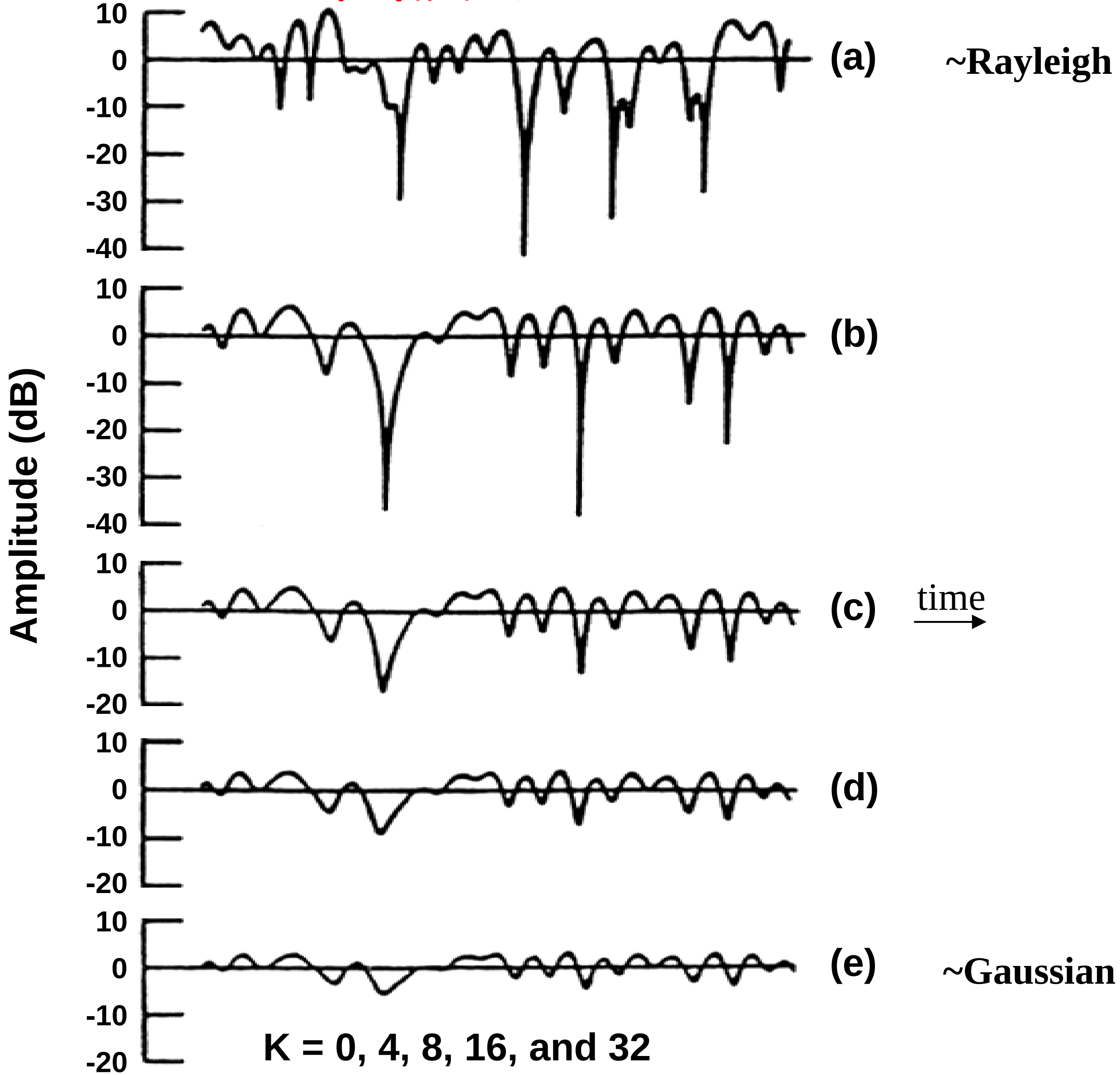
Rician Fading

- When K=0, the channel exhibits Rayleigh fading and for $K \to \infty$ 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.



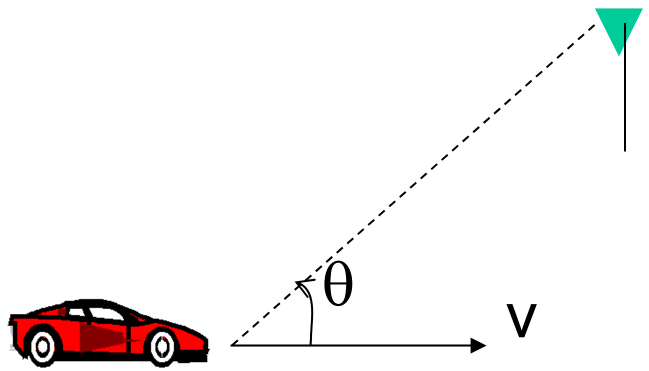
The Rice pdf for several values of K

Rician Fading Profiles for a Mobile at 90 Km/Hr



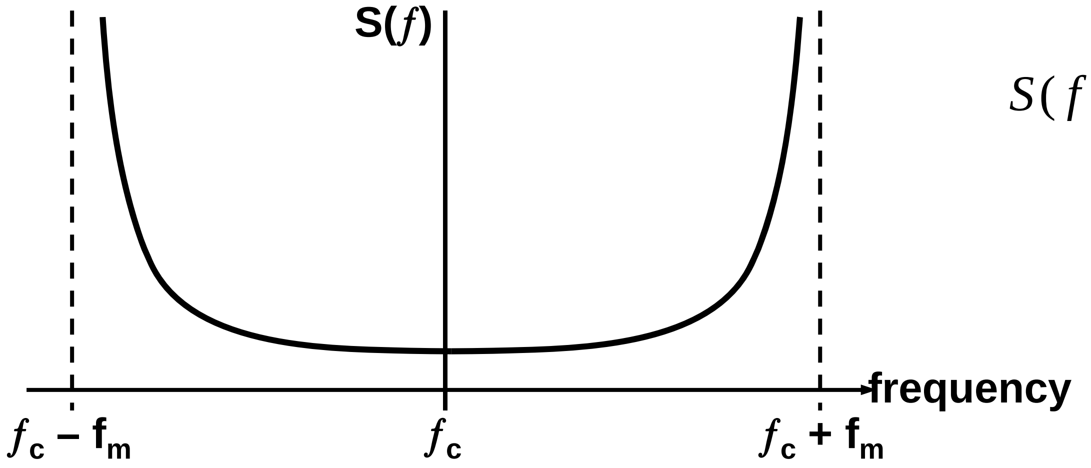
Doppler Shift

- 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)



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

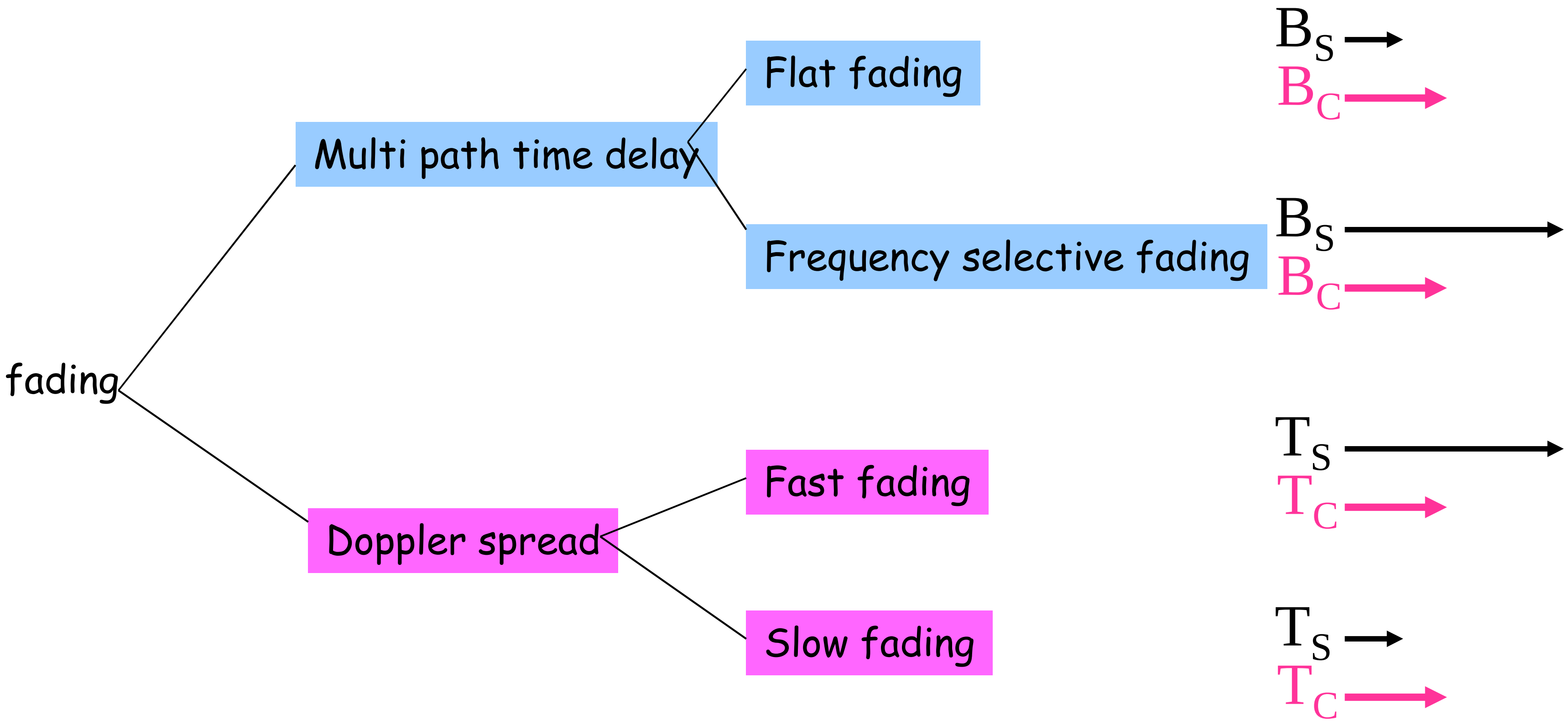
Effect of Doppler Shift

- 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) Tc
  - Represent the time duration that channel is stable
  - If symbol time is smaller than Tc, it is called slow fading. Otherwise it is fast fading.

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



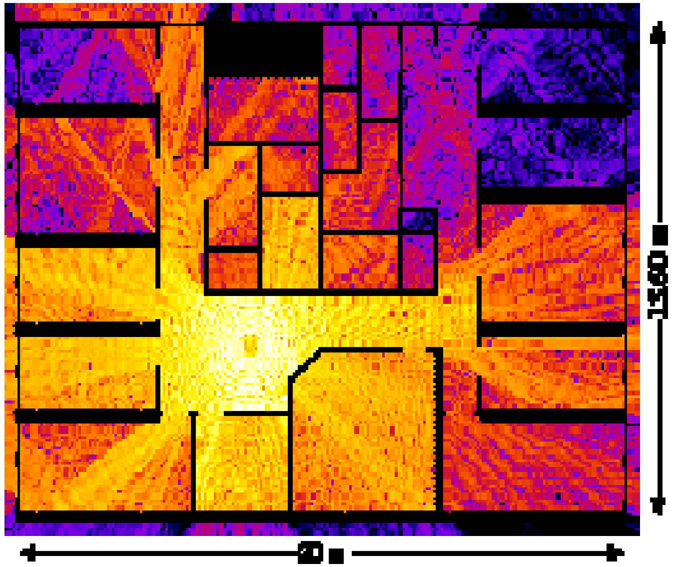
Summary of radio propagation and mitigations

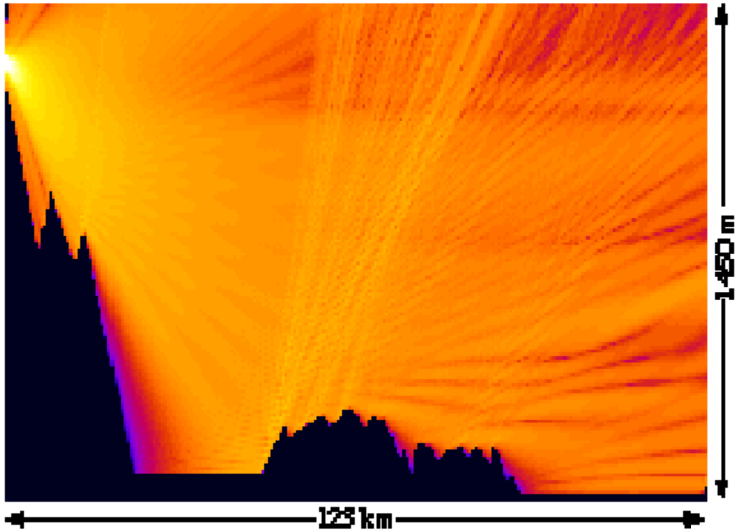
- Shadowing
  - Problem: received signal strength
  - Mitigation:
    - increase transmit power
    - Reduce cell size
- Fast fading
  - Problem: error rate (BER, FER, PER)
  - Mitigation:
    - Interleaving
    - Error correction coding
    - Frequency hopping
    - Diversity techniques
- Delay spread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

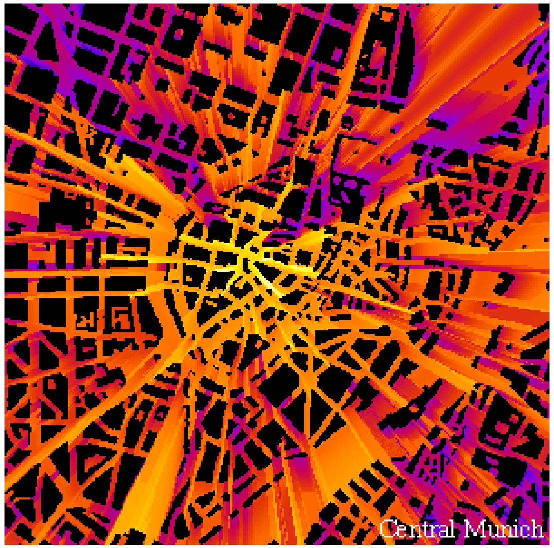
How to create propagation models?

- 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

Real world example







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