King Fahd University of Petroleum & Minerals
Computer Engineering Dept

COE 543 – Mobile and Wireless Networks

Term 022

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Lecture Contents

1.

Cellular Concept

- Optimize the operation of low-power radios spread out over the geographical area
- Cell: service area where a group of mobiles or terminals (referred to as users) are served *primarily*[1] by one basestation – usually located at the centre of the cell
- Cell radius depends on the propagation conditions and the network design – ranges from few meters for indoor or microcellular networks to 10s of kilometers of rural service areas

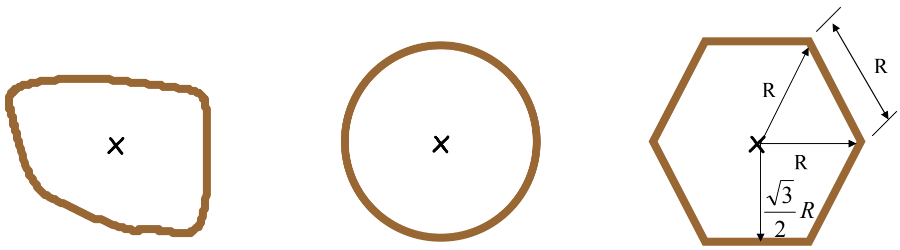
1. As we will see, there can be situations where a mobile is served by more than one basestation

Cellular Concept

- A basestation/network provides service for users by coordinating access (time slots, frequency channels, or codes) to channels
- Bandwidth (channels) is (are) split amongst a group of cells – called cluster
  - Cluster is repeated to cover a wider geographical area
- Radio coverage is irregular – depending on terrain – first order approximation is the use of hexagonal cells

Cell Shape

- Radio coverage is irregular – depending on terrain – first order approximation is the use of hexagonal cells
- Other shapes (circular, squares) may be used depending on the intended purpose
  - E.g. indoor networks may assume squares/rectangular

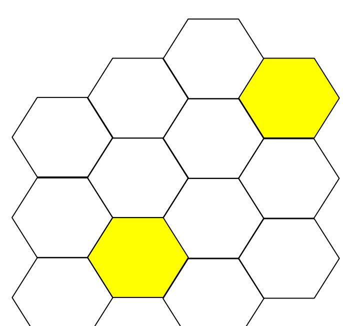


coverage in practice | ideal coverage for omni-directional antenna at the BTS | shape used for design - mostly

Cellular Design – Frequency Reuse

- If service area is divided into cells as shown, then it is desirable to use one set channels in more than one cell ➔ Reuse Concept
- This would increase utilization and overall capacity

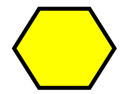
- Network design should also take into consideration "co-channel" interference
- Too much reuse may lead to unacceptable signal quality → deteriorating capacity
- Function of distance or "Reuse Factor" and communication technology



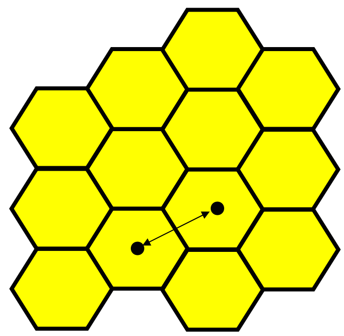
Frequency Reuse Factor of 1

- One set of channel is used in every cell
- Interference is expected to be high
- Distance between co-channel cells equal to

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



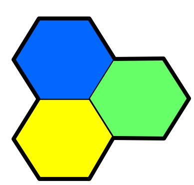
cluster made of 1 cell



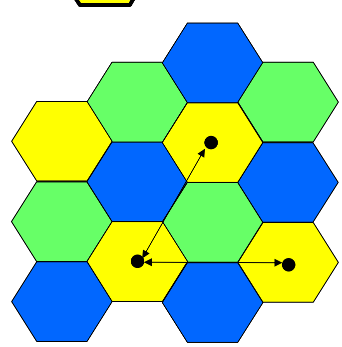
Frequency Reuse Factor of 3

- One set of channel is used in every cell
- Interference is expected to be high
- Distance between co-channel cells equal to

$$D = 3R$$



cluster made of 3 cells



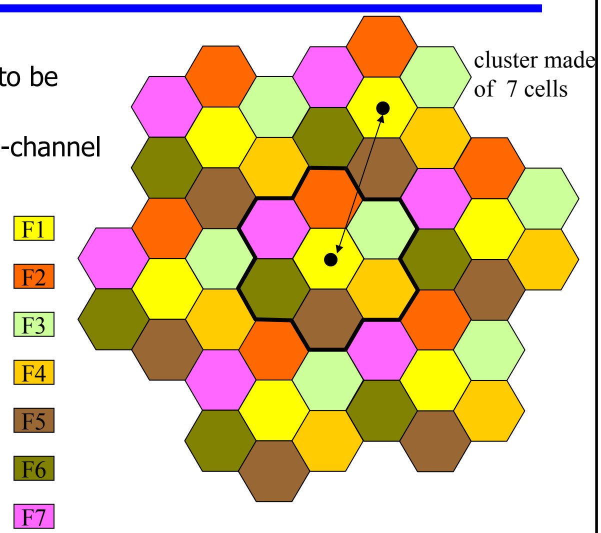
Frequency Reuse Factor of 7

Example:

Interference is expected to be high

- Distance between co-channel cells equal to

$$D = \sqrt{21}R$$



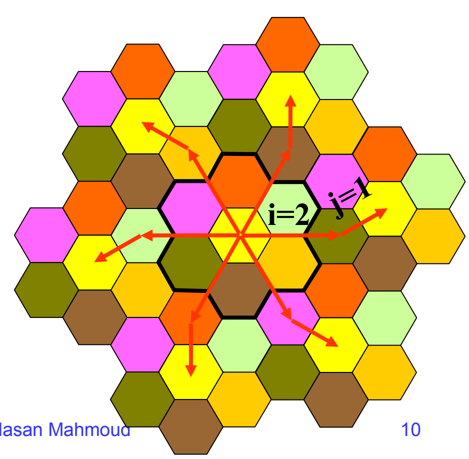
Cluster Size and Reuse Distance

- The reuse distance D is given by

$$D = \sqrt{3N}R \qquad N = i^2 + j^2 + ij \qquad i, j = 0,1,2,3,\ldots$$

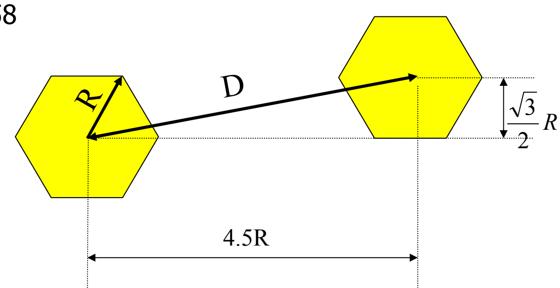
N is the cluster size

i	j	N	D/R
1	0	1	sqrt(3)=1.7
	1	3	3
2	0	4	2Xsqrt(3)=3.46
	1	7	sqrt(21)=4.6
3	0	9	3Xsqrt(3)=5.19
	1	13	sqrt(39)=6.25



Co-channel Interference Ratio

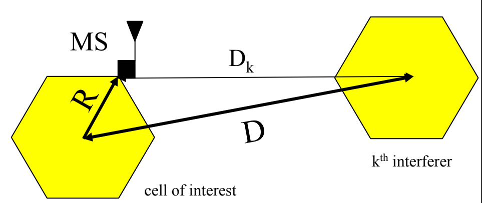
- Distance between co-channel cells
- For example for a reuse factor of 7 (in figure):
  - N = 7
  - D = sqrt(3XN)R = sqrt(21)R
  - q = sqrt(21) = 4.58



Co-channel Interference Ratio – cont'd

- The signal quality is measure as the ratio of the desired signal power to the total interference power
- Referred to SIR (or SNR)

$$\frac{S}{I} = \frac{S}{\sum_{\forall k} I_k}$$

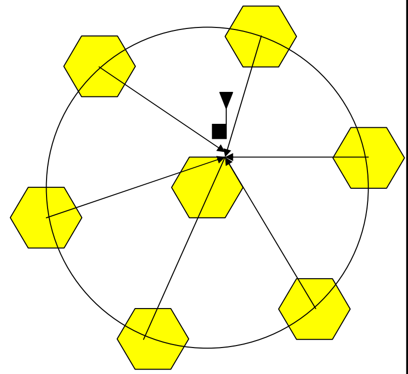


where S is the desired signal power (power received from the *home* basestation), and I is the total interference power

1^{st} Tier of Co-channel Interferers

- 6 interferers (downlink analysis)
- Each at distance of D/R = sqrt(3N)
- SIR is given by

$$\frac{S}{I} = \frac{S}{\sum_{k=1}^{6} I_k}$$



- But the power, P_r, received at a distance d is given by

$$P_r = \frac{P_0}{d^\alpha}$$

where α is the path-loss exponent

- Therefore the SIR is given by $\frac{S}{I} = \frac{1}{\sum_{k=1}^{6} \left(\frac{D_k}{R} \right)^{-\alpha}}$

1^{st} Tier of Co-channel Interferers – cont'd

- If we make the assumption that $D_k \approx D$ for all k, then SIR can be written as

$$\frac{S}{I} = \frac{1}{\sum_{k=1}^{6} (q)^{-\alpha}} = \frac{q^\alpha}{6}$$

Example 1:

- For AMPS (using analog FM) uses an SIR level of 18 dB. Calculate the reuse frequency factor – Assume a path-loss exponent of 4

- Solution: SIR = 18 dB or 63.1 (on the linear scale)

Using the previous equation, the reuse ratio is given by

$$q = 6\left(\frac{S}{I}\right)^{1/\alpha}$$

Or q = 4.41 and the reuse frequency factor N is given by

$$N = \frac{q^2}{3}$$

Or 6.49 ≈ 7

Example 2:

- Consider a cellular system with 395 total allocated voice channel frequencies. If the traffic is uniform with an average call holding time of 120 seconds and the call blocking during the system busy hour is 2%, calculate
  a) The number of calls per cell site per hour
  b) The mean SIR for cell reuse factors equal to 4, 7, and 12

  Assume omni-directional antennas with six interferers in the first tier and a slope for the path-loss of 40 dB/decade

Example 2: cont'd

- Solution:
  For a reuse factor of N = 4, the number of channels per cell is equal to 395/4 ≈ 99 channels

  Using Erlang's B formula (tables) for 99 channels and 2% blocking ➔ traffic load = 87 Erlangs

  $$\text{Since} \quad \frac{\text{No of calls per cell site per hour X 120}}{3{,}600} = 87$$

  therefore, the no of calls per cell site per hour = 87 X 30 = 2,610

  q = sqrt(3XN) = 3.5 and SIR = $q^{\alpha}/6$ = 25 or 14 dB

Example 2: cont'd

- Solution: cont'd
  Repeating the calculations for N = 7 and N = 12, we can write the following table

N	q	Voice Channels per Cell	Calls per Cell per Hour	Mean SIR (dB)
4	3.5	99	2610	14.0
7	4.6	56	1376	18.7
12	6.0	33	739	23.3

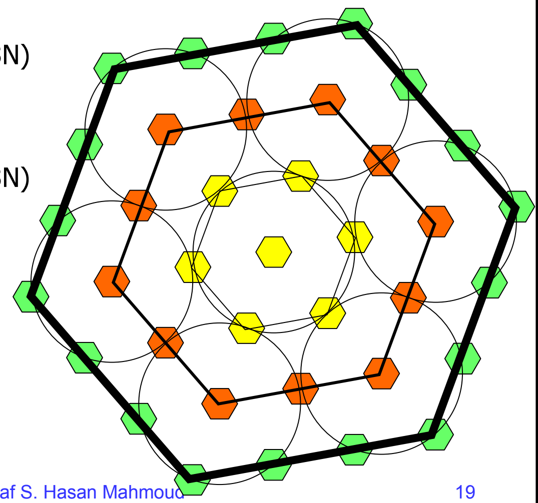
72% reduction

66.4% increase

You can note that by increasing N, the SIR is improving, however, the call capacity of the cell site is reduced!!

2^{nd}/3rd Tiers of Co-channel Interferers

- 2^{nd} tier of interferers:
  - 12 interferers
  - Each at distance 2Xsqrt(3N)
- 3^{rd} tier of interferers:
  - 18 interferers
  - Each at distance 3Xsqrt(3N)



Exercises

- Derive an expression for SIR taking into account the 2^{nd} tier of co-channel interferers – Quantify the effect on SIR value of adding the 2^{nd} tier to the formula
- Derive an expression for SIR taking into effect the interferences contributed by the first T (T = 1, 2, 3, and 4) tiers. – plot the SIR curves versus the path-loss exponent (let α range from 2 to 6 in steps of 0.2)

Worst Case Scenario

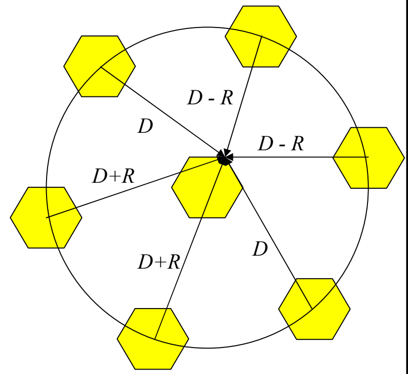
- Mobile of interest is at the edge of the cell
  - Distance of R from cell centre
- Distances from other interfering cells is as shown

$$\frac{S}{I} = \frac{R^{-\alpha}}{2(D-R)^{-\alpha} + 2D^{-\alpha} + 2(D+R)^{-\alpha}}$$

- Writing this in terms of the reuse ratio

$$\frac{S}{I} = \frac{1}{2\left[(q-1)^{-\alpha} + q^{-\alpha} + (q+1)^{-\alpha}\right]}$$

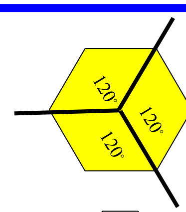
- Example: For AMPS: N = 7, a = 4, SIR using the above formula is 17.3 dB (lower than previously estimated)

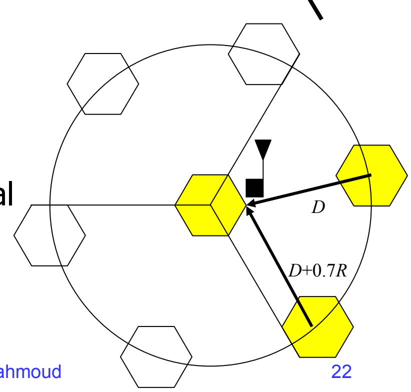


Directional Antennas

- 3 Sectors case
  - Each sector is assigned a set of channels
- No of interferers = 2 per sector
- SIR is given by $\frac{S}{I} = \frac{1}{q^{-\alpha} + (q+0.7)^{-\alpha}}$
- Example: For AMPS: N = 7, α = 4

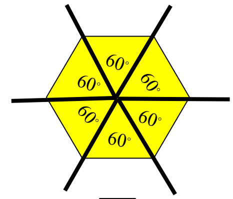
With 3 sectors per cell, SIR is equal to 24.5 dB (about 7 dBs higher the omni-directional case)





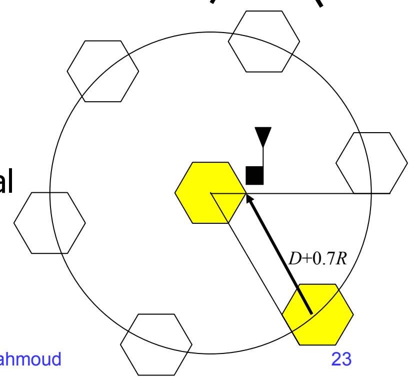
Directional Antennas – cont'd

- 6 Sectors case
  - Each sector is assigned a set of channels
- No of interferers = 1 per sector
- SIR is given by $\frac{S}{I} = \frac{1}{(q+0.7)^{-\alpha}}$



- Example: For AMPS: N = 7, α = 4

With 6 sectors per cell, SIR is equal to 29 dB (about 11 dBs higher the omni-directional case)



Erlang-B Model: Revisited

- Erlang-B formula (refer to notes given during second week of semester)

Erlang-B Tables (Sample)

P(B)= Trunks	0.01	0.015	0.02	0.03	0.05	0.07	0.1	0.2	0.5
l	0.010	0.015	0.020	0.031	0.053	0.075	0.111	0.250	1.000
2	0.153	0.190	0.223	0.282	0.381	0.471	0.595	1.000	2.732
3	0.455	0.536	0.603	0.715	0.899	1.057	1.271	1.930	4.591
4	0.870	0.992	1.092	1.259	1.526	1.748	2.045	2.944	6.501
5	1.361	1.524	1.657	1.877	2.219	2.504	2.881	4.010	8.437
6	1.913	2.114	2.277	2.544	2.961	3.305	3.758	5.108	10.389
7	2.503	2.743	2.936	3.250	3.738	4.139	4.666	6.229	12.351
8	3.129	3.405	3.627	3.987	4.543	4.999	5.597	7.369	14.318
9	3.783	4.095	4.345	4.748	5.370	5.879	6.546	8.521	16.293
10	4.462	4.808	5.084	5.529	6.216	6.776	7.511	9.684	18.271
11	5.160	5.539	5.842	6.328	7.076	7.687	8.487	10.857	20.253
12	5.876	6.287	6.615	7.141	7.950	8.610	9.477	12.036	22.237
13	6.607	7.049	7.402	7.967	8.835	9.543	10.472	13.222	24.223
14	7.352	7.824	8.200	8.803	9.730	10.485	11.475	14.412	26.211
15	8.108	8.610	9.010	9.650	10.633	11.437	12.485	15.608	28.200
16	8.875	9.406	9.828	10.505	11.544	12.393	13.501	16.807	30.190
17	9.652	10.211	10.656	11.368	12.465	13.355	14.523	18.010	32.181
18	10.450	11.024	11.491	12.245	13.389	14.323	15.549	19.215	34.173
19	11.241	11.854	12.341	13.120	14.318	15.296	16.580	20.424	36.166
20	12.041	12.680	13.188	14.002	15.252	16.273	17.614	21.635	38.159

Erlang-B Tables (Sample)

P(B)= Trunks	0.005	0.01	0.015	0.02	0.03	0.05	0.07	0.1
20	11.092	12.041	12.680	13.188	14.002	15.252	16.273	17.614
21	11.860	12.848	13.514	14.042	14.890	16.191	17.255	18.652
22	12.635	13.660	14.352	14.902	15.782	17.134	18.240	19.693
23	13.429	14.479	15.196	15.766	16.679	18.082	19.229	20.737
24	14.214	15.303	16.046	16.636	17.581	19.033	20.221	21.784
25	15.007	16.132	16.900	17.509	18.486	19.987	21.216	22.834
26	15.804	16.966	17.758	18.387	19.395	20.945	22.214	23.885
27	16.607	17.804	18.621	19.269	20.308	21.905	23.214	24.939
28	17.414	18.646	19.487	20.154	21.224	22.869	24.217	25.995
29	18.226	19.493	20.357	21.043	22.143	23.835	25.222	27.053
30	19.041	20.343	21.230	21.935	23.065	24.803	26.229	28.113
31	19.861	21.196	22.107	22.830	23.989	25.774	27.239	29.174
32	20.685	22.053	22.987	23.728	24.917	26.747	28.250	30.237
33	21.512	22.913	23.869	24.629	25.846	27.722	29.263	31.302
34	22.342	23.776	24.755	25.532	26.778	28.699	30.277	32.367
35	23.175	24.642	25.643	26.438	27.712	29.678	31.294	33.435
36	24.012	25.511	26.534	27.346	28.649	30.658	32.312	34.503
37	24.852	26.382	27.427	28.256	29.587	31.641	33.331	35.572
38	25.694	27.256	28.322	29.168	30.527	32.624	34.351	36.643
39	26.539	28.132	29.219	30.083	31.469	33.610	35.373	37.715

Example 3:

- Compare the spectral efficiency of the digital system (IS-54) with that of the analog system (AMPS) using the following data:
  - The total # of channels is 416
  - The # of control channels = 21 (i.e. 395 channels for voice)
  - The channel bandwidth is 30 kHz
  - The reuse factor, N = 7
  - The total available bandwidth for each direction = 12.5 MHz
  - Coverage area = 10,000 km2
  - The required SIR for AMPS = 18 dB (or 63.1)
  - The required SIR for IS-54 = 14 dB (or 25.1)
  - Call blocking = 2.5%

Example 3: cont'd

- **Solution:**

Analog System:
\# of voice channels per cell site = 395/7 = 56
The offered traffic load (using Erlang-B tables @ 2% blocking) = 45.6 Erlangs per cell site
The carried load = (1-2%)X45.6 = 44.98 Erlangs / cell site

$$\text{Spectral Efficiency} = \frac{\text{Carried Load X No of cell sites}}{\text{Total BW X Total Area}}$$

$$= \frac{44.98 \text{ X } (10{,}000/(2.6R^2))}{12.5 \text{ X } 10{,}000} = 1.384/R^2 \text{ Erlangs/Km}^2\text{/MHz}$$

Digital System:
\# of channels per 30 kHz = 3 → # of voice channels per cell site = 56X3 = 168
Offered traffic load = 154.5 Erlangs per cell site
Carried traffic load = (1-2%)X154.5 = 151.4 Erlangs per cell site

$$\text{Spectral Efficiency} = \frac{151.4 \text{ X } (10{,}000 /(2.6R^2))}{12.5 \text{ X } 10{,}000} = 7.386 /R^2 \text{ Erlangs/Km}^2\text{/MHz}$$

→ Relative (Digital to Analog) Efficiency = 7.386/1.384 = 5.34

Example 4:

- Consider a cellular system with 395 total allocated voice channels of 30 kHz each. The total available bandwidth in each direction is 12.5 MHz. The traffic is uniform with average call holding time of 120 seconds, and call blocking during the system busy hour is 2%. Calculate:
  a) The calls per cell site per hour
  b) The mean SIR
  c) The spectral efficiency in Erlangs/km^2/MHz
  d) The reuse factor, N = 7

For a cell reuse factor of N equal to 4, 7, and 12, respectively, and for omni-directional, 120°, and 60° systems, calculate the call capacity.

Plot spectral efficiency versus cell radius for N = 7 and comment on the results. Assume that there are 10 mobiles/km^2 with each mobile generating traffic of 0.02 Erlangs. The slope of path loss is α = 40 dB per decade

Example 4: cont'd

- **Solution**:

Considering the first tier of interferers – SIR is given by

Mean SIR = $1/\Sigma\,(q_i^{-\alpha})$ for all interfering ith co-channel, or

Mean SIR = $q^{-\alpha}/m$, assuming m co-channels all at distance D

In decibels,

Mean SIR = $\alpha 10$ log (sqrt(3N)) – 10 log m

where α is the path loss component, and

m is the number of interferers (m = 6, for omni- directional, m = 2 for 120°, and m = 1 for 60°)

The traffic per cell site = V X t X Ac

where V = no of mobile per km^2

t = traffic in Erlangs per mobile

Ac = area of cell = $2.6R^2$

➔ Therefore traffic per cell site = $10X0.02X2.6R^2 = 0.52\ R^2$

Example 4: cont'd

- **Solution**:cont'd

$$\text{The spectral efficiency} = \frac{\text{Traffic carried per cell X Nc}}{\text{Total BW X Total Area}}$$

$$= \frac{\text{Traffic carried per cell}}{\text{Total BW X } 2.6\, R^2}$$

For N = 7 and 120° sectorized cell site:
No of voice channels per sector = 395/(7X3) = 19
Offered traffic per sector = 12.3 Erlangs or 36.9 Erlangs per cell site
Carried traffic per cell site = (1-0.02)X36.9 = 36.2 Erlangs

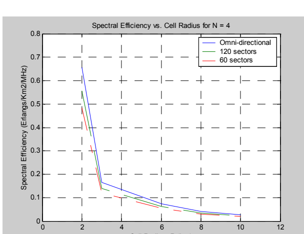
But carried traffic = No of calls per cell site per hour X 120/3600
➔ No of calls per cell site per hour = 1,086
➔ Cell radius R =sqrt(36.2/0.52) = 8.3 km
Spectral efficiency = 36.2/(2.6R^2 X 12.5) = 0.0162 Erlangs/km^2/MHz
Mean SIR = 40log sqrt(3X7) – 10log 2 = 23.43 dB

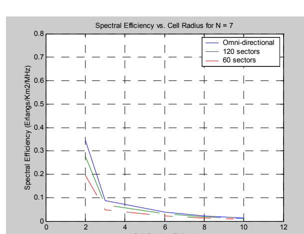
Example 4: cont'd

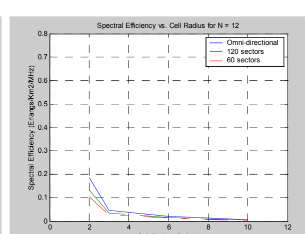
- **Solution**:cont'd

The previous calculations can be repeated for all other combinations (N, no of sectors)
Comments:

1. Sectorization reduces co-channel interference and improves mean SIR for a given N. However it reduces trunking efficiency since available channels per sector are fewer. As a result spectral efficiency is lower if N is kept fixed
2. Since a sectorized cellular system has fewer co-channel interferers it is possible to reduce cluster size (N) and hence improve the spectrum efficiency of the overall system
3. If an SIR of 18 dB is required for AMPS to work properly, this can be provided by (N, S) = (7,1), (4, 3), or (3, 6)



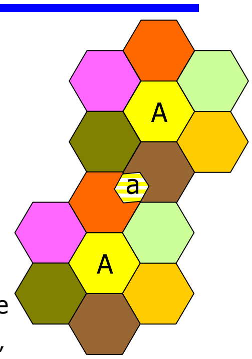




Capacity Expansion Techniques

- Use of Directional Antennas (refer to previous slides)
- Cell Splitting
- Lee's Mircocell Method
- Overlaid Cells
- Use of Smart Antennas

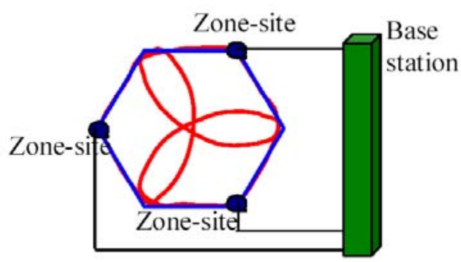
Cell Splitting



- Splitting cells into smaller cells and allowing additional channels in the smaller cells:
  - A smaller cell "a" is introduced – half the area of the original cell
  - Channels used in cells "A" are reused in "a" to minimize interference
- Problems & solutions:
  - If the transmit power of "a" is the same as other BSs
  - "a" point of view: SIR is maintained
  - "A" point of view: SIR is increased (reuse distance is decreased by half)
    - Solution1: reduce the power of "a" but SIR for "a" increases!
    - Solution2: channels used within "a" are used in "A" only at distances of less than R/2 ➔ Overlaid cell concept
- Downside of cell splitting:
  - Reduced capacity of the bigger cell
  - Increased handoffs

Lee’s Microcell Method

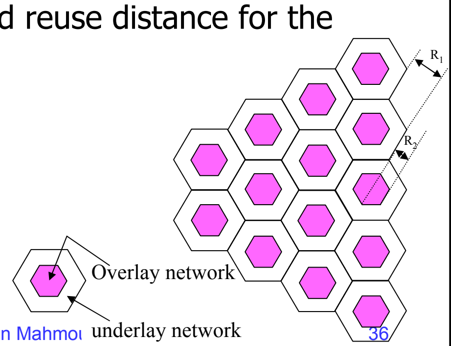
- Use of direct sectorization leads to reduced truncking efficiency since channels are partitions between different sectors
  - Leads to increased handoffs too
- Lee’s microcell:
  - One BS but three zone-sites located at the corners of the cells
  - All three zone-sites act as receivers
  - ONLY one zone-site transmits to the mobile (the BS chooses the one which has best reception from mobile) ➔ LOW interference
- Cluster size can be reduced to 3 from 7 ➔ Capacity increase of 2.33



Check the example 5.12 in the book [Pahlavan]

Using Overlaid Cells

- Channels are divided among a larger macrocell that exists with a smaller microcell contained entirely within the macrocell
- Same BS serves both macro- and microcells
- R1 and D1 are the radius and reuse distance for the macrocells
- R2 and D2 are the radius and reuse distance for the microcells
- By design: $D_2/R_2 > D_1/R_1$ ➔ $SIR_{microcells} > SIR_{macrocells}$
- Use this increase in system SIR in gaining capacity (e.g. reducing BW requirement)



Using Overlaid Cells - Example

- AMPS - underlay network:
  - Channel = 30 kHz, SIR requirement = 18 dB
- AMPS – overlay network:
  - Channel = 15 kHz, SIR requirement = 24 dB
- From the layout:

$$10\log\frac{\left(D_2/R_2\right)^4}{\left(D_1/R_1\right)^4}=6 \text{ dB}$$

If N = 7 and $D_1 = D_2$ ➔ R_2 = 1/sqrt(2) R_1
Therefore, the area for the microcell, A_2, is half of the area for the macrocell, A_1
➔ A_2 and A_1-A_2 are equal

Let M be the no of channel available to the overlay and underlay cells, therefore 15kHzXM + 30kHzXM = total traffic BW of AMPS = 395X30kHz ➔ M = 263

Hence, for a full hexagonal cell, the number of available channels is equal to 2XM/N = 526/N or 526/395 134% more channels compared to the non-overlaid network

Reuse Partitioning

- Channels are devided among larger macrocells and smaller microcells
- BW in both cells remains the same
- Since R_2 (radius for microcells) is less than R_1 (radius for macrocells) ➔ Received signal is better (for the same tx cell site power) ➔ microcells has lower co-channel interference level
- Therefore microcells can employ a smaller frequency reuse factor
- Complexity of BS - handoffs

Reuse Partitioning - Example

- Uderlay-network: N1 = 7 ➔ D1/R1 = 4.6 (provides the required SIR = 18 dB)
- For the overlay network, if we deploy N2 = 3, then D2 = 3 R1 (from geometry)
- But to maintain the required SIR, D2/R2 should equal to 4.6, or 3R1/R2 = 4.6 ➔ R2 = 0.652 R1
- Distributing the total channels, Nc = 395, according to area, then the L channels per cell site is given by

  $Nc = 7X(1-0.652^2)XL + 3X0.652^2XL$ ➔ L = 75
- Overlay cell uses = 32 channels while the underlay cell uses = 43 channels
- Original AMPS provides Nc/7 = 56 channels per cell site ➔ New capacity = 75/56 = 134%

Smart Antenna

- Users can use same physical channel as long as they are not located in the same region with respect to the BS – referred to as space-division multiple access (SDMA)
- A narrow antenna beam is directed towards the mobile of interest
- Co-channel interference is greatly reduced ➔ reduced frequency factor ➔ increased capacity
- Example:
  - FH-GSM study reported new capacity = 300%
  - CDMA study reported new capacity = 500%

Cellular Concept

References:

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