Cellular Telephony

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History

- First public mobile telephone service introduced in 25 U.S. cities in 1946
 - One single high powered transmitter in each city
 - 120 KHz of RF bandwidth in half duplex mode
 - FM "Push to talk" telephone
 - Actual telephone grade speech occupies only 3 KHz of baseband!
 - Mid 1960's the bandwidth per call was cut to 30KHz
- IMTS (Improved Mobile Telephone Service) introduced in the 1960's
 - Main Innovation: Automated Channel Trunking
 - Support a large number of subscribers from a small pool of channels
 - When a subscriber calls she is dynamically allocated a channel
 - When the call is over the channel is returned to the pool
 - The probability that all subscribers will call at the same time is small
- IMTS was handicapped by the lack of spectrum and inefficient use
 - 12 channels and only 543 subscribers in 1976 (NYC)

History: IMTS Vs. Cellular

• IMTS is low infrastructure and high power

$$P_r = c/d^n, 2 \le n \le 5$$

- Cellular is high infrastructure and low power
 - Motivation: Squeeze more out of the allocated spectrum
- US Advanced Mobile Phone System (AMPS) spectrum allocations
 - 1983: 40 MHz in the 800 MHZ band, 666 duplex channels
 - 30 KHz per channel
 - 1989: 10 MHz (166 channels) more
 - AMPS is FM with FDMA
- US Digital Cellular (USDC) came in 1991
 - 3 users per 30 KHz
 - Compatible with AMPS
 - Digital modulation (DQPSK), speech coding, TDMA



History

- Qualcomm introduced CDMA in the 1990's
 - Code division instead of frequency division
 - Can operate at much smaller signal to interference ratios

System	Multiple Access	Spectrum	Channel Bandwidth
AMPS 1983	FDMA	824-894 MHz	30 KHz
USDC 1991	TDMA	824-894 MHz	30 KHz
IS-95 1993	CDMA	824-894 MHz 1.8-2.0 GHz	1.25 MHz
GSM 1990	TDMA	890-960 MHz	200 KHz



Cellular Telephony: The Basic Innovation

- Divide the area into cells
- Each cell has a base station





Cellular Telephony: The Basic Idea

- The base stations are connected to the public telephone network
- The cell phone connects with the base stations in its cell
- As the caller moves from one cell to another the call is handed-off from one base station to another





The Basic Motivation

- Suppose there are 7 frequency channels denoted A,B,C,D,E,F,G
- Then maxium number of calls in the area will be 7
- If many callers use the same frequency at the same time the signal power can become too small in relation to the interference power
- Signal power, $S = c/d^n$
- Interference, $I = c/d^n + c/d^n$
- Signal to Interference ratio

- S/I = 0.5

The Basic Motivation

- Suppose there are 7 frequency channels denoted A,B,C,D,E,F,G
- Suppose the frequencies can be re-used as shown
- Then the maximum number of calls is ideally 49
- ♦ How?
- Keep the transmission power high enough to cover the cell
- But keep it low enough to allow re-use of the frequency



Understanding the Frequency Re-use Concept

- Divide the metropolitan area into cells
- Allocate a frequency channel(s) to each cell
- Put a base station in the center of each cell that transmits with equal power in all directions
- The cell area is that which can be reached by the base station
 - Assume each cell is the same size and shaped like a hexagon
 - In practice this is only an approximation



Understanding the Frequency Re-use Concept

- N= Cluster size
 - Cluster is a group of cells that collectively use all the available channels, e.g., N = 7
 - From the geometry of hexagons feasible cluster sizes are

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

where *i*,*j* are non-negative integers

- Typical N values used are 7, 12

- *S* = Total number of duplex channels available
- ♦ k = number of channels given to each cell
- Then S = k N
- If the cluster is replicated M times in the area then the total number of channels used in the area is the capacity (C),

$$C = M k N = M S$$



Example: Allocating channels to cells

- ♦ Total bandwidth = 33 MHz
- Channel bandwidth = 50 KHz/duplex channel
- ◆ Total available channels = 33,000/50 = 660 channels
 - For N = 4, Channels per cell = 660/4 = 165 channels
 - For N = 7, Channels per cell = 660/7 = 95 channels
 - For N = 12, Channels per cell = 660/12 = 55 channels
- Suppose there are 84 cells, 600 voice channels, 60 control channels
 - N=7 implies M = 12 implies C = $12 \times 600 = 7200$ calls
 - N= 12 implies M = 7 implies C = 7 x 600 = 4200 calls



Control Channels

- Suppose 1 MHz is allocated to control channels with 50 KHz per duplex channel
- Then number of control channels = 1000/50 = 20
- Thus number of voice channels = 640
- If each cell needs only one control channel then for N=7 we need only 7 control channels
- Thus 653 channels voice channels can be divided amongst 7 cells



Interference and System Capacity

- Interference is the major limiting factor in cellular systems
- Source of interference
 - Other mobile in the same cell or neighboring cells
 - Other base stations
 - Non-cellular transmissions that leak energy into the cellular band
- Interference on voice channels causes cross-talk and bad connections
- Interference on control channels causes missed and blocked calls
- Co-channel interference
 - Interference from cells that use the same frequency channels
- Adjacent channel interference
 - Interference from signals which are adjacent in frequency to the desired signal
 - Results from imperfect receiver filters or powerful nearby transmitters



Co-channel Interference and System Capacity

• Received power at distance d

$$P_r = c/d^n, 2 \le n \le 5$$

• The call quality depends on the biterror rate, which depends on the signal to interference ratio

$$S/I = (c/R^n)/(\sum_{i=1}^{i_o} (c/D_i^n))$$

$$= \left(D/R \right)^n / i_0$$

where i0 is the number of interfering base stations

• From the hexagonal geometry

$$D = \sqrt{3NR} \Longrightarrow S/I = (\sqrt{3N})^n / i_o$$





Deriving Cluster Size from Signal to Interference Ratio

• In the USAMPS cellular system with 30 KHz voice channels the signal to interference ratio should be no less than 18 dB

$$S/I = (\sqrt{3N})^n / i_o$$

- Putting this and i0 = 6 in the equation we get N > 6.43, i.e., N = 7
- This equation is optimistic
- ◆ If the mobile is on the boundary of the cell then the distances from the first tier interfering cells is *D*-*R*, *D*+0.5*R*, *D*, *D*-0.5*R*, *D*+*R*
 - This is the worst-case
 - The signal to interference ratio turns out to be 17 dB
 - Thus *N* has to be increased beyond 7 to 12 (i=2, j=2)
 - This causes a capacity reduction of 7/12
- In this way co-channel interference determines the cluster size and the capacity of cellular systems



The GSM Architecture



- Each frequency channel is 200 KHz with a data rate of 270.833 Kbps
- 8 users share each channel by TDMA
- Each user gets to send data at 24.7 Kbps
- The rest is control channel



Making a Call

- Base stations send synchronization signal
- When a GSM mobile is powered on it first locks on to this signal
- To originate a call the user dials the number and pushes the "send"
- The mobile transmits the request to the base station on random access channel running Slotted Aloha
- If the base station receives the signal time slots are allocated to the mobile and it receives timing and transmit power commands
- Meanwhile the subscribers IMSI (International Mobile Subscriber Identity) is authenticated by the MSC
- If authentication is successful the dialed party is called and the connection established to the BTS serving the mobile
- The BTS then transfers the mobile to new channels and time slots that are to be used for the call



Receiving a Call

- The HLR is a database that contains subscriber and current location information for each subscriber in the same city as the MSC
- VLR is a database that temporarily stores the IMSI and customer information for each roaming subscriber in the area of the MSC
 - Every mobile that is powered on synchronizes with the nearest BTS and registers in the VLR which then updates the current location information in the appropriate HLR
- When someone calls a subscriber the call first goes to the HLR of the subscriber
- The HLR directs the call to the current MSC of the subscriber which in turn directs it to the appropriate BSC and BTS
- The BTS pages the mobile which responds on the random access channel
- New channels and slots are then assigned by the BTS for the call



Satellite Telephony

- Low earth orbit satellites are used to connect mobiles
- Data rates are low (< 20 Kbps)
- Promises ubiquitous coverage



Summary

- Wireless telephony is in a period of explosive growth
 - By the ear 2010 there should be equal number of wired and wireless subscribers
- Most of this growth is cellular telephones
- Based on an intensive terrestrial infrastructure to achieve high capacities
 - Cells are getting smaller making infrastructure more intensive
- Basic capacity calculations for FDMA cellular systems
- Looked at the architecture of the GSM cellular system
 - This architecture is well defined
 - Others such as AMPS, USDC are similar

