CEG5103 - Wireless and Sensor Networks for IoT
EE5023 - Wireless Networks

Assoc Prof Tham Chen Khong (CK Tham)
E-mail: eletck@nus.edu.sg

Scope

- Part I – Wireless Networks
  - Wireless channel characteristics
  - Medium Access Control (MAC) techniques
  - Routing protocols and Ad-Hoc Networks
  - TCP over Wireless Networks
  - Wireless Mesh Networks
- Part II – Wireless Sensor Networks
  - Recent Advances: Internet of Things (IoT)
  - Collaborative Signal Processing and Data Fusion
  - Energy models for sensor networks
  - Low Energy Routing protocols for sensor networks
  - Sensor Selection and Tracking
  - Case Studies: Anomaly Detection, Vehicular Sensor Networks
- 2 Assignments corresponding to Parts I and II of the module
- Mid-Term Test (24 Feb 2023, 6pm), Exam (29 April 2023, 9am)

CEG5103 / EE5023

Wireless Channel Characteristics

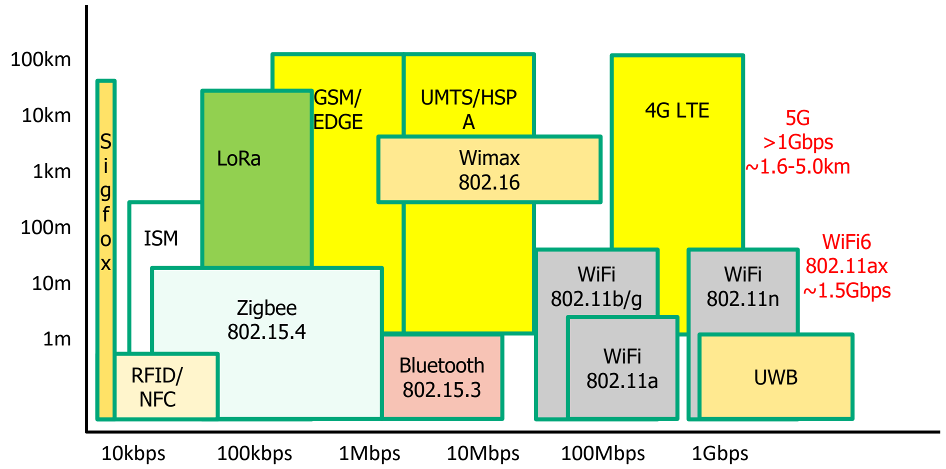
Lecture 1

Reference book:
Wireless Communications: Principles and Practice (2nd Edition)
by Theodore S. Rappaport (Prentice Hall)

Wireless Comes of Age

- Guglielmo Marconi invented wireless telegraph in 1896
  - Communication by encoding alphanumeric characters in analog signal
  - Sent telegraphic signals across the Atlantic Ocean
- Communications satellites launched in 1960s
- Advances in wireless technology
  - Radio, television, mobile telephone, communication satellites
- More recently
  - Satellite communications
  - Mobile cellular networks
  - Wireless Local Area Networks (LANs)
  - Personal Area Networks (PAN) & Body Area Networks (BAN)
  - Mobile ad hoc networks (MANET)
  - Wireless mesh networks
  - Wireless sensor networks
  - Vehicular networks

Types of Wireless Networks

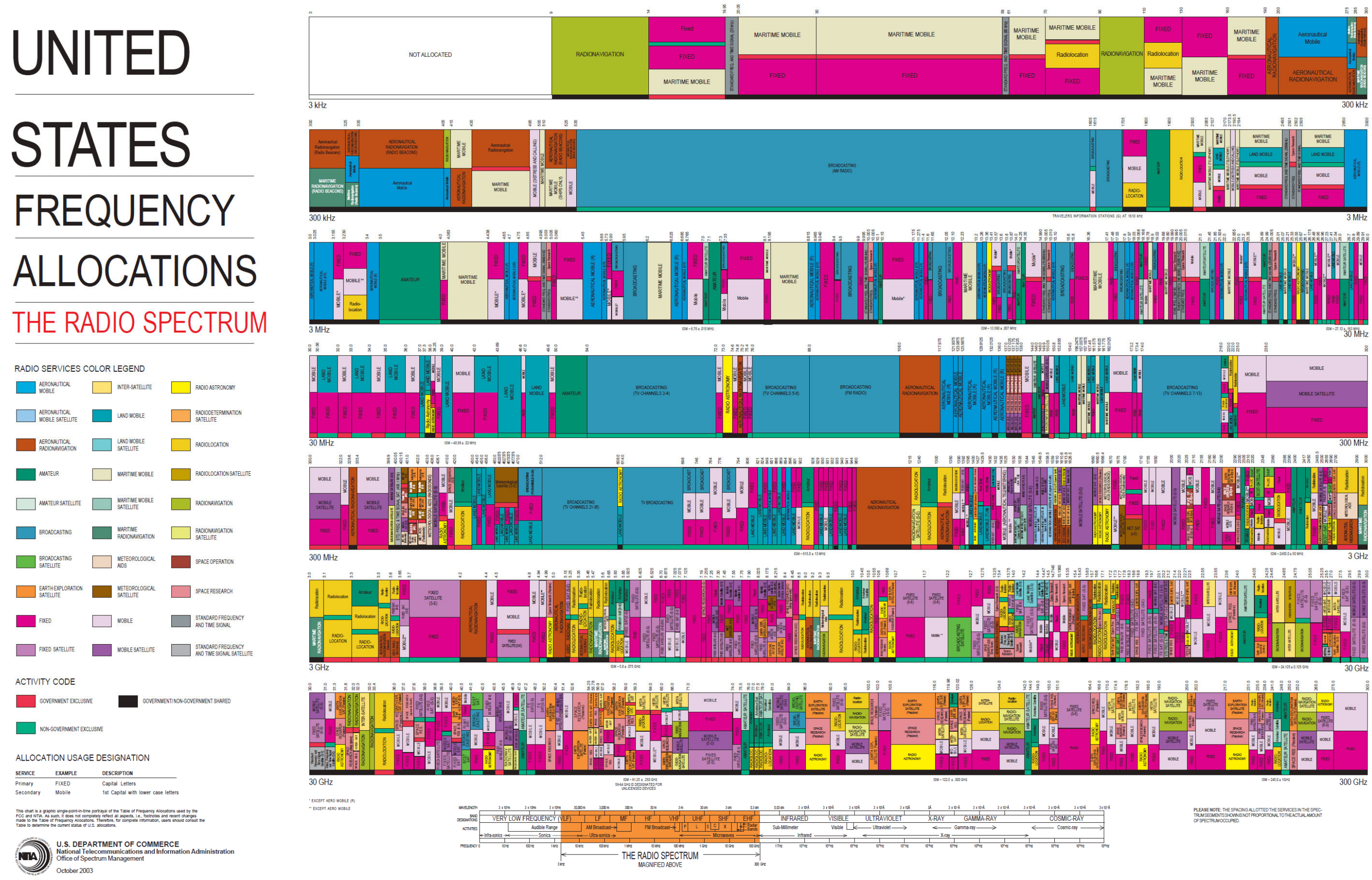


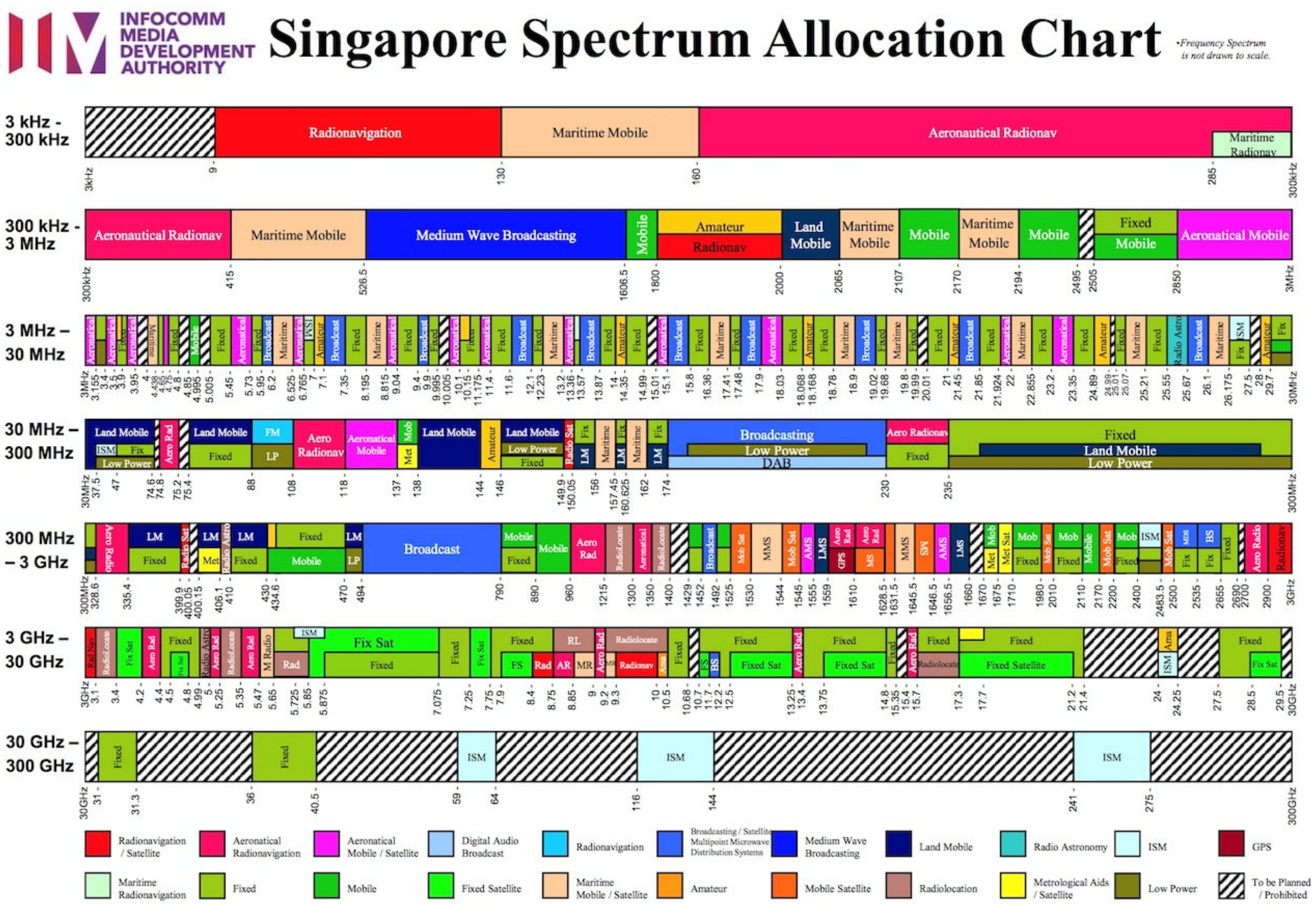
- Cellular Technologies
  - 2nd Generation : GSM
  - 3rd Generation: WCDMA
  - 4th Generation: LTE
  - 5th Generation
- Personal Area Networks (PANs)
  - Bluetooth (IEEE 802.15.3)
  - Zigbee (IEEE 802.15.4)
- Wireless LAN
  - IEEE 802.11 a/b/g/n/ac/ax
- Wireless Broadband
  - WiMAX (IEEE 802.16)
- Others
  - RFID
  - Ultra WideBand (UWB)
  - Sigfox
  - LoRa & LoRaWAN

Network Characteristics

	Wireless Network	Fixed (Wired) Network
Terminal-to-network channel	Unpredictable, time varying, poor at times	Constant, high quality
Transmission medium	Shared	Dedicated to 1 terminal
Privacy, security	Vulnerable: signals radiated in the air	Wiretapping requires special measures
Bandwidth allocation	Policy-based (radio spectrum) e.g. 4G, 5G	Technology-based and cost-based (e.g. optical fibre)
Network configuration	Frequent changes during calls, e.g. due to mobility	Rarely changes

Note: Cellular networks have better assured service levels


UNITED
STATES
FREQUENCY
ALLOCATIONS
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
ACTIVITY CODE
ALLOCATION USAGE DESIGNATION
3 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
THE RADIO SPECTRUM
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003


INFOCOMM MEDIA DEVELOPMENT AUTHORITY
Singapore Spectrum Allocation Chart
*Frequency Spectrum is not drawn to scale.
3 kHz - 300 kHz
Radionavigation
Maritime Mobile
Aeronautical Radionav
Maritime Radionav
300 kHz - 3 MHz
Aeronautical Radionav
Maritime Mobile
Medium Wave Broadcasting
Mobile
Amateur
Radionav
Land Mobile
Fixed
Aeronautical Mobile
3 MHz – 30 MHz
30 MHz – 300 MHz
Land Mobile
ISM
Fix
Low Power
Aero Rad
Fixed
FM
LP
Aero Radionav
Aeronautical Mobile
Mob
Met
Amateur
Radio Sat
LM
Maritime
Fix
Broadcasting
DAB
300 MHz – 3 GHz
Broadcast
Mobile
Aero Rad
MMS
GPS
ISM
3 GHz – 30 GHz
Fix Sat
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Rad
AR
MR
RL
Radiolocate
Radionav
Fixed Sat
Fixed Satellite
30 GHz – 300 GHz
Fixed
ISM
Radionavigation / Satellite
Aeronautical Radionavigation
Aeronautical Mobile / Satellite
Digital Audio Broadcast
Radionavigation
Broadcasting / Satellite Multipoint Microwave Distribution Systems
Medium Wave Broadcasting
Land Mobile
Radio Astronomy
ISM
GPS
Maritime Radionavigation
Fixed
Mobile
Fixed Satellite
Maritime Mobile / Satellite
Amateur
Mobile Satellite
Radiolocation
Metrological Aids / Satellite
Low Power
To be Planned / Prohibited

Radio Propagation - Factors

- Understanding of how radio propagates provide insights to challenges and limitations
- Factors that affect radio propagation:
  - *Antenna type and height*
  - Distance related signal attenuation ($\propto 1/d^2$)
  - Line-of-Sight vs Non-Line-of-Sight propagation
  - Shadowing
  - Multipath fading
  - Obstacles and corners
  - Size of coverage ($\propto$ transmitter power)
  - Frequency band
  - Signal bandwidth
  - Speed of mobility

Signal Attenuation

- Strength of signal falls off with distance over transmission medium
- Attenuation factors for unguided media:
  - Received signal must have sufficient strength so that circuitry in the receiver can interpret the signal
  - Signal must maintain a level sufficiently higher than noise to be received without error
  - Attenuation is greater at higher frequencies, causing distortion

I. Large Scale Path Loss

Signal Attenuation

dB(decibel): ratio of 2 power values on a log scale

- Average received signal power S is:

  $S = kr^{-a}$ assume transmit power = 1

  where

  k = constant (function of λ, antenna heights, antenna gains, effective areas, etc.)

  r = transmitter-receiver distance

  a = signal attenuation or path loss exponent

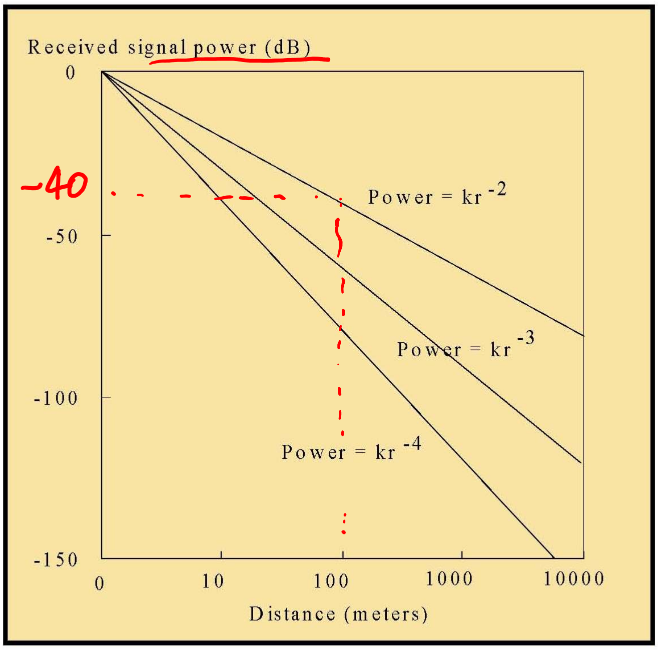
  Or in dB: $S_{dB} = 10 \log_{10} S$ dB $= 10\log_{10} k r^{-a}$

  $= 10[\cancel{\log k} - a \log r]$

  2   100

- Typical values of a:

a = 2	: free space
a = 3	: open country
a = 2.1-2.4	: urban, antenna ht 50-93 m
a = 2.5-3.8	: urban, antenna ht 10-50 m
a = 1.2-6.5	: indoor – hard partitioned
a = 1.6-1.8	: indoor – factory LOS
a = 1.9-2.8	: indoor – factory open
a = 2.4-3.8	: indoor – open plan
a = 4.2	: indoor – 1 floor separation
a = 5.0	: indoor – 2 floor separation
a = 3.0-6.2	: residential houses

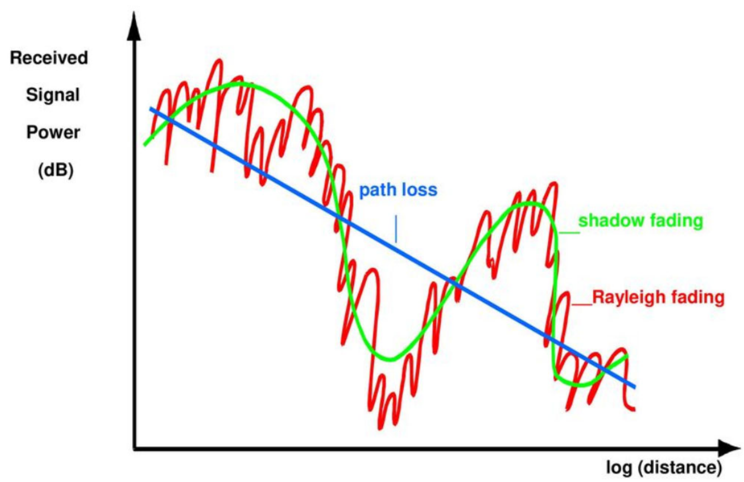


log-distance path loss model

Receive power = 0.0001 unit if original signal is 1 unit

Fading

- *Fading* is variation of the attenuation of a signal with various variables such as time, position and radio frequency.
- It is often modeled as a random process.



Shadow Fading / Shadowing

time-varying received signal

- Shadow fading is caused by the nature of the terrain and local geographical features, where the signal is blocked by natural obstacles.
- Each terminal i receives a signal of power T_i and the distribution of this signal power is Gaussian, i.e.

$$p(T_i) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(T_i - \bar{T})^2}{2\sigma^2} \right]$$

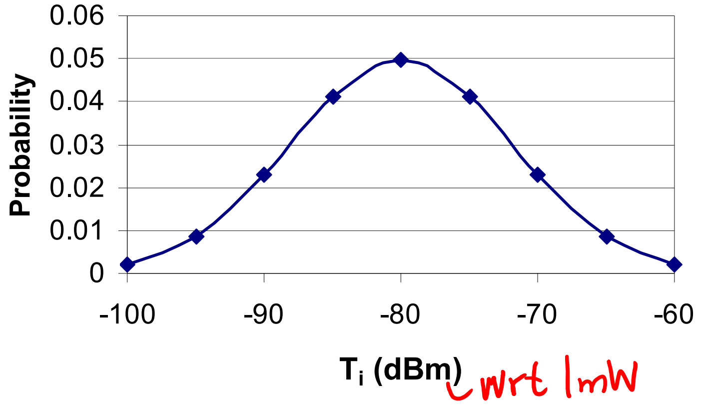
where $\bar{T}$ and σ are the mean and standard deviation of T_i, respectively.

- Typically σ is in the range of 6 to 12 dB. *note*: distance dependent mean and std dev have units in dB
- Variation of T_i with location is called ***Shadow fading /shadowing***

(same T-R separation) (log-normal shadowing)

e.g. 100m

log-normal distribution
(normal in dB)

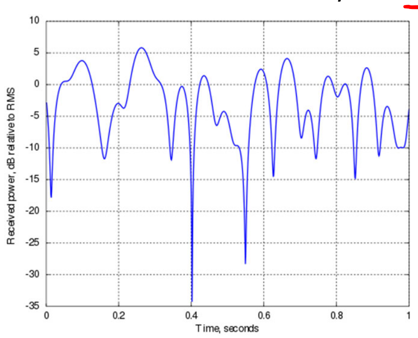


Power

wrt 1mW

II. Small-Scale Fading / Multipath Fading

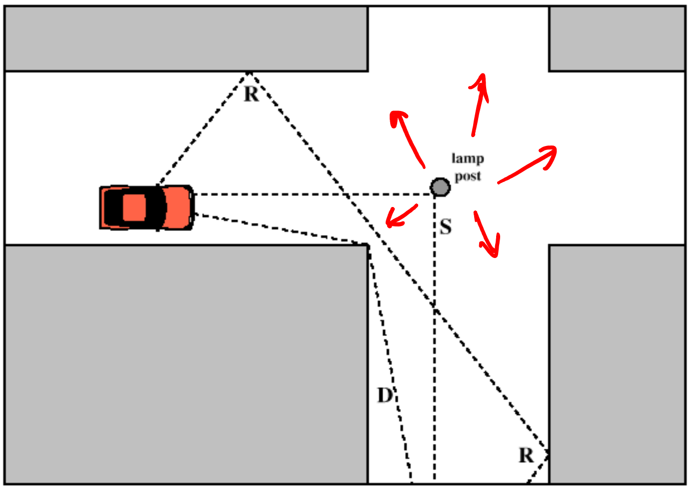
- Multipath fading
  - Line of Sight (LOS) or non-LOS
    - Rayleigh fading - when there is no dominant propagation along a line of sight (LOS) between the transmitter and receiver, i.e. non-LOS



    - Rician fading - when there is a dominant line of sight (LOS)
  - Fast fading, Slow fading (wrt symbol period)
  - Frequency-dependent fading: Flat fading, Frequency-Selective fading (wrt bandwidth of signal)

Multipath Propagation

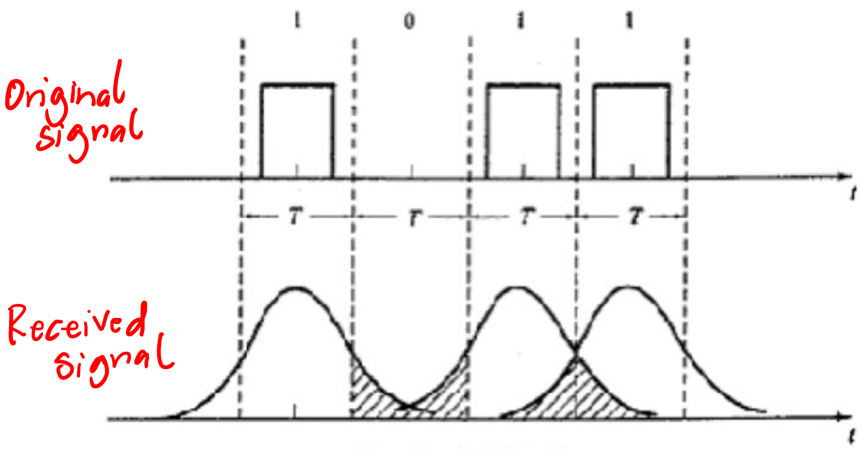
- 1 Reflection - occurs when signal encounters a surface that is large relative to the wavelength of the signal
- 2 Diffraction - occurs at the edge of an impenetrable body that is large compared to wavelength of the signal
- 3 Scattering – occurs when incoming signal hits an object whose size is in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



Sketch of 3 important propagation mechanisms:
- Reflection (R),
- Diffraction (D),
- Scattering (S)

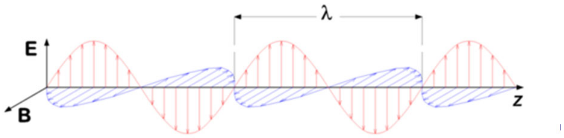
Effects of Multipath Propagation

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



Inter Symbol Interference.

Multipath Fading



- Consider vertically polarised transmission & vertical component of EM field E_z. Suppose ***no strong LOS path*** between transmitter and receiver, i.e. ***receiver receives many scattered or reflected waves*** from all directions.
- Consider 1 ray, $\cos\omega_c t$, arriving at angle θ w.r.t. direction of motion. Received ray is:

$$
\begin{aligned}
e(t) &= C\cos(\omega_c t + \omega_\theta t + \psi) \\
&= C\cos(\omega_\theta t + \psi)\cos\omega_c t - C\sin(\omega_\theta t + \psi)\sin\omega_c t \\
&= x(t)\cos\omega_c t + y(t)\sin\omega_c t
\end{aligned}
$$

where: $f_\theta = f_d \cos\theta$ = Doppler shift due to mobile antenna movement

$\omega_\theta = 2\pi f_d \cos\theta$

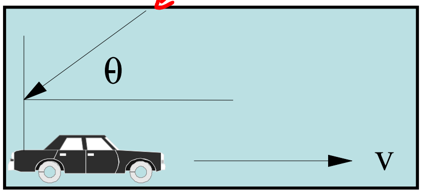
f_d = ***maximum Doppler shift (freq)*** = v/λ

λ = wavelength of carrier = c/f_c

f_c = carrier frequency

c = speed of light (3 x 10^8 m/s)

ψ = path delay → phase



e.g. if v = 100 km/h (27.8 m/s) & f_c = 850 MHz, then $f_d = v/\lambda = v.f_c/c$ = 78.7 Hz

Multipath Fading (cont.)

- Next, consider N rays arriving at different θ's. All the rays add to give:

$$
\begin{aligned}
E_z(t) &= \sum_{n=1}^{N} C_n\cos(\omega_n t + \psi_n)\cos\omega_c t - \sum_{n=1}^{N} C_n\sin(\omega_n t + \psi_n)\sin\omega_c t \\
&= A_c(t)\cos\omega_c t - A_s(t)\sin\omega_c t \\
&= r(t)\cos[\omega_c t + \phi(t)]
\end{aligned}
$$

where $\omega_n = 2\pi f_d \cos\theta_n$ is the Doppler shift of the n^{th} ray

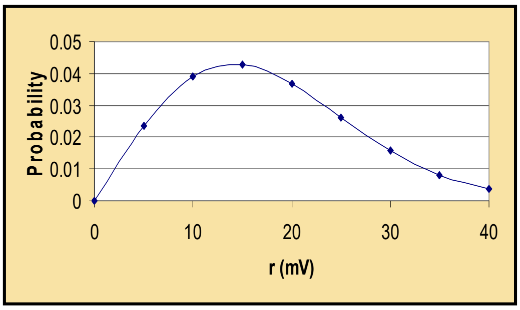
- As the sum of many independent terms, $A_c(t)$ and $A_s(t)$ have Gaussian distributions [***Central Limit Theorem***], with zero mean and variance

$$\sigma^2 = E\{A_c^2(t)\} = E\{A_s^2(t)\} = \sum_{n=1}^{N} C_n^2 / N$$

- The received envelope* $r(t) = [A_c^2(t) + A_s^2(t)]^{1/2}$, has a ***Rayleigh distribution***:

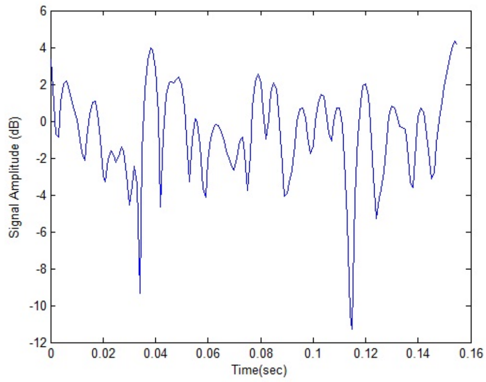
$$p(r) = \frac{r}{\sigma^2}\exp\left[-\frac{r^2}{2\sigma^2}\right]$$

*received signal amplitude



Multipath Fading (cont.)

- Mean: $\bar{r} = E[r] = \int_0^\infty r p(r) dr = 1.2533\sigma$
- Mean square: $E[r^2] = E\{A_c^2(t)\} + E\{A_s^2(t)\} = \int_0^\infty r^2 p(r) dr = 2\sigma^2$
- Variance: $\sigma_r^2 = E[r^2] - (E[r])^2 = 0.4292\sigma^2$
- Phase $\phi(t)$ has a ***uniform distribution*** over range of $\pm\pi$.
- ***Fast fading*** occurs when many fades occur within a symbol duration, which is the time to send one symbol. For binary data, a symbol is just a bit.

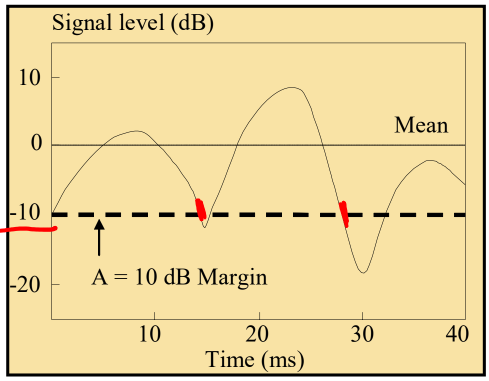


- ***Slow fading*** occurs when a fade occurs over several symbol durations.
- ***Diversity reception*** is a way to overcome fading adversities:
  - Space diversity
  - Time diversity
  - Frequency diversity
  - Code diversity

Rayleigh Fading – Level Crossing Rate

- The ***level crossing rate*** is the no. of times per second the signal envelope fades below the ***fade margin***, *A*. The level crossing rate is a 2nd-order statistic given by:

$$N_A = \int_0^\infty \dot{r} p(r = A, \dot{r}) d\dot{r} = \sqrt{2\pi} f_d \frac{A}{\sqrt{2}\sigma} \exp\left[-\frac{A^2}{2\sigma^2}\right]$$



where $\dot{r} = {}^{dr}/_{dt}$, and $p(r = A, \dot{r})$ is the joint distribution

$$p(r, \dot{r}) = \frac{r}{\sqrt{2\pi\upsilon^2}\sigma^2} \exp\left[-\frac{1}{2}\left(\frac{r^2}{\sigma^2} + \frac{\dot{r}^2}{\upsilon^2}\right)\right]$$

and υ^2 is the variance of the derivative of the quadrature components, i.e.

$$\upsilon^2 = E\{\dot{A}_c^2(t)\} = E\{\dot{A}_s^2(t)\} = 2\pi^2 f_d^2 \sigma^2$$

- The ***fade margin*** is the minimum received signal level for successful recovery of the information/message
- Suppose f_d = 10 and $A^2/(2\sigma^2)$ = 0.1, then N_A = 7.17
- Suppose f_d = 10 and $A^2/(2\sigma^2)$ = 0.01, then N_A = 2.48

normalized fade margin

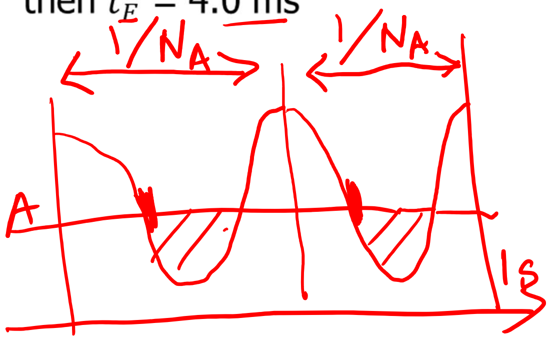
Rayleigh Fading – Ave. Fade Duration

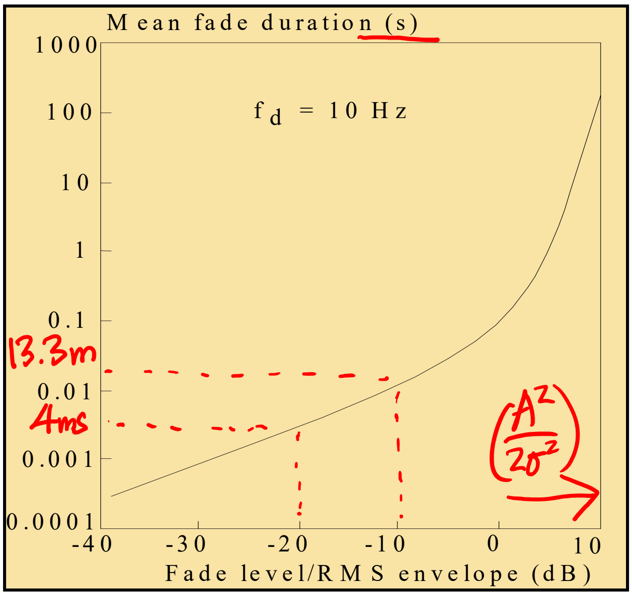
Bad!

- Average fade duration in seconds (time that envelop is < A) is:

$$\bar{t}_F = \frac{P(r \le A)}{N_A} = \frac{1}{\sqrt{2\pi} f_d} \frac{\sqrt{2}\sigma}{A}\left[\exp\left(\frac{A^2}{2\sigma^2}\right) - 1\right]$$

- Suppose f_d = 10 and $A^2/(2\sigma^2)$ = 0.1, then $\bar{t}_F$ = 13.3 ms
- Suppose f_d = 10 and $A^2/(2\sigma^2)$ = 0.01, then $\bar{t}_F$ = 4.0 ms





Rayleigh Fading – Inter-fade Duration

Good!

- Ave. inter-fade duration in seconds (time that envelope is > A) is:

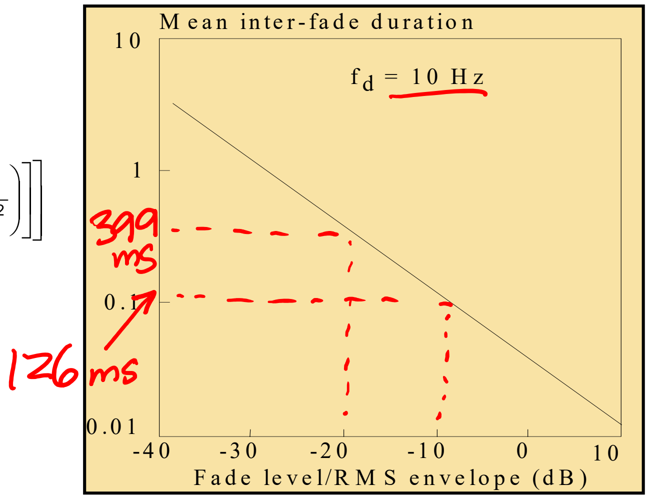
$$\bar{t}_{IF} = \frac{1}{N_A} - \bar{t}_F = \frac{1}{N_A} - \frac{P(r \le A)}{N_A}$$

$$= \frac{1}{N_A}\left[1 - P(r \le A)\right]$$

$$= \frac{1}{\sqrt{2\pi} f_d \frac{A}{\sqrt{2}\sigma} \exp\left(-\frac{A^2}{2\sigma^2}\right)}\left[1 - \left[1 - \exp\left(-\frac{A^2}{2\sigma^2}\right)\right]\right]$$

$$= \frac{1}{\sqrt{2\pi} f_d} \frac{\sqrt{2}\sigma}{A}$$

where $P(r \le A)$ is the prob. that the envelope $r \le A$, is:



$$P(r \le A) = \int_0^A p(r)dr = \int_0^A \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right)dr = 1 - \exp\left(-\frac{A^2}{2\sigma^2}\right)$$

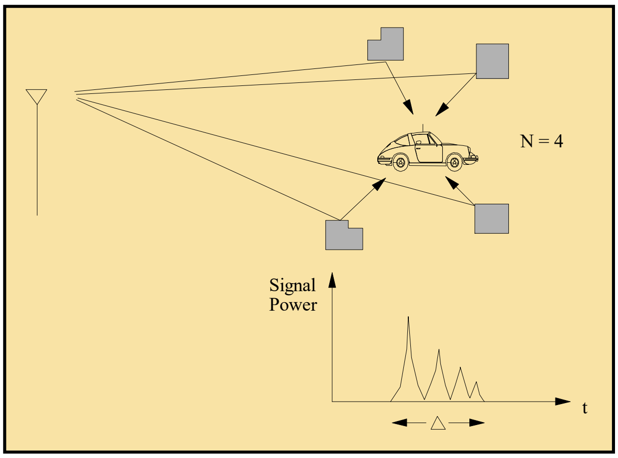
- Suppose f_d = 10 and $A^2/(2\sigma^2)$ = 0.1, then = 126 ms
- Suppose f_d = 10 and $A^2/(2\sigma^2)$ = 0.01, then = 399 ms

Delay Spread

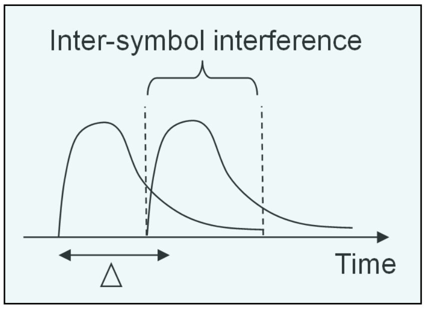
- ***Delay spread*** occurs when the base station transmits a signal, say, an impulse $s_0(t) = a_0\delta(t)$, and because of multipath scattering, many delayed versions of the scattered signals are received.
- The received impulse signal is:

$$s(t) = a_0 \sum_{i=1}^{n} a_i \delta(t - \tau_i) \cdot e^{j\omega t} = E(t) e^{j\omega t}$$

where n = no. of paths, a_i = attenuation of the i^{th} path; and τ_i = delay.



- As no. of scatterers increases, discrete impulses merge into a continuous pulse of length Δ, commonly known as the delay spread.
- Delay spread limits data rate to below 1/Δ to avoid ***inter-symbol interference***, beyond which special measures are required to overcome data error.



Delay Spread (cont.)

- Mean delay spread is: $\bar{\tau} = \int_0^{\infty} tE(t)dt$
- Delay spread variance is: $\sigma_\tau^2 = \int_0^{\infty} t^2 E(t)dt - (\bar{\tau})^2$

Note: Mean delay spread in urban environment generally higher because of scattering effects arising from building surfaces causing rays to decay more slowly.

Parameter	Urban	Suburban
Mean delay spread, $\bar{\tau}$	1.5 - 2.5 μs	0.1 - 2.0 μs
Corresponding path length	450 - 750 m	30 - 600 m
Maximum delay time (-30 dB)	5.0 - 12.0 μs	0.3 - 7.0 μs
Corresponding path length	1.5 - 3.6 km	0.9 - 2.1 km
Range of delay spread, Δ_i	1.0 - 3.0 μs	0.2 - 2.0 μs

Other Path Loss & Fading Models

- Several path loss models have been proposed for outdoor and indoor environments.
- Basically, follow the standard path loss model with modifications to include adjustment factors for:
  - Terrain
  - Type of environment (e.g. rural/urban)
  - Adjustment factors for the type of building materials and floors in the case of indoor environments.

- Other multi-path fading models (distribution of received signal amplitude):
  - Rician distribution: when strong Line of Sight (LOS) is present
  - Nakagami (multiple random Rayleigh fading signals) etc.

Error Compensation Mechanisms

- To compensate for channel impairments
  - 1. Forward error correction
  - 2. Adaptive equalization
  - 3. Diversity techniques

1. Forward Error Correction

- Transmitter adds error-correcting code to data block
  - Code is a function of the data bits
- Receiver calculates error-correcting code from incoming data bits
  - If calculated code matches incoming code, no error occurred
  - If error-correcting codes do not match, receiver attempts to determine bits in error and correct

2. Adaptive Equalization

- Adapts filter coefficients in response to time-varying communications channel
- Can be applied to transmissions that carry analog or digital information
  - Analog voice or video
  - Digital data, digitized voice or video
- Used to combat inter-symbol interference
- Involves gathering dispersed symbol energy back into its original time interval
- Techniques
  - Lumped analog circuits
  - Sophisticated digital signal processing algorithms

3. Diversity Techniques

- Diversity is based on the fact that individual channels experience independent fading events
- Types of diversity techniques:
  - a — Space diversity – techniques involving physical transmission path, e.g. multiple antennas (MIMO is an example of this)
  - b — Frequency diversity – techniques where the signal is spread out over a larger frequency bandwidth, or carried on multiple frequency carriers, e.g. spread spectrum and OFDM (Orthogonal Frequency Division Multiplexing)
  - c — Time diversity – techniques aimed at spreading the data out over time
  - d — Code diversity – e.g. CDMA (Code Division Multiple Access)

    Spread spectrum

Signal-to-Noise Ratio (per bit) Normalized SNR

- Ratio of signal energy per bit (E_b) to noise power density per Hertz (N_0):

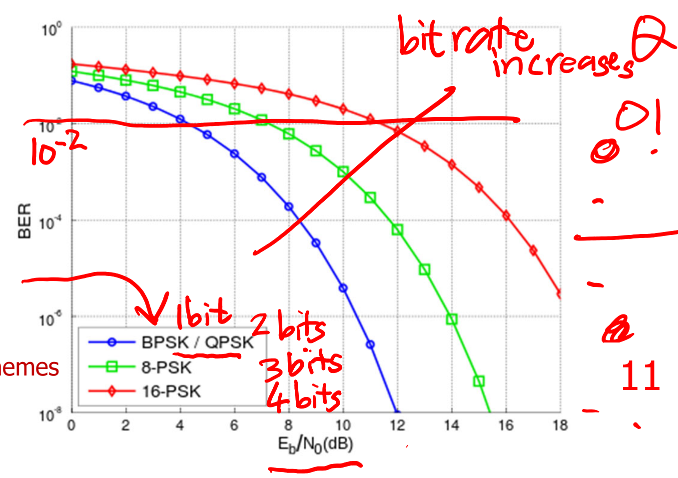
$$\frac{E_b}{N_0} = \frac{S/R}{N_0}$$

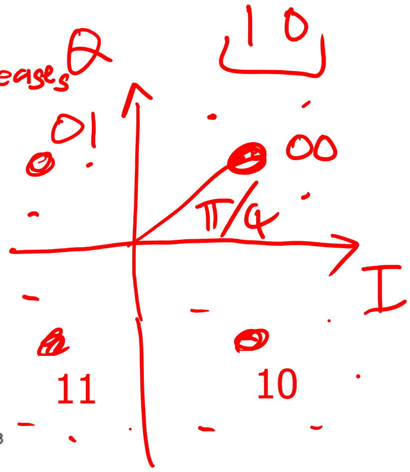
- Bit Error Rate (BER) for digital data transmission is a function of E_b/N_0
  - as bit rate R increases, transmitted signal power S must increase to maintain required E_b/N_0

Worse

better

phase





different modulation schemes

Other Impairments

- Atmospheric absorption – water vapor and oxygen contribute to attenuation
- Refraction – bending of radio waves as they propagate through the atmosphere
- Adjacent channel interference – disturbances from radio signals at adjacent frequency channels
- RF frontends – quality of RF electronics and antenna design
- Thermal noise – in electronic devices and transmission media

The End

Questions?