

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

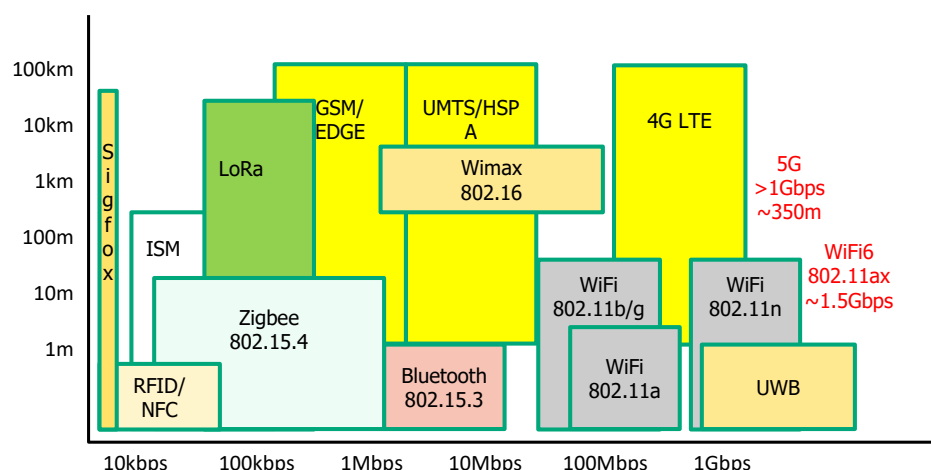
Reference book:

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
- 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





- 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

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	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

- 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

- 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

- Average received signal power S is:

$$S = kr^{-a}$$

where

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

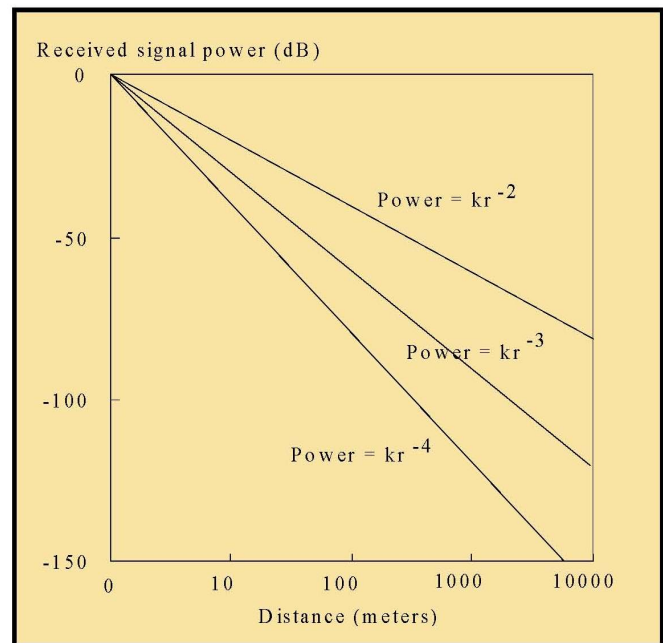
r = transmitter-receiver distance

a = signal attenuation or **path loss factor**

Or in dB: $S_{dB} = 10 \log_{10} S$ dB

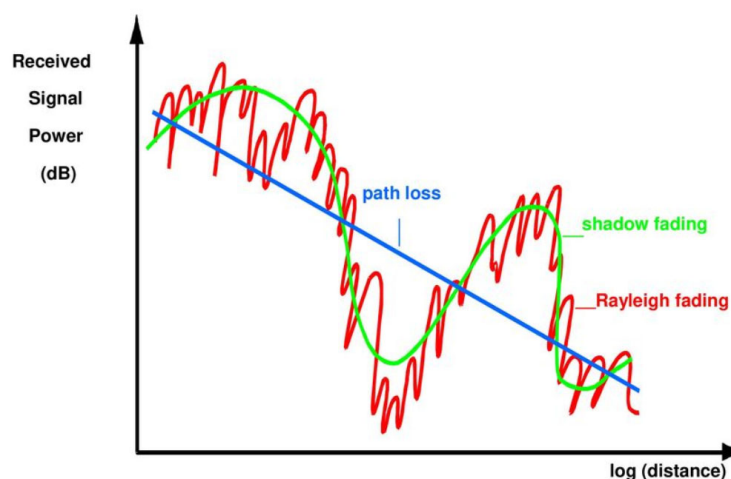
- Typical values of a :

$a = 2$: 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



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.



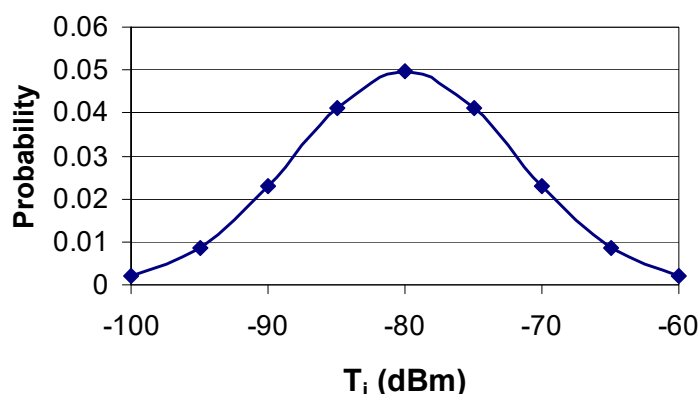
→time-varying received signal

- 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.

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

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

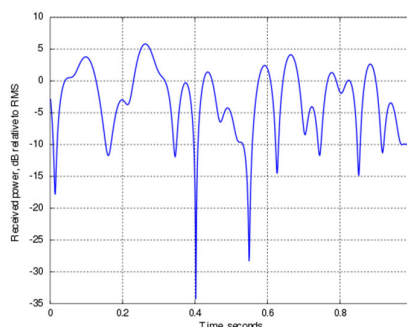


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II. Small-Scale Fading / Multipath Fading

- 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

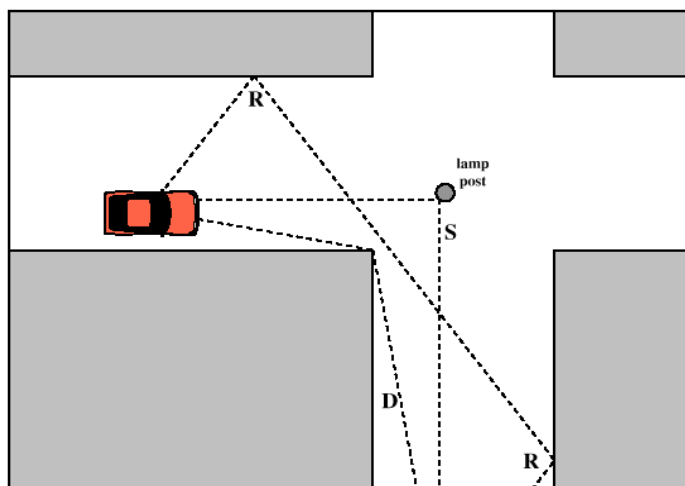


- Rician fading - when there is a dominant line of sight (LOS)
- Fast fading, Slow fading (wrt symbol period)
- Frequency-dependent fading: Flat fading, Frequency-Selective fading (wrt bandwidth of signal)

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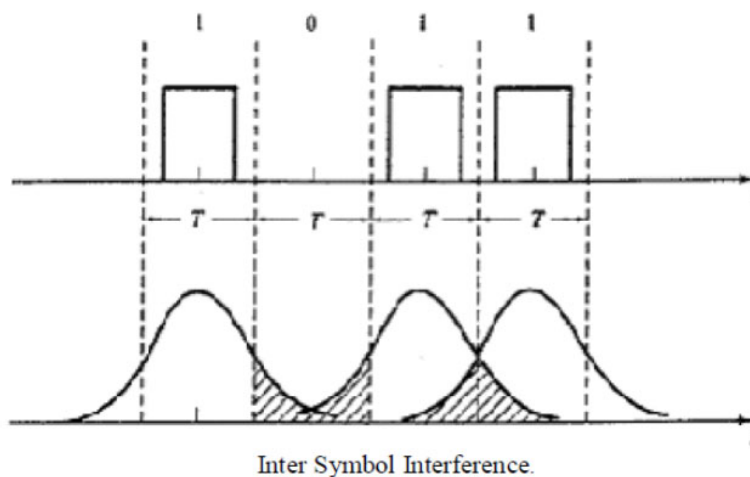
- Reflection - occurs when signal encounters a surface that is large relative to the wavelength of the signal
- Diffraction - occurs at the edge of an impenetrable body that is large compared to wavelength of the signal
- Scattering – occurs when incoming signal hits an object whose size is in the order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

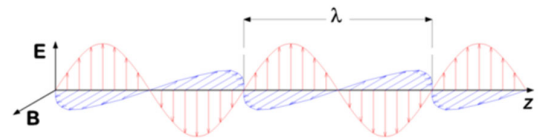


Sketch of 3 important propagation mechanisms:

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

- 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





- 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

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

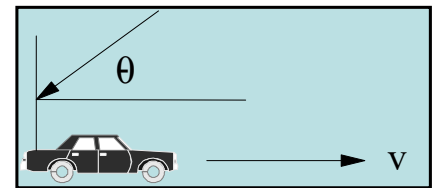
$$f_d = \text{maximum Doppler shift (freq)} = v/\lambda$$

$$\lambda = \text{wavelength of carrier} = c/f_c$$

$$f_c = \text{carrier frequency}$$

$$c = \text{speed of light (3 x 10}^8 \text{ m/s)}$$

$$\psi = \text{path delay}$$



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

- 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

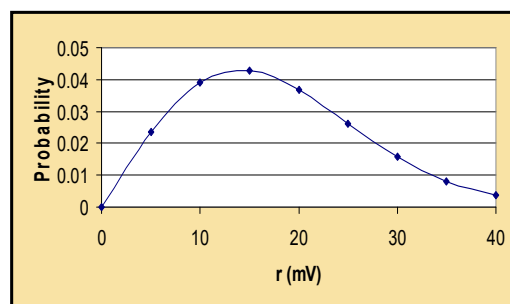
- As the sum of many independent terms, $A_c(t)$ and $A_s(t)$ have Gaussian distributions [**Central Limit Theorem**], with zero mean and variance

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

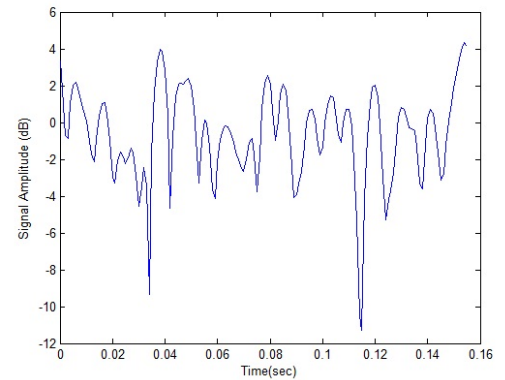
- The **received envelope*** $r(t) = [A_c^2(t) + A_s^2(t)]^{1/2}$, has a **Rayleigh distribution**:

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

*received signal amplitude



- Mean: $\bar{r} = E[r] = \int_0^\infty rp(r)dr = 1.2533\sigma$
- 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



- 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:

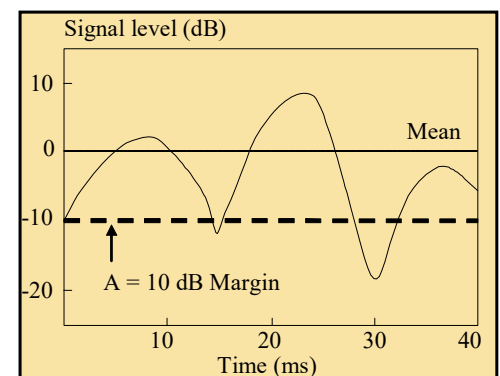
$$N_A = \int_0^\infty \dot{r} p(r = A, \dot{r}) d\dot{r} = \sqrt{2\pi} f_d \frac{A}{\sqrt{2}\sigma} \exp\left[-\frac{A^2}{2\sigma^2}\right]$$

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

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

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

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



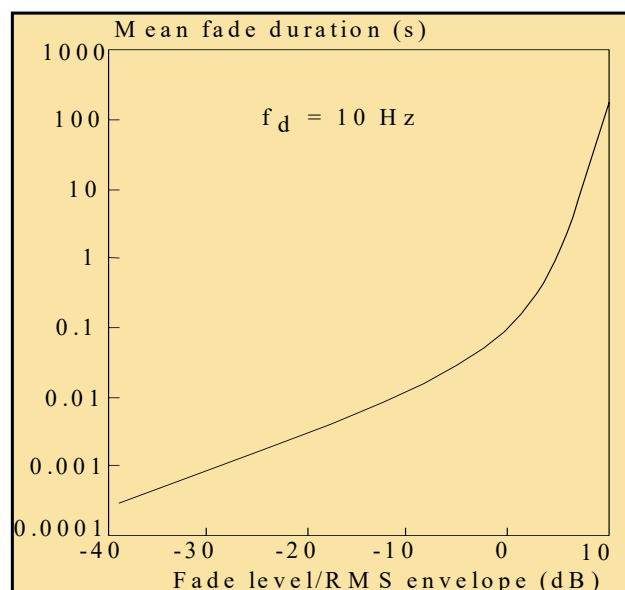
- The **fade margin** is the minimum received signal level for successful recovery of the information/message
- Suppose $f_d = 10$ and $A^2/(2\sigma^2) = 0.1$, then $N_A = 7.17$
- Suppose $f_d = 10$ and $A^2/(2\sigma^2) = 0.01$, then $N_A = 2.48$

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

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



- 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

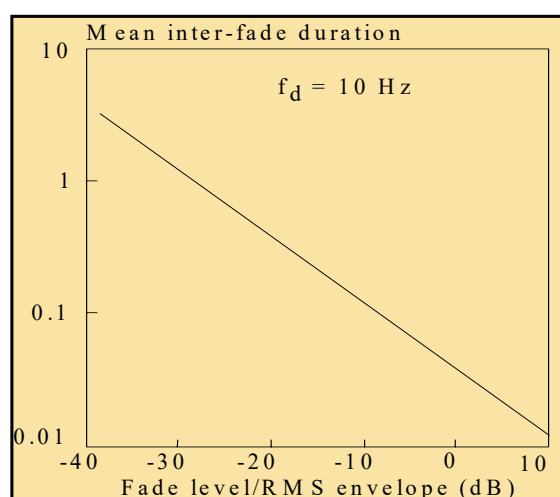


- Ave. inter-fade duration in seconds (time that envelope is $> A$) is:

$$\begin{aligned} \bar{t}_{IF} &= \frac{1}{N_A} - \bar{t}_F = \frac{1}{N_A} - \frac{P(r \leq A)}{N_A} \\ &= \frac{1}{N_A} [1 - P(r \leq A)] \\ &= \frac{1}{\sqrt{2\pi}f_d} \frac{A}{\sqrt{2}\sigma} \exp\left(-\frac{A^2}{2\sigma^2}\right) \left[1 - \left[1 - \exp\left(-\frac{A^2}{2\sigma^2}\right) \right] \right] \\ &= \frac{1}{\sqrt{2\pi}f_d} \frac{\sqrt{2}\sigma}{A} \end{aligned}$$

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

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



- 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

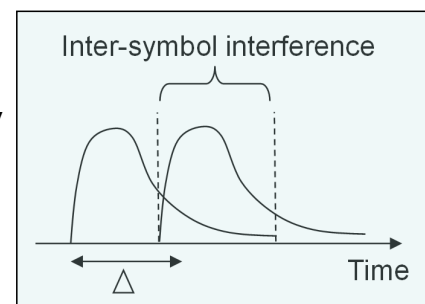
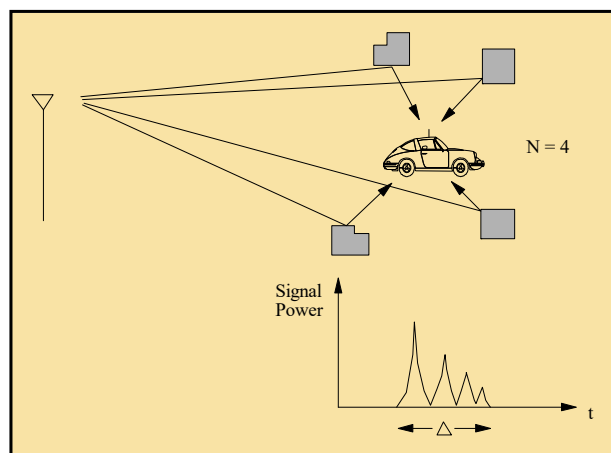
- **Delay spread** occurs when the base station transmits a signal, say, an impulse $s_0(t) = a_0\delta(t)$, and because of multipath scattering, many delayed versions of the scattered signals are received.

- 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.



- Mean delay spread is:

$$\bar{\tau} = \int_0^{\infty} t E(t) dt$$

- 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

- 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.

- 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

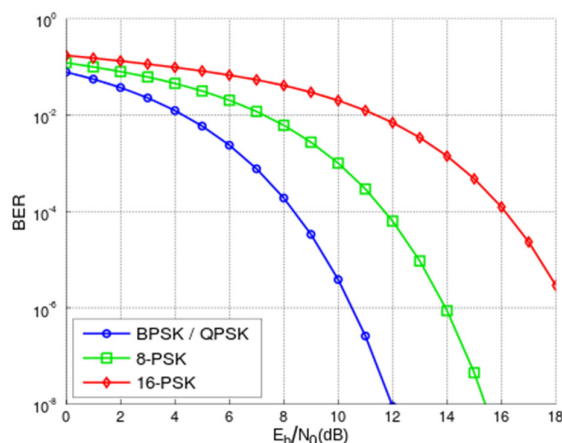
- Adapts filter coefficients in response to time-varying communications channel
- Can be applied to transmissions that carry analog or digital information
 - Analog voice or video
 - Digital data, digitized voice or video
- Used to combat inter-symbol interference
- Involves gathering dispersed symbol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

- 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)

- 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



- 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?