16.582/16.418 Wireless Communication

Notes II: Cellular Wireless Systems

Lecture Outline

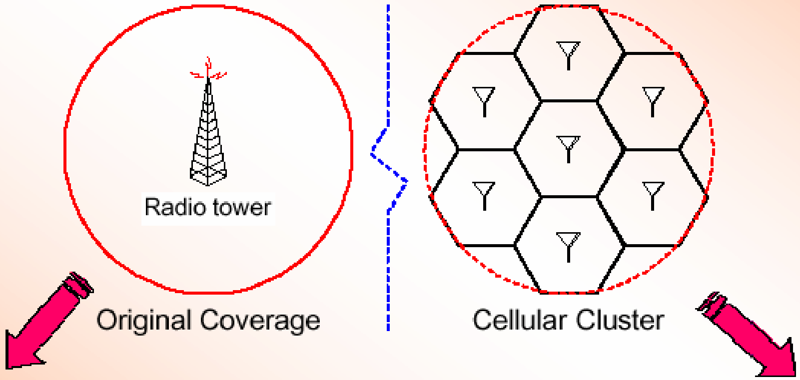
- The Cellular Concept
  - Interference and Reuse in Cellular Systems
  - Calculating the Reuse of Different Systems
  - Tradeoffs in the Reuse Pattern
- Traffic and Capacity Engineering
  - Calculating Grade of Service
  - Calculating Blocking Probability
  - Trunking Efficiency
- Tradeoffs between Capacity, Reuse and Interference

The Cellular Concept

- Traditional mobile radio systems were designed around very high power output to cover large geographic areas
- Coverage area is approximately 50-100 mile separation
- Frequencies were limited resulting to serious spectrum congestion
- This was the motivating factor for the development of "cellular telephone system"
- Cellular Telephone Objectives
  - Spectral efficiency
  - Affordability
  - Large subscriber capacity
  - Nationwide compatibility
  - Quality service
- In Cellular System (CS) large coverage area with one high power Tx is divided into small, localized coverage areas called CELLS
- Each cell has a Base Station (Cell Site)
- Each Base Station uses much less power output for transmission

Cellular Basics

- In cellular systems large coverage area with one high power Tx is divided into small, localized coverage areas called CELLS

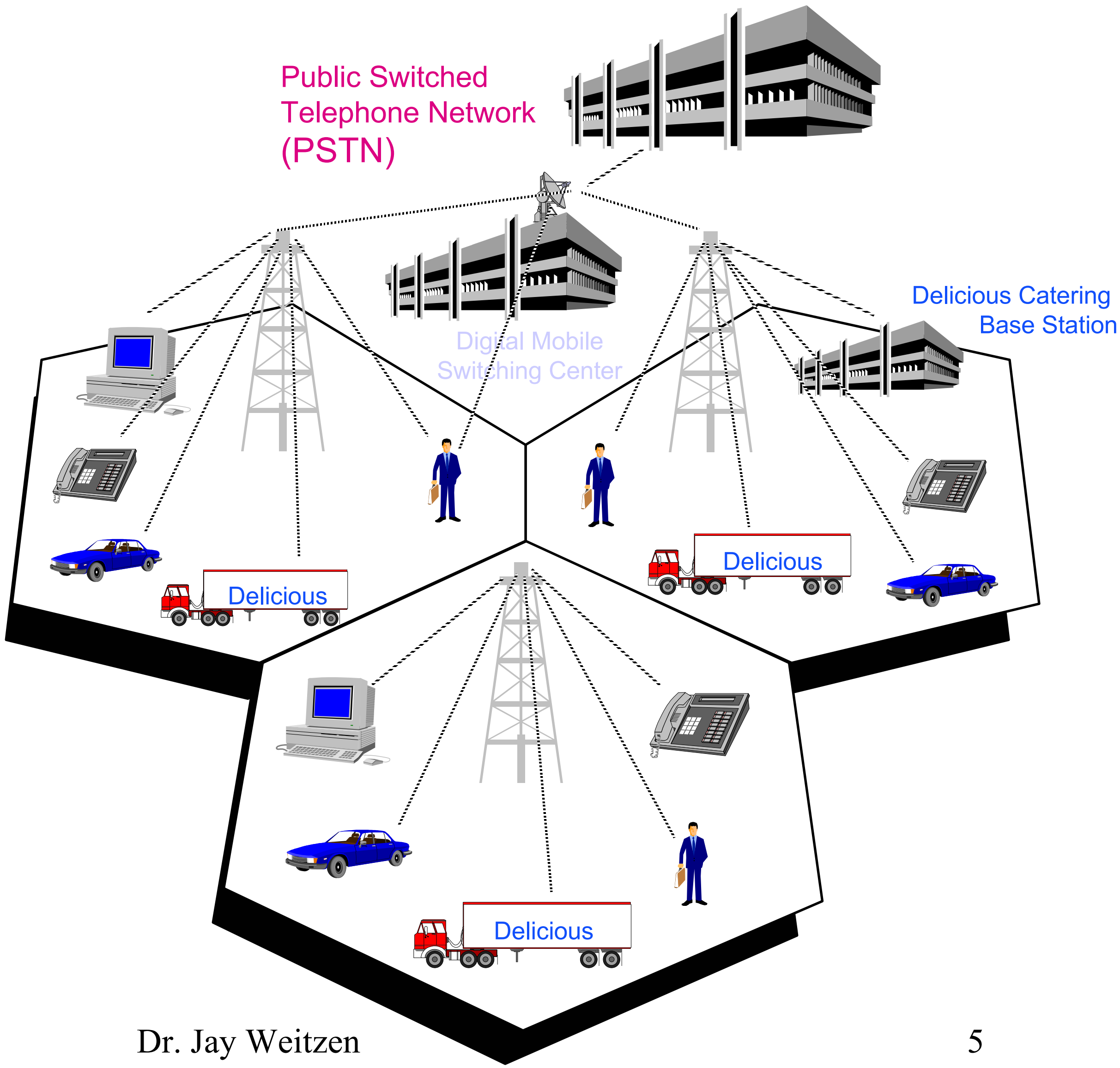


- Large coverage area
- Single high power transmission
- Poor transmission quality
- Excessive delays in call setup
- Limited frequency reuse
- Demand in excess of capacity
- Limited service areas

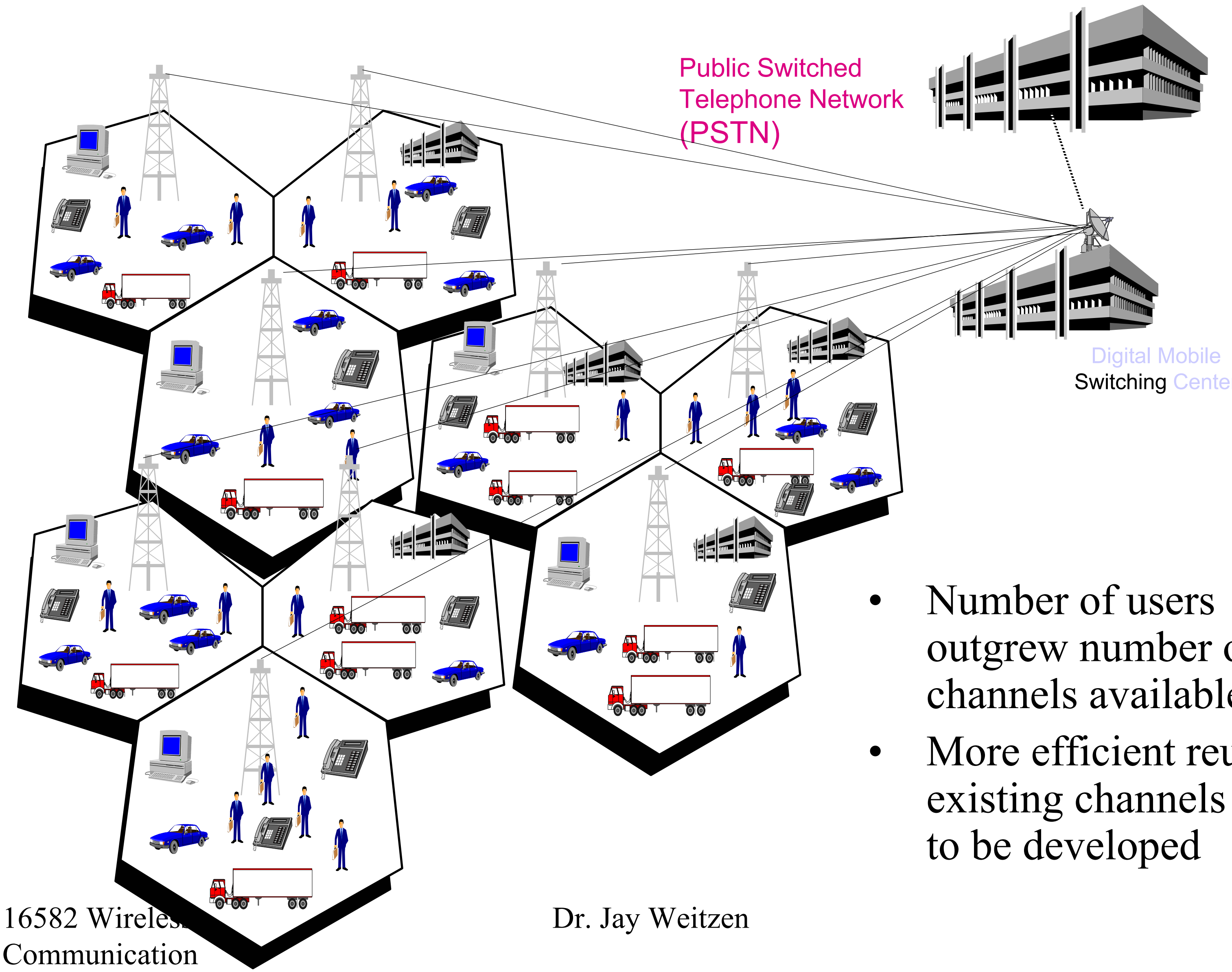
- Small coverage area
- Multiple low power transmitters
- Good transmission quality
- Acceptable delays in call setup
- Good frequency reuse
- Demand proportional to capacity
- Extended service areas

Cellular Telephone Arrives

- Make coverage areas smaller, but more of them
- Develop a means to hand call from one coverage area to another
- Call these coverage areas *cells*



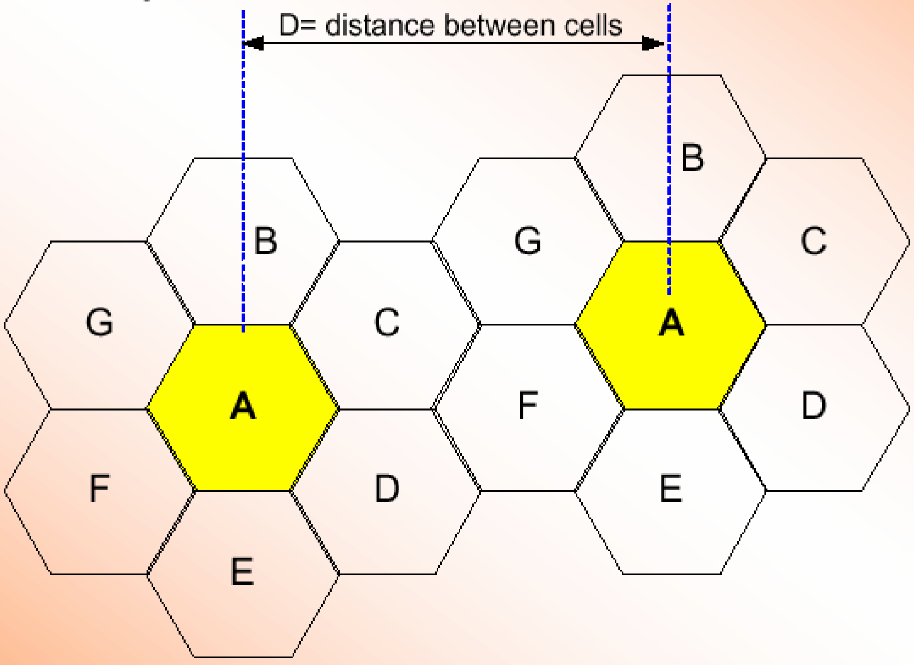
Cells Become Crowded



- Number of users outgrew number of channels available
- More efficient reuse of existing channels had to be developed

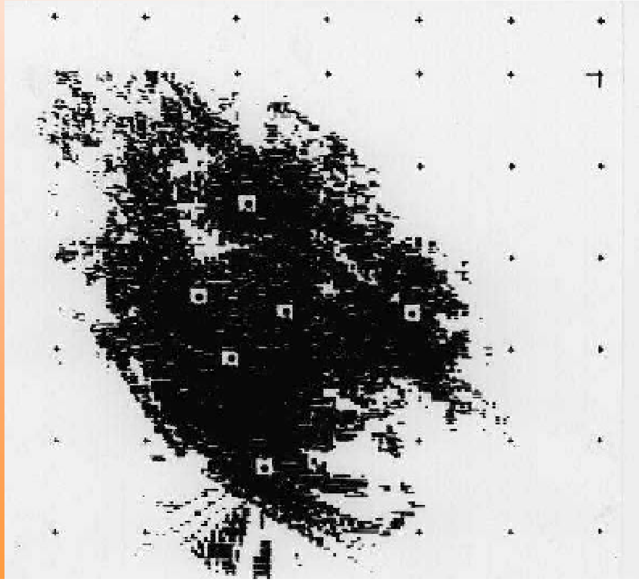
Frequency Reuse

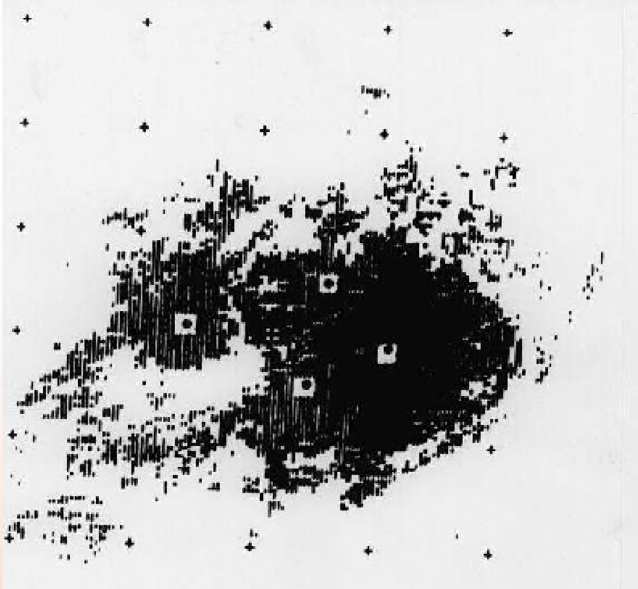
- Frequency Reuse (FR) is a technique for allocating channel groups for all the cellular systems



- Same frequency is assigned to all cells on frequency group A (same frequencies are reused)
- Frequency reuse introduces interference (cochannel/adjacent channel)

- All the cells in a theoretical discussion are considered hexagons
- However in reality, the cells are rarely hexagon in shape
- Actual cell geometry depends on
  - The terrain contour and topography
    - presence of water, foliage, man made structure (height & density)
  - Location of the antenna and its height



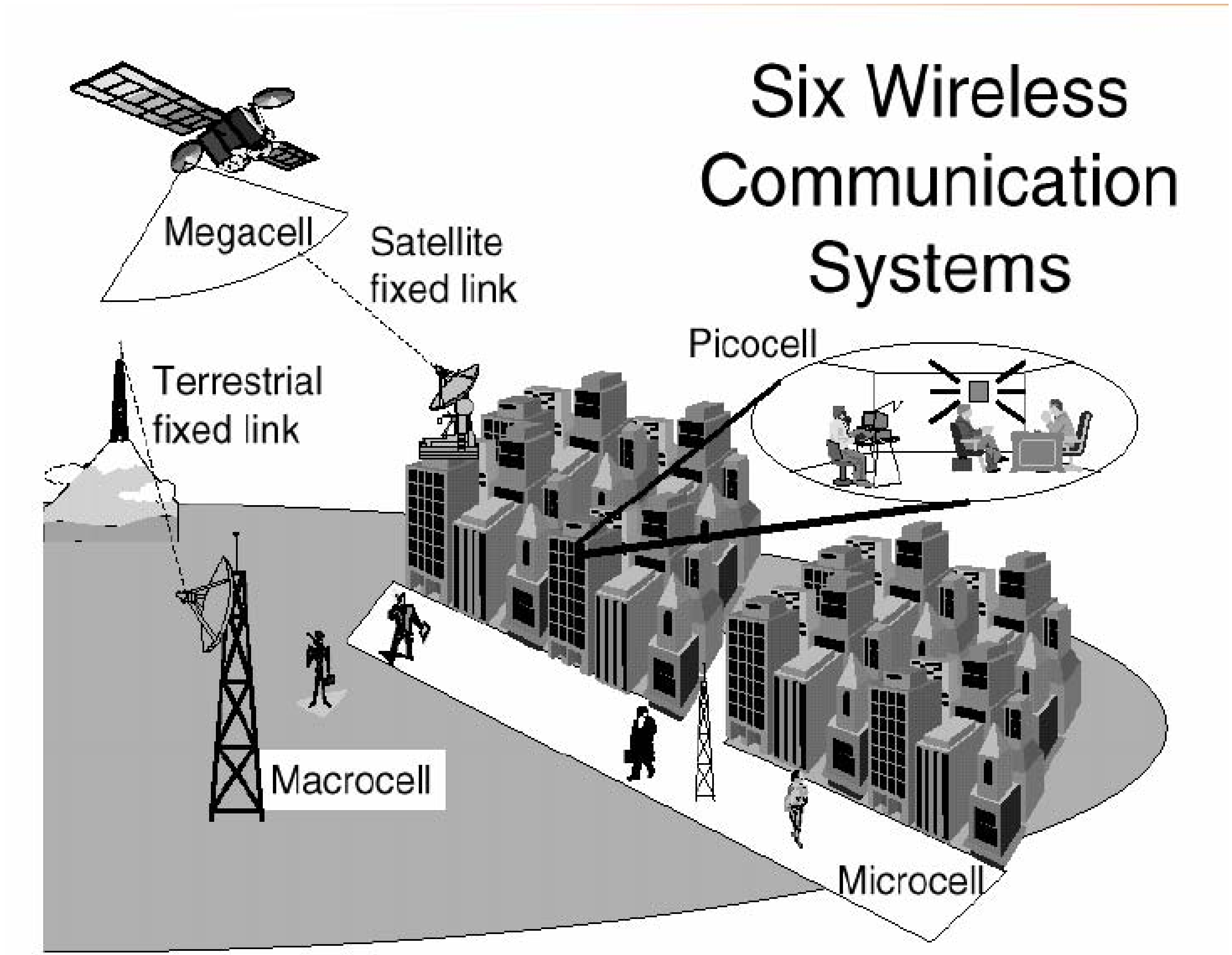


Cellular Reuse

- After a certain number of cells, the assigned spectrum of a cell can be reused *(frequency reused)*
- This increases the capacity of the coverage area
- Actual cell coverage area is irregular and depends on the terrain, multipath characteristics of the radio channel, etc.
- Actual cell structure is not hexagonal
- New cells and channels are added (or cell splitting or sectoring is used) as traffic increases
- For design convenience, the shape of a cell can be any regular polygon, e.g. circle, square, triangle, and hexagon
- Honeycomb (Hexagonal) cells are frequently used. Why?
  - Requires the fewest number of cells for a given distance between center and furthest point on the perimeter

Cellular Terminology

- Strongest mobiles are those closest to the Base Station
- Weakest mobiles are located at the edge of the cell or far away from the cell cite
- **Footprint**
  - Actual radio coverage area
  - Determined from measured data
- **Blind Spot**
  - Region in the coverage area with high likelihood of deep fade due to shadowing coursed by obstructions
- **Cell Sizes:**
  - Macrocell
    - 2 ~ 20 Km
    - shadowing
    - Rice/Rayleigh
  - Microcell
    - 0.4 ~ 2 Km
    - Rice/Rayleigh
  - Picocell
    - 20 ~ 400 m


Six Wireless
Communication
Systems
Megacell
Satellite
fixed link
Terrestrial
fixed link
Picocell
Macrocell
Microcell

Cellular System Design Issues

- **Motivation**
  - Frequency Reuse
    - Low Power Transmission
    - Increased Capacity
    - Effective Coverage Area, etc.
- **Design Parameters**
  - Co-channel Interference (CI) Issues:
    - Interference between signals having the same frequency
  - Adjacent Channel Interference (ACI) Issues:
    - Interference between signals having frequencies close together
  - Example:
    - channel 1 has frequencies 825.030 MHz and 870.030 MHz
    - channel 2 has frequencies 825.060 MHz and 870.060 MHz

Interference And Noise

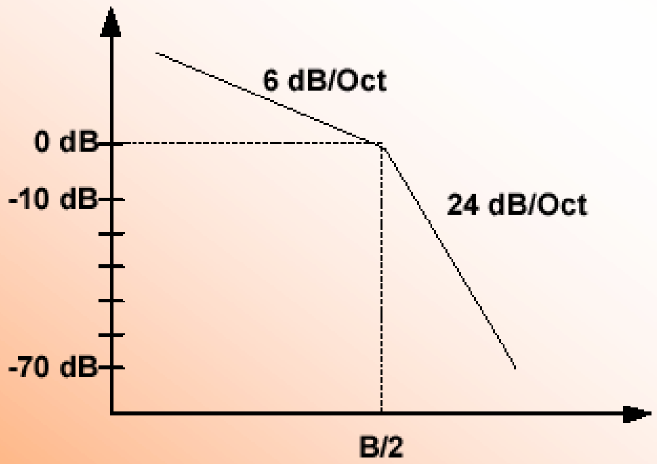
- Noise-Limited Environment
  - Occurs when only two transceivers are in use
  - Thermal noise is dominant
  - To improve performance, increase Signal-to-Noise Ratio
- Interference-Limited Environment
  - Occurs when many transceivers are in use (some users in near-by channels uses the same frequency)
  - Interference is dominant (noise is still present)
  - Cellular systems are interference-limited
- Major Types of Interference in cellular systems are
  - **Cochannel Interference (CCI)**
    - when 2 or more communication channels are assigned the same frequency, interference between them are called CCI

- CCI affects both the Mobile Unit and the Base Station
- The Q-factor ($Q = D/R$) is used to measure the level of CCI
  - Higher Q value improves transmission quality due to smaller level of CCI
  - Note that increasing D improves isolation of RF energy between Cells, hence minimizes interference

- **Adjacent Channel Interference (ACI)**
  - Interference between signals having frequencies close together or interference from signals adjacent in frequency to the desired signal
  - Simply known as interference from neighboring Cells
  - Mainly due to the imperfect receiver filters allowing nearby frequency to leak into the pass band of the desired signal (out-of-band interference)

① Next-channel Interference (NCI)

- for voice channels, filter characteristics is 6 dB per octave in the voice band and 24 dB per octave in the fall-off

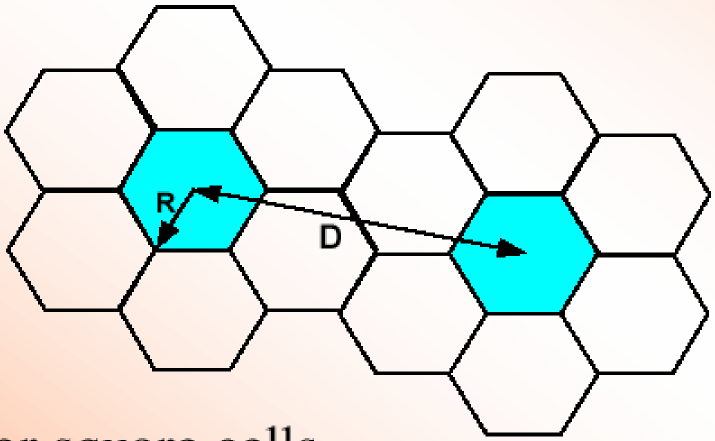


- if the next channel is stronger than 24 dB, it will interfere with the desired signal
- serious if adjacent channel user is closer to the Base Station than the desired signal (near-far-effect)

- NCI can be reduced by
  - careful filtering
  - better channel assignment (large separation)
  - reducing near-far effect
  - reducing CCI will reduce NCI

❍ D/R Radio

Is an important measure of the frequency reuse concept



❍ For hexagonal cells

$$\frac{D}{R} = \sqrt{3N} \triangleq Q$$

❍ For square cells

$$Q \triangleq \frac{D}{R} = \sqrt{2N}$$

❍ For triangular cells

$$Q \triangleq \frac{D}{R} = \sqrt{\frac{3}{2}N}$$

② Neighboring-channel Interference

- Simultaneous transmission of all the channels in a Cell Site will require proper channel isolation, otherwise ACI will occur
- Near-Far effect
  - Some Mobiles are closer to the Base Station than others
  - The near Mobiles has stronger signal which causes ACI to the signals further away
  - Near-Far effect occur only at reception point
- ACI can occur at both Mobile and Base Station

Signal to Interference Ratio (C/I)

- The Signal-to-Interference Ratio (SIR) is given by

$$\frac{S}{I} = \frac{S}{\sum_{k=1}^{N_I} I_k} \qquad (no\,noise)$$

where I_k = power of the k-th Interferer

N_I = number of Interferers ($N_I = 6$ when $N = 7$)

- When the transmit power of each Based Station is equal, and path loss exponent is the same throughout the coverage area, SIR can be approximated by

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{k=1}^{N_I} (D_k)^{-n}}$$

where n = propagation path loss slope which depends on terrain environment ($2 \le n \le 5$)

- If all the interfering BSs are equidistant from the Mobile, then

$$\frac{S}{I} = \frac{(D/R)^n}{N_I} = \frac{(\sqrt{3N})^n}{N_I} \quad (assuming\ that\ D_1 = D_2 = \cdots = D_k = D)$$

- For 7-cluster

$$\frac{S}{I} = \frac{1}{\sum_{k=1}^{6}\left(\frac{D_k}{R}\right)^{-n}} = \frac{1}{6(Q)^{-n}} = \frac{Q^n}{6} \quad (i.e., D_1 = D_2 = \cdots = D_6 = D)$$

- Hence

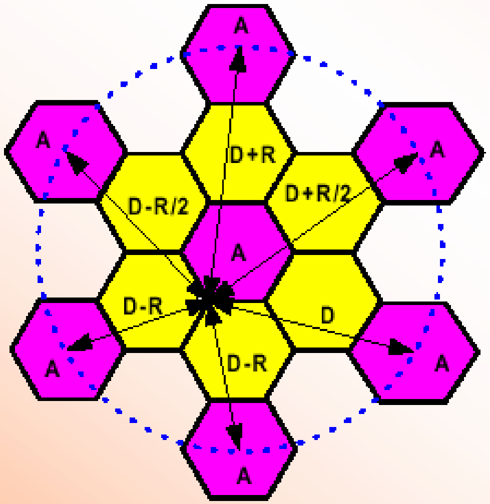
$$Q^n = 6\left(\frac{S}{I}\right) \Rightarrow Q = \left[6\left(S/I\right)\right]^{1/n}$$

- But since Q = $(3N)^{1/2}$

$$N = \frac{1}{3}\left[\left(6\left(S/I\right)\right)^2\right] \cong 7$$

Worst Case Interference Issues

- Mobiles are at the edge of the Cell (Refer to Fig. 2.5, page 41)



- In this situation, the Mobile is at the Cell boundary
- It experiences worst case co-channel interference on the forward channel

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{k=1}^{N_I} (D_k)^{-n}} = \frac{R^{-n}}{2(D-R)^{-n} + D^{-n} + \left(D-\frac{R}{2}\right)^{-n} + \left(D+\frac{R}{2}\right)^{-n} + (D+R)^{-n}}$$

- If written in terms of Q, one obtains

$$\frac{S}{I} = \frac{1}{2(Q-1)^{-n} + Q^{-n} + \left(Q-\frac{1}{2}\right)^{-n} + \left(Q+\frac{1}{2}\right)^{-n} + (Q+1)^{-n}}$$

- Note that repositioning the Mobile to a different base will give a different result, unless the distances are also changed

- **Example (see example 2.2 p. 40)**

  Assuming that SIR of 15 dB is required for satisfactory performance, find Q and N. n is given as 4 and 3.

Spectral Efficiency

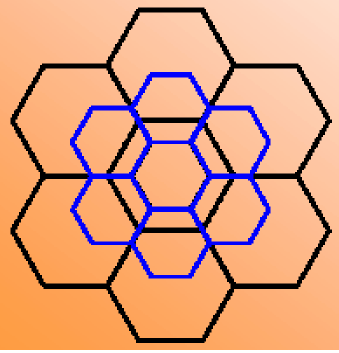
- Spectral Efficiency is the maximum number of cells that can be served at a given frequency and in a given area

$$\eta = \frac{(\text{traffic per cell}) \times N}{B_t \times A} \quad Erlangs/MHz/km^2$$

where N = cluster size, B_t = total available bandwidth, A = cell area

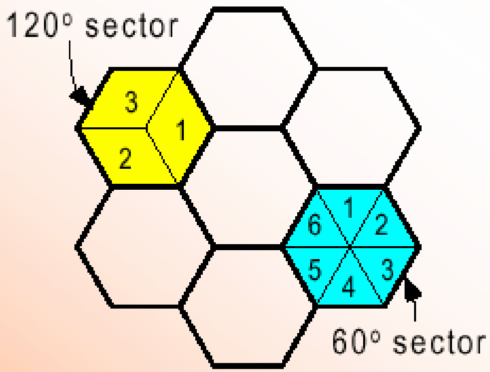
- For voice quality, η depends on bandwidth B, which depends on SIR
- Spectral efficiency (or system capacity) may be improved in 3 ways

① **Cell Splitting:** A process of subdividing a congested cell into smaller cells, each with its base station



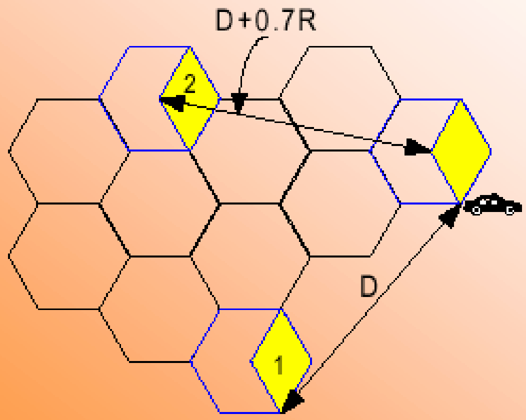
- R is decreased
- Q = D/R remains unchanged relatively
- Gives rise to microcells
- Increases channel reuse thereby increasing the capacity
- More cells implies more cell boundaries will be crossed more often, hence increasing trunking and handoff

② **Sectoring:** A process of replacing a single omni-directional antenna with directional antenna



- R is unchanged and D is reduced
- Also increases amount of channel reuse thereby increasing the capacity
- more cells implies more cell boundaries will be crossed more often, hence increasing trunking and handoff
- Interference is reduced

- For a 3-cell sector, number of interferers is reduced from 6 to 2



$$\frac{S}{I} = \frac{R^{-n}}{D^{-n} + (D+0.7R)^{-n}}$$

$$\frac{S}{I} = \frac{R^{-n}}{(D+0.7R)^{-n}} = (Q+0.7)^{n}$$

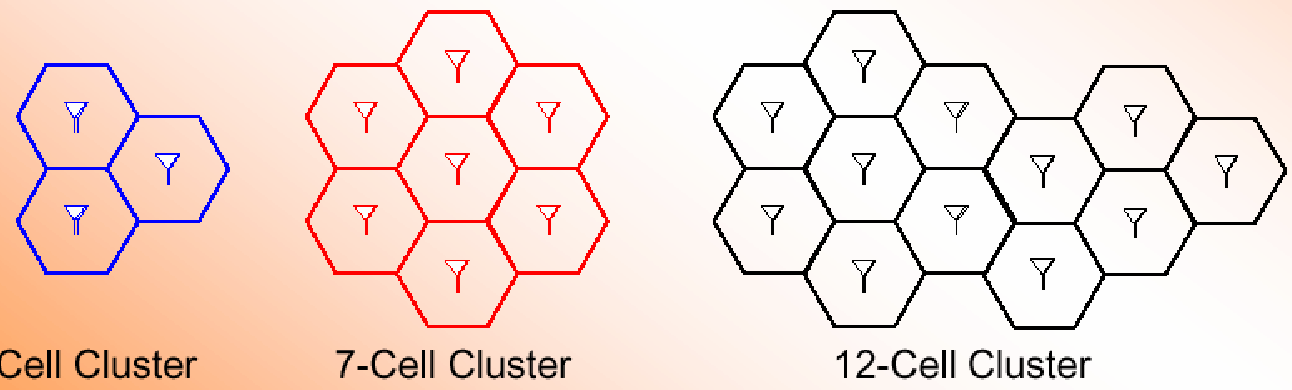
- For a 6-cell sector, number of interferers is reduced from 6 to 1

③ Microcell Approach

- In 7-cell cluster, the cells can be grouped into 3 zones
- Each Cell is connected to the Base Station
- The Mobile will be served by the zone with the strongest signal
- No handoff necessary
- Decreases interference, and improves capacity

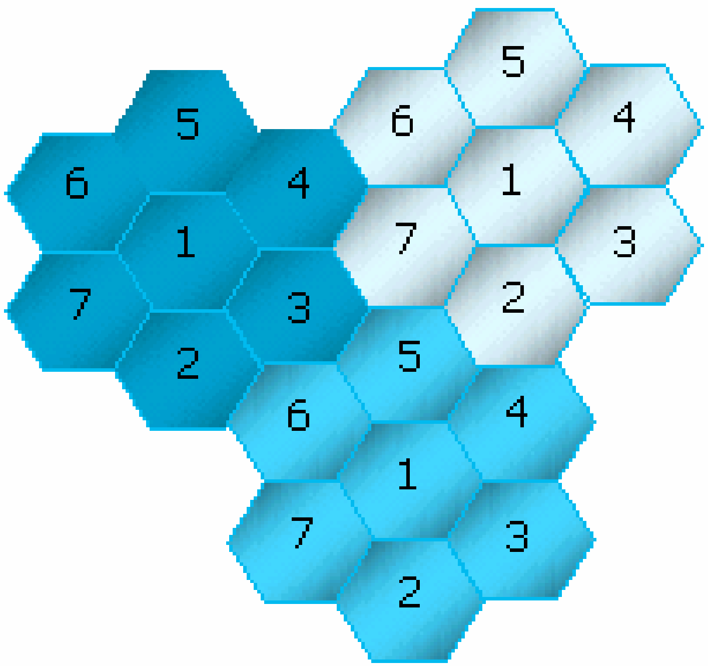
- Channel 1 and 2 have frequencies close to one another
  - Hence they are adjacent channels
- Signals having frequencies of channel 1, 825.030 (mobile) and 870.030 MHz (base station) are co-channel signals

Examples of Cell Clusters (also see Fig. 2.8)

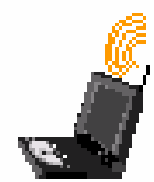


Tradeoffs in Cluster Size

- Ideal hexagonal grid (N=7)

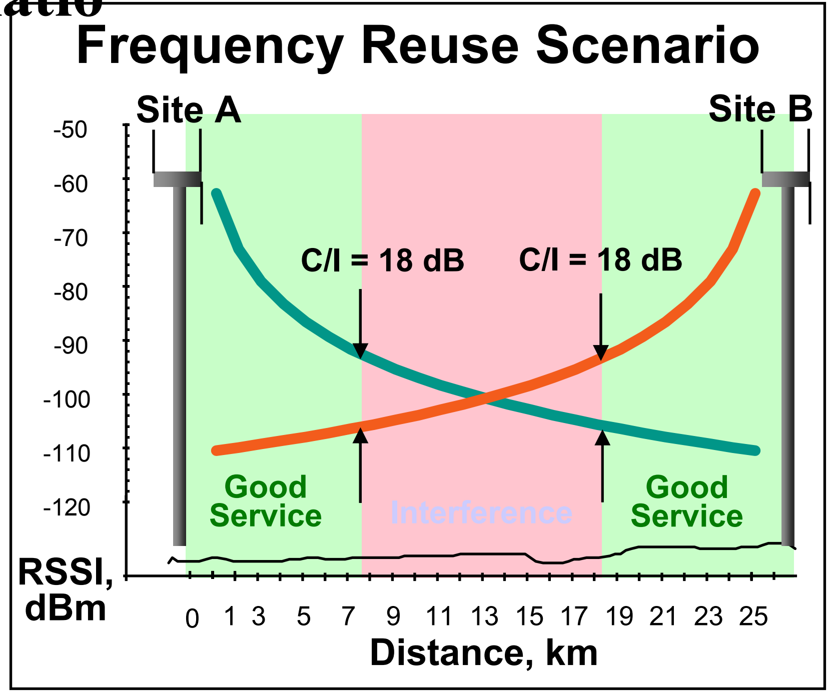


- Assuming that the cell size is kept constant and fixed spectrum per cluster, more cells per cluster mean:
  - Fewer channels per cell
  - Less system capacity
  - Less co-channel interference (co-channel cells farther apart
- Goal is to maximize system capacity subject to interference limitations



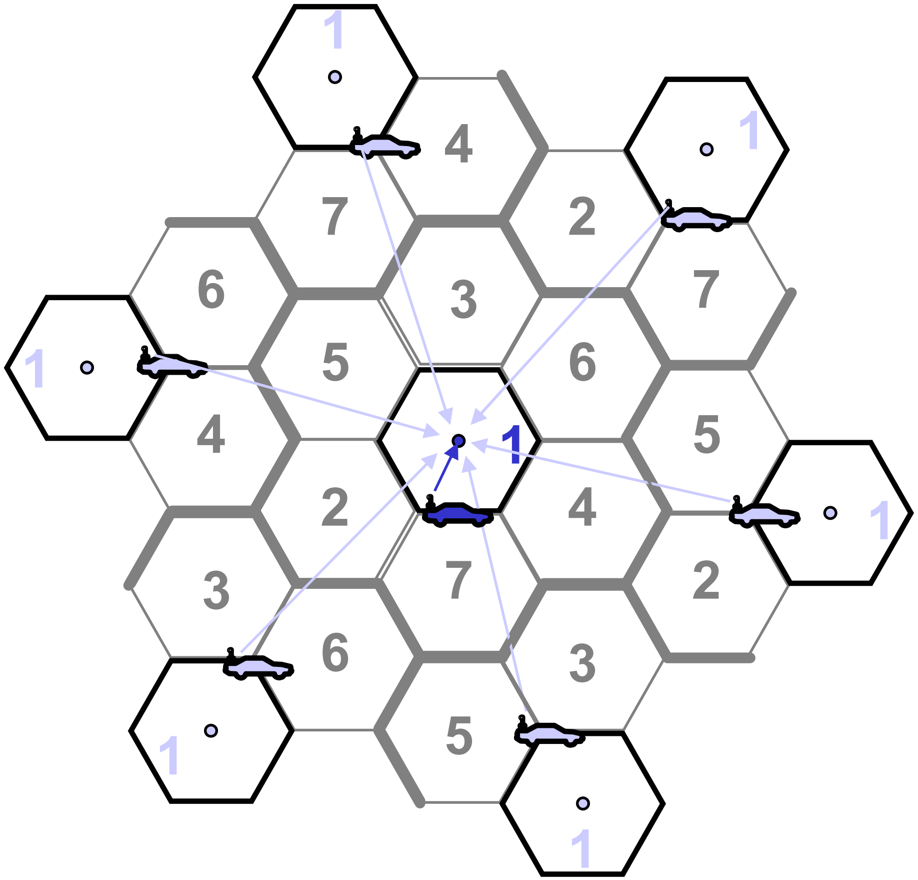
Co-Channel Interference Model

C/I is Carrier-to-Interference Ratio



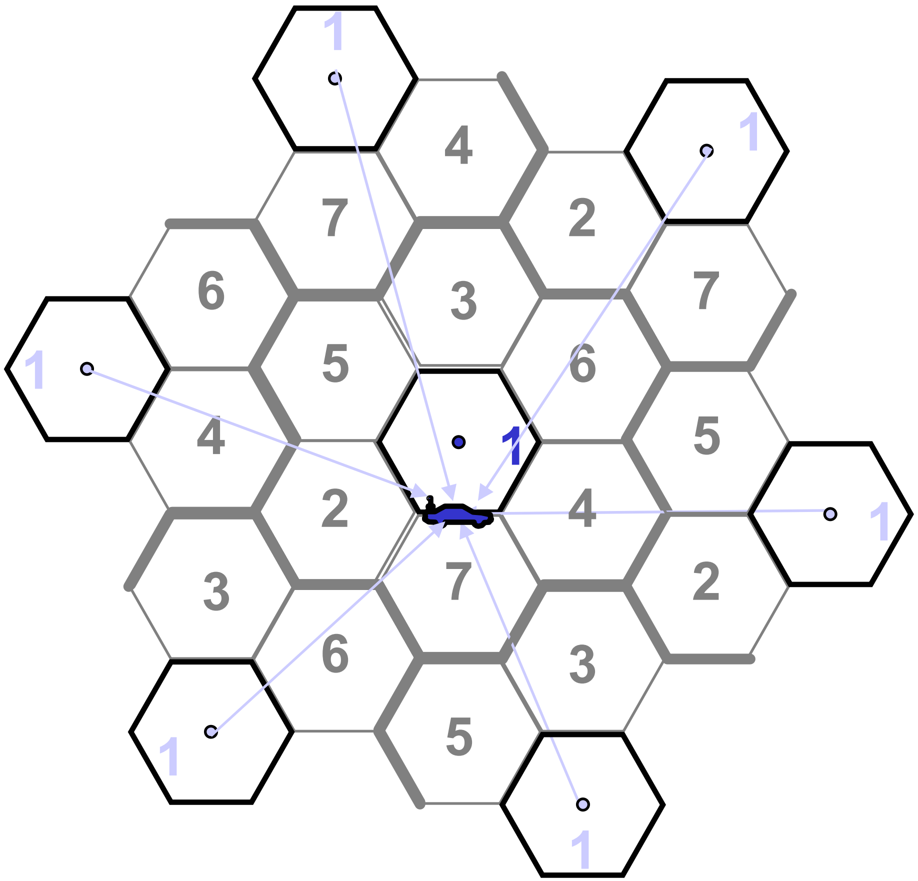
- AMPS modulation characteristics require ≅ 18 dB co-channel C/I over single interferer (≅17dB over multiple interferers ∑)
- Between a pair of sites using same channel, three C/I regions exist:
  - Site A C/I better than 18 dB
  - Neither site gives usable C/I
  - Site B C/I better than 18 dB
- Other sites needed to serve region where neither A nor B has good C/I
- Rate of signal decay determines how close next co-channel site can be and how many additional sites on other channels are needed in between
- With proper planning, it is possible to determine required separation between co-channel sites to avoid interference

Co-Channel Interference Uplink/Reverse Path



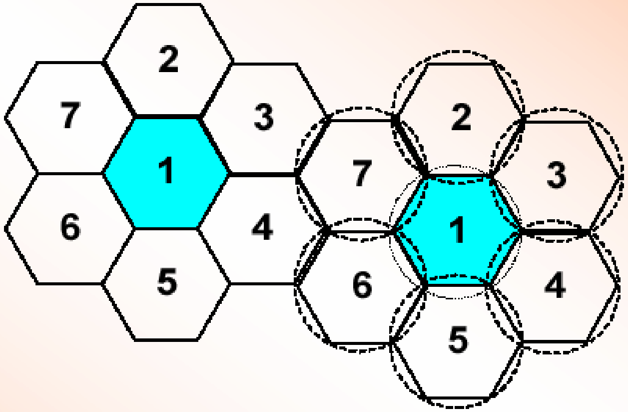
- Co-channel interference can occur on uplink, downlink, or both
- On the uplink, interference occurs at cell site receiver, from mobiles in surrounding co-channel cells

Co-Channel Interference Downlink/Forward Path



On the downlink, interference occurs at mobile user's receiver due to signals from surrounding co-channel cells

❍ Cell Geometry (see Fig. 2.1, 2.2)



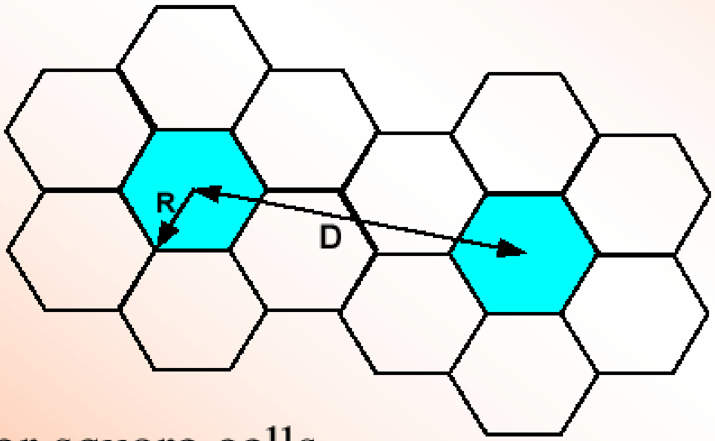
Let:

- R = Radius (center-to-vertex) or maximum distance in service area
- D = Distance between two nearest frequency reuse cells (co-channels cells)
- N = Cluster size (number of cells in the frequency reuse pattern)
- S = Number of duplex channels in a cellular group
- K = Number of channels per cell
- Q = Frequency reuse factor (cochannel interference reduction factor)

D/R Ratio

- **D/R Radio**

  Is an important measure of the frequency reuse concept



- For hexagonal cells

$$\frac{D}{R} = \sqrt{3N} \triangleq Q$$

- For square cells

$$Q \triangleq \frac{D}{R} = \sqrt{2N}$$

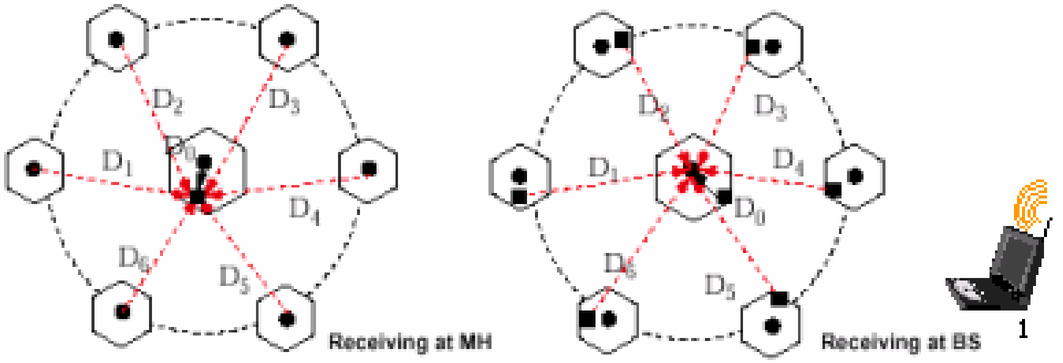
- For triangular cells

$$Q \triangleq \frac{D}{R} = \sqrt{\frac{3}{2}N}$$

Determining Cluster Size N

- $$\frac{C}{I} = \frac{C}{\sum_{i=1}^{N} I_i} = \frac{P_0 R^{-\gamma}}{P_0 \sum_{i=1}^{N} (D_i)^{-\gamma}} = \frac{1}{\sum_{i=1}^{N} \left[\frac{D_i}{R}\right]^{-\gamma}}$$

  where C is the desired carrier power, I_i is the signal power of the i-th interferer, R is the radius of hexagon, and D_i is the frequency reuse distance to the i-th interferer.
- When required C/I is 16dB, N=7 is necessary



- For N = 7 (hexagon), the D/R relationship requires that C/I ~ 18 dB

$$N=7,\ D/R=\sqrt{21}=4.6$$
$$N=4,\ D/R=\sqrt{12}=3.46$$
$$N=3,\ D/R=\sqrt{9}=3$$

- The cluster pattern (which can be repeated) is given by the equation

$$N=i^2+ij+j^2$$

where i, j =0, 1, 2, 3, …

$i=1,\ j=1$	$N=3$
$i=2,\ j=0$	$N=4$
$i=2,\ j=1$	$N=7$
$i=2,\ j=2$	$N=12$
$i=3,\ j=2$	$N=19, etc$

- Procedures for locating cochannel cells:
  - ***i*** is the direction perpendicular to the side of the hexagon
  - ***j*** is the direction rotated 60° clockwise or counterclockwise from ***i***

(see Table 2.1)

Example 2.1

If a total of 33 MHz of bandwidth his allocated to a particular FDD cellular system which uses 25 kHz pairs, compute the number of channles available per cell if a system uses

- 4 cell reuse
- 7 cell reuse
- 12 cell reuse

If 1 MHz is allocated for control chanels, determine a distribution of control and voice channels in each cell for each of the 3 systems

Example 2.1 Solution

Channels =33000/50 =660 channels

N=4: 660/4 = 165

N=7: 660/7 =95

N=12: 660/12 = 55

1 MHz control = 1000/50 =20

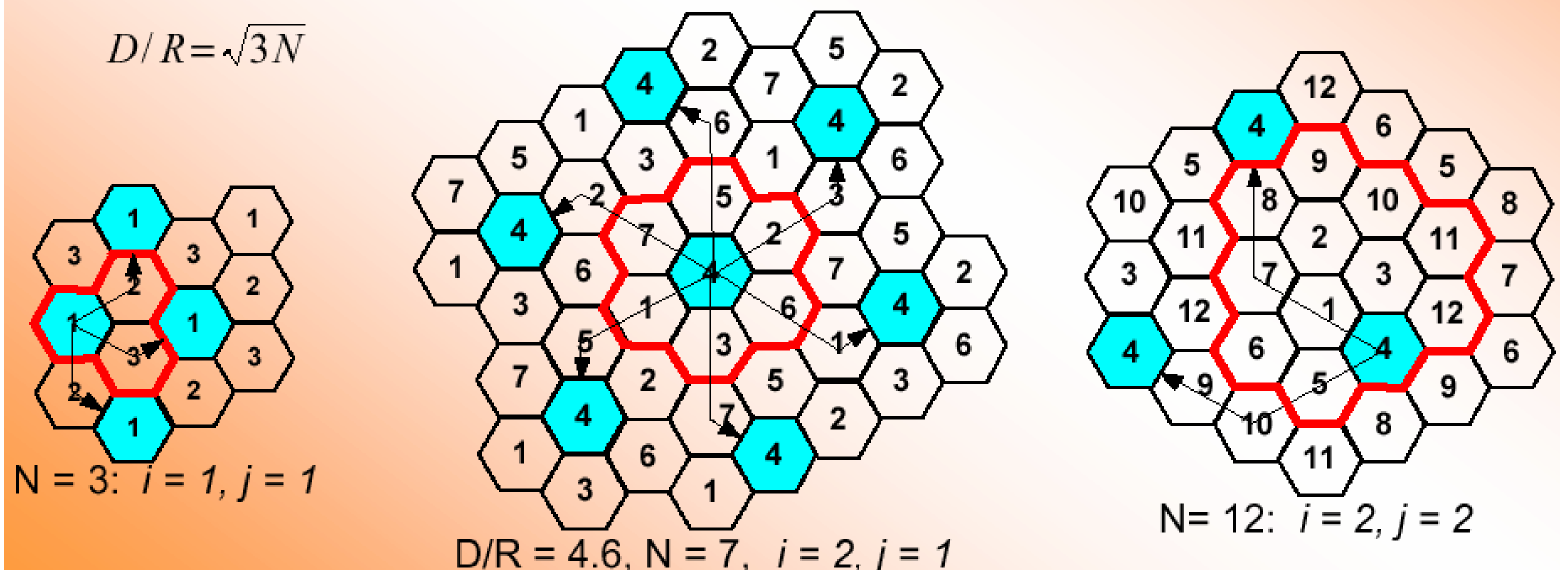
N=4 160 Voice + 5 Control

N=7 …

N=12 …

- Trade off between Q and N
  - In a cluster, increasing Q also increases N, thereby reducing capacity
- Any cluster arrangement satisfying the relationship $N = i^2 + ij + j^2$ is possible

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



- Trade off between Q and N
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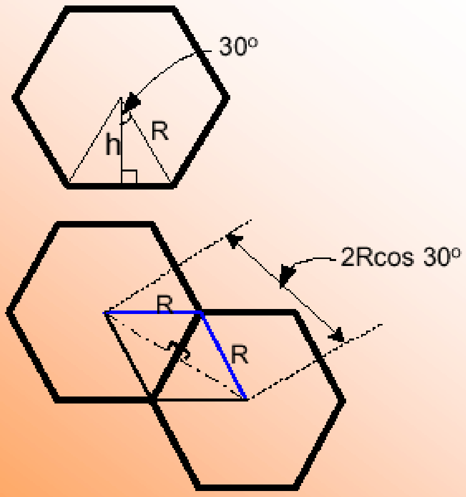


$$\sin 30^o = \frac{1}{2}$$

$$\cos 30^o = \frac{adj}{hypo} = \frac{h}{R} = \frac{\sqrt{3}}{2}$$

$$h = R\cos 30^o$$

$$2h = 2R\cos 30^o$$

$$= 2R \cdot \frac{\sqrt{3}}{2} = \sqrt{3}R$$

- Channel assignment per cell need not be uniform
  - for example, busy highways within a cell may be assigned more channels than sparsely used highways
- However, total voice channels which can be assigned to a cluster of cells cannot exceed the FCC allocation of 312 voice channels in the original allocation or 395 channels in the extended allocation
- For N = 7, we have:

Cell 1: 1, 8, 15, 22, 29, …,	295, 302, 309
Cell 2: 2, 9, 16, 23, 30, …,	296, 303, 310
Cell 3: 3, 10, 17, 24, 31, …,	297, 304, 311
Cell 4: 4, 11, 18, 25, 32, …,	298, 305, 312
Cell 5: 5, 12, 19, 26, 33, …,	299, 306
Cell 6: 6, 13, 20, 27, 34, …,	300, 307
Cell 7: 7, 14, 21, 28, 35, …,	301, 308

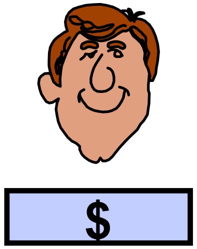
Control Channels: 313, 314, 315, …. 332, 333

REUSE for MAJOR TECHNOLOGIES DEPLOYED IN NORTH AMERICA

Technology	Standards Documents	First Used	Modul-ation	Service Types	Band-width	Reuse
AMPS Advanced Mobile Phone Service	EIA/TIA 553 IS-19 mobile IS-20 base sta.	1983	Analog FM 17 dB C/I	Voice	30 kHz	7
NAMPS Narrowband AMPS	IS-88	1990	Analog FM 17 dB C/I	Voice SMS	10 kHz	7
D-AMPS Digital AMPS North American TDMA	IS-54B	1993	Digital DQPSK 14 dB C/I (fragile)	Voice Data	30 kHz	7
	IS-136	1995		+CAVE +DCCH +SMS		
GSM European 2nd-Generation TDMA	ETSI/TIA/ITU multiple documents	1992	Digital GMSK 7 dB C/I (robust)	Voice SMS Cell Bcst frq hop'g	200 kHz	4
CDMA Code Division Multiple Access	IS-95B, Joint Std. 008, + features stds	1995	Digital QPSK Spread Spectrum	Voice SMS Data +more	1250 kHz	1

Basics Of Traffic Engineering

Traffic Engineering Objectives



- Traffic engineering is a discipline concerned with keeping both system customers and accountants happy.
- Traffic engineering finds answers to questions at every stage in the development of a cellular system
- In Initial Design:
  - How many cells are needed?
  - What size of switch is required?
  - How many cell site trunks and how much microwave should we install?
- Ongoing during Operation:
  - How many radios for each cell or sector are required to meet projections?
  - When are new cells needed for capacity?

Common Definitions

Table 2.3 Definitions of Common Terms Used in Trunking Theory

Set-up Time: The time required to allocate a trunked radio channel to a requesting user.

Blocked Call: Call which cannot be completed at time of request, due to congestion. Also referred to as a *lost call*.

Holding Time: Average duration of a typical call. Denoted by H (in seconds).

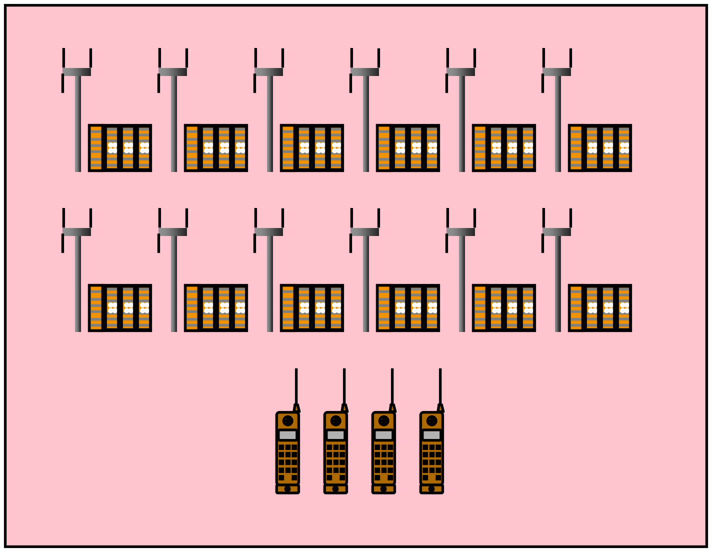
Traffic Intensity: Measure of channel time utilization, which is the average channel occupancy measured in Erlangs. This is a dimensionless quantity and may be used to measure the time utilization of single or multiple channels. Denoted by A.

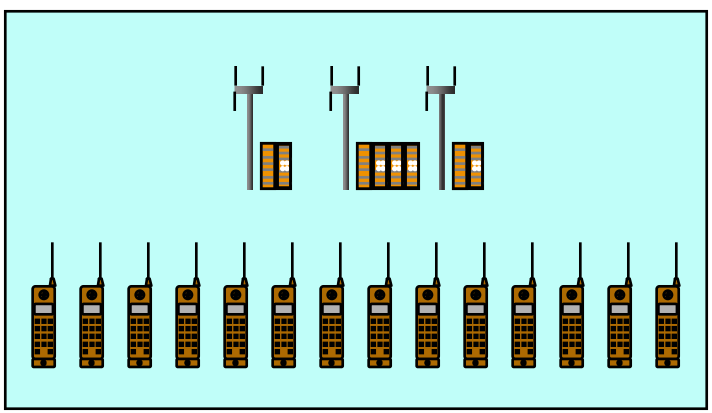
Load: Traffic intensity across the entire trunked radio system, measured in Erlangs.

Grade of Service (GOS): A measure of congestion which is specified as the probability of a call being blocked (for Erlang B), or the probability of a call being delayed beyond a certain amount of time (for Erlang C).

Request Rate: The average number of call requests per unit time. Denoted by λ seconds^{-1}.

A Game of Avoiding Extremes





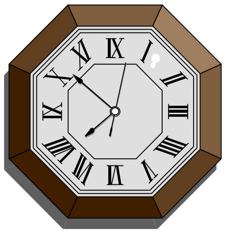
The traffic engineer must walk a fine line between two problems:

- **<u>Overdimensioning</u>**
  - **too much cost**
  - insufficient resources to construct
  - traffic revenue is too low to support costs
  - very poor economic efficiency!
- **<u>Underdimensioning</u>**
  - **blocking**
  - poor technical performance (**interference**)
  - capacity for billable revenue is low
  - revenue is low due to poor quality
  - users unhappy, cancel service
  - very poor economic efficiency!

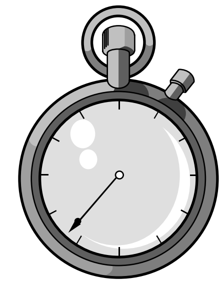
Basics of Traffic Engineering:
Terminology & Concept of a Trunk

- Traffic engineering in telephony is focused on the **voice paths which users occupy**. They are called by many different names:
  - **trunks**
  - **circuits**
  - **radios, transceivers ("TRXs"), channel elements (CDMA)**
- Some other common terms are:
  - **trunk group**
    - a trunk group is several trunks going to the same destination, combined and addressed in switch translations as a unit , for traffic routing purposes
    - **member**
    - one of the trunks in a trunk group

Units of Traffic Measurement



Traffic is expressed in units of Circuit Time



General understanding of telephone traffic engineering began around 1910. An engineer in the Danish telephone system, Anger K. Erlang, was one of the first to master the science of trunk dimensioning and publish the knowledge for others. In his honor, the basic unit of traffic is named the **Erlang**.

- An **Erlang** of traffic is one circuit continuously used during an observation period one hour long.

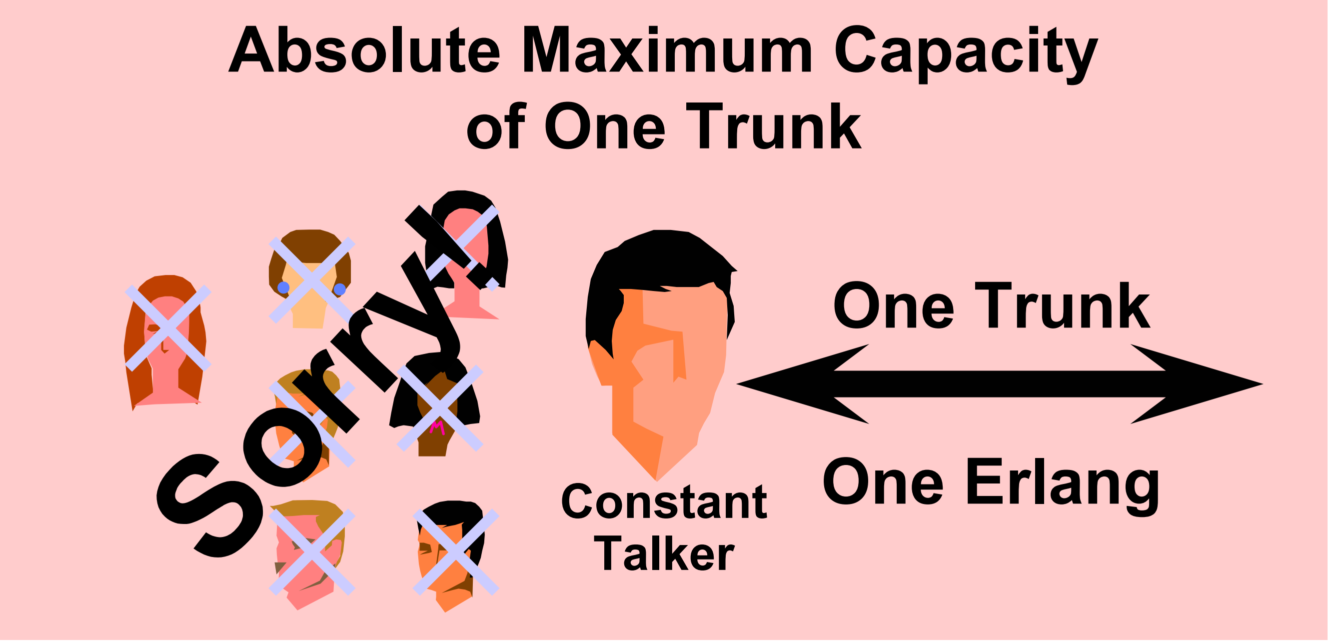
Other units have become popular among various users:

- **CCS** (Hundred-Call-Seconds)
- **MOU** (Minutes Of Use)
- It's easy to convert between traffic units if the need arises:

1 Erlang = 60 MOU = 36 CCS

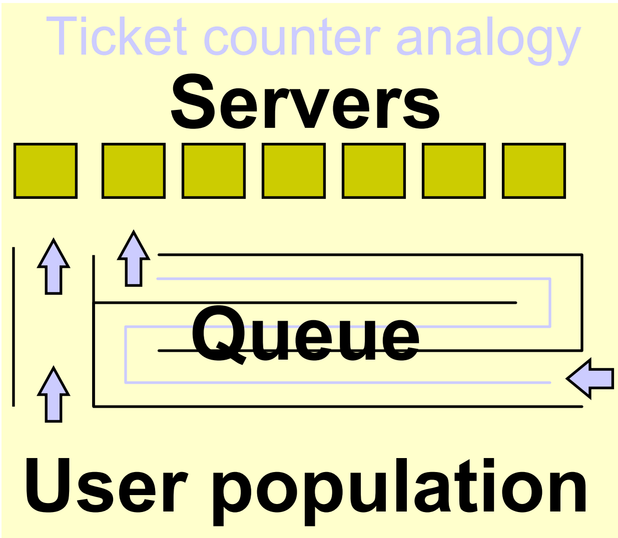
How Much Traffic Can One Trunk Carry?

- Traffic studies are usually for periods of one hour
- In one hour, one trunk can carry one hour of traffic -- *One Erlang*
- If nothing else matters, this is the limit!
- If anyone else wants to talk -- sorry!



- We must not plan to keep trunks busy all the time. There must be a reserve to accommodate new talkers! How much reserve? next!

Traffic Engineering And Queuing Theory



Queues we face in everyday life

1) for telephone calls
2) at the bank
3) at the gas station
4) at the airline counter

- Traffic engineering is an application of a science called *queuing theory*
  - Queuing theory relates user arrival statistics, number of servers, and various queue strategies, with the probability of a user receiving service
  - If waiting is not allowed, and a blocked call simply goes away, *Erlang-B* formula applies *(popular in wireless)*
  - If unlimited waiting is allowed before a call get served, the *Erlang-C* formula applies
  - If a wait is allowed but is limited in time, *Binomial & Poisson* formulae apply
  - *Engset* formulae apply to rapid, packet-like transactions such as paging channels

Offered Traffic and Call Duration

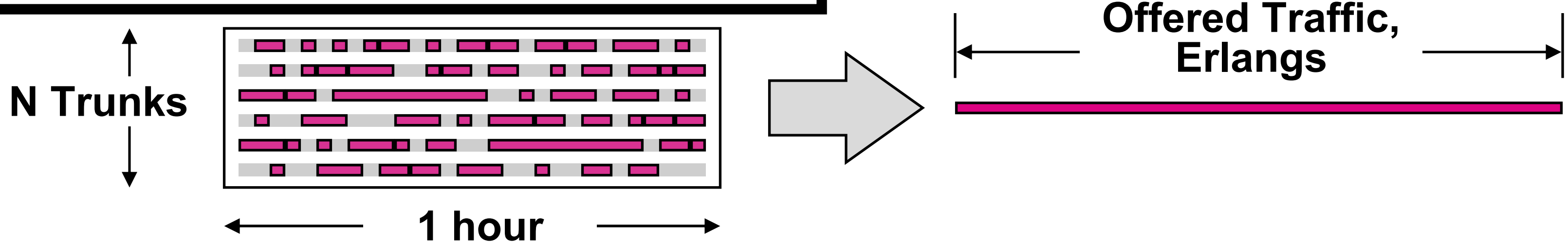
$\mathbf{A = \lambda \times t_m}$

A = Traffic intensity (Erlangs)

λ = Arrival rate (average number of calls per unit of time)

$\mathbf{t_m}$ = Holding time (Avg call duration)

Traffic intensity A is the amount of traffic users attempt to transmit through the system at some given time.



Example:

λ = 1000 call attempts in the busy hour

$\mathbf{t_m}$ = 150 seconds average call duration

What's the offered traffic intensity?

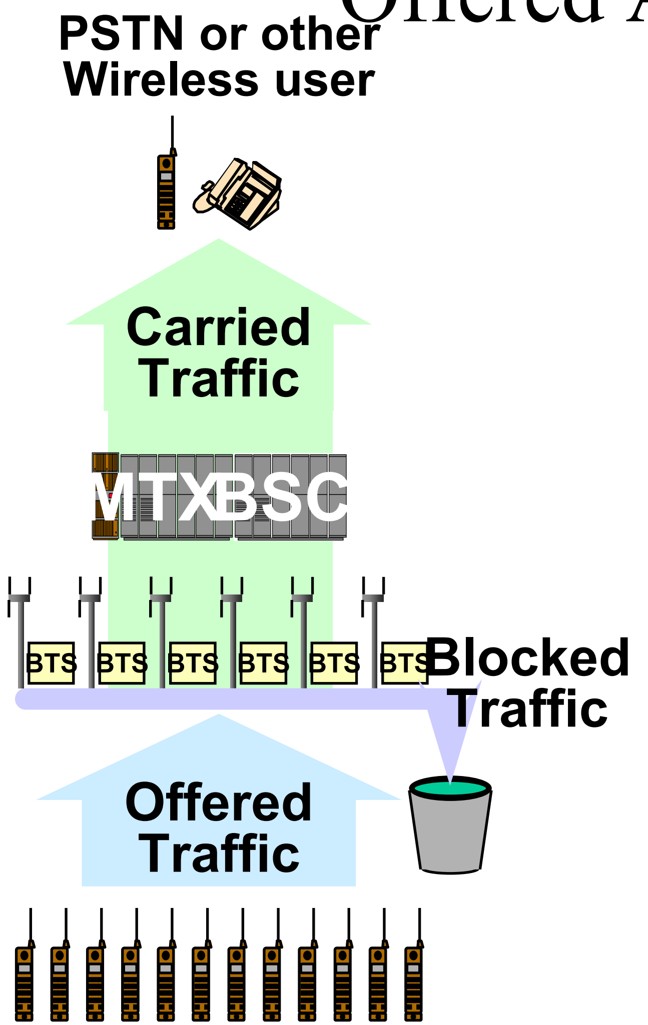
Solution:

$\mathbf{A = \lambda \times t_m}$

= 1000 x (150 / 3600)

= **41.667 Erlangs**

Offered And Carried Traffic



- *Offered traffic* is what users attempt to originate
- *Carried traffic* is the traffic actually successfully handled by the system
- *Blocked traffic* is the traffic that could not be handled
  - Since blocked call attempts never materialize, blocked traffic must be ***estimated*** based on number of blocked attempts and average duration of successful calls

Offered Traffic =
Carried Traffic + Blocked Traffic

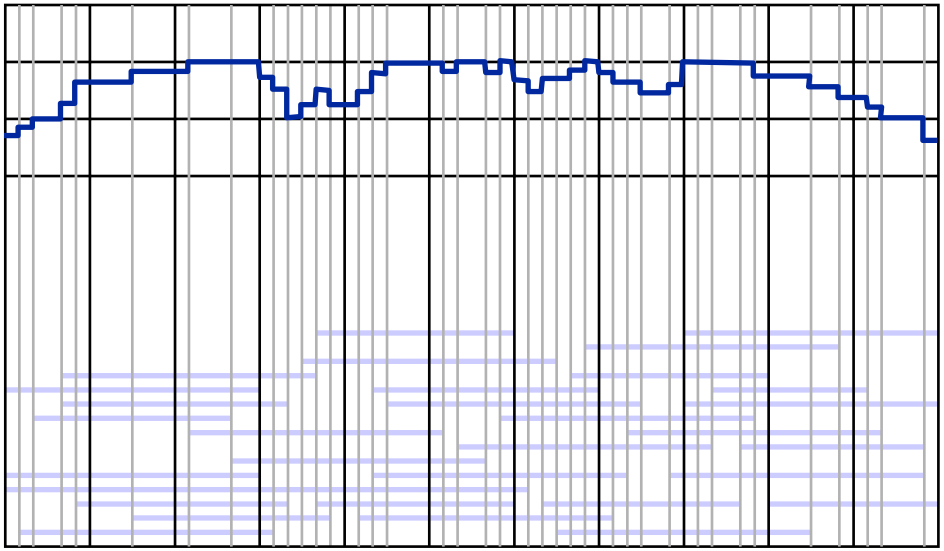
$T_{Off} = N_{CA} \times T_{CD}$

T_{Off} = Offered traffic

N_{CA} = Number of call attempts

T_{CD} = Average call duration

Loss Systems



- Traffic analysis can be performed on two categories of systems: loss systems and delay systems.
- In a loss system, overload traffic is cleared from the system.
- In a delay system, overload traffic is queued until enough clear facilities are available to service it.

Loss Systems, cont.

- Cellular systems exhibit properties similar to loss systems. We say “blocked calls are cleared.”
- Packet switching systems are examples of delay systems.
- The “blocking probability” is the basic measure of performance of a cellular (loss) system.

Traffic profile: Out of 15 sources, only 10 are ever occupied simultaneously, and on the average, only 8 are. Total traffic volume is about 88 minutes (1.47 Erlangs).

Carried Traffic

$$P_j(A) = \frac{A^j}{j!} e^{-A}$$

Poisson arrival distribution

The probability of *j* circuits all being busy at any time, given a traffic intensity *A*.

$$P(>t) = e^{-t/tm}$$

Exponential holding time distribution

The probability that a holding time exceeds a value *t*, given the average holding time t_m.

Trunking Efficiency

Example: a trunk group has enough servers to handle *all the traffic offered to it.* The arrival rate λ is 2 calls per minute and the average holding time t_m is 1.5 mins. What percentage of the total traffic is carried by the first six circuits? How much traffic is carried by all remaining circuits?

Solution: First, let's see what the traffic intensity *A* is. In the period of consideration, $A = \lambda \mathbf{x}\, t_m$, = 2.0 calls/min x 60 min/1 erl x 1.5 min x 1 erl/60 min

= 3.0 erl.

The probability of *j* circuits being busy at any instant, if all requests are served immediately, is:

$$P_j(A) = \frac{A^j}{j!} e^{-A}$$

Trunking Efficiency Example, cont.

Solution (cont.):

The traffic intensity for the six circuit group is determined by taking the total traffic amount possible for groups of 1, 2, …, 6 circuits (which is, of course, 1, 2, …, 6 Erlangs), and multiplying by the probability that for the three Erlangs of traffic, the group is busy. This can be condensed to the format:

$$A_6 = \sum_{j=1}^{6} jP_j(A)$$

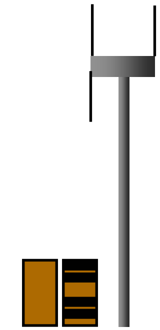
So, $A_6 = 1P_1(3) + 2P_2(3) + 3P_3(3) + 4P_4(3) + 5P_5(3) + 6P_6(3)$

Then, $A_6 = e^{-3}\left(\left(\frac{3^1}{1!}\right) + 2\left(\frac{3^2}{2!}\right) + 3\left(\frac{3^3}{3!}\right) + 4\left(\frac{3^4}{4!}\right) + 5\left(\frac{3^5}{5!}\right) + 6\left(\frac{3^6}{6!}\right)\right)$ = 2.75 Erlang.

Trunking Efficiency Example, conclusion

- Since the first six trunks carry 2.75 Erlangs, and the total traffic is 3 Erlangs, the rest (3 - 2.75 = 0.25 Erlangs) is carried on the remainder of the trunks in the trunk group.
- Thus, the first six trunks carry 91.7% of the total traffic, leaving 8.3% for the rest of the trunk group. If there are 200 circuits offering/taking traffic, 194 carry the remaining 8.3 % of the traffic.

Number of Trunks vs. Utilization Efficiency



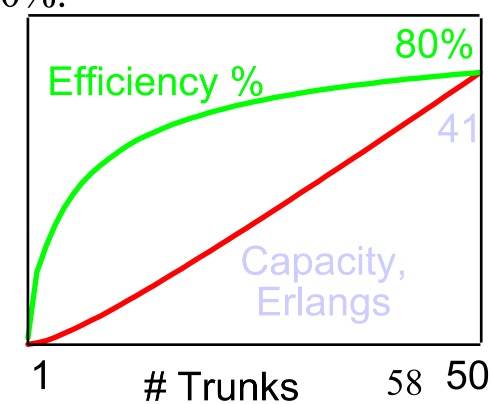
- Imagine a cell site with *just **one** voice channel*. At a **P.02** Grade of Service, how much traffic could it carry?
  - The trunk can only be used 2% of the time, otherwise the blocking will be worse than 2%.
  - 98% *availability* forces 98% *idleness*. It can only carry .02 Erlangs. Efficiency 2%!

- Adding just one trunk relieves things greatly. Now we can use trunk 1 heavily, with trunk 2 handling the overflow. Efficiency rises to 11%

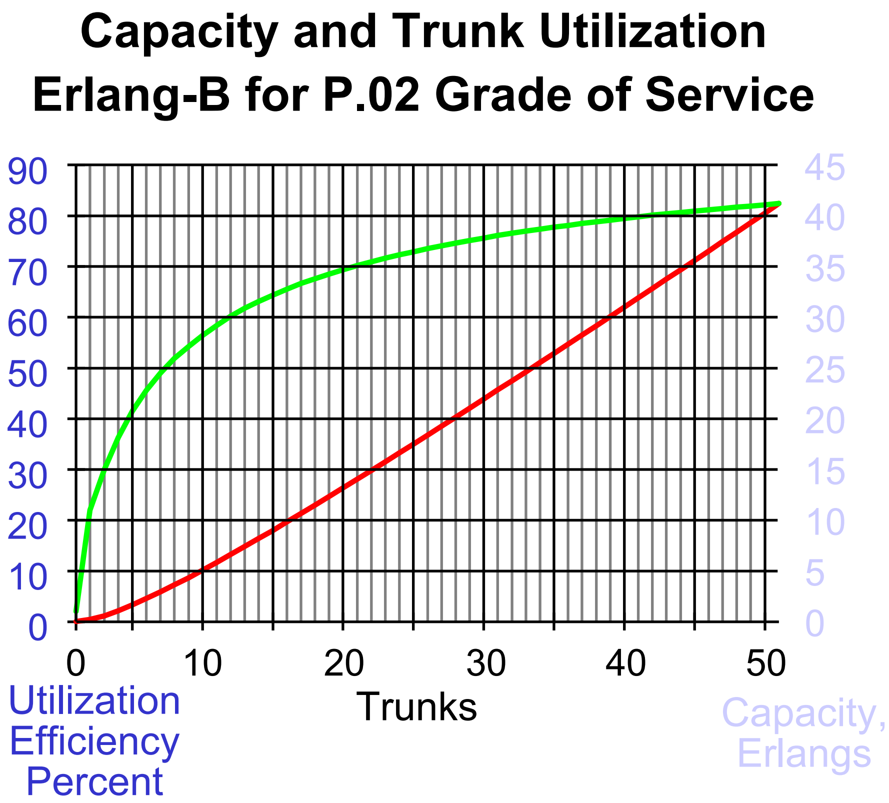
Erlang-B P.02 GOS

Trks	Erl	Eff%
1	0.02	2%
2	0.22	11%

- **The Principle of Trunking Efficiency**
- **For a given grade of service, trunk utilization efficiency increases as the number of trunks in the pool grows larger.**
  - For trunk groups of several hundred, utilization approaches 100%.



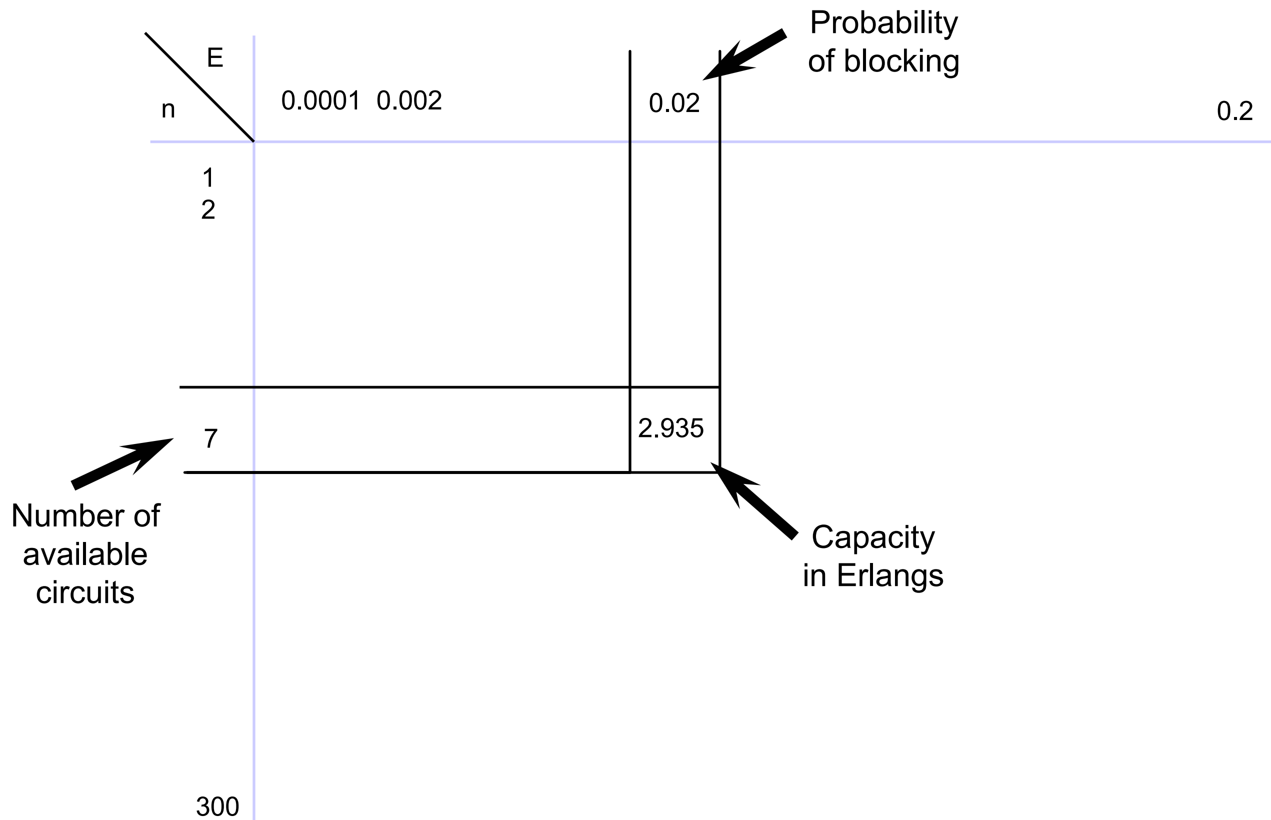
Number of Trunks, Capacity, and Utilization Efficiency



- The graph at left illustrates the capacity in Erlangs of a given number of trunks, as well as the achievable utilization efficiency
- For accurate work, tables of traffic data are available
  - Capacity, Erlangs
  - Blocking Probability (GOS)
  - Number of Trunks
- Notice how capacity and utilization behave for the numbers of trunks in typical cell sites

Traffic Engineering & System Dimensioning

Using Erlang-B Tables to determine Number of Circuits Required



A = f (E,n)

Erlang B-Formula

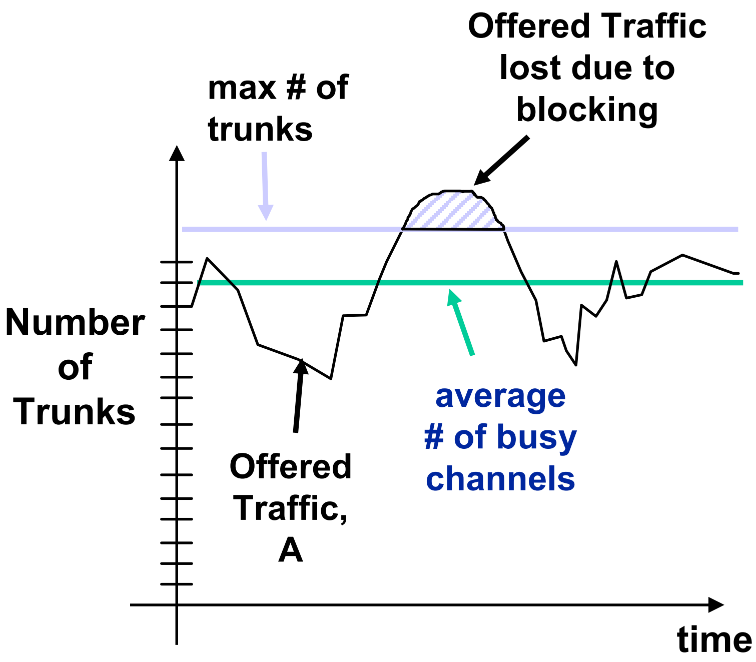
$$Pr[blocking] = \frac{\frac{A^C}{C!}}{\sum_{k=0}^{C} \frac{A^k}{k!}} = GOS$$

Equation Behind the Erlang-B Table

- The Erlang-B formula is fairly simple to implement on hand-held programmable calculators, in spreadsheets, or popular programming languages.

$$P_n(A) = \frac{\frac{A^n}{n!}}{1 + \frac{A}{1!} + \ldots + \frac{A^n}{n!}}$$

$P_n(A)$ = Blocking Rate (%)
with n trunks
as function of traffic A
A = Traffic (Erlangs)
n = Number of Trunks



Erlang-B Traffic Tables
Abbreviated - For P.02 Grade of Service Only

#Trunks	Erlangs
1	0.0204
2	0.223
3	0.602
4	1.09
5	1.66
6	2.28
7	2.94
8	3.63
9	4.34
10	5.08
11	5.84
12	6.61
13	7.4
14	8.2
15	9.01
16	9.83
17	10.7
18	11.5
19	12.3
20	13.2
21	14
22	14.9
23	15.8
24	16.6
25	17.5

#Trunks	Erlangs
26	18.4
27	19.3
28	20.2
29	21
30	21.9
31	22.8
32	23.7
33	24.6
34	25.5
35	26.4
36	27.3
37	28.3
38	29.2
39	30.1
40	31
41	31.9
42	32.8
43	33.8
44	34.7
45	35.6
46	36.5
47	37.5
48	38.4
49	39.3
50	40.3

#Trunks	Erlangs
51	41.2
52	42.1
53	43.1
54	44
55	44.9
56	45.9
57	46.8
58	47.8
59	48.7
60	49.6
61	50.6
62	51.5
63	52.5
64	53.4
65	54.4
66	55.3
67	56.3
68	57.2
69	58.2
70	59.1
71	60.1
72	61
73	62
74	62.9
75	63.9

#Trunks	Erlangs
76	64.9
77	65.8
78	66.8
79	67.7
80	68.7
81	69.6
82	70.6
83	71.6
84	72.5
85	73.5
86	74.5
87	75.4
88	76.4
89	77.3
90	78.3
91	79.3
92	80.2
93	81.2
94	82.2
95	83.1
96	84.1
97	85.1
98	86
99	87
100	88

#Trunks	Erlangs
100	88
102	89.9
104	91.9
106	93.8
108	95.7
110	97.7
112	99.6
114	101.6
116	103.5
118	105.5
120	107.4
122	109.4
124	111.3
126	113.3
128	115.2
130	117.2
132	119.1
134	121.1
136	123.1
138	125
140	127
142	128.9
144	130.9
146	132.9
148	134.8

#Trunks	Erlangs
150	136.8
152	138.8
154	140.7
156	142.7
158	144.7
160	146.6
162	148.6
164	150.6
166	152.6
168	154.5
170	156.5
172	158.5
174	160.4
176	162.4
178	164.4
180	166.4
182	168.3
184	170.3
186	172.4
188	174.3
190	176.3
192	178.2
194	180.2
196	182.2
198	184.2

#Trunks	Erlangs
200	186.2
202	188.1
204	190.1
206	192.1
208	194.1
210	196.1
212	198.1
214	200
216	202
218	204
220	206
222	208
224	210
226	212
228	213.9
230	215.9
232	217.9
234	219.9
236	221.9
238	223.9
240	225.9
242	227.9
244	229.9
246	231.8
248	233.8

#Trunks	Erlangs
250	235.8
300	285.7
350	335.7
400	385.9
450	436.1
500	486.4
600	587.2
700	688.2
800	789.3
900	890.6
1000	999.1
1100	1093

Basic Traffic Engineering Example

- **Number of calls per Cell (assume N=7)**
  - Let's illustrate the call carrying capacity of each cell using the original allocation of 333 channels and 21 control channels
  - Hence, available channels is given by

$$\frac{333-21}{7} \approx 45 \text{ radio channels} \quad \text{i.e., } K = 45$$

  - Let blocking probability, B = 2%
  - Average holding time per call = 100 sec
  - Offered load per cell = 35.6 Erlangs
    - Erlang is the unit in which traffic load on the system is measured
    - If a call last for 1 hour, the traffic load due to this call is 1 Erlang
    - The offered load is given by

$$\frac{\text{average calling time (minutes)} \times \text{total customers}}{60 \text{ minutes}}$$

$$\text{No. of calls/cell/hr} = \frac{35.6 \times 3600\,\text{sec}}{100\,\text{sec}} = 1281.6$$

$$\text{Assume calls/customer/busy hr} = 60\%$$

$$\text{No. of customer/cell} = \frac{1281.6}{0.6} = 2136$$

$$\text{No. of customers/radio channel} = \frac{2136}{45} = 47.5$$

$$\text{No. of call/channel/hr} = \frac{1281.6}{45} = 28.48$$

- The higher the blocking probability, the more customers, but the radio quality is less

$$B\uparrow \rightarrow C\uparrow \rightarrow Quality\downarrow$$

- Try a similar calculation for $N = 4$ and $N = 12$
- Proper channel assignment is necessary to reduce cochannel interference

Example

Example 2.4

How many users can be supported for 0.5% blocking probability for the following number of trunked channels in a blocked calls cleared system? (a) 1, (b) 5, (c) 10, (d) 20, (e) 100. Assume each user generates 0.1 Erlangs of traffic.

Solution to Example 2.4

From Table 2.4 we can find the total capacity in Erlangs for the 0.5% GOS for different numbers of channels. By using the relation $A = UA_u$, we can obtain the total number of users that can be supported in the system.

(a) Given $C = 1$, $A_u = 0.1$, $GOS = 0.005$

From Figure 2.6, we obtain $A = 0.005$.

Therefore, total number of users, $U = A/A_u = 0.005/0.1 = 0.05$ users.

But, actually one user could be supported on one channel. So, $U = 1$.

(b) Given $C = 5$, $A_u = 0.1$, $GOS = 0.005$

From Figure 2.6, we obtain $A = 1.13$.

Therefore, total number of users, $U = A/A_u = 1.13/0.1 \approx 11$ users.

(c) Given $C = 10$, $A_u = 0.1$, $GOS = 0.005$

From Figure 2.6, we obtain $A = 3.96$.

Therefore, total number of users, $U = A/A_u = 3.96/0.1 \approx 39$ users.

(d) Given $C = 20$, $A_u = 0.1$, $GOS = 0.005$

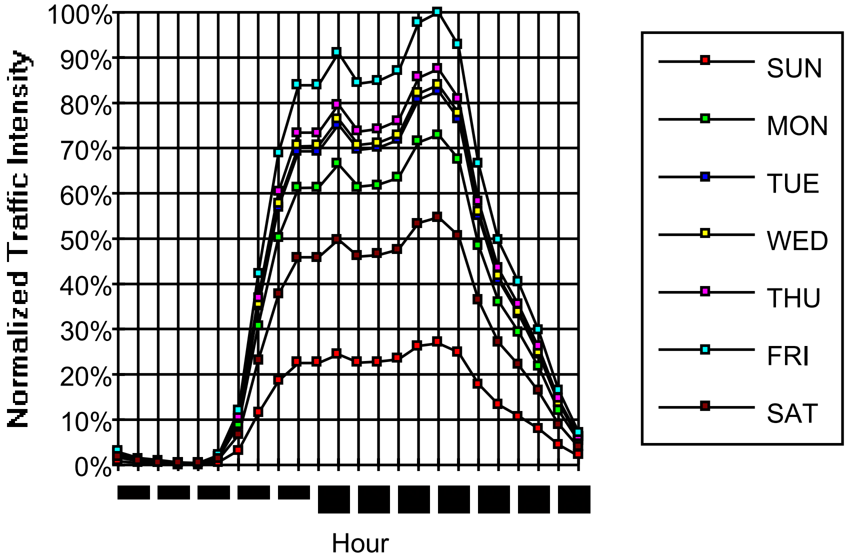
From Figure 2.6, we obtain $A = 11.10$.

Therefore, total number of users, $U = A/A_u = 11.1/0.1 = 110$ users.

(e) Given $C = 100$, $A_u = 0.1$, $GOS = 0.005$

Wireless Traffic Variation with Time: A Cellular Example

Typical Traffic Distribution on a Cellular System



Actual traffic from a cellular system in the mid-south USA in summer 1992. This system had 45 cells and served an area of approximately 1,000,000 population.

- Peak traffic on cellular systems is usually daytime business-related traffic; on PCS systems, evening traffic becomes much more important and may actually contain the system busy hour
- Evening taper is more gradual than morning rise
- Wireless systems for PCS and LEC-displacement have peaks of residential traffic during early evening hours, like wireline systems
- Friday is the busiest day, followed by other weekdays in backwards order, then Saturday, then Sunday
- **There are seasonal and annual variations, as well as long term growth trends**

Busy-Hour

- In telephony, it is customary to collect and analyze traffic in hourly blocks, and to track trends over months, quarters, and years
- When making decisions about number of trunks required, we plan the trunks needed to support the busiest hour of a normal day
  - Special events (disasters, one-of-a-kind traffic tie-ups, etc.) are not considered in the analysis *(unless a marketing-sponsored event)*
- Which Hour should be used as the Busy-Hour?
  - Some planners choose one specific hour and use it every day
  - Some planners choose the busiest hour of each individual day ("floating busy hour")
  - Most common preference is to use "floating (bouncing)" busy hour determined individually for the total system and for each cell, but to exclude special events and disasters
  - In the example just presented, 4 PM was the busy hour every day

Tradeoffs for Blocking, Capacity and Quality

- The higher the blocking probability, the more customers, but the radio quality is less

$$B\uparrow \rightarrow C\uparrow \rightarrow Quality\downarrow$$

- Try a similar calculation for $N = 4$ and $N = 12$
- Proper channel assignment is necessary to reduce cochannel interference

- Larger number of cells per cluster reduces co-channel interference
- It will also reduce adjacent channel interference. However it will handle less traffic because of trunking inefficiency

N	Cha-nnels	D/R	Calls/ cell/hr	Customers /cell	Customers/ channel	Calls/ channel /hr	Approx C/I (dB)	Comments
3	104	3	3308	5408	52	31.8	11	Increased TE Increased CI Increase ACI
4	78	3.46	2405	4008	51	30.8	13	Increased TE Increased CI Increase ACI
7	45	4.6	1281	2138	47	28.5	18	-
12	26	6	662	1104	42	25.5	23	Reduced TE Reduced CI Reduced ACI

TE = Trunking Efficiency

- Any cluster arrangement satisfying the relationship

$$N = i^2 + ij + j^2$$

  is possible
- D/R ratio is critical to minimizing the co-channel interference
- Proper channel assignment is necessary to reduce adjacent channel interference
- Larger number of cells per cluster arrangement reduces cochannel interference
  - It will also reduce adjacent channel interference, although it will handle less total traffic because of trunking inefficiency

Directional Cells versus Omnidirectional

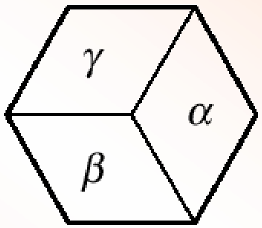
- While omni antennas radiate and receive signals from all direction, Directional Antennas (DAs) radiate and receive signals from a particular direction
- The antenna is vertical (vertical polarization) because signals radiated vertically cannot reach the mobile
- Only signals radiated perpendicularly to the antenna are likely to reach the mobile
- Directional cell may be constructed from an omni-cell by installing directional antennas at the Cell Site

- **120^o Antenna:**
  - Typically, 120^o directional antennas are used for $N = 7$ cell clusters
  - An $N = 7$ frequency reuse pattern with 120^o directional antennas require a $3 \times 7 = 21$ channel set

- Channel Assignment:

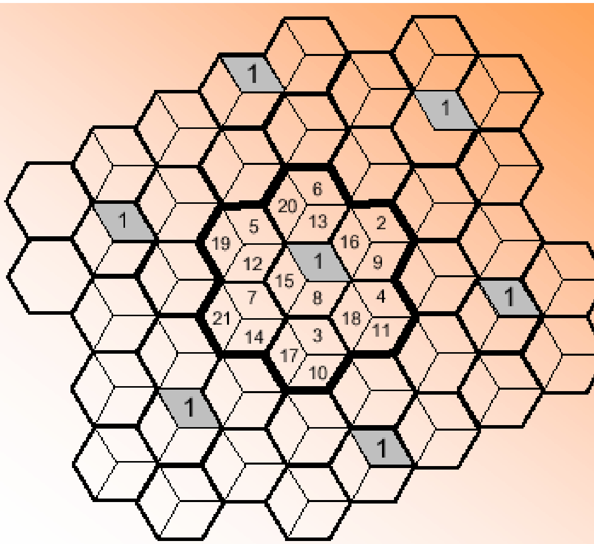
Cell 1: α-face 1, 22, 43, 64, 85, 106, 127, 148, 169, 190, 211, 232, 253, 274, 295
β-face 8, 29, 50, 71, 92, 113, 134, 155, 176, 197, 218, 239, 260, 281, 302
γ-face 15, 36, 57, 78, 99, 129, 141, 162, 183, 204, 225, 246, 267, 288, 309

Cell 2: α-face 2, 23, ...
β-face 9, 30, ...
γ-face 16, 37, …

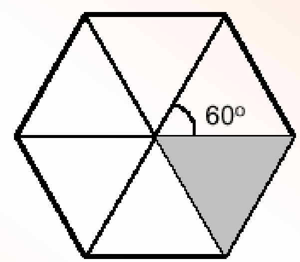


Cell 7: α-face 7, 28, ...
β-face 14, 35, ...
γ-face 21, 42, …
⋮

- Only radio channels in cell 1 face α (1, 22, 43, 64, …, 295) will be repeated in the next cluster containing cell 1 and face α



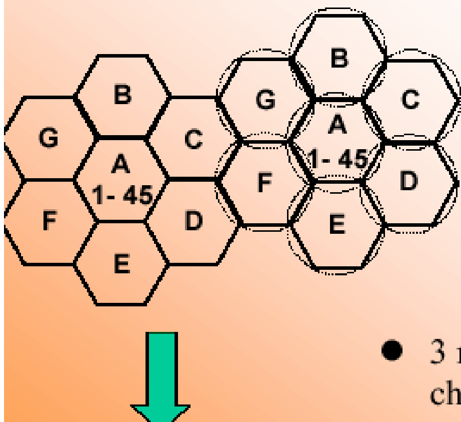
- **60^{o} Antenna:**
- Instead of using 120^{o} directional antennas at a Cell Site, we may install 6-sector antenna, each covering 60^{o} wide area thereby reducing further the cochannel interference



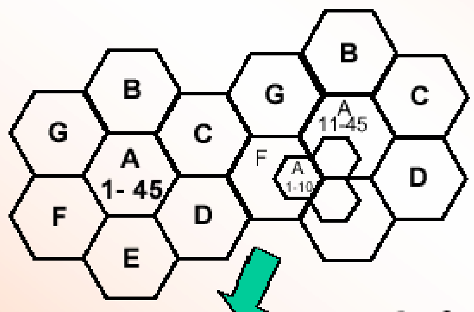
- A 6-sector antenna arrangement with $N = 4$ cell cluster pattern is generally used by Motorola

Cell Splitting

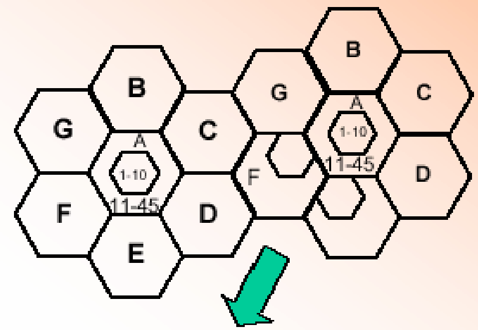
- Cell splitting may be used when the traffic load carried by the original cell exceeds its capacity
- In cell splitting, the distance between adjacent Cell Site is cut in half, and the nominal coverage area of the newly established cell is reduced to a quarter of the area of site
- Thus, the Cell Site density is quadrupled



- Channels 1-45 of set A served in Large Cells before splitting



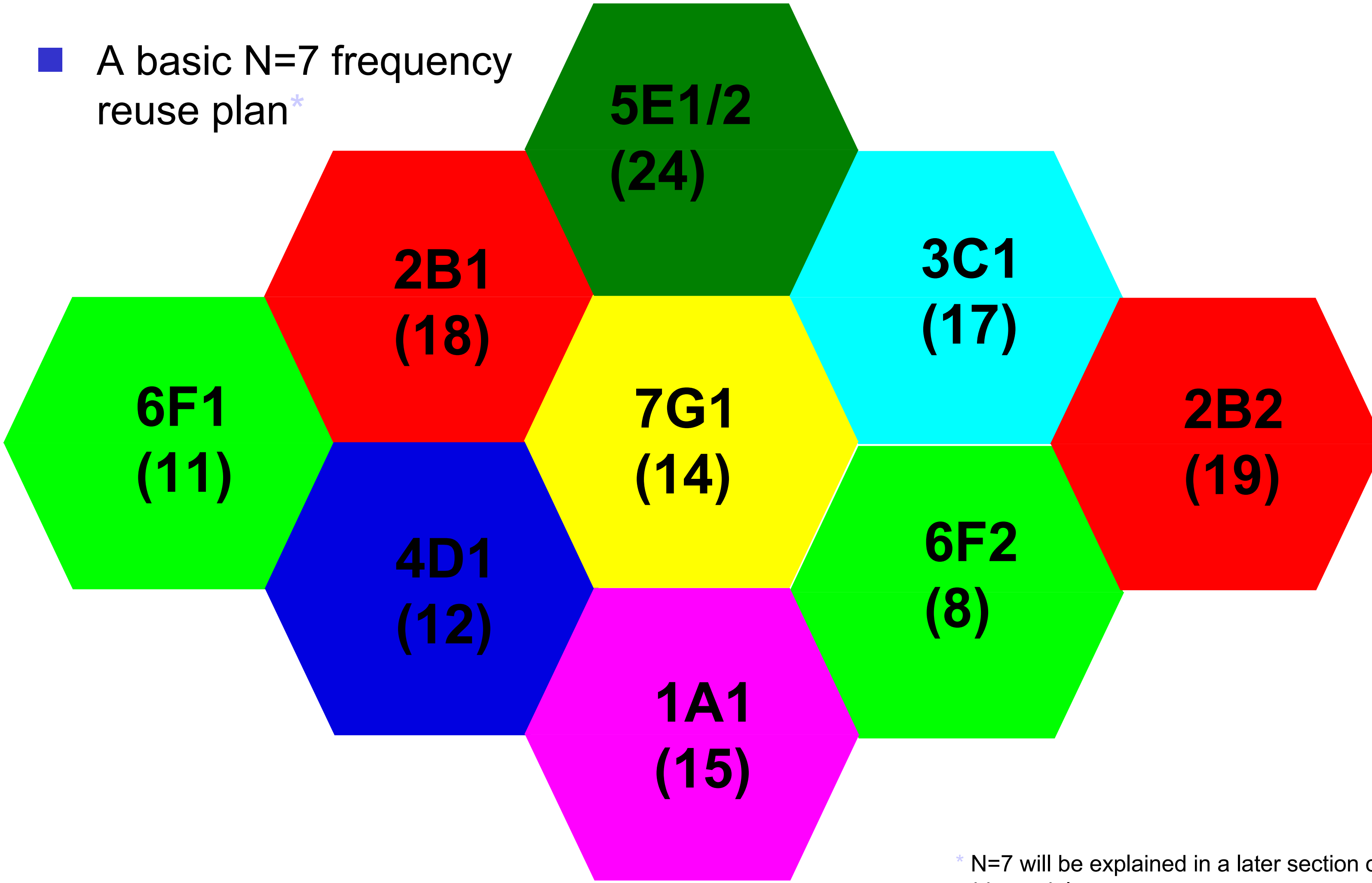
- 3 new Cell Sites added forcing channels to be segmented
- Channels 1-10 of set A served in Small Cell and channels 11-45 served in Large Cells with channel segmentation



- 3 new Cell Sites added plus 2 Overlaid Cells
- Channels 1-10 of set A served in Small Cell and channels 11-45 in Large Cells with 1-10 serving Small Cell area and 11-45 serving entire Large Cell with Overlay

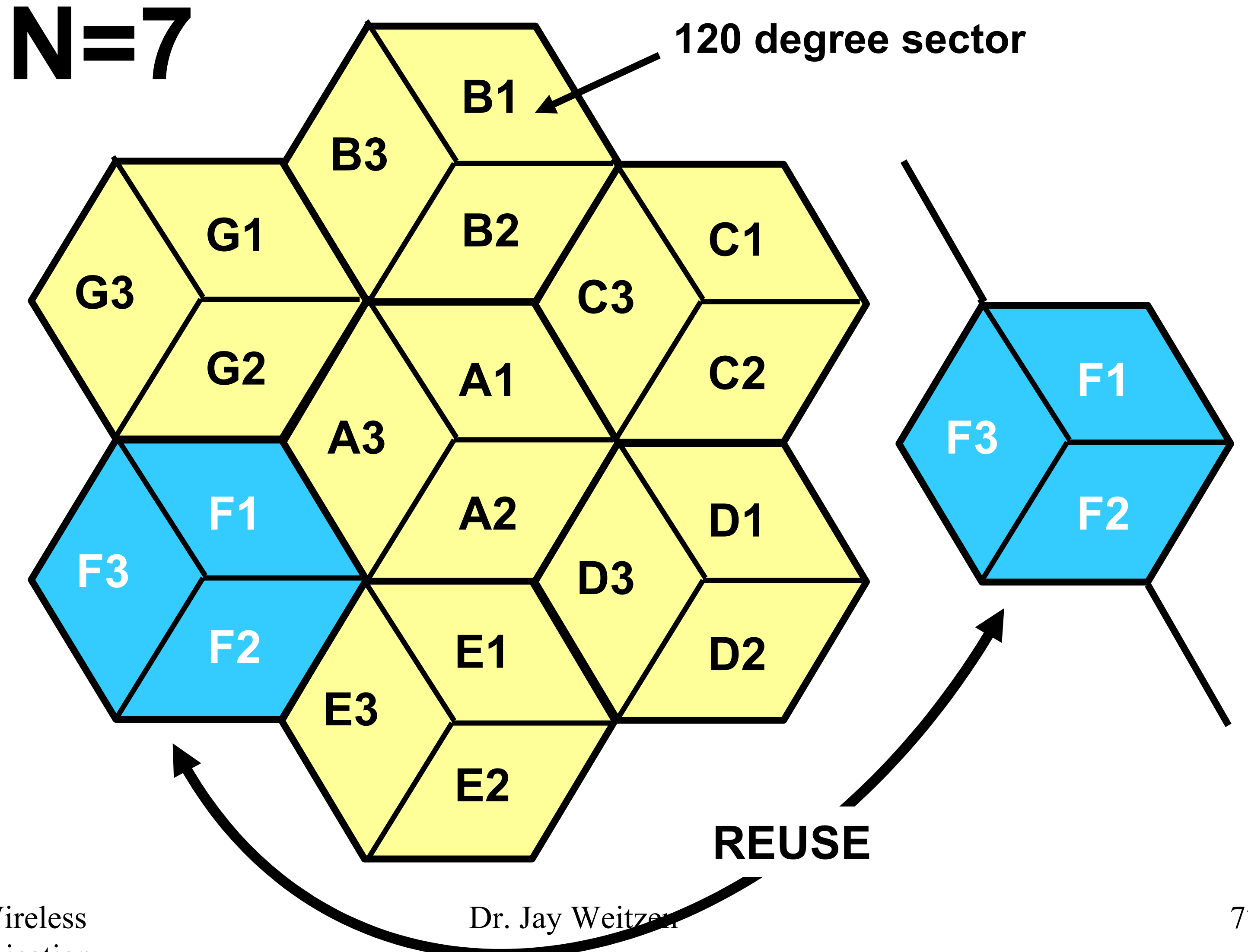
Cell Splitting

- A basic N=7 frequency reuse plan*



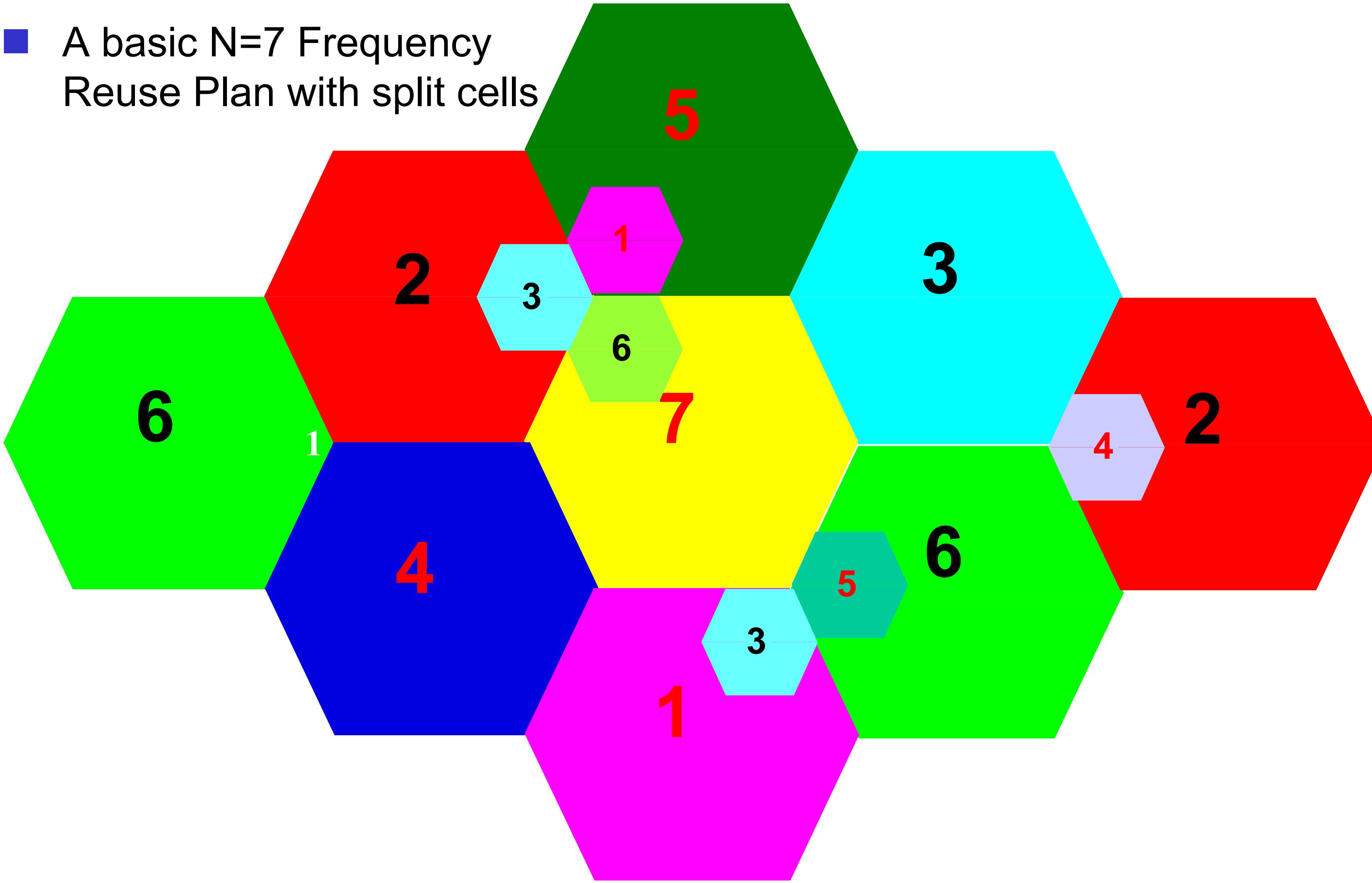
* N=7 will be explained in a later section of this module

Sector Cell Cluster – Frequency Reuse

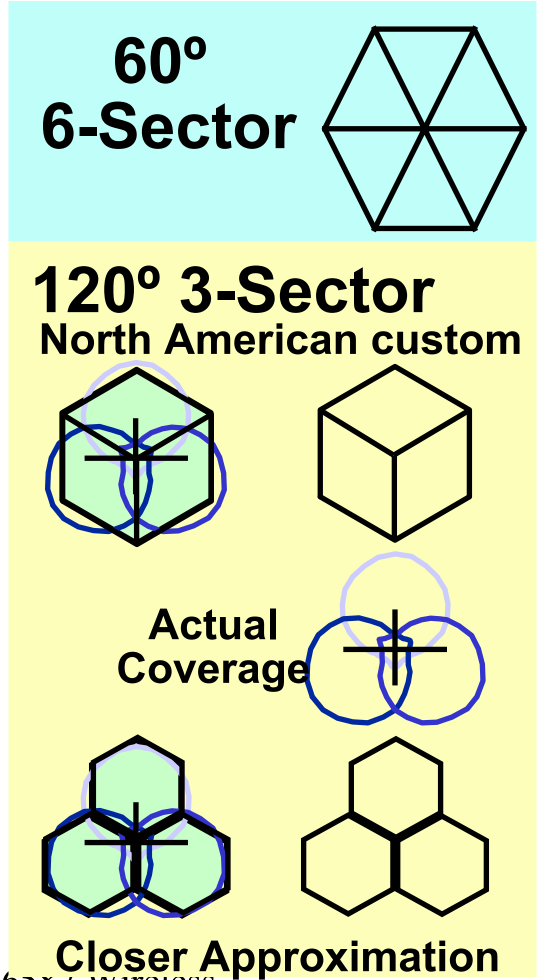


Cell Splitting

- A basic N=7 Frequency Reuse Plan with split cells



Sectorization



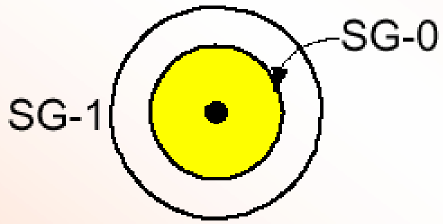
Idealized, easy-to-draw shapes are used to sketch relationships between cells

- 6-sector 60-degree cell example at left
- 3-Sector 120-degree cells are commonly drawn under either of two conventions
- **North American** cellular engineers like to use a single hexagon to represent the cell, and to divide it into three sectors
  - this arrangement is easy to sketch and convenient to manipulate when considering sectorizing existing omni cells
- **Outside North America**, the custom is to draw three separate adjoining hexagons to represent the three sectors
  - this arrangement matches actual antenna coverage patterns much more closely
  - better for judging interference relationships

- Ideally, the new Cell Site locations are at points carried by the existing cells
- All existing cells need not be split at the same time
- Only those cells which have traffic overloads are candidates for splitting
- However, if cells are split in only a part of a system, serious channel assignment problems will be encountered
- The difficulty encountered when all the cell sites are not split can be resolved by implementing the overlaid concept (dual Cell Site)

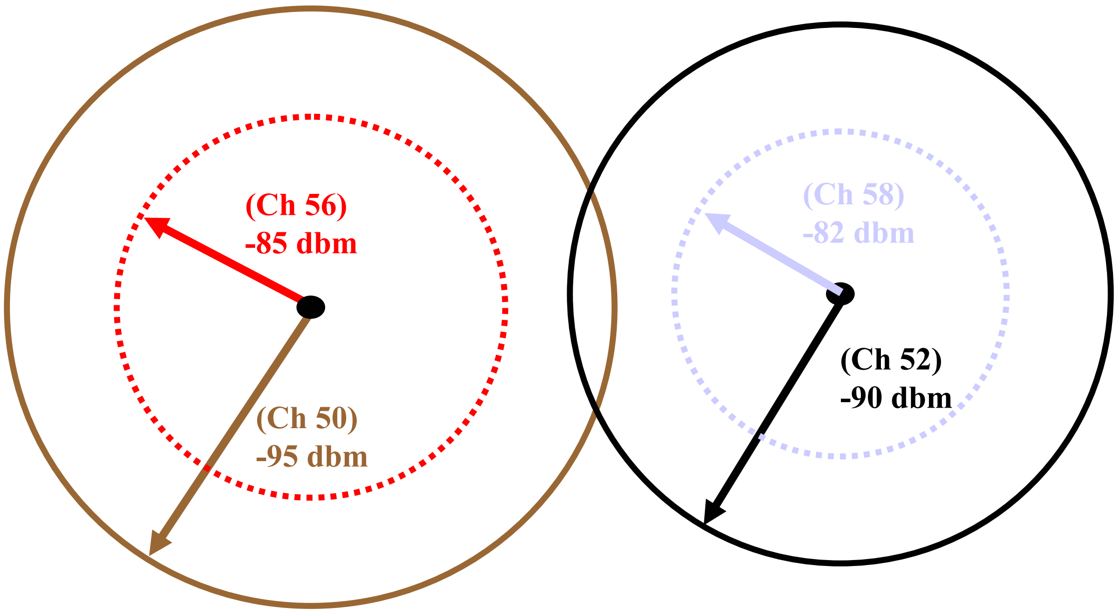
Overlay/Underlay

- Dual Cell Site concept recognizes that when multiple CS coexist, the cellular pattern can be viewed as a superposition of a fragmentary smaller cell patterns on top of a complete larger cell pattern
- In regions with cells of 2 sizes, the channel set assigned to any CS must be further subdivided into larger and smaller cell groups



- The division of CS into Server Group (SG) is sometimes done in the software by channel assignment
  - This is done by adjusting the power levels emitted by the antenna (power control), and handoff thresholds so that a group of channels only serve the smaller cell

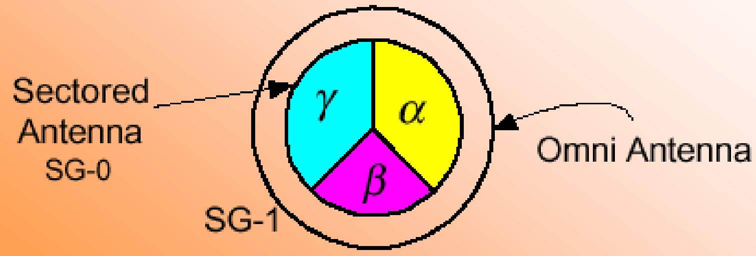
Overlay/Underlay



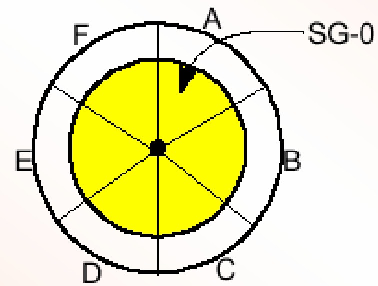
Cell A
Channel 50
Channel 57

Cell B
Channel 52
Channel 59

- A call served by a smaller cell channel will be handed off to a channel belonging to the larger cell as the mobile unit moves away from the smaller SG cell site
- Within the software, there is also an arrangement for upward handoff when the mobile unit in the larger server group (SG-1) moves close to smaller group SG-0
- Both SG-0 and SG-1 commonly uses omni-directional antenna
- In some situations, smaller cells may have only directional antenna while larger cells may have only omni antennas
- The directional antennas may be 120° or 60° antennas

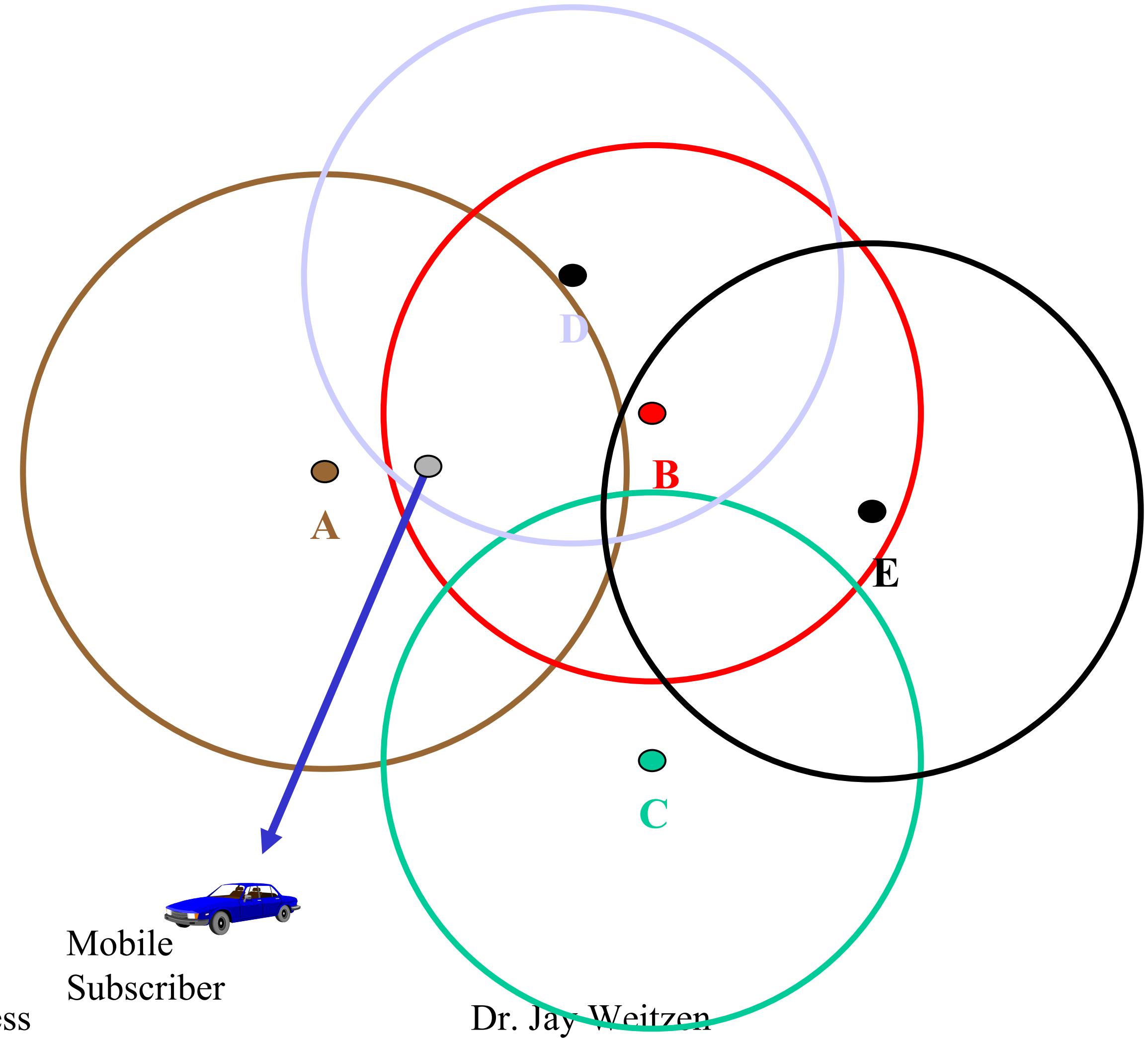


Overlaid Cell Site with directional antennas in SG-0 only



Overlaid Cell Site with 6-directional antennas

Directed Retry



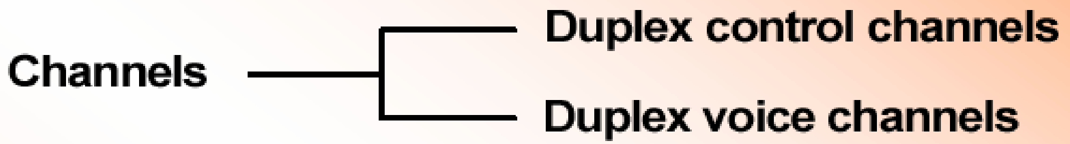
Summary

- Mythical hexagon cell geometry used in cellular system analysis
  - Really found in real system
- Different frequency reuse patterns
  - We can lay out Cell Sites of different frequency reuse factor depending whether $N = 3, 4, 7, 12, 19$, etc.
  - Frequency reuse pattern is determined by equation $N = i^2 + ij + j^2$
    - An important parameter for cochannel assignment is D/R ratio
    - Mathematically, $D/R = (3N)^{0.5}$
    - In setting D/R ratio, we must remember that the carrier signal/impairment ratio is empirically required to be $\geq$ 18 dB
    - The smaller this ratio, the more cochannel interference
    - Smaller ratio means lower value of N, i.e., less Cell Sites per cluster
    - A smaller number of cell sites has the advantage of lower cost and more traffic carrying capacity at the expense of cochannel interference
  - Cochannel Interference (CI)
    - In order to reduce CI, directional antennas are used. However, there is impact on call carrying capacity per antenna face

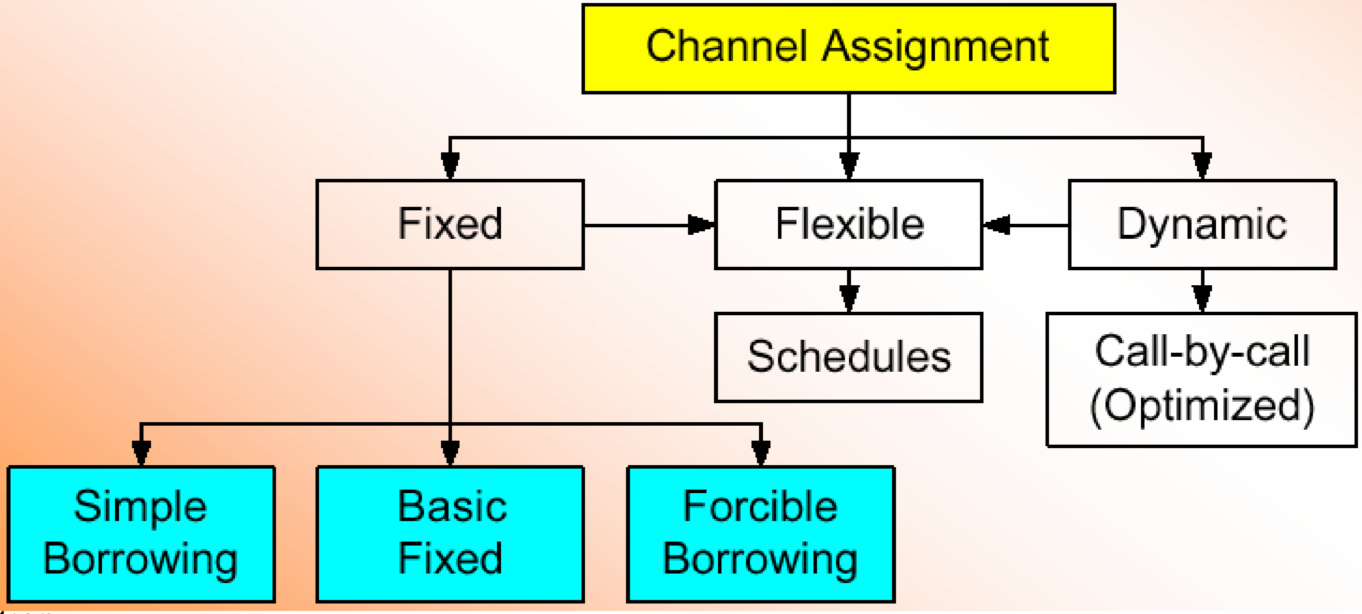
    - Trunking Efficiency
    - Cost
- Different Types of Cell Sites, e.g.,
    - Omni
    - 3-face
    - 6-sector
- Cell Splitting
    - Needed when a given cell cannot handle the traffic load
    - When large and small cells coexit, careful frequency assignment is necessary since D/R ratio is not satisfied
- Overlaid (dual) cell sites
    - Overlaid cells are necessary when all cells are not split at the same time
- Reuse partitioning
    - Can be used for dual Cell Sites
    - It increases the system capacity without significantly affecting performance (C/I ratio)

Channel Allocation and Reuse Strategies

- Refers to allocation of specific channels to Cell Site and Mobile Un



- Channel assignment is a design parameter which may result to efficient utilization of the spectrum by frequency reuse
- **Classification**



- **Fixed Channel Assignment**
  - Basic Fixed:
    - A fixed channel is assigned to a Cell Site on a long-term basis and to a Mobile Unit on a short term basis
    - The same radio frequency is reused by another Cell at some distance, D, away
  - Simple Borrowing
    - if all the channels are in use, call is not blocked, but channels are borrowed from neighboring Cells
    - only if neighboring channels are unused
  - Forcible-borrowing
    - channels must be borrowed if required, even if it is in use
    - channels are assigned dynamically

- Disadvantages
  - multiple providers utilizes fragmented spectrum instead of sharing common allocation
  - it leads to inefficient spectrum utilization

- **Dynamic Channel Assignment**
  - No fixed channel assigned to each Cell Site
  - All channel management/assignment are referred to the MSC
  - Channels are assigned on a call-by-call basis by MSC
  - This is probably the most efficient resource allocation technique

- **Flexible Channel Assignment**
  - Combines aspects of both fixed and dynamic strategies
  - Some channels are fixed and some are managed by the MSC