Wireless Communication

Chapter 3

The Cellular Concept –

System Design Fundamentals

3.1 Introduction

- The design objective of early mobile radio systems was to achieve a large coverage area by using a single, high powered transmitter with an antenna mounted on a tall tower.
- This meant that it was impossible to reuse those same frequencies throughout the system.

- The cellular concept was a major breakthrough in solving the problem of spectral congestion and user capacity.

- It enables a fixed number of channels to serve an arbitrarily large number of subscribers by reusing the channels throughout the coverage region.

3.2 Frequency Reuse

- Cellular radio systems rely on an intelligent allocation and reuse of channels throughout a coverage region.
- cell – allocated a group of radio channels.
- frequency reuse or frequency planning.
- center-excited cells or edge-excited cells.
- If each cell is allocated a group of k channels, and if the S channels are divided among N cells into unique and disjoint channel groups, the total number of available radio channels can be expressed as

$$S = kN$$

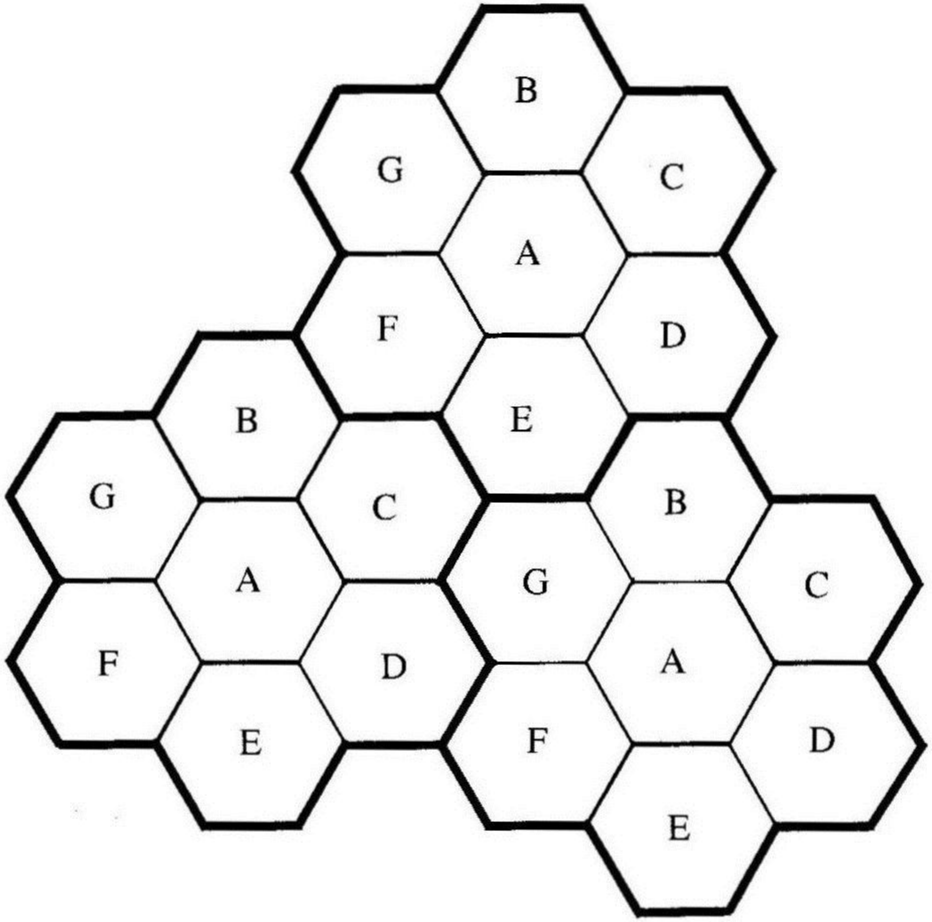


Figure 3.1 Illustration of the cellular frequency reuse concept. Cells with the same letter use the same set of frequencies. A cell cluster is outlined in bold and replicated over the coverage area. In this example, the cluster size, *N*, is equal to seven, and the frequency reuse factor is 1/7 since each cell contains one-seventh of the total number of available channels.

- The N cells which collectively use the complete set of available frequencies is called a cluster.
- If a cluster is replicated M times within the system, the total number of duplex channels C (or capacity) is given by

$$C = MkN = MS$$

- The factor of N is called the cluster size and is typically equal to 4, 7, or 12.
- The frequency reuse factor of a cellular system is given by $1/N$.

- N can only have values which satisfy Equation

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

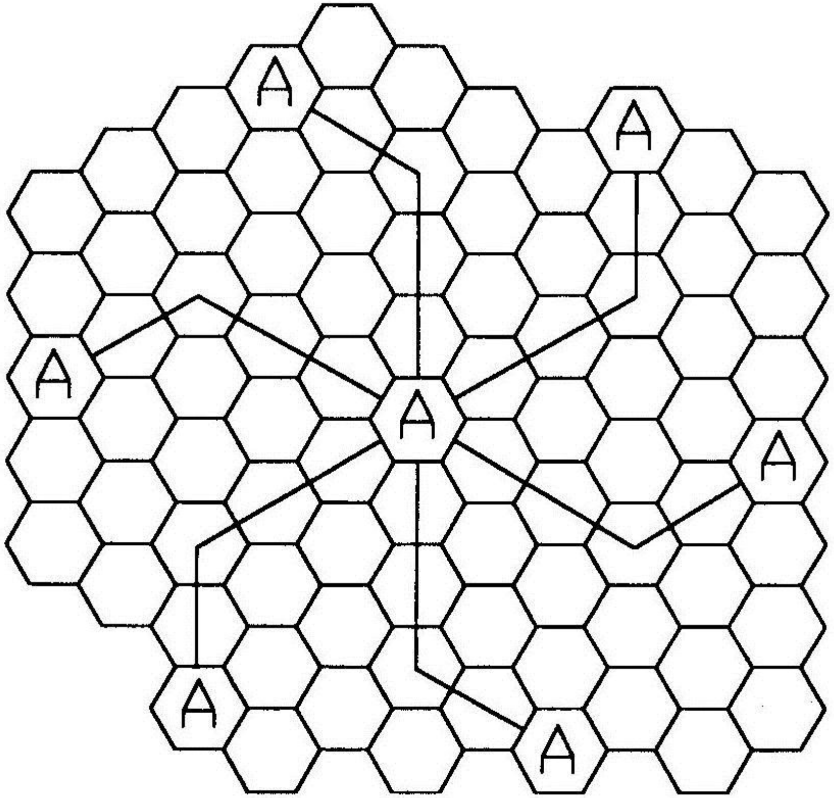


Figure 3.2 Method of locating co-channel cells in a cellular system. In this example, $N = 19$ (i.e., $i = 3$, $j = 2$). (Adapted from [Oet83] © IEEE.)

- Finding the nearest co-channel neighbors of a particular cell
  (a) move *i* cells along any chain of hexagons and then
  (b) Turn 60 degrees counter-clockwise and move *j* cells.

Example 3.1

If a total of 33 MHz of bandwidth is allocated to particular FDD cellular telephone system which uses two 25 kHz simplex channels to provide full duplex voice and control channels, compute the number of channels available per cell if a system uses (a) four-cell reuse, (b) seven-cell reuse, and (c) 12-cell reuse. If 1 MHz of the allocated spectrum is dedicated to control channels, determine an equitable distribution of control channels and voice channels in each cell for each of the three systems.

Solution :

Total bandwidth = 33 MHz

Channel bandwidth = 25 kHz *2 simplex channels = 50 kHz

Total available channels = 33000/50 = 660 channels.

(a) $N = 4$, $660/4 = 165$

(b) $N=7$, $660/7 \approx 95$

(c) $N=12$, $660/12 \approx 55$

In practice, the control channel are allocated separately as 1 per cell

3.3 Channel Assignment Strategies

- The objectives of channel assignment strategies are to increase capacity and minimize interference.
- Channel assignment strategies are classified as either fixed and dynamic.
- In a fixed channel assignment strategy, each cell is allocated a predetermined set of voice channel.

If all the channels in that cell are occupied, the call is blocked.

A variation is the borrowing strategy.

- In a dynamic channel strategy, voice channels are not allocated to different cells permanently.

  This strategy reduces the likelihood of blocking.

  Mobile switching center (MSC) must collect real-time data on channel occupancy, traffic distribution, and radio signal strength indications (RSSI) of all channels.

3.4 Handoff Strategies

- When a mobile moves into a different cell while a conversation is in progress, the MSC automatically transfers the call to a new channel belonging to the new base station – involving
  - (1) indentifying a new base station and
  - (2) allocating channels associated with the new base station.

- Handoff –
  - high priority over call initiation requests
  - must be performed successfully
  - Infrequently
  - be imperceptible.
- The margin $\Delta = P_{r\,\text{handoff}} - P_{r\,\text{minimum usable}}$ cannot be too large or too small.

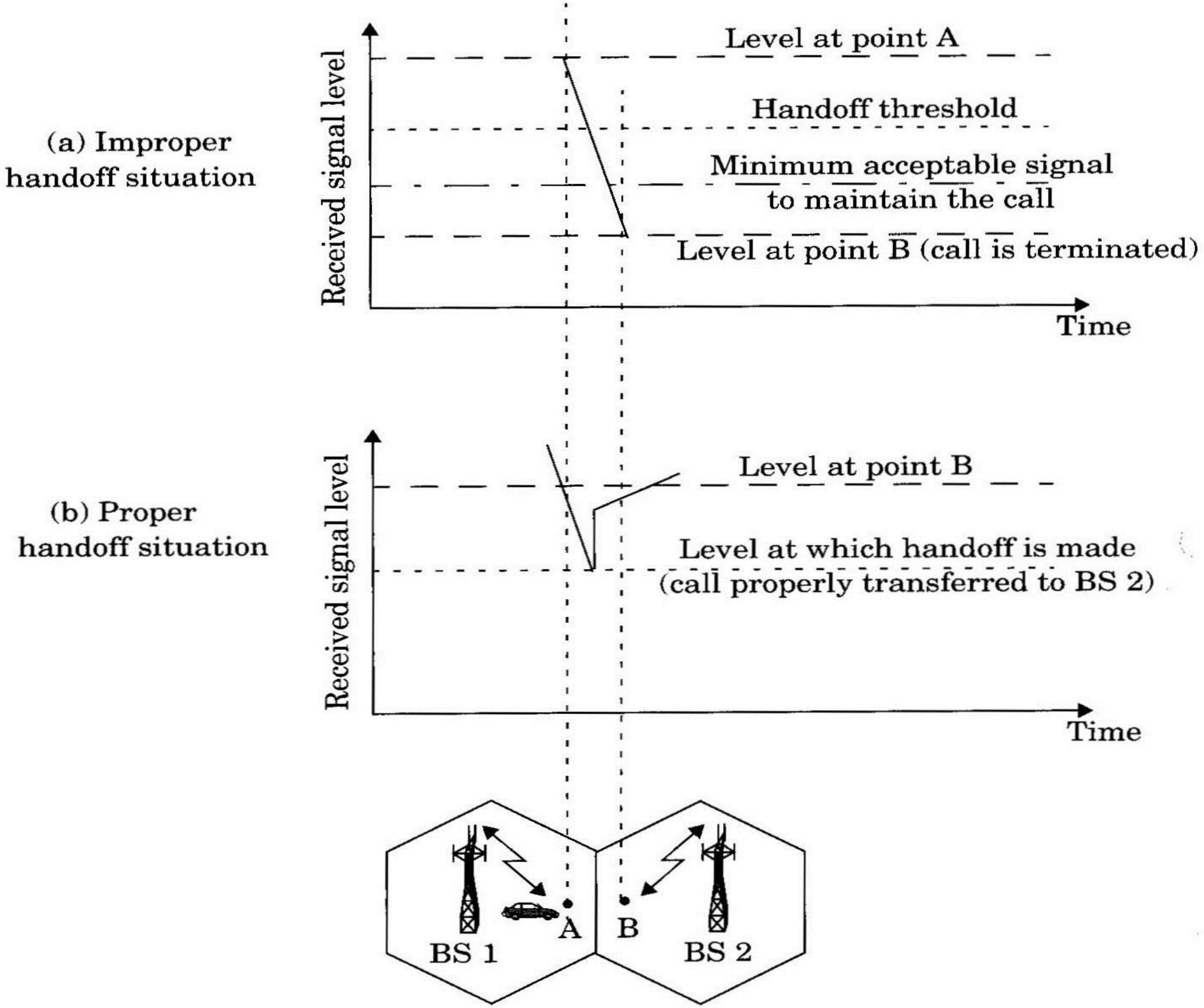


Figure 3.3 Illustration of a handoff scenario at cell boundary.

- In deciding when to handoff, it is important to ensure that the drop in the measured signal level is not due to momentary fading.
- Information about the vehicle speed is useful in handoff decisions.
- Dwell time – The time over which a call may be maintained within a cell without handoff.
- The statistics of dwell time are important in the practical design of handoff algorithm.

- In first generation analog cellular system, the locator receiver is used for handoff.
- In second generation system, handoff decisions are mobile assisted – mobile assisted handoff (MAHO).
- Intersystem handoff – different cellular systems – roamer.

3.4.1 Prioritizing Handoffs

- Guard channel concept – can be used with dynamic channel assignment strategies to increase spectrum utilization.
- Queuing of handoff – possible due to the fact that there is a finite time interval between handoff threshold time and call-terminated time.

3.4.2 Practical Handoff Considerations

- Several handoff schemes have been devised to handle the simultaneous traffic of high speed and low speed users – minimizing the handoff intervention from the MSC.

- Umbrella cell approach

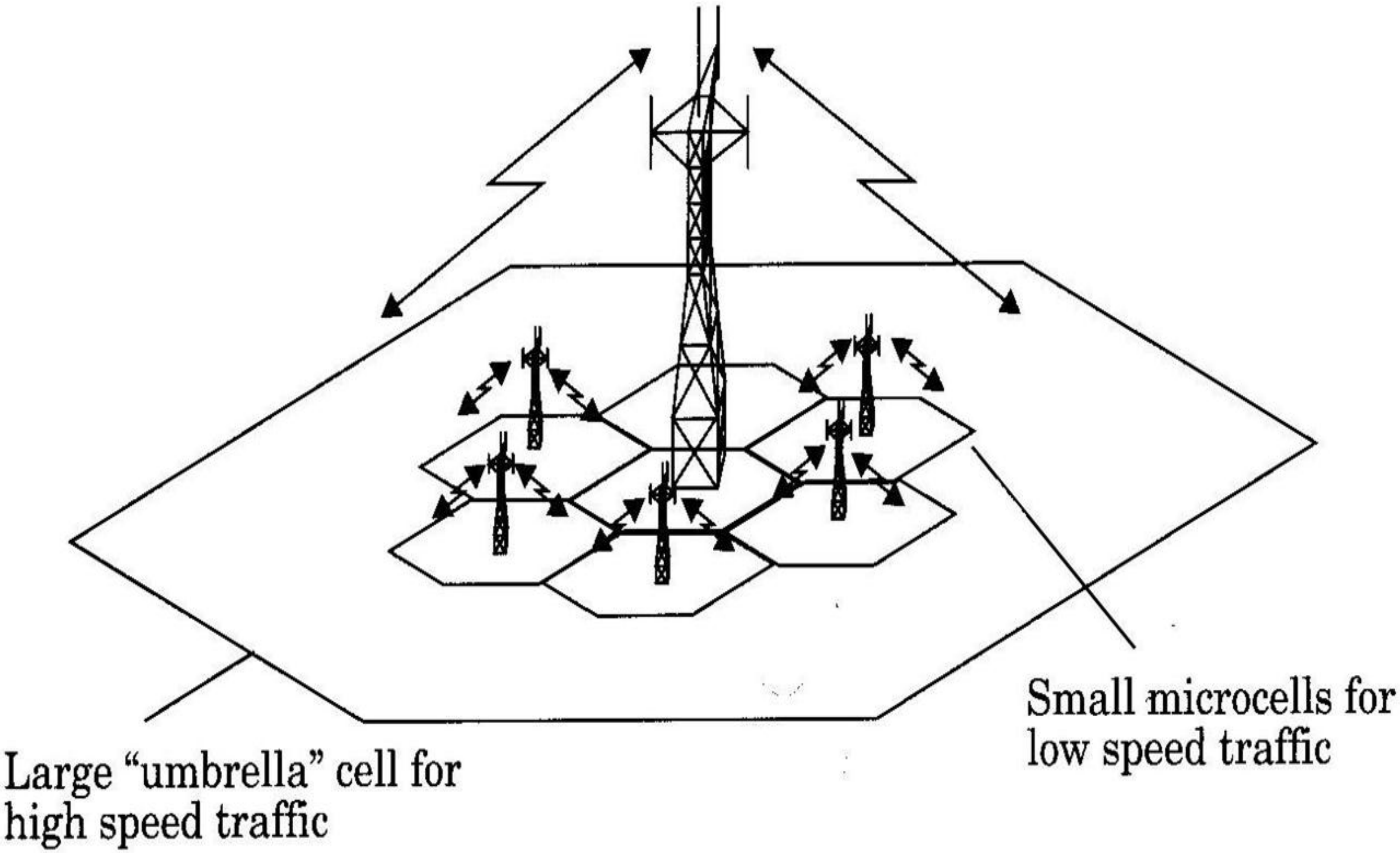


Figure 3.4 The umbrella cell approach.

- Another practical problem for low speed users is cell dragging.
- Handoff speed – 1st generation : 10 s

  2nd generation :1~2 s
- Handoff decision may also based on co-channel and adjacent channel interference.
- The IS-95 code division multi access (CDMA) spread spectrum cellular system use soft handoff rather than hard handoff.

3.5 Interference and System Capacity

- Source of interference include: another mobile in the same cell, a call in progress in a neighboring cell, other base station, any noncellular systems.
- The two major types of system-generated cellular interference are co-channel interference and adjacent channel interference.

3.5.1 Co-channel Interference and System Capacity

- Frequency reuse implies that in a given coverage area there are several cells that use the same set of frequencies. These cells are called co-channel cells.
- The interference between signals from these cells is called co-channel interference.
- To reduce co-channel interference, co-channel cells must be physically separated by a minimum distance.

- The co-channel interference ratio is a function of the radius of the cell (*R*) and the distance between centers of the nearest co-channel cell (*D*) .
  - *D*/*R* increased, co-channel interference decreased.
  - The co-channel reuse ratio is related to the cluster size. For a hexagonal geometry

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

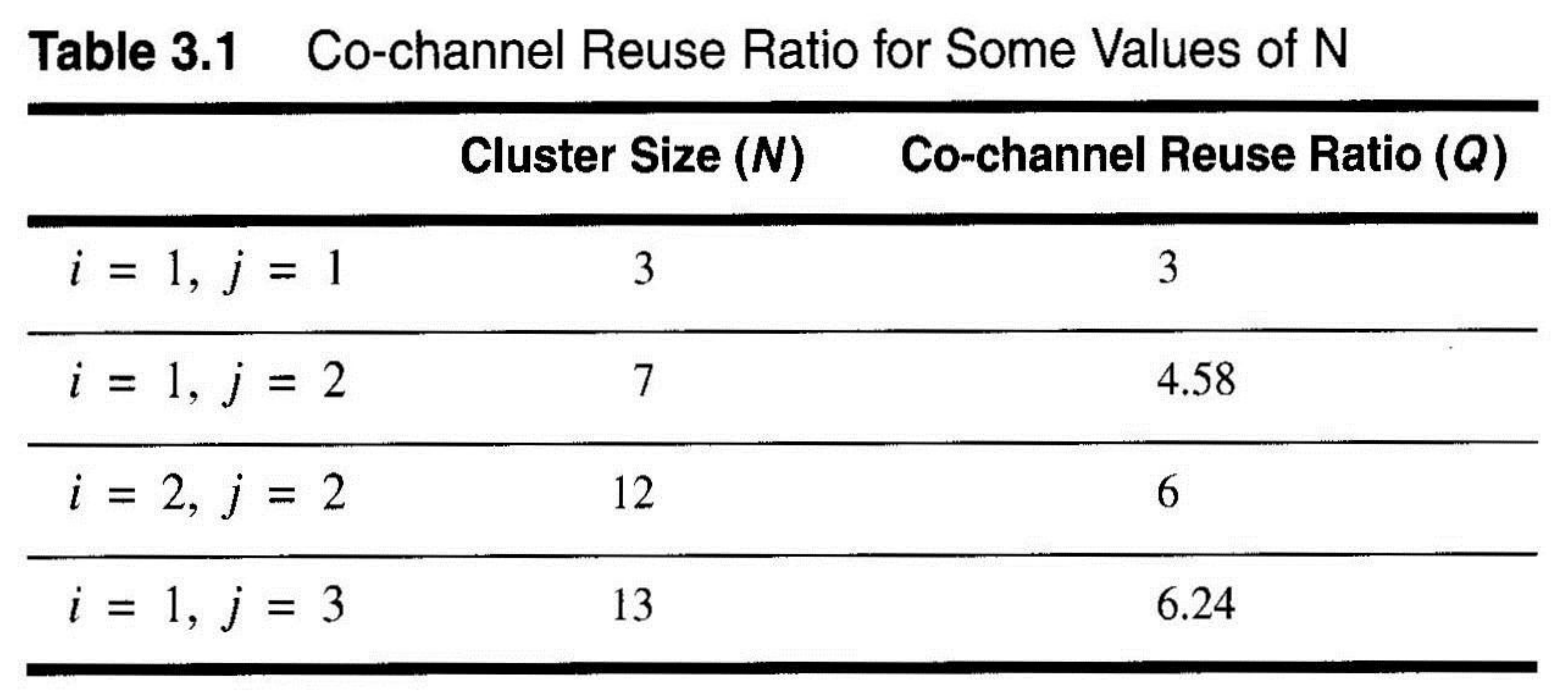


Table 3.1 Co-channel Reuse Ratio for Some Values of N

	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

- $Q\downarrow$, capacity ↑

  $Q\downarrow$, co-channel interference ↑

  A trade-off must be made between these two objectives in actual cellular design.
- The signal-to-interference ratio (*S/I* or *SIR*） for a mobile receiver can be expressed as

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

- The average received power P_r at a distance d is

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

or

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

where P_0 is the power received at a distance d_0 , and n is the path loss exponent (typically ranging between 2 and 4)

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

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

if all D_i are the same.

- For a seven-cell cluster

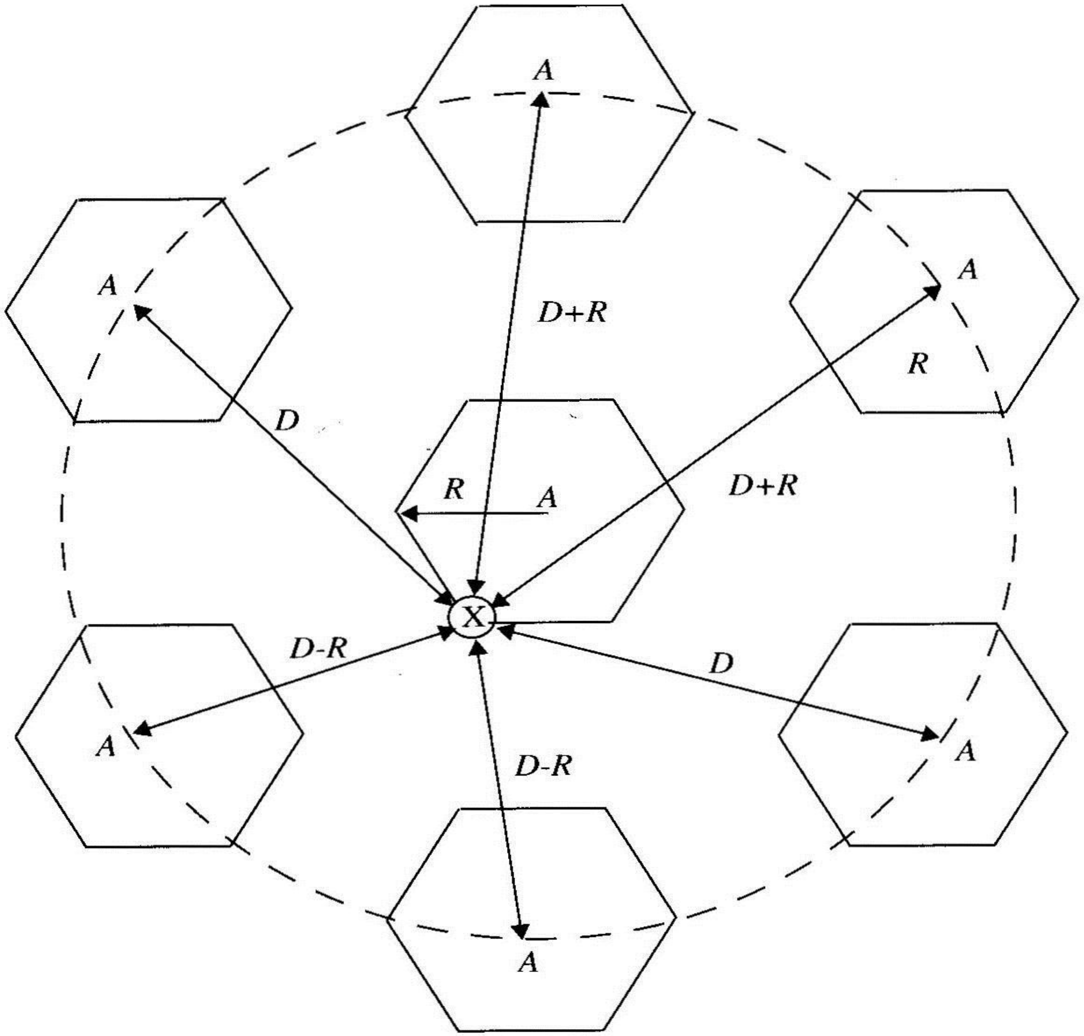


Figure 3.5 Illustration of the first tier of co-channel cells for a cluster size of $N = 7$. An approximation of the exact geometry is shown here, whereas the exact geometry is given in [Lee86]. When the mobile is at the cell boundary (point X), it experiences worst case co-channel interference on the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

- SIR for the worst case can be approximated as

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

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

For N = 7, Q = 4.6 ⇨ S/I = 17dB less than 18dB requirement. Hence, choose N = 9

This entails a significant decrease in capacity. From 1/7 spectrum utilization to 1/9.

- In practice, a capacity reduction of 7/9 would not be tolerable to accommodate for the worst case situation which rarely occurs.

Example 3.2

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 six co-channel cells in the first tier, and all of them are at the same distance from the mobile. Use suitable approximations.

Solution :

(a) $n = 4$

let us consider a seven-cell reuse pattern.

Using Eq. (3.4), co-channel reuse ratio $D/R = 4.583$

Using Eq. (3.9), signal-to-noise interference ratio

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

$N = 7$ can be used.

(b) $n = 3$

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

when $N = 12$, $D/R = 6.0$

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

so, $N = 12$ is used.

3.5.2 Channel Planning for Wireless System

- Typically, about 5% of the entire mobile spectrum is devoted to control channels (vital for initiating, requesting, or paging a call) , while 95% of the spectrum is dedicated to voice channel (carrying revenue – generating calls).
- Since control channels are vital, the frequency reuse strategy for them is generally more conservative than for voice channels. In example 3.3, 21-cell reuse for control channels, whereas 7-cell reuse for voice channels.

3.5.3 Adjacent Channel Interference

- Resulting from signals which are adjacent in frequency to the desired signal.
- The near-far effect: a nearby transmitter captures the receiver of the subscriber or the base station.
- Adjacent channel interference can be minimized through careful filtering and channel assignments.
- A cell need not be assigned channels which are all adjacent in frequency. Neighboring cells avoid the use of adjacent channels.

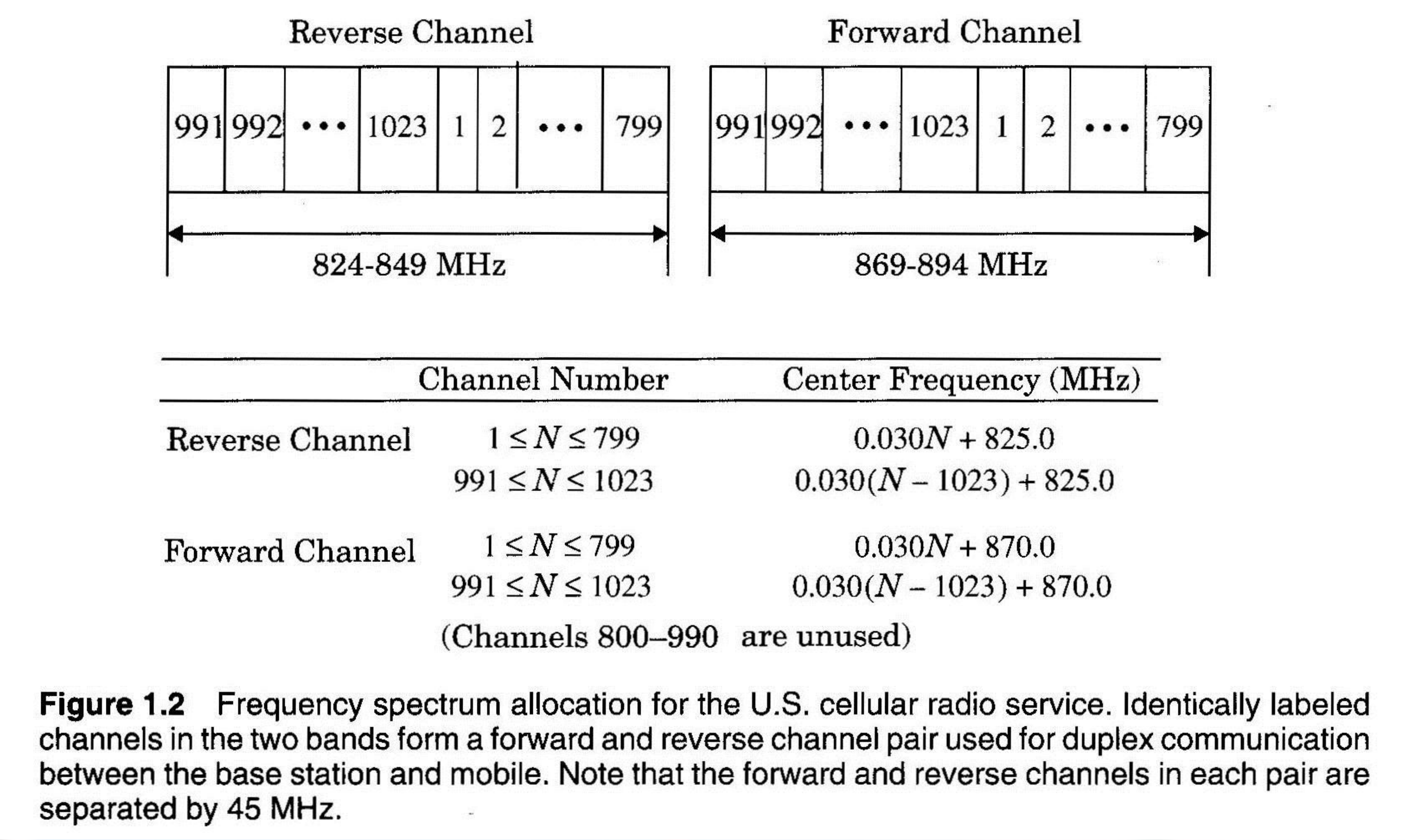
Example 3.3

- 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. In 1989, the FCC allocated an additional 10 MHz (166 channels) of spectrum for cellular services.

- There are now 832 channels used in AMPS.

- The extended band has channels number as 667 through 799, and 990 through 1023.



	Channel Number	Center Frequency (MHz)
Reverse Channel	$1 \le N \le 799$	$0.030N + 825.0$
	$991 \le N \le 1023$	$0.030(N - 1023) + 825.0$
Forward Channel	$1 \le N \le 799$	$0.030N + 870.0$
	$991 \le N \le 1023$	$0.030(N - 1023) + 870.0$

(Channels 800–990 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.

- In order to encourage competition, the FCC licensed the channels to two competing operators in every service area.
- The channels used by the two operators are distinguished as *block A* and *block B* channels.
  - Block B is operated by companies which have traditionally provided telephone services (called *wireline* operators.
  - Block A is operated by companies that have not traditionally provided telephone services (called *nonwireline operators*).

- Out of the 416 channels used by each operator, 395 are voice channels and the remaining 21 are control channels.
  - Block A – voice channels 1~312, 667~716, 991~1023.
control channels 313~333.
  - Block B – voice channels 355~666, 717~799.
control channels 334~354.

- One control channel is provided for each bank of trunked voice channels.

- For an AMPS system, a single cell is assigned a single control channel.

- Thus, control channels obey a 21-cell reuse scheme and are assigned over three clusters before being reused, even through the voice channels may be assigned using a seven-cell reuse scheme.

- 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.
- In a seven-cell reuse system, each cell uses three subsets of channels.
- This channel assignment scheme is illustrated in Table 3.2.
- The total number of voice channels in a cell is about 57.
- The shaded set of numbers correspond to the control channels.

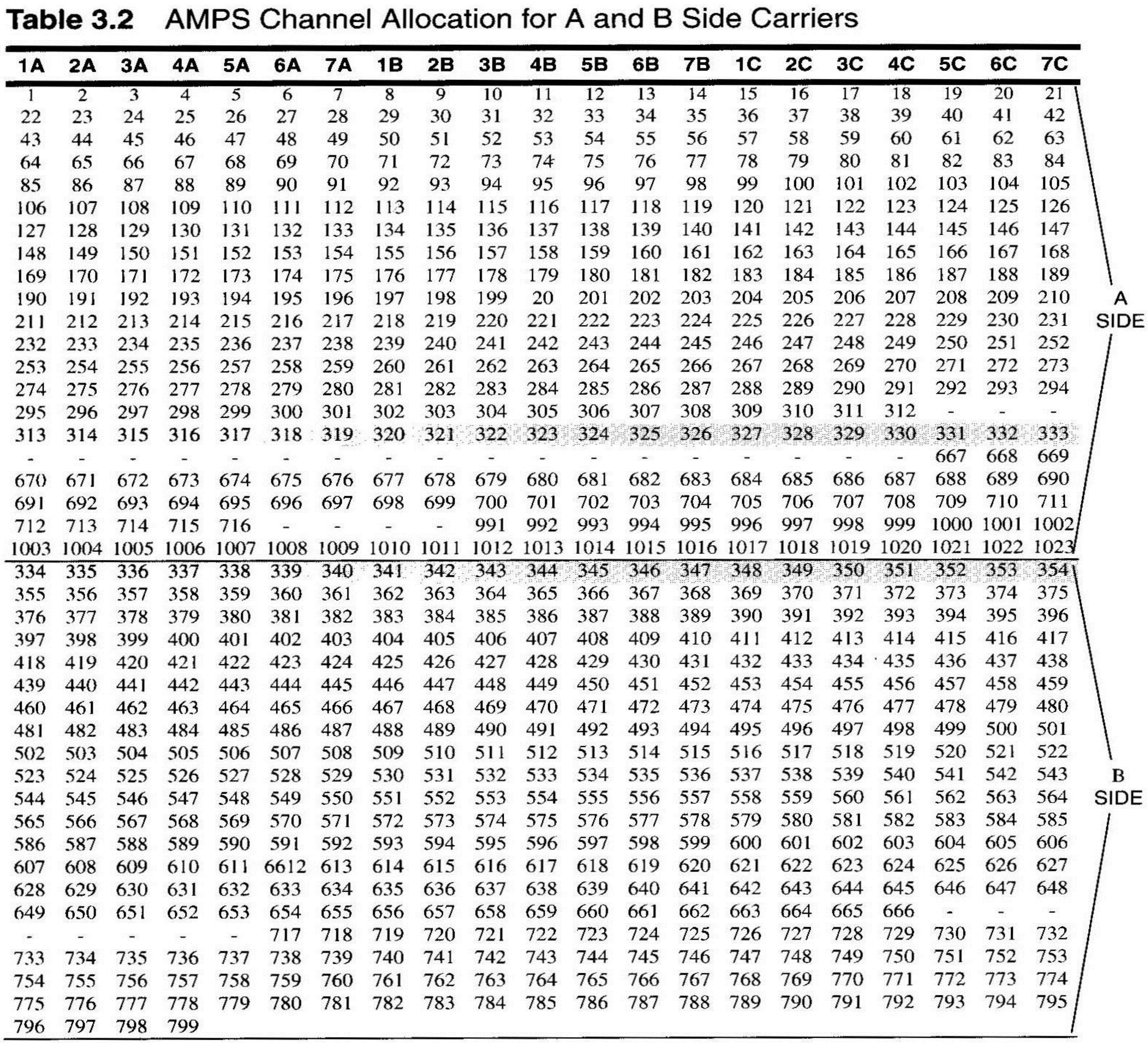


Table 3.2 AMPS Channel Allocation for A and B Side Carriers

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	A SIDE
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	-	-	-	
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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	
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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	
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733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	
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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																		

3.5.4 Power Control for Reducing Interference

- The power levels transmitted by every subscriber unit are under constant control by the serving base stations.
- To ensure that each mobile transmits the smallest power necessary to maintain a good quality link on the reverse channel.
- Prolong battery life and reduce the reverse channel *S/I* .

3.6 Trunking and Grade of Service

- The concept of trunking allows a large number of user to share the relatively small number of channels in a cell by providing access to each user, on demand, from a pool of available channels.
- A user is blocked, i.e., denied access to the system.
- In some system, a queue may be used to hold the requesting users until a channel becomes available.

- One Erlang represents the amount of traffic intensity carried by a channel that is completely occupied (i.e. one call-hour per hour or one call-minute per minute).

  For example:

  0.5 Erlangs of traffic – a radio channel that is occupied for 30 minutes during an hour.

- The grade of service (GOS) is a measure of the ability of a user to access a trunked system during the busiest hour, and is typically given as the likelihood that a call is blocked, or the likelihood of a call experiencing a delay greater than a certain queuing time.

TABLE 3.3 Definitions of Common Terms Used in Trunking Theory

Set-up Time	The time required to allocate a trunked radio channel to a requesting user.
Blocked Call	Call which cannot be completed at time of request, due to congestion. Also referred to as a *lost call*.
Holding Time	Average duration of a typical call. Denoted by H (in seconds).
Traffic Intensity	Measure of channel time utilization, which is the average channel occupancy measured in Erlangs. This is a dimensionless quantity and may be used to measure the time utilization of single or multiple channels. Denoted by A.

Load – Traffic intensity across the entire trunked radio system, measured in Eelang.

Grade of Service (GOS) – A measure of congestion which is specified as the probability of a call being blocked (for Erlang B), or the probability of a call being delayed beyond a certain amount of time (for Erlang C).

Request Rate – The average number of call requests per unit time. Denoted by λ seconds^{-1} .

- Traffic intensity A_u of each user is given by

$$A_u = \lambda H$$

- Total traffic intensity A for U users

$$A = UA_u$$

- Traffic intensity per channel A_c

$$A_c = UA_u / C$$

- The maximum possible carried traffic is the total number of channels, C, in Erlangs.

- There are two types of trunked systems.

(1) Blocked calls cleared:

This is known as an M/M/m/m queue and leads to the derivation of the Erlang B formula.

$$P_r[blocking] = \frac{\frac{A^C}{C!}}{\sum_{k=0}^{C} \frac{A^k}{k!}} = GOS$$

where C is the number of trunked channel and A is the total offered traffic.

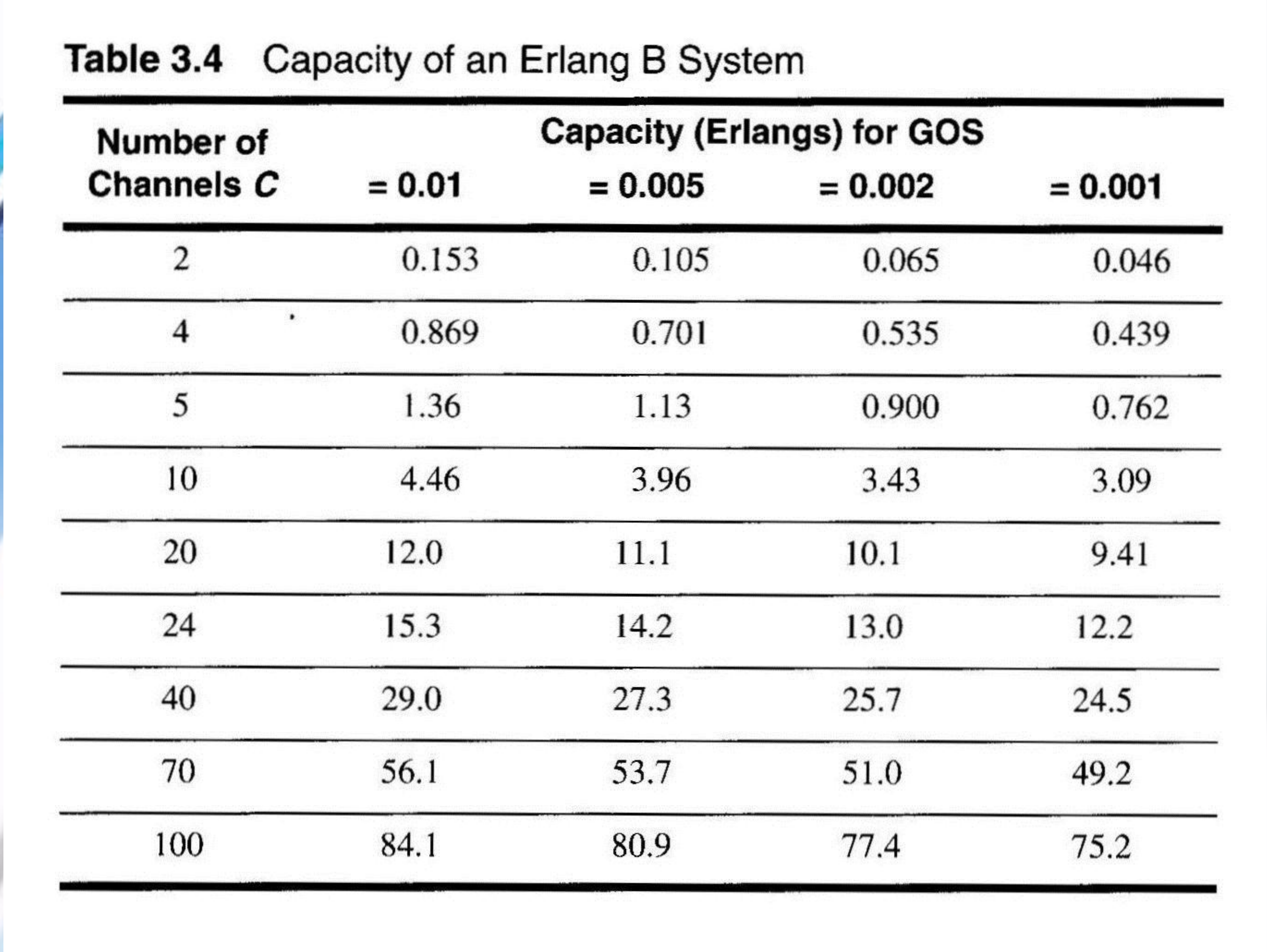

Table 3.4 Capacity of an Erlang B System

Number of Channels C	Capacity (Erlangs) for GOS = 0.01	= 0.005	= 0.002	= 0.001
2	0.153	0.105	0.065	0.046
4	0.869	0.701	0.535	0.439
5	1.36	1.13	0.900	0.762
10	4.46	3.96	3.43	3.09
20	12.0	11.1	10.1	9.41
24	15.3	14.2	13.0	12.2
40	29.0	27.3	25.7	24.5
70	56.1	53.7	51.0	49.2
100	84.1	80.9	77.4	75.2

(2) Blocked calls delayed

Erlang *C* formula

$$P_r[delay > 0] = \frac{A^C}{A^C + C!(1 - \frac{A}{C})\sum_{k=0}^{C-1} \frac{A^k}{k!}}$$

- The GOS of a trunked system is given by

$$\begin{aligned} P_r[delay > t] &= P_r[delay > 0] P_r[delay > t \mid delay > 0] \\ &= P_r[delay > 0] \exp(-(C - A)t / H) \end{aligned}$$

- The average delay D for all calls is

$$D = P_r[delay > 0] \frac{H}{C - A}$$

where the average delay for those calls which are queued is given by $H/(C-A)$.

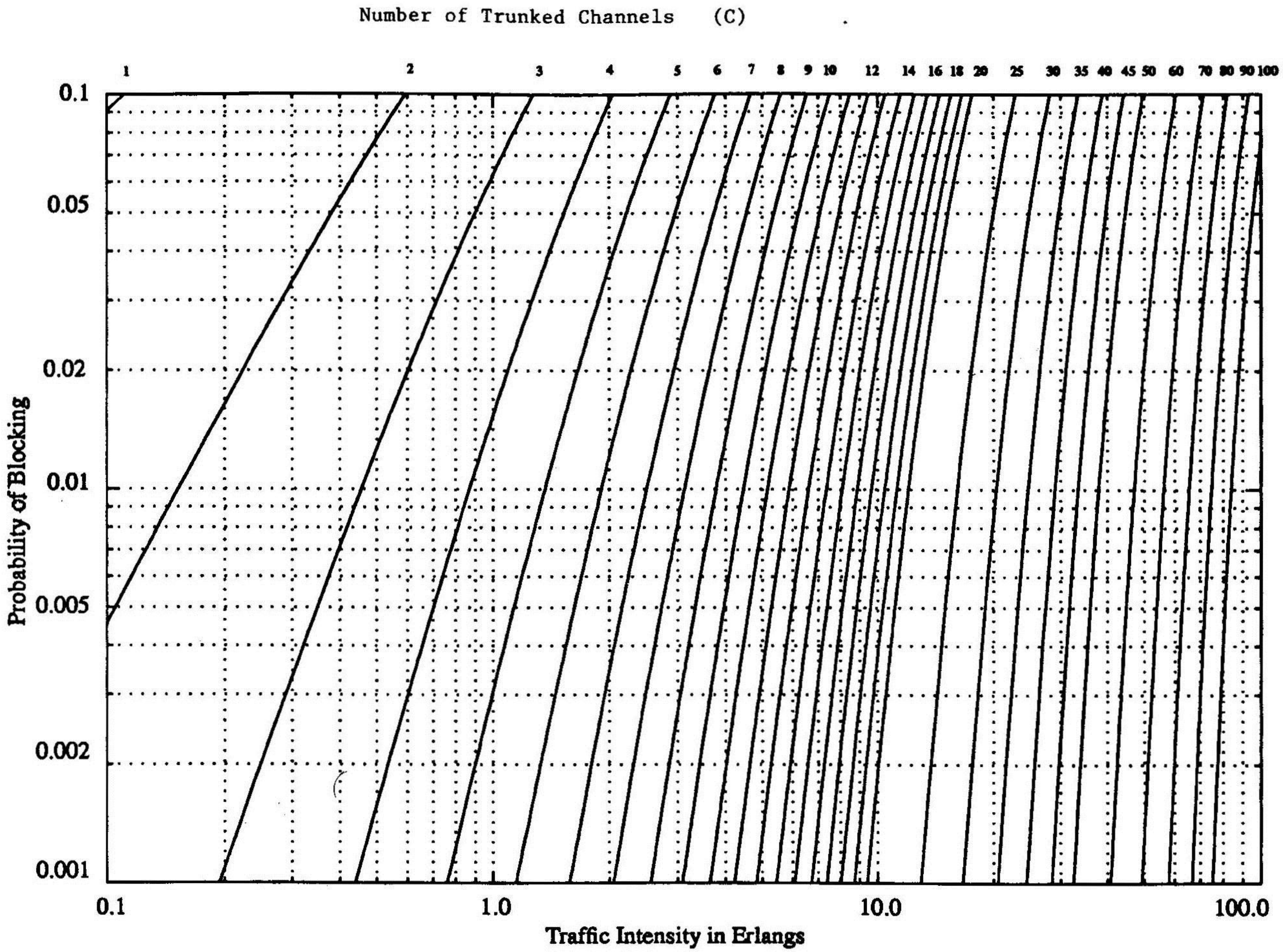

Figure 3.6 The Erlang B chart showing the probability of blocking as functions of the number of channels and traffic intensity in Erlangs.

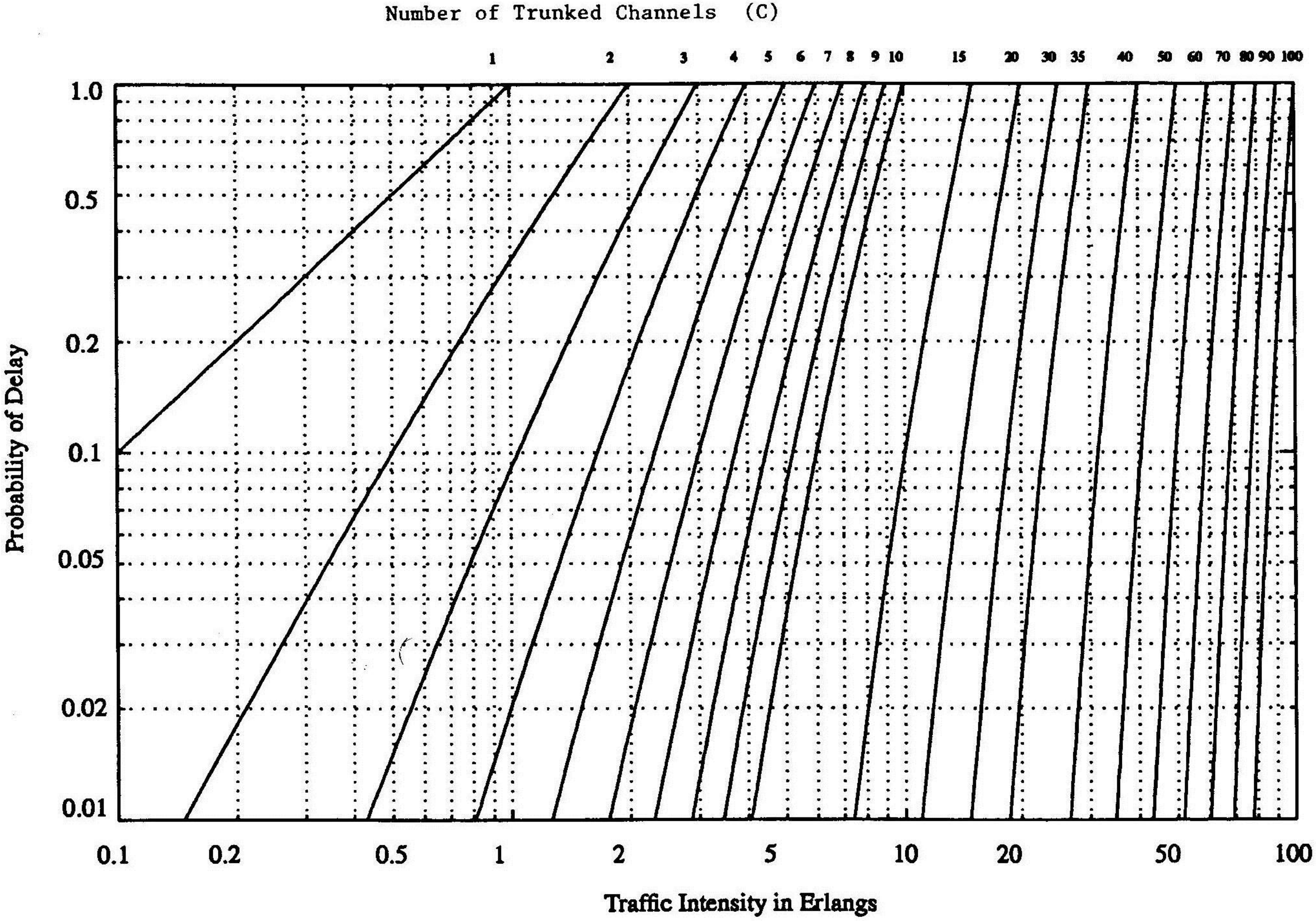

Figure 3.7 The Erlang C chart showing the probability of a call being delayed as a function of the number of channels and traffic intensity in Erlangs.

Example 3.4

How many users can be supported for 0.5% blocking probability for the following number of trunked channels in a blocked calls cleared system? (a) 1, (b) 5, (c) 10, (d) 20, (e) 100. Assume each user generates 0.1 Erlangs of traffic.

Solution :

By using $A = UA_u$

(a) $C = 1, A_u = 0.1, GOS = 0.005$

$U = A/A_u = 0.005/0.1 = 0.05$

(b) $C = 5, A_u = 0.1, GOS = 0.005$

$U = A/A_u = 1.13/0.1 \approx 11$

(c) $C = 10, A_u = 0.1, GOS = 0.005$

$U = A/A_u = 3.96/0.1 \approx 39$

(d) $C = 20, A_u = 0.1, GOS = 0.005$

$U = A/A_u = 11.1/0.1 \approx 110$

(e) $C = 100, A_u = 0.1, GOS = 0.005$

$U = A/A_u = 80.9/0.1 \approx 809$

Example 3.5

An urban area has a population of two million residents. Three competing trunked mobile networks (system A, B and C) provide cellular service in this area. System A has 394 cells with 19 channels each, system B has 98 cells with 57 channels each, and system C has 49 cells, each with 100 channels. Find the number of users that can be supported at 2% blocking if each user averages two calls per hour at an average call duration of three minutes. Assuming that all three trunked systems are operated at maximum capacity, compute the percentage market penetration of each cellular provider.

Solution :

System A:

$$\text{probability of blocking} = 2\% = 0.02$$

$$\text{Traffic intensity per user, } A_u = \lambda H = 2 \times (3/60) = 0.1 \text{ Erlangs}$$

$$GOS = 0.02, C = 19 \Rightarrow \text{Total carried traffic } A = 12 \text{ Erlangs}$$

$$U = A/A_u = 12/0.1 = 120$$

$$\text{System A} = 120 \times 394 \text{ cells} = 47280$$

System B:

$$\text{probability of blocking} = 2\% = 0.02$$

$$\text{Traffic intensity per user, } A_u = \lambda H = 2 \times (3/60) = 0.1 \text{ Erlangs}$$

$$GOS = 0.02, C = 57 \Rightarrow \text{Total carried traffic } A = 45 \text{ Erlangs}$$

$$U = A/A_u = 145/0.1 = 450$$

$$\text{System A} = 450 \times 98 \text{ cells} = 44100$$

Solution :

System C:

$\text{probability of blocking} = 2\% = 0.02$

$\text{Traffic intensity per user, } A_u = \lambda H = 2 \times (3/60) = 0.1 \text{ Erlangs}$

$GOS = 0.02, C = 100 \Rightarrow \text{Total carried traffic } A = 88 \text{ Erlangs}$

$U = A/A_u = 88/0.1 = 880$

$\text{System A} = 880 \times 49 \text{ cells} = 43120$

There are two million residents in the given urban area

System A is $47{,}280/2{,}000{,}000 = 2.36\%$

System B is $44{,}100/2{,}000{,}000 = 2.205\%$

System C is $43{,}120/2{,}000{,}000 = 2.156\%$

The market penetration of the three systems combined is equal to

$(47{,}280 + 44{,}100 + 43{,}120)/2{,}000{,}000 = 6.725\%$

Example 3.6

A certain city has an area of 1300 square miles and is covered by a cellular system using a seven-cell reuse pattern. Each cell has a radius of four miles and the city is allocated 40 MHz of spectrum with a full duplex channel bandwidth of 60 kHz . Assume a GOS of 2% for an Erlang B system is specified. If the offered traffic per user is 0.03 Erlanges, compute

(a) the number of cells is the service area,

(b) the number of channels per cell,

(c) traffic intensity of each cell,

(d) the maximum carried traffic,

(e) the total number of users that can be served for 2% GOS,

(f) the number of mobiles per unique channel (where it is understood that channels are reused)

(g) the theoretical maximum number of users that could be served at one time by system.

Solution :

(a) $\text{Total area} = 1300 \text{ miles, cell radius} = 4 \text{ miles}$

$\text{The area of a cell} = 2.5981R^2 = 2.5981 \times (4)^2 = 41.57$

$\text{The total number of cells are } N_C = 1300/41.57 = 31 \text{ Cells}$

(b) $\text{The number of channels per cell}$

$= 40{,}000{,}000 \; /(60{,}000 \times 7) = 95 \text{ channels/cell}$

(c) $C = 95, GOS = 0.02$

$\text{From the Erlang B} \Rightarrow A = 84 \text{ Erlangs/cell}$

(d) $\text{Maximum carried traffic} = \text{number of cells} \times \text{traffic intensity cell}$

$= 31 \times 84 = 2604 \text{ Eralngs}$

(e) $\text{Given traffic per user} = 0.03$

$\text{Total number of users} = \text{Total traffic/traffic per user}$

$= 2604 / 0.03 = 86{,}800$

Solution :

(f) Number of mobiles per channel = number of users/number of channels

$$= 86{,}800/666 = 130$$

(g) $C \times N_C = 95 \times 31 = 2945$

$2945 / 86{,}800 = 0.034 = 3.4\%$

which is 3.4% of the customer base.

Example 3.7

A hexagonal cell within a four-cell system has a radius of 1.387 km. A total of 60 channels are used within the entire system. If the load per user is 0.029 Erlangs, and $\lambda = 1$ call/hour, compute the following for an Erlang C system that has a 5% probability of a delayed call:

(a) How many users per square kilometer will this system support?

(b) What is the probability that a delayed call will have to wait for more than 10 s?

(c) What is the probability that a call will be delayed for more than 10 seconds?

Solution :

$$R = 1.387\text{, area} = 2.598 \times (1.387)^2 = 5\text{ sq km}$$

$$\text{Number of cells per cluster} = 4$$

$$\text{Number of channels per cell} = 60/4 = 15$$

(a) $C = 15, P_r[\text{delay} > 0] = 0.05 \Rightarrow \text{Traffic intensity } = 9.0\text{ Erlangs}$

$$\text{Number of users} = \text{total traffic intensity/ traffic per user}$$

$$= 9.0/0.029 = 310\text{ users}$$

$$310\text{ users}/5\text{ sq km} = 62\text{ users/sq km}$$

(b)

$$\lambda = 1\text{, Holding Time}$$

$$H = A_u/\lambda = 0.029\text{ hour} = 104.4\text{ seconds}$$

$$P_r[delay > t \mid delay] = \exp(-(C - A)t / H)$$

$$= \exp(-(15 - 9.0)10/104.4) = 56.29\%$$

Solution **:**

(c) $P_r[delay > 0] = 5\% = 0.05$

$$P_r[delay > 10] = P_r[delay > 0]P_r[delay > t \mid delay]$$

$$= 0.05 \times 0.5629 = 2.81\%$$

- Trunking efficiency is a measure of the number of users which can be offered a particular GOS with a particular configuration of fixed channels.

  From Table 3.4,

  - 10 channels at a GOS = 0.01 can support 4.46 Erlangs.
  - Two groups of 5 channels can support

    2*1.36 = 2.72 Erlangs

3.7 Improving Coverage and Capacity in Cellular Systems

3.7.1 Cell Splitting

- Cell splitting is the process of subdividing a congested cell into smaller cells.
- Since it increases the number of times that channels are reused (or decreases the cluster area). Cell splitting increases the capacity of a cellular system.
- Cell splitting generally does not upset the channel allocation scheme required to maintain the minimum co-channel reuse ratio Q between co-channel cells.

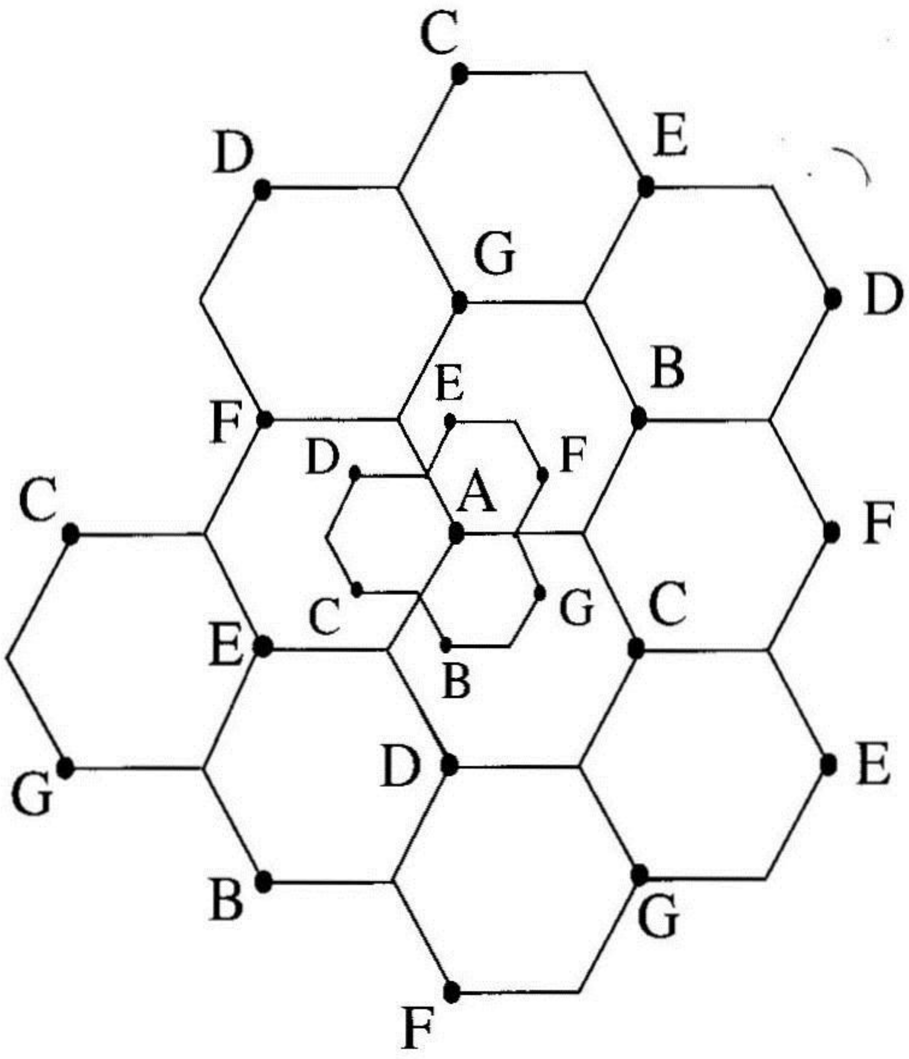

Figure 3.8 Illustration of cell splitting.

$$P_r[\text{at old cell boundry}] \propto P_{t1} R^{-n}$$

$$= P_r[\text{at new cell boundry}] \propto P_{t2} (R/2)^{-n}$$

$$\Rightarrow \quad P_{t2} = \frac{P_{t1}}{16}$$

a 12 dB reduction of the old transmit power.

Example 3.8

Consider Figure 3.9. Assume each base station uses 60 channels, regardless of cell size. If each original cell has a radius of 1 km and each microcell has a radius of 0.5 km, find the number of channels contained in a 3 km by 3 km square centered around A under the following conditions:

(a) without the use of microcells;

(b) when the lettered microcells as shown in Figure 3.9 are used;

(c) if all the original base stations are replaced by microcells.

Assume cells on the edge of the square to be contained within the square.

Solution :

(a) The area contains five base station.

Total number of channels without cell splitting $= 5 \times 60 = 300$ channels.

(b) The base station A is surrounded by six microcells.

The total number of station $= 5 + 6 = 11$.

Total number of channels $= 11 \times 60 = 660$ channels.

(c) The total number of station $= 5 + 12 = 17$

Total number of channels $= 17 \times 60 = 1020$ channels

Theoretically, if all cells were microcells having half the radius of the original cell, the capacity increase would approach four.

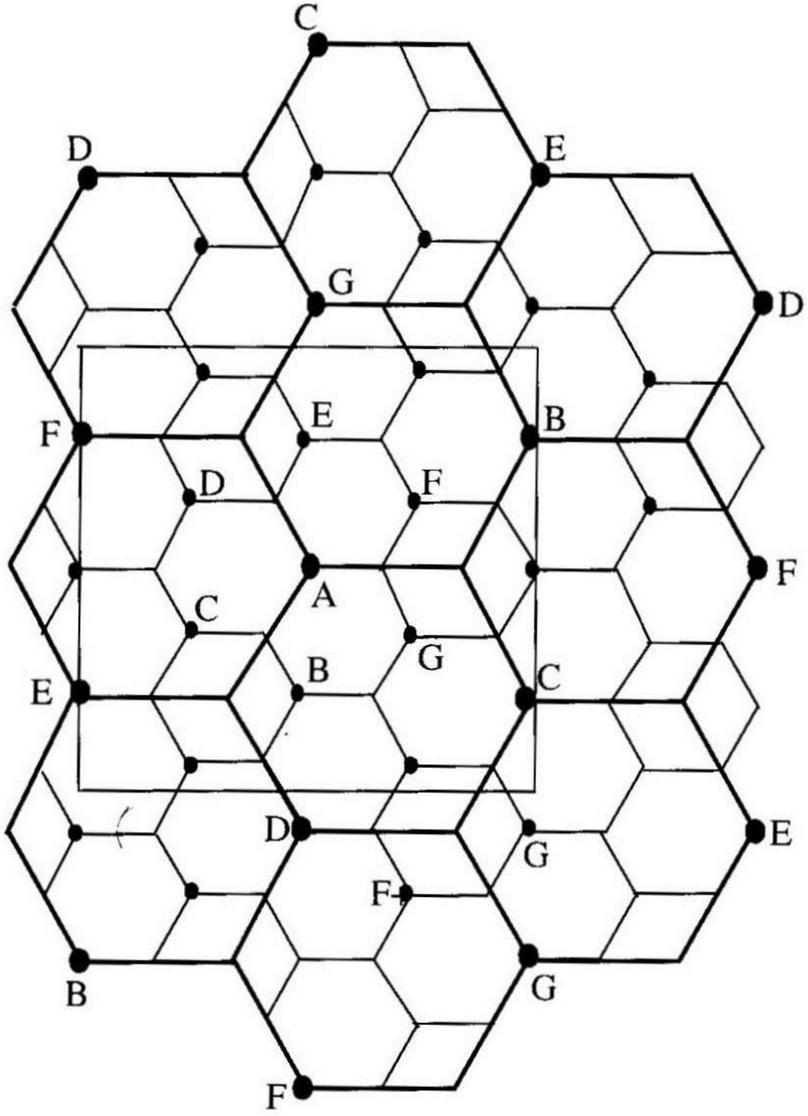

Figure 3.9 Illustration of cell splitting within a 3 km by 3 km square centered around base station A.

- Antenna downtilting is often used to limit the radio coverage of newly formed microcells.

3.7.2 Sectoring

- By decreasing the cell radius *R* and keeping the co-channel reuse ratio *D/R* unchanged, cell splitting increases the number of channels per unit area.
- Another way to increase capacity is to keep the cell radius unchanged and seek methods to decrease the *D/R* ratio.
- Sectoring increases SIR so that the cluster size may be reduced.

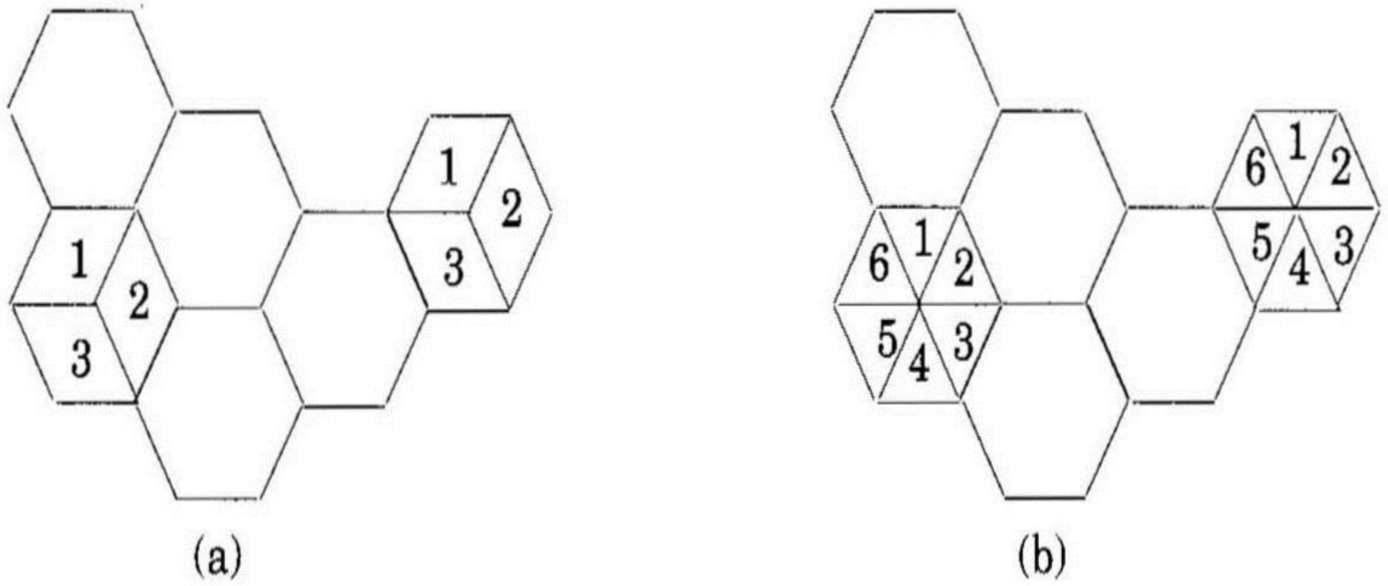

Figure 3.10 (a) 120° sectoring; (b) 60° sectoring.

S/I increases to 24.2 dB.

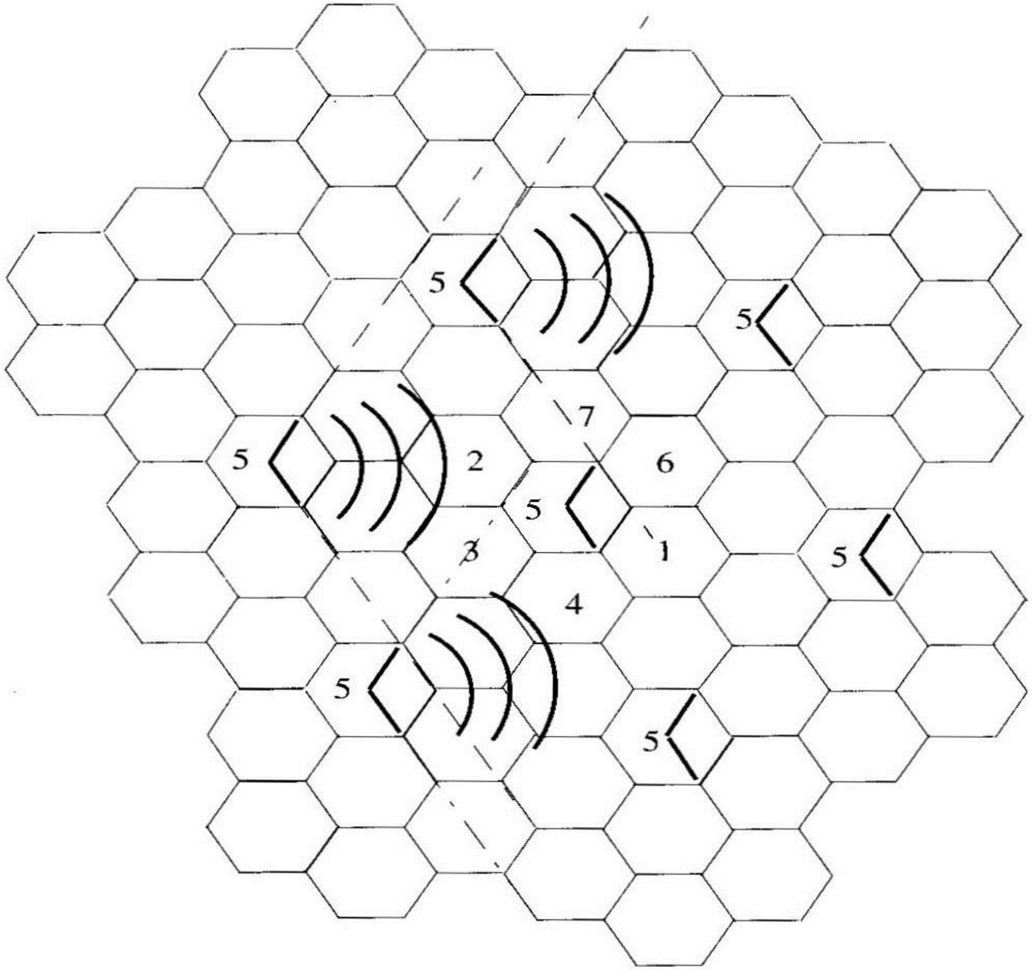

Figure 3.11 Illustration of how 120° sectoring reduces interference from co-channel cells. Out of the 6 co-channel cells in the first tier, only two of them interfere with the center cell. If omnidirectional antennas were used at each base station, all six co-channel cells would interfere with the center cell.

- The penalty from sectoring:
  - an increased number of antennas at each base station.
  - a decrease in trunkung efficiency due to the channel sectoring.
  - the increased number of handoffs – usually is not a major concern.
- Some operators shy away from sectoring approach, because it breaks up the available trunked pool into several small pools, and decreases trunking efficiency.

Example 3.9

- Consider a cellular system in which an average call lasts two minutes, and the probability of blocking is to be no more than 1 %.
- Assume that every subscriber makes one call per hour, on average.
- If there are a total of 395 traffic channels for a seven-cell reuse system, there will be about 57 traffic channels per cell.
- Assume that blocked calls are cleared so the blocking is described by the Erlang B distribution.
- From the Erlang B distribution, it can be found that the unsectored system may handle 44.2 Erlang or 1326 calls per hour.

Example 3.9

- Now employing 120° sectoring, there are only 19 channels per antenna sector (57/3 antennas).
- For the same probability of blocking and average call length, it can be found from the Erlang B distribution that each sector can handle 11.2 Erlangs or 336 calls per hour.
- Since each cell consists of three sectors, this provides a cell capacity of $3\times336 = 1008$ calls per hour, which amounts to a 24% decrease when compared to the unsectored case.
- Thus, sectoring decreases the trunking efficiency while improving the S/I for each user in the system.

Example 3.9

- It can be found that using 60° sectors improves the *S/I* even more.
- In this case, the number of first tier interferences is reduced from six to only one. This results in *S/I* = 29 dB for a seven-cell system and enables four-cell reuse.
- Of course, using six sectors per cell reduces the trunking efficiency and increases the number of necessary handoffs even more.
- If the unsectored system is compared to the six sector case, the degradation in trunking efficiency can be shown to be 44%. (The proof of this is left as an exercise.)

3.7.3 Repeaters for Range Extension

- Repeaters – to provide dedicated coverage for hard-to-reach areas, such as within buildings, or in valleys or tunnels.

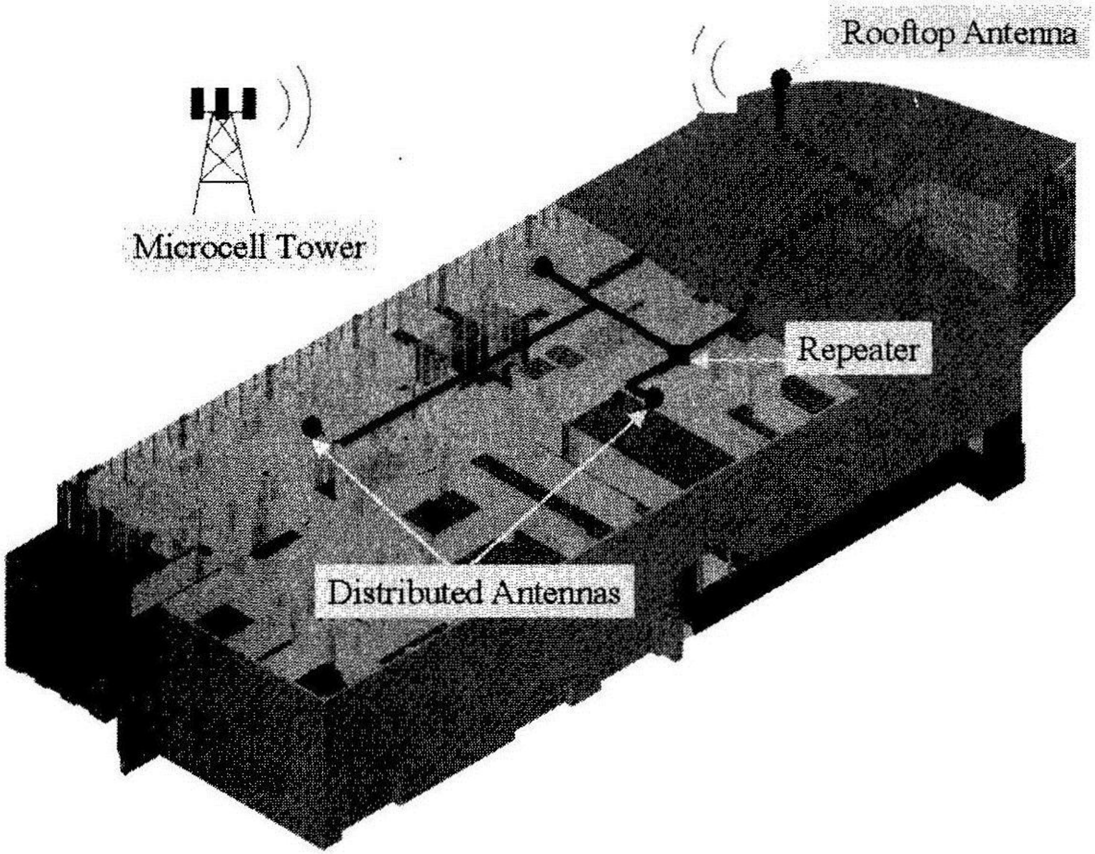

Figure 3.12 Illustration of how a distributed antenna system (DAS) may be used inside a building. Figure produced in SitePlanner®. (Courtesy of Wireless Valley Communications Inc.)

3.7.4 A Microcell Zone Concept

- When sectoring is employed, the increased number of handoffs results in an increased load in MSC. A solution to this problem is a Microcell Zone Concept.

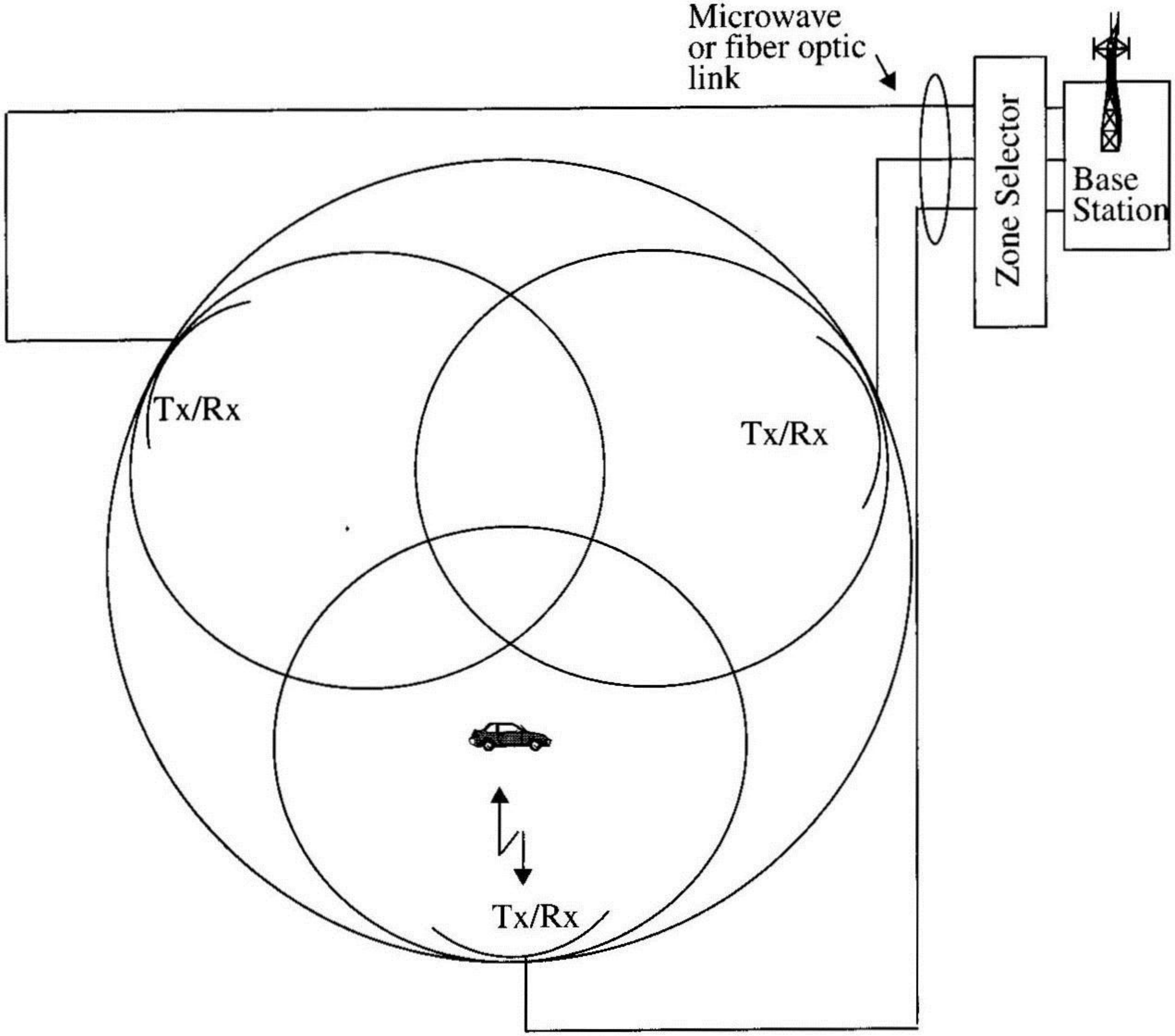

Figure 3.13 The microcell concept [adapted from [Lee91b] © IEEE].

- Antennas are placed at the outer edges of the cell. Each of the three zone sites are connected to a base station. Any base station channel may be assigned to any zone.
- As a mobile travels from one zone to another within the cell, it retains the same channel. The base station simply switches the channel to a different zone site.
- The advantage of the zone cell technique is that the co-channel interference in the cellular system is reduced

$$S/I \geq 18\,dB \Rightarrow N = 7 \Rightarrow D/R = 4.6$$

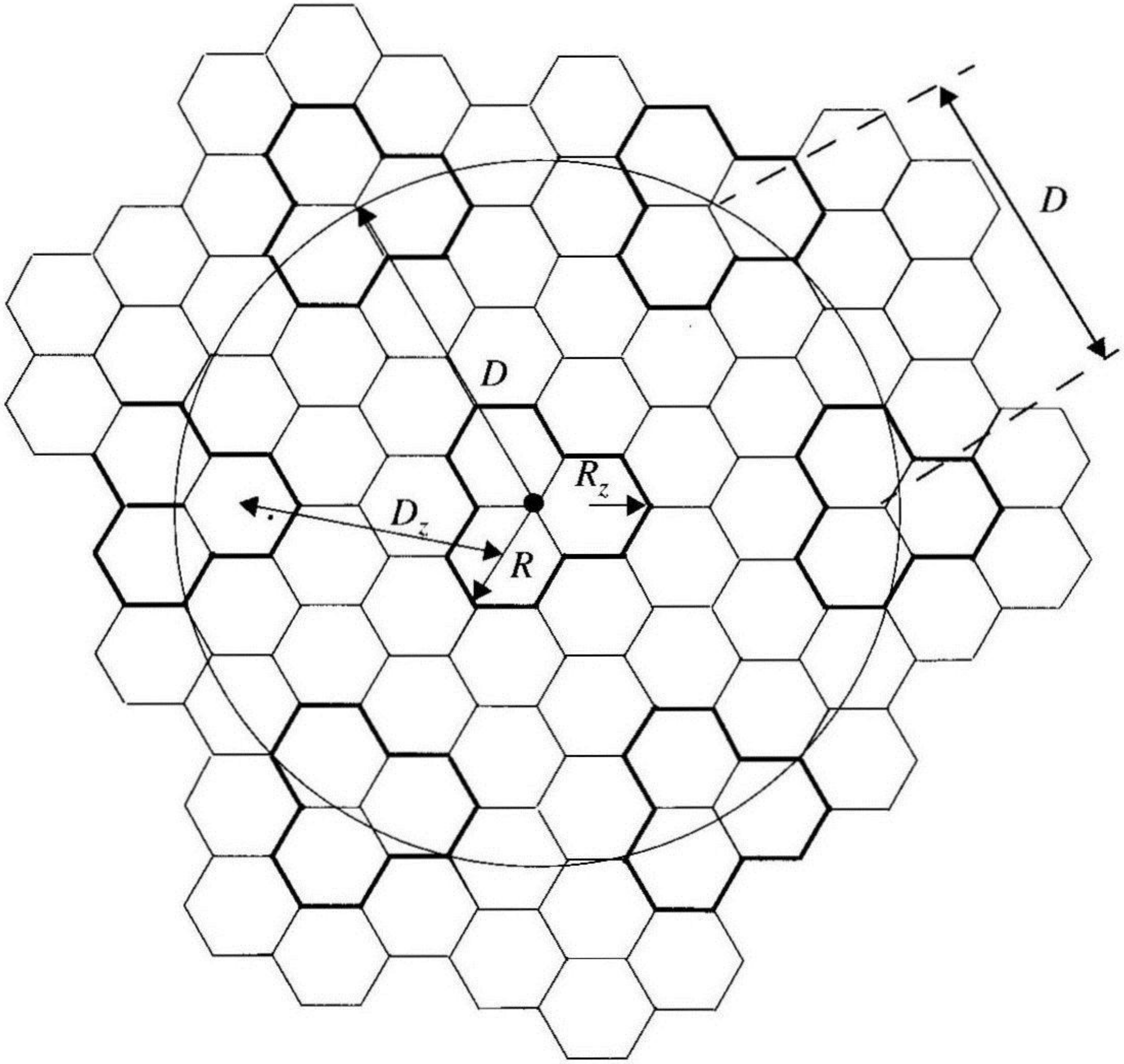

Figure 3.14 Define D, D_z, R, and R_z for a microcell architecture with $N = 7$. The smaller hexagons form zones and three hexagons (outlined in bold) together form a cell. Six nearest co-channel cells are shown.

$D_Z / R_Z = 4.6$

From the geometry

$D/R = 3 \Rightarrow N = 3$

$\frac{7}{3} = 2.33$ Times increase in capacity

No loss in trunking efficiency is experienced.

Many communication system use this technique.