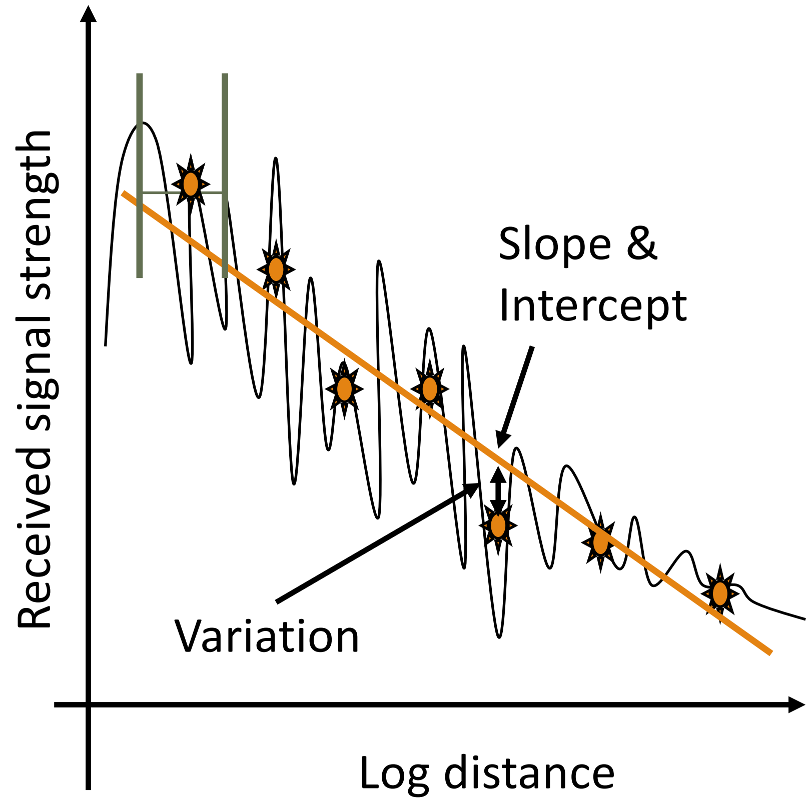
Lecture 5

Large Scale Fading and Network Deployment

+ Large Scale Fading

- "Large" scale variation of signal strength with distance
  - Consider **average** signal strength values
  - The average is computed either over short periods of time or short lengths of distance
  - A straight line is fit to the average values
- The slope and the intercept give you the expression for the *path loss*
- The variation around the fit is the shadow fading component

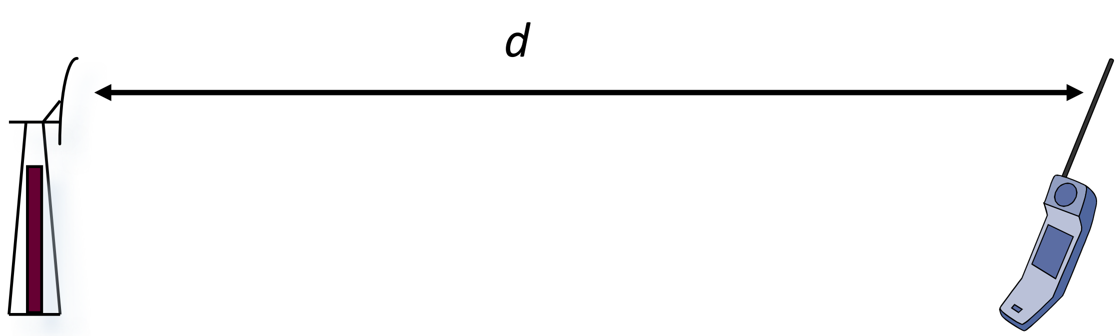


Path Loss Models

- Path Loss Models are 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 sight 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 with distance

+ The Free Space Loss

- Assumption
  - 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, and the received power is P_r
- The *path loss* is $L_p = P_t\,(\text{dB}) - P_r\,(\text{dB})$
- Isotropic antennas
  - Antennas radiate and receive equally in all directions with unit gain



The Free Space Model

- The relationship between P_t and P_r is given by

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

  - The wavelength of the carrier is $\lambda = c/f$

- In dB

$$P_r\,(\text{dBm}) = P_t\,(\text{dBm}) - 21.98 + 20\log_{10}(\lambda) - \mathbf{20\log_{10}(\boldsymbol{d})}$$

$$L_p(d) = P_t - P_r = 21.98 - 20\log_{10}(\lambda) + \mathbf{20\log_{10}(\boldsymbol{d})}$$
$$= L_0 + 20\log_{10}(d)$$

  - L_0 is called the path loss at the first meter (put $d = 1$)

- We say there is a **20 dB per decade** loss in signal strength

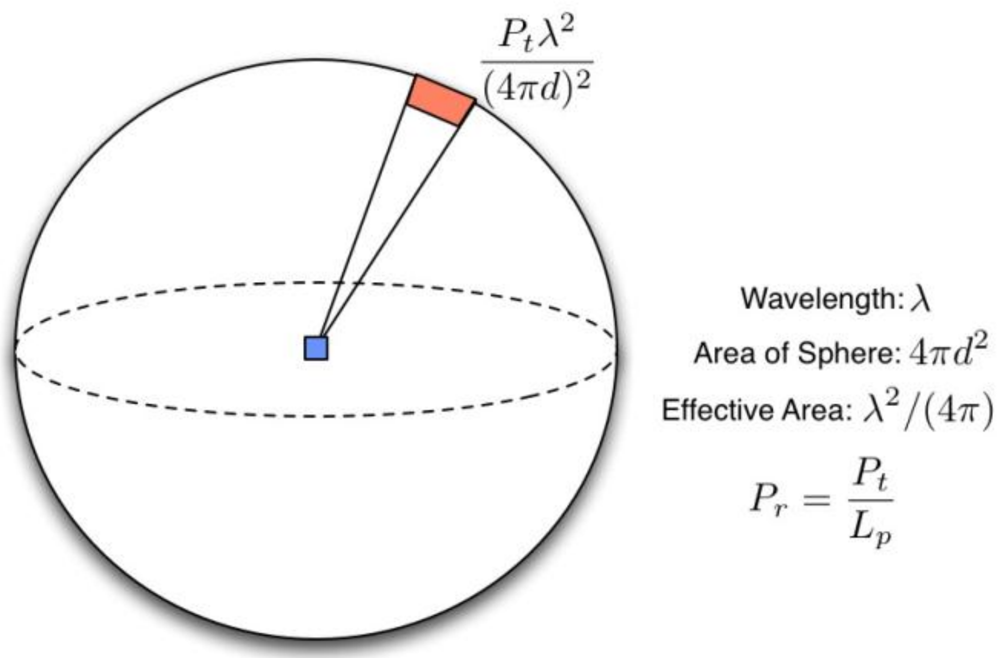
A simple explanation of free space loss

- 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:

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



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

Summary: Free space loss

- Transmit power P_t and 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:

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

- where *d* is in meters

In dB, we have:

$$P_r\,(\text{dBm}) = P_t\,(\text{dBm}) - 21.98 + 20\log_{10}(\lambda) - 20\log_{10}(d)$$

$$\text{Path Loss} = L_p = P_t - P_r = 21.98 - 20\log_{10}(\lambda) + 20\log_{10}(d)$$

Free Space Propagation

- Notice that factor of 10 increase in distance
  - => 20 dB increase in path loss (20 dB/decade)
- Note that higher the frequency the greater the path loss for a fixed distance

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

Distance	880 MHz	1960 MHz
1 km	91.29 dB	98.25 dB

7 dB greater path loss for PCS band compared to cellular band in the US

Example

- Consider Design of a Point-to-Point link connecting LANs in separate buildings across a freeway
  - Distance .25 mile
  - Line of Sight (LOS) communication
  - Unlicensed spectrum – 802.11b at 2.4GHz
- Maximum transmit power of 802.11 AP is P_t = 24 dBm
- The minimum received signal strength (RSS) for 11 Mbps operation is -80 dBm
- Will the signal strength be adequate for communication?
- Given LOS
  - Can approximate propagation with Free Space Model

+ Example (Continued)

- Example
  - Distance .25 mile ~ 400m; Receiver Sensitivity Threshold = - 80dBm
- The Received Power P_r is given by: $P_r = P_t$ - Path Loss

$P_r = P_t - 21.98 + 20 \log_{10}(\lambda) - 20 \log_{10}(d)$

$= 24 - 21.98 + 20 \log_{10}(3\text{x}10^8/2.4\text{x}10^9) - 20 \log_{10}(400)$

$= 24 - 21.98 - 18.06 - 52.04$

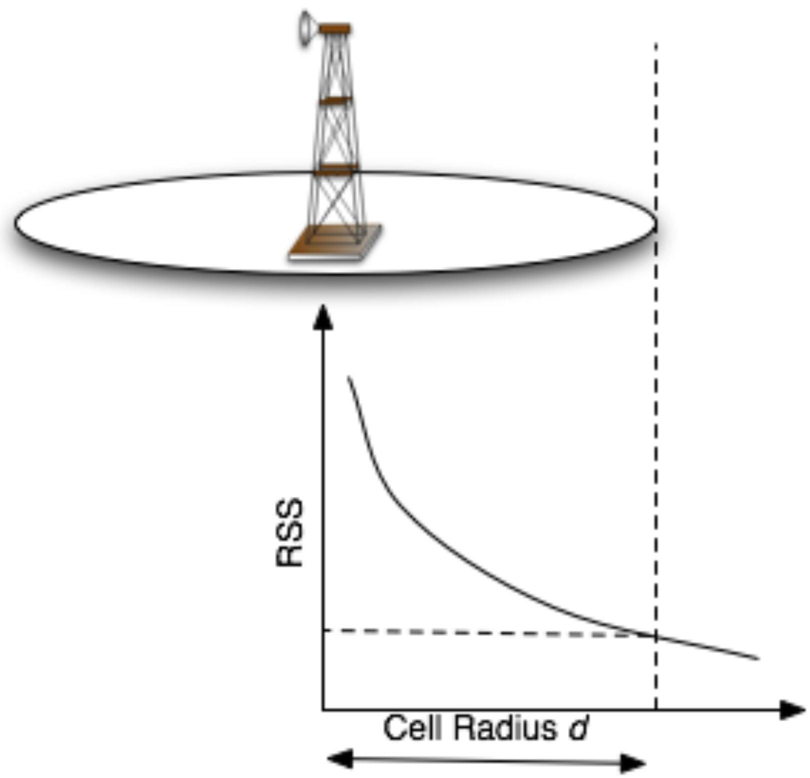
$= 24 - 92.08 = -68.08$ dBm

$L_0 = 40$ dB at 2.4 GHz

P_r is well above the required -80 dBm for communication at the maximum data rate – so link should work fine

Cell/Radio Footprint

- The Cell is the area *covered* by a single transmitter
- Path loss model roughly determines the size of cell
- What does "covered" mean?



Link Budget

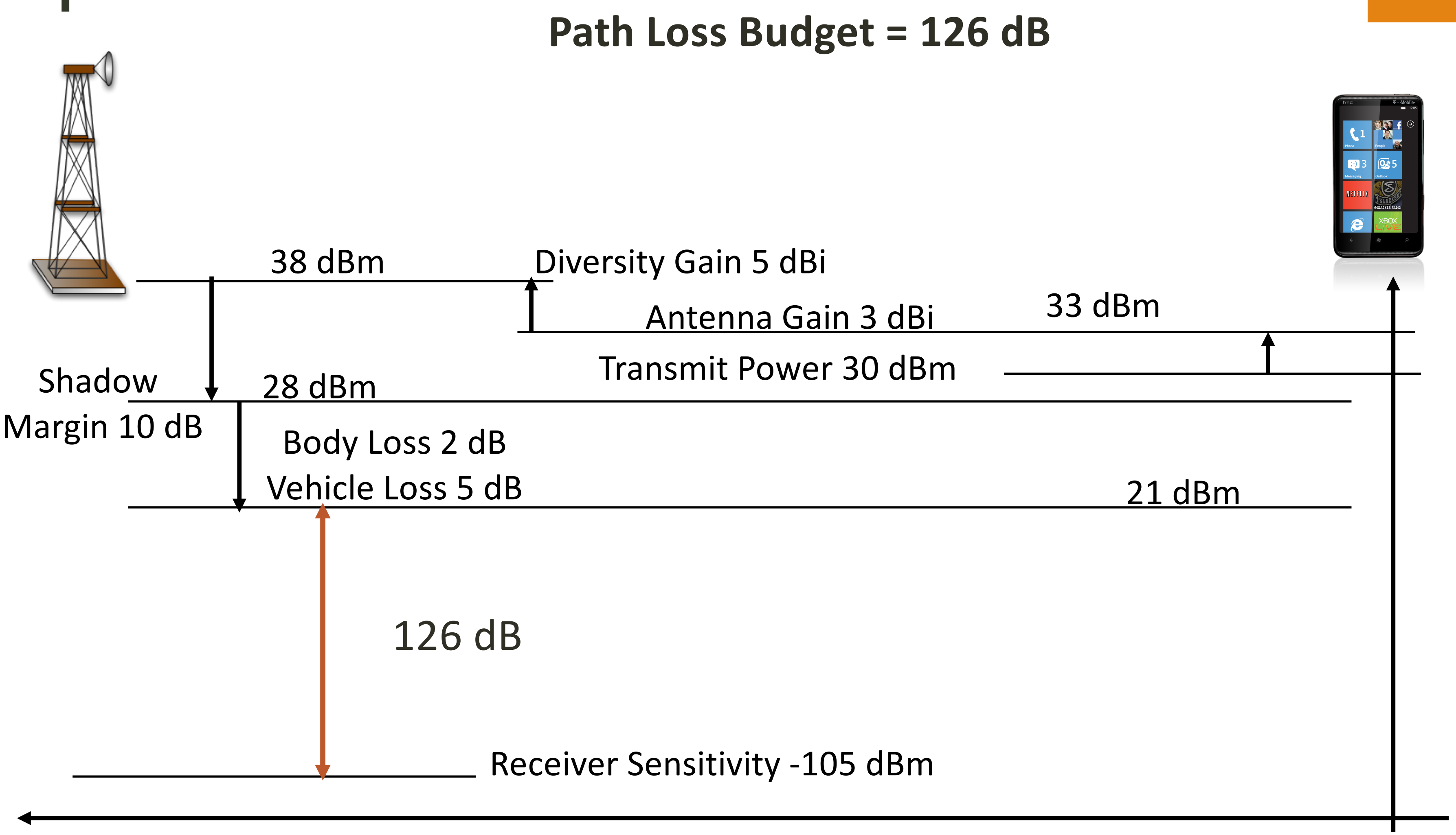
- Typical Factors in Link Budget
  - Transmit Power (in dBm),
  - Antenna Gain, Diversity Gain
  - Receiver Sensitivity
  - Margins
    - Shadow Margin, Interference Margin, Fading Margin
  - Losses
    - Vehicle Penetration Loss (3-6 dB)
    - Body Loss (2-3 dB)
    - Building Penetration Loss (5-20 dB depending on building material
    - Electronic Losses: Combiner Loss, Filter Loss, etc.
- Gains are added, Losses are subtracted (e.g.,f = 1900 MHz)

Example of Link Budget

Link	Uplink	Downlink
Transmit power	30 dBm	30 dBm
Antenna gain	3 dBi	5 dBi
Diversity gain	5 dB	0 dB
Shadow margin	10 dB	10 dB
Body penetration	2 dB	2 dB
Vehicle penetration	5 dB	5 dB
Receiver sensitivity	-105 dBm	-90 dBm
Path Loss Budget	126 dB	108 dB

Typical Cellular System is Downlink Limited!

Calculation of link Budget: Uplink



Determining Coverage

- Link Budget
  - Used to plan useful coverage of cells
  - Roundtrip performance of satellites, etc.
- Simply a balance sheet of all gains and losses on a transmission path.
  - Gains are added (transmit power, antenna gains)
  - Losses are subtracted (path loss)
- Used to find max allowable path loss in each link (i.e., uplink and downlink)
  - Ensure adequate RSS at end of each link

- Simple Example
  - The path loss budget is 108 dB
  - The path loss model is given by

$$L_p = 98 + 32 \log_{10} d$$

(d is in km)

- The cell radius should be

$$98 + 32 \log_{10} d = 108 \Rightarrow \log_{10} d = 10$$

$$d = 10^{(10/32)} = 2.05 \text{ km}$$

General Formulation of Path Loss

- Depending on the environment, it is seen that the path loss (or the RSS) varies as some power of the distance from the transmitter *d*

$$P_r(d) \propto \left(\frac{P_t}{d^\alpha}\right) \quad \text{OR} \quad P_r(d) = \left(\frac{P_t}{L_0(d/d_0)^\alpha}\right)$$

- Here α is called the path-loss exponent or the path-loss gradient or the distance-power gradient
- The quantity L_0 is a constant that is computed at a reference distance d_0
  - This reference distance is 1m in indoor areas and 100m or 1 km in outdoor areas

More Comments

- Path loss is a function of a variety of parameters
  - Terrain
  - Frequency of operation
  - Antenna heights
- Extremely site specific
  - Varies depending on environment
    - Example: indoor Vs outdoor
    - Example: microcell Vs macrocell
    - Example: rural Vs dense urban
- Large number of measurement results are available for different scenarios, frequencies and sites
- Empirical models are popular

Environment Based Path Loss

- Basic characterization: $L_p = L_0 + 10\alpha \log_{10}(d)$
  - L_0 is frequency dependent component (often path loss at 1m)
  - The parameter α is called the "path loss gradient" or exponent
  - The value of α determines how quickly the RSS falls with d

- α determined by measurements in typical environment
  - For example
    - $\alpha = 2.5$ might be used for rural area
    - $\alpha = 4.8$ 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
    - Two popular measurement based models are Okumura-Hata, and COST 231
  - Do some measurements and feed it into simulations (ray tracing)

Okumura-Hata Model

- Okumura collected measurement data and plotted a set of curves for path loss in urban areas around 900 MHz
  - Hata came up with an empirical model for Okumura's curves

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

$$a(h_{re}) = 3.2 (\log [11.75\, h_{re}])^2 - 4.97 \text{ dB}$$

  - Note: f_c is in MHz, d is in km, and antenna heights are in meters
  - This is valid only for $400 \leq f_c \leq 1500$ MHz for a large city
  - $30 \leq h_{te} \leq 200$ m; $1 \leq h_{re} \leq 10$ m;
- Other forms depending on the scenario

Example of Hata's Model

- Consider the parameters
  - 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?
  - $L_p = 120 = 118.14 + 31.8 \log d \Rightarrow d = 10^{(1.86/31.8)} = 1.14$ 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)

Indoor Path Loss Models

- Indoor applications
  - Wireless PBXs
  - Wireless Local Area Networks
- Approach is similar to outdoor models
  - Distances are smaller
  - Site specificity is more important
    - Variety of obstructions
    - Walls, floors, vending machines, bookcases, human beings etc.

Motley-Keenan and Rappaport Models

- Assume that the path loss exponent $\alpha = 2$
- Draw a straight line between the transmitter and receiver
- Assign a loss of some dB to each obstruction that is intersected by this straight line
  - Example: Concrete wall 7 dB, Cubicle partition 4 dB
- The path loss is given by:

$$L_p = L_0 + 20\log d + \sum_i m_i W_i + \sum_j n_j F_j$$

- m_i is the number of partitions of type i and W_i is the loss associated with that partition
- n_j is the number of floors of type j and F_j is the loss associated with that floor
- L_0 is determined as before (the path loss at one meter)

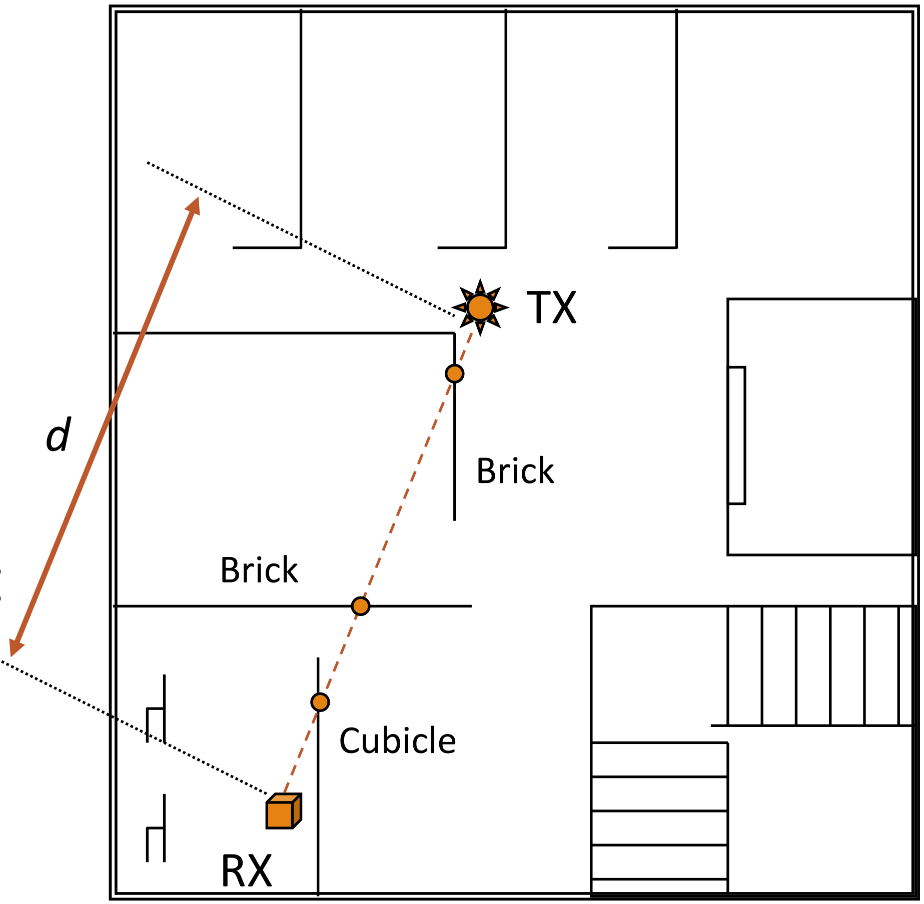
Sample numbers

Source: Harris Semiconductors

Signal attenuation of 2.4 GHz 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 of Partition Dependent Model

- Example:
  - The straight line intersects two brick walls and one cubicle partition
  - $L_p = L_0 + 20 \log d + 2W_{brick} + W_{cubicle}$
- In some models, the path loss exponent α is different from 2



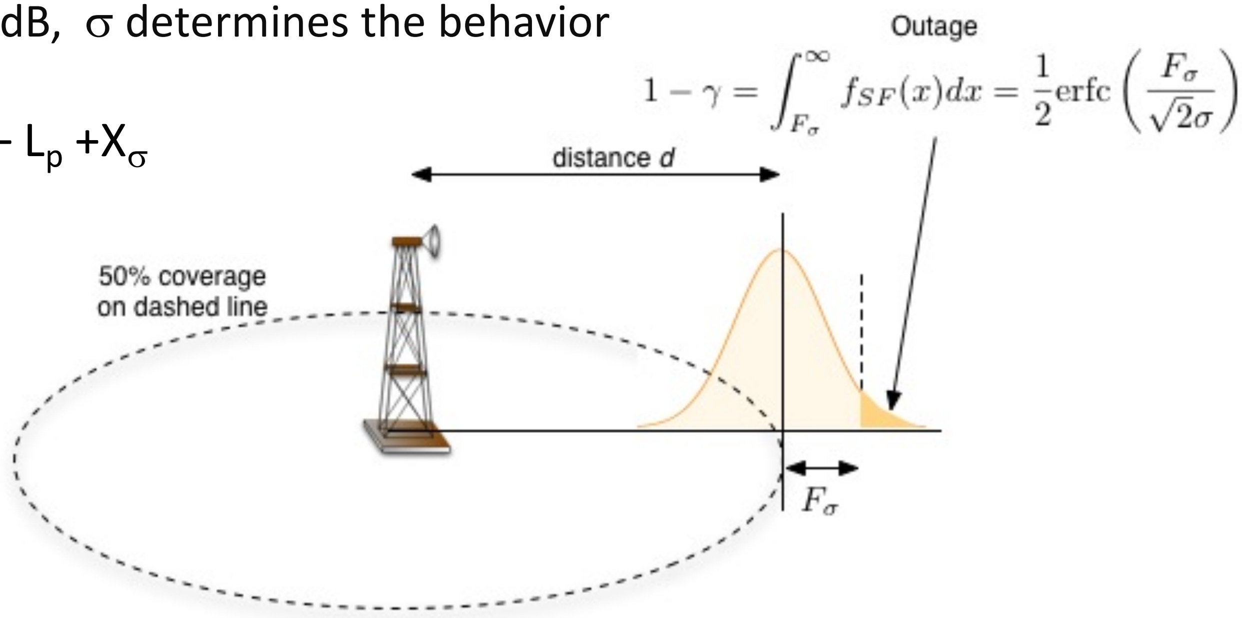
Some Notes

- Empirical models have their disadvantages
  - Example: Okumura-Hata model applies to cities that are like Tokyo (what does that mean? When is a city like Tokyo?)
  - Depends on the interpretation of people
    - Some people may consider Pittsburgh to be a small city
    - Others may think of it as a medium city
- Some models have limited applicability
  - Example: COST-231 model cannot be used if $h_{te} < h_{roof}$ where h_{roof} is the average height of buildings in the area
- There are many other models
  - Models for microcellular environments
  - Terrain dependent (e.g., Longley-Rice)

Shadow Fading

- Shadowing occurs when line of sight is blocked - Modeled by a random signal component X_σ
- 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
- Since X_σ can be modeled in dB as normally distributed with mean = zero and standard deviation σ dB, σ determines the behavior

$$P_r = P_t - L_p + X_\sigma$$



How shadow fading affects system design

- Typical values for σ are
  - Rural 3 dB, suburban 6 dB, urban 8 dB, dense urban 10 dB
- Since X is normal in dB Pr is normal
  - $P_r = P_t - L_p + X_\sigma$
- Prob $\{P_r(d) > \text{Threshold}\}$ can be found from a normal distribution table with mean P_r and standard deviation σ
- In order to make at least Y% of the locations have adequate RSS
  - Reduce cell size
  - Increase transmit power
  - Make the receiver more sensitive

Example of Shadowing Calculations

- The path loss of a system is given by $L_p = 47 + 40 \log_{10} d - 20 \log_{10} h_b$ where 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 dB
- $20 \log_{10} h_b = 20 \log_{10} 10 = 20$ dB
- $127 = 47 + 40 \log_{10} d - 20 \Rightarrow d = 316$m
- 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 shadow margin to have acceptable RSS in 90% of the locations at the cell edge?

+ Example again

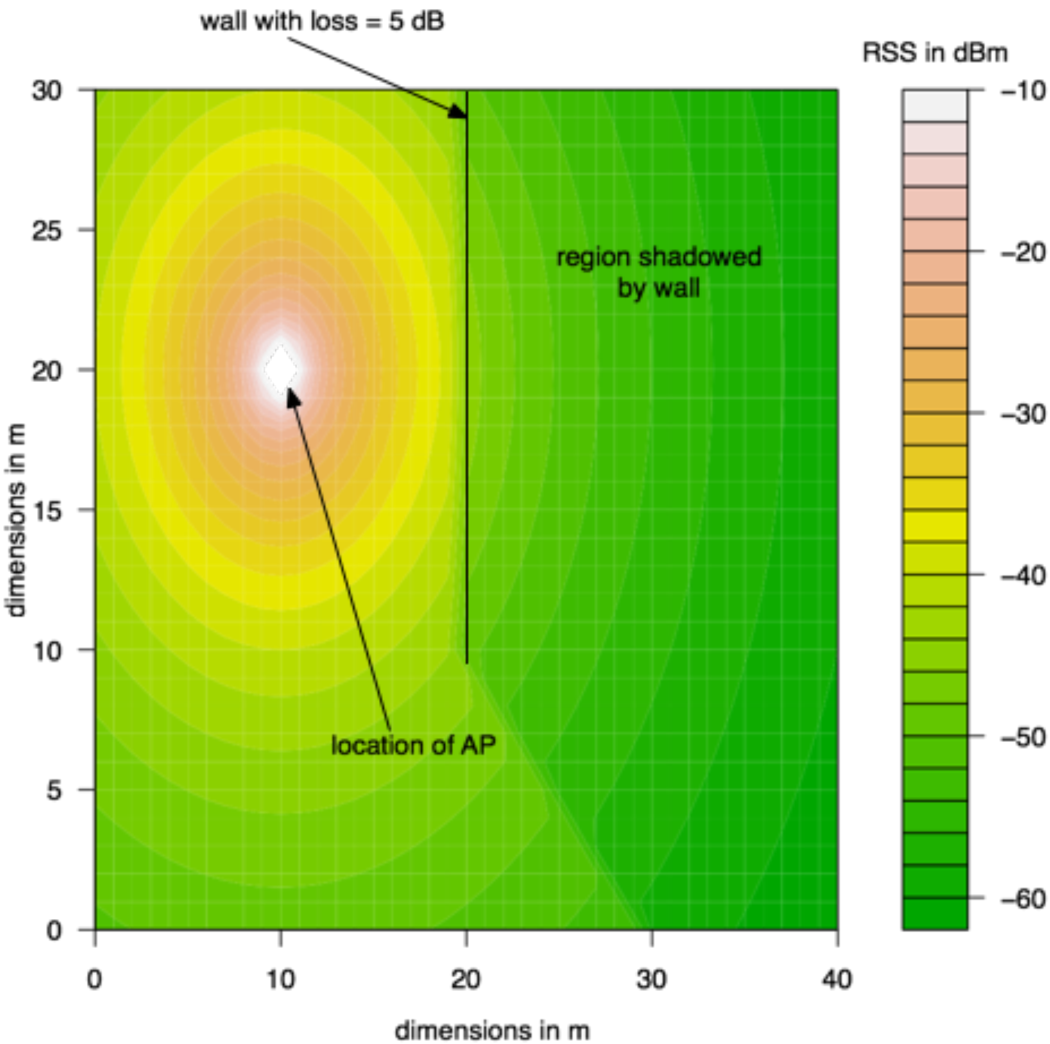
Fading Margin is the amount of extra path loss added to the path loss budget to account for shadowing

.9 → SFM = 1.282σ

.95 → SFM = 1.654σ

- Let **X** be the shadow fading component
  - **X** = N(0,6) and we need to find *F* such that **P**{**X** > *F* } = 0.1 or we need to solve Q(F/σ) = 0.1
  - Use tables or software
- 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 values to determine the **Shadow Fading Margin**

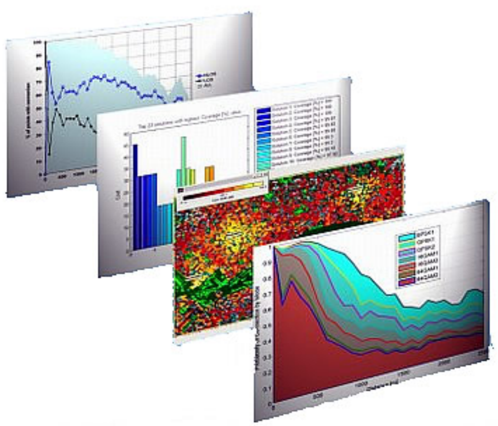
Cell Coverage modeling

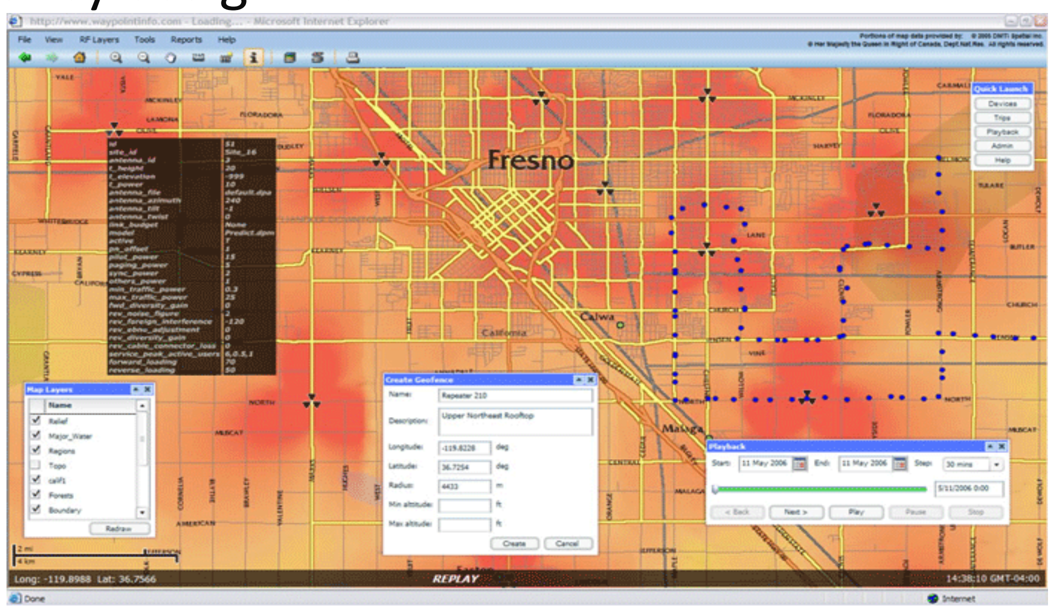


- Simple path loss model based on environment used as first cut for planning cell locations
- Refine with measurements to parameterize model
- Alternately use ray tracing: approximate the radio propagation by means of geometrical optics- consider line of sight path, reflection effects, diffraction etc.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

Cellular CAD Tools

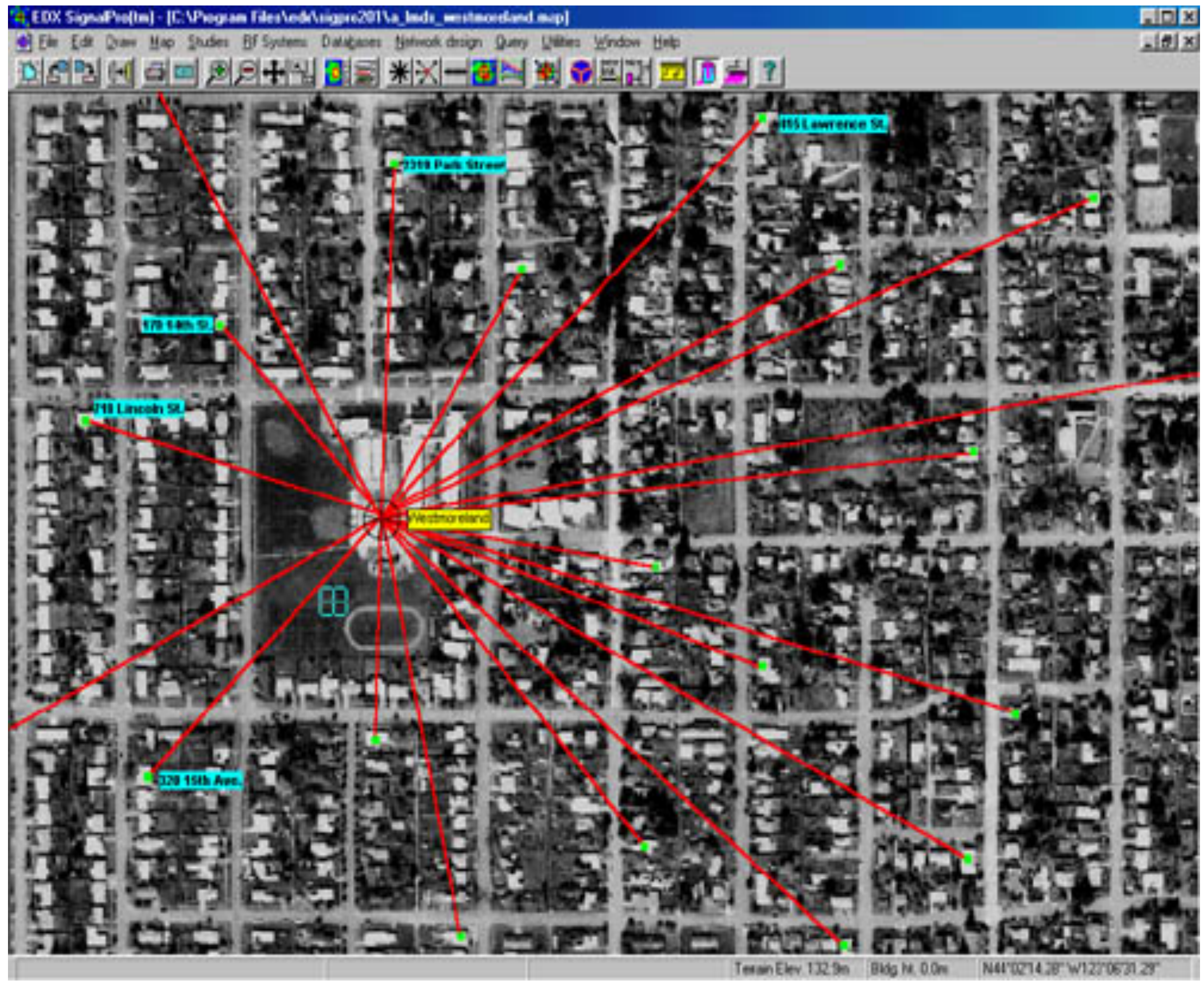
- Use GIS terrain data base, along with vehicle traffic/population density overlays and propagation models
- Output map with cell coverage at various signal levels and interference values
  - To plan out cell coverage area, cell placement, handoff areas, interference level frequency assignment





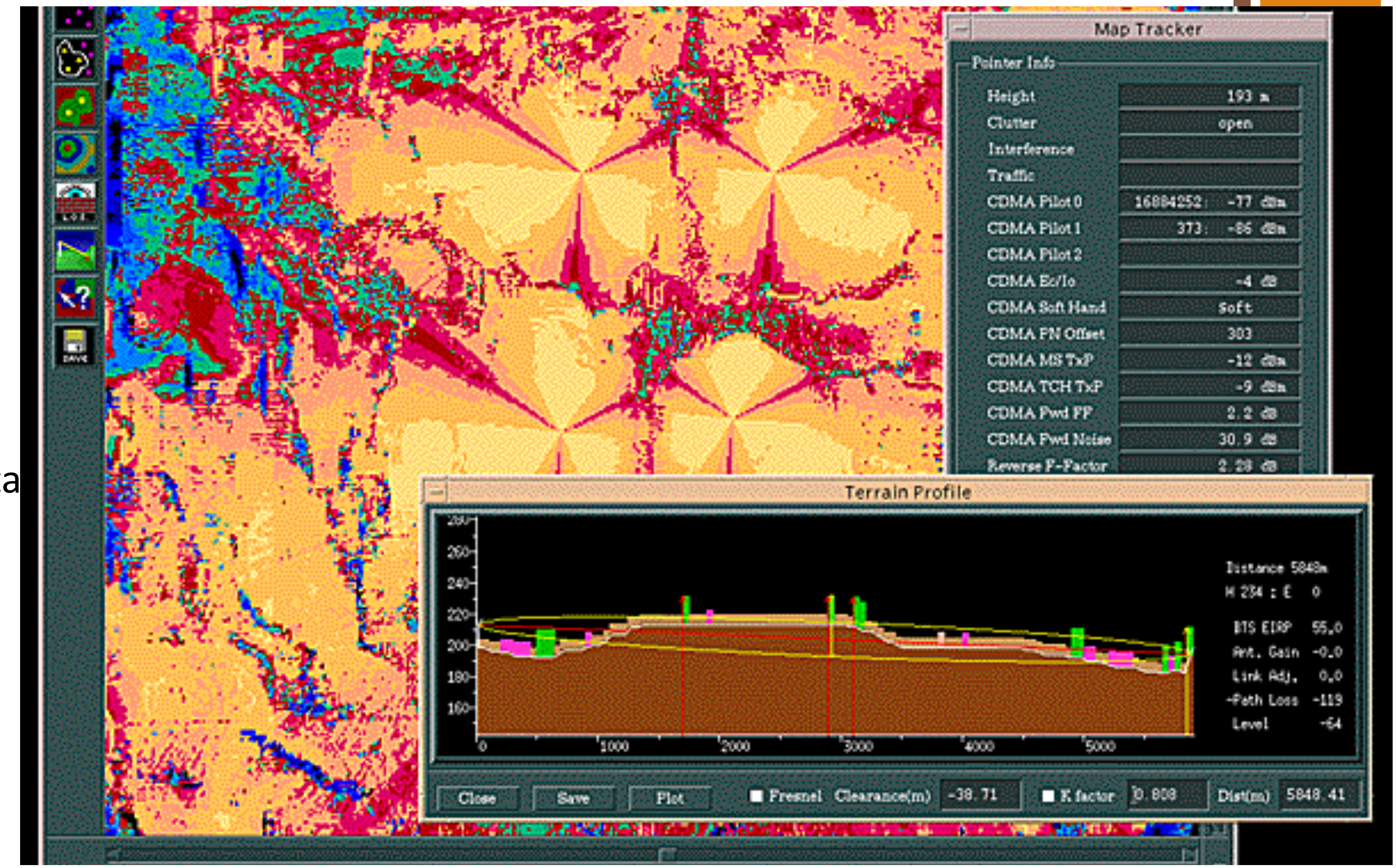
Use GIS maps

- This shows possible location of cell site and possible location of users where signal strength prediction is desired



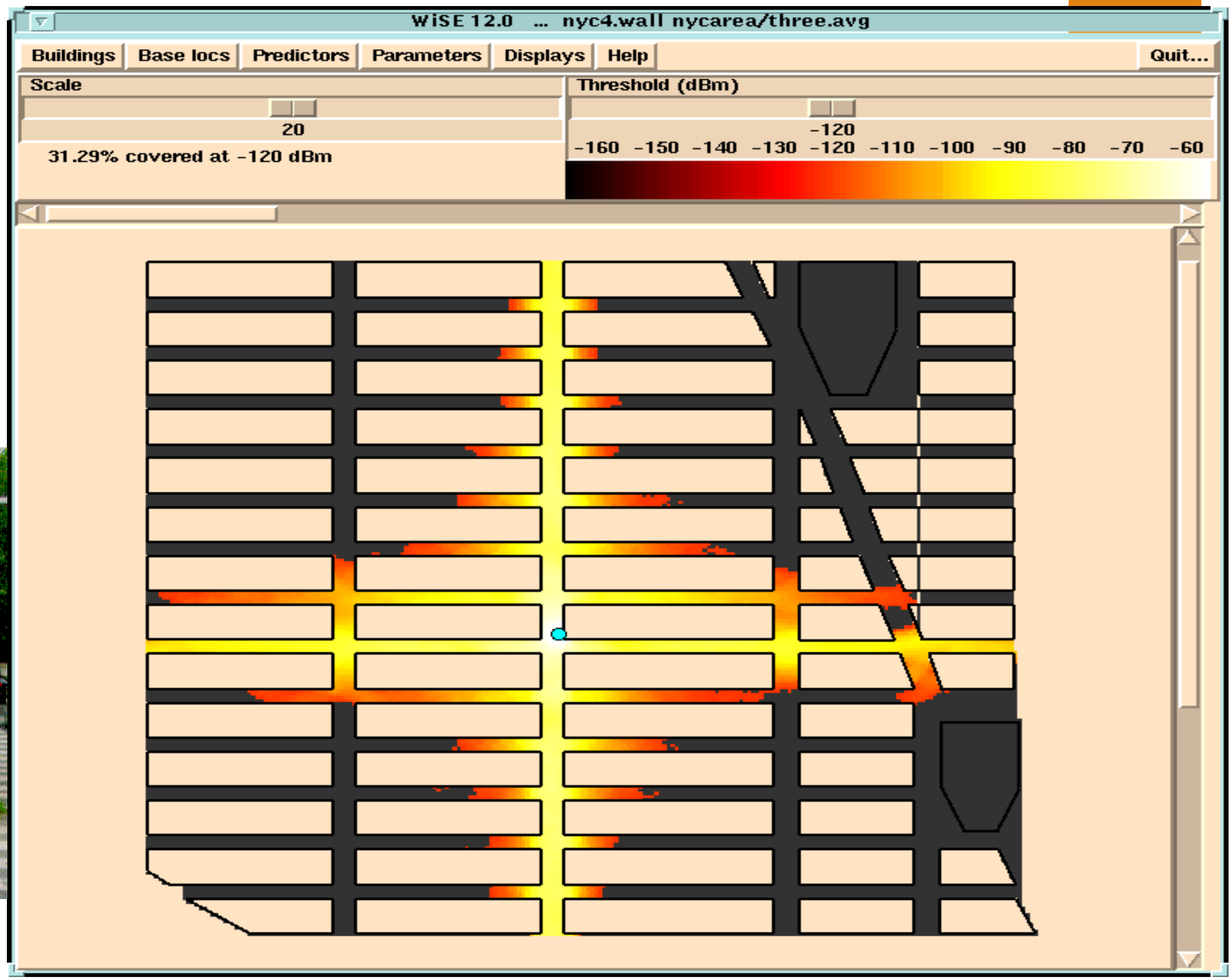
Outdoor Model

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

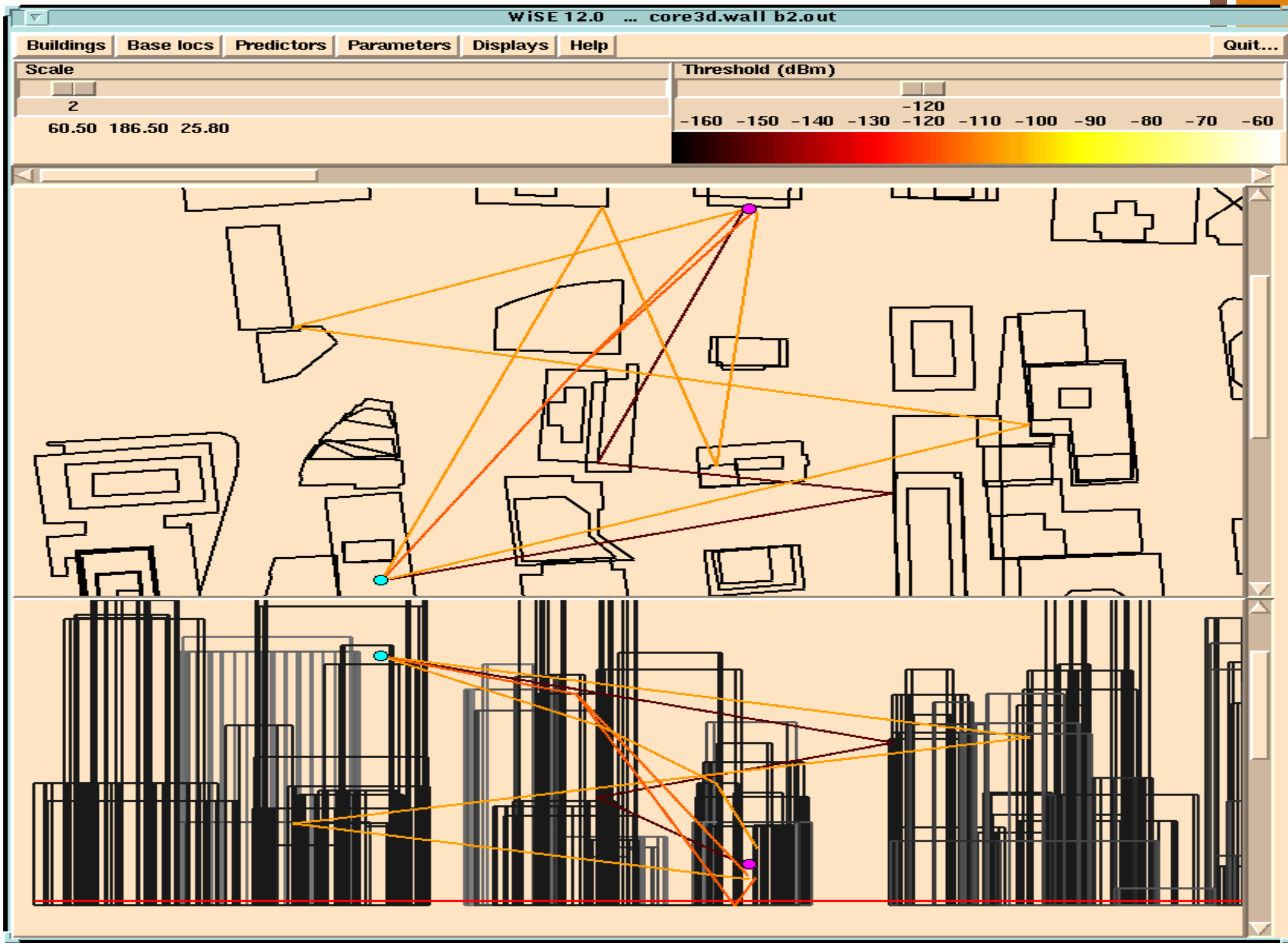


+ Typical City pattern

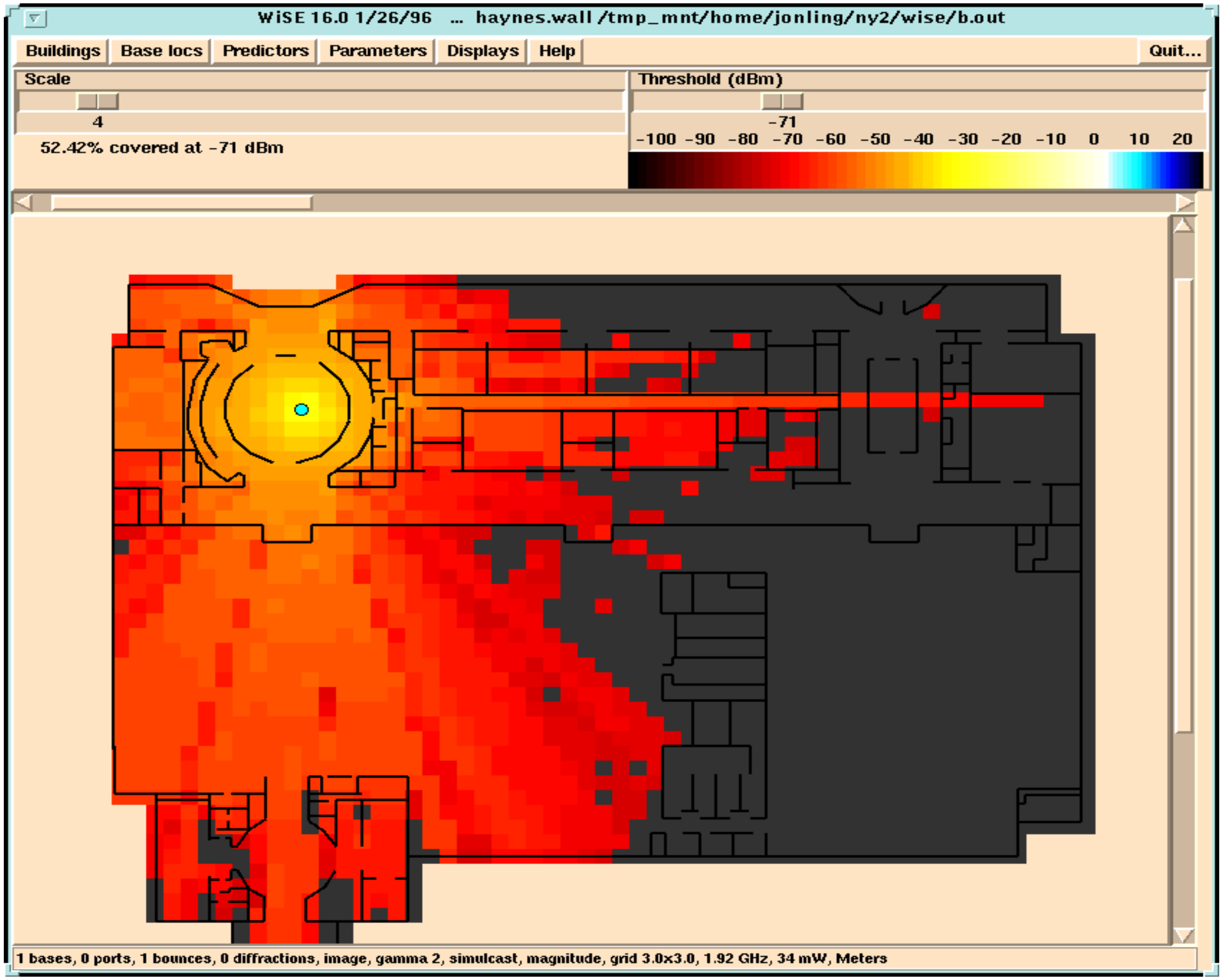
Microcell diamond
Radiation pattern



+ Ray Tracing Mode

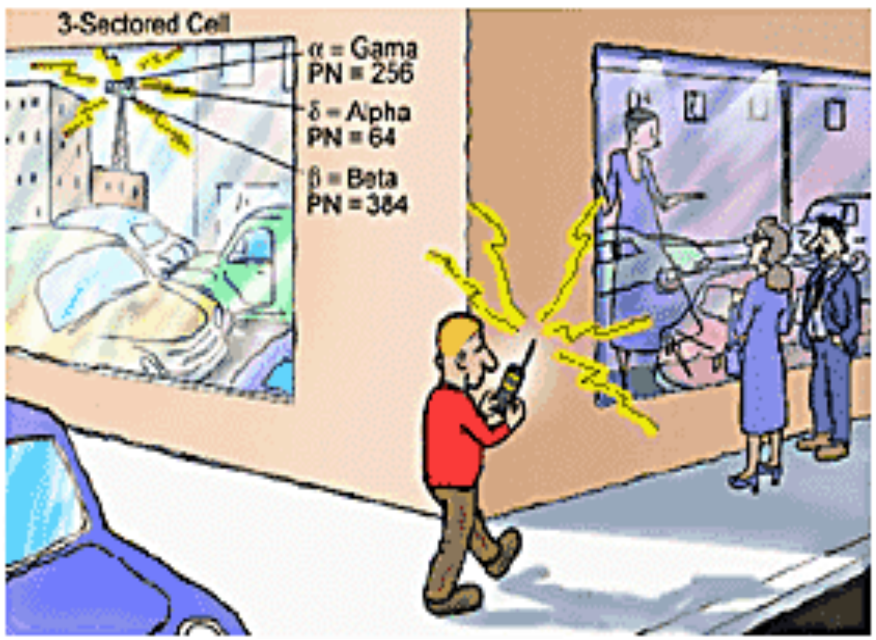


Indoor Models



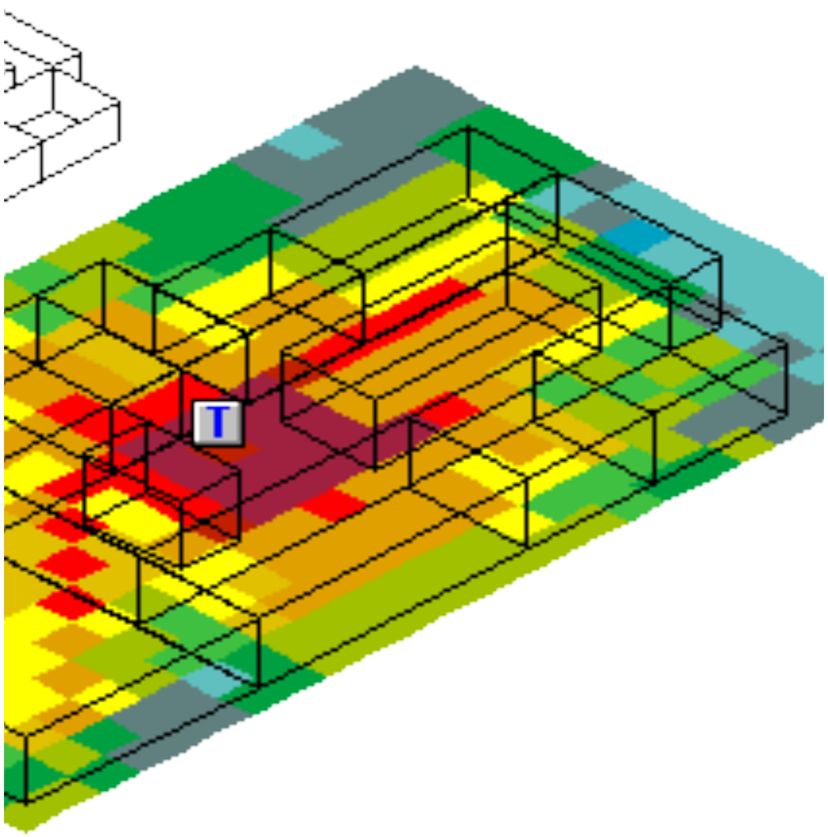
+ Cellular CAD Tools

- CAD tool – first cut cell site placement, augmented by extensive measurements to refine model and tune location and antenna placement/type



Temporary cell

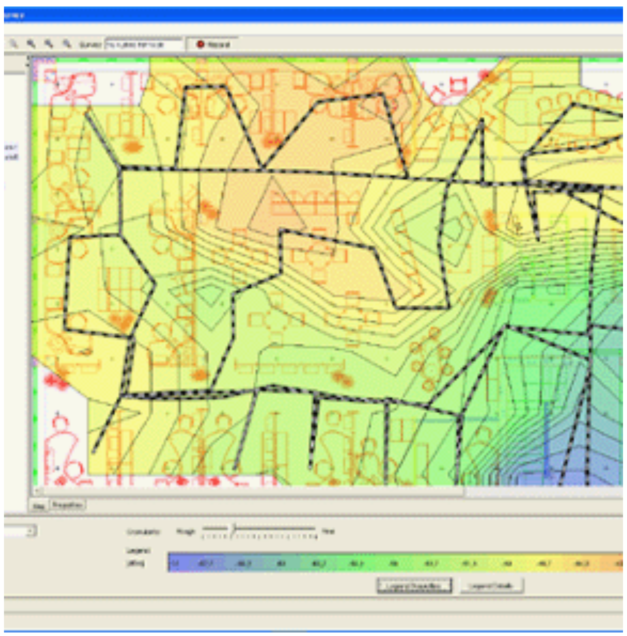
Signal strength prediction for Indoor WLANS

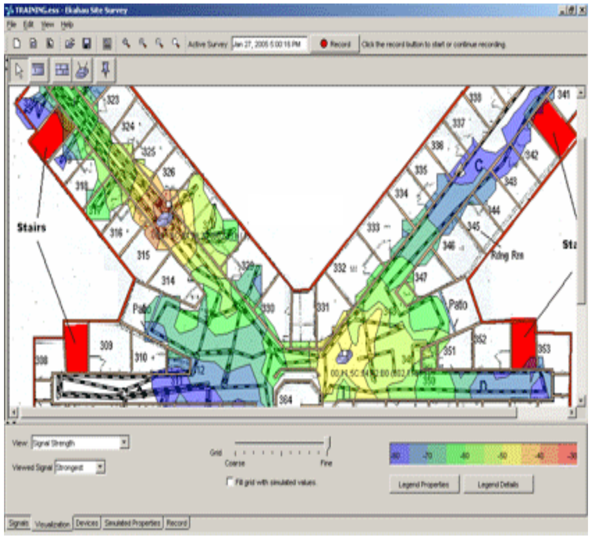


- Motorola LAN Planner
- Lucent: WiSE tool
- Given building/space to be covered and parameters of building and AP – predicts signal coverage

Site Survey Tools

- Software to measure signal strength and recording in order to construct a coverage map of structure – must drive/walk around structure to gather data
- NOKIA site survey tool, Ekahau Site Survey, Motorola LAN survey, etc.





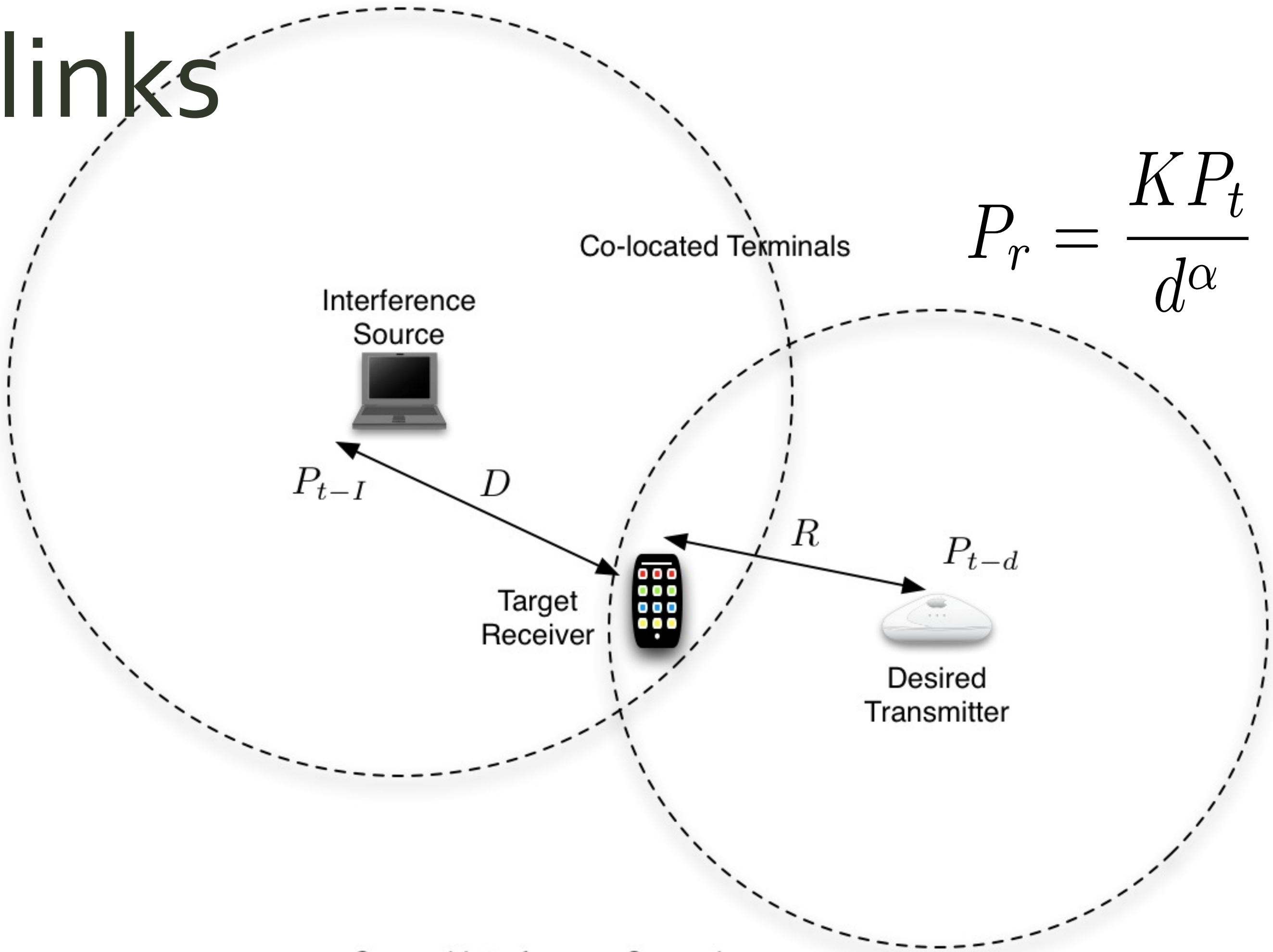
How about Interference?

- Coverage implies there is enough signal strength
  - But how about competing signal strength from a different base station?
  - Interference has a significant impact on the quality of a radio channel
- Next we look at interference and frequency reuse

Basic Interference Scenario – Two links

$$P_r = \frac{KP_t}{d^\alpha} = KP_t d^{-\alpha}$$

K = const



General Interference Scenario

$$S_r = \frac{P_{r-d}}{P_{r-I}} = \frac{KP_{t-d}R^{-\alpha}}{KP_{t-I}D^{-\alpha}} = \frac{P_{t-d}}{P_{t-I}}\left(\frac{D}{R}\right)^\alpha$$

Design and Deployment in Cellular Networks

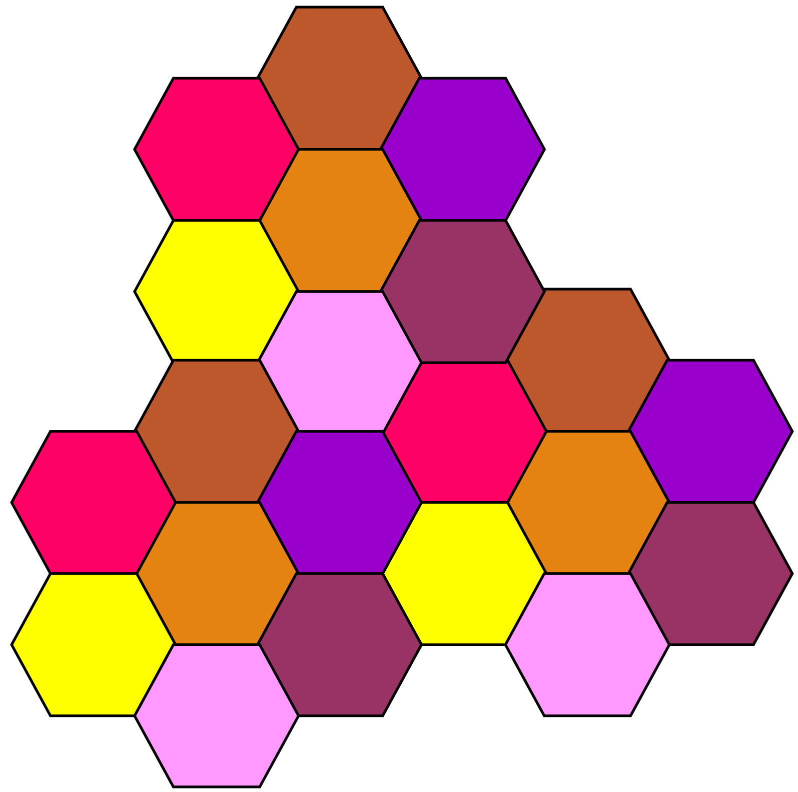
- Ad hoc networks
  - Usually no architectural design
  - Most design is at the protocol level – routing, MAC etc.
- Infrastructure networks
  - Deploy a cellular topology based on some requirements
    - Frequency reuse
    - Start with large cells initially
  - As demand increases
    - Capacity enhancement techniques
      - Reuse partitioning
      - Sectored cells
      - Migration to digital systems
      - Dynamic channel allocation

Design Challenge

- How can we reuse frequency bands such that
  - Interference is not so high as to make communications impossible
  - The available spectrum is reused to make the best use of capacity

Cellular Concept

- Proposed by Bell Labs in 1971
- Geographic Service divided into smaller “cells”
- Neighboring cells do not use same set of frequencies to prevent interference
- Often approximate coverage area of a cell by an idealized hexagon
- Increase system capacity by frequency reuse



The Cellular Concept

- Deploy a large number of low-power transmitters (Base Stations) each having a limited coverage area
- Reuse the spectrum several times in the area to be covered to increase capacity
- Issues:
  - Capacity (traffic load) in a cell
    - One measure = number of ***communication channels*** that are available
  - Performance
    - Call blocking probability, handoff dropping probability, throughput etc.
  - **Interference**

Cellular Concept

- Why not a large radio tower and large service area?
  - Number of simultaneous users would be very limited (to total number of traffic channels *T*)
  - Mobile handset would have greater power requirement

- Cellular concept - small cells with frequency reuse
  - Advantages
    - Lower power handsets
    - Increases system capacity with frequency reuse
  - Drawbacks:
    - Cost of cells
    - Handoffs between cells must be supported
    - Need to track user to route incoming call/message

Recap: Communication Channel

- A frequency band allocated for voice or data communications
  - Simplest example: Frequency division multiple access (FDMA) with Frequency Division Duplexing (FDD)
    - 30 kHz bands are allocated for one conversation
    - Separate bands are allocated for uplink (MH to BS) and downlink (BS to MH)
- A set of time slots allocated for voice or data communications
- A set of spread-spectrum codes allocated for voice or data communications

Types of Interference

- TDMA/FDMA based systems
  - Co-channel interference
    - Interference from signals transmitted by another cell using the same radio spectrum
  - Adjacent channel interference
    - Interference from signals transmitted in the same cell with overlapping spectral sidelobes
- CDMA systems
  - Interference from within the cell
  - Interference from outside the cell

Clustering in TDMA/FDMA

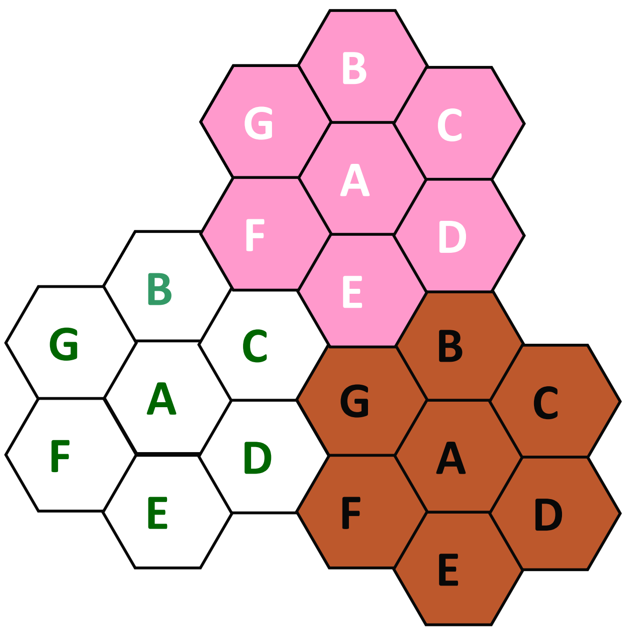
- Adjacent cells CANNOT use the same channels
  - Co-channel interference will be too severe
- The available spectrum is divided into chunks (sub-bands) that are distributed among the cells
- Cells are grouped into clusters
  - Each cluster of cells employ the entire available radio spectrum
  - The spatial allocation of sub-bands has to be done to minimize interference

Cellular Concept (cont)

- Let T = total number of duplex channels
  - N_c cells = size of cell cluster (typically 4, 7, 9, 12, 21)
  - $L = T/N_c$ = number of channels per cell
- For a specific geographic area, if **clusters** are replicated M times, then total number of channels
  - System capacity = $M \times T$
  - Choice of N_c determines distance between cells using the same frequencies – termed **co-channel cells**
  - N_c depends on how much interference can be tolerated by mobile stations and path loss

Cell Design - Reuse Pattern

- Example: cell cluster size $N_c = 7$, frequency reuse factor = 1/7;
- Assume $T = 490$ total channels, $L = T/N_c = 70$ channels per cell



Assume T = 490 total channels, $N_c = 7$, N = 70 channels/cell

Clusters are replicated M=3 times

System capacity = 3 x 490 = 1470 total channels

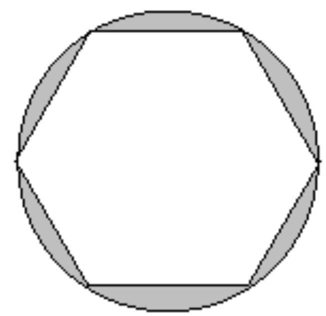
Cellular Geometry

- Propagation models represent cell as a circular area
- Approximate cell coverage with a hexagon - allows easier analysis
- Frequency assignment of *F* MHz for the system
- The multiple access techniques translates *F* to *T* traffic channels
- Cluster of cells N_c = group of adjacent cells which use all of the systems frequency assignment

Theoretical Propagation Pattern

Cellular Grid Design

Actual Cellular Grid Layout

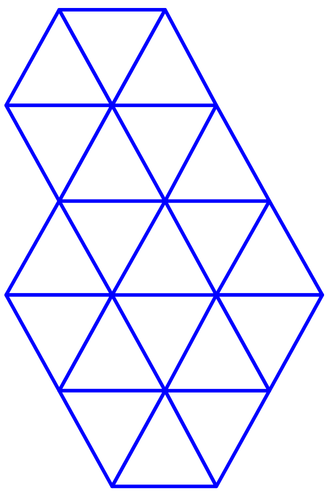


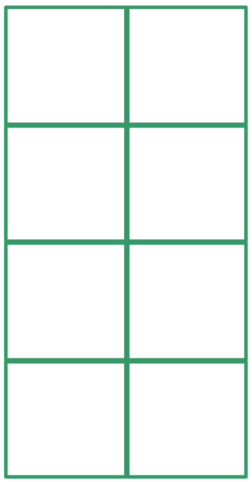
Cellular Geometry

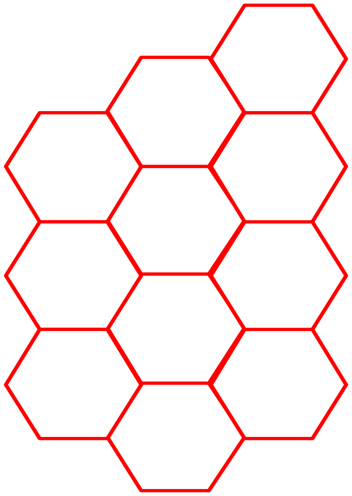
- Cells do not have a “nice” shape in reality
- A model is required for
  - Planning the architecture
  - Evaluating performance
  - Predict future requirements
- Simple Model:
  - All cells are identical
  - There are no ambiguous areas
  - There are no areas that are NOT covered by any cell

Possibilities for cell geometry model

- Equilateral triangle, square or regular hexagon



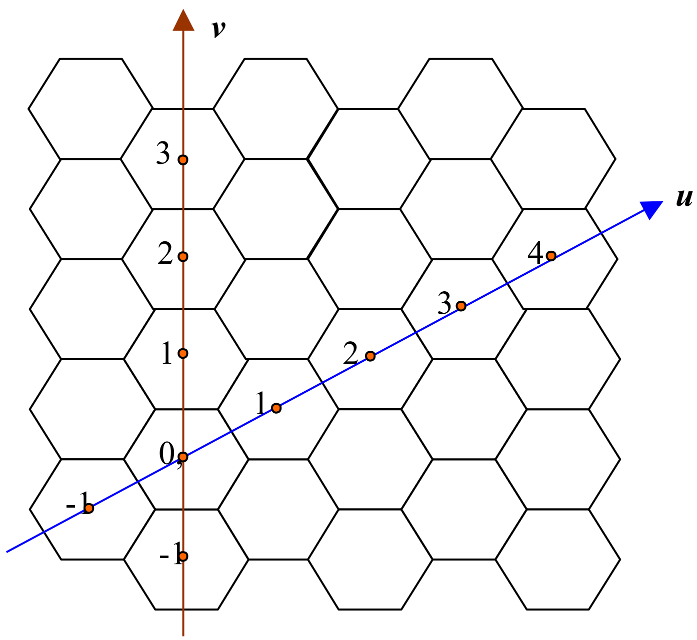




Why hexagon?

- Among the three choices, the hexagon is the closest approximation to a circle
- For a given radius (largest possible distance from center of a polygon to its edge) a hexagon has the largest area
- A circle is sometimes used when continuous distributions are being considered

+ Determining co-channel cells and the reuse factor

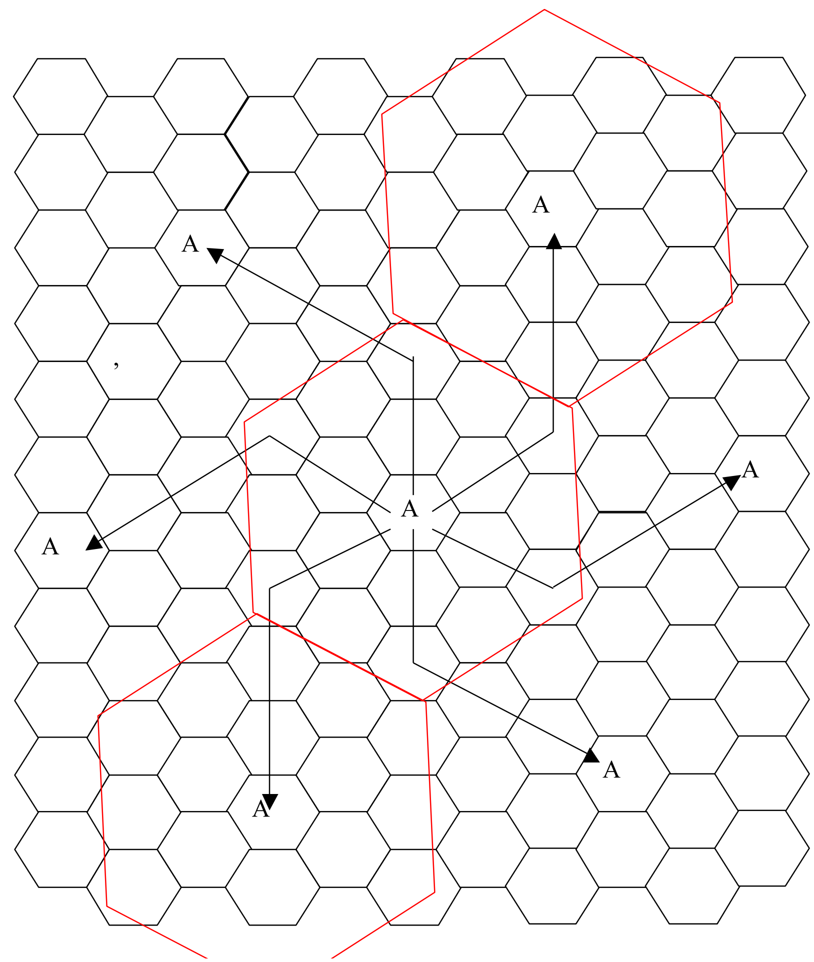


- Co-channel cells must be placed as far apart as possible for a *given cluster size*
- Hexagonal geometry has some properties that can be employed to determine the co-channel cell
- Co-ordinate system: u and v co-ordinates

Cells are placed so that their centers have integer co-ordinates

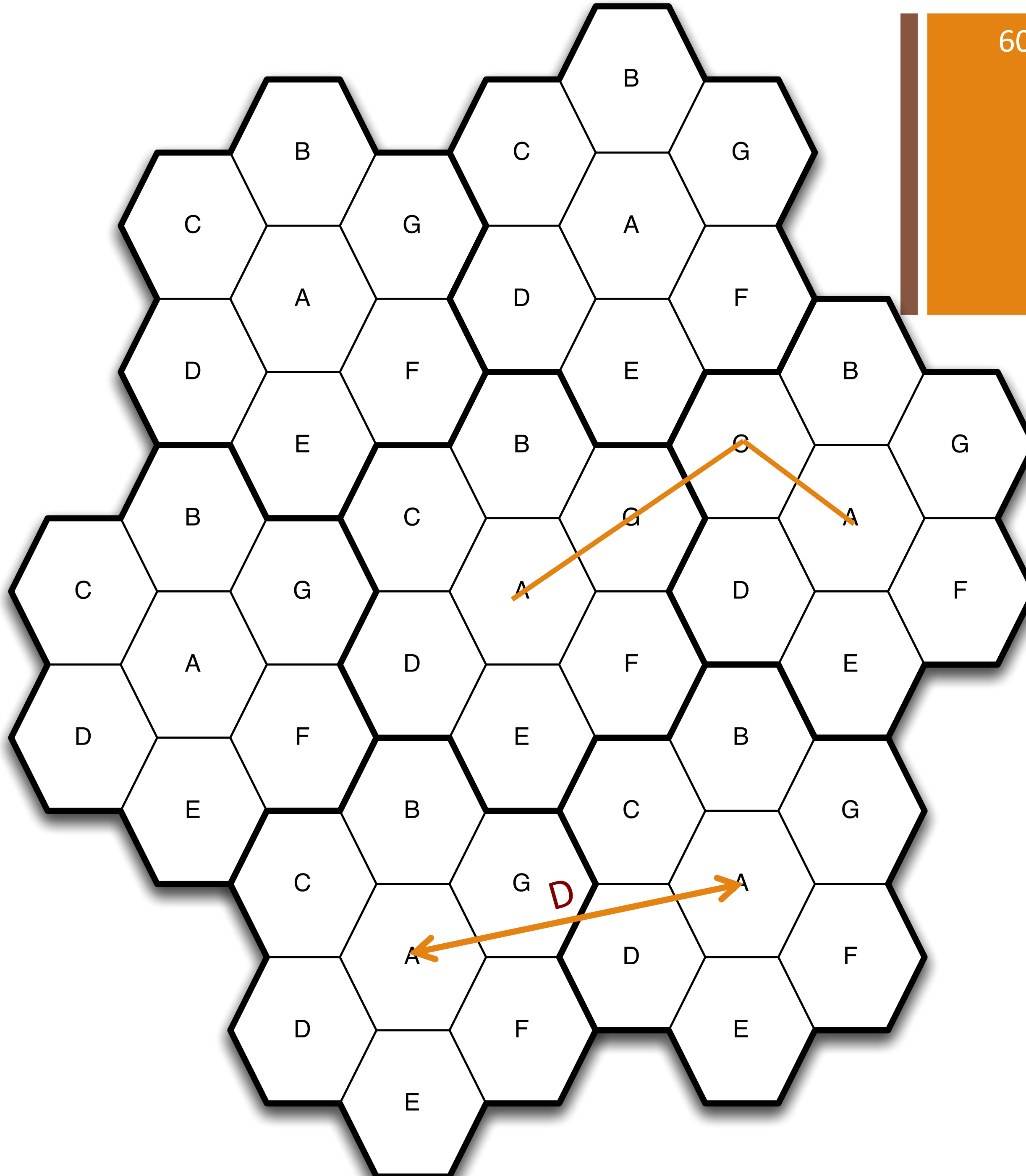
Finding (placing) Co-channel cells (continued)

- Move a distance *i* along the *u* direction and a distance *j* along the *v* direction
- The cluster size $N_c = i^2 + ij + j^2$



+ Example: i = 2, j = 1

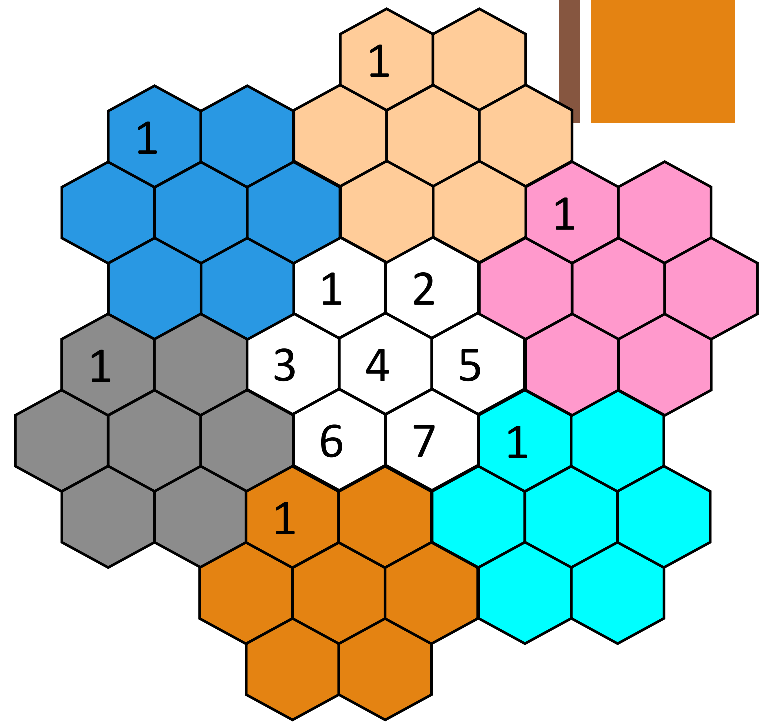
Cluster size
$N_c = 7$



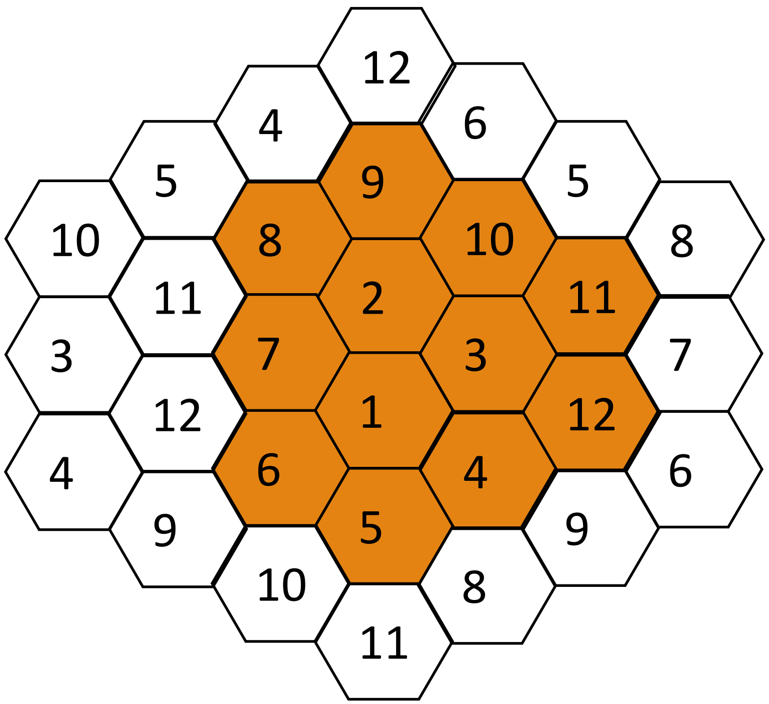
Used in
Advanced Mobile
Phone Service (AMPS)

More Examples

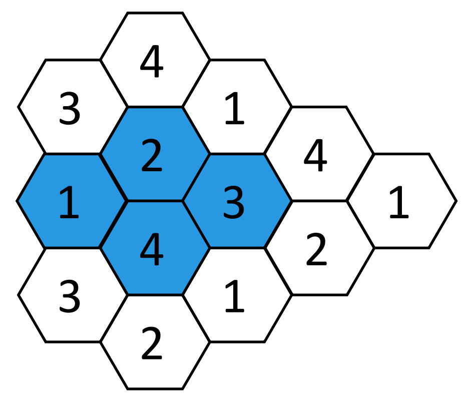
$N_c = 7$ (i =2, j =1)



$N_c = 12$ (i=2, j=2)



$N_c = 4$ (i =2, j=0)



Some results

- N_c = number of cells in a cluster
- R = radius of a cell
- D = distance between co-channel cells

$$\frac{D}{R} = \sqrt{3N_c}$$

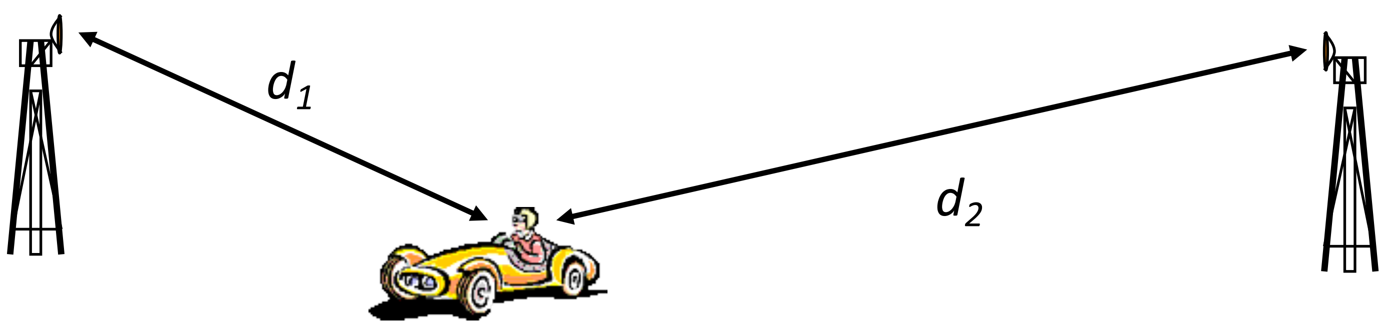
- N_c can only take values that are of the form $i^2 + ij + j^2$; i, j are integers
- There are exactly six co-channel cells for a hexagonal geometry

+ Revisiting Signal to interference ratio calculation

- General:

$$S_r = \frac{P_{desired}}{\sum_i P_{Interference,i}} \qquad S_r = \frac{KP_t d_1^{-\alpha}}{KP_t d_2^{-\alpha}} = \left(\frac{d_2}{d_1}\right)^{\alpha}$$

- One desired signal and one interfering signal at distances d_1 and d_2



S_r in a hexagonal architecture

- With J_s interfering base stations

$$S_r = \frac{d_0^{\alpha}}{\sum_{n=1}^{J_s} d_n^{\alpha}}$$

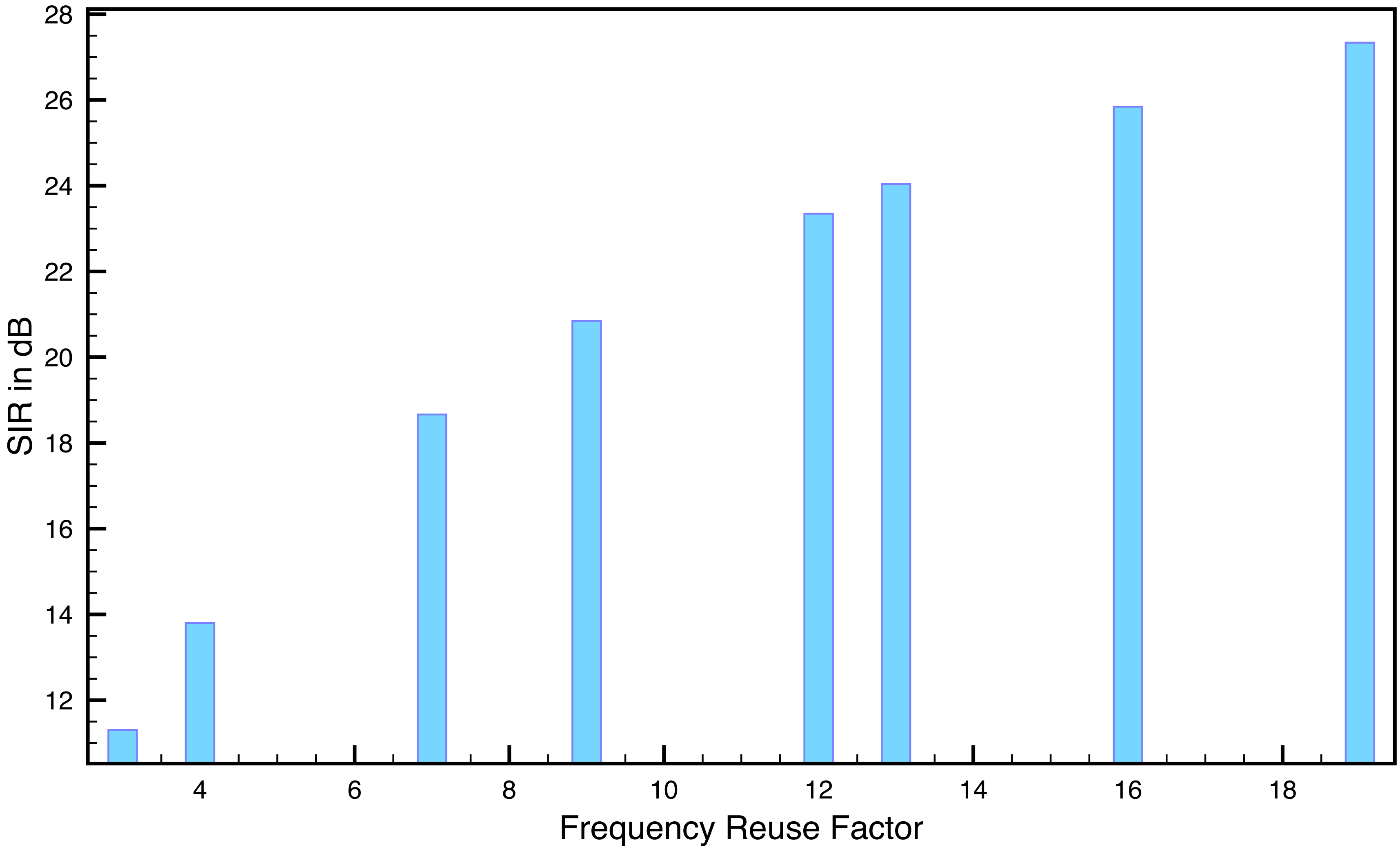
  - J_s = 6 for a hexagonal architecture
  - α = 4 for urban areas

- Maximum distance of the MS from a desired BS is *R*
- Approximate distance of the MS from each of the co-channel interferers is *D*
- The expression for S_r is:

$$S_r \approx \frac{R^{-4}}{J_s D^{-4}} = \frac{R^{-4}}{6D^{-4}} = \frac{1}{6}\left(\frac{D}{R}\right)^4 = \frac{3}{2}N_c^2$$

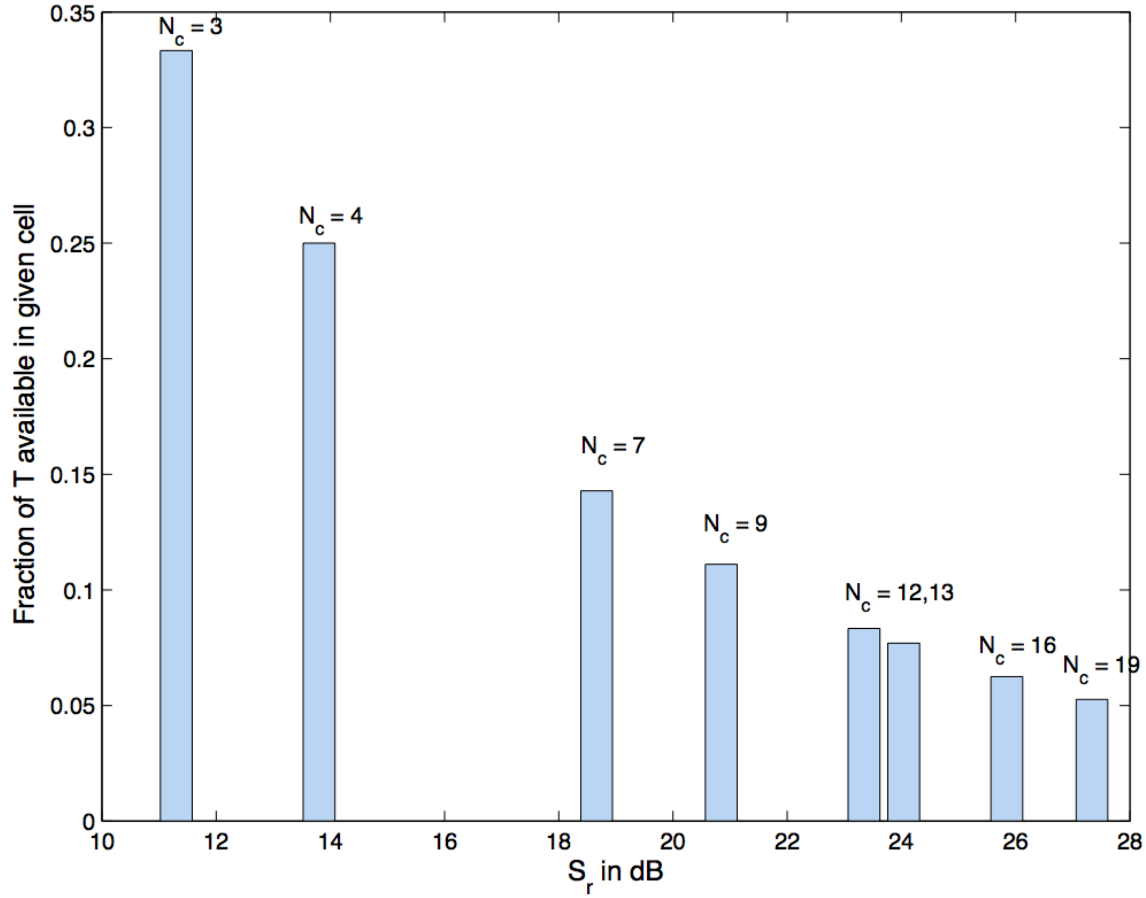
Solve for D/R

S_r as a function of the cluster size

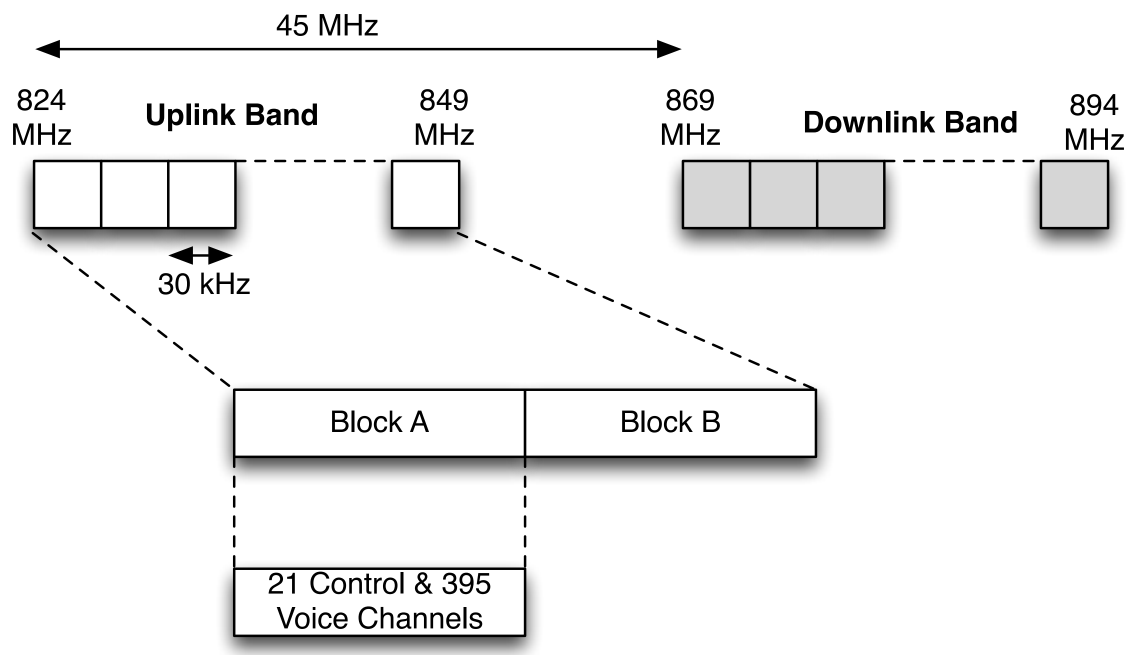


Issues Revisited

- Cluster size N_c determines
  - The co-channel interference
  - The number of channels allocated to a cell
  - **Larger N_c is, smaller is the co-channel interference**
  - **Larger N_c is, smaller is the number of channels available for a given cell**
    - **Capacity reduces**
- What N_c should we use based on SIR or C/I?



Example: AMPS



- Voice channels occupy 30 kHz and use frequency modulation (FM)
- 25 MHz is allocated to the uplink and 25 MHz for the downlink
- 12.5 MHz is allocated to non-traditional telephone service providers (Block A)
- 12.5 MHz / 30 kHz = 416 channels
- 395 are dedicated for voice and 21 for control

Reuse in AMPS

- Subjective voice quality tests indicate that S_r = 18 dB is needed for good voice quality
- This implies N_c = 7
  - See next slide also
- Cells do not actually conform to a hexagonal shape and usually a reuse factor of N_c = 12 is needed

Frequency Reuse

Solving for *D/R* results in

$$\frac{D}{R} = (6S_r)^{1/\alpha}$$

Remember $D/R = \sqrt{3N_c}$
which results in

$$N_c = \frac{1}{3}(6S_r)^{2/\alpha}$$

Example: Consider cellular system with
- S_r requirement of 18 dB
- Suburban propagation environment with $\alpha = 4$.

Determine the minimum cluster size.

18 dB ➔ $18 = 10 \log_{10}(x)$ ➔
$1.8 = \log_{10}(x)$ ➔ $x = 10^{1.8}$ ➔
$x = 63.0957$.

$N_c = 1/3 \times (6 \times 63.0957)^{0.5} = 6.4857$

Since N_c must be an integer, you round up to nearest feasible cluster size
=> $N_c = 7$

+ AMPS: Adjacent channel interference

- Cluster size is $N_c = 7$
- Consider the 395 voice channels
  - 1: 869.00 – 869.03 MHz
  - 2: 869.03 – 869.06 MHz …
- Cell A is allocated channels 1,8,15…
- Cell B is allocated channels 2,9,16…
- Channels within the cell have sufficient separation so that adjacent channel interference is minimized

+ Frequency Assignment

- Typical C/I values used in practice are 13-18 dB.
- Once the frequency reuse cluster size Nc is determined, frequencies must be assigned to cells
- Must maintain C/I pattern between clusters
- Within a cluster – seek to minimize adjacent channel interference
- Adjacent channel interference is interference from frequency adjacent in the spectrum

- Example: You are operating a cellular network with 25KHz NMT traffic channels 1 through 12.
  - Label the traffic channels as {f1, f2, f3, f4, f5, f6, f7, f8, f9, f10, f11, f12}
  - Place the traffic channels in the cells above such that a frequency reuse cluster size of 4 is used and adjacent channel interference is minimized