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- Cluster size
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- Interference:
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Cellular Concept

- The area served by mobile phone systems is divided into small areas known as cells.
- Each cell contains a base station (BS), which communicates with a mobile unit using two types of radio channels: Control channels, and Data channels.
- Each BS communicates with mobiles.
Solves the problem of Spectral congestion and user capacity by means of frequency reuse

Offers high capacity in a limited spectrum allocation

Offers system level approach, using low power transmitters instead of a single not interfere with the nearest location, high power transmitter (large cell) to cover larger area.

A portion of the total channels available is allocated to each base station.

Neighbouring base stations are assigned different groups channels, in order to minimise interference.
Cell Shapes

Not suitable, (different distance from the cell’s Centre to different point in the perimeter)

Ideal shape, but has dead zones

Area $a = 2R^2$

Area $a = \frac{3^{3/2}}{16} R^2$
Cell Shapes – Hexagonal

Reasons:
- The highest-degree of regular polygons that can tile a plane.
- Approximate the circular contours of equal received signal strength when the propagation is isotropic in the horizontal plane.
- Only small difference from the centre to other point in the perimeter.

Hexagonal cells are widely used to understand and evaluate system concepts. Is the basic geographic unit of a cellular system.

Real Cell Shape:
- System planning, terrain and other effects result in cells that are far less regular, even for elevated base station antennas.
- Base stations location is strongly influenced by the practical problem of finding acceptable sites and may not follow the regular hexagonal grid.
Cell Size

Wireless cells can be categorized as:

- **Macro cell**: 10km
- **Micro cell**: 1 km – Shopping centres, airports etc.
- **Pico cells**: 50 – 300 m – Inside building
- **Femto cells**: 10 – 40 m – Inside rooms

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Typical Cell Radius</th>
<th>PA Power: Range &amp; (Typical Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro</td>
<td>&gt;1 km</td>
<td>20 W ~ 160 W (40 W)</td>
</tr>
<tr>
<td>Micro</td>
<td>250 m ~ 1 km</td>
<td>2 W ~ 20 W (5 W)</td>
</tr>
<tr>
<td>Pico</td>
<td>100 m ~ 300 m</td>
<td>250 mW ~ &gt;2 W</td>
</tr>
<tr>
<td>Femto</td>
<td>10 m ~ 50 m</td>
<td>10 mW ~ 200 mW</td>
</tr>
</tbody>
</table>
Cell Size – Macro Cells

- Cell size is quite large, typically ~ 10 km
- Covering large areas, e.g. suburban areas
- Small number of base stations - 30-45 m height to cover a wider coverage area (e.g. 500 m or more).
- Lower capacity
- High power – 20 – 160 W (Typical 60 W)
- Poor service at the cell edge which includes a large percentage of the cell area.
Cell Size – Micro Cells

- Cell size: 1 km –
- Shopping centres, airports etc.
- Quality of service – Leads to improved throughput - i.e., higher capacity, which is 80-98% higher than Macro cells
- Too many base station – 15-25 m height to cover a limited area (e.g., 200 m) to provide capacity to a hot spot or coverage in a dead zone.
- Lower delays – Faster down loads
- Reduced transmit power – 2 – 20 W (Typical 5 W)
- Large number of handovers
- Require accurate power control to reduce interference
Cell Size – Pico Cells

- 4 – 100 m – Inside building
- Quality of service - Leads to improved throughput - i.e., higher capacity, which is 80-98% higher than Macro cells
- Flexibility
- High number of base station - 10-15 m height to cover a limited area (e.g., 100 m) to provide capacity to a hot spot or coverage in a dead zone.
- Low transmit power – 250 mW – 2 W
- Lower delays – Faster down loads
- Better cell-edge performance, particularly for the uplink than large cells.
- Higher level of handover
- Require accurate power control to reduce interference
Cell Size – Femto Cells

- Femto cells: 10 – 40 m – Inside rooms
- In-building coverage: small cells provide better outdoor-to-indoor coverage. Considering that 40% of mobile traffic originates from home and 25% from work, this can represent a significant source of revenue for network operators.
- Better cell-edge performance, particularly for the uplink than large cells.
- Low cost
Compact base stations (C-BTS)

They are

- Small size and weight (e.g., a few kilograms)
- Easy to deploy and maintain
- They come with varying output power ranging from a half-watt to a few watts
- Low gain antenna
- Fully integrated base stations that include baseband processing and radio module in one physical unit
- Used tunnels and subway stations etc.
Note that the effective antenna height can significantly affect the achieved cell radius in addition to the Tx power level. An antenna installed in a location with higher or lower altitude will have more or less favorable RF propagation conditions, which will influence the size of the coverage footprint (cell radius).
Mobile Communs. - Cellular Spectrum

Phone Transmit

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>A band</td>
<td>333</td>
</tr>
<tr>
<td>B band</td>
<td>333</td>
</tr>
<tr>
<td>A' band</td>
<td></td>
</tr>
<tr>
<td>B' band</td>
<td></td>
</tr>
</tbody>
</table>

Base Transmit

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>A band</td>
<td>333</td>
</tr>
<tr>
<td>B band</td>
<td>333</td>
</tr>
<tr>
<td>A' band</td>
<td></td>
</tr>
<tr>
<td>B' band</td>
<td></td>
</tr>
</tbody>
</table>

20 MHz Guard
Cell Cluster

- A cluster is a group of cells
- No channels are reused within a cluster
- Assume $C$ channel in a system
- Therefore a cluster covers the entire area and the system capacity to maintain simultaneous calls is $C$

<table>
<thead>
<tr>
<th>Cell</th>
<th>Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>900</td>
</tr>
<tr>
<td>2</td>
<td>900.3</td>
</tr>
<tr>
<td>3</td>
<td>900.6</td>
</tr>
<tr>
<td>4</td>
<td>900.9</td>
</tr>
<tr>
<td>5</td>
<td>901.2</td>
</tr>
<tr>
<td>6</td>
<td>9001.5</td>
</tr>
<tr>
<td>7</td>
<td>9001.8</td>
</tr>
</tbody>
</table>

A 7 cells cluster
Frequency Reuse - Concept

- Adjacent cells are assigned different frequencies to avoid interference or crosstalk

- 10 to 50 frequencies assigned to each cell

- The coverage area of cells is called the footprint and is limited by a boundary so that the same group of channels can be used in cells that are far enough apart

- The essential idea of cellular radio is to transmit at power levels sufficiently low so as to not interfere with the nearest location at which the same channel is reused.
Cells with the same number have the same set of frequencies.

$N$-cluster is repeated $M$ times over the same area, therefore system capacity $C = MN$.

*Note: Maximum capacity is achieved when $N = 1$, i.e., all available channels are reused in each cell.*

$N$ can only have certain values as given by:

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

where $i$ and $j$ are non-negative integers.
The displacements between any two cells can be expressed as a linear combination of the two basis vectors $\mathbf{v}_1$ and $\mathbf{v}_2$ having an angle of $60^\circ$. Then $|\mathbf{v}_1|$ and $|\mathbf{v}_2| = (3)^{0.5} R$.

Or, the centre-to-centre distance between two neighbouring cells is

$$D_{nc} = 2R \cos \left( \frac{\pi}{6} \right) \text{ or } \sqrt{3}R$$
Frequency Reuse Distance *contd.*

The centre-to-centre distance between any two co-channel cells is

\[ D_{cc} = \sqrt{i^2 + j^2 + ij \cdot (\sqrt{3}R)} \]

Where \( i, j = 0, 1, 2 \) etc. represent the centre of a cell (reference). For adjoining cells, either \( i \) or \( j \) can change by 1, but not both.

Cell area

\[ a = |\mathbf{v}_1 \times \mathbf{v}_2| = 3R^2 \sin (30^\circ) \]

\[ a = \left( \frac{3\sqrt{3}}{2} \right) R^2 \]
The greater the reuse distance, the lower the probability of interference. Likewise, the lower the power levels used in cells sharing a common channel, the lower the probability of interference.

Thus, a combination of power control and frequency planning is used in cellular systems to prevent interference.
Cluster Size

Area of a region can be expressed by

\[ A = D_{cc}^2 \sin 60^\circ \]

• The number of cells per cluster within an area of radius \( D_{cc} \) (i.e. in reuse pattern) is:

\[ N = \frac{|U_1 \times U_2|}{|V_1 \times V_2|} = \frac{1}{3} \left( \frac{D_{cc}}{R} \right)^2 \]

Also \( N = A/a \)

• Frequency reuse factor = \( 1/N \)

• Area of the cluster

\[ A = \sqrt{3} \frac{D_{cc}^2}{2} \]
To find the nearest co-channel neighbours one must do the followings:

1. move $i$ cells in the $U$ direction
2. turn $60^\circ$ counter-clockwise and move $j$ cells in the $V$

see Fig. $N = 7$, $i = 2$ and $j = 1$
Data

- Co-channel reuse ratio $Q = D_{cc} / R = \sqrt{(3N)}$

<table>
<thead>
<tr>
<th>$i$</th>
<th>$j$</th>
<th>$N$</th>
<th>$Q=D/R$</th>
<th>System Quality (I.e., co-channel interference)</th>
<th>Traffic capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1.73</td>
<td>Lowest</td>
<td>Highest</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>3*</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>4*+</td>
<td>3.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>7*</td>
<td>4.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>9*</td>
<td>5.2</td>
<td>Highest</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>12*+</td>
<td>6</td>
<td></td>
<td>Lowest</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21*=</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Note: Maximum capacity is achieved when $N = 1$, i.e., all available channels are re-used in each cell.
- As $Q$ increases the $D_{cc}$ also increases, and co-channel interference decreases.

* Most common,  + Digital network,  = Analogue network
Frequency Reuse efficiency

\[ \eta_{fr} = \frac{\text{No. of available user channels in real system}}{\text{No. of available user channels in ideal system}} \]

Note: In ideal system there are no co-channel interference

- Frequency reuse factor \( = \frac{1}{N} \)
  
  \( N \) is the number of channels
The choice of channel assignment strategies impacts the performance particularly as to how calls are managed when a mobile user is handed off from one cell to another.

There are basically two strategies:

- Fixed
- Dynamic
Channel Assig. Strat. - Fixed

- Each cell is allocated a predetermined set of voice channels irrespective of the number of customers in that cell. *This results in traffic congestion and some calls being lost when traffic gets heavy*

- Call attempted within the cell can only be served by the unused channels in that particular cell

- Call is *Blocked* if channels are occupied

- If all the channels are occupied cell may be allowed to use channels from a neighbouring cell

- Used in TDMA/FDMA cellular radio systems
Channel Assig. Strat. - Dynamic

- Channels are not allocated to different cells permanently.
- Is ideal for bursty traffic
- Each time a call request is being made, the serving BS request a channel from MSC.

- MSC allocate a channel by using an algorithm that takes into account:
  - the likelihood of future blocking within the cell
  - the frequency reuse of the candidate channels
  - the reuse distance of the channels
  - cost functions

- MSC requires to collect real time data on:
  - channel occupancy and traffic distribution
  - radio signal strength of the channels on a continuous basis
Channel Assig. Strat. - Dynamic

- Since a cell is allocated a group of frequency carries (e.g. $f_1$-$f_7$) for each user, then

  Bandwidth of that cell $B_{ce} = a$ range from carrier frequencies

- Adopted in GSM, DCS and other systems
Channel Capacity

Cluster with size $N = 7$

$k = \text{Number of channels / cell}$

No. of cluster

Channel capacity $C = MkNB = MS$

Duplex frequency bandwidth / channel

Total duplex channels available for reuse: $S = kNB$
E.g. for GSM:

**Normally 25MHz/200kHz/channel = 125 channels /cluster**

For $N = 7$, $k = 17 - 18$ channel/cell
And for $M = 3$,
$C = 3 \times 125 = 375$ channel

Or for
$S = 8$, $N = 9$, and $B = 2 \times 200$ kHz = 0.4 MHz.
Thus $k = 2.2$ channels. $\text{Cell}^{-1}.\text{MHz}^{-1}$

For analogue systems
$k = 1.9$ channels. $\text{Cell}^{-1}.\text{MHz}^{-1}$
Communications using Base Stations

- Each BS continuously transmits control information via control channels
- When a mobile is switched on, it
  - It scans the control channels and tunes to a channel with the strongest signal, which is transmitted from BSs
  - The mobile exchanges identification information with BS to establish authorization to use the network
  - Then mobile is ready to initiated and receive a call
Cellular Network

Network and Switching Subsystem (NSS)
- HLR
- GMSC
- VLR
- MSC

Radio Sub System (RSS)
- BSC
- BS

PSTN

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Cellular Network - RSS

- **Base Station Subsystem (BSS):**
  - **Base Transceiver Station (BTS)**
    - including transmitter, receiver, antenna
  - **Base Station Controller (BSC)**
    - switching between BTSs
    - controlling BTSs
    - network resources management
    - mapping of radio channels ($U_m$) onto terrestrial channels (A interface)

  - **BSS = BSC + \sum BTS + interconnection**

- **Mobile Stations (MS)**
Cellular Network - NSS

The main component of the public mobile network
- switching, mobility management, interconnection to other networks, system control

- **Mobile Services Switching Center (MSC)**
  - Connecting several BSC
  - Controls all connections via a separated network to/from a mobile terminal

- **Home Location Register (HLR)**
  - Central master database containing user data, permanent and semi-permanent data of all subscribers assigned to the HLR

- **Visitor Location Register (VLR)**
  - Local database for a subset of user data, including data about all user currently in the domain of the VLR
Cellular Network - MSC

- **Its roles are:**
  - Switching and additional functions for mobility support
  - network resources management
  - interworking functions via Gateway MSC (GMSC)
  - integration of several databases

- **Its functions are:**
  - specific functions for paging and call forwarding
  - termination of SS7 (signaling system no. 7)
  - mobility specific signaling
  - location registration and forwarding of location information
  - provision of new services (fax, data calls)
  - support of short message service (SMS)
  - generation and forwarding of accounting and billing information
Cellular Network - Operation Subsystem

- Enables centralized operation, management, and maintenance of all cellular subsystems

- Authentication Center (AUC)
  - generates user specific authentication parameters on request of a VLR
  - authentication parameters used for authentication of mobile terminals and encryption of user data on the air interface within the system

- Equipment Identity Register (EIR) for Mobile Identification Number (MIN)
  - registers mobile stations and user rights
  - stolen or malfunctioning mobile stations can be locked and sometimes even localized

- Operation and Maintenance Center (OMC)
  - different control capabilities for the radio subsystem and the network subsystem
Cellular Network - Mobile Registration

- MSC
- VLR
- HLR
- VLR
- MSC

Terminal Moves into area

Send MIN

Update location

Cancel location

CLR

CANCEL LOCATION

MIN

UPDATE LOCATION

Home Location Register (HLR)
Visitor Location Register (VLR)

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Cellular Network - Mobile Terminated Call

1- Calling a mobile unit
2- Call forwarding to GMSC
3- Signal call setup to HLR
4&5- Request MSRN from VLR
6- Forward responsible MSC to GMSC
7- Forward call to current MSC
8&9- Get current status of MU
10&11- Paging of MSU
12&13- MU answers
14&15- Security checks
16&17- Call set up connection
Cellular Network - Mobile Originated Call

1&2- Connection request
3&4- Security check
5-8- Check resources (free circuit)
9&10- Call set up
Cellular Network – MTC and MOC

**MTC**
- Paging request
- Channel request
- Immediate assignment
- Paging response
- Authentication request
- Authentication response
- Ciphering command
- Ciphering complete
- Setup
- Call confirmed
- Assignment command
- Assignment complete
- Alerting
- Connect
- Connect acknowledge
- Data/speech exchange

**MOC**
- Channel request
- Immediate assignment
- Service request
- Authentication request
- Authentication response
- Ciphering command
- Ciphering complete
- Setup
- Call confirmed
- Assignment command
- Assignment complete
- Alerting
- Connect
- Connect acknowledge
- Data/speech exchange

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Steps in Controlled Call between Mobile Users

- Mobile unit initialization
- Mobile-originated call
- Paging
- Call accepted
- Ongoing call
- Handoff

Additional functions
- Call blocking
- Call termination
- Call drop
- Calls to/from fixed and remote mobile subscriber
Handoff (Handover)

- The **process of switching** a user from one cell to another while a conversion is in progress.
- It is a complex procedure because the base stations have to calculate exactly when a user is crossing the cell boundary. This could take **several seconds**, so if the mobile user is **moving too fast** the call will be dropped.
- **Speed limit:**
  - Analogue systems: 100 km/h
  - Digital systems: 300 km/h
  Some systems can complete handoff to the cruising speed of an airliner.
Handoff - Types

- **No handoff**
  - The most simple
  - A new call is made once a mobile unit has moved out of the range of a base station.
  - Not common, since it takes up to 30 sec. to set up a new call

- **Hard handoff**
  - Mobile unit need to break its connection with on BS before connecting to another
  - Not too reliable to establish a new call.
    - A cell could be already full or no cell being available at all.
    - Repeated handoff in areas with poor power reception within the same cell since no other BS can accept the call.
  - Results in a noticeable break in conversation especially when MU is moving fast between small cells

- **Soft handoff**
  - A new link is set up to BS in the new cell before the old one is dropped.
  - Reliable, calls are dropped only if MU is moving very fast.
  - A connection with two different BSs is rather difficult with existing systems. 3G overcomes this problem.
Handoff - Types

- **Inter-cell handoff:** MU moving from its current cell to the adjacent cell using the same channel

- **Intra-cell handoff:** MU moving from its current cell to the adjacent cell using a new channel
Handoff - Operation

- Is based on periodical measurements of the received signal strength and link quality recorded by the MU and passed on to the BS
- BS reports the hand-off request to BSC, MSC
  - In 2G systems BSC handles the handover
- The BS with the highest received signal level and an ideal channel is detected.
- Identifying new BS. The system switches the call to a stronger-frequency channel in a new site without interrupting the call or alerting the user
- Allocation of voice and control signals to channels associated with the BS. During a call, two parties are on one voice channel
- If there is no new BS, the hand-off fails and the call is terminated.
Initially MU is assigned to BS1.

A call will be dropped when:
- there is an excessive delay by the MSC in assigning a hand-off,
- the $\Delta$ is set too small for the hand-off time in the system.
Handoff Operation - *contd.*

- For successful Hand-off an **OPTIMUM SIGNAL LEVEL** is required at which to initiate a Hand-off.
- Once a particular signal level is specified, as the minimum useable signal for acceptable voice quality at the BS receiver (normally at -90 dBm or -100 dBm), a slightly stronger signal level is used as a threshold at which a Hand-off is made. This margin is given by:

\[ \Delta = P_{r\text{handoff}} - P_{r\text{minimum usable}} \]

- If \( \Delta \) is too large, unnecessary hand-offs, which burden the MSC may occur,
- If \( \Delta \) is too small, there may be insufficient time to complete a hand-off before a call is lost due to weak signal condition.
In deciding when to hand-off, it is important to ensure:
- the drop in the measured signal level is not due to momentary **fading**
- the mobile is actually moving away from the serving BS.

For this to happen the BS monitors the signal level for a certain period of time before a hand-off is initiated.

The length of time needed to decide if a hand-off is necessary depends:
- on the speed at which the MU is moving.

If the slope of the short term average received signal level in a given time interval is steep, the hand-off should be made quickly.
Handoff Procedure

MU  \(\text{BTS}_{\text{old}}\)  \(\text{BSC}_{\text{old}}\)  MSC  \(\text{BSC}_{\text{new}}\)  \(\text{BTS}_{\text{new}}\)

- Measurement report
- Measurement result
- HO decision
- HO required
- HO request
- Resource allocation
- HO request ack
- Ch. activation
- Ch. activation ack
- HO complete
- Clear command
- Clear complete
- Link establishment
- HO command
- HO access
- HO command
- HO command
- HO command

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Handoff - Practical Considerations

- **Speed** at which a MU passes through the coverage area
  - Cars takes seconds to pass through
  - Pedestrian may never need a handoff during a call

- **Ability to obtain new cell site:**
  - Service providers find it very difficult to obtain new physical cell site location in urban areas. Therefore implement what is called the “umbrella cell approach”

- Speed of mobile is estimated by the BS or MSC by monitoring average signal strength
- BS may transfer high speed mobile to the co-located microcell without MSC intervention

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Large area for high speed mobiles

For low speed traffic
Handoff - Practical Considerations

- **Cell dragging:**
  - Mainly in micro cell systems
  - Results from pedestrian: In urban area, because of line of sight radio path strong signal is received by the BS
  - As the mobile moves away from the BS, the average signal strength does not decay rapidly. This creates a few problems:
    - Handoff-problem: The user is well outside the desired range, and with the signal strength within the cell still being strong, therefore no handoff.
    - Interference
    - Management problem.
Handoff Performance Metrics

- Cell blocking probability – *probability of a new call being blocked*
- Call dropping probability – *probability that a call is terminated due to a handoff*
- Call completion probability – *probability that an admitted call is not dropped before it terminates*
- Probability of unsuccessful handoff – *probability that a handoff is executed while the reception conditions are inadequate*
- Handoff blocking probability – *probability that a handoff cannot be successfully completed*
- Handoff probability – *probability that a handoff occurs before call termination*
- Rate of handoff – number of handoffs per unit time
- Interruption duration – *duration of time during a handoff in which a mobile is not connected to either base station*
- Handoff delay – *distance the mobile moves from the point at which the handoff should occur to the point at which it does occur*
Mode of Communication

- **Frequency Division Duplex (FDD)**
  - Uses two different frequency bands (*uplink* and *downlink*)
  - A symmetric communication channel (*uplink* and *downlink* use the same capacity)
Mobile Positioning

- Mobile positioning refers to determining the position of the mobile device. Its purpose is to provide location-based services (LBS), including wireless emergency services.
- Mobile location refers to the location estimate derived from the mobile positioning operation.
- Methods:
  - Network based
  - Handset based positioning..
Mobile Positioning – Network Based

- Uses mobile network + network-based position determination equipment (PDE)
  - SS7 and Mobile Positioning (SS7 is a communications protocol that provides signalling and control for various network services and capabilities.
    - The easiest method
      - MSC launch a SS7 message containing the cell of origin (COO) or cell ID (of the corresponding cell site currently serving the user).
    - Covering a large area, the COO may be used by LBS to approximate the location of the user.
    - A large degree of uncertainty that should be taken into account by the LBS application in term of required quality of service (QOS).
  - Network based PDE
  - Angle of Arrival Method - between the mobile phone and the cellular antenna.
  - Time of Arrival Method - of signals between the mobile phone and the cellular antenna
  - Radio Propagation Techniques - utilize a previously determined mapping of the radio frequency (RF) characteristics to determine an estimate of the mobile device position
  - Hybrid Methods
Mobile Positioning – Handset Based

- **Subscriber Identity Module (SIM) Toolkit**
  - Positioning information may be as approximate as COO or more precise through additional means such as use of the mobile network operation called timing advance (TA) or a procedure called network measurement report (NMR).
  - SIM toolkit is a good technique to obtain position information while the mobile device is in the idle state.

- **Enhanced Observed Time Difference (E-OTD)**

- **Global Positioning System (GPS)**
  - The most accurate (when satellites are acquired/available), but is often enhanced by additional network equipment.

- **Mobile IN Technologies**
Cellular System - Power Control

- It desirable to introduce *dynamic power* control
  - To have a high SNR:
    received power must be sufficiently above the background noise for effective communication – $P_r > N_T$ (Noise total power)

Rapid changes to the received power is due to:
- Reflection - Diffraction and - Scattering

- To reduce co-channel interference, alleviate health concerns, save battery power:
  minimize mobile transmitted power

- To equalize the received power level from all mobile units at the BS
Power Control - Types

- Open-loop power control
  - Depends solely on mobile unit
  - No feedback from BS
  - Continuous transmission of a “Pilot Signal, thus allowing MU to use it for
    - Timing for forward link (BS → MU)
    - Phase reference for demodulation
    - Power control
  - Assumptions: Forward and reverse links are correlated
  - Not as accurate as closed-loop, but can react quicker to fluctuations in signal strength
Power Control - Types

- Closed-loop power control
  - Adjusts signal strength in reverse channel (MU → BS) based on metric of performance in the reverse channel
    - Received power level
    - Received SNR
    - Or received bit error rate (BER)
  - BS makes power adjustment decision and communicates to a power adjustment command to the mobile on a control channel
Interference

- Interference is the major limiting factor in the performance of cellular radio systems. Sources of interference include:
  - another mobile in the same cell
  - a call in progress in the neighbouring cell
  - other BSs operating in the same frequency band
  - any non-cellular system which inadvertently leaks energy into the cellular frequency band.

**Interference effects:**
- on voice channel causes *crosstalk*
- on control channels it leads missed and blocked calls due to errors in the digital signalling.
Interference - *contd.*

- Interference is more severe in the urban areas, due to:
  - the greater RF noise floor
  - large number of BSs and mobiles

*Interference has been recognised as a major bottleneck in increasing capacity and is often responsible for dropped calls*

**Types of Interference**

- Co-channel
- Adjacent channel
- Power level
- Multipath
Co-channel Interference (CCI)

- Is due to frequency reuse in a given coverage area.

- Unlike thermal noise, which can be overcome by increasing the signal-to-noise ratio, CCI can not be reduced by simply increasing the signal (carrier) power at the transmitter. This is because an increase in carrier transmit power increases the interference to neighbouring co-channel cells.

- To reduce CCI, co-channel cells needs to be physically separated by a minimum distance to provide sufficient isolation due to propagation.
The signal-to-interference ratio (SIR) for a mobile receiver monitoring a forward channel is given as:

\[
SIR = \frac{S}{\sum_{i=1}^{i_o} I_i}
\]

where

- \(i_o\) = No. of co-channel interfering cells
- \(S\) = Signal power from a desired BS
- \(I_i\) = interference power caused by the \(i^{th}\) interfering co-channel cell BS.

\(SIR \approx 17 - 19\) dB
Average received power $P_r$ at a distance $d$ from the transmitting antenna is:

$$P_r = P_0 \left( \frac{d}{d_0} \right)^{-n}$$

Or in dB

$$P_r (dBm) = P_0 (dBm) - 10n \log\left( \frac{d}{d_0} \right)$$

where

- $P_0 = $ Power received at a close-in reference point in the far field region of the antenna at a small distance $d_0$ from the Tx antenna.
- $n = $ Path loss exponent. $2 < n < 4$ for urban cellular.
Co-channel Interference - *contd.*

- Let's consider the forward link where:

  
  \[ S \propto R^{-n} \quad \text{And} \quad I_i \propto (D_i)^{-n} \]

- Mobile unit

![Diagram with desired BS and interfering BS]
Co-channel Interference - *contd.*

- Assuming
  - transmitted power of each BS is equal
  - $n$ is the same throughout the coverage area,

$\downarrow$ If all the interfering BSs are equidistant from the desired BS
$\downarrow$ If this distance is equal to the distance $D_{cc}$ between the cells
$\downarrow$ Since $Q = D_{cc}/R$

$$SIR = \frac{R^{-n}}{i_0} \sum_{i=1}^{i_0} (D_i)^{-n}$$

$$SIR = \left( \frac{D_{cc}}{R} \right)^n i_0 = \left( \frac{\sqrt{3N}}{i_0} \right)^n$$
Co-channel Interference - Example

- For the USA AMPS cellular system which uses FM and 30 kHz channels, a 7-cell cluster might be used there could be up to 6 immediate interference, Assuming the fourth power propagation law, an approximate value of the SNI would be:

Solution:

\[ SIR = \frac{S}{\sum 6I'} = \frac{R^{-4}}{6D_{cc}^{-4}} \]

since \( D_{cc}/R = (3N)^{1/2} \), then

\[ SIR = 1.5 \ N^2 = 1.5 \ (7)^2 = 74 \]

in dB \( SIR = 10 \log (74) = 19 \ \text{dB} \).

Compared with 13 dB for GSM
Co-channel Interference

If stations A and B are using the same channel, the signal power from B is co-channel interference:

\[ SIR(d_A, D_{cc}) = P_A(d_A) - P_B(D_{cc} - d_A) \]

\[ = -\log_{10}[(D_{cc} / d_A) - 1] \quad dB \]
Spectrum Efficiency

- Defined as the traffic capacity unit (i.e. number of channel /cell) divided by the product of bandwidth and the cell area.
- Is dependent on the number of radio channels per cell and the cluster size (number of cells in a group of cells):
- Cellular system capacity or spectrum efficiency can be most easily and inexpensively increased by:
  - subdividing cells into smaller cells
  - sectorising the cells.

A reuse pattern of $N_s/N$, $N_s$ is the number of sectors.
Some current and historical reuse patterns are

3/7 (North American AMPS),
6/4 (Motorola NAMPS),
3/4 (GSM).
How to Reduce CCI – *Sectorisation* (Directional Antenna)

- Use of a directional antenna instead of omnidirectional antenna: 120° or 60° sector antenna
- The frequency band is further subdivided (denoted 1-1, 1-2, 1-3, etc.). This does not use up frequencies faster (same number of channels/cell)

Cell with 3 sectors having their own frequencies and antennas
How to Reduce CCI – Sectorisation

For a 7-cell cluster, the MU will receive signals from only 2 other cluster (instead of 6 in an omnidirectional antenna).

For worst case, when mobile is at the edge of the cell:

\[ SIR = \frac{R^{-n}}{D_{cc}^{-n} + (D_{cc} + 0.7R)^{-n}} \]

- Desired channel
- Interfering co-channel cells @ D distance
How to Reduce CCI – *contd.*

- **Sequential Transmitter**
  - Only one transmitter is being used while all the surrounding transmitters are switched off (i.e., transmitters are turned on in turn)

![Diagram showing sequential transmitter with time delay between transmitters](attachment:sequential_transmitter_diagram.png)
Adjacent Channel Interference (ACI)

- Results from signals which are adjacent in frequency to the desired signal due to imperfect receiver filters.
- It can be serious if an adjacent channel user is transmitting in very close range to a mobile unit. This is referred to as the NEAR-FAR EFFECT (NFF).
- NFF also occurs when a mobile close to a BS transmits on a channel close to one being used by a weak mobile.

Can be minimised by:

- careful filtering
- careful channel assignments:
  - careful frequency allocation
  - sequential assigning successive channels in the frequency band to different cells.
Adjacent Channel Interference - *contd.*
Out-of-Cell Interference

Q - If a single high-power source does not provide sufficient capacity and cannot combat the shadowing effect, could multiple high-power sources provide a solution?

i.e.,
- For indoor deployment, can one simply install a large number of picocell eNodeBs into the indoor area and reduce the inter-cell distance, so the picocells effectively act like femtocells?
- A similar question applies for outdoor deployment: can one simply install a large number of macrocell eNBs and reduce the inter-cell distance, so these macrocells can act like microcells?

Ans.
In the early days of wireless communication, with a very limited base station, many networks were indeed deployed this way. However, there are several undesirable effects if high-power base stations are deployed too close to each other.
It is desirable for the inter-cell distance $D_{nc}$ to be slightly more than twice the value of $B$, $D_{nc} > 2*B$

so that the in-cell signal level will have a slower attenuation ($\propto R^{-2}$)

but out-of-cell interference $I_{oc}$ will have a faster attenuation ($\propto R^{-4}$).

Since $B$ is a function of the base station antenna height $h_{bs}$, for a certain antenna height $h_{bs}$, only properly spaced base stations can maximize the $S/I$. 

$D_{nc} = 2R > 2B$
Out-of-Cell Interference

If the neighbouring base stations are installed too close to each other so that the inter-cell distance $D_{nc} < 2B$, then $I_{oc}$ will not attenuate fast enough, thus the overall $S/I$ degrades.

$D_{nc} = 2R < 2B$
Out-of-Cell Interference

Total out-of-cell interference

\[ I_{oc\text{-}total} = \sum_{i}^{n} I_{i\text{-}1st} + \sum_{j}^{m} I_{j\text{-}2nd} + \sum_{k}^{o} I_{k\text{-}kt} + \]

1st tier neighbours  
2nd tier neighbours  
kth tier neighbours  

Total out-of-cell interference to one cell (blue) is the sum of interference contributed from all neighbours
### Approaches to Cope with Increasing Capacity

- **Adding new channels or new frequency band**
  - GSM uses two bands in Europe: 890-960 MHZ, and 1710 – 1880 MHz
- **Decrease cell size and at the same time reduce transmit power** (to keep CCI low)
- **Frequency borrowing**
  frequencies are taken from adjacent cells by congested cells
- **Increase the number of cell per cluster**
  - **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 (100 m – 1 km in diameter)**
  - compared to the standard cell size of 2-20 km in diameter
  - antennas move to buildings, hills, and lamp posts
- **Smart antennas**
Cell Splitting

- Consider the number of voice circuits per given service area.
  - If a base station can support $X$ number of voice circuits, then cell splitting can be used to increase capacity.

Before cell splitting

After cell splitting

- As shown above a rough calculation shows a factor of 4 increase.
- This is the reason for using more base stations in a given area.
Cell Splitting

- This increase does not hold indefinitely for several reasons:
  - Eventually the BSs become so close together that line-of-sight conditions prevail and path loss exponent becomes less (e.g., 2 versus 4)
  - Obtaining real estate for increased number of base stations is difficult
  - As cell sizes become smaller, number of handoffs increases; eventually speed of handoff becomes a limiting factor

- Mini cells will have their own Tx and Rx antennas

\[ P_u = P_{tu} R^{-n} \]

Power at the boundary of un-split cell:

\[ P_{ms} = P_{tms} \left( \frac{R}{2} \right)^{-n} \]

Power at the boundary of a new mini cell:

Where \( P_{tu} \) = transmitted power un-split cell

\( P_{tms} \) = transmitted power from mini cell

To maintain the same CCI performance \( P_u = P_{ms} \)

\[ P_{tms} = \frac{P_{tu}}{2^n} \]
Cell Splitting – Micro and Femto-Cells

Microcells and femtocells are deployed by most major carriers as a way to allow their customers, both businesses as well as individuals, to deploy their own network(s) anywhere there is an Internet connection.

The sheer number of cells (large and small area), the inability for the carriers to control the position and use of them, and the handover between these ad hoc cells and the overall network create significant challenges in spectrum and interference management.
Small Cells for Higher Capacity

There are two very different in-building service objectives.

- Maximize the in-building coverage - the footprint from each indoor cell should be as large as possible in order to minimize the total indoor cell count.

- Maximize the in-building capacity - the footprint from each indoor cell should be as small as possible in order to maximize the total indoor cell count, which results in maximum capacity.

Obviously, for serving hotspots the main goal is to maximize the in-building capacity so one must minimize the footprint of each indoor cell.
Small Cells for Higher Capacity

Data capacity from a cell is defined as the aggregate cell throughput per cell.

With identical conditions (e.g., same channel bandwidth),

The aggregate throughput from a cell is the same regardless of the size.

Therefore, regardless of whether it is a macrocell, microcell, picocell, or femtocell, the aggregate cell throughput from each cell remains the same.

It also means that total capacity is inversely proportional to the square of the cell radii, i.e. if the cell radii are halved, the total capacity is quadrupled.
Small Cells for Higher Capacity

- The total capacity in a building can be increased significantly by using a large number of femtocells with very small footprints.
- The cell radii of femtocells are about 10%–30% of those of picocells.
- Therefore, by using a large number of femtocells, the total indoor capacity can be increased by a factor of 10–100 compared to the case of using a few picocells.

Q- Why the Picocell is not the Best Candidate for a High-Capacity Indoor Solution?
Small Cells for Higher Capacity

Q- Why the Picocell is not the Best Candidate for a High-Capacity Indoor Solution

A- it is necessary to consider the purpose for which they are designed. The picocell has higher power and larger cell radius, which makes it a more appropriate candidate for applications that demand larger coverage footprints (> 100 meters).

E.g., dense “urban canyons” (see Figure), outdoor theme parks, and so on. These areas need high capacity, but a high percentage of traffic is voice (which requires each cell to connect a higher number of active users). MU may be moving at driving speed, so larger cell radii and faster handover are needed. They are typically more expensive than femtocells, but also the better candidate for serving outdoor hotspots.
Indoor services do not need to handle MU that is moving at high speed.
Within the small footprint of a femtocell, the number of simultaneous connections does not need to be as large as in an outdoor situation.
The combined factors of lower power and lower processing power make the cost of a femto cells much lower, but also make femtocells more suitable for high-capacity indoor applications.

Using a small number of picocells with higher power can cover the entire building. But, when comparing the following coverage options:
(a) Small number of picocells with higher power
(b) Larger number of femtocells with lower power

Option (b) will provide much more uniform Coverage in a highly cluttered indoor environment, see Fig.
Small Cells for Higher Capacity-
Indoor Coverage

Most in-building environments will have many man-made objects that act as obstacles to radio propagation; therefore one must consider the so-called “shadowing effect.” A large number of low-power femtocells provides much better “macroscopic diversity” (i.e., each location will likely receive signals from multiple cells arriving from different directions), which is very effective in combatting the shadowing effect.

Single picocell: a single obstacle will cause a coverage shadow. (Right) Multiple femtocells: no shadow is caused unless all femtocells are obstructed.
Smart Antennas

- BSs transmits the signal to the desired MU
  - With a maximum gain
  - Minimized transmitted power to other MUs.
- Overcomes the delay spread and multipath fading.
- Two types:
  - Switched-beam antenna
    • Cell sectrisation: where a physical channel, such as a frequency, a time slot, a code or combination of them, can be reused in different minisectors if the CCI is tolerable.
  - Adaptive beam-forming antenna
    • BS can form multiple independent narrow beams to serve the MUs (i.e. two or more MUs which are not close to each other geometrically can be served by different beams. Therefore, the same physical channel can be assigned to two or more MUs in the same cell if the CCI among them is tolerable.
Signal-to-Noise Ratio (SNR)

\[ SNR_{\text{Total}} = \frac{S}{N + I_T} \]

- \( S \) is the signal power
- \( N \) is the total noise power at the receiver stage.
  \( N = N_{th} + N_{amp} \)
- \( I_T \) is the total interfering signal power = CCI + ACI

Average power of thermal noise \( N_{th} = KTB \quad R=1 \text{ ohm} \)

\[ B = \text{Bandwidth} \]
\[ T = \text{Absolute temperature in degree Kelvin} \]
\[ K = \text{Boltzmann’s constant} = 1.38 \times 10^{-23} \text{ W/Hz/K}^o \]
What is the goal in cellular systems?

- Increase capacity while minimizing the interference
Glossary

- **AMPS**: advanced mobile phone service; another acronym for analog cellular radio
- **BTS**: base transceiver station; used to transmit radio frequency over the air interface
- **CDMA**: code division multiple access; a form of digital cellular phone service that is a spread spectrum technology that assigns a code to all speech bits, sends scrambled transmission of the encoded speech
- **DAMPS**: digital advanced mobile phone service; a term for digital cellular radio in North America.
- **DCS**: digital cellular system
- **E–TDMA**: extended TDMA; developed to provide fifteen times the capacity over analog systems by compressing quiet time during conversations
- **ESN**: electronic serial number; an identity signal that is sent from the mobile to the MSC during a brief registration transmission
- **FCC**: Federal Communications Commission; the government agency responsible for regulating telecommunications in the United States.
- **FCCH**: frequency control channel
- **FDMA**: frequency division multiple access; used to separate multiple transmissions over a finite frequency allocation; refers to the method of allocating a discrete amount of frequency bandwidth to each user
Glossary

- **FM**: frequency modulation; a modulation technique in which the carrier frequency is shifted by an amount proportional to the value of the modulating signal
- **FRA**: fixed radio access
- **GSM**: Global System for Mobile Communications; standard digital cellular phone service in Europe and Japan; to ensure interpretability between countries, standards address much of the network wireless infra
- **MS or MSU**: mobile station unit; handset carried by the subscriber
- **MSC**: mobile services switching center; a switch that provides services and coordination between mobile users in a network and external networks
- **MTSO**: mobile telephone switching office; the central office for the mobile switch, which houses the field monitoring and relay stations for switching calls from cell sites to wireline central offices (PSTN)
- **MTX**: mobile telephone exchange
- **NADC**: North American digital cellular (also called United States digital cellular, or USDC); a time division multiple access (TDMA) system that provides three to six times the capacity of AMPS
- **NAMPS**: narrowband advanced mobile phone service; NAMPS was introduced as an interim solution to capacity problems; NAMPS provides three times the AMPS capacity to extend the usefulness of analog systems
Glossary

- **PCS**: personal communications service; a lower-powered, higher-frequency competitive technology that incorporates wireline and wireless networks and provides personalized features
- **PSTN**: public switched telephone network; a PSTN is made of local networks, the exchange area networks, and the long-haul network that interconnect telephones and other communication devices on a worldwide basis
- **RF**: radio frequency; electromagnetic waves operating between 10 kHz and 3 MHz propagated without guide (wire or cable) in free space
- **SIM**: subscriber identity module; a smartcard which is inserted into a mobile phone to get it going
- **SNSE**: supernode size enhanced
- **TDMA**: time division multiple access; used to separate multiple conversation transmissions over a finite frequency allocation of through-the-air bandwidth; used to allocate a discrete amount of frequency band
Summary

- Cell Shapes & Clusters Size
- Frequency Reuse
- Handoff Strategies
- Interference (CCI + ACI)
- How to Combat Interference
- Signal-to-Noise Ratio
Next Lecture

Traffic Engineering