Cellular Wireless Networks

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Winter Semester 2017-18

Outline I

About Cellular Wireless Networks I

- Cellular technology is the underlying technology for mobile telephones, personal communications systems, wireless Internet and wireless Web applications, and much more.
- Cellular technologies and standards, they are categories into three group of generations.

  1. Analog Generation
  2. Digital Generation
  3. High Speed Digital systems Generation

Principles of Cellular Networks I

- Cellular radio is a technique that was developed to increase the capacity available for mobile radio telephone service.
- Prior to the introduction of cellular radio, mobile radio telephone service was only provided by a high-power transmitter/receiver.
- A typical system would support about 25 channels with an effective radius of about 80 km.
- The way to increase the capacity of the system is to use lower-power systems with shorter radius and to use numerous transmitters/receivers

Cellular Network Organization I

- The essence of a cellular network is the use of multiple low-power transmitters, on the order of 100 W or less.
- Because the range of such a transmitter is small, an area can be divided into cells, each one served by its own antenna.
- Each cell is allocated a bandof frequencies and is served by a base station, consisting of transmitter, receiver, and control unit.
- Adjacent cells are assigned different frequencies to avoid interference or crosstalk.
- However, cells sufficiently distant from each other can use the same frequency band.
- The first design decision to make is the shape of cells to cover an area.

Cellular Network Organization II

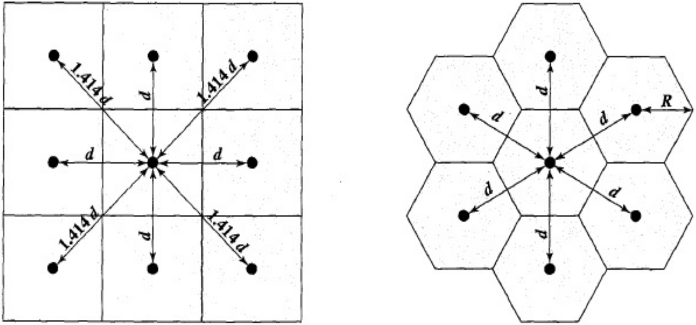
- A matrix of square cells would be the simplest layout to define (Figure 1.1a).
- However, this geometry is not ideal.
- If the width of a square cell is d, then a cell has four neighbors at a distance d and four neighbors at a distance $\sqrt{2}d$.
- As a mobile user within a cell moves toward the cell's boundaries, it is best if all of the adjacent antennas are equidistant.
- This simplifies the task of determining when to switch the user to an adjacent antenna and which antenna to choose.
- A hexagonal pattern provides for equidistant antennas (Figure 1.1b).

Cellular Network Organization III

- The radius of a hexagon is defined to be the radius of the circle that circumscribes it (equivalently, the distance from the center to each vertex; also equal to the length of a side of a hexagon).
- For a cell radius R, the distance between the cell center and each adjacent cell center is $d = \sqrt{3}R$.

Cellular Network Organization IV

Cellular Geometries



(a) Square pattern

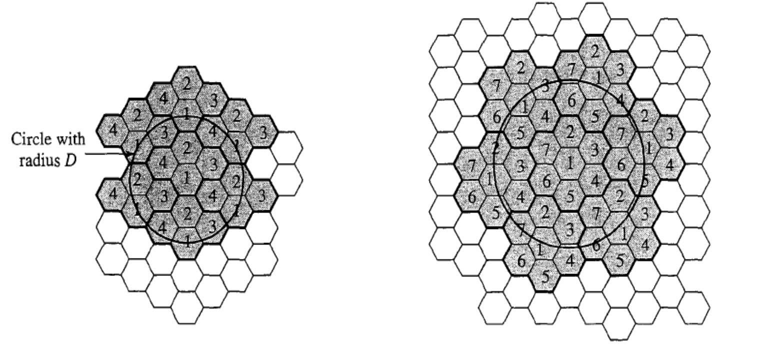
(b) Hexagonal pattern

Frequency Reuse I

- In a cellular system, each cell has a base transceiver.
- The transmission power is carefully controlled (to the extent that it possible in the highly variable mobile communication environment) to allow communication within the cell using a given frequency band while limiting the power at that frequency that escapes the cell into adjacent cells.
- Nevertheless, it is not practical to attempt to use the same frequency band in two adjacent cells.
- Instead, the objective is to use the same frequency band in multiple cells at some distance from one another.
- This allows the same frequency band to be used for multiple simultaneous conversations in different cells.
- Within a given cell, multiple frequency bands are assigned, the number of bands depending on the traffic expected.

Frequency Reuse II

Frequency Reuse Patterns

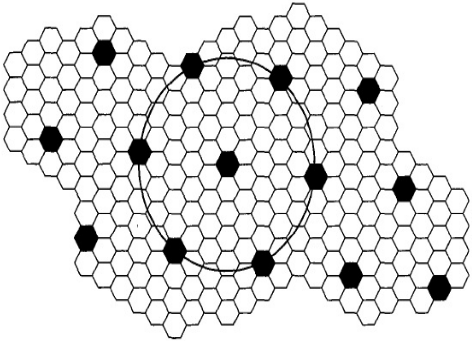


(a) **Frequency reuse pattern for $N = 4$**

(b) **Frequency reuse pattern for $N = 7$**

Frequency Reuse III

Frequency Reuse Patterns



(c) Black cells indicate a frequency reuse for $N = 19$

Frequency Reuse IV

- In characterizing frequency reuse, the following parameters are commonly used:
  - D = minimum distance between centers of cells that use the same frequency band (called cochannels)
  - R = radius of a cell
  - d = distance between centers of adjacent cells ($d = \sqrt{3}R$)
  - N = number of cells in a repetitious pattern(each cell in the pattern uses a unique set of frequency bands), termed the reuse factor
- In a hexagonal cell pattern, only the following values of N are possible:

$$N = I^2 + J^2 + (I \times J). \qquad I,\ J\ =\ 0,\ 1,\ 2,\ 3,\ \cdots \tag{1}$$

Frequency Reuse V

- Hence, possible values of N are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, and so on.
- The following relationship holds:

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

- This can also be expressed as

$$\frac{D}{d} = \sqrt{N} \tag{3}$$

Increasing Capacity I

- In time, as more customers use the system, traffic may build up so that there are not enough frequency bands assigned to a cell to handle its calls.
- A number of approaches have been used to cope with this situation, including the following:
  - **Adding new channels:** Typically, when a system is set up in a region, not all of the channels are used, and growth and expansion can be managed in an orderly fashion by adding new channels.
  - **Frequency borrowing:** In the simplest case, frequencies are taken from adjacent cells by congested cells. The frequencies can also be assigned to cells dynamically.

Increasing Capacity II

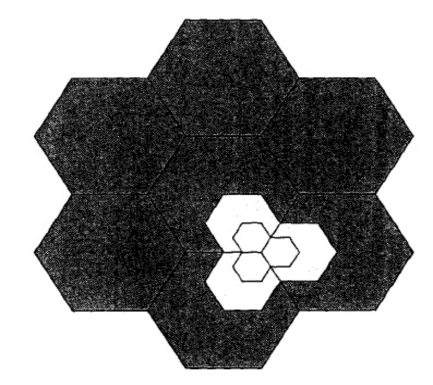
- **Cell splitting:** In practice, the distribution of traffic and topographic features is not uniform, and this presents opportunities of capacity increase. Cells in areas of high usage can be split into smaller cells. Generally, the original cells are about 6.5 to 13 km in size. The smaller cells can themselves be split; however, 1.5 km cells are close to the practical minimum size as a general solution. To use a smaller cell, the power level used must be reduced to keep the signal within the cell. Also, as the mobile units move, they pass from cell to cell, which requires transferring of the call from one base transceiver to another. This process is called a handoff. As the cells get smaller, these handoffs become much more frequent.

Increasing Capacity III

- **Cell sectoring:** With cell sectoring, a cell is divided into a number of wedgeshaped sectors, each with its own set of channels, typically 3 or 6 sectors per cell. Each sector is assigned a separate subset of the cell's channels, and directional antennas at the base station are used to focus on each sector.
- **Microcells:** As cells become smaller, antennas move from the tops of tall buildings or hills, to the tops of small buildings or the sides of large buildings, and finally to lamp posts, where they form microcells. Each decrease in cell size is accompanied by a reduction in the radiated power levels from the base stations and the mobile units. Microcells are useful in city streets in congested areas, along highways, and inside large public buildings.

Increasing Capacity IV

Cell Splitting



Increasing Capacity V

Typical Parameters for Macrocells and Microcells

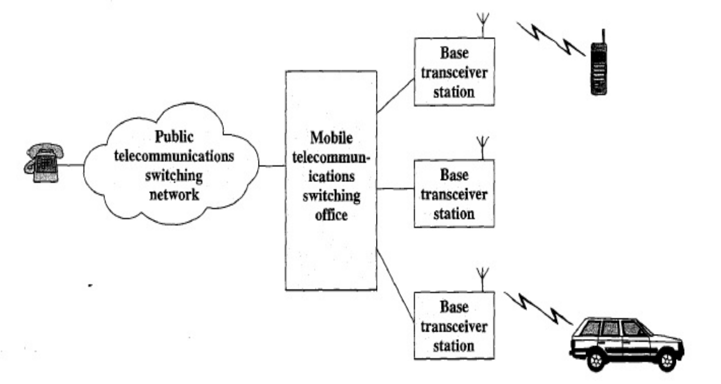
	Macrocell	Microcell
Cell radius	1 to 20 km	0.1 to 1 km
Transmission power	1 to 10 W	0.1 to 1 W
Average delay spread	0.1 to 10 μs	10 to 100 ns
Maximum bit rate	0.3 Mbps	1 Mbps

Operation of Cellular Systems I

- In the principal elements of a cellular system.
- In the approximate center of each cell is a *Base Station* (*BS*).
- The *BS* includes an antenna, a controller, and a number of transceivers, for communicating on the channels assigned to that cell.
- The controller is used to handle the call process between the mobile unit and the rest of the network.
- At any time, a number of mobile units may be active and moving about within a cell, communicating with the *BS*.
- Each *BS* is connected to a *Mobile Telecommunications Switching Office* (*MTSO*), with one *MTSO* serving multiple *BS*s.
- Typically, the link between an *MTSO* and a *BS* is by a wire line, although a wireless link is also possible.
- The *MTSO* connects calls between mobile units.

Operation of Cellular Systems II

Overview of Cellular System



Operation of Cellular Systems III

- The use of a cellular system is fully automated and requires no action on the part of the user other than placing or answering a call.
- Two types of channels are available between the mobile unit and the *BS*:
  1. Control channels are used to exchange information having to do with setting up and maintaining calls and with establishing a relationship between a mobile unit and the nearest *BS*.
  2. Traffic channels carry a voice or data connection between users.

Operation of Cellular Systems IV

- The steps in a typical call between two mobile users within an area controlled by a single *MTSO*:
  - **Mobile unit initialization:** When the mobile unit is turned on, it scans and selects the strongest setup control channel used for this system. Cells with different frequency bands repetitively broadcast on different setup channels. The receiver selects the strongest setup channel and monitors that channel. The effect of this procedure is that the mobile unit has automatically selected the *BS* antenna of the cell within which it will operate. Then a handshake takes place between the mobile unit and the *MTSO* controlling this cell, through the *BS* in this cell. The handshake is used to identify the user and register its location. As long as the mobile unit is on, this scanning procedure is repeated periodically to account for the motion of the unit. If the unit enters a new cell,

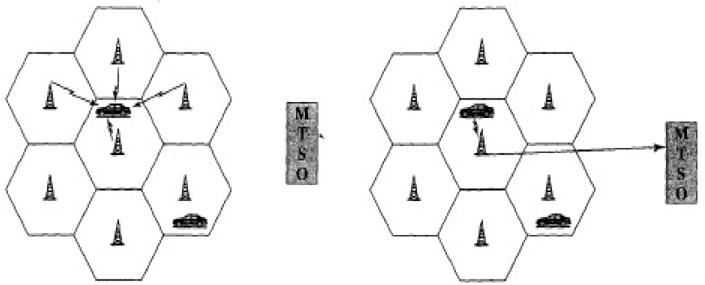
Operation of Cellular Systems V

then a new *BS* is selected. In addition, the mobile unit is monitoring for pages.

- **Mobile-originated call:** A mobile unit originates a call by sending the number of the called unit on the preselected setup channel. The receiver at the mobile unit first checks that the setup channel is idle by examining information in the forward (from the *BS*) channel. When an idle is detected, the mobile unit may transmit on the corresponding reverse (to *BS*) channel. The *BS* sends the request to the *MTSO*.

Operation of Cellular Systems VI

Example of Mobile Cellular Call



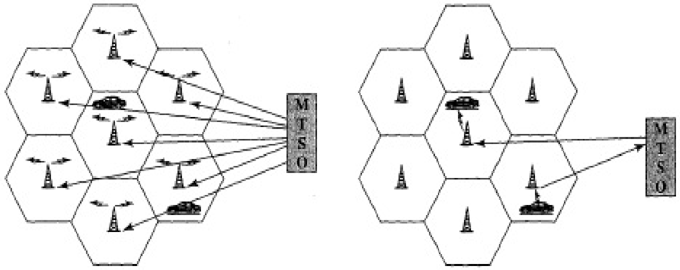
(a) Monitor for strongest signal (b) Request for connection

Operation of Cellular Systems VII

- **Paging:** The *MTSO* then attempts to complete the connection to the called unit. The *MTSO* sends a paging message to certain *BS*s depending on the called mobile unit number. Each *BS* transmits the paging signal on its own assigned setup channel.
- **Call accepted:** The called mobile unit recognizes its number on the setup channel being monitored and responds to that *BS*, which sends the response to the *MTSO*. The *MTSO* sets up a circuit between the calling and called *BS*s. At the same time, the *MTSO* selects an available traffic channel within each *BS*'s cell and notifies each *BS*, which in turn notifies its mobile unit. The two mobile units tune to their respective assigned channels.

Operation of Cellular Systems VIII

Example of Mobile Cellular Call



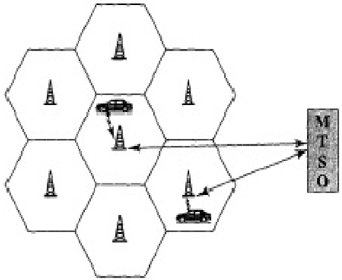
(c) Paging (d) Call accepted

Operation of Cellular Systems IX

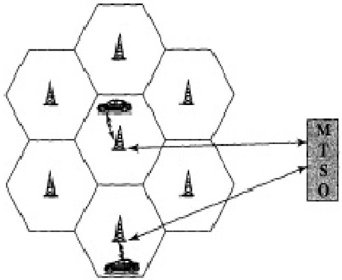
- **Ongoing call:** While the connection is maintained, the two mobile units exchange voice or data signals, going through their respective *BS*s and the *MTSO*.
- **Handoff:** If a mobile unit moves out of range of one cell and into the range of another during a connection, the traffic channel has to change to one assigned to the *BS* in the new cell. The system makes this change without either interrupting the call or alerting the user.

Operation of Cellular Systems X

Example of Mobile Cellular Call



(e) Ongoing call



(f) Handoff

Operation of Cellular Systems XI

- **Call blocking:** During the mobile-initiated call stage, if all the traffic channels assigned to the nearest *BS* are busy, then the mobile unit makes a preconfigured number of repeated attempts. After a certain number of failed tries, a busy tone is returned to the user.
- **Can termination:** When one of the two users hangs up, the *MTSO* is informed and the traffic channels at the two *BS*s are released.
- **Call drop:** During a connection, because of interference or weak signal spots in certain areas, if the *BS* cannot maintain the minimum required signal strength for a certain period of time, the traffic channel to the user is dropped and the *MTSO* is informed.

Operation of Cellular Systems XII

- **Calls to/from fixed and remote mobile subscriber:** The *MTSO* connects to the public switched telephone network. Thus, the *MTSO* can set up a connection between a mobile user in its area and a fixed subscriber via the telephone network. Further, the *MTSO* can connect to a remote *MTSO* via the telephone network or via dedicated lines and set up a connection between a mobile user in its area and a remote mobile user.

Mobile Radio Propagation Effects I

- Mobile radio communication introduces complexities not found in wire communication or in fixed wireless communication.
- Two general areas of concern are signal strength and signal propagation effects.

  1. **Signal strength:** The strength of the signal between the base station and the mobile unit must be strong enough to maintain signal quality at the receiver but not so strong as to create too much cochannel interference with channels in another cell using the same frequency band. Several complicating factors exist. Human-made noise varies considerably, resulting in a variable noise level. For example, automobile ignition noise in the cellular frequency range is greater in the city than in a suburban area. Other signal sources vary from place to place. The signal strength varies as a function of

Mobile Radio Propagation Effects II

distance from the *BS* to a point within its cell. Moreover, the signal strength varies dynamically as the mobile unit moves.

2. **Fading:** Even if signal strength is within an effective range, signal propagation effects may disrupt the signal and cause errors.

- In designing a cellular layout, the communications engineer must take account of these various propagation effects, the desired maximum transmit power level at the base station and the mobile units, the typical height of the mobile unit antenna, and the available height of the *BS* antenna.
- These factors will determine the size of the individual cell.
- Unfortunately, as just described, the propagation effects are dynamic and difficult to predict.

Mobile Radio Propagation Effects III

- The best that can be done is to come up with a model based on empirical data and to apply that model to a given environment to develop guidelines for cell size.
- One of the most widely used models was developed by Okumura et al. [OKUM68] and subsequently refined by Hata [HATA80].
- The original was a detailed analysis of the Tokyo area and produced path loss information for an urban environment.
- Hata's model is an empirical formulation that takes into account a variety of environments and conditions.

Mobile Radio Propagation Effects IV

- For an urban environment, predicted path loss is

$$L_{dB} = 69.55 + 26.16 \log f_c - 13.82 \log h_t - A(h_r) + (44.9 - 6.55 \log h_t) \log d \tag{4}$$

where,
f_c = carrier frequency from 150 MHz to 1500 MHz
h_t = height of transmitting antenna from 30 m to 300 m
h_r = height of receiving antenna from 1 m to 10 m
d = propagation distance between antennas from 1 km to 20 km
$A(h_r)$ = correction factor for mobile unit antenna height.

- For a small or medium sized city, the correction factor is given by

$$A(h_r) = (1.1 \log f_c - 0.7)h_r - (1.56 \log f_c - 0.8)dB \tag{5}$$

Mobile Radio Propagation Effects V

- And for a large city it is given by

$$A(h_r) = 8.29[\log(1.54h_r)]^2 - 1.1dB \qquad for\ f_c \leq 300MHz \tag{6}$$

$$A(h_r) = 3.2[\log(11.75h_r)]^2 - 4.97dB \qquad for\ f_c \geq 300MHz \tag{7}$$

- To estimate the path loss in a suburban area, the formula for urban path loss is modified as

$$L_{dB}(suburban) = L_{dB}(urban) - 2[\log(f_c/28)]^2 - 5.4 \tag{8}$$

- And for the path loss in open areas, the formula is modified as

$$L_{dB}(open) = L_{dB}(urban) - 4.78(\log f_c)^2 - 18.733(\log f_c) - 40.98 \tag{9}$$

Mobile Radio Propagation Effects VI

- The Okumura/Hata model is considered to be among the best in terms of accuracy in path loss prediction and provides a practical means of estimating path loss in a wide variety of situations.

Handoff I

- Handoff is the procedure for changing the assignment of a mobile unit from one *BS* to another as the mobile unit moves from one cell to another.
- Handoff is handled in different ways in different systems and involves a number of factors.
- Handoff may be network initiated, in which the decision is made solely by the network measurements of received signals from the mobile unit.
- Alternatively, mobile unit assisted handoff schemes enable the mobile unit to participate in the handoff decision by providing feedback to the network concerning signals received at the mobile unit.

Handoff II

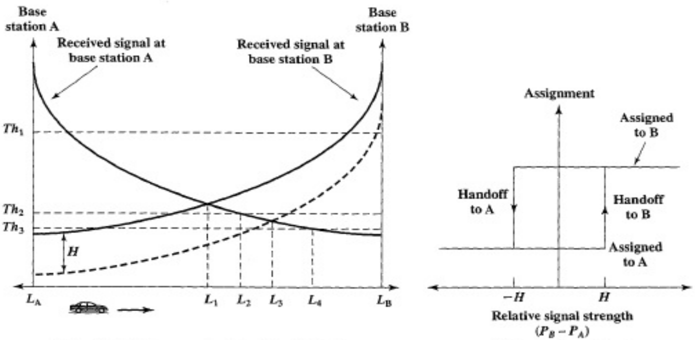
- In either case, a number of different performance metrics may be used to make the decision.
  - **Cell blocking probability:** The probability of a new call being blocked, due to heavy load on the *BS* traffic capacity. In this case, the mobile unit is handed off to a neighboring cell based not on signal quality but on traffic capacity.
  - **Call dropping probability:** The probability that, due to a handoff, a call is terminated.
  - **Call completion probability:** The probability that an admitted call is not dropped before it terminates.
  - **Probability of unsuccessful handoff:** The probability that a handoff is executed while the reception conditions are inadequate.
  - **Handoff blocking probability:** The probability that a handoff cannot be successfully completed.

Handoff III

- **Handoff probability:** The probability that a handoff occurs before call termination.
- **Rate of handoff:** The number of handoffs per unit time.
- **Interruption duration:** The duration of time during a handoff in which a mobile unit is not connected to either base station.
- **Handoff delay:** The distance the mobile unit moves from the point at which the handoff should occur to the point at which it does occur.

Handoff IV

Handoff between Two Cells



(a) Handoff decision as a function of handoff scheme

(b) Hysteresis mechanism

Handoff V

- The principal parameter used to make the handoff decision is measured signal strength from the mobile unit at the *BS*.
- Typically, the *BS* averages the signal over a moving window of time to remove the rapid fluctuations due to multipath effects.
- Figure shows the average received power level at two adjacent base stations as a mobile unit moves from *BS A*, at L_A, to *BS B*, at L_B.
- This figure is useful in explaining various handoff strategies that have been used to determine the instant of handoff:

Handoff VI

- **Relative signal strength:** The mobile unit is handed off from *BS A* to *BS B* when the signal strength at *B* first exceeds that at *A*. If the signal strength at *B* subsequently falls below that of *A*, the mobile unit is handed back to *A*. In Figure handoff occurs at point L_1. At this point, signal strength to *BS A* is still adequate but is declining. Because signal strength fluctuates due to multipath effects, even with power averaging, this approach can lead to a ping-pong effect in which the unit is repeatedly passed back and forth between two *BS*s.

Handoff VII

- **Relative signal strength with threshold:** Handoff only occurs if (1) the signal at the current *BS* is sufficiently weak (less than a predefined threshold) and (2) the other signal is the stronger of the two. The intention is that so long as the signal at the current *BS* is adequate, handoff is unnecessary. If a high threshold is used, such as Th_1, this scheme performs the same as the relative signal strength scheme. With a threshold of Th_2, handoff occurs at L_2. If the threshold is set quite low compared to the crossover signal strength (signal strength at L_1), such as Th_3, the mobile unit may move far into the new cell (L_4) before handoff. This reduces the quality of the communication link and may result in a dropped call. A threshold should not be used alone because its effectiveness depends on prior knowledge of the crossover signal strength between the current and candidate base stations.

Handoff VIII

- **Relative signal strength with hysteresis:** Handoff occurs only if the new base station is sufficiently stronger (by a margin H) than the current one. In this case, handoff occurs at L_3. This scheme prevents the ping-pong effect, because once handoff occurs, the effect of the margin H is reversed. The term hysteresis refers to a phenomenon known as relay hysteresis and can be appreciated with the aid of Figure. We can think of the handoff mechanism as having two states. While the mobile unit is assigned to *BS A*, the mechanism will generate a handoff when the relative signal strength reaches or exceeds the H. Once the mobile unit is assigned to B, it remains so until the relative signal strength falls below $-H$, at which point it is handed back to A. The only disadvantage of this scheme is that the first handoff may still be unnecessary if *BS A* still has sufficient signal strength.

Handoff IX

- **Relative signal strength with hysteresis and threshold:** Handoff occurs only if (1) the current signal level drops below a threshold, and (2) the target base station is stronger than the current one by a hysteresis margin H. In our example, handoff occurs at L_3 if the threshold is either Th_1 or Th_2 and at L_4 if the threshold is at Th_3.
- **Prediction techniques:** The handoff decision is based on the expected future value of the received signal strength.

- The handoff decision is complicated by the use of power control techniques, which enable the *BS* to dynamically adjust the power transmitted by the mobile unit.

Power Control I

- A number of design issues make it desirable to include a dynamic power control capability in a cellular system:
  1. The received power must be sufficiently above the background noise for effective communication, which dictates the required transmitted power. As the mobile unit moves away from the transmitter, the received power declines due to normal attenuation. In addition, the effects of reflection, diffraction, and scattering can cause rapid changes in received power levels over small distances. This is because the power level is the sum from signals coming from a number of different paths and the phases of those paths are random, sometimes adding and sometimes subtracting. As the mobile unit moves, the contributions along various paths change.

Power Control II

2. At the same time, it is desirable to minimize the power in the transmitted signal from the mobile unit, to reduce cochannel interference (interference with channels on the same frequency in remote cells), alleviate health concerns, and save battery power.
3. In *Spread Spectrum* (*SS*) systems using *Code Division Multiple Access* (*CDMA*), it is desirable to equalize the received power level from all mobile units at the *BS*. This is crucial to system performance because all users have the same frequency allocation.

- Cellular systems use the two kinds of power control.

Power Control III

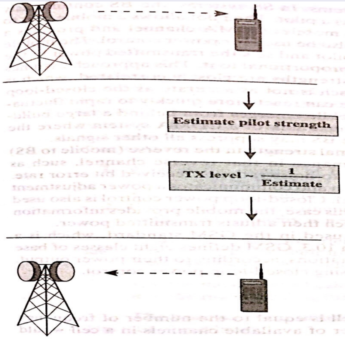
1. **Open-loop power control:** Open-loop power control depends solely on the mobile unit, with no feedback from the *BS*, and is used in some *SS* systems. In *SS* systems, the *BS* continuously transmits an unmodulated signal, known as a pilot. The pilot allows a mobile unit to acquire the timing of the forward (*BS* to mobile) *CDMA* channel and provides a phase reference for demodulation. It can also be used for power control. The mobile unit monitors the received power level of the pilot and sets the transmitted power in the reverse (mobile to *BS*) channel inversely proportional to it. This approach assumes that the forward and reverse link signal strengths are closely correlated, which is generally the case. The open-loop approach is not as accurate as the closed-loop approach. However, the open-loop scheme can react more quickly to rapid fluctuations in signal strength, such as when a mobile unit emerges from behind a

Power Control IV

large building. This fast action is required in the reverse link of a *CDMA* system where the sudden increase in received strength at the *BS* may suppress all other signals.

Power Control V

Open-loop power control



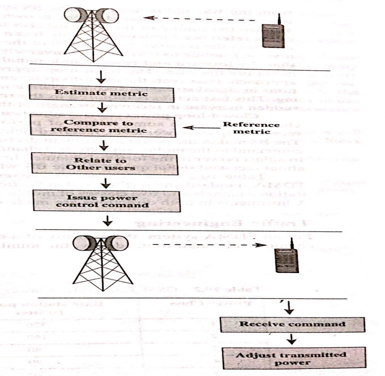
(a) Open-loop power control

Power Control VI

2. **Closed-loop power control:** Closed-loop power control adjusts signal strength in the reverse (mobile to *BS*) channel based on some metric of performance in that reverse channel, such as received signal power level, received signal-to-noise ratio, or received bit error rate. The *BS* makes the power adjustment decision and communicates a power adjustment command to the mobile unit on a control channel. Closed-loop power control is also used to adjust power in the forward channel. In this case, the mobile unit provides information about received signal quality to the *BS*, which then adjusts transmitted power.

Power Control VII

Closed-loop power control



(b) Closed-loop power control

Power Control VIII

- Table shows the power classes used in the *GSM* standard, which is a *TDMA* standard.
- *GSM* defines eight classes of base station channels and five classes of mobile stations, according to their power output.
- Adjustments in both directions are made using closed-loop power control.

Power Control IX

GSM Transmitter Classes

Power Class	Base Station Power (watts)	Mobile Station Power (watts)
1	320	20
2	160	8
3	80	5
4	40	2
5	20	0.8
6	10	
7	5	
8	2.5	

Traffic Engineering I

- For an *FDMA* system, the capacity of a cell is equal to the number of frequency channels allocated to it.
- Ideally, the number of available channels in a cell would equal the total number of subscribers who could be active at any time.
- In practice, it is not feasible to have the capacity to handle any possible load at all times.
- Fortunately, not all subscribers place calls at the same time and so it is reasonable to size the network to be able to handle some expected level of load.
- This is the discipline of traffic engineering.
- Traffic engineering concepts were developed in the design of telephone switches and circuit-switching telephone networks, but the concepts equally apply to cellular networks.

Traffic Engineering II

- Consider a cell that has L potential subscribers (L mobile units) and that is able to handle N simultaneous users (capacity of N channels).
- If $L \leq N$, the system is referred to as nonblocking; all calls can be handled all the time.
- If $L > N$, the system is blocking; a subscriber may attempt a call and find the capacity fully in use and therefore be blocked.
- For a blocking system, the fundamental performance questions we wish to answer are
  1. What is the degree of blocking; that is, what is the probability that a call request will be blocked? Alternatively, what capacity (N) is needed to achieve a certain upper bound on the probability of blocking?

Traffic Engineering III

2. If blocked calls are queued for service, what is the average delay? Alternatively, what capacity is needed to achieve a certain average delay?

- In this subsection, we briefly introduce the relevant traffic engineering concepts and give an example of their use.
- Appendix B examines the subject in more detail.
- Two parameters determine the amount of load presented to a system:
  $\lambda =$ the mean rate of calls (connection requests) attempted per unit time
  $h =$ the mean holding time per successful call

Traffic Engineering IV

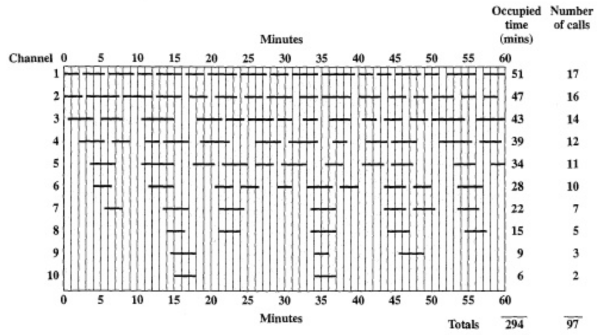
- The basic measure of traffic is the traffic intensity, expressed in a dimensionless unit, the erlang:

$$A = \lambda h \tag{10}$$

- A can be interpreted in several ways.
- It is a normalized version of λ: A equals the average number of calls arriving during the average holding period.
- We can also view the cell as a multiserver queuing system where the number of servers is equal to the channel capacity N.
- The average service time at a server is h.
- A basic relationship in a multiserver queue is $\lambda h = \rho N$, where ρ is server utilization, or the fraction of time that a server is busy.
- Therefore, $A = \rho N$ and is a measure of the average number of channels required.

Traffic Engineering V

Example Distribution of Traffic in a Cell with Capacity 10



Note: Horizontal lines indicate occupied periods to the nearest 1/2 minute

Traffic Engineering VI

- Typically, a blocking system is sized to deal with some upper limit of traffic intensity.
- It is generally thought unreasonable to size for the highest surge of traffic anticipated; rather, the common practice is to size the system to meet the average rate encountered during a busy hour.
- The busy hour is the 60-minute period during the day when the traffic is highest, in the long run.
- $ITU - T$ recommends taking the average of the busy hour traffic on the 30 busiest days of the year, called the ”mean busy-hour traffic,” and using that quantity to size the system.
- The North American practice is to take the average over the 10 busiest days.
- These are typically measurements of carried rather than offered traffic and can only be used to estimate the true load.

Traffic Engineering VII

- The parameter A, as a measure of busy-hour traffic, serves as input to a traffic model.
- The model is then used to answer questions such as those posed in the beginning of this subsection.
- There are two key factors that determine the nature of the model:

  1. The manner in which blocked calls are handled
  2. The number of traffic sources

- Blocked calls may be handled in one of two ways.
- First, blocked calls can be put in a queue awaiting a free channel; this is referred to as *Lost Calls Delayed* (*LCD*), although in fact the call is not lost, merely delayed.
- Second, a blocked call can be rejected and dropped.

Traffic Engineering VIII

- This in turn leads to two assumptions about the action of the user.
- If the user hangs up and waits some random time interval before another call attempt, this is known as *Lost Calls Cleared* (*LCC*).
- If the user repeatedly attempts calling, it is known as *Lost Calls Held* (*LCH*).
- For each of these blocking options, formulas have been developed that characterize the performance of the system.
- For cellular systems, the *LCC* model is generally used and is generally the most accurate.
- The second key element of a traffic model is whether the number of users is assumed to be finite or infinite.
- For an infinite source model, there is assumed to be a fixed arrival rate.

Traffic Engineering IX

- For the finite source case, the arrival rate will depend on the number of sources already engaged.
- In particular, if the total pool of users is L, each of which generates calls at an average rate of λ/L, then, when the cell is totally idle, the arrival rate is λ.
- However, if there are K users occupied at time t, then the instantaneous arrival rate at that time is $\lambda(L-K)/L$.
- Infinite source models are analytically easier to deal with.
- The infinite source assumption is reasonable when the number of sources is at least 5 to 10 times the capacity of the system.

Infinite Sources, Lost Calls Cleared I

- For an infinite source *LCC* model, the key parameter of interest is the probability of loss, or grade of service.
- Thus a grade of service of 0.01 means that, during a busy hour, the probability that an attempted call is blocked is 0.01.
- Values in the range 0.01 to 0.001 are generally considered quite good.
- The equation of infinite source *LCC*, known as *Erlang B*, has the following form:

$$P = \frac{\frac{A^N}{N!}}{\sum_{x=0}^{N} \frac{A^x}{x!}} \tag{11}$$

where, $A =$ offered traffic, erlangs
$N =$ number of servers
$P =$ probability of blocking (grade of service)

Infinite Sources, Lost Calls Cleared II

- This equation is easily programmed, and tables of values are readily available.
- Table 10.3 is an extract from such a table.
- Given the offered load and number of servers, the grade of service can be calculated or determined from a table.
- More often, the inverse problem is of interest: determining the amount of traffic that can be handled by a given capacity to produce a given grade of service.
- Another problem is to determine the capacity required to handle a given amount of traffic at a given grade of service.
- For both these problems, tables or suitable trial-and-error programs are needed.
- Two important points can be deduced from Table 10.3:

Infinite Sources, Lost Calls Cleared III

1. A larger-capacity system is more efficient than a smaller-capacity one for a given grade of service.
2. A larger-capacity system is more susceptible to an increase in traffic.

Infinite Sources, Lost Calls Cleared IV

Erlang B Table

Number of servers (N)	Capacity (erlangs) for grade of service of $P = 0.02$ (1/50)	$P = 0.01$ (1/100)	$P = 0.005$ (1/200)	$P = 0.002$ (1/500)	$P = 0.001$ (1/1000)
1	0.02	0.01	0.005	0.002	0.001
4	1.09	0.87	0.7	0.53	0.43
5	1.66	1.36	1.13	0.9	0.76
10	5.08	4.46	3.96	3.43	3.09
20	13.19	12.03	11.10	10.07	9.41
24	16.64	15.27	14.21	13.01	12.24
40	31.0	29.0	27.3	25.7	24.5
70	59.13	56.1	53.7	51.0	49.2
100	87.97	84.1	80.9	77.4	75.2

Infinite Sources, Lost Calls Cleared V

- All of the preceding discussion deals with offered traffic.
- If sizing is done on the basis of system measurement, all that we are likely to have is carried traffic.
- A program can readily be developed that accepts carried traffic as input and then performs a seeking algorithm to work backward to offered traffic.
- The relationship between carried traffic C and offered traffic A is

$$C = A(1 - P) \tag{12}$$

For small values of P, A is a good approximation of C.

Effect of Handoff I

- One complication in cellular traffic models not found in other such models is the effect of handoff.
- The arrival rate of calls at a cell has two components: new calls placed by mobile units in the cell (λ_1), and calls handed off to the cell for mobile units entering the cell while connected (λ_2).
- The total arrival rate is $\lambda = \lambda_1 + \lambda_2$.
- Similarly, the completion rate consists of calls being terminated and calls being handed off.
- The model must be adjusted accordingly to obtain overall arrival rates and holding times.

Effect of Handoff II

Cell Traffic Model