Cellular Networks
Outline

• Introduction
• Frequency reuse
• Channel assignment strategies
• Techniques to increase capacity
• Handoff
Mobile phone subscribers worldwide
Base Station

Forward voice channel
Reverse voice channel
Forward control channel
Reverse control channel
Cellular Concept

• Challenge: limited spectrum allocation (government regulation)

• A single high-powered transmitter
  – good coverage
  – interference: impossible to reuse the same frequency

• Example:
  – One tower system in New York City in 1970
    • Maximum 12 simultaneous calls/1000 square miles
Cellular Concept

• developed by Bell Labs 1960’s-70’s
• areas divided into cells
• a system approach, no major technological changes
• a few hundred meters in some cities, 10s km at country side
• each served by base station with lower power transmitter
• each gets portion of total number of channels
• neighboring cells assigned different groups of channels, interference minimized
Cell Shape

- Factors
  - Equal area
  - Non overlap between cells

- Choices

A1
A2
A3
For a given $S$

- $A_3 > A_1$
- $A_3 > A_2$
- $A_3$ provides maximum coverage area for a given value of $S$
- By using hexagon geometry, the fewest number of cells covers a given geographic region
- Actual cellular footprint is determined by the contour of a given transmitting antenna
Cellular Network Architecture

- Mobile Switching Center
- Public Telephone network and Internet
- Wired network
Cellular Network Architecture

• **Cell**
  – Covers geographic region
  – Base station (BS): analogous to 802.11 AP
  – Mobile users attach to network through BS
  – Air interface: physical and link layer protocol between mobile and BS

• **MSC**
  – Connects cells to wide area network
  – Manages call setup
  – Handles mobility
Ingredients 1: Mobile Phones, PDAs & Co.

The visible but smallest part of the network!
Ingredients 2: Antennas

Still visible – cause many discussions…
Ingredients 3: Infrastructure 1

Base Stations

Cabling

Microwave links
Ingredients 3: Infrastructure 2

Not “visible“, but comprise the major part of the network (also from an investment point of view…)

Switching units

Management

Data bases

Monitoring
Cellular networks: the first hop

- Two techniques for sharing mobile-to-BS radio spectrum
  - combined FDMA/TDMA:
    - divide spectrum in frequency channels
    - divide each channel into time slots
  - CDMA:
    - code division multiple access
Frequency Reuse

- Adjacent cells assigned different frequencies to avoid interference or crosstalk
- Objective is to reuse frequency in nearby cells
  - 10 to 50 frequencies assigned to each cell
  - transmission power controlled to limit power at that frequency escaping to adjacent cells
  - the issue is to determine how many cells must intervene between two cells using the same frequency
Frequency Reuse

• each cell allocated a group of $k$ channels
  – a cluster has $N$ cells with unique and disjoint channel
• groups, $N$ typically 4, 7, 12
• total number of duplex channels $S = kN$
System Capacity

• Cluster repeated $M$ times in a system
• Total number of channels that can be used (capacity)
  – $C = MkN = MS$
Shall we use a larger cell or a smaller cell?
Cell Size: Tradeoff

- Smaller cells $\Rightarrow$ higher $M$ $\Rightarrow$ higher $C$
  + Channel reuse $\Rightarrow$ higher capacity
  + Lower power requirements for mobiles

- Additional base stations required
- More frequent handoffs
- Greater chance of ‘hot spots’
Effect of cluster size \( N \)

- **channels unique in same cluster, repeated over clusters**
- **keep cell size same**
  - large \( N \): weaker interference, but lower capacity
  - small \( N \): higher capacity, more interference need to maintain certain S/I level
- **frequency reuse factor: \( N \)**
  - each cell within a cluster assigned \( 1/N \) of the total available channels
Channel Assignment Strategies: Fixed Channel Assignments

• Each cell is allocated a predetermined set of voice channels.

• If all the channels in that cell are occupied, the call is blocked, and the subscriber does not receive service.

• Variation includes a borrowing strategy: a cell is allowed to borrow channels from a neighboring cell if all its own channels are occupied. This is supervised by the MSC.
How can we do better?
Channel Assignment Strategies:
Dynamic Channel Assignments

• Voice channels are not allocated to different cells permanently.

• Each time a call request is made, the serving base station requests a channel from the MSC.

• The switch then allocates a channel to the requested call based on a decision algorithm taking into account different factors: frequency re-use of candidate channel and cost factors.

• Dynamic channel assignment is more complex (real time), but reduces likelihood of blocking.
Interference and System Capacity

• major limiting factor in performance of cellular radio systems

• sources of interference:
  – other mobiles in same cell
  – a call in progress in a neighboring cell
  – other base stations operating in the same frequency band
  – Non-cellular system leaking energy into the cellular frequency band

• effect of interference:
  – voice channel: cross talk
  – control channel: missed or blocked calls

• two main types:
  – co-channel interference
  – adjacent channel interference
Co-Channel Interference

• Cells that use the same set of frequencies are called co-channel cells.
• Interference between the cells is called co-channel interference.
• Co-channel reuse ratio: $Q = \frac{D}{R}$
  – $R$: radius of cell
  – $D$: distance between nearest co-channel cells
• Small $Q \Rightarrow$ small cluster size $N \Rightarrow$ large capacity
• Large $Q \Rightarrow$ good transmission quality
• Tradeoff must be made in actual cellular design
When is the worst-case interference?
Worst Case Interference

• When the mobile is at the cell boundary (point A), it experiences worst case co-channel interference on the forward channel.

• The marked distances between the mobile and different co-channel cells are based on approximations made for easy analysis.
Worst Case Interference

\[ S/I \sim R^{-4} / [2(D-R)^{-4} + 2(D+R)^{-4} + 2D^{-4}] \]
Adjacent Channel Interference

- Interference resulting from signals which are adjacent in frequency to the desired signal.
- Due to imperfect receiver filters that allow nearby frequencies to leak into pass band.
- Can be minimized by careful filtering and assignments, and by keeping frequency separation between channels in a given cell as large as possible, the adjacent channel interference may be reduced considerably.
Approaches to Increasing Capacity

- **Frequency borrowing**
  - frequencies are taken from adjacent cells by congested cells

- **Cell splitting**
  - cells in areas of high usage can be split into smaller cells

- **Cell sectoring**
  - cells are divided into a number of wedge-shaped sectors, each with their own set of channels

- **Microcells**
  - antennas move to buildings, hills, and lamp posts
Cell Splitting

- subdivide a congested cell into smaller cells
- each with its own base station, reduction in antenna and transmitter power
- more cells $\rightarrow$ more clusters $\rightarrow$ higher capacity
- achieves capacity improvement by essentially rescaling the system.
Cell Splitting from radius $R$ to $R/2$
Sectoring

• In basic form, antennas are omni-directional
• Replacing a single omni-directional antenna at base station with several directional antennas, each radiating within a specified sector.
Sectoring

• achieves capacity improvement by essentially rescaling the system.
• less co-channel interference, number of cells in a cluster can be reduced
• Larger frequency reuse factor, larger capacity
Micro Cell Zone Concept

- Large control base station is replaced by several lower powered transmitters on the edge of the cell.
- The mobile retains the same channel and the base station simply switches the channel to a different zone site and the mobile moves from zone to zone.
- Since a given channel is active only in a particular zone in which mobile is traveling, base station radiation is localized and interference is reduced.
Handover

- **Reasons for handover**
  - Moving out of range
  - Load balancing

- **Cell, BSC (base station controller), MSC (mobile switching center)**

- **Handover scenarios**
  - Intra-cell handover (e.g., change frequency due to narrowband interference)
  - Inter-cell, intra-BSC handover (e.g., movement across cells)
  - Inter-BSC, intra-MSC handover (e.g., movement across BSC)
  - Inter MSC handover (e.g., movement across MSC)
4 types of handover

1. MS -> BTS -> BSC -> MSC
2. MS -> BTS -> BSC
3. MS -> BTS
4. MS -> BTS -> BSC
Handoffs

• important task in any cellular radio system
• must be performed successfully, infrequently, and imperceptible to users.
• identify a new base station
• channel allocation in new base station
• high priority than initiation request (block new calls rather than drop existing calls)
Handoffs

Level at A

Handoff threshold

Minimum acceptable signal to maintain the call

Level at B

A

B

Δ
Choice of Margin

• Δ too small:
  – Insufficient time to complete handoff before call is lost
  – More call losses

• Δ too large:
  – Too many handoffs
  – Burden for MSC
Proper Handoff

Level at A

Level at B

Handoff threshold

Minimum acceptable signal to maintain the call

\( \Delta \)
Styles of Handoff

- **Network Controlled Handoff (NCHO)**
  - in first generation cellular system, each base station constantly monitors signal strength from mobiles in its cell
  - based on the measures, MSC decides if handoff necessary
  - mobile plays passive role in process
  - burden on MSC
Styles of Handoff

• Mobile Assisted Handoff (MAHO)
  – present in second generation systems
  – mobile measures received power from surrounding base stations and report to serving base station
  – handoff initiated when power received from a neighboring cell exceeds current value by a certain level or for a certain period of time
  – faster since measurements made by mobiles, MSC don’t need monitor signal strength
Types of Handoff

• **Hard handoff - (break before make)**
  – FDMA, TDMA
  – mobile has radio link with only one BS at anytime
  – old BS connection is terminated before new BS connection is made.
Types of Handoff

- **Soft handoff (make before break)**
  - CDMA systems
  - mobile has simultaneous radio link with more than one BS at any time
  - new BS connection is made before old BS connection is broken
  - mobile unit remains in this state until one base station clearly predominates
Brief Outline of Cellular Process

• Telephone call placed to mobile user
• Telephone call made by mobile user
Telephone call to mobile user

• Step 1 – The incoming telephone call to Mobile X is received at the MSC.
• Step 2 – The MSC dispatches the request to all base stations in the cellular system.
• Step 3 – The base stations broadcast the Mobile Identification Number (MIN), telephone number of Mobile X, as a paging message over the FCC throughout the cellular system.
Telephone call to mobile user

• Step 4 – The mobile receives the paging message sent by the base station it monitors and responds by identifying itself over the reverse control channel.

• Step 5 – The base station relays the acknowledgement sent by the mobile and informs the MSC of the handshake.

• Step 6 – The MSC instructs the base station to move the call to an issued voice channel within in the cell.
Telephone call to mobile user

• Step 7 – The base station signals the mobile to change frequencies to an unused forward and reverse voice channel pair.

• At the same time, another data message (alert) is transmitted over the forward voice channel to instruct the mobile to ring.
Telephone Call Placed by Mobile

• Step 1 – When a mobile originates a call, it sends the base station its telephone number (MIN), electronic serial number (ESN), and telephone number of called party. It also transmits a station class mark (SCM) which indicates what the maximum power level is for the particular user.

• Step 2 – The cell base station receives the data and sends it to the MSC.
Telephone Call Placed by Mobile

• Step 3 – The MSC validates the request, makes connection to the called party through the PSTN and validates the base station and mobile user to move to an unused forward and reverse channel pair to allow the conversation to begin.
Roaming

- All cellular systems provide roaming service
  - This allows subscribers to operate in service areas other than the one from which service is subscribed.
  - When a mobile enters a city or geographic area that is different from its home service area, it is registered as a roamer in the new service area.
Roaming (Cont.)

• **Registration**
  – MSC polls for unregistered mobiles
  – Mobiles respond with MINs
  – MSC queries mobile’s home for billing info

• **Calls**
  – MSC controls call and bills mobile’s home
Development of mobile telecommunication systems

FDMA
- CT0/1
- AMPS
- NMT
- CT2
- IS-136
- TDMA
- D-AMPS
- GSM
- PDC

TDMA
- EDGE
- GPRS
- IMT-FT
- DECT
- IMT-SC
- IS-136HS
- UWC-136
- IMT-DS
- UTRA FDD / W-CDMA
- LTE
- WiMax

CDMA
- cdmaOne
- cdma2000 1X
- IMT-MC
- cdma2000 1X EV-DO
- 1X EV-DV (3X)
- 1X EV-DO

1G
2G
2.5G
3G
4G
Cellular Standards: Brief Overview

• **1G systems**: analog and only voice channels

• **2G systems**: digital and voice channels
  – IS-136 TDMA: combined FDMA/TDMA (north America)
  – GSM (global system for mobile communications): combined FDMA/TDMA
    – most widely deployed
    – Circuit switched data

• **IS-95 CDMA**: code division multiple access
Cellular Standards: Brief Overview

• **2.5 G systems: voice and data channels**
  – for those who can’t wait for 3G service: 2G extensions
  – theoretical data rates up to about 144kbit/s
  – enhanced data rates for global evolution (EDGE)
    • also evolved from GSM, using enhanced modulation
    • Data rates up to 384K
  – general packet radio service (GPRS)
    • first always-on data service
    • evolved from GSM
    • data sent on multiple channels (if available)

• **CDMA-2000 (phase 1)**
  – data rates up to 144K
  – evolved from IS-95
Cellular Standards: Brief Overview

• 3G systems: voice/data
  – data rates of 384kbit/s and more
• UN's International Telecommunications Union IMT-2000 standard requires stationary speeds of 2Mbps and mobile speeds of 384kbps for a "true" 3G.
  – Universal Mobile Telecommunications Service (UMTS)
    • GSM next step, but using CDMA
  – CDMA-2000
  – Edge
  – WCDMA
  – EVDO
Cellular Standards: Brief Overview

• 4G systems
  – Theoretical data rates: ~10Mbps downstream,
    ~5Mbps upstream
  – LTE and WiMAX
  – MIMO
  – OFDMA
MIMO

SISO

SIMO

MISO

MIMO

Single user

Multi-user

Multi-cell

Interference user
Advanced Antenna Techniques

- Single data stream / user
- Beam-forming
  - Coverage, longer battery life
- Spatial Division Multiple Access (SDMA)
  - Multiple users in same radio resource
- Multiple data stream / user Diversity
  - Link robustness
- Spatial multiplexing
  - Spectral efficiency, high data rate support
Diversity Gain

- Receive diversity
  - Transmitter modulates bits with $R$ bits / s / Hz
  - Receiver combines signals from different paths
  - Systems works with as little as one of $Mr$ paths

Presence of multiple paths ensures “quality”
Transmit diversity
- Transmitter modulates bits with $R$ bits / s / Hz
- Diversity encoder ensures every bit -> every antenna
- Systems works with as little as one of $M_t M_r$ paths

Redundancy across multiple paths ensures “quality”
Multiplexing Gain

- Spatial multiplexing [Paulraj & Kailath’94] [Foschini’96]
  - Transmitter demultiplexes bits into \( M_t \) streams
  - Bits modulated onto symbols with \( R \) bits / s / Hz
  - Total spectrum efficiency is \( M_t R \) bits / s / Hz
  - Symbols separated at receiver and demultiplexed

Multiplexing takes advantage of multiple spatial data pipes
Cellular Standards: Brief Overview

• 4G systems
  – Theoretical data rates: ~10Mbps downstream, ~5Mbps upstream
  – LTE and WiMAX
  – MIMO
  – OFDMA
Single Carrier System

Sequential Transmission of Waveforms
Waveforms are Short Duration T
Waveforms Occupy Full System Bandwidth 1/T
FDM vs. OFDM

Conventional Frequency Division Multiplex (FDM) multicarrier modulation technique

Orthogonal Frequency Division Multiplex (OFDM) multicarrier modulation technique
OFDM: Dense Multichannel System

Conventional Multichannel System

Non Overlapping Adjacent Channels.

Channels separated by More Than Their Two Sided bandwidth

OFDM Multichannel System

50% Overlap of Adjacent Channels
Available bandwidth is Used Twice
Multi-Carrier System

Parallel Transmission of Waveforms
Waveforms are Long Duration MT
Waveforms Occupy $\frac{1}{M}$ th Of System Bandwidth $\frac{1}{T}$
From OFDM to OFDMA

TDMA

TDMA\OFDMA

N

M
LTE Generic Frame structure

Available Downlink Bandwidth is Divided into Physical Resource Blocks

<table>
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<th>Bandwidth (MHz)</th>
<th>1.25</th>
<th>2.5</th>
<th>5.0</th>
<th>10.0</th>
<th>15.0</th>
<th>20.0</th>
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<tr>
<td>Subcarrier bandwidth (kHz)</td>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical resource block (PRB) bandwidth (kHz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
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<tr>
<td>Number of available PRBs</td>
<td>6</td>
<td>12</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
</tbody>
</table>

Resource Block:
- 7 symbols X 12 subcarriers (short CP), or;
- 6 symbols X 12 subcarriers (long CP)

LTE Reference Signals are Interspersed Among Resource Elements

[source: 3GPP TR 25.814]
• One element that is shared by the LTE Downlink and Uplink is the generic frame structure. The LTE specifications define both FDD and TDD modes of operation. This generic frame structure is used with FDD. Alternative frame structures are defined for use with TDD.

• LTE frames are 10 msec in duration. They are divided into 10 subframes, each subframe being 1.0 msec long. Each subframe is further divided into two slots, each of 0.5 msec duration. Slots consist of either 6 or 7 OFDM symbols, depending on whether the normal or extended cyclic prefix is employed.

[source: 3GPP TR 25.814]
LTE Uplink (SC-FDMA)

- SC-FDMA is a new single carrier multiple access technique which has similar structure and performance to OFDMA.

A salient advantage of SC-FDMA over OFDM is low to Peak to Average Power Ratio (PAPR):

Increasing battery life
5G?

• No one knows for sure

• Innovations under development
  – Massive dense small cells
  – Tight integration between cellular and WiFi
  – Multihop wireless networks
  – Use more spectrum
    • 60GHz
    • Unlicensed spectrum, e.g., white space
  – New apps: Internet of things, wearable computing