EEG473 Mobile Communications
Module 2 : Week # (6)

The Cellular Concept –
System Design Fundamentals

Interference and System Capacity

- Interference is <u>the major limiting factor</u> in the performance of cellular radio systems. It is **a major bottleneck in increasing capacity** and is often responsible for dropped calls.

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

- Interference **<u>on voice channels</u>** causes **cross talk**, where **the subscriber hears interference in the background due to an undesired transmission.**

- **<u>On control channels</u>**, **interference leads to missed and blocked calls due to errors** in the digital signaling.

Sources of interference

1. <u>Another mobile</u> in the same cell,

2. A call in progress <u>in a neighboring cell</u>,

3. <u>Any non-cellular system</u> which inadvertently <u>leaks energy into the cellular frequency band.</u>

4. <u>Other base stations operating in the same frequency</u> band. (In practice, the transmitters from competing cellular carriers are often a significant source of out-of-band interference, since competitors often locate their base stations in close proximity to one another in order to provide comparable coverage to customers.)

The two major types of cellular system interference:

1. Co-channel interference

2. Adjacent channel interference.

1. Co-channel Interference

- **Co-channel cells:** cells that use the same set of frequencies in a coverage area (Frequency reuse concept)

- **Co-channel interference:** The interference between signals from co-channel cells.

- Unlike thermal noise which can be overcome by increasing the signal-to- noise ration (SNR), **co-channel interference cannot be combated by simply increasing the carrier power of a transmitter.**

- This is because an increase in carrier transmit power increases the interference to neighboring co-channel cells.

- **To reduce co-channel interference, co-channel cells <u>must be physically separated by a minimum distance to provide sufficient isolation due to propagation.</u>**

(**When** the **size of each cell is the same**, and **the BSs transmit the same power**.)
The co-channel interference ratio depends on:

- **The radius of the cell (R)**
- **The distance between centers of the nearest co-channel cells (D).**

- **Q = D/R = co channel reuse ratio = the spatial separation between co-channel cells relative to the coverage distance of a cell**.

- Interference is **reduced when Q is increased** (improved isolation of RF energy from the co-channel cell).

- *Q* is related to the **cluster size(N)** **for a hexagonal geometry**

$$Q = \frac{D}{R} = \sqrt{3N}$$

For a hexagon we can define both an inner radius and an outer radius. Both are useful.
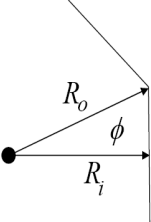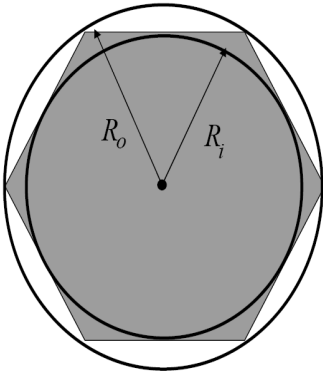
$$R_i = R_o \cos\phi = R_o \cos\frac{2\pi}{12} = R_o \frac{\sqrt{3}}{2}$$

Note that a hexagon has 6 faces or, equivalently, 12 "half-faces."

19-cell reuse example (N=19)

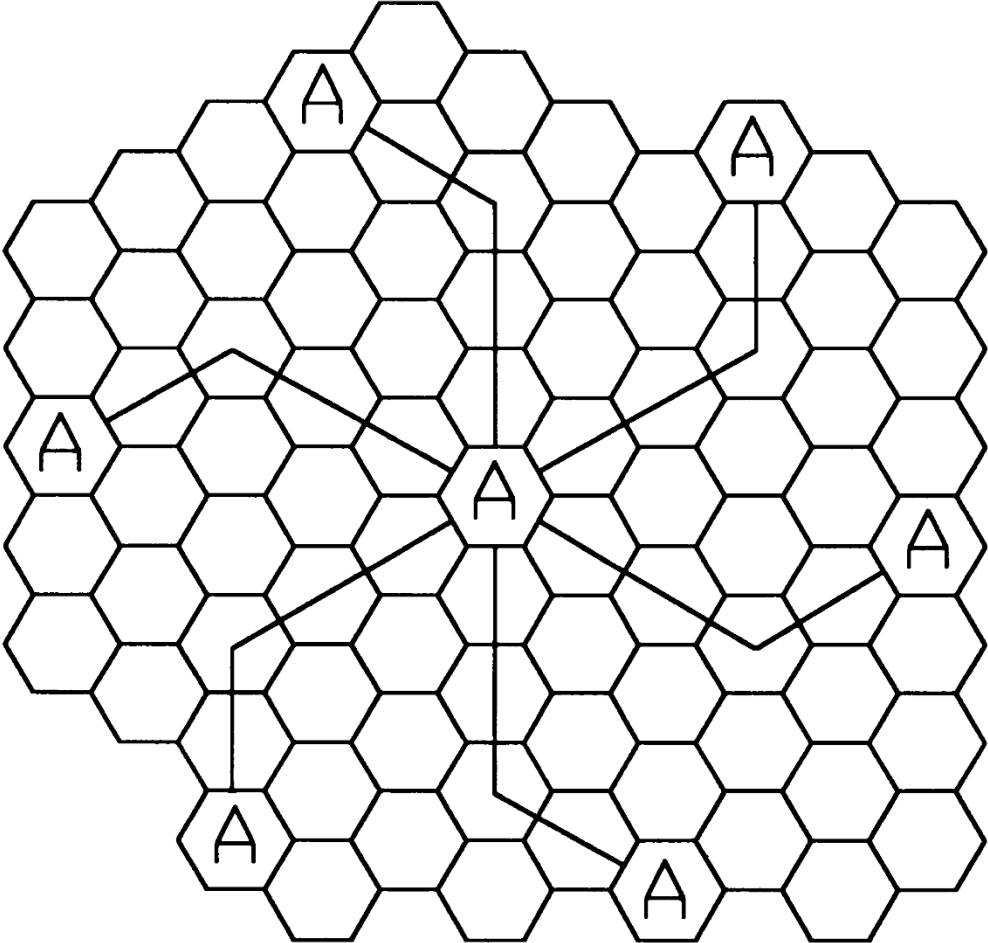**i= 3 and j = 2 (example, N = 19).**

Figure 3.2 Method of locating co-channel cells in a cellular system. In this example, $N = 19$ (i.e., $I = 3, j = 2$). (Adapted from [Oet83] © IEEE.)

$$C = MS = MkN$$

• **A large cluster size** (N) indicates that <u>the ratio between the cell radius and the distance between co-channel cells is large</u>.

• Conversely, **a small cluster size** (N) indicates that <u>co-channel cells are located much closer together</u>.

• **The value for N** is a function of **how much interference** a mobile or base station can tolerate while maintaining a sufficient quality of communications.

• From a design viewpoint, the smallest possible value of N is desirable in order to maximize "C".

• The **frequency reuse factor** of a cellular system is given by **1 /N,** since each cell within a cluster is only assigned 1/N of the total available channels in the system.

$$Q = \frac{D}{R} = \sqrt{3\tilde{N}}$$

A small value of Q provides larger capacity since the cluster size N is small.
(Smaller N is greater capacity)

A large value of Q higher transmission quality **(less co-channel interference)**

A trade-off must be made between these two objectives in actual cellular design.

Table 3.1 Co-channel Reuse Ratio for Some Values of N

	Cluster Size (N)	Co-channel Reuse Ratio (Q)
$i = 1, j = 1$	3	3
$i = 1, j = 2$	7	4.58
$i = 2, j = 2$	12	6
$i = 1, j = 3$	13	6.24

The signal-to-interference ratio **(S/I or SIR)** for a mobile receiver which monitors a forward channel =

$$\frac{S}{I} = \frac{S}{\sum_{i=1}^{i_0} I_i}$$

S : the desired signal power from the desired base station

I_i : the interference power caused by the ith interfering co-channel cell base station.

i_0 : the number of co-channel interfering cells.

The average received signal strength at any point decays as a power law of the distance of separation between a transmitter and receiver. (Propagation measurements)

The average received power (Pr) at a distance (d) => R from the transmitting antenna is approximated by

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

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

where
(P_0) is the power received at a close-in reference point in the far field region of the antenna at a small distance (d_0) from the transmitting antenna, and (n) is the path loss exponent. (The path loss exponent typically ranges between 2 and 4 in urban cellular systems.)

Assume:

- **<u>the forward link</u>** where the desired signal is the serving base station and where the interference is due to co-channel base stations.
- The transmit power of each base station is equal
- The path loss exponent is the same throughout the coverage area,
- **S/I for a mobile can be approximated as**

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

D_i is the distance of the ith interferer from the mobile, **I_i will be proportional to $(D_i)^{-n}$**

Considering only the first layer of interfering cells, if all the interfering base stations are equi-distant from the desired base station and if this distance is equal to the distance D between cell centers, then:

$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0}$$

relates S/I to the cluster size N, also, overall capacity of the system can be obtained from N $C = MkN = MS$

For Example: the **U.S. AMPS cellular system** which uses FM and 30 kHz channels, subjective tests indicate that sufficient voice quality is provided when **S/I is greater than or equal to 18 dB.**

the six closest cells are close enough to create significant interference. assuming a path loss exponent $n = 4$.

Then, the cluster size N should be at least 6.49, (Thus a minimum cluster size of 7)

Co-channel cells for 7-cell reuse
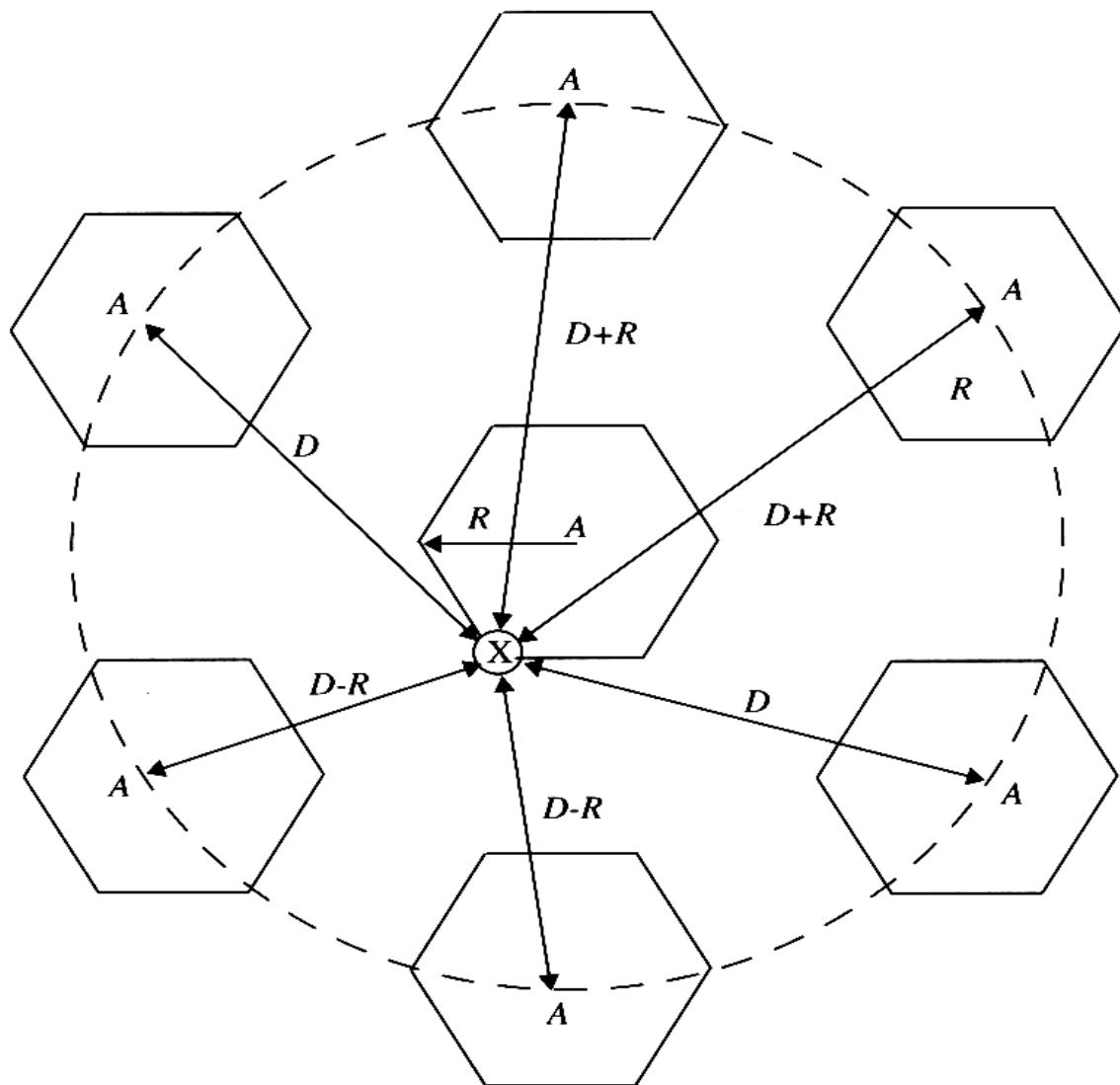
Figure 3.5 Illustration of the first tier of co-channel cells for a cluster size of $N = 7$. An approximation of the exact geometry is shown here, whereas the exact geometry is given in [Lee86]. When the mobile is at the cell boundary (point X), it experiences worst case co-channel interference on the forward channel. The marked distances between the mobile and different co-channel cells are based on approximations made for easy analysis.

- From the previous figure, it can be seen for a 7-cell cluster, with the mobile unit is at the cell boundary, the mobile is a distance

- **D-R** from the two nearest co-channel interfering cells

- approximately: **D + R/2, D, D - R/2, D + R** from the other interfering cells in the first tier.

- Assume n=4, the signal-to-interference ratio for the worst case can be closely approximated as (an exact expression is worked out by

$$\frac{S}{I} = \frac{R^{-4}}{2(D-R)^{-4} + 2(D+R)^{-4} + 2D^{-4}}$$

- Equation (2.10) can be rewritten in terms of the co-channel reuse ratio Q, as

$$\frac{S}{I} = \frac{1}{2(Q-1)^{-4} + 2(Q+1)^{-4} + 2Q^{-4}}$$

For N = 7, the co-channel reuse ratio Q is 4.6, and the worst case S/I is approximated as 49.56 (**17 dB**) using equation (2.11), whereas an exact solution using equation (2.8) yields **17.8 dB**.

Hence for **a 7-cell cluster**, the S/I ratio is **slightly less than 18 dB** for the worst case. To design the cellular system for proper performance in the worst case , it would be necessary to **increase N to the next largest size**, which from equation (2.3) is found to be **12 (corresponding to i = j = 2).**

This obviously entails a significant decrease in capacity, since 12- cell reuse offers a spectrum utilization of 1/12 within each cell, whereas 7-cell reuse offers a spectrum utilization of 1/7. In practice, a capacity reduction of 7/12 would not be tolerable to accommodate for the worst case situation which rarely occurs. **From the above discussion it is clear that co-channel interference determines link performance, which in turn dictates the frequency reuse plan and the overall capacity of cellular systems**.

Example 2.2

If a signal to interference ratio of 15 dB is required for satisfactory forward channel performance of a cellular system, what is the frequency reuse factor and cluster size that should be used for maximum capacity if the path loss exponent is (a) $n = 4$, (b) $n = 3$? Assume that there are 6 co-channels cells in the first tier, and all of them are at the same distance from the mobile. Use suitable approximations.

Solution to Example 2.2

$$Q = \frac{D}{R} = \sqrt{3N}$$

$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0}$$

(a) $n = 4$

First, let us consider a 7-cell reuse pattern.

Using equation (2.4), the co-channel reuse ratio $D/R = 4.583$.

Using equation (2.9), the signal-to-noise interference ratio is given by

$$S/I = (1/6) \times (4.583)^4 = 75.3 = 18.66 \text{ dB}.$$

Since this is greater than the minimum required S/I, $N = 7$ can be used.

b) $n = 3$

First, let us consider a 7-cell reuse pattern.

Using equation (2.9), the signal-to-interference ratio is given by

$$S/I = (1/6) \times (4.583)^3 = 16.04 = 12.05 \text{ dB}.$$

Since this is less than the minimum required S/I, we need to use a larger N.

Using equation (2.3), the next possible value of N is 12, $(i = j = 2)$.
The corresponding co-channel ratio is given by equation (2.4) as

$$D/R = 6.0.$$

Using equation (2.3) the signal-to-interference ratio is given by

$$S/I = (1/6) \times (6)^3 = 36 = 15.56 \text{ dB}.$$

Since this is greater than the minimum required S/I, $N = 12$ can be used.

2. Adjacent Channel Interference

- Adjacent channel interference: Interference resulting from signals which are **adjacent in frequency** to the desired signal

- Results from **imperfect receiver filters** which allow nearby frequencies to leak into the passband.

- The problem can be particularly serious with **the near-far effect**.

- The base station may have difficulty in discriminating the desired mobile user from the "bleedover" caused by the close adjacent channel mobile.

- Adjacent channel interference can be minimized through **<u>careful filtering</u>** and <u>**channel assignments**</u>.

- Since each cell is given only a fraction of the available channels, **<u>a cell need not be assigned channels which are all adjacent in frequency.</u>** (By keeping the frequency separation between each channel in a given cell as large as possible)

- **<u>If the frequency reuse factor is small</u>**, the separation between adjacent channels <u>may not be sufficient</u> to keep the adjacent channel interference level within tolerable limits.

- For example, **if a mobile is 20 times as close to the base station as another mobile** and has energy spill out of its passband, the signal-to- interference ratio for the weak mobile (before receiver filtering) is approximately

$$\frac{S}{I} = (20)^{-n}$$

For a path loss exponent n = 4, this is equal to 52 dB. If the intermediate frequency (IF) filter of the base station receiver has a slope of 20 dB/octave,

then an adjacent channel interferer must be displaced by **at least six times** the pass-band bandwidth from the center of the receiver frequency passband **to achieve 52 dB attenuation.** Here, a **separation** of **approximately six channel bandwidths** is required for typical filters in **order to provide 0 dB SIR** from a close-in adjacent channel user.

This implies that a channel separation greater than six is needed to bring the adjacent channel interference to an acceptable level, or tighter base station filters are needed when close-in and distant users share the same cell.

Anti-Aliasing Filter (AAF) Design

AAA: anti aliasing attenuation
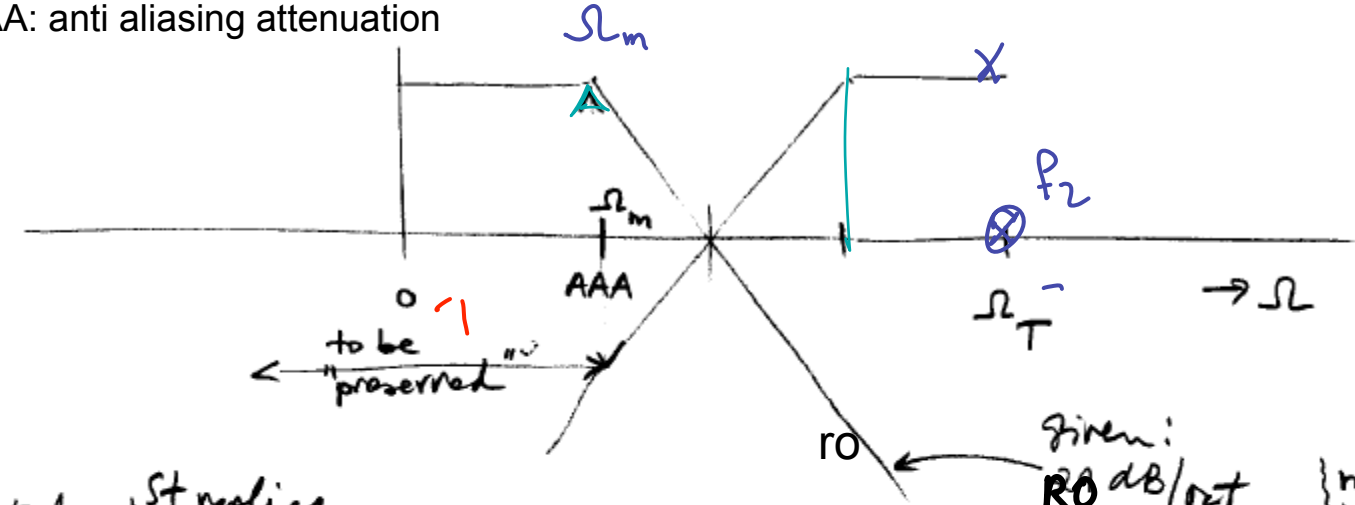
only 1ˢᵗ replica

$$AAA = \cancel{X} \, dB$$

given:
RO dB/oct } not inexpensive!
} less stable!
↑ doubling in frequency

$$\Rightarrow \text{from } \Omega_m \text{ to } \Omega_T - \Omega_m \text{ we need } \cancel{\text{XXX}} \; AAA \, dB$$

@ $RO \, dB/oct$ we need 2 octaves

$$\Omega_m \rightarrow 2\Omega_m \rightarrow 4\Omega_m \leq \frac{\Omega_T}{T} - \Omega_m$$

oct 1   oct 2

$$\frac{\Omega}{T} \geq 5\Omega_m$$
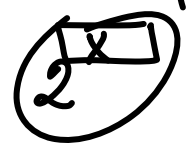
⇒ determines needed filter

OR

⇒ determines Ω_T

@ RO dB/oct we need $\frac{AAA}{RO}$ octaves

(1) $f_1 \longrightarrow 2f_1$

(2) $\longrightarrow 4f_1$

(3) $\longrightarrow 8f_1$

$\boxed{2}^{\times}$

$$\boxed{2^{AAA/RO} \Omega_m \leq \Omega_T - \Omega_m}$$

$$\Omega_T \geq \left(2^{AAA/RO} + 1\right) \Omega_m$$

$RO = 20 \, dB/oct \rightarrow \frac{5\Omega}{20} = 2.6 > \Omega_T \geq (2^{2.6} + 1) \Omega_m = \cancel{259} \, 7 \, \Omega_m$

$\underline{\text{"inexpensive"}}$

$$\boxed{\Omega_T = 7 \Omega_m}$$

Ω_m

$52dB$

AAA

$20 \, dB/oct$

Ω_T

$$\boxed{\text{separation} = 6\Omega_m}$$
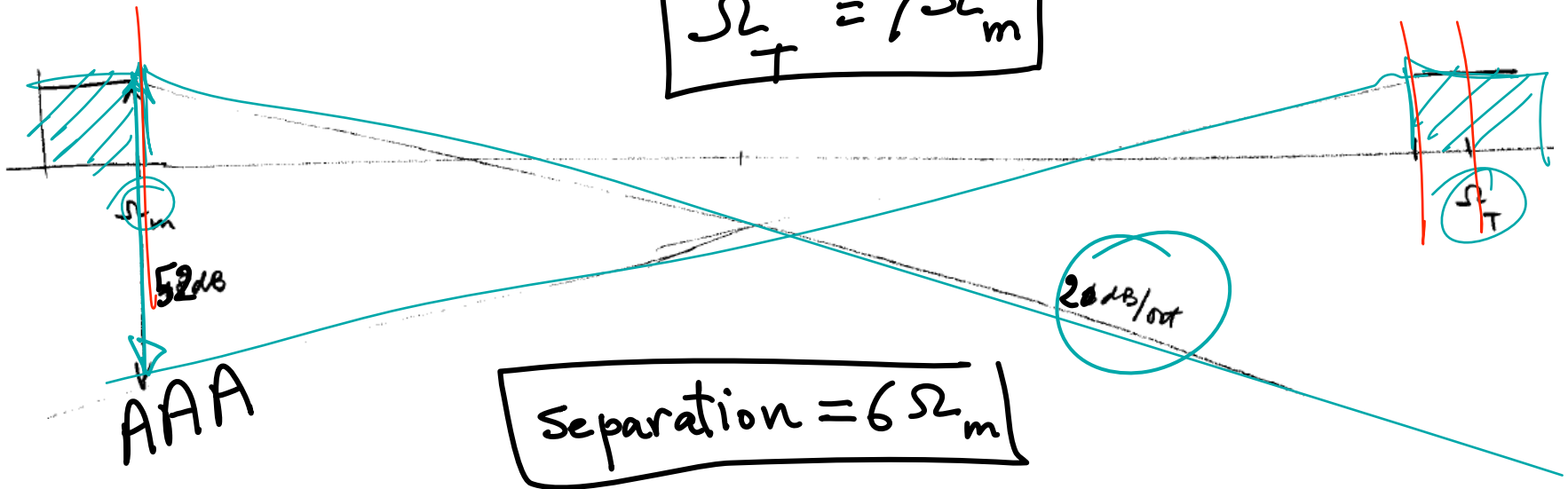
Example 2.3

This example illustrates how channels are divided into subsets and allocated to different cells so that adjacent channel interference is minimized.

The United States AMPS system initially operated with **666 duplex channels**, **166 new channels**, **now 832 channels used** in **AMPS**.

The forward channel **(870.030 MHz)** along with the corresponding reverse channel **(825.030 MHz)** is numbered as **channel 1**.

Similarly the forward channel **889.98 MHz** along with the reverse channel **844.98 MHz** is numbered as **channel 666** (see Figure 1.2).

The extended band has channels numbered as **667 through 799, and 990 through 1023.**
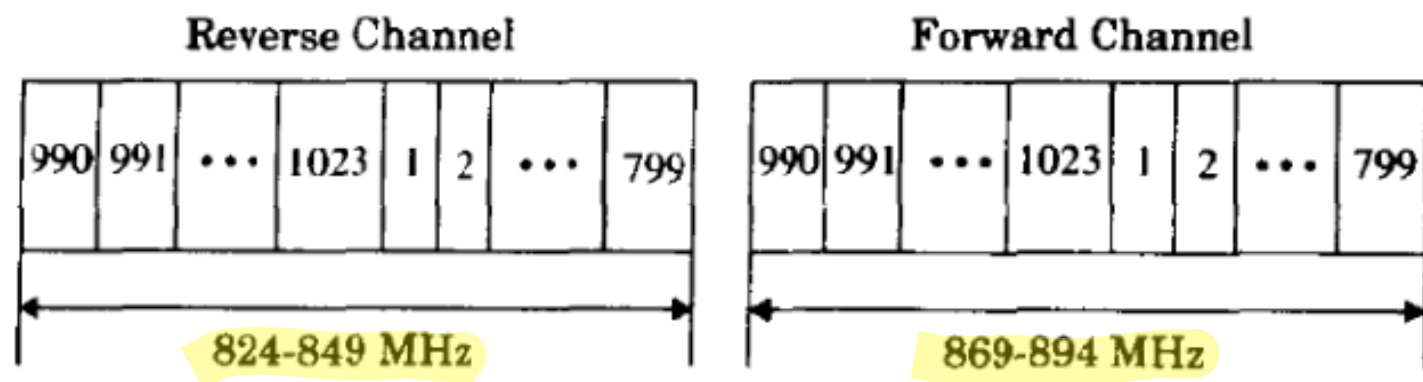
	Channel Number	Center Frequency (MHz)
Reverse Channel	$1 \leq N \leq 799$	$0.030N + 825.0$
	$990 \leq N \leq 1023$	$0.030(N - 1023) + 825.0$
Forward Channel	$1 \leq N \leq 799$	$0.030N + 870.0$
	$990 \leq N \leq 1023$	$0.030(N - 1023) + 870.0$

(Channels 800 - 989 are unused)

Figure 1.2

Frequency spectrum allocation for the U.S. cellular radio service. Identically labeled channels in the two bands form a forward and reverse channel pair used for duplex communication between the base station and mobile. Note that the forward and reverse channels in each pair are separated by 45 MHz.

- **two competing operators in every service area**: each operator received half of the total channels.

- Out of the **416 channels** used by each operator, **395** are voice channels and the remaining **21** are control channels.

- Channels **1** through **312** (voice channels) and channels **313** through **333** (control channels) **are block A channels,** and channels **334** through **354** (control channels) and channels **355** through **666** (voice channels) are **block B channels**.

- Channels **667** through **716** and **991** through **1023** are the extended **Block A** voice channels, and channels **717** through **799** are extended **Block B** voice channels.

- Each of the **395 voice channels** are divided into **21 subsets**, each containing about **19 channels**. In each subset, the closest adjacent channel is **21 channels** away. 19×21

- In a **7-cell reuse system**, each cell uses **3 subsets of channels**. The 3 subsets are assigned such that every channel in the cell is assured of being separated from every other channel by <mark>**at least 7 channel spacings.**</mark>

- This channel assignment scheme is illustrated in Table 2.2. As seen in Table 2.2, each cell uses channels in the subsets, **iA + iB + iC**, where **i** is an integer from **1 to 7**.

- The total number of voice channels in a cell is about **57**. The channels **listed in the upper half of the chart belong to block A and those in the lower half belong to block B.**

- The shaded set of numbers correspond to the control channels which are standard to all cellular systems in North America.

AMPS Duopoly Channels

Table 3.2 AMPS Channel Allocation for A and B Side Carriers

1A	2A	3A	4A	5A	6A	7A	1B	2B	3B	4B	5B	6B	7B	1C	2C	3C	4C	5C	6C	7C
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63
64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84
85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105
106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126
127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147
148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168
169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189
190	191	192	193	194	195	196	197	198	199	20	201	202	203	204	205	206	207	208	209	210
211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231
232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252
253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273
274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294
295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	-	-	-
313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	667	668	669
670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690
691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711
712	713	714	715	716	-	-	-	-	991	992	993	994	995	996	997	998	999	1000	1001	1002
1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023
334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354
355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375
376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396
397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417
418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438
439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459
460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480
481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501
502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522
523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543
544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564
565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585
586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606
607	608	609	610	611	6612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627
628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648
649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	-	-	-
-	-	-	-	-	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732
733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753
754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774
775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795
796	797	798	799																	

A SIDE (rows 1–1023)

B SIDE (rows 334–799)

2.5.3 Power Control for Reducing Interference

- In practical cellular radio and personal communication systems the power levels transmitted by every subscriber unit **are under constant control** by the serving base stations.

- This is done to ensure that each **mobile transmits the smallest power** necessary to maintain a good quality link on the reverse channel.

- Power control not only helps (1) **prolong battery life** for the subscriber unit, but also (2) **dramatically reduces the reverse channel S/I in the system**.

- Power control is especially important for emerging CDMA spread spectrum systems that allow every user in every cell to share the same radio channel.

Home work # (3)

- Prove that : Q=sqrt(3N) for hexagonal cells. (bonus)

- Solve Question # 3.5   (Rappaport book)