Path Loss

Radio Wave Propagation

- The wireless radio channel puts fundamental limitations to the performance of wireless communications systems
- Radio channels are extremely random, and are not easily analyzed
- Modeling the radio channel is typically done in statistical fashion

Linear Path Loss

- Suppose s(t) of power P_t is transmitted through a given channel
- The received signal r(t) of power P_r is averaged over any random variations due to shadowing.
- We define the linear path loss of the channel as the ratio of transmit power to receiver power

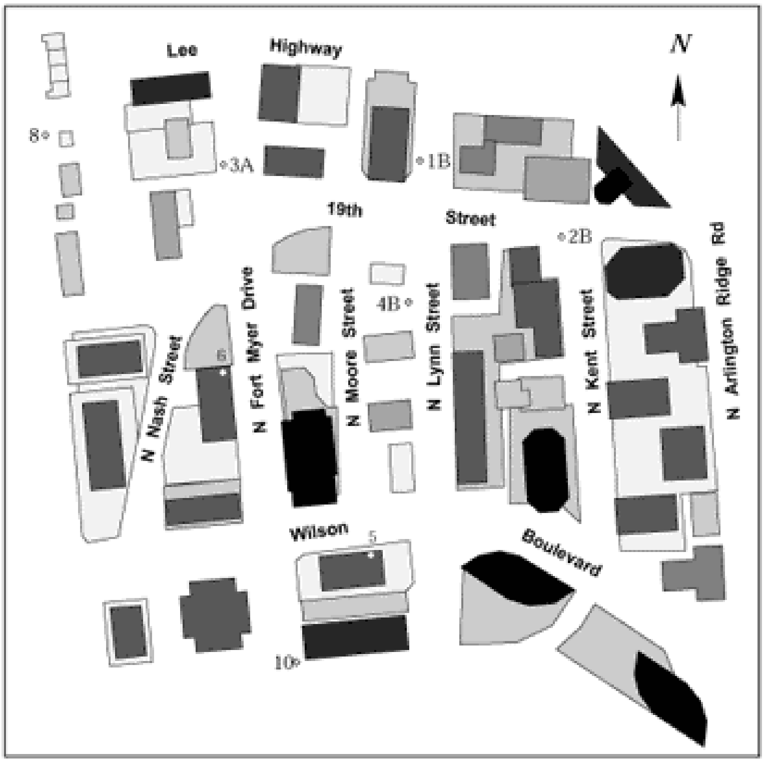
$$P_L = \frac{P_t}{P_r}$$

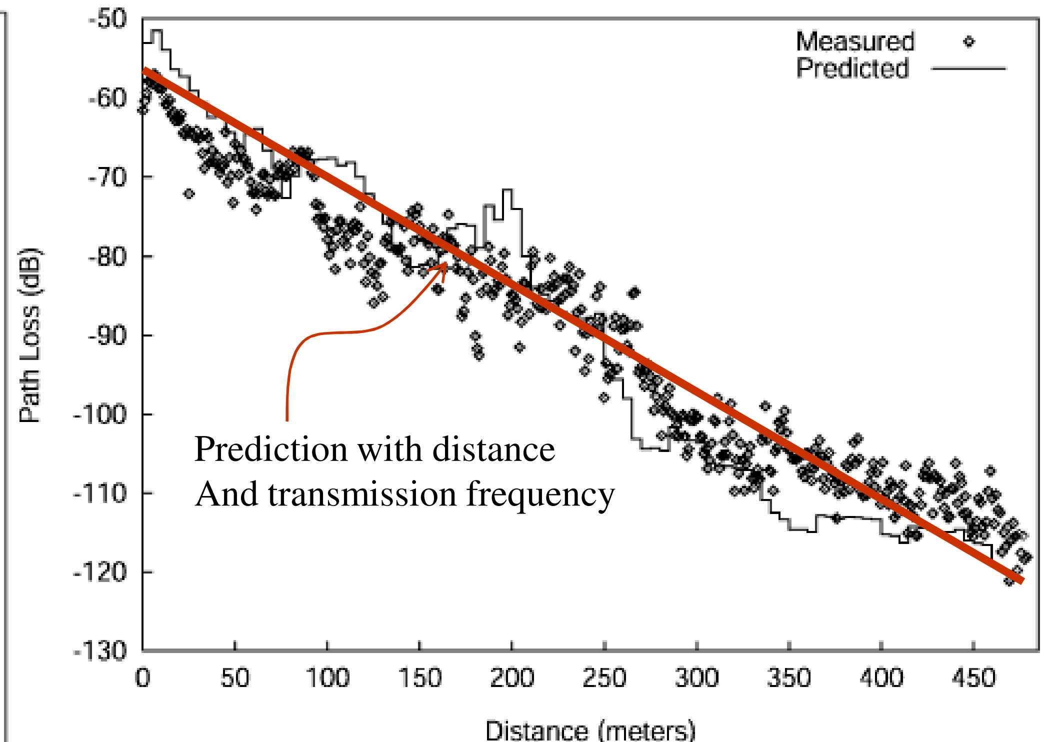
- We define the path loss of the channel also in dB

$$P_L \text{ dB} = 10 \log_{10} \frac{P_t}{P_r} \text{ dB} \;\; \text{(nonnegative number)}$$

Experimental results

- The measurements and predictions for the receiving van driven along 19th St./Nash St.





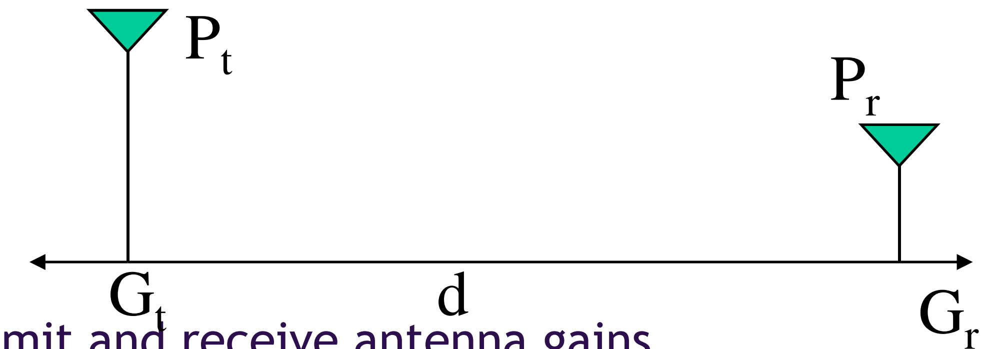
Line-of-Sight Propagation

- Attenuation
  - The strength of a signal falls off with distance
- Free Space Propagation
  - The transmitter and receiver have a clear line of sight path between them. No other sources of impairment!
  - Satellite systems and microwave systems undergo free space propagation
  - The free space power received by an antenna which is separated from a radiating antenna by a distance is given by Friis free space equation

Friis Free Space Equation

- The relation between the transmit and receive power is given by Friis free space equations:

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



- G_t and G_r are the transmit and receive antenna gains
- λ is the wavelength
- d is the T-R separation
- P_t is the transmitted power
- P_r is the received power
- P_t and P_r are in same units
- G_t and G_r are dimensionless quantities.

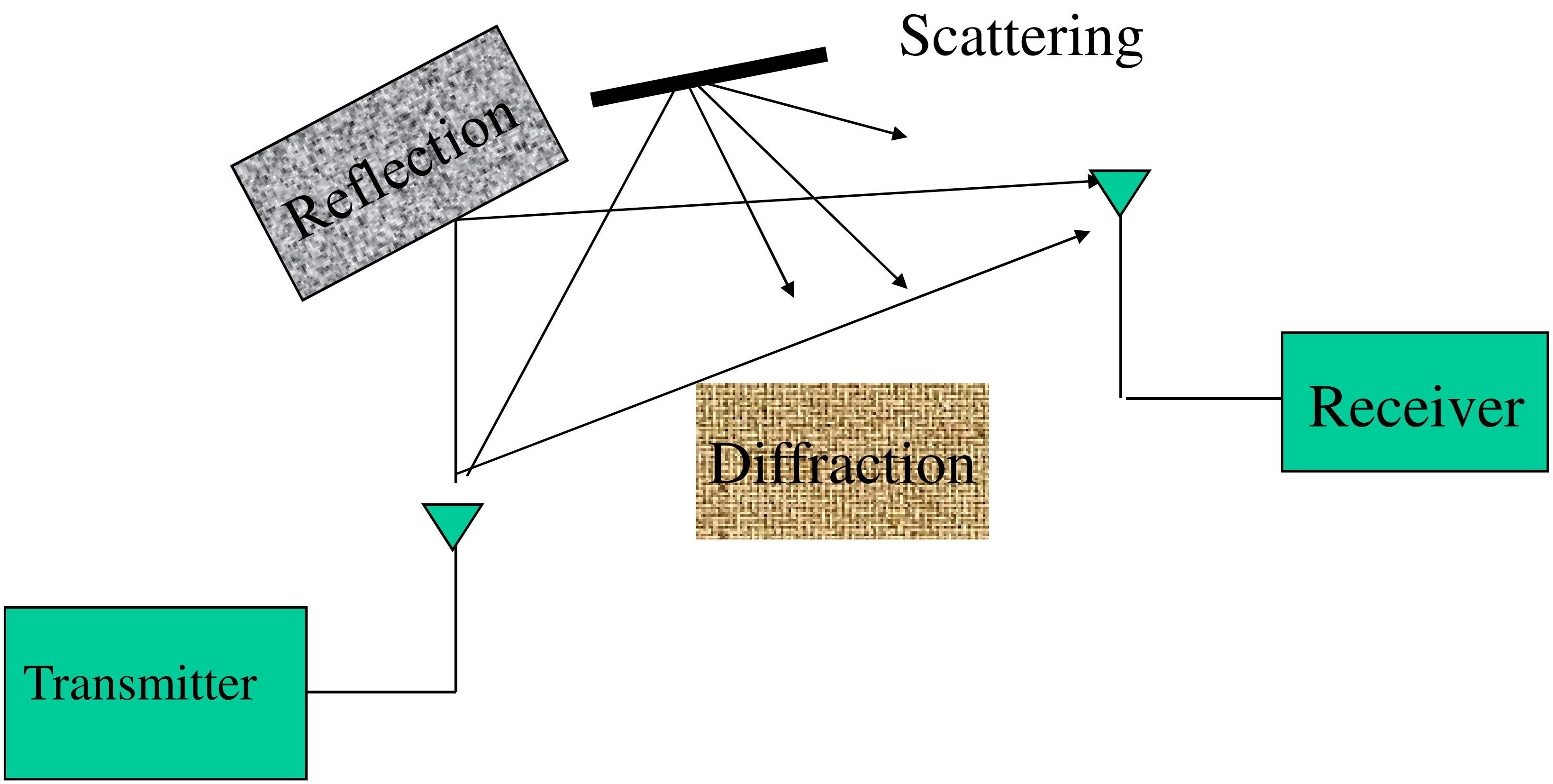
Free Space Propagation Example

- The Friis free space equation shows that the received power falls off as the square of the T-R separation distances
  - The received power decays with distance by 20 dB/decade
- EX: Determine the isotropic free space loss at 4 GHz for the shortest path to a geosynchronous satellite from earth (35,863 km).
- $P_L = 20\log_{10}(4\times10^9) + 20\log_{10}(35.863\times10^6) - 147.56\text{dB}$
- $P_L = 195.6$ dB
- Suppose that the antenna gain of both the satellite and ground-based antennas are 44 dB and 48 dB, respectively
- $P_L = 195.6 - 44 - 48 = 103.6$ dB
- Now, assume a transmit power of 250 W at the earth station. What is the power received at the satellite antenna?

Basic Propagation Mechanisms

- Reflection, diffraction, and scattering:
- Reflection occurs when a propagating electromagnetic wave impinges upon an object
- Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp edges
- Scattering occurs when the medium through which the wave travels
  - consists of objects with dimensions that are small compared to the wavelength, or
  - the number of obstacles per unit volume is large.

Basic Propagation Mechanisms

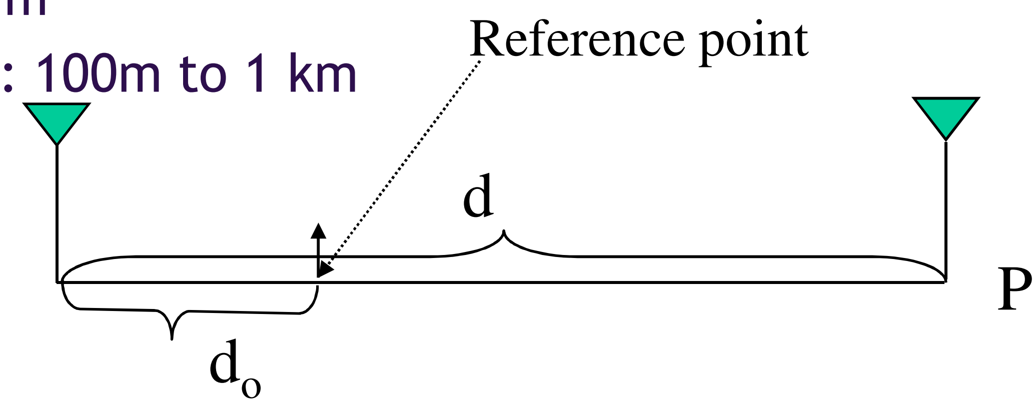


Free Space Propagation

- Can be also expressed in relation to a reference point, d_0

$$P_r(d) = P_t K \left(\frac{d_0}{d}\right)^2 \qquad d \geq d_0$$

- K is a unitless constant that depends on the antenna characteristics and free-space path loss up to distance d_0
- Typical value for d_0:
  - Indoor:1m
  - Outdoor: 100m to 1 km



Simplified Path Loss Model

- Complex analytical models or empirical measurements when tight system specifications must be met
  - Best locations for base stations
  - Access point layouts
- However, use a simple model for general tradeoff analysis

$$P_r = P_t K \left[\frac{d_0}{d}\right]^\gamma$$

- dB attenuation model

$$P_r \text{ dBm} = P_t \text{ dBm} + K \text{ dB} - 10\gamma \log_{10}\left[\frac{d}{d_0}\right]$$

- d_0: close-in reference point

Typical Pathloss Exponents

- Empirically, the relation between the average received power and the distance is determined by the expression where γ is called the path loss exponent
- The typical values of γ are as: $P_r \propto d^{-\gamma}$

Environment	Path Loss exponent, γ
Free Space	2
Urban Area	2.7 to 3.5
Suburban Area	3 to 5
Indoor (line-of-sight)	1.6 to 1.8

Radio System Design

- <u>Fade Margins:</u> The difference between the normal received power and the power required for minimum acceptable performance is referred to as the fade margin. Greater fade margins imply less frequent occurrences of minimum performance levels.
- When large fade margins are provided, the received signal power during unfaded conditions is so strong that bit errors are virtually nonexistent.
- To minimize dynamic range requirements in a receiver and reduce interference between systems, adaptive transmitter power control (ATPC) is sometimes used. Thus, when excess power is unnecessary, it is not used.

Noise Power

- Noise power in a receiver is usually dominated by thermal noise generated in the frontend receiver amplifier. In this case, the noise power can be determined as follows:

$$P_N = FkT_0B$$

F=the receiver noise figure
T_0= the reference receiver temperature in degrees Kelvin (290^0)
K=1.38×10^{-23} is Boltzmann's constant
B=the receiver bandwidth

- The noise figure of any device is defined as the ratio of the input SNR to the output SNR.

$$F=SNR_{in}/SNR_{out}$$

System Gain/Fade Margin

- System Gain is defined to be the difference, in decibels, of the transmitter output power and the minimum receive power for the specified error rate:

$$A_s = 10\log_{10}\left(\frac{P_t}{P_{req}}\right)$$

- Combining the noise figure and the system gain equations:

$$A_s = 10\log_{10}\left(\frac{P_t}{\mathrm{SNR}FkT_0B}\right) - D$$

D is the degradation from the ideal performance

$\mathrm{SNR}=P_{req}/P_N$

- System gain, in conjunction with antenna gains and path losses, determines the fade margin (assuming free space path loss)

$$\text{Fade Margin} = A_s + G_T + G_R + 20\log_{10}\lambda - A_f - 20\log_{10}(4\pi d)$$

  - A_f=system (branching and coupling) loss, G_T and G_R=transmit and receive antenna gains, λ=transmitted wavelength($\lambda=c/f_c$), d=distance

Cell Radius Prediction

- The signal level is same on a circle centered at the base station with radius R
- Find the distance R such that the received signal power cannot be less than P_{min} dBm
- The received signal power at a distance d=R is specified by

$$P_r(d)(dB) = P_t(dB) + 10\log_{10} K - 10\gamma \log_{10}\left(\frac{d}{d_0}\right)$$

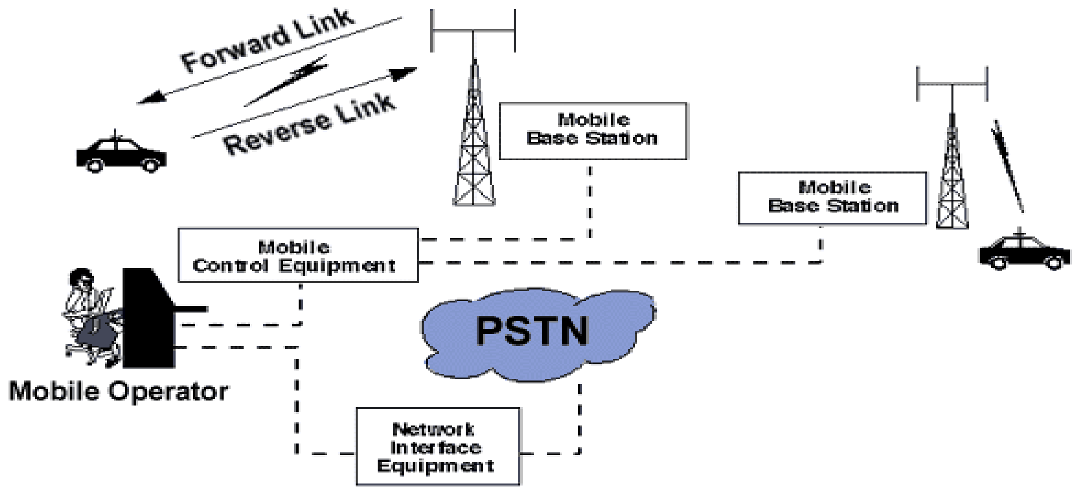
$$P_r(R) \leq P_{min}$$

- Solving the above equation for the radius R, we obtain

$$R \leq d_0 \times 10^{0.1(P_T/\gamma)}$$

  - where $P_T = P_{min} - P_t - 10\log_{10} K$

Mobile Telephone Network

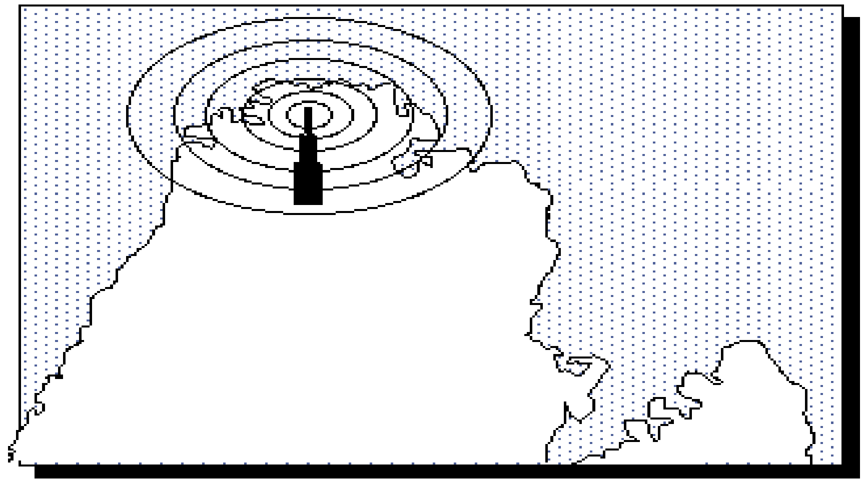


- Each mobile uses a separate, temporary radio channel
- The cell site talks to many mobiles at once
- Channels use a pair of frequencies for communication
  - forward link
  - reverse link

Limited Resource → Spectrum

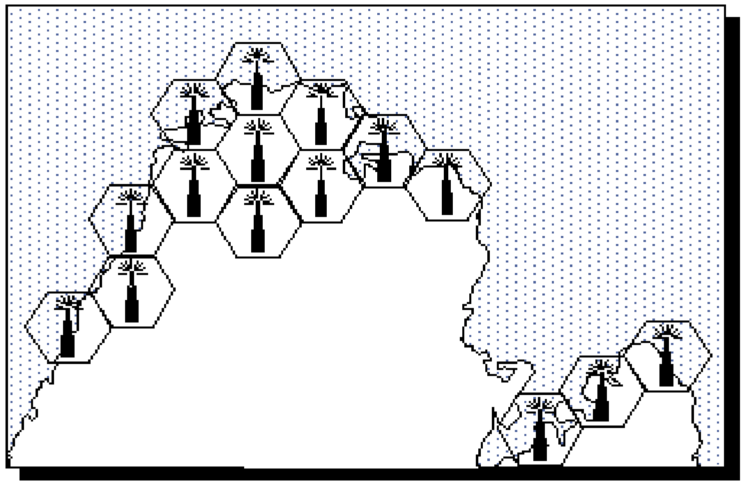
- Wireline communications, i.e., optical, 10^{-10}
- Wireless communications impairments far more severe
  - 10^{-2} and 10^{-3} are typical operating BER for wireless links
  - More bandwidth can improve the BER and complex modulation and coding schemes
- Everybody wants bandwidth in wireless, more users
- How to share the spectrum for accommodating more users

Early Mobile Telephone System



- Traditional mobile service was structured in a fashion similar to television broadcasting
- One very powerful transmitter located at the highest spot in an area would broadcast in a radius of up to 50 kilometers
- This approach achieved very good coverage, but it was impossible to reuse the frequencies throughout the system because of interference

Cellular Approach



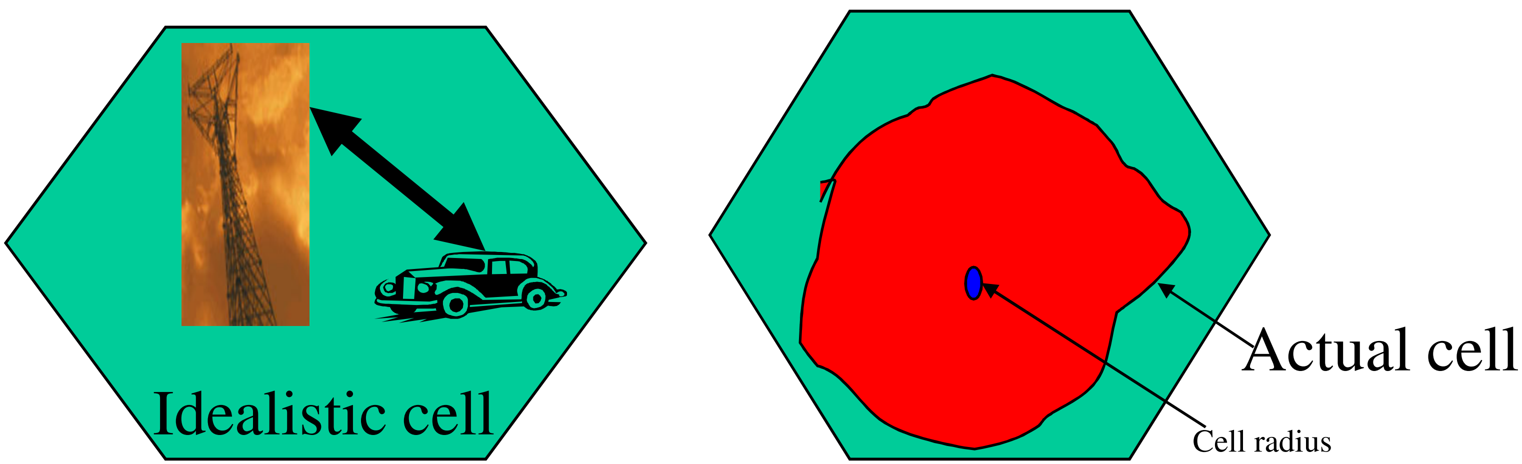
- Instead of using one powerful transmitter, many low-power transmitters were placed throughout a coverage area to increase the capacity
- Each base station is allocated a portion of the total number of channels available to the entire system
- To minimize interference, neighboring base stations are assigned different groups of channels

Why Cellular?

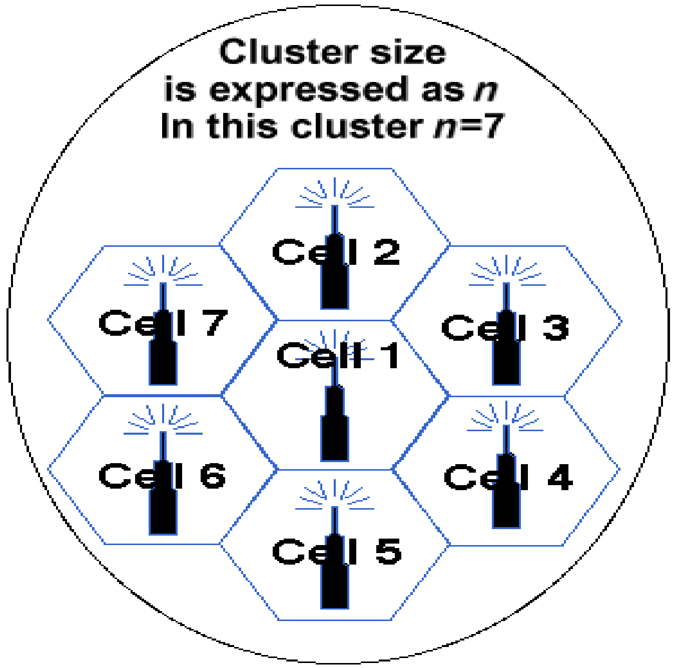
- By systematically spacing base stations and their channel groups, the available channels are:
  - distributed throughout the geographic region
  - maybe reused as many times as necessary provided that the interference level is acceptable
- As the demand for service increases the number of base stations may be increased thereby providing additional radio capacity
- This enables a fixed number of channels to serve an arbitrarily large number of subscribers by reusing the channel throughout the coverage region

Cells

- A cell is the basic geographic unit of a cellular system
- The term *cellular* comes from the honeycomb shape of the areas into which a coverage region is divided
- Each cell size varies depending on the landscape
- Because of constraints imposed by natural terrain and man-made structures, the true shape of cells is not a perfect hexagon



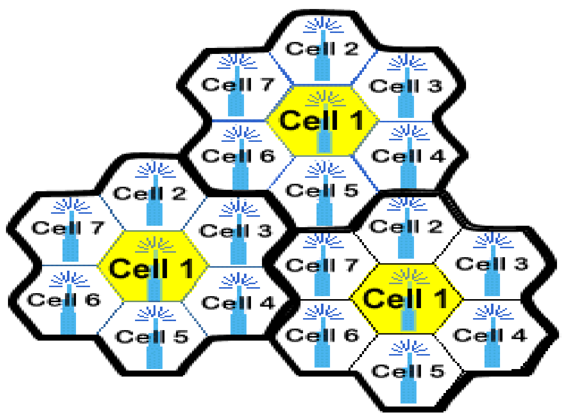
Cell Cluster Concept



- A cluster is a group of cells
- No channels are reused within a cluster

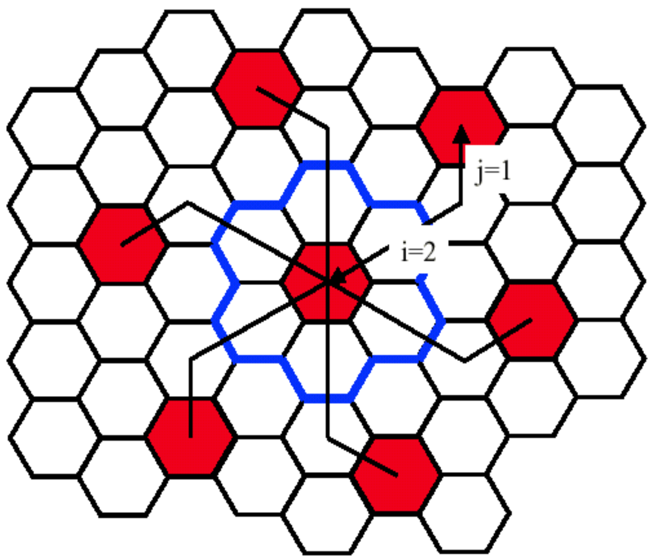
Frequency Reuse

- Cells with the same number have the same set of frequencies
- 3 clusters are shown in the figure
- Cluster size N = 7
- Each cell uses 1/N of available cellular channels (frequency reuse factor)

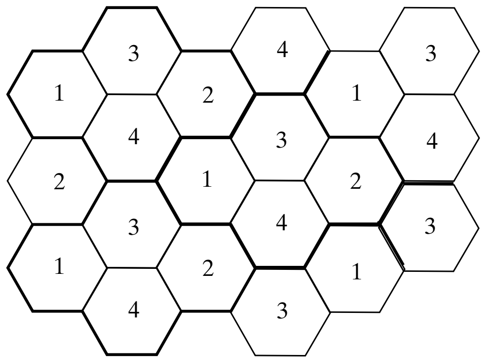


Method for finding Co-channel Cells

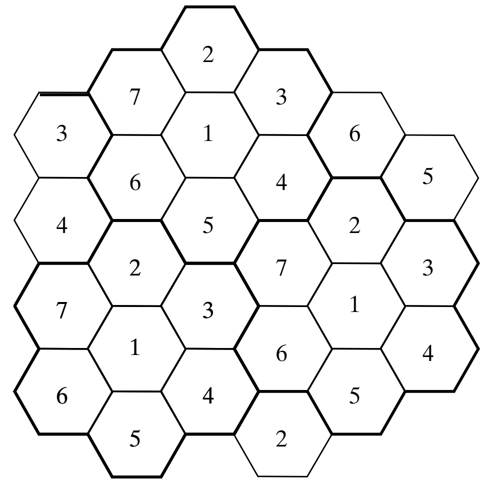
- Hexagonal cells: N can only have values which satisfy $N = i^2 + ij + j^2$ where i and j are non-negative integers
- To find the nearest co-channel neighbors of a particular cell one must do the following
  - Move i cells along any chain of hexagons
  - Turn 60 degrees counter-clockwise and move j cells
- This method is illustrated for i = 2 and j = 1



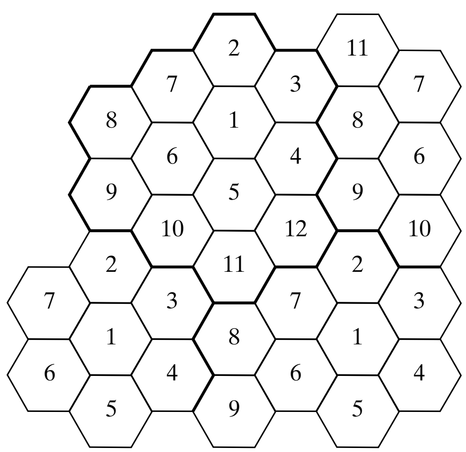
Hexagonal Cell Clusters



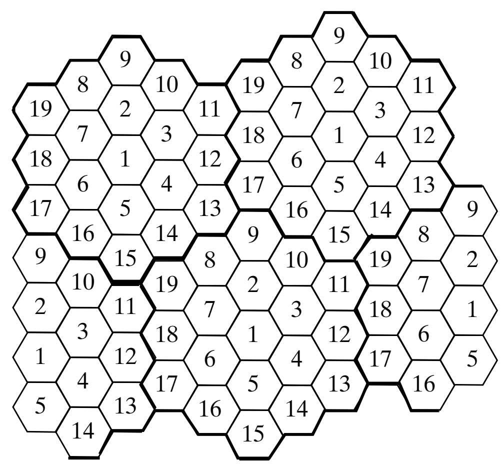
(a) $i = 2$ and $j = 0$



(b) $i = 1$ and $j = 2$



(c) $i = 2$ and $j = 2$

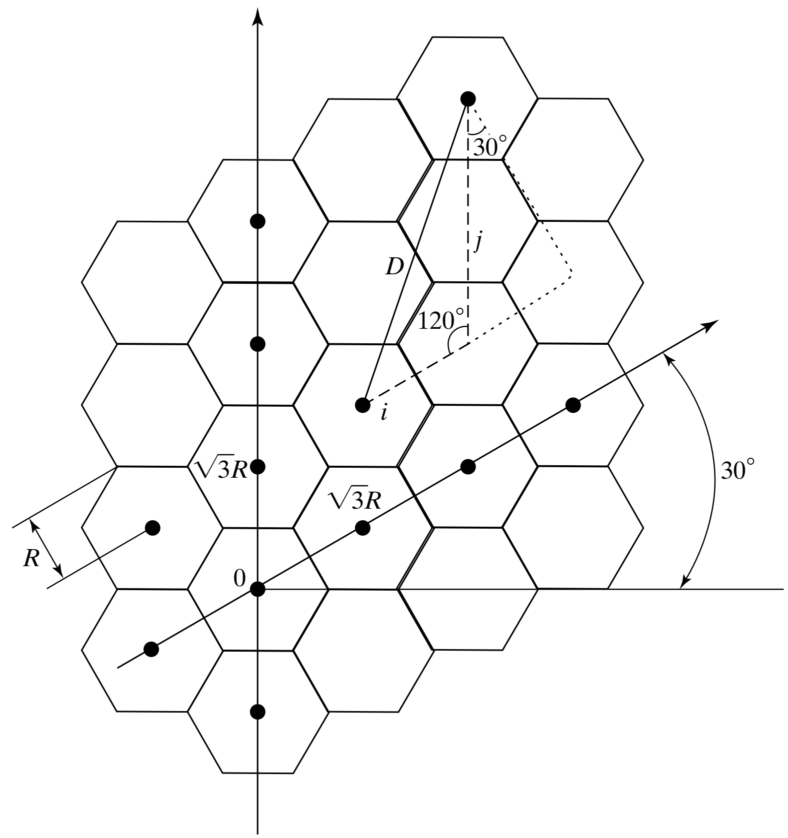


(d) $i = 2$ and $j = 3$

Geometry of Hexagonal Cells

- Distance between nearest cochannel cells
- A hexagon has exactly six equidistant neighbors separated by multiple of 60 degrees
- Approximate distance between the centers of two nearest cochannel cells is

$$D = \sqrt{3N}R$$



Frequency Reuse Ratio

- The frequency reuse ratio is defined as

$$q = \frac{D}{R}$$

- The frequency reuse patterns below apply to hexagonal cells,

$$q = \frac{D}{R} = \sqrt{3N}$$

Frequency Reuse Pattern (i, j)	Cluster Size N	Frequency Reuse Ratio q
$(1, 1)$	3	3.00
$(2, 0)$	4	3.46
$(2, 1)$	7	4.58
$(3, 0)$	9	5.20
$(2, 2)$	12	6.00
$(3, 1)$	13	6.24
$(3, 2)$	19	7.55
$(4, 1)$	21	7.94
$(3, 3)$	27	9.00
$(4, 2)$	28	9.17
$(4, 3)$	37	10.54

Co-channel Interference and System Capacity

- There are several cells that use the same set of frequencies in a given coverage area
  - these cells are called co-channel cells
  - the interference between signals from these cells is co-channel interference
- Co-channel interference cannot be combated by simply increasing the carrier power of a transmitter
  - an increase in carrier transmit power increases the interference to neighboring co-channel cells
- To reduce co-channel interference
  - co-channel cells must be physically separated by a minimum distance to provide sufficient isolation due to propagation

Frequency reuse ratio

- When the size of each cell is approximately the same, and the base stations transmit the same power, then

$$q = \frac{D}{R} = \sqrt{3N}$$

  - if the radius of the cell is R
  - and the distance between centers of the nearest co-channel cells is D
  - N is the cluster size
  - the parameter q is called the co-channel reuse ratio
- A small value of q provides larger capacity since N is small
- A large value of q improves the transmission quality

Signal to Interference Ratio (SIR)

- Let N_I be the number of co-channel interfering cells
- P_r is the desired signal power from the desired base station
- P_i is the interference power caused by the i^{th} interfering co-channel cell base station
- The SIR (S/I) at the desired mobile receiver is

$$\frac{S}{I} = \frac{P_r}{\sum_{i=1}^{N_I} P_i}$$

Recall Power-Distance Relation

- Average received signal strength at any point in a mobile radio channel is

$$P_r = P_t K \left(\frac{d}{d_0} \right)^{-\gamma}$$

  - If d_0 is the close-in reference point in the far field region of the antenna from the transmitting antenna
  - P_t is the transmitter power
  - γ is the path loss exponent
  - P_r is the received power at a distance d

Approximated SIR

- SIR for a mobile can be approximated as

$$\frac{S}{I} = \frac{R^{-\gamma}}{\sum_{i=1}^{N_I} (D_i)^{-\gamma}}$$

  - If the transmit power of each base station is equal
  - γ is same throughout the coverage area
  - D_i is the distance of the i^{th} interferer from the mobile
- SIR as considering only the first layer of interfering cells can be simplified as

$$\frac{S}{I} = \frac{(D/R)^{\gamma}}{N_I} = \frac{\left(\sqrt{3N}\right)^{\gamma}}{N_I}$$

  - if all interfering base stations are equi-distant from each other and this distance is $D_i \approx D$

Approximated SIR

- With hexagon shaped cellular systems, there are always six cochannel interfering cells in the first tier.
- The frequency reuse ratio can be expressed as

$$q = \left(N_I \times \frac{S}{I}\right)^{1/\gamma} = \left(6 \times \frac{S}{I}\right)^{1/\gamma}.$$

- Example: For the U.S. AMPS analog FM system, a value of S/I = 18 dB or greater is acceptable.
  - With a path loss exponent of γ=4, the frequency reuse ratio q is determined as

$$q = (6 \times 10^{1.8})^{1/4} = (6 \times 63.1)^{0.25} \simeq 4.41.$$

  - Therefore, the cluster size N should be

$$N = q^2/3 = 6.49 \simeq 7.$$

S/I Ratio vs Cluster Size

- Suppose the acceptable S/I in a cellular system is 20 dB. $\gamma=4$, what is the minimum cluster size? Consider only the closest interferers.