EE5132 - Wireless and Sensor Networks
EE5023 - Wireless Networks

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(Part I based on slides by Prof Lawrence Wong, ECE)

Scope

- Part I – Wireless Network Systems
  - Wireless channel characteristics
  - Medium Access Control (MAC) techniques
  - Routing protocols and wireless ad-hoc networks
  - TCP over wireless networks
  - Wireless mesh networks
- Part II – Wireless Sensor Networks
  - Recent Advances: Internet of Things (IoT)
  - Energy models for sensor networks
  - Routing protocols for sensor networks
  - Collaborative Signal Processing and Data Fusion
  - Collaborative Signal & Information Processing and Tracking
- 2 Assignments corresponding to Parts I and II of the module

Wireless Channel Characteristics

Chapter 1

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

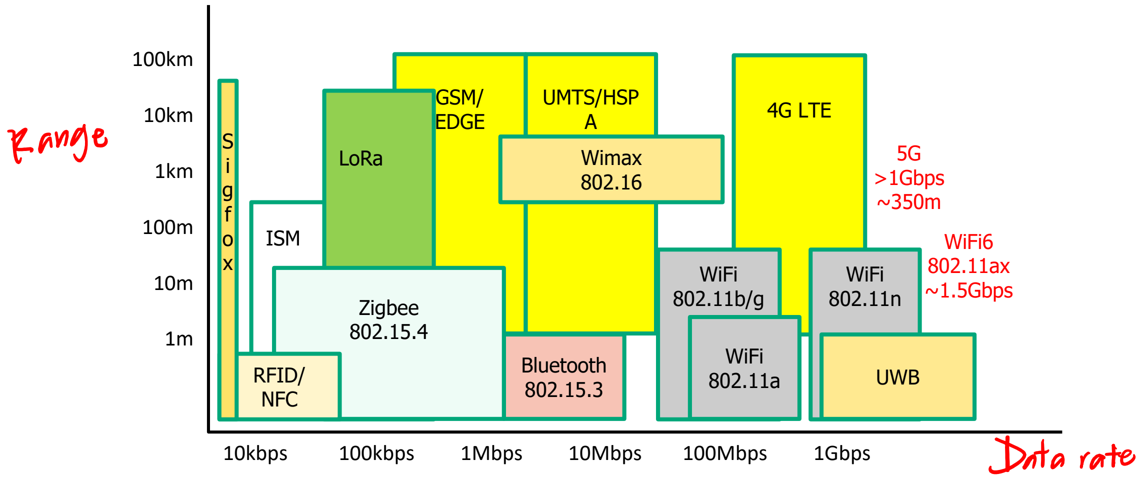
Wireless Comes of Age

- Guglielmo Marconi invented wireless telegraph in 1896
  - Communication by encoding alphanumeric characters in analog signal
  - Sent telegraphic signals across the Atlantic Ocean

Titanic

- 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

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 enough power
  - Attenuation is greater at higher frequencies, causing distortion

I. Large Scale Path Loss Signal Attenuation

①

- 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

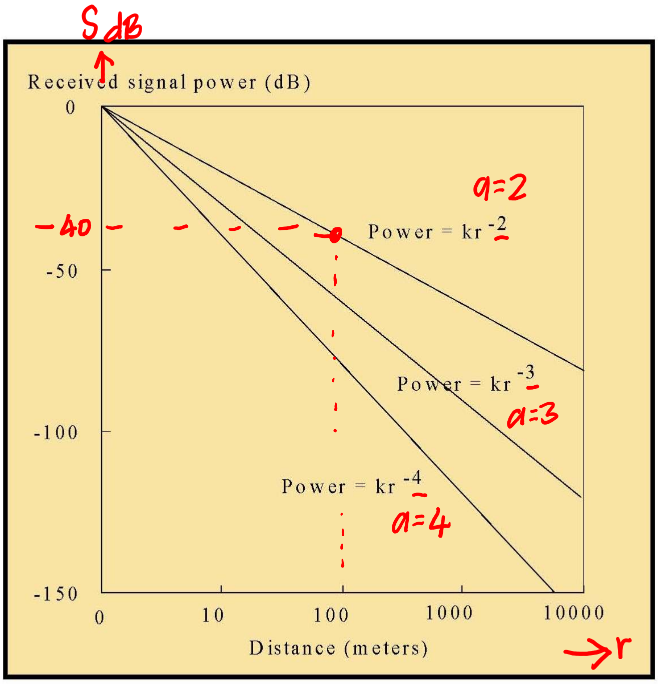
  a = signal attenuation or path loss factor

  Or in dB: $S_{dB} = 10 \log_{10} S$ dB $= 10 \log kr^{-a}$ $= 10[\cancel{\log k} - a \log r]$

  2 100

- Typical values of a:

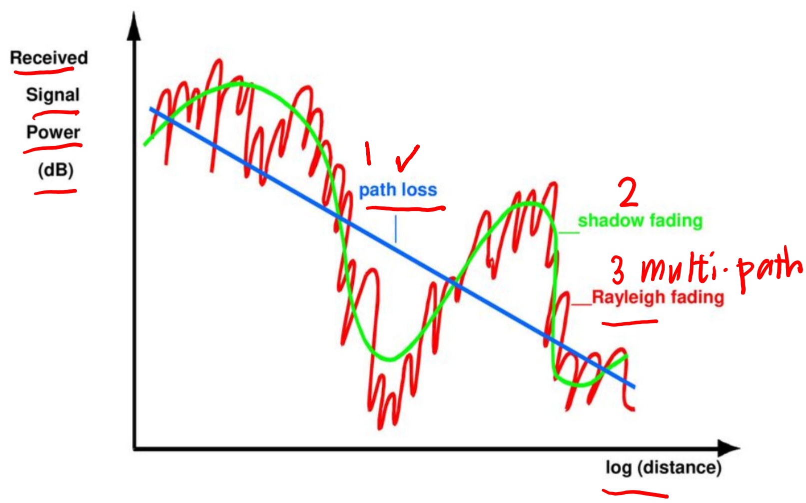
a = 2	: free space
a = 3	: open country
a = 2.1-2.4	: urban, antenna ht 50-93 m
a = 2.5-3.8	: urban, antenna ht 10-50 m
a = 1.2-6.5	: indoor – hard partitioned
a = 1.6-1.8	: indoor – factory LOS
a = 1.9-2.8	: indoor – factory open
a = 2.4-3.8	: indoor – open plan
a = 4.2	: indoor – 1 floor separation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



received signal is 0.0001 if original signal is 1 (power)

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

2

→time-varying received signal

- Shadowing 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.

distribution

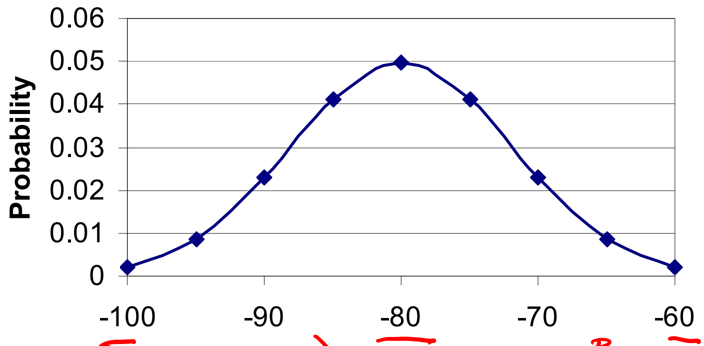
$$p(T_i) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(T_i - \bar{T})^2}{2\sigma^2}\right]$$

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.

log-normal shadowing

- Variation of T_i ~~with location~~ is called ***shadowing***

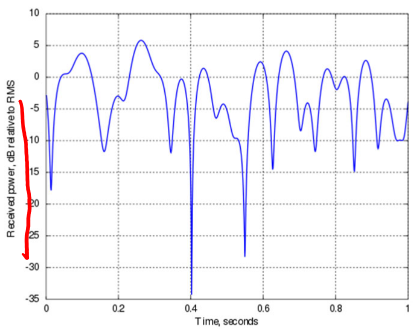


(at a certain distance) $10 \log \frac{P_r}{1\,mW}$

II. Small-Scale Fading / Multipath Fading

3

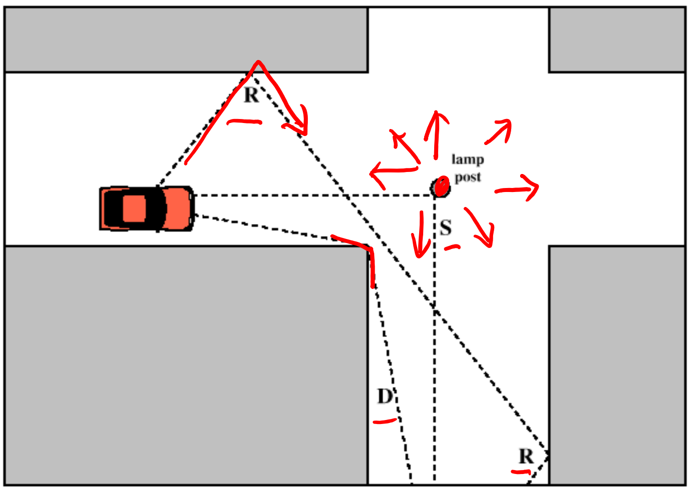
- Multipath fading
  - Line of Sight (LOS) or non-LOS
    - (i) Rayleigh fading - when there is no dominant propagation along a line of sight (LOS) between the transmitter and receiver, i.e. non-LOS



    - (ii) 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

- 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 the signal
- Scattering – occurs when incoming signal hits an object whose size is in the order of the wavelength of the signal or less



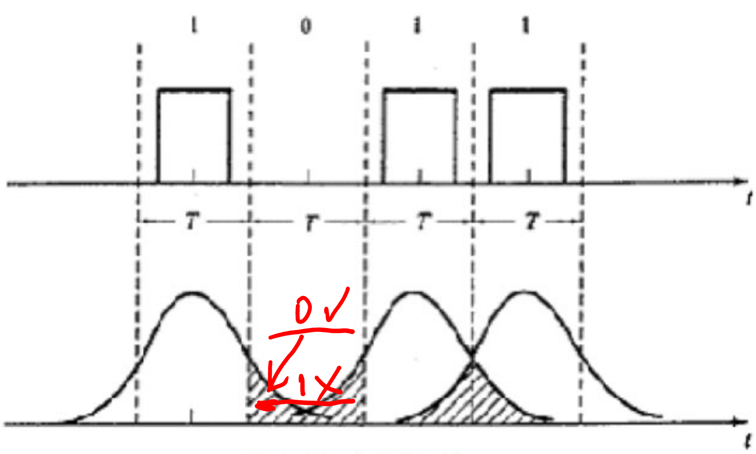
Sketch of 3 important propagation mechanisms:

- Reflection (R),
- Diffraction (D),
- Scattering (S)

o Receiver

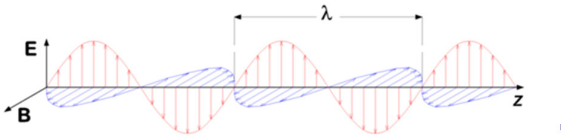
Effects of Multipath Propagation

- 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:

$2\pi f_c$

Sum of cosines formula

amplitude

$$e(t) = C\cos(\omega_c t + \omega_\theta t + \psi)$$
$$= C\cos(\omega_\theta t + \psi)\cos\omega_c t - C\sin(\omega_\theta t + \psi)\sin\omega_c t$$
$$= x(t)\cos\omega_c t + y(t)\sin\omega_c t$$

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

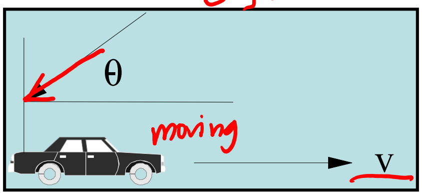
λ = wavelength of carrier = c/f_c

f_c = carrier frequency

c = speed of light (3×10^8 m/s)

psi ψ = path delay phase change

Source



Receiver

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:

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

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

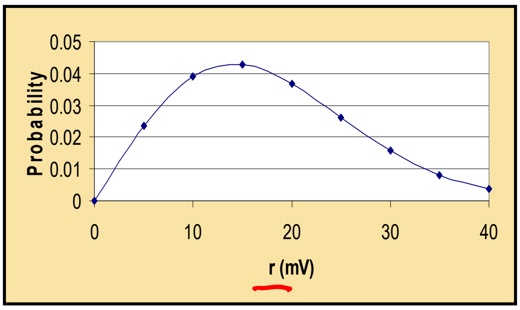
- As the sum of many independent terms, $A_c(t)$ and $A_s(t)$ have Gaussian distributions [***Central Limit Theorem***], with zero mean and variance

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

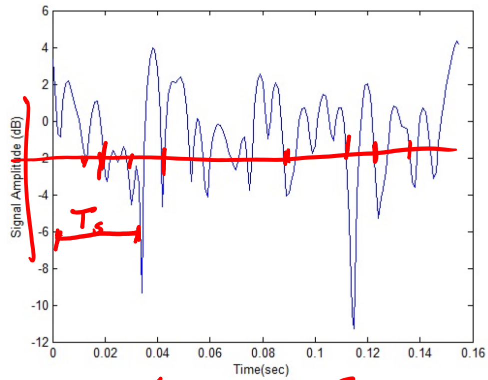
- The received envelope* $r(t) = [A_c^2(t) + A_s^2(t)]^{1/2}$, has a ***Rayleigh distribution***:

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

*received signal amplitude



Multipath Fading (cont.)

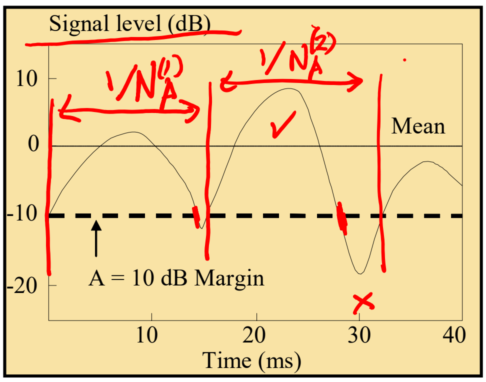


- Mean: $\bar{r} = E[r] = \int_0^\infty r p(r) dr = 1.2533\sigma$
- Mean square: $E[r^2] = E\{A_c^2(t)\} + E\{A_s^2(t)\} = \int_0^\infty r^2 p(r) dr = 2\sigma^2$
- Variance: $\sigma_r^2 = E[r^2] - (E[r])^2 = 0.4292\sigma^2$
- Phase $\phi(t)$ has a ***uniform distribution*** over range of $\pm\pi$.
- ***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. → BPSK QPSK ? bitrate
  symbol rate = bitrate
- ***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

CDMA

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:



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

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

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

(no need to worry abt this)

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

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

- 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 $N_A = 2.48$

normalised fade margin

Rayleigh Fading – Ave. Fade Duration

Bad!

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

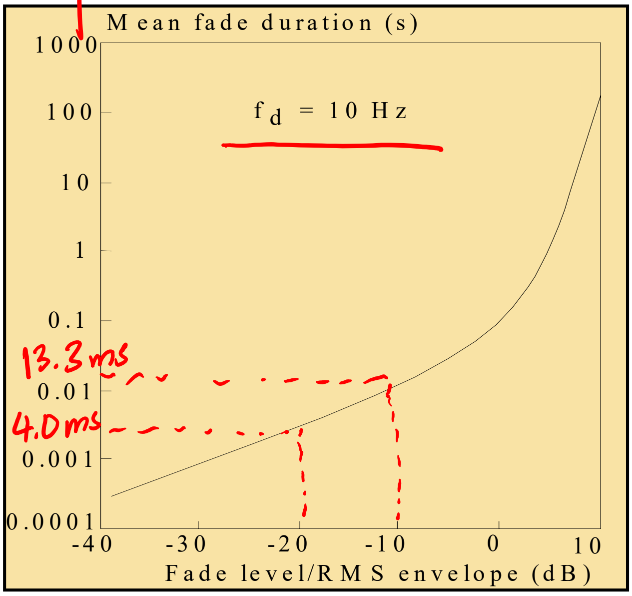
$N_A = 5$ crossings/sec

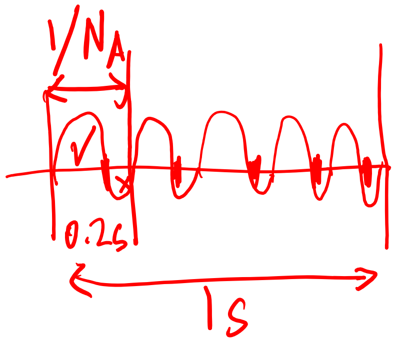
$1/N_A = 0.2s$

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

- 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

$\bar{t}_F$



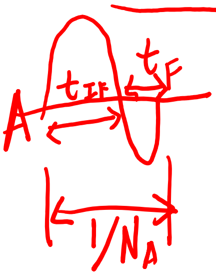


$\left(\frac{A^2}{2\sigma^2}\right) \rightarrow$

Rayleigh Fading – Inter-fade Duration

Good part

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

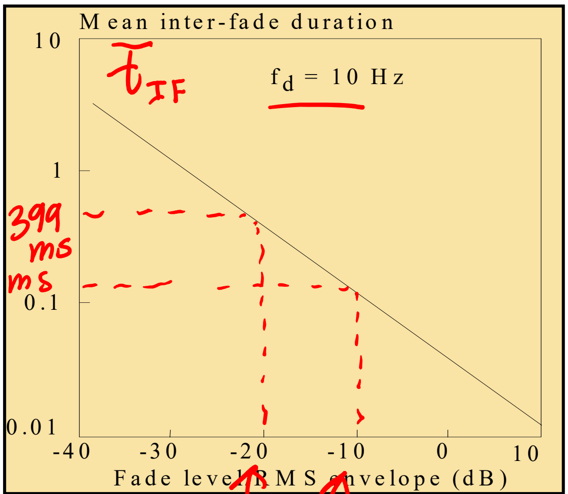


$$\bar{t}_{IF} = \frac{1}{N_A} - \bar{t}_F = \frac{1}{N_A} - \frac{P(r \le A)}{N_A}$$

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

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

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



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

$A^2/2\sigma^2$

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

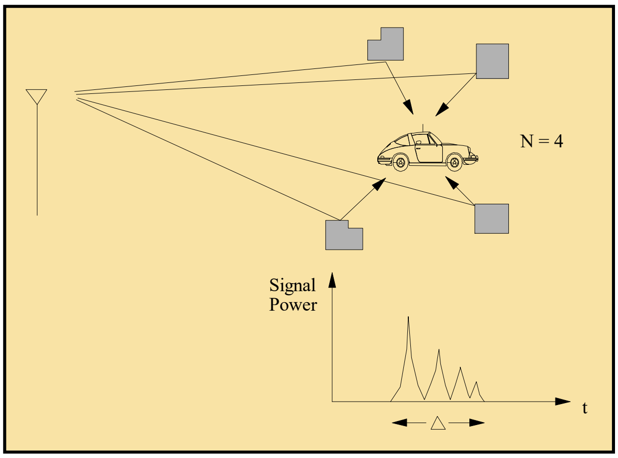
- Suppose $f_d = 10$ and $A^2/(2\sigma^2) = 0.1$, then = 126 ms
- Suppose $f_d = 10$ and $A^2/(2\sigma^2) = 0.01$, then = 399 ms

Delay Spread

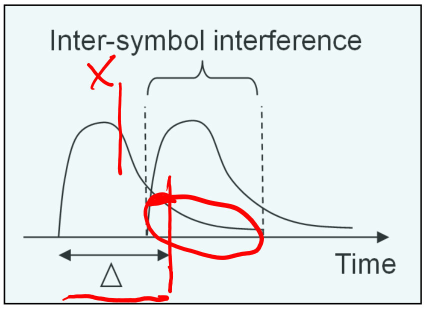
- ***Delay spread*** occurs when the base station transmits a signal, say, an impulse $s_0(t) = a_0\delta(t)$, and because of multipath scattering, many delayed versions of the scattered signals are received.
- The received impulse signal is:

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

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 $1/\Delta$ 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: $\sigma_\tau^2 = \int_0^\infty t^2E(t)dt - (\bar{\tau})^2$

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 etc.

multiple random Rayleigh fading signals

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:
  - Space diversity – techniques involving physical transmission path, e.g. multiple antennas (MIMO is an example of this)
  - 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)
  - Time diversity – techniques aimed at spreading the data out over time
  - Code diversity – e.g. CDMA (Code Division Multiple Access)

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

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

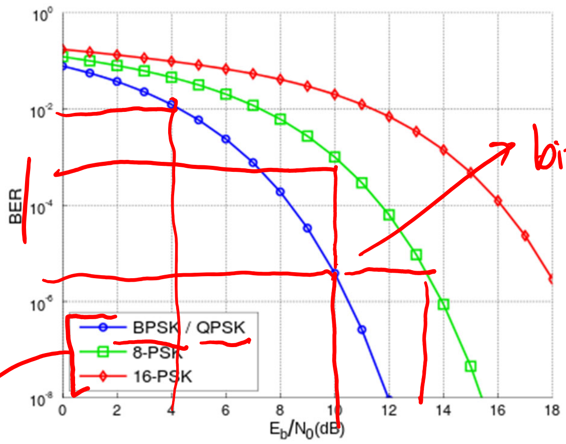
$$\boxed{\frac{E_b}{N_0}} = \frac{S/R}{N_0}$$

- 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

different modulation schemes



bitrate increasing

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?