Wireless Communication Fundamentals

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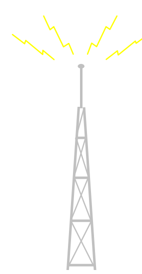
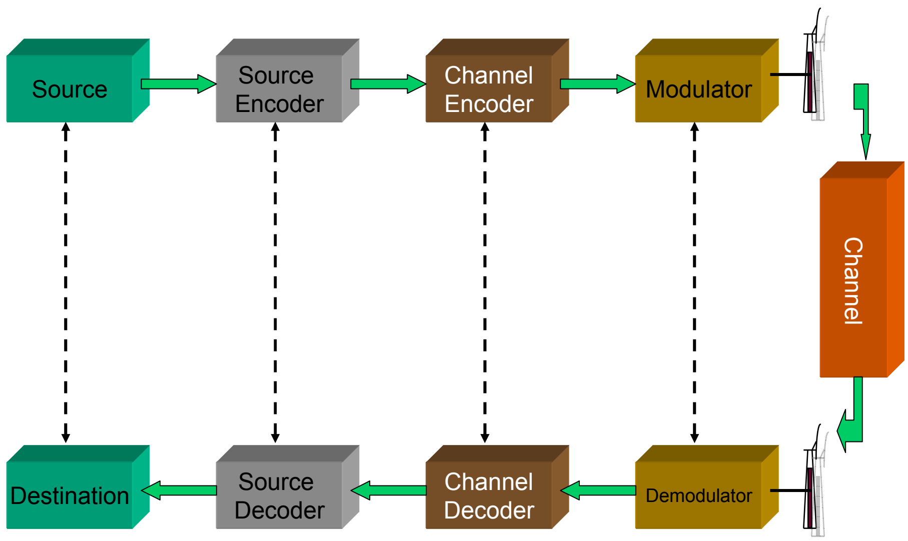
Telcom 2720
Slides 2
http://www.tele.pitt.edu/~dtipper/2720.html

Wireless Issues



- **Wireless link implications**
  - communications channel is the air
    - poor quality: fading, shadowing, weather, etc.
  - regulated by governments
    - frequency allocated, licensing, etc.
  - limited bandwidth
    - Low bit rate, frequency planning and reuse, interference
  - power limitations
    - Power levels regulated, must conserve mobile terminal battery life
  - security issues
    - wireless channel is a *broadcast* medium!
- Wireless link implications for communications
  - How to send signal?
  - How to clean up the signal in order to have good quality
  - How to deal with limited bandwidth?
    - Design network and increase capacity/share bandwidth in a cell

Typical Wireless Communication System



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Components of Communication system

- Source
  - Produces information for transmission (e.g., voice, keypad entry, etc.)
- Source encoder
  - Removes the redundancies and efficiently encodes the alphabet
  - Example: In English, you may encode the alphabet "e" with fewer bits than you would "q" using a vocoder
- Channel encoder
  - Adds redundant bits to the source bits to recover from any error that the *channel* may introduce
- Modulator
  - Converts the encoded bits into a *signal* suitable for transmission over the channel
- Antenna
  - A transducer for converting guided signals in a transmission line into electromagnetic radiation in an unbounded medium or vice versa
- Channel
  - Carries the signal, but will usually distort it
- Receiver – reverses the operations

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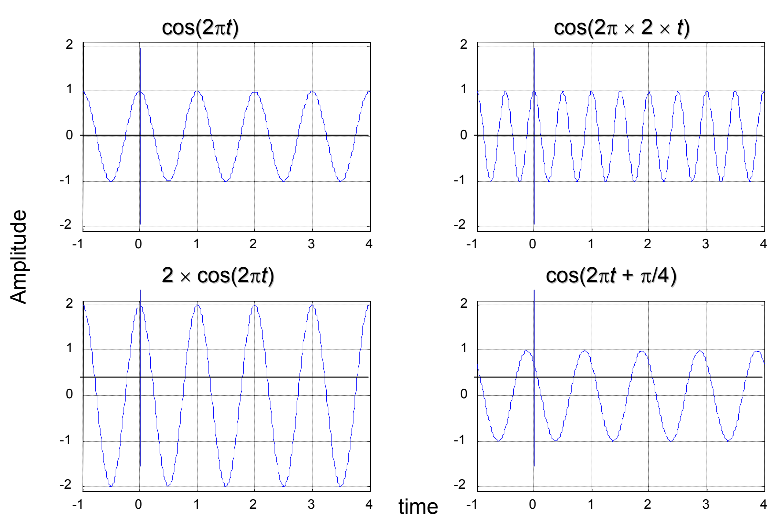
Signals

- Signal - physical representation of data
- Mathematically, a signal is represented as a function of time – or can be expressed as a function of frequency
- Any electromagnetic signal can be shown to consist of a collection of sinusoids at different amplitudes, frequencies, and phases
- General sine wave
  - $s(t) = A \cos(2\pi f t + \phi)$
- Next slide shows the effect of varying each of the three parameters
  - $A = 1$, $f = 1$ Hz, $\phi = 0 \Rightarrow T = 1$s
  - Increased peak amplitude; A=2
  - Increased frequency; $f = 2 \Rightarrow T = ½$
  - Phase shift; $\phi = \pi/4$ radians (45 degrees)
- Note: 2π radians = 360° = 1 period

The sinusoid – $A\cos(2\pi ft + \phi)$



Frequency-Domain Concepts

- Period (T) - amount of time it takes for one repetition of the signal $T = 1/frequency$
- Phase (ϕ) - measure of the relative position in time within a single period of the signal
- Wavelength (λ) - distance occupied by a single cycle of the signal
  - Or, the distance between two points of corresponding phase of two consecutive cycles
- For electromagnetic waves in air or free space,
  $\lambda = c/f$ where c is the speed of light = 3×10^8
- Spectrum - range of frequencies that a signal contains
- Absolute bandwidth - width of the spectrum of a signal
- Effective bandwidth (or just bandwidth) - narrow band of frequencies that most of the signal's energy is contained in

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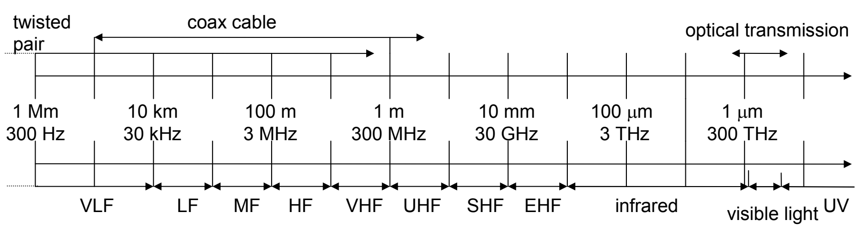
Frequencies for Communication



- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency
- UHF = Ultra High Frequency
- SHF = Super High Frequency
- EHF = Extra High Frequency
- UV = Ultraviolet Light

- Frequency and wavelength: $\lambda = c/f$
- Wavelength λ, speed of light $c \cong 3 \times 10^8$ m/s, frequency f in Hz

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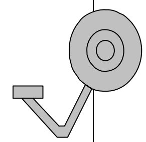
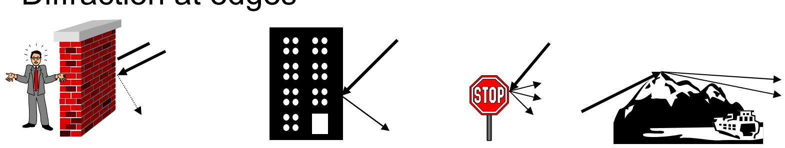
What is Signal Propagation?

- How is a radio signal transformed from the time it leaves a transmitter to the time it reaches the receiver
- Important for the design, operation and analysis of wireless networks
  - Where should base stations/access points be placed
  - What transmit powers should be used
  - What radio frequencies need be assigned to a base station
  - How are handoff decision algorithms affected…
- Propagation in free open space like light rays
- In general make analogy to light and sound waves



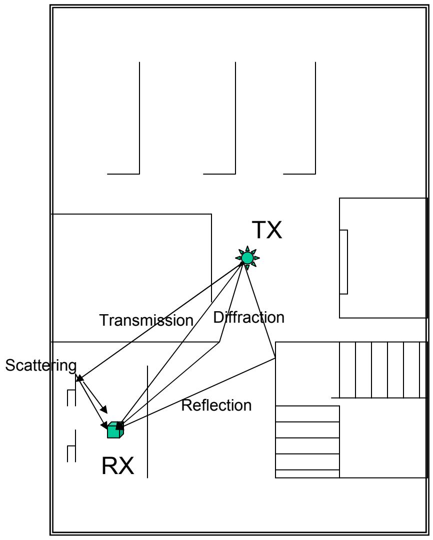
Signal Propagation

- Received signal strength (RSS) influenced by
  - Fading – signal weakens with distance - proportional to $1/d^2$ (d = distance between sender and receiver)
  - Frequency dependent fading – signal weakens with increase in f
  - Shadowing (no line of sight path)
  - Reflection off of large obstacles
  - Scattering at small obstacles
  - Diffraction at edges



shadowing reflection scattering diffraction

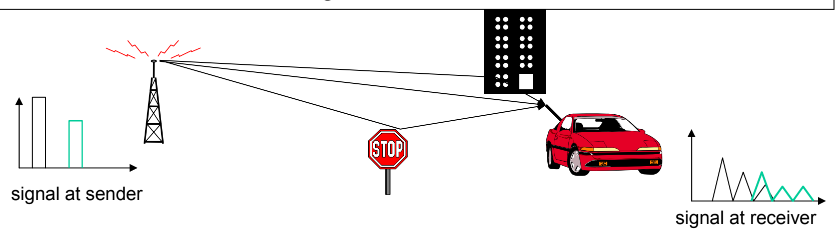
Signal Propagation



- Effects are similar indoors and out
- Several paths from Tx to Rx
  - Different delays, phases and amplitudes
  - Add motion – makes it very complicated
- Termed a multi-path propagation environment

Multipath propagation

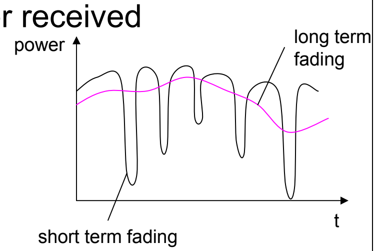
- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



- Time dispersion: signal is dispersed over time
- ➔ interference with "neighbor" symbols, Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted
- ➔ distorted signal depending on the phases of the different parts
- Result is limitation of maximum bit rate on channel

Effects of mobility

- Time Variations in Signal Strength
- Channel characteristics change over time and location
  - signal paths change
  - different delay variations of different signal parts
  - different phases of signal parts
- ➔ quick changes in the power received (short term or fast fading)

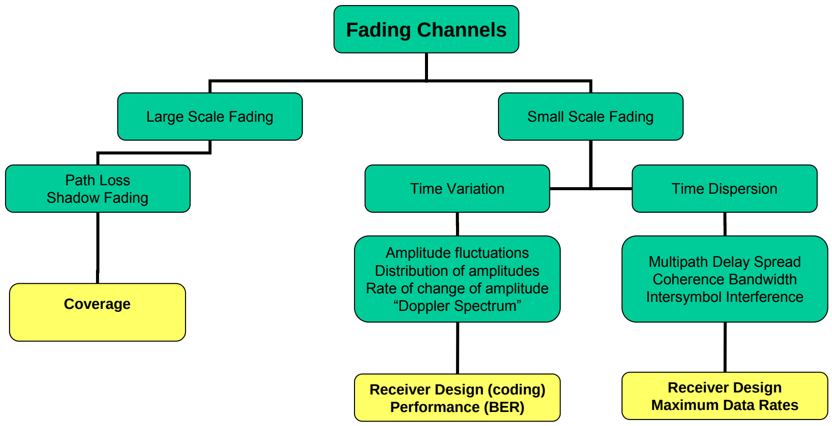


- Additional changes in
  - distance to sender
  - obstacles further away
- ➔ slow changes in the average power received (long term fading)

The Radio Channel

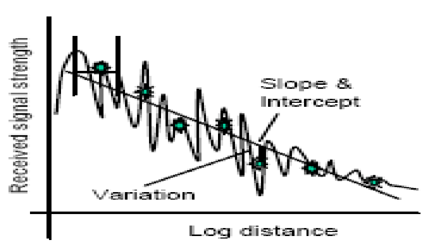
- Three main issues in radio channel
  - **Achievable signal coverage**
    - What is geographic area covered by the signal
    - Governed by path loss
  - **Achievable channel rates (bps)**
    - Governed by multipath delay spread
  - **Channel fluctuations – effect data rate**
    - Governed by Doppler spread and multipath

Communication Issues and Radio Propagation



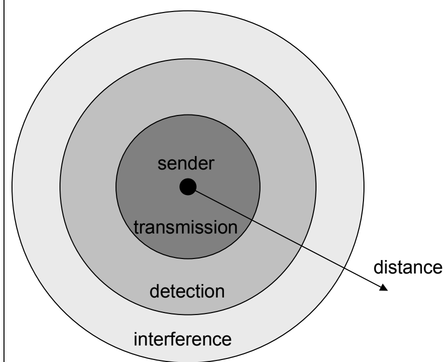
Coverage

- Determines
  - Transmit power required to provide service in a given area (link budget)
  - Interference from other transmitters
  - Number of base stations or access points that are required
- Parameters of importance (Large Scale/Term Fading effects)
  - Path loss (long term fading)
  - Shadow fading



Signal Coverage ranges

- Transmission range
  - communication possible
  - low error rate
- Detection range
  - detection of the signal possible
  - no communication possible
- Interference range
  - signal may not be detected
  - signal adds to the background noise



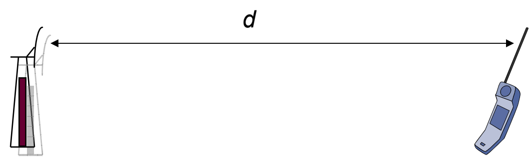
Decibels

- Power (signal strength) is expressed in decibels (dB) for ease of calculation
  - Values relative to 1 mW are expressed in dBm
  - Values relative to 1 W are expressed in dBW
  - Other values are simply expressed in dB
- Example 1: Express 2 W in dBm and dBW
  - dBm: $10 \log_{10} (2 \text{ W} / 1 \text{ mW}) = 10 \log_{10}(2000) = 33$ dBm
  - dBW: $10 \log_{10} (2 \text{ W} / 1 \text{ W}) = 10 \log_{10}(2) = 3$ dBW
- In general dBm value = 30 + dBW value
- Note 3 dB implies doubling/halving power

Free Space Loss Model

- Assumptions
  - Transmitter and receiver are in free space
  - No obstructing objects in between
  - The earth is at an infinite distance!
  - The transmitted power is P_t
  - The received power is P_r
  - Isotropic antennas
    - Antennas radiate and receive equally in all directions with unit gain
- The *path loss* is the difference between the received signal strength and the transmitted signal strength

  $PL = P_t\,(\text{dB}) - P_r\,(\text{dB})$



Free space loss

- Transmit power P_t
- Received power P_r
- Wavelength of the RF carrier $\lambda = c/f$
- Over a distance *d* the relationship between P_t and P_r is given by:

$$P_r = \frac{P_t \lambda^2}{(4\pi)^2 d^2}$$

- In dB, we have:
- P_r (dBm)= P_t (dBm) - 21.98 + 20 $\log_{10}(\lambda)$ – 20 $\log_{10}(d)$
- Path Loss = PL = $P_t - P_r$ = 21.98 - 20$\log_{10}(\lambda)$ + 20$\log_{10}(d)$

Free Space Propagation

- Notice that factor of 10 increase in distance => 20 dB increase in path loss (20 dB/decade)

Distance	Path Loss at 880 MHz
1km	91.29 dB
10Km	111.29 dB

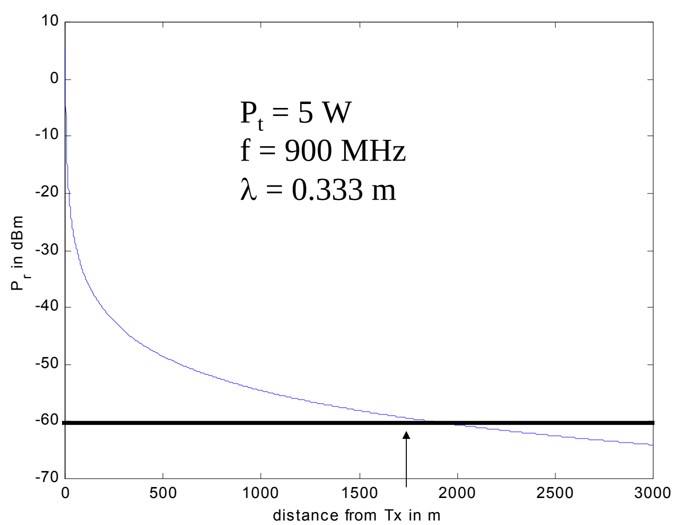
- Note that higher the frequency the greater the path loss for a fixed distance

Distance	880 MHz	1960MHz
1km	91.29 dB	98.25 dB

thus 7 dB greater path loss for PCS band compared to cellular band

Example

Can use model to predict coverage area of a base station



If we require -60dbm RSS

A simple explanation of free space loss

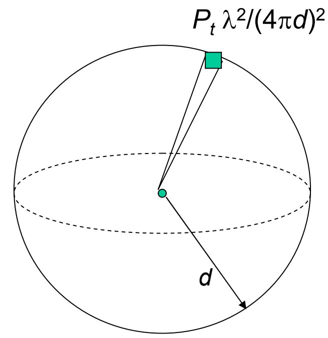
- Isotropic transmit antenna
  - Radiates signal equally in all directions
- Assume a point source
  - At a distance *d* from the transmitter, the area of the sphere enclosing the Tx is

    $A = 4\pi d^2$
  - The "power density" on this sphere is

    $P_t / 4\pi d^2$
- Isotropic receive antenna
  - Captures power equal to the density times the area of the antenna
  - Ideal area of antenna is

    $A_{ant} = \lambda^2/4\pi$
- The received power is:

  $P_r = P_t / 4\pi d^2 \times \lambda^2/4\pi = P_t\, \lambda^2/(4\pi d)^2$



$P_r = P_t / L_p$

Isotropic and Real Antennas

- Isotropic antennas are "ideal" and cannot be achieved in practice
  - Useful as a theoretical benchmark
- Real antennas have gains in different directions
  - Suppose the gain of the transmit antenna in the direction of interest is G_t and that of the receive antenna is G_r
  - The free space relation is:

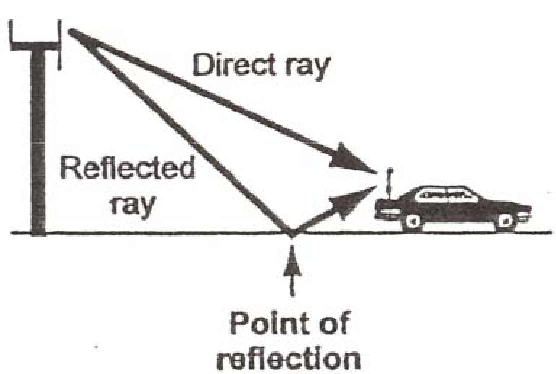
$$P_r = P_t\, G_t\, G_r\, \lambda^2/(4\pi d)^2$$

- The quantity $P_t\, G_t$ is called the effective isotropic radiated power (EIRP)
  - This is the transmit power that a transmitter should use were it having an isotropic antenna

Path Loss Models

- In practice to accurately predict signal propagation different types of models used
  - Breakdown phenomena into different categories based on geography and use physics of signal propagation to estimate path loss
    - Free Space, Reflection, diffraction, etc.
  - Use empirical models
    - Measurement based model
- Consider basics of each type

Reflection with partial cancellation



Propagation over smooth plane

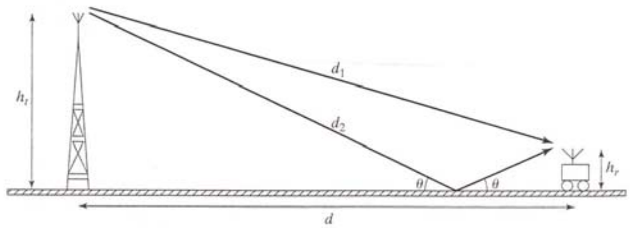


Figure 2.16 Two-path propagation over a flat plane.

$$d_1 = \sqrt{d^2 + (h_t - h_r)^2} \qquad d_2 = \sqrt{d^2 + (h_t + h_r)^2}$$

Propagation over smooth plane:

Received signal power – with perfect reflection

$$P_r(d) = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 |1 + \alpha_f e^{-j\beta_f} \exp[j(\phi_2 - \phi_1)]|^2$$

where $\phi_2 - \phi_1 = \frac{2\pi}{\lambda}(d_2 - d_1)$

$$\begin{aligned} P_r(d) &= P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \left|1 - \cos\left(\frac{2\pi \Delta d}{\lambda}\right) - j \sin\left(\frac{2\pi \Delta d}{\lambda}\right)\right|^2 \\ &= P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \left[2 - 2\cos\left(\frac{2\pi \Delta d}{\lambda}\right)\right] \\ &= 4 P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \sin^2\left(\frac{\pi \Delta d}{\lambda}\right), \end{aligned}$$

Propagation over smooth plane:

Received signal power

$$\Delta d = d_2 - d_1 \approx \frac{2h_t h_r}{d}$$

$$P_r(d) \approx 4P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \sin^2\left(\frac{2\pi h_t h_r}{\lambda d}\right)$$

$$L_p(d) = \left[4\left(\frac{\lambda}{4\pi d}\right)^2 \sin^2\left(\frac{2\pi h_t h_r}{\lambda d}\right)\right]^{-1}$$

$$= -10\log_{10}\left[4\left(\frac{\lambda}{4\pi d}\right)^2 \sin^2\left(\frac{2\pi h_t h_r}{\lambda d}\right)\right] \quad \text{(dB)}.$$

Reflection Loss

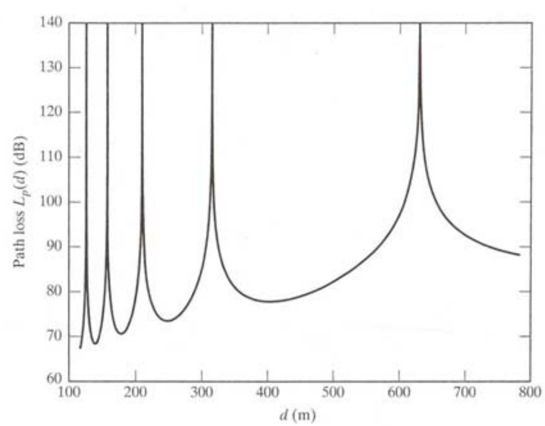


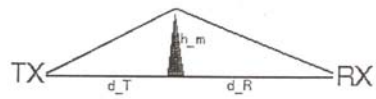
Figure 2.17 The path loss $L_p(d)$ in dB versus distance d in the two-path model.

Diffraction loss

- The diffraction parameter *v* is defined as

$$\upsilon = h_m \sqrt{\frac{2}{\lambda}\left(\frac{1}{d_t}+\frac{1}{d_r}\right)}$$

- h_m is the height of the obstacle
- d_t is distance transmitter-obstacle
- d_r is distance receiver-obstacle



- The diffraction loss L_d (dB) is approximated by

$$L_d = \begin{cases} 6+9v-1.27v^2 & 0<v<2.4 \\ 13+20\log v & v>2.4 \end{cases}$$

Diffraction Loss

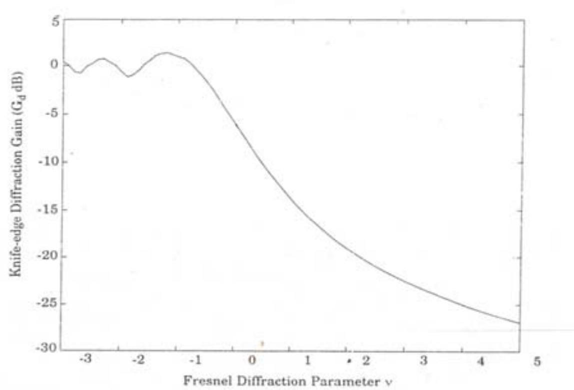
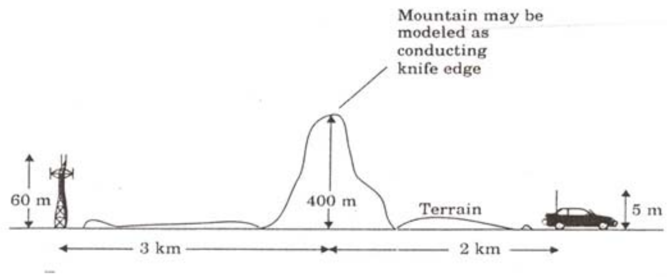


Figure 3.14
Knife-edge diffraction gain as a function of Fresnel diffraction parameter v.

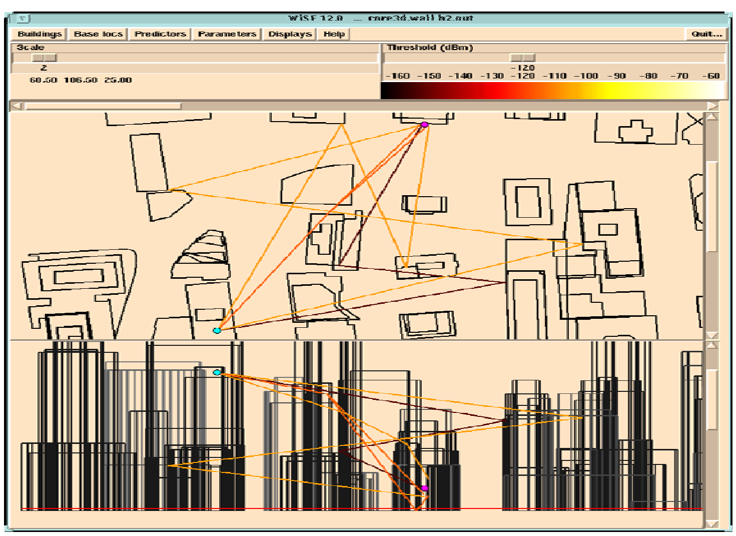
Diffraction Example



Ray Tracing

Use basic principles and site specific information to estimate signal strength at key points in the coverage area

Several CAD tools for doing this



Path Loss Models

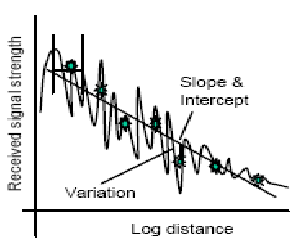
- Commonly used to estimate link budgets, cell sizes and shapes, capacity, handoff criteria etc.
- "Macroscopic" or "large scale" variation of RSS
- Path loss = loss in signal strength as a function of distance
  - Terrain dependent (urban, rural, mountainous), ground reflection, diffraction, etc.
  - Site dependent (antenna heights for example)
  - Frequency dependent
  - Line of site or not
- Simple characterization: $PL = L_0 + 10\alpha \log_{10}(d)$
  - L_0 is termed the frequency dependent component
  - The parameter α is called the "path loss gradient" or exponent
  - The value of α determines how quickly the RSS falls
  - Can be based on measurement data

Environment Based Path Loss

- Basic characterization: $PL = L_0 + 10\alpha \log_{10}(d)$
- Can be written in terms of received power:

$$P_r = K P_t d^{-\alpha}$$

- α determined by measurements in typical environment
  - For example
    - α = 2.5 might be used for rural area
    - α = 4.8 might be used for dense urban area (downtown Pittsburgh)
- Variations on this approach
  - Try and add more terms to the model
  - Directly curve fit data
- Indoor and Outdoor Models
  - Okumura-Hata, COST 231, JTC



Okumura-Hata Model

- Okumura collected measurement data (in Tokyo) and plotted a set of curves for path loss in urban areas
  - Hata came up with an empirical model for Okumura's curves

  L_p = 69.55 + 26.16 log f_c – 13.82 log h_{te} – $a(h_{re})$ + (44.9 –6.55 log h_{te})log d

  Where f_c is in MHz, d is distance in km, and h_{te} is the base station transmitter antenna height in meters and h_{re} is the mobile receiver antenna height in meters

  for fc > 400 MHz and large city

  $a(h_{re})$ = 3.2 (log [11.75 h_{re}])^2 – 4.97 dB
- See Table 2.1 in textbook for other cases

Example of Hata's Model

- Consider the case where

  h_{re} = 2 m ← receiver antenna's height
  h_{te} = 100 m ← transmitter antenna's height
  f_c = 900 MHz ← carrier frequency
- L_p = 118.14 + **31.8 log *d***
  - The path loss exponent for this particular case is α = 3.18
- What is the path loss at d = 5 km?
  - d = 5 km ➔ L_p = 118.14 + 31.8 log 5 = 140.36 dB
- If the maximum allowed path loss is 120 dB, what distance can the signal travel?
  - L_p = 120 = 118.14 + 31.8 log d => d = $10^{(1.86/31.8)}$ = 1.14 km

COST 231 Model

- Models developed by COST
  - European Cooperative for Science and Technology
  - Collected measurement data
  - Plotted a set of curves for path loss in various areas around the 1900 MHz band
  - Developed a Hata-like model

L_p = 46.3 + 33.9 log f_c – 13.82 log h_{te} - $a(h_{re})$ + (44.9 –6.55 log h_{te})log d + C

- C is a correction factor
  - C = 0 dB in dense urban; -5 dB in urban; -10 dB in suburban; -17 dB in rural
- Note: f_c is in MHz (between 1500 and 2000 MHz), d is in km, h_{te} is effective base station antenna height in meters (between 30 and 200m), h_{re} is mobile antenna height (between 1 and 10m)
- Additional outdoor models for microcells in Table 2.2

Indoor Path loss Models

Indoor Propagation models similar to outdoor

- Discuss two popular models

  Partition dependent model

$$L_p = L_0 + 20\log d + \sum_{type} m_{type} W_{type} + X$$

m_{type} = the number of partitions of type

w_{type} = the loss in dB associated with that partition

d = distance between transmitter and receiver point in meter

X = the shadow fading

L_0 = the path loss at the first meter, computed by

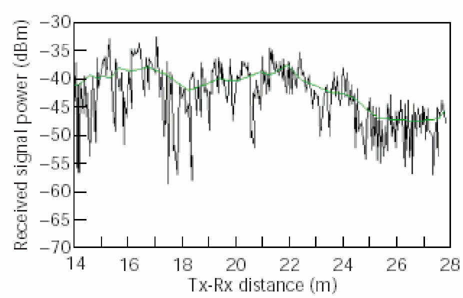
$$L_0 = 10\log\left(\left(\frac{4\pi d_0 f}{3\times 10^8}\right)^2\right)$$

where d_0 = 1 m.

f = operating frequency of the transmitter

Indoor Propagation Models

2.4GHz Signal attenuation through:	dB
Window in brick wall	2
Metal frame, glass wall into building	6
Office wall	6
Metal door in office wall	6
Cinder Wall	4
Metal door in brick wall	12.4
Brick wall next to metal door	3



Example Partition Model

Consider an AP operating at 2.412GHz. The distance from the AP to a receiving terminal is approximately 10 meters. There are two office walls and one metal door in office wall between the AP and the receiver. The AP operates at a power level of 100mW (20dBm). Use the partition dependent model to determine the path loss and received signal strength at the receiver location, consider a shadow fading of 13 dBm

$$L_p = L_0 + 20\log d + \sum_{type} m_{type} W_{type} + X$$

$$L_0 = 10\log\left(\left(\frac{4\pi d_0 f}{3\times 10^8}\right)^2\right)$$

$w_{office\ wall}$ = 6 dB, $w_{metaldoor\ in\ office\ wall}$ = 6 dB

X = 13 dBm

L_0 = 10 $\log_{10}((4\pi \times 1 \times 2.412 \times 10^9)/(3 \times 10^8))^2$ = $10\log_{10}((101.034)^2)$ = 40.1

L_p = 40.1 +20log(10) + (2*6 +6) +13 = 91.1 dB

Power received = $P_r = P_t - L_p$ = 20dBm – 91.1 dB = - 71.1 dBm

The JTC Indoor Path Loss Model

$$L_{Total} = A + B\log_{10}(d) + L_f(n) + X_\sigma$$

Similar to Okumura –Hata model in cellular (curve fitting to measure values used to set up model

- *A* is an environment dependent fixed loss factor (dB)
- *B* is the distance dependent loss coefficient,
- *d* is separation distance between the base station and portable, in meters
- L_f is a floor penetration loss factor (dB)
- *n* is the number of floors between the access point and mobile terminal
- X_σ is a shadowing term

Note may add shadowing to either JTC or Partition model

JTC Model (Continued)

Environment	Residential	Office	Commercial
A (dB)	38	38	38
B	28	30	22
$L_f(n)$ (dB)	4n	15 + 4(n-1)	6 + 3(n-1)
Log Normal Shadowing Std. Dev. (dB)	8	10	10

JTC Model (Continued)

- Example

Consider an AP on the first floor of a 3 floor house
The distance to a third floor home office is approximately 8 meters
If the AP operates at a power level of .05 W using the JTC model determine the path loss and received signal strength in the office area

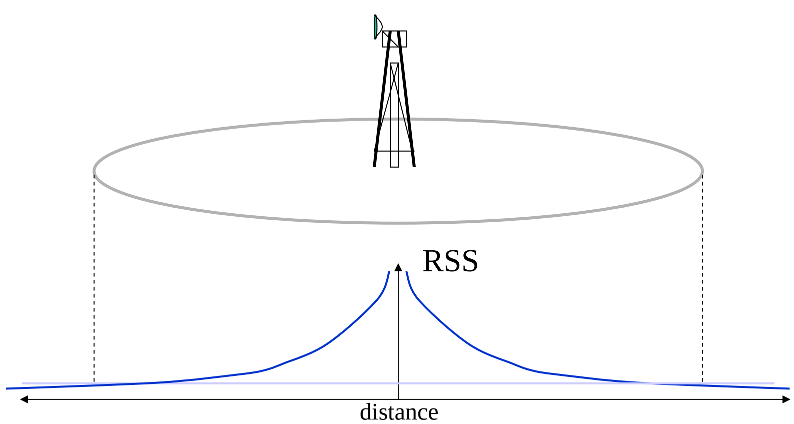
Using the JTC model with residential parameter set

$L_{total} = A + B \log_{10}(d) + L_f(n) + 8 = 38 + 28 \log_{10}(8) + 4x2 + 8 = 79.28$ dB

Power received = $P_r = P_t - L_{total} = 16.98$ dbm – 79.28 dB = -62.29 dBm

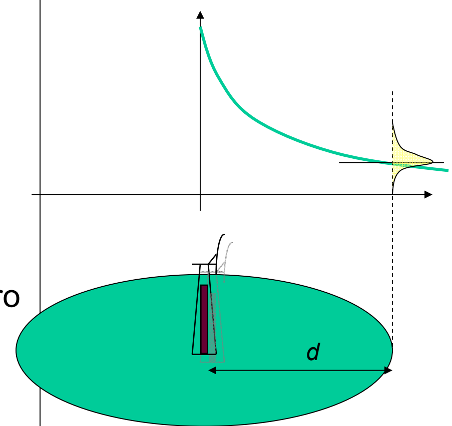
Cell

- Cell is the area covered by a single transmitter
- Path loss model determines the size of cell



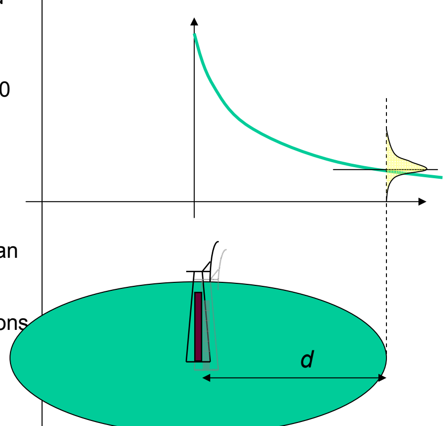
Shadow Fading

- Shadowing occurs when line of site is blocked
- Modeled by a random signal component X_σ
- $P_r = P_t - L_p + X_\sigma$
- Measurement studies show that X_σ can be modeled with a lognormal distribution ➔ normal in db with mean = zero and standard deviation σ db
- Thus at the "designed cell edge" only 50% of the locations have adequate RSS



How shadow fading affects system design

- Since X_σ can be modeled in db as normally distributed with mean = zero and standard deviation σ db
- σ determines the behavior
- Typical values for σ are rural 3 db, suburban 6 db, urban 8 db, dense urban 10 db.
- Since X is normal in db P_r is normal
- $P_r = P_t - L_p + X_\sigma$
- Prob $\{P_r(d) > T\}$ can be found from a standard normal distribution table with mean P_r and σ
- In order to make at least 90% of the locations have adequate RSS
  - Reduce cell size
  - Increase transmit power
  - Make the receiver more sensitive
- Shadow Margin is the amount of extra path loss added to the path loss budget to account for shadowing

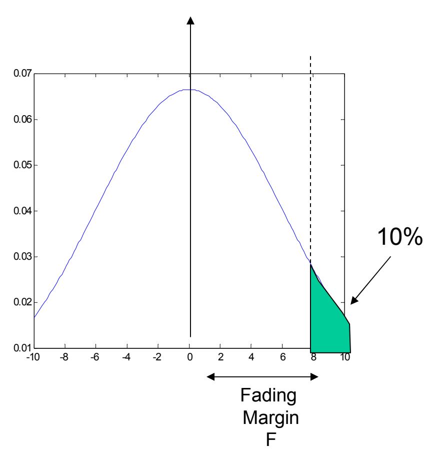


Example of Shadow Calculations

- The path loss of a system is given by
  - $L_p = 47 + 40 \log_{10} d - 20 \log_{10} h_b$
  - h_b = 10m, P_t = 0.5 W, receiver sensitivity = -100 dBm
  - What is the cell radius?
- $P_t = 10 \log_{10} 500 = 27$ dBm
- The permissible path loss is 27-(-100) = 127 dBm
- $20 \log_{10} h_b = 20 \log_{10} 10 = 20$ dB
- $127 = 47 + 40 \log_{10} d - 20$ => d = 316m
- But the real path loss at any location is
  - 127 + **X** where **X** is a random variable representing shadowing
  - Negative **X** = better RSS; Positive **X** = worse RSS
- If the shadow fading component is normally distributed with mean zero and standard deviation of 6 dB. What should be the fading margin to have acceptable RSS in 90% of the locations at the cell edge?

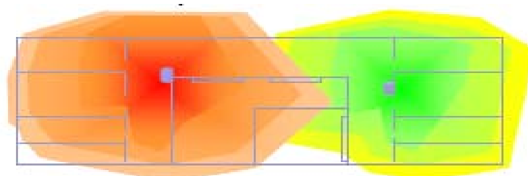
Example again

- Let **X** be the shadow fading component
  - **X** = N(0,6)
  - We need to find F such that **P**{**X** > F } = 0.1
- We need to solve Q(F/σ) = 0.1
- Use tables or software
  - Q(u) = 0.5 erfc(u/√2)
- In this example F = 7.69 dB
  - Increase transmit power to 27 + 7.69 = 34.69 dBm = 3 W
  - Make the receiver sensitivity -107.69 dBm
  - Reduce the cell size to 203.1 m
- In practice use .9 or .95 quantile vales to determine shadow margin SM
- .9 -> SM = 1.282 σ
- .95 -> SM = 1.654 σ



Cell Coverage modeling

- Simple path loss model based on environment used as first cut for planning cell locations
- Refine with measurements to parameterize model
- Alternately use ray tracing: approximate the radio propagation by means of geometrical optics- consider line of sight path, reflection effects, diffraction etc.
- CAD deployment tools widely used to provide prediction of coverage and plan/tune the network



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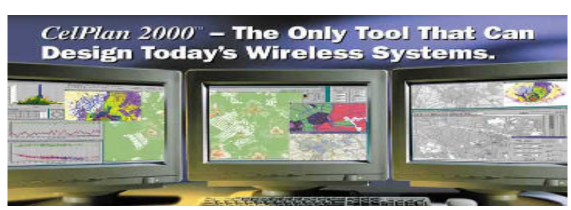
Cellular CAD Tools

- **Use GIS terrain data base, along with vehicle traffic/population density overlays and propagation models**
- **Output map with cell coverage at various signal levels and interference values**
  - To plan out cell coverage area, cell placement, handoff areas,Interference level frequency assignment



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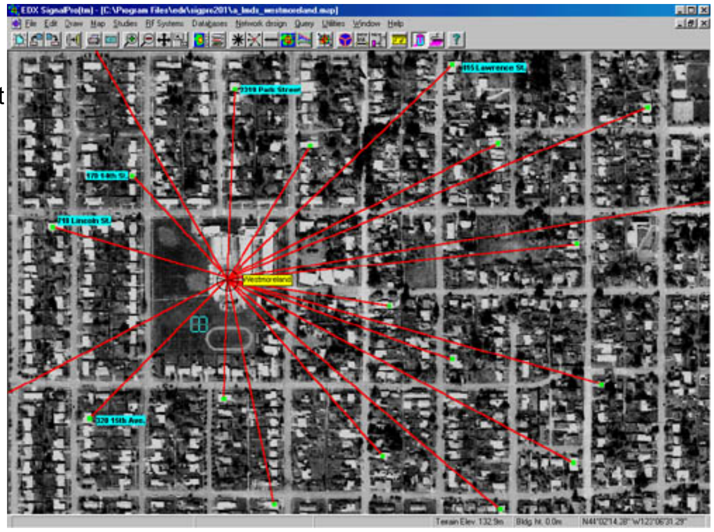
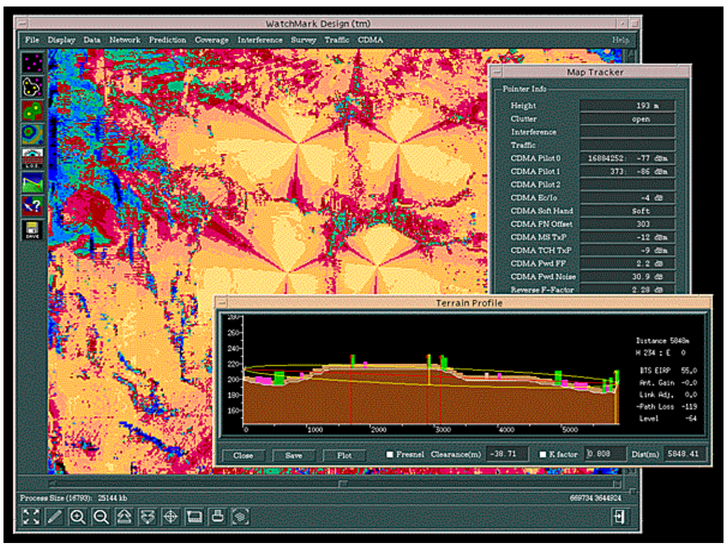
Use GIS maps

- CAD tools rely on government GIS data to provide terrain info
- This shows possible location of cell site and possible location of users where signal strength prediction is desired



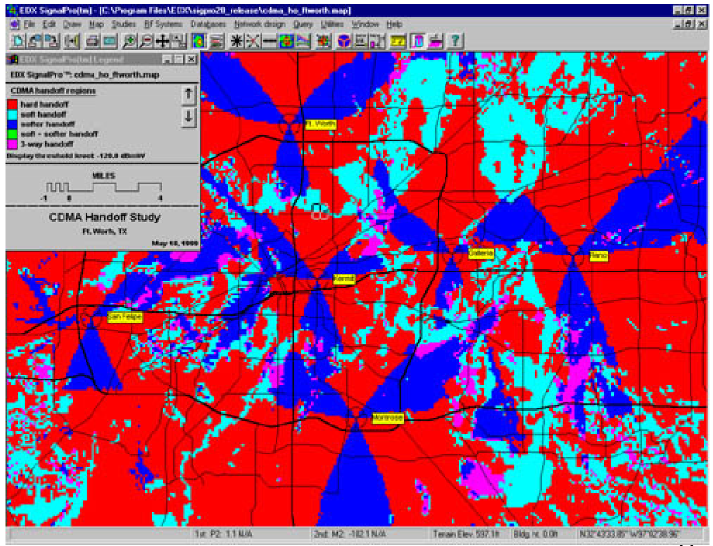
Outdoor Model

Models provide a variety of propagation models: free space, Okumura-Hata, etc.



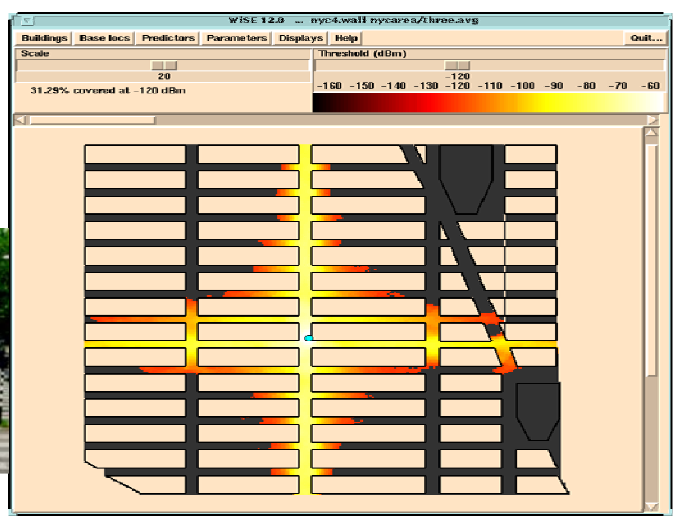
Cellular CAD Tools

Tools provide Handoff info as well as coverage

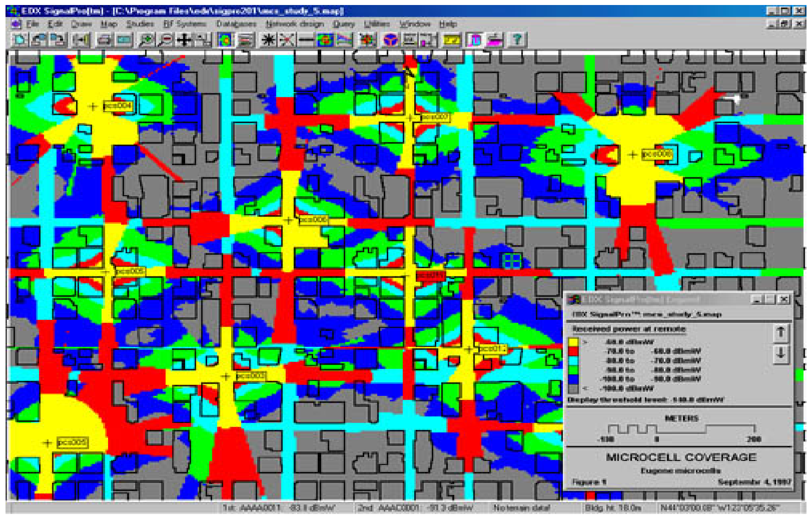


Typical City pattern

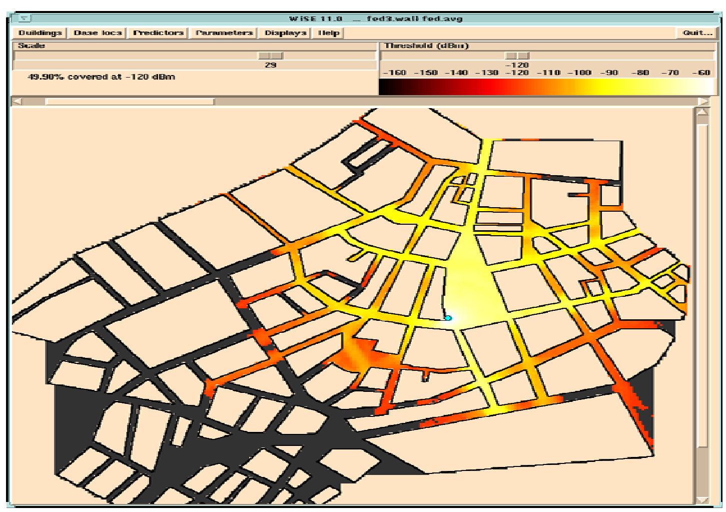
Microcell diamond Radiation pattern



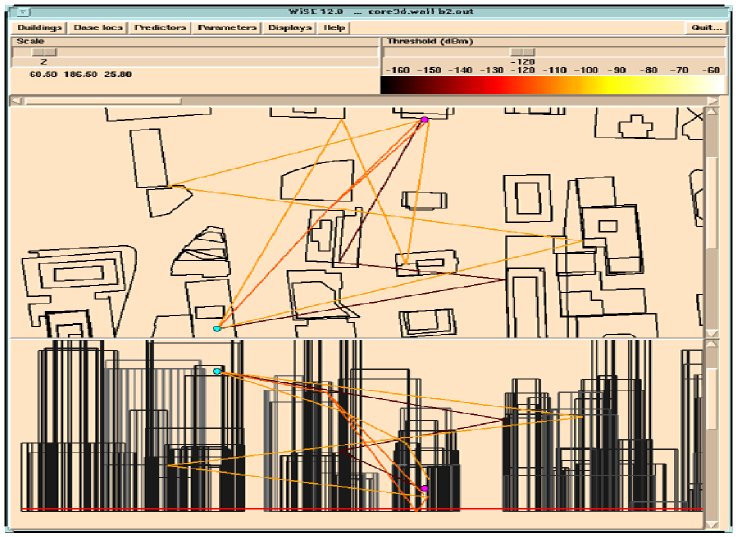
Cellular CAD Tools



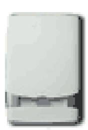
City Model with Hill

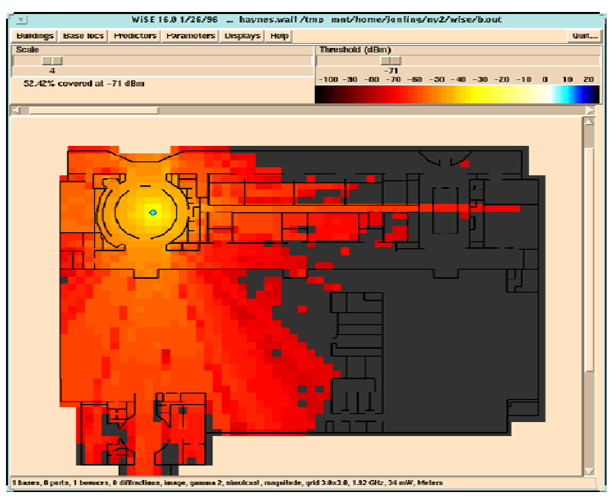


Ray Tracing Mode



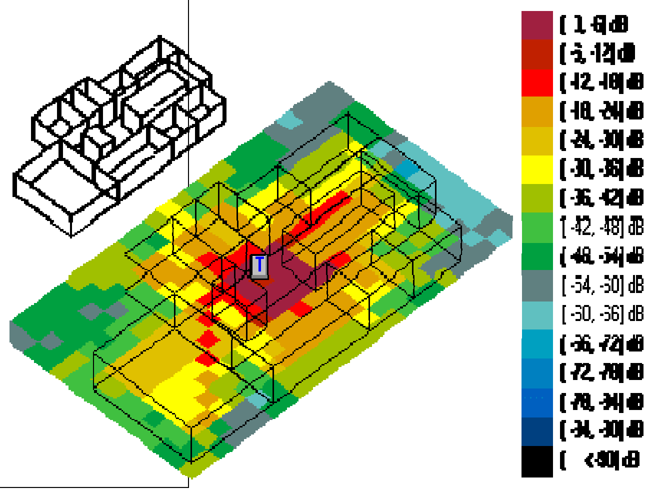
Indoor Models





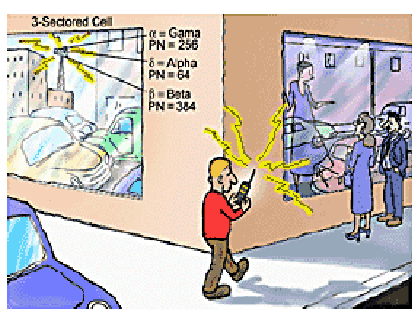
Indoor tools for WLANs

- Lucent
- Motorola
- Cisco



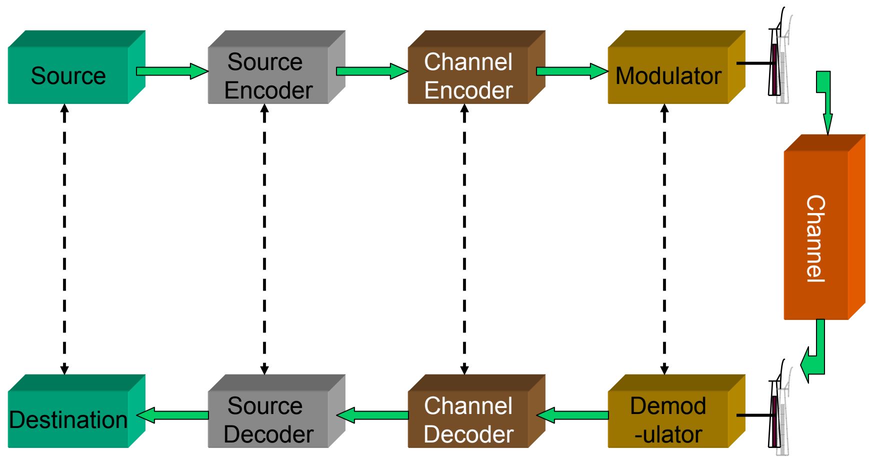
Cellular CAD Tools

- CAD tool cell site placement, augmented by extensive measurements to refine model and tune location and antenna placement/type –similar tools for WLANs



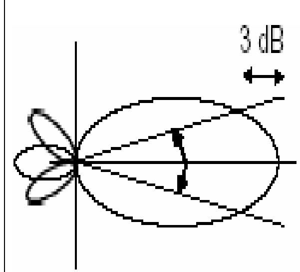
Temporary cell

Typical Wireless Communication System



Antennas

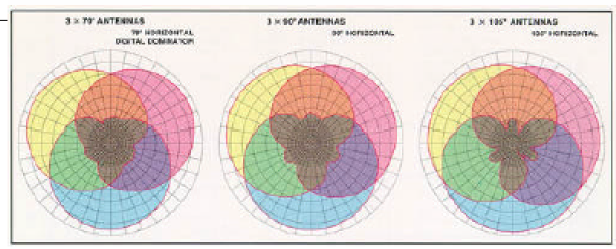
- **Antenna**
  - Converts guided signals into electromagnetic radiation as efficiently as possible in the direction required
- **Radiation pattern**
  - Way in which energy propagates in as a function of direction
- **Antenna Beamwidth**
  - The beamwidth is the angle of coverage where the radiated energy is 3 dB down from the peak of the beam (half-power)
- **Front-to-Back Ratio**
  - The ratio of the power in the main lobe to the power in the lobe created at the back of the antenna



Antenna Beamwidth

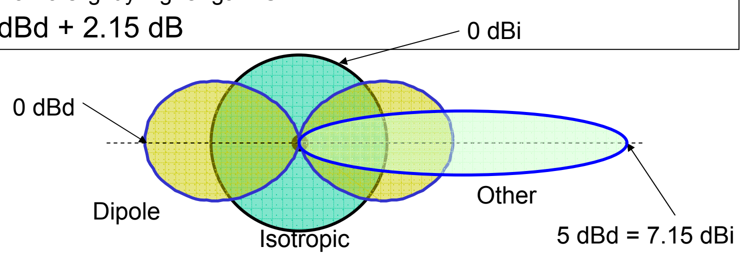
- By narrowing the beamwidth we can increase the gain and create sectors at the same time
- Graph shows 3 sectors with different horizontal antenna beamwidths

Source: Decibel Products website



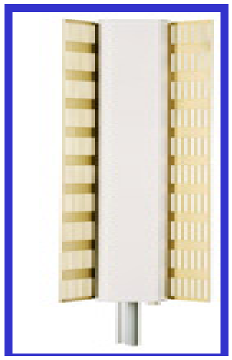
Antenna Gain

- The "gain" of an antenna in a given direction is the ratio of the power density produced by it in that direction divided by the power density that would be produced by a reference antenna in the same direction
- Two types of reference antennas are generally used
  - Isotropic antenna: gain is given in dBi
  - Half-wave dipole antenna: gain is given in dBd
- Manufacturers often use dBi in their marketing
  - To show a slightly higher gain ☺
- dBi = dBd + 2.15 dB



Antennas

- Down Tilt: process of forcing the antenna beam downward to reduce co-channel interference
  - Mechanical Down tilt
    - Simply tilt the antenna manually (i.e.: the antenna appears to be at an angle)
  - Electrical Down tilt
    - Down tilt is performed by injecting a different phase delay to each of the elements in a dipole array. The beam is forced downward, but the physical antenna still appears to be vertically straight up
- Directional antennas can be created using antenna arrays or horn/dish elements



45^0 Beamwidth
19 dBd Gain
Panel Antenna

Cellular Antennas

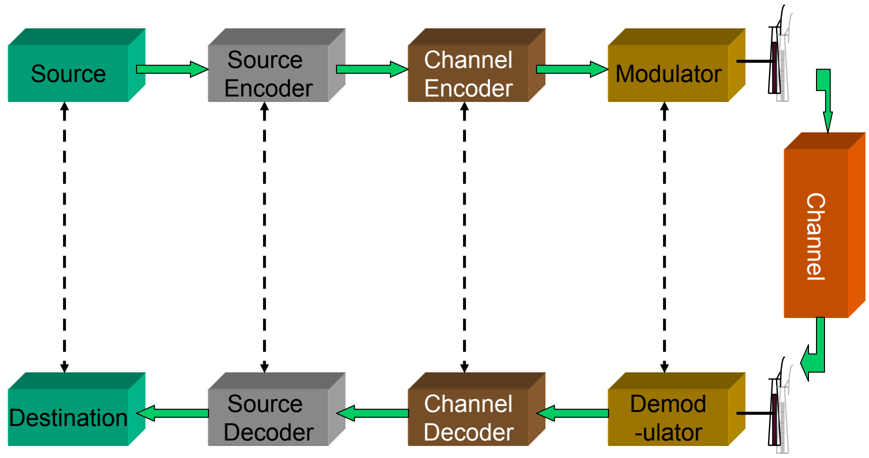
Cells are typically sectored into 3 parts each having 120^0 sector of the cell to cover

1 transmit antenna in middle of each sector face

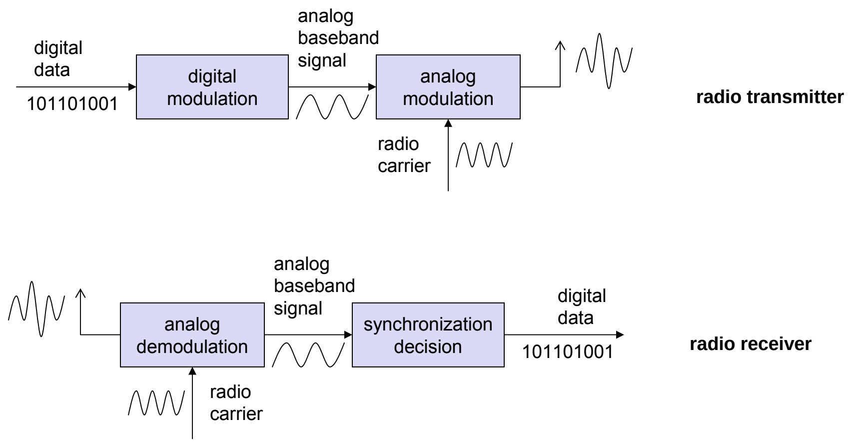
2 receive antenna at edge of sector face on the tower.

This is done to provide antenna diversity – it combats fast fading – as only 1 antenna will likely be in fade at any point in time. Can get 3-5 dB gain in the system

Typical Wireless Communication System



Modulation and demodulation



Modulation

- Modulation
  - Converting digital or analog information to a waveform suitable for transmission over a given medium
  - Involves varying some parameter of a carrier wave (sinusoidal waveform) at a given frequency as a function of the message signal
  - General sinusoid
    - $A \cos(2\pi f_C t + \varphi)$

Amplitude (A), Frequency (f_C), Phase (φ)

  - If the information is digital changing parameters is called "keying" (e.g. ASK, PSK, FSK)

Modulation

- Motivation
  - Smaller antennas (e.g., λ /4 typical antenna size)
    - λ = wavelength = c/f , where c = speed of light, f= frequency.
    - 3000Hz baseband signal => 15 mile antenna, 900 MHz => 8 cm
  - Frequency Division Multiplexing – provides separation of signals
  - medium characteristics
  - Interference rejection
  - Simplifying circuitry

- Modulation
  - shifts center frequency of baseband signal up to the radio carrier
- Basic schemes

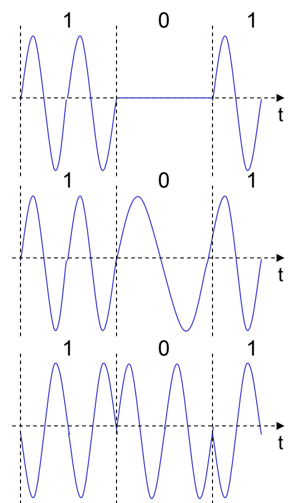
– Amplitude Modulation (AM)	Amplitude Shift Keying (ASK)
– Frequency Modulation (FM)	Frequency Shift Keying (FSK)
– Phase Modulation (PM)	Phase Shift Keying (PSK)

Digital Transmission

- Current wireless networks have moved almost entirely to digital modulation
- Why Digital Wireless?
  - Increase System Capacity (voice compression) more efficient modulation
  - Error control coding, equalizers, etc. => lower power needed
  - Add additional services/features (SMS, caller ID, etc..)
  - Reduce Cost
  - Improve Security (encryption possible)
  - Data service and voice treated same (3G systems)
- Called digital transmission but actually *Analog signal carrying digital data*

Digital modulation Techniques

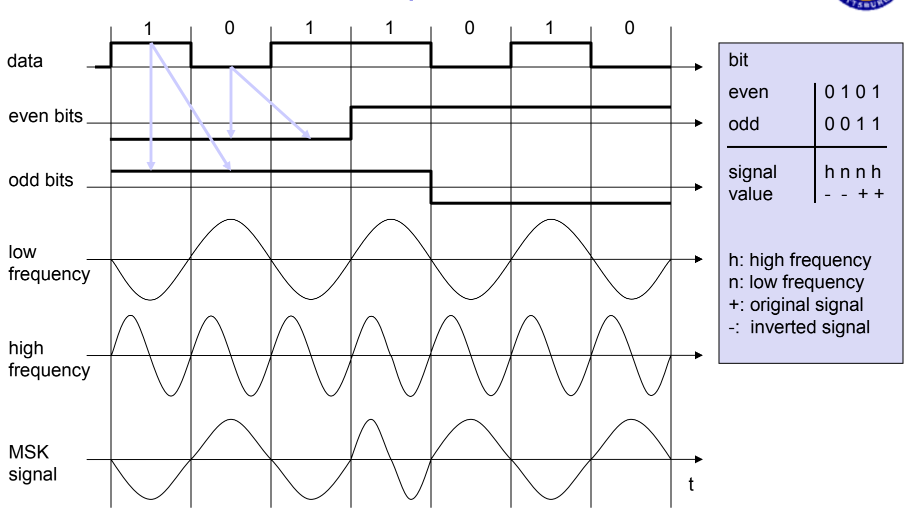
- Amplitude Shift Keying (ASK):
  - change amplitude with each symbol – frequency constant
  - low bandwidth requirements
  - very susceptible to interference
- Frequency Shift Keying (FSK):
  - change frequency with each symbol
  - needs larger bandwidth
- Phase Shift Keying (PSK):
  - Change phase with each symbol
  - More complex
  - robust against interference
- Most systems use either a form of FSK or PSK



Advanced Frequency Shift Keying

- bandwidth needed for FSK depends on the distance between the carrier frequencies
- special pre-computation avoids sudden phase shifts ➔ MSK (Minimum Shift Keying)
- bit separated into even and odd bits, the duration of each bit is doubled
- depending on the bit values (even, odd) the higher or lower frequency, original or inverted is chosen
- the frequency of one carrier is twice the frequency of the other
- even higher bandwidth efficiency using a Gaussian low-pass filter ➔ GMSK (Gaussian MSK), used in GSM cellular network

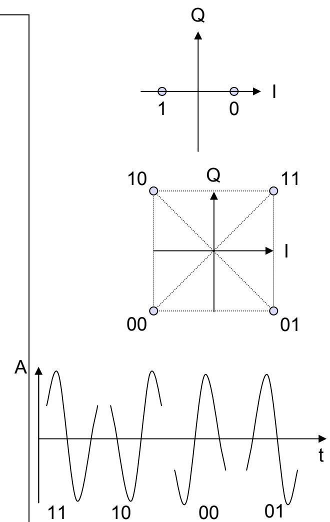
Example of MSK



No phase shifts!

Advanced Phase Shift Keying

- BPSK (Binary Phase Shift Keying):
  - bit value 0: sine wave
  - bit value 1: inverted sine wave
  - very simple PSK
  - low spectral efficiency
  - robust, used e.g. in satellite systems
- QPSK (Quadrature Phase Shift Keying):
  - 2 bits coded as one symbol
  - symbol determines shift of sine wave
  - needs less bandwidth compared to BPSK
  - more complex
- Often also transmission of relative, not absolute phase shift: DQPSK - Differential QPSK
- N level PSK possible (N bits per channel symbol



QPSK Quick Review

In QPSK, we use two bits to represent on one of four phases.

Example: We represent 1 by a $-V_e$ Voltage
0 by a $+V_e$ Voltage (NRZ)

Then the QPSK symbol is decided as follows.

01 : $\cos(2\pi f_c t + \pi/4)$

11 : $\cos(2\pi f_c t + 3\pi/4)$

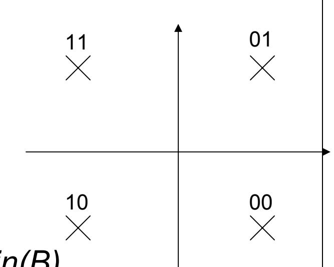
10 : $\cos(2\pi f_c t + 5\pi/4)$

00 : $\cos(2\pi f_c t + 7\pi/4)$

All symbols last for $2T$ seconds.

Why do we choose this mapping?

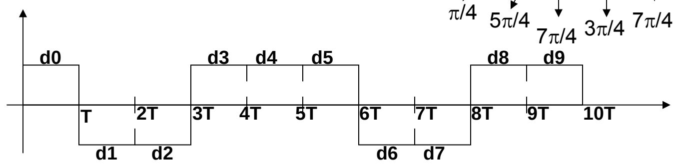
cos(A+B) = cos(A)cos(B) – sin(A)sin(B)



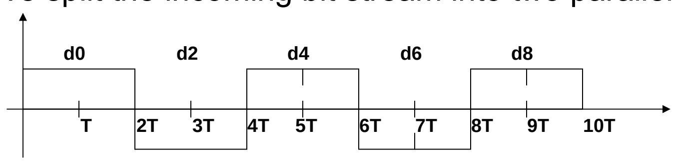
Example of QPSK

- Suppose we send a data stream 01 10 00 11 00

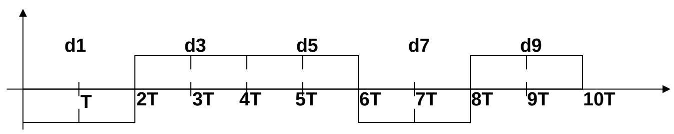
$\pi/4$ $5\pi/4$ $7\pi/4$ $3\pi/4$ $7\pi/4$



- We split the incoming bit stream into two parallel paths.



In-phase



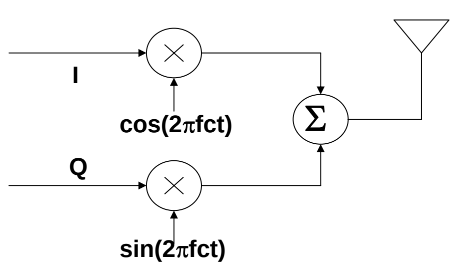
Quadrature

Example of QPSK (cont.)

Consider the first dibit (0,1). This is mapped to:

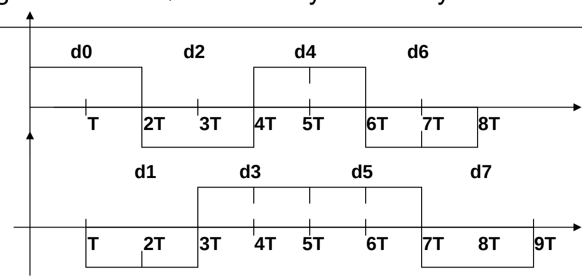
$$\cos\left(2\pi f_c t + \tfrac{\pi}{4}\right) = \cos\left(2\pi f_c t\right)\cos\left(\tfrac{\pi}{4}\right) - \sin\left(2\pi f_c t\right)\sin\left(\tfrac{\pi}{4}\right)$$
$$= \sqrt{\tfrac{1}{2}}\cos\left(2\pi f_c t\right) - \sqrt{\tfrac{1}{2}}\sin\left(2\pi f_c t\right)$$
$$= \sqrt{\tfrac{1}{2}}\left[d_0 \cos\left(2\pi f_c t\right) + d_1 \sin\left(2\pi f_c t\right)\right]$$

In-phase **Quadrature**



Offset QPSK

- Also called staggered QPSK – use in IS-95 reverse channel
- Idea: reduce the amount of discontinuity in phase so that a near constant envelope modulation scheme is achieved.
- Stagger the I and Q channels by half the symbol duration.

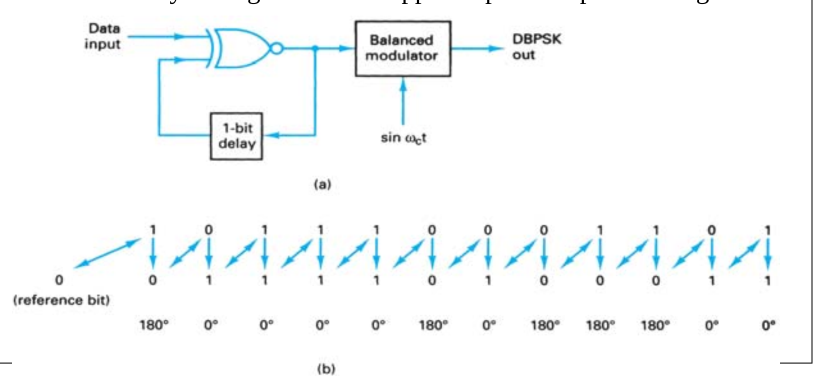


The phase changes are now restricted to ± 90° instead of ± 180°. The increase in sidelobe levels compared to QPSK after non-linear amplification is about 30%.

Disadvantage: We can no longer do differential detection.

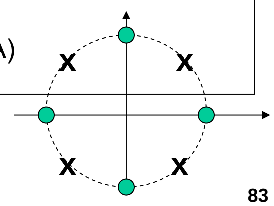
D Phase-Shift Keying (PSK)

- Differential PSK (DPSK)
  - Phase shift with reference to previous bit
    - Binary 0 – signal burst of same phase as previous signal burst
    - Binary 1 – signal burst of opposite phase to previous signal burst

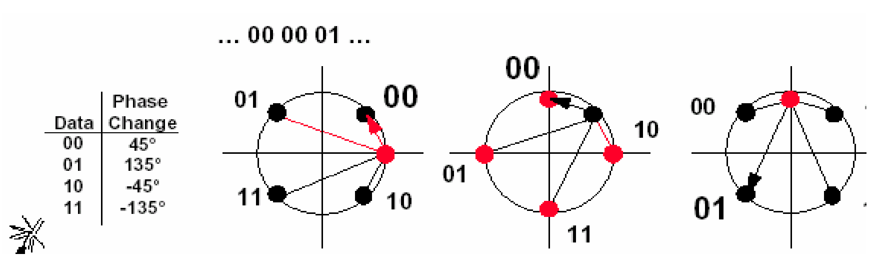


π/4 - DQPSK

- Idea: Use two QPSK constellations shifted by 45° and switch between the constellation each symbol. The discontinuity in phase can be a maximum of ±135°. (Other possibilities are ±45°).
- This reduces abrupt phase changes by a reasonable factor.
- Differential encoding and demodulation is possible.
- π/4 – DQPSK is used in several cellular and wireless standards.
  - IS-136 digital TDMA standard for 2G cellular in the US/NA
  - Pacific digital cellular (RDC) in Japan
  - Terrestrial European Trucked Radio (TETRA)



Example transitions in π/4-DQPSK



•**Advantages**

  •**Differential detection – self clocking**

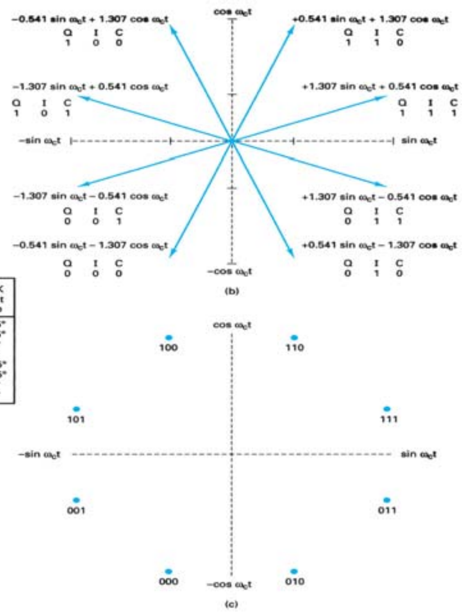
  •**Bandwidth efficient**

8 –PSK

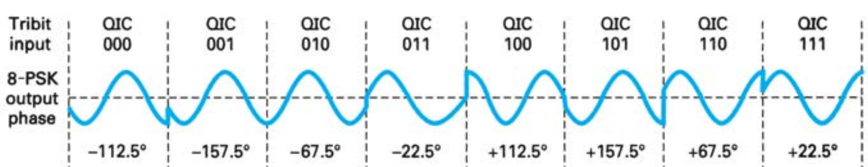
Increasing the number of levels increases the data rate – but Increases the symbol error rate as the symbols are closer together in the constellation space

Binary input			8-PSK output phase
Q	I	C	
0	0	0	−112.5°
0	0	1	−157.5°
0	1	0	−67.5°
0	1	1	−22.5°
1	0	0	+112.5°
1	0	1	+157.5°
1	1	0	+67.5°
1	1	1	+22.5°

(a)



8-PSK Output

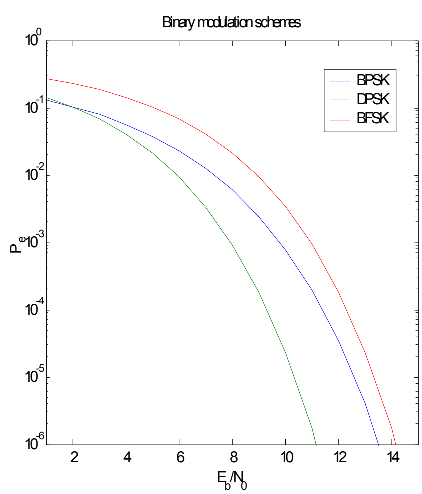


Selection of Encoding/Modulation Schemes

- Performance in an Noisy channel
  - How does the bit error rate vary with the energy per bit available in the system
- Performance in fading multipath channels
  - Same as above, but add multipath and fading
- Bandwidth requirement for a given data rate
  - Also termed spectrum efficiency or bandwidth efficiency
  - How many bits/sec can you squeeze in one Hz of bandwidth
- Cost
  - The modulation scheme needs to be cost efficient

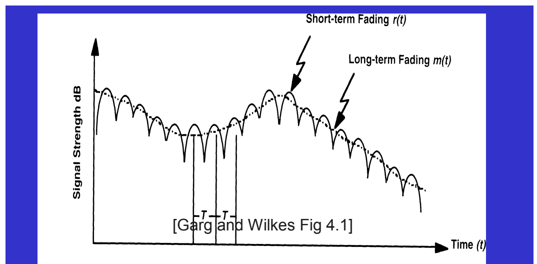
Performance in Noisy channels

- AWGN = Additive While Gaussian Noise
  - This has a flat noise spectrum with average noise power of N_0
- The probability of bit error (bit error rate) is measured as a function of ratio of the "energy per bit" – E_b to the average noise value
  - BER or P_e variation with E_b/N_0
  - E_b/N_0 is a measure of the "power requirements"
- Tradeoffs
- Some form of PSK used in most wireless systems



Effect of Mobility?

- A moving receiver can experience a positive or negative Doppler shift in received signal, depending on direction of movement
  - Results in widening frequency spectrum
- Fading is a combination of fast fading (Short term fading) and slow (log-normal) fading

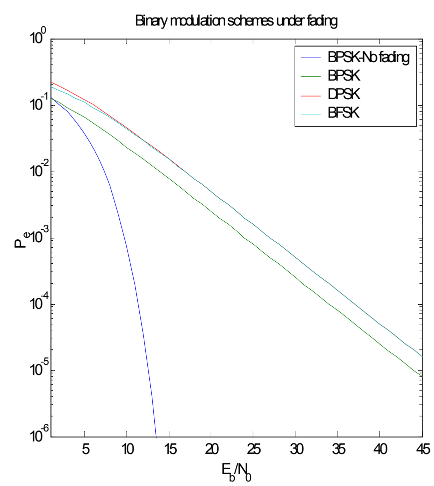


[Garg and Wilkes Fig 4.1]

Fig. 4.1 A Mobile Radio Signal Fading Representation

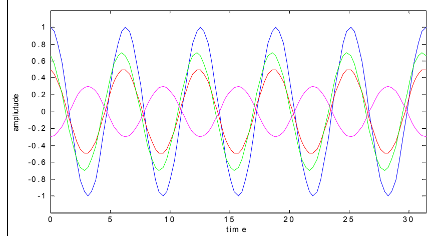
Performance in Fast Fading Channels

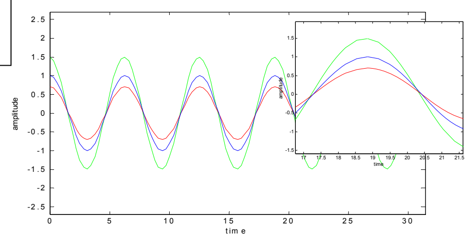
- The BER is now a function of the "average" E_b/N_0
- The fall in BER is linear
- Large power consumption on average to achieve a good BER
  - 30 dB is three orders of magnitude larger
- Must use diversity techniques to overcome effect of Short Term (Fast) Fading and Multipath Delay

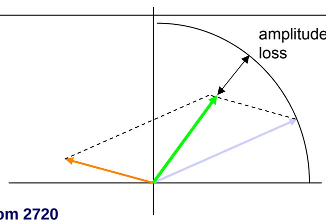


Small scale/Fast fading

- Multipath = several delayed replicas of the signal arriving at the receiver
- Fading = constructive and destructive adding of the signals
- Rapid fluctuation in amplitude with time
- Results in poor signal quality
- Digital communications
  - High bit error rates







Small scale fading amplitude characteristics

- Narrowband fading :
  - channel is the same for all *f* in signal
- Symbol duration > time delays of multipath components
- Radio channel model
  - Collapse multipath components into one ``fading'' component

$$h(t) = A\delta(t-\tau)$$

$$H(f) = Ae^{-j2\pi f\tau}$$

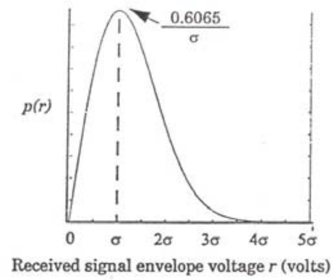
$$|H(f)| = A$$

Magnitude spectrum independent of *f* – *the channel appears flat for all frequencies – flat fading channel*

Small scale fading amplitude characteristics

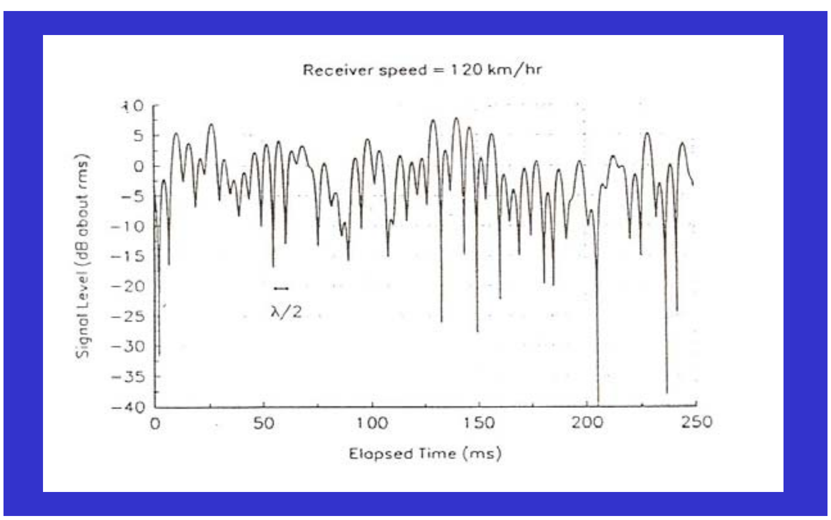
- In line-of sight situations the amplitudes A have a Ricean distribution
  – Strong LOS component - results in better performance
- Amplitudes A are Rayleigh distributed when no line of sight or weak line of sight component
  – Worst case scenario – results in the poorest performance
- Other distributions have been found to fit the amplitude distribution depending on situation
  – Nakagami

$$f_{ric}(r)=\frac{r}{\sigma^2}\exp(\frac{-(r^2+K^2)}{2\sigma^2})I_0(\frac{Kr}{\sigma^2}), \quad r\geq 0, K\geq 0$$



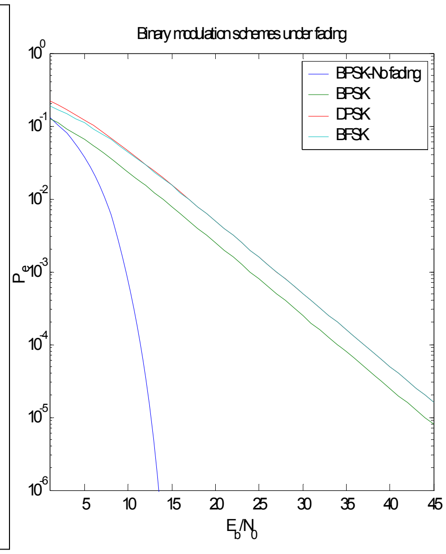
$$f_{ray}(r)=\frac{r}{\sigma^2}\exp(-\frac{r^2}{2\sigma^2}), \quad r\geq 0$$

A typical Rayleigh fading envelope at 900 MHz



Performance in Rayleigh Fading Channels

- The BER is now a function of the “average” E_b/N_0
- The fall in BER is linear not exponential as in AWGN case
- Large power consumption on average to achieve a good BER
  - 30 dB is three orders of magnitude larger
- See Table 3A.1 for BER formulas for AWGN and Rayleigh Fading channels



Time variation of the channel

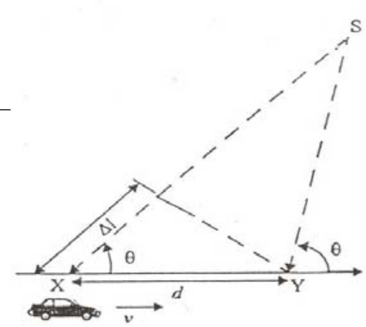
- The radio channel is NOT time invariant
  - Movement of the mobile terminal
  - Movement of objects in the intervening environment
- How quickly does the channel fade (change)?
  - For a time invariant channel, the channel does not change – the signal level is always high or low
  - For time variant channels, it is important to know the rate of change of the channel (or how long the channel is constant)
  - Depends on
    - Velocity of mobile relative to transmitter
    - How one defines change (10dB or 30dB?)

Doppler spectrum

- The distribution of the rate of change of the signal depends on the fading-whether it is correlated or uncorrelated.
- This rate is expressed in units of frequency called Doppler spectrum
- The maximum Doppler shift is

$$f_m = \frac{f_c v}{c}$$

f_c is carrier frequency
c: speed of light
v the velocity of mobile terminal



Doppler spectrum (continued)

- If the fading is uncorrelated, the Doppler is flat, i.e. the signal changes can occur at all possible rates and each rate is equally likely.
- In outdoor scenarios, the fading is correlated and the Doppler spectrum is shown to have the form:

$$S(f) = \frac{1.5}{\pi f_m \sqrt{1-(f/f_m)^2}}, \qquad |f| < f_m$$

- Example

  v = 100 km/h

$$\frac{f_m}{f_c} = \frac{100\times10^3}{3\times10^8\times3600} = \frac{1}{108\times10^5}$$

At 900 MHz, f_m is about 83.3 Hz
i.e. the channel changes could occur 83.3 times a second.

Coherence time of a channel

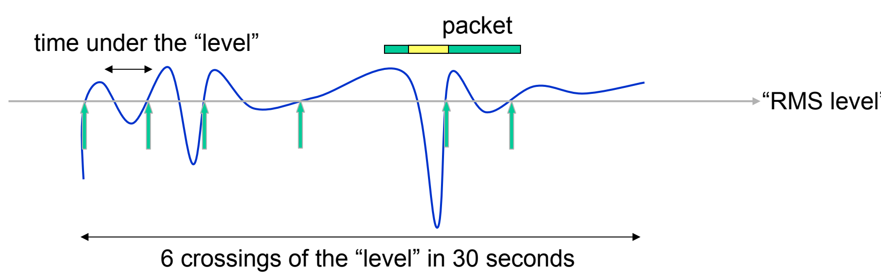
- It is the average time for which the channel can be assumed to be constant.
- A good approximation for the coherence time is

$$T_c \approx \frac{9}{16 \pi f_m}$$

- From the previous example, T_c =2.1 ms. If the symbol is larger than 2.1 ms, the symbol is distorted.
- The minimum symbol rate in the previous channel should be

$1/2.1 \times 10^{-3}$ = 500 symbols/sec

Fade rate and fade duration



- The signal "level" is the dB above or below the RMS value
- Fade rate determines how quickly the amplitude changes (frequency → Doppler Spectrum)
- Fade duration tells us how long the channel is likely to be "bad"
- Design error correcting codes and interleaving depths to correct errors caused by fading

Fade rate and duration

Fade rate or Level crossing rate: $N_R = \sqrt{2\pi} f_m \bar{r} \exp(-\bar{r}^2)$ $\qquad \bar{r} = r / r_{rms}$

Average fade duration: $$\tau = \frac{\exp(\bar{r}^2) - 1}{\bar{r} f_m \sqrt{2\pi}} \qquad \bar{r} = r / r_{rms}$$

f_m = maximum Doppler shift = f_c v/c
v is the mobile velocity
c is the speed of light
f_c is the carrier frequency

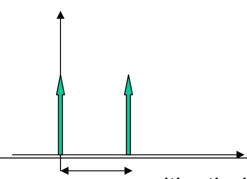
- This provides an idea of how long a signal will be in fade for a level below the mean signal level, i.e. how many bits could be in error.
- Example: v= 30m/sec, fc = 900 MHz, 10 Db fade ➔ r = .316, fm = 90Hz, Nr = 64.5 /sec

Small scale fading-time dispersion

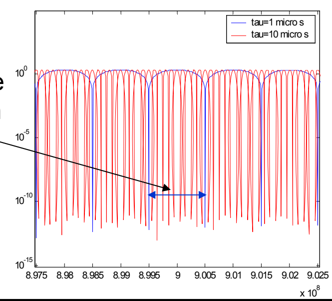
- When data rates are high, the symbol duration becomes smaller
- the channel becomes wideband or frequency selective, i.e. the frequency response is no longer flat for all frequencies in the signal.
- Consequently, the time dispersion of signals happen.

Time dispersion in a radio channel

- Time domain view
- There are multipath components that can cause inter-symbol interference if the symbol duration is smaller than the multipath delay spread
- Linear time invariant impulse response
  - $h(t) = \sum \alpha_k \delta(t-\tau_k) e^{j\theta_k}$



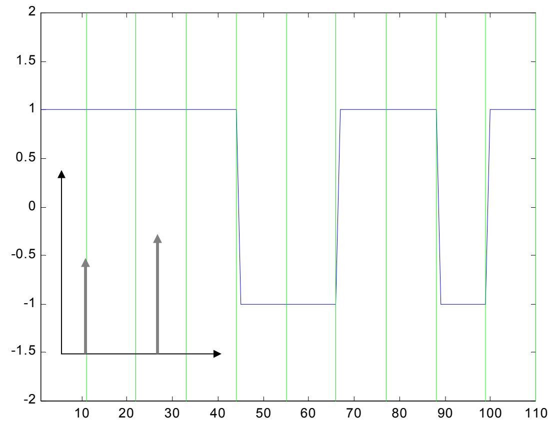
- Frequency domain view
- There are multipath components that can cause the radio channel to have a "coherence bandwidth"
- The coherence bandwidth limits the maximum data rate that can be supported over the channel



Example in a two-path channel

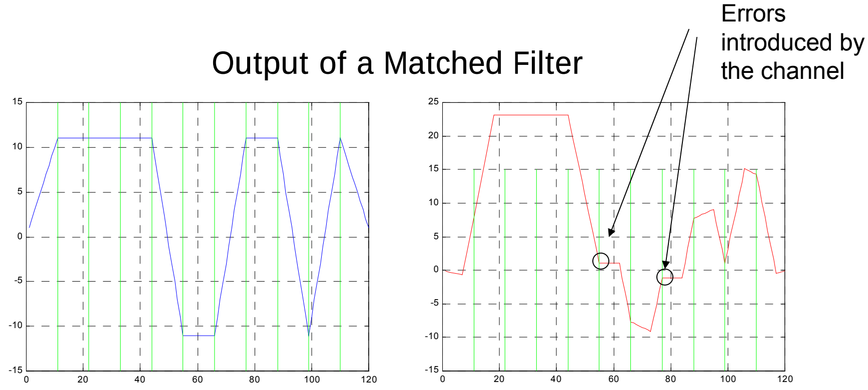
- Random data sequence of ten data bits
  - Spreading by 11 chips using a Barker pulse
- Two path channel with inter-path delay of 17 chips > bit duration
- Multipath amplitudes
  - Main path: 1
  - Second path: 1.1
- Just for illustration!
- Reality:
  - Many multipath components
  - Rayleigh fading amplitudes
  - Noise!

Data and Channel



Output with Multipath

Output of a Matched Filter



Without Multipath With Multipath

The RMS Delay Spread

- The RMS delay spread is a function of the α_k and $\nwarrow_k$
  - α_k usually are Rayleigh distributed
  - $\nwarrow_k$ are fixed, Poisson, modified Poisson etc.
- The larger the RMS delay spread, the smaller is the data rate that can be supported over the channel
- RMS delay spread varies between a few microseconds in urban areas to a few nanoseconds in indoor areas
  - Higher data rates are possible indoor and not outdoor !
- The coherence bandwidth determines whether a signal is narrowband or wideband

Multipath delay spread and coherence bandwidth

•Channel response: $h(t) = \sum_{i=1}^{L} \alpha_i \delta(t-\tau_i) e^{j\varphi_l}$ $\quad E\{\alpha_i^2\} = 2\sigma_i^2$

•***RMS Delay spread:*** $\tau_{rms} = \sqrt{\frac{\sum_{k=1}^{N} \tau_k^2 \sigma_k^2}{\sum_{k=1}^{N} \sigma_k^2} - \left(\frac{\sum_{k=1}^{N} \tau_k \sigma_k^2}{\sum_{k=1}^{N} \sigma_k^2}\right)^2}$

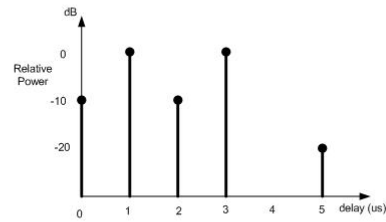
Measured RMS delay spread values

•Indoor areas: 30-300 ns
•Open areas: ≈ 0.2 us
•Suburban areas: ≈1 us
•Urban areas: 1-5 us
•Hilly urban areas: 3-10 us

•***Coherence bandwidth*** B_c of the channel is approximately $1/5\tau_{rms}$

Example

Consider the power delay profile given here



$$\tau_M = \frac{0.1\times 0 + 1\times 1 + 0.1\times 2 + 1\times 3 + 0.01\times 5}{0.1+1+0.1+1+0.01}$$
$$= 1.47\ \mu s$$

$$\langle \tau^2 \rangle = \frac{0.1\times 0^2 + 1\times 1^2 + 0.1\times 2^2 + 1\times 3^2 + 0.01\times 5^2}{0.1+1+0.1+1+0.01}$$
$$= 4.82\ \mu s^2$$

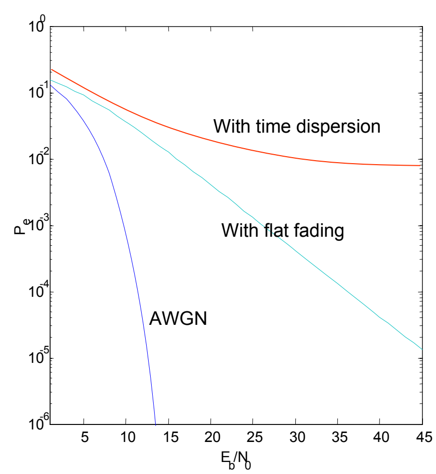
$$\tau_{RMS} = \sqrt{4.82 - 1.47^2} = 1.39\ \mu s$$

$$\mathrm{B_c} = \frac{1}{5\times 1.39} = 143.9\ kHz$$

σ_k PI	τ_k Delay(us)
0.1	0
1	1
0.1	2
1	3
0.01	5

What does time dispersion do?

- Multipath delay or coherence bandwidth results in **irreducible error rates**
- Even if the power is infinitely increased, there will be large number of errors
- The only means of overcoming the effects of dispersion are to use diversity techiques such as
  - Direct sequence spread spectrum
  - Orthogonal frequency division multiplexing (OFDM)
  - Equalization



Summary

- Considered basics of wireless communication
- Signal propagation
  - Coverage modeling
  - Small Scale Fading effects
- Antennas
- Modulation