THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 62, No. 7, September 1983
Printed in U.S.A.

Alternative Cell Configurations for Digital Mobile Radio Systems

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(Manuscript received January 19, 1982)

This paper introduces a novel class of antenna configurations and applies it to cellular digital mobile radio systems with frequency reuse. Directional antennas are used extensively. Cooperation between more base stations than are in the conventional three-corner directional antenna scheme is required for the alternative cells. The paper studies the relationship between signal-to-cochannel interference and trunking efficiency (availability of channels) and compares conventional systems with the same base-station locations. We concluded that the new antenna configurations can significantly improve trunking efficiency. Time-division retransmission systems with space diversity are considered for some cases. Furthermore, we show how transmitter power weighting (i.e., certain transmitters have higher output power than others) can improve the signal-to-cochannel-interference ratio for the novel cellular systems.

I. INTRODUCTION

Good spectral efficiency in digital mobile radio systems is obtained through frequency reuse. That is, each cell in the cellular system is assigned a number of channels in a frequency-division system, and each channel (frequency) is reused at a cell further away. The closer this second cell is, the higher the system capacity. On the other hand, cochannel interference increases when the interfering cells are too close. Omnidirectional and directional antenna arrangements have

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been considered in cochannel interference reduction. The concept of centrally located base stations with omnidirectional antennas is one possibility. Another suggested scheme is cooperating base stations with 120-degree directional antennas in three corners in a hexagonal cell. In this paper we generalize these antenna configuration ideas. Cooperation between more base stations and extensive use of directional antennas reduce cochannel interference. For example, all channels allocated to three cells in a conventional three-corner scheme can be made available in one "supercell" with the area three times the initial cell. The local availability of channels is now significantly improved. This leads to improved trunking efficiency.

As we will see, working with cells can sometimes be confusing. However, all comparisons below will be made with the same number of base stations per unit area. As a matter of fact, the base-station locations are always the same.

Choice of modulation scheme also affects spectral efficiency. In this paper we will, however, only deal with the frequency-reuse issue for a given modulation scheme, e.g., Quadriphase Shift Keying (QPSK).

This paper will discuss two main ideas. The first is the design of supercells with cooperation between a large number of directional base-station transmitters. The second idea is base-station transmitter power weighting. Since cochannel interference is affected differently by different transmitters, it can be reduced by choosing proper power levels for the base-station transmitters in cellular systems composed by supercells.

The rest of this paper is organized as follows. Section II contains background material on conventional cellular systems, time-division retransmission, and propagation and interference models used in the analysis. Section III contains the new antenna configurations, and Section 3.1 the calculations of signal-to-cochannel-interference ratios for cellular systems with these configurations. Section 3.2 presents the transmitter power weighting analysis. Section IV contains a discussion and conclusions.

II. BACKGROUND MATERIAL

Before we discuss cellular systems in any detail, we will give some brief background information about conventional cellular arrangement, the time-division retransmission method, and signal propagation and interference models for the fading land mobile radio channel.

2.1 Conventional cellular arrangement

We will discuss frequency reuse in cellular systems for digital mobile radio systems. Figure 1 shows an example of a cellular system with three hexagonal cells ($N = 3$) per cluster. Frequencies are assigned as

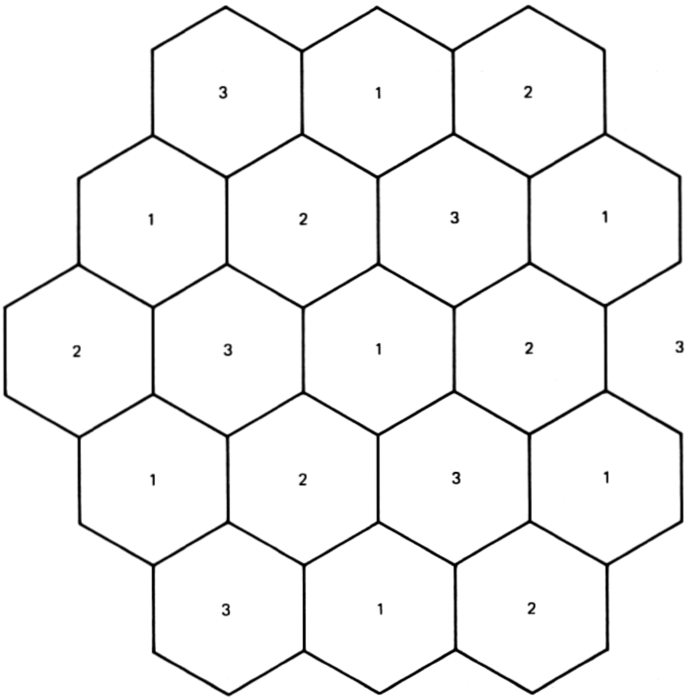

Fig. 1—Example of a cellular system. Each cell is a hexagon of equal area. The frequencies are reused. Cells marked with the same digit use the same frequency channel set. In a cluster of $N = 3$ cells, all channels are used.

in Fig. 2. The channel bandwidth is denoted B_c and the total system bandwidth is denoted B_T. Note that for a fixed total number of channels, a fixed antenna configuration, and a fixed cell size, a large frequency reuse factor, N, gives good cochannel interference (the interfering cells get further away) but a lower number of channels per base station (a low number of channels available at any particular location). This number is inversely proportional to N.

The antennas in each cell in Fig. 1 might be omnidirectional and then located in the center of the cell or 120-degree directional located in each of three corners.[1,2]

2.2 Time-division retransmission

The time-division retransmission (TDR) concept is described in Refs. 3 and 4. The basic ideas are the following. The fading channel changes "slowly" (during one burst or package). Communication in both directions takes place in packages transmitted in the same frequency band: first mobile-to-base and then base-to-mobile. During mobile-to-base transmission, the channel is estimated for maximal-

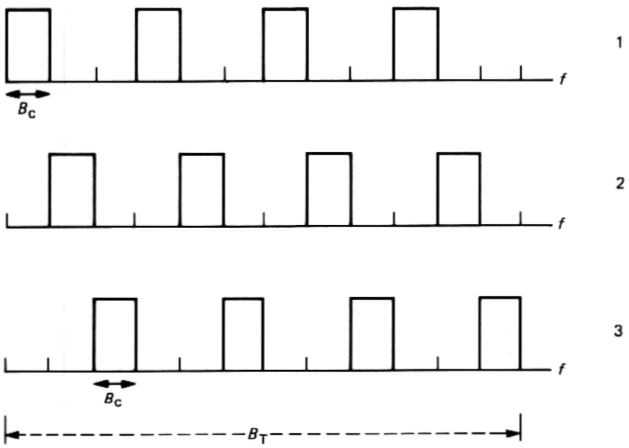

Fig. 2—Frequency plan for the cellular system with $N = 3$, shown in Fig. 6. The channel set marked 1 is used in each cell marked 1, etc. By channel we will consistently mean a two-way channel, including overhead for synchronization (when required).

ratio, space-diversity combining in both directions. Several schemes[3] have been proposed for performing the required co-phasing, for transmission from and reception at the base station. Because all diversity combining takes place at the base stations, the mobile equipment is relatively simple. As a consequence, it is feasible to use more than two branches of diversity with TDR.

We mention the concept of TDR because some of the cellular systems might require diversity because of short-frequency reuse distance and thus high cochannel interference.

2.3 Signal propagation and interference

It is assumed that mobile radio reception in an urban environment is characterized by

$$P(\bar{r}) = |\bar{r}|^{-\alpha} S(\bar{r}) \cdot R^2(\bar{r}), \tag{1}$$

where $P(\bar{r})$ is the received signal power at location $\bar{r}$ (position vector relative to a transmitter).[1,3,4] The first factor $|\bar{r}|^{-\alpha}$ is a reduction factor due to the distance between the mobile unit and the transmitter and α is the propagation constant. It is normally assumed that α is in the range three to four in the urban environment.[1,3] In free space, $\alpha = 2$.

The second factor, $S(\bar{r})$, represents shadow fading,[1,3,4] and the third factor, $R^2(\bar{r})$, represents Rayleigh fading.[4,5] R is the envelope of the received signal. It is modeled as a random variable with the density function

$$p(R) = 2Re^{-R^2}, \tag{2}$$

with $E\{R^2\} = 1$ (see Refs. 4 and 5). In general, R varies with vehicle location and signal frequency.

We will consider propagation and interference in cellular systems with frequency reuse, and use the same basic assumptions as in Refs. 1 and 3.

It is assumed that the cochannel interference is formed by the incoherent sum of contributions from many interfering sources. This sum is assumed to be equivalent to stationary Gaussian noise.[1,3] It is assumed that the shadow and Rayleigh fading of the total interference is negligible compared to the fading of the signal.[1,3,4]

It is also assumed that cochannel interference is the main source of additive signal degradation. The additive thermal background noise is assumed to be negliglible compared to the cochannel interference. Thus, the transmitter power and the cell sizes are assumed to be such that alien background noise from sources other than mobile units and transmitters in the cellular system is negligble compared to cochannel and adjacent-channel interference.

Below we will use the same technique as in Refs. 1 and 3 for calculating cochannel interference. The signal-to-interference ratio is defined as the ratio of the signal power to the total interference power, based on the $|\bar{r}|^{-\alpha}$ propagation law and averaged over shadow and Rayleigh fading. It is assumed that the fading is flat over the band of each channel.

III. NOVEL ANTENNA CONFIGURATIONS

In this section we will present some new methods of organizing antennas covering the hexagons in a cellular system. Analysis of signal-to-cochannel interference for some of these schemes is presented in Section 3.1. Adjacent channel interference is calculated in Ref. 6. These calculations are carried out based on the propagation assumptions made in the introduction and in Refs. 1 and 3.

Figure 3 illustrates the key idea in this paper. Assume base stations in three of the corners in Fig. 1. Form "supercells" by grouping the three cells with C/3 different channels in each into a new "cell" and let the total number of channels, i.e., C, be available throughout the cell. A new cellular system is formed, where the building block now is a cell with a centerbase station and six 120-degree corner stations.

Consequently, the cochannel interference properties of the cell in Fig. 3 are merely fair. By simply rotating the 120-degree corner antennas 30 degrees, one obtains a new larger hexagon (see Fig. 4). The radius of this cell is $r\sqrt{3}$, where r is the radius of the basic hexagonal cell in the three-corner system. The large hexagon is shown solid in Fig. 4.

It is clear from Fig. 4 that the area of the large hexagon ("super

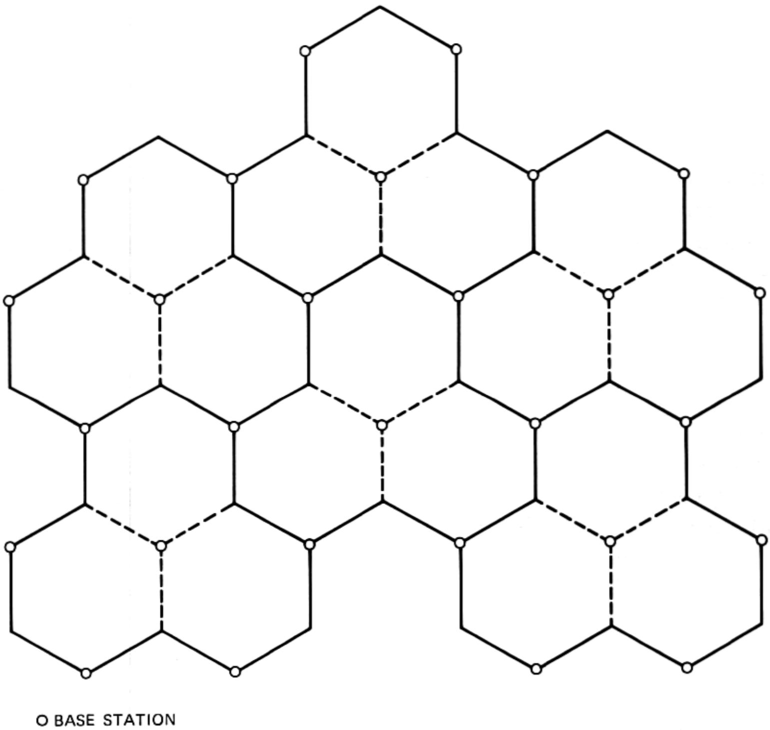

Fig. 3—A cellular system where "supercells" are formed by merging three conventional cells.

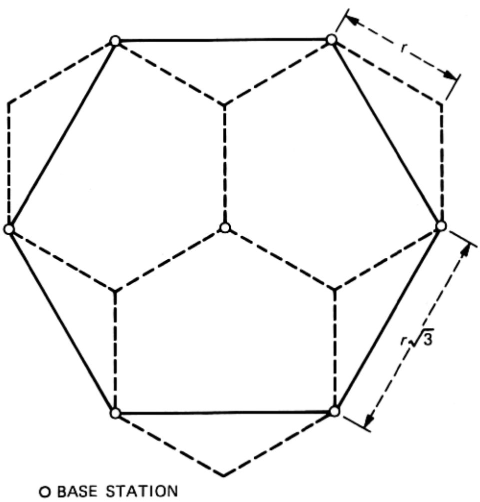

Fig. 4—Comparison between three conventional hexagonal cells (dashed) and a "superhexagon" (solid).

hexagon") is the same as that of three basic hexagonal cells. It is also clear that the cellular system based on the superhexagon has its base stations at exactly the same locations as the basic system with which we started.

Below, we will consider systems based on the superhexagon (and variations thereof). Above, we said that C/3 channels from each of the three basic cells were combined into C channels available throughout the supercell. This will mean not only increased channel availability but also somewhat increased cochannel interference, as we will see. The supercell will also be used with C/3 different channels available throughout the cell. This will mean decreased channel availability and decreased cochannel interference.

Figure 5 shows a number of ways to organize the antennas to cover a cell (hexagon). All the cells in Fig. 5 are shown with equal base-station locations. The shortest distance between base stations is $r\sqrt{3}$, where r is the radius of the basic cell *a*. It is assumed that the cellular system consists of a number of cells with equal antenna arrangements in each cell. Different cellular systems can be constructed based on the cells shown in Fig. 5.

By a cell we will mean the basic building block in a cellular system, like those in Fig. 5. Sometimes we will refer to a cell as a supercell. For these cases, this cell can be thought of as a combination of a group of smaller cells. Throughout the paper, comparisons will only be made between cellular systems where the base stations have identical locations.

Other cell types (triangular, square, etc.) are, of course, also conceivable (see e.g., Ref. 7). Groups of such basic cells can also be combined into "supercells," much the same way as we have done here for hexagons. The discussion in this paper will, however, be confined to the cells in Fig. 5.

Cases a, b, and c in Fig. 5 are considered in Refs. 1 and 3. In Fig. 5a the antenna is centrally located in each cell and is omnidirectional. In Fig. 5b the antenna is also centrally located in each cell, but the base station now consists of three 120-degree antennas. One of them serves a particular mobile unit at a particular moment. Because of the directivity of the antenna, interference is reduced during mobile-to-base transmission. Further improvements are obtained by placing 120-degree antennas in three cell corners (see Fig. 5c). This arrangement improves signal-to-interference ratios in both directions. The reason is that the distance from a base station to the desired mobile unit is improved relative to the distance to interference sources [see eq. (1) above]. The maximum distance from the desired mobile unit to the closest base station is the same in cells a, b, and c. In cell c it is assumed that the corner base station with the best signal-to-interfer-

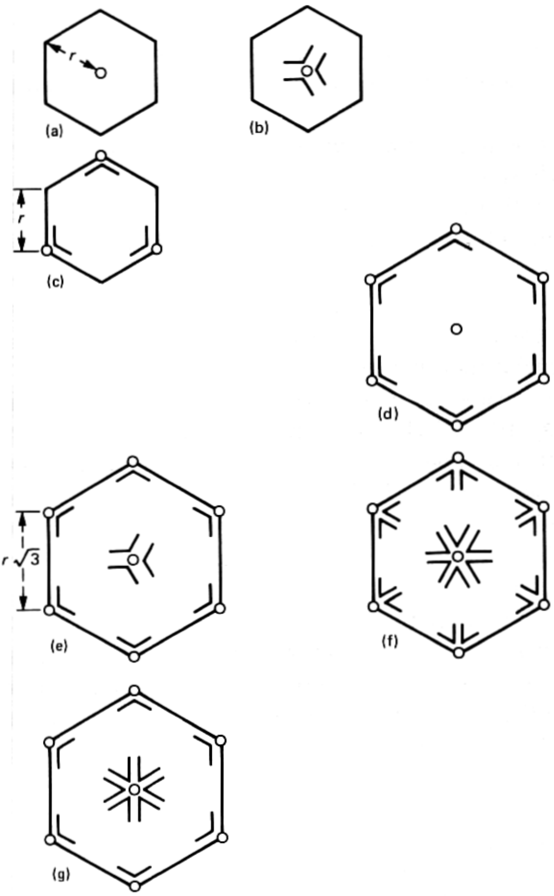

Fig. 5—Different ways of arranging antennas in a cell. Cell a has an omnidirectional antenna in the center of the cell. Cell b has 120-degree antennas in the center of the cell. Cell c has 120-degree antennas in three corners. Cells d, e, f, and g have antennas in all corners and in the center of the cell. Various combinations of 120-degree antennas, 60-degree antennas, and omnidirectional antennas are considered. The cells above will be referred to as cell a to cell g in the text. The cell radius is denoted r for the cells a to c. The radius is $r\sqrt{3}$ for cells d to g. The base-station locations are the same for all cells.

ence ratio serves the mobile unit. The three base stations require coordination so that the desired mobile unit is served by the base station with the best signal-to-interference ratio.

Figures 5d to 5g show arrangements with antennas placed in each cell corner and in the center of the cell. Figure 5e (cell type e) is the one we arrived at in the example above in Fig. 4. Figure 5d shows 120-degree antennas in the corners and an omnidirectional antenna in the center. Figure 5c shows 120-degree antennas in all places. Figure 5f shows the corresponding case with 60-degree antennas. Finally, Fig.

5g shows a hybrid between e and f. Below, we will concentrate on case e and f. Analysis will also be presented for some cases with cell d. For simplicity, the cells will be referred to as cells a to g in the following.

It is evident from Fig. 5 that the maximum distance from a desired mobile unit to the closest base station, d_0, is unchanged in cells d, e, f, and g, compared to cells a, b, and c. Figures 6 and 7 show cells e and f in more detail. It is easily seen that the maximum distance to the closest serving base station is $d_0 = r$ for all cells in Fig. 5.

Figure 6 shows the service areas for the different antennas for the cell in Fig. 5e, assuming all base stations are transmitting at equal power level. It is clear that the worst-case locations (in terms of

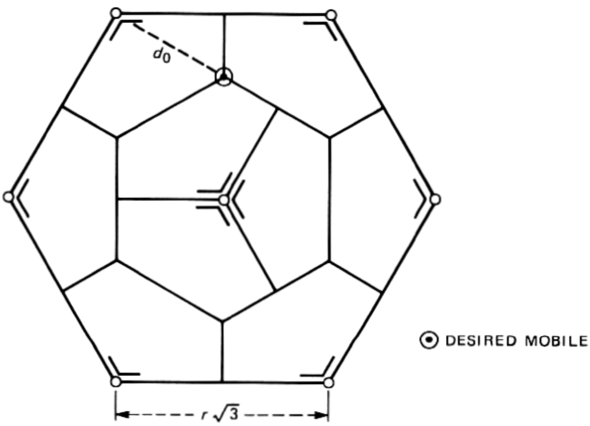

Fig. 6—Coverage areas for the 120-degree antennas in cell e. The example shows the location of a desired mobile unit with maximum distance to a base station.

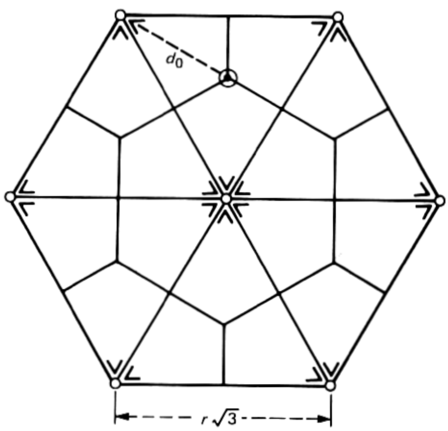

Fig. 7—Same as Fig. 6 for cell f.

maximum distance to the closest base station) for the desired mobile unit is on distance $d_0 = r$ from three base stations. Figure 6 shows that seven different antenna locations have to be coordinated so that a mobile unit within a particular cell is served by the base station with the best signal-to-interference ratio. Typically, only three stations are involved in this comparison for one particular location.

Figure 7 shows the service areas of the 60-degree antennas for the cell in Fig. 5f. Cell f has large similarities to cell e. The signal-to-interference ratio is improved for some cases, though (see tables below). This is, of course, due to the increased directivity of the base stations.

3.1 Cochannel-interference analysis for novel antenna configurations

Tables I to III summarize the results of some of the cochannel-interference calculations based on the assumptions presented above. For background, see Refs. 1 and 3. The cells are defined in Fig. 5. Column 1 also gives the number of base stations per cell (3/3 indicates 3 120-degree stations, 12/6 indicates 12 60-degree stations, etc.). The total number of base stations per unit area and the base-station locations are the same for all schemes (cells). For details of the calculations for cell e, i.e., 120-degree base stations in each of the six corners of the hexagon and in the center (see the appendix). Note that the signal-to-cochannel-interference ratio is not dependent on a particular modulation scheme or on a particular cell size, r. It is purely given by the relationships of distances from the desired base station to the desired mobile unit, and from the interfering base stations or mobile units.

It is assumed in the calculations that the background noise from other sources is negligible. The calculated signal-to-interference ratio determines which modulation method can be used (in terms of required detection efficiency) and how many branches of diversity (M) are required.[1,8]

Table I gives the results for various cell types for a cluster of one cell ($N = 1$), i.e., all frequency channels are used in each cell. The closest (and largest) cochannel interference comes from adjacent cells. The propagation exponent is assumed to be $\alpha = 3$. Some results for $N = 1$, $\alpha = 4$ are summarized in Table II.

Table I gives both average and worst-case signal-to-interference ratios for both mobile-to-base transmission and base-to-mobile transmission. For all cases, it is assumed that the desired mobile unit is in the least favorable location, with respect to the base stations in the cell where it is served. Worst-case mobile-to-base interference means that all mobile units in the interfering cells are in such positions that their contribution to the total interference is maximum. Average

Table I—Signal-to-cochannel interference ratio, $N = 1$, $\alpha = 3$

Base-Station Configuration		Mobile-to-Base						Base-to-Mobile			
		Worst Case		Average				Worst Case		Average	
Cell	No./Type of Stations per Cell	Center	Corner	Center,	M	Corner,	M		M		M
a	1	−10		−6.9	24			−4.8	20	−4.8	20
c	3/3		−4.3			−1.8	12	−1.8	12	>−1.8	12
d	6/3+1	−2.8	2.9	0.3	8	5.4	4	4.4	4	>4.4	
e	6/3+3/3	2.0	2.9	5.1	4	5.4	4	4.4	4	10.6	3
f	12/6+6/6	5.0	5.9	8.1	3	8.4	3	4.4	4	>10.6	

* (Cell type, see Fig. 5.)

Table II—Signal-to-cochannel interference ratio, $N = 1$, $\alpha = 4$

Base-Station Configuration		Mobile-to-Base						Base-to-Mobile			
		Worst Case		Average				Worst Case		Average	
Cell	No./Type of Stations per Cell	Center	Corner	Center,	M	Corner,	M		M		M
a	1	−10.5						−3.8		−3.8	
c	3/3		−3.6					−0.8		>−0.8	
d	6/3+1	−1.5	6.1	4.2				8.3			
e	6/3+3/3			9.0	3			8.3	3	>8.3	
f	12/6+6/6			12.0	2			8.3	3	>8.3	

* (Cell type, see Fig. 5.)

mobile-to-base interference means that the desired mobile unit still is in its worst possible location, but the interfering mobile units are at equally probable locations within their respective cells. The average is formed as described in Ref. 1.

The base-to-mobile signal-to-interference ratio for the worst case occurs when the desired mobile unit is in its least favorable position with respect to any serving base station in the cell, and when the interfering base stations are those which are as close as possible to the desired mobile unit. With one omnidirectional centrally located base station, there is only one case—worst case and average case are the same. When several 120-degree antennas serve the mobile units from various directions, as in cell e, for example, the worst case is a very pessimistic assumption (see the appendix for details).

Tables I to III also contain columns for the number of diversity branches (M) required with space diversity and ideal maximal-ratio

Table III—Signal-to-cochannel interference ratio, $N = 3$, $\alpha = 3$

Base-Station Configuration		Mobile-to-Base						Base-to-Mobile			
		Worst Case		Average				Worst Case		Average	
Cell	No./Type of Stations per Cell	Center	Corner	Center,	M	Corner,	M		M		M
a	1	0.6		2.8							
c	3/3					7.5	3	8.0	3		
d	6/3+1			10.0		14.7		12.6			
e	6/3+3/3			14.8	2	14.7	2	12.6	2	17.9	2
f	12/6+6/6			17.8	2	17.7	2	12.6	2	>17.9	2

* (Cell type, see Fig. 5.)

combining and coherent ideal Binary Phase Shift Keying (BPSK) modulation to achieve the bit error probability of 10^{-3}. This is to give an idea of what the calculated signal-to-interference ratios mean in a cellular system.

For details about the calculations of the signal-to-interference ratios in Tables I to III, see the appendix. Cells a and c have been considered before in Refs. 1 and 3. Some of the signal-to-interference ratios from Tables I to III are from these references. From the signal-to-interference results in Table I, we note that the cells a and c give extremely low values. Many branches of space diversity are required. With cells e and f, more "reasonable" numbers of M are required. Note that cell *d* is not attractive, since the center base station is very sensitive to interference during mobile-to-base transmission.

Table III gives the signal-to-interference results for clusters consisting of $N = 3$ cells and for a propagation constant of $\alpha = 3$. The results for cells a and c are from Refs. 1 and 3. Note the significant improvements by using cells e and f. For this case, two branches of diversity ($M = 2$) are sufficient for several modulation schemes.

Table III contains results for $N = 3$, $\alpha = 3$. The corresponding results for cell c for $\alpha = 4$ are given in Refs. 1 and 3. For cells d, e, and f, these $\alpha = 4$ results will, of course, be better than the corresponding $\alpha = 3$ results in Table III. They can easily be obtained using the same technique as for the $N = 1$, $\alpha = 4$ case and for the $N = 3$, $\alpha = 3$ case.

Figure 8 shows a detailed comparison of cells e and c. The comparison in Fig. 8 is as before at equal d_0 and at equal base-station locations.

The base-station transmitter power is also equal for the two schemes in Fig. 8. Thus, when comparing the schemes in Fig. 8, we observe the following:

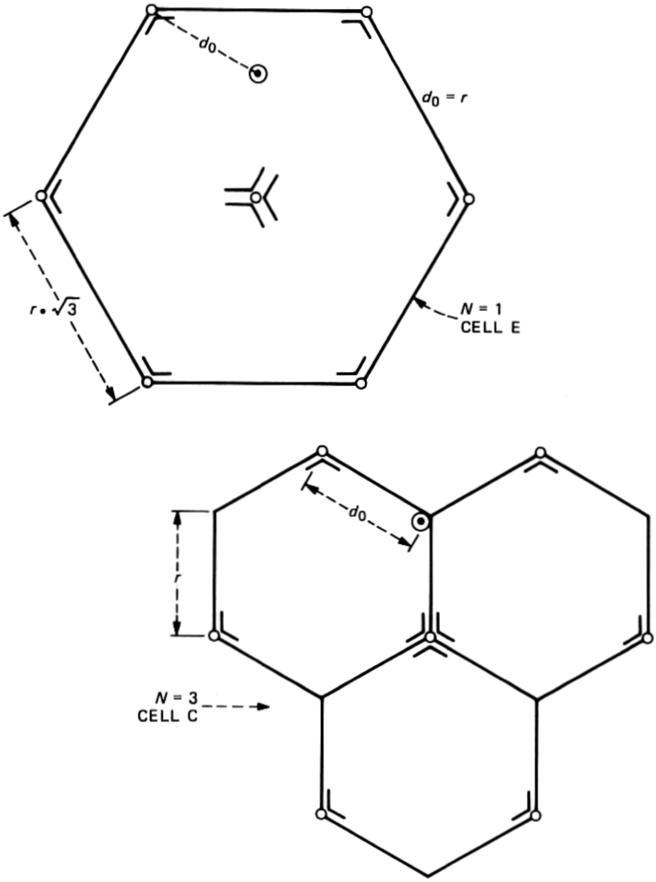

Fig. 8—Comparisons between $N = 3$, cell c radius r and $N = 1$, cell e, radius $r\sqrt{3}$.

1. The number of base stations per unit area is *the same.*
2. The locations of the base stations are the same.
3. The average cochannel interference is comparable (see Table I).
4. The total number of channels served per cell ($N = 1$, cell e or f) and per cluster of cells ($N = 3$, cell c) is the same.
5. The number of channels available at any point of location is three times higher in cells e and f than in cell c. This leads to improved trunking efficiency (see Section 3.3).
6. The number of channels per 120-degree transmitter is three times larger in cells e and f than in cell c.
7. The adjacent-channel-interference problem is worse in cells e and f than in cell c.

It should also be pointed out that, at the worst-case location for mobile-to-base transmission, there are two base stations within the same distance from the mobile unit for cell c, and sometimes three for cell e (see Fig. 8).

Note that the comparison made in Fig. 8 for $N = 1$, cells e and f and $N = 3$, cell c, can be extended to other N's with similar conclusions. For example, the case with $N = 3$, cells e, and f should be compared to $N = 9$, cell c for the same number of base stations per unit area and with an increase of a factor of three of the number of locally available channels at any particular point of location (see Fig. 9). The adjacent-channel-interference problem is now less serious.

We can also compare two systems based on different cells with the same number of cells (N) per cluster. As an example, consider $N = 3$, cell c and e (or f) with the same number of base stations per unit area and the same base-station locations. Table III gives cochannel-interference results. For this situation we can conclude that:

1. The number of base stations per unit area is the same (same locations).
2. The average cochannel interference is better with cells e and f than with c.
3. The total number of channels served per cell is the same. The total number of channels per three cells of type c is three times that of the number of channels available in one cell of type e, f.
4. The total number of channels available at any specific location is the same in the two cases.
5. The number of channels per 120-degree transmitter is the same.
6. The adjacent-channel-interference problems are worse for cell c than e, f.

3.2 Transmitter power weighting

All the transmitters in systems based on cells a, b, and c (see Fig. 5) have the same properties. Except for the edges in the whole cellular system, the interference situation is the same around each transmitter. All transmitters above are assumed to be transmitting at the same power levels.

The situation is different for cells of type e, f. The center transmitters clearly have a different environment than the corner transmitters. It is not immediately clear why these transmitter power levels should be the same, as we assumed in the analysis above. On the contrary, there are possible improvements in base-to-mobile cochannel interference through reduction of the transmitter power levels for the center stations compared to the corner stations. The consequences of this are that the worst-case location for base-to-mobile and mobile-to-base transmission cochannel interference might be different and that the

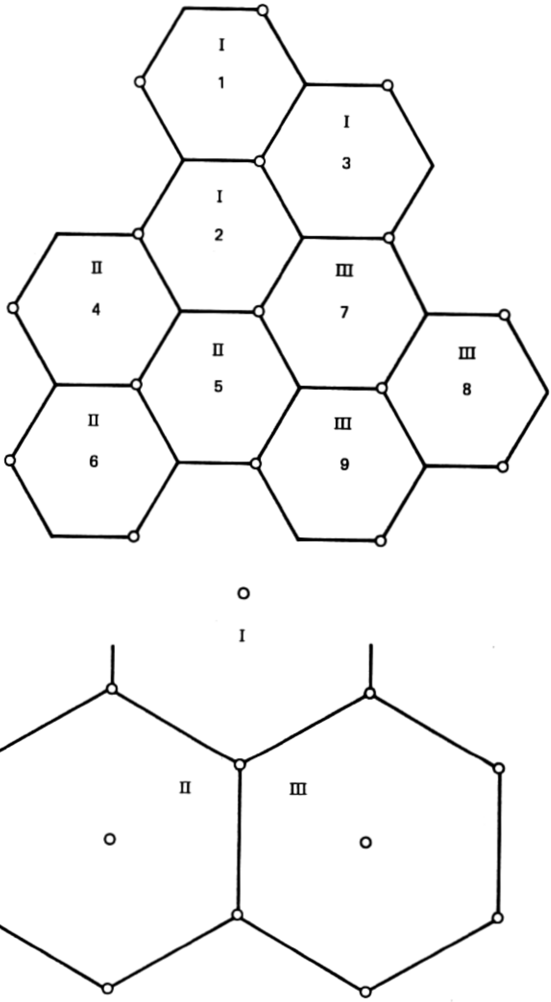

Fig. 9—Comparison between a conventional cellular system with $N = 9$ cells in a cluster and a system based on cell e with $N = 3$ cells in a cluster.

base-to-mobile interference can be improved, for both worst case and average. Mobile-to-base transmission is not affected.

We will now give two examples of what the weighting should be for improving the worst-case components among all the contributions to cochannel interference for the base-to-mobile transmission.

Figure 10 shows the $N = 1$ case with cell e. Assume for simplicity that the radius is one. Assume that the mobile unit is in position M. Furthermore, assume that the worst-case cochannel-interference components will occur somewhere along a straight line from the center

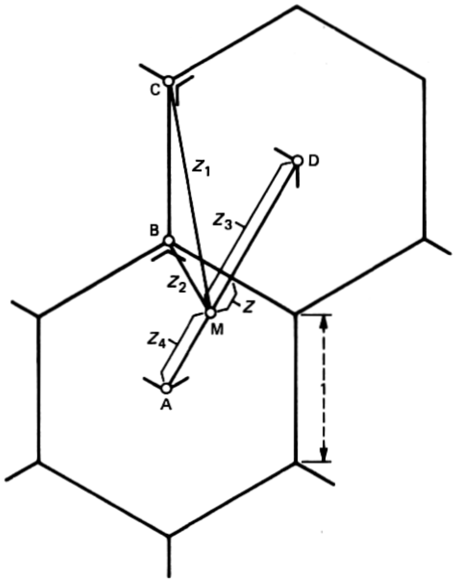

Fig. 10—Notations for analysis of worst-case cochannel interference for cell e, $N = 1$ with transmitter-power weighting.

stations A and D (due to symmetry). The two closest interfering stations are D and C and the two closest base stations serving the mobile unit M are A and B.

Assume that the transmitter power of the corner transmitters is P. The center station has the transmitter power βP, where β is the weighting factor. The dominating components in the cochannel-interference ratio are:

1. For a mobile unit served from corner station B, the signal-to-cochannel-interference ratio is

$$\left(\frac{Z_1}{Z_2}\right)^{\alpha} = \left[\frac{1 + \left(\frac{\sqrt{3}}{2} + Z\right)^2}{\frac{1}{4} + Z^2}\right]^{\alpha/2}, \tag{3}$$

when the interferer is station C, and is

$$\frac{1}{\beta}\left(\frac{Z_3}{Z_2}\right)^{\alpha} = \frac{1}{\beta}\left[\frac{\left(\frac{\sqrt{3}}{2} + Z\right)^2}{\frac{1}{4} + Z^2}\right]^{\alpha/2}, \tag{4}$$

when the interferer is station D. Z is the distance from the mobile unit to the cell boundary (see Fig. 10).

2. For a mobile unit served from the center station A, the signal-to-cochannel-interference ratio is

$$\beta\left(\frac{Z_1}{Z_4}\right)^{\alpha}=\beta\left[\frac{1+\left(\frac{\sqrt{3}}{2}+Z\right)^2}{\left(\frac{\sqrt{3}}{2}-Z\right)^2}\right]^{\alpha/2}, \tag{5}$$

when the interferer is station C, and is

$$\left(\frac{Z_3}{Z_4}\right)^{\alpha}=\left[\frac{\left(\frac{\sqrt{3}}{2}+Z\right)^2}{\left(\frac{\sqrt{3}}{2}-Z\right)^2}\right]^{\alpha/2}, \tag{6}$$

when the interferer is station D.

What is the best choice for β? Select β so that the worst-case location (M) has as large a signal-to-interference ratio as possible. This optimization depends on the propagation exponent, α, i.e., β is a function of α. We found that the best weighting parameter is $\beta = 0.23$, with $Z = 0.416$ for $\alpha = 4$.

This should be compared with the nonweighted case where $\beta = 1$. Here the worst-case term for the cochannel-interference occurs for $Z = 0$. Thus, the improvement of the worst-case cochannel-interference component with weighting is 6.4 dB for $\alpha = 4$.

It can also be expected that the average base-to-mobile cochannel interference is improved significantly by means of weighting. The worst contributors to the noise are the center base stations, and they are now reduced in power. The optimum β with this criterion might differ from the optimum β derived above.

More terms than the worst one, of course, have to be taken into account in a complete analysis. There seems to be room for signficant improvements by means of weighting, however.

Transmitter-power weighting can also be employed for cell e, Fig. 5, with $N = 3$ cells in a cluster. The definitions of locations and parameters are equivalent to the above (see Fig. 11). We assume that the worst-case mobile location for the base-to-mobile cochannel-interference contribution occurs on the straight line from transmitter location A to E (see Fig. 11).

Using the same technique as in the appendix and above, we have the following worst-case cochannel-interference components:

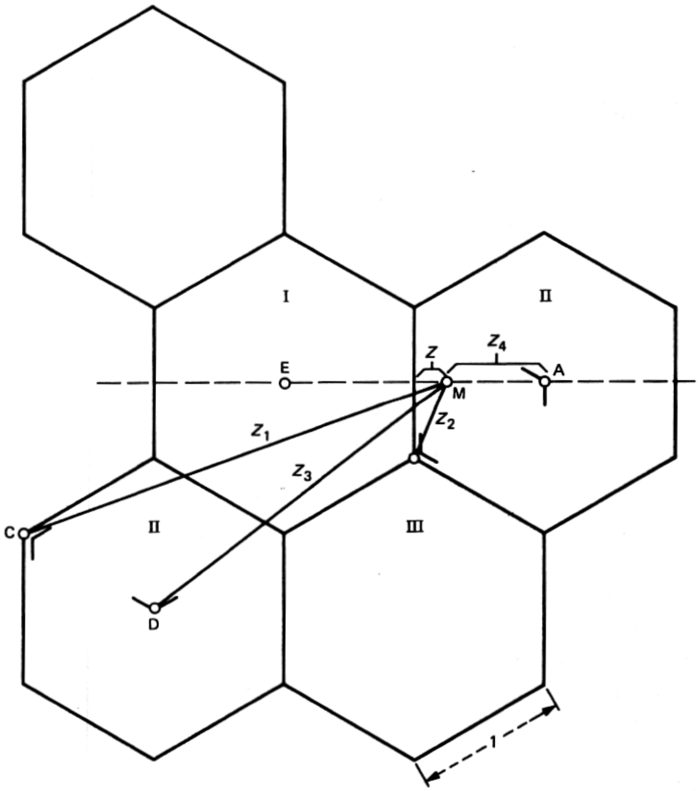

Fig. 11—Same as Fig. 10 with $N = 3$.

1. For a mobile unit served from corner station B, the signal-to-cochannel-interference ratio is

$$\left(\frac{Z_1}{Z_2}\right)^{\alpha} = \left[\frac{1 + \left(\frac{3\sqrt{3}}{2} + Z\right)^2}{\frac{1}{4} + Z^2}\right]^{\alpha/2}, \tag{7}$$

when the interferer is station C, and is

$$\frac{1}{\beta}\left(\frac{Z_3}{Z_2}\right)^{\alpha} = \left[\frac{\left(\frac{3}{2}\right)^2 + (\sqrt{3} + Z)^2}{\frac{1}{4} + Z^2}\right]^{\alpha/2}, \tag{8}$$

when the interferer is station D.

2. For a mobile unit served from the center station A, the signal-to-cochannel-interference ratio is

$$\beta\left(\frac{Z_1}{Z_4}\right)^{\alpha} = \left[\frac{1+\left(\frac{3\sqrt{3}}{2}+Z\right)^2}{\left(\frac{\sqrt{3}}{2}-Z\right)^2}\right]^{\alpha/2}, \tag{9}$$

when the interferer is station C, and is

$$\left(\frac{Z_3}{Z_4}\right)^{\alpha} = \left[\frac{\left(\frac{3}{2}\right)^2+(\sqrt{3}+Z)^2}{\left(\frac{\sqrt{3}}{2}-Z\right)^2}\right]^{\alpha/2}, \tag{10}$$

when the interferer is station D. As in the previous example, the transmitter power of all center stations is βP, where P is the transmitter power of the corner stations. The parameter β is the weighting.

The minimum worst-case cochannel-interference components [eqs. (7) to (10)] occur for the parameters in Table IV. This table shows optimum weighting for minimizing the worst-case contribution to the signal-to-cochannel interference ratio for $N = 3$, cell e.

The gain in the table above is the improvement of the worst-case cochannel-interference contribution with optimum weighting compared with no weighting. For the no-weighting case ($\beta = 1$), the worst case is $Z = 1/2\sqrt{3} \approx 0.289$.

The average cochannel interference will also be improved for the $N = 3$ case with proper weighting. The optimum β has to be found, however. The optimization above was only carried out for the worst-case components.

The extreme case of center base-station power weighting is $\beta = 0$. For this case, there are no center stations at all. This cell is shown in Fig. 12. One third of the base stations can be saved. However, the cochannel interference increases compared to cell e, Fig. 5, particularly mobile-to-base. The mobile transmitter power must also be increased

Table IV—Optimum weighting

α	β	Z	Gain
4	0.276	0.401	5.6 dB
3.7	0.303	0.401	5.2 dB
3	0.381	0.401	4.2 dB

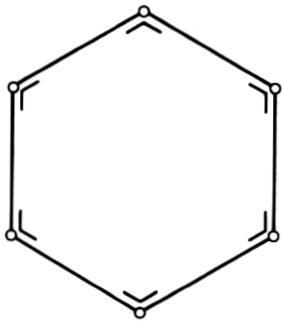

Fig. 12—A cell with one-third fewer base stations than cell e, Fig. 5.

somewhat. The distance to the nearest transmitter is significantly increased for the cell in Fig. 12 compared with cell e.

3.3 Trunking efficiency

We saw above in Section 3.1 that the local availability of channels with cell e is three times that with a cluster of three conventional cells of type c. This three-fold increase in availability of channels leads to improved trunking efficiency with cell e. To illustrate this gain, we give the following example.

Compare a system based on the "superhexagon" cell e with a total of 45 available channels and a system based on the conventional cell c. In the latter case, we assume that 15 channels are available at each station. Thus, in a cluster of 3 cells, type c, there are a total of 45 channels, as with cell e. However, with cell e, the 45 channels are available at all locations throughout the cell e, while with the cluster of 3 cells of type c, 15 channels are available in each cell.

The traffic behavior of Mobile Radio-Telephone Systems might be modeled by Erlang C tables. (The calls are delayed, but eventually placed. The calls are not rerouted over alternate facilities, nor do they go away.)

Assume a blocking probability of two percent using Erlang C tables; the traffic carried by the system in cell e is 32.03 erlangs, while the system with cell c carries 8.03 erlangs in each cell, or 24.1 erlangs in a cluster of three cells. Thus, the system based on cell e carries 7.93 erlangs more per area corresponding to one cell e (3 cells of type c) than the conventional system.

Instead, using Erlang B tables, the traffic carried by the system with cell e is 35.61 erlangs, while with cell c, the traffic in each cell is 9.01 erlangs and in a cluster of three cells about 27.0 erlangs. Thus, the system based on cell e carries 8.6 erlangs more per area corresponding to one cell e (3 cells of type c) than the conventional system.

The best model is perhaps a modified Erlang B—something between Erlang B and C. Some percentage of the calls may never be made or may be rerouted. In any case, the basic conclusion is the same: A significant improvement of the trunking efficiency is achieved with cell e.

3.4 Relationship with dynamic channel assignment schemes

In the example above, it is evident that the trunking efficiency is improved by using cell e instead of a cluster of three cells of type c. The increased local availability of channels should also improve the capability of matching nonuniform geographic traffic patterns.

With conventional cells, this problem is dealt with by using dynamic channel assignment schemes.[4,9] The novel cell types, e.g., cell e, are somewhat like this. The control algorithm is fixed with cell e, however. Further work, especially simulations, is required for evaluating the above relationship.

IV. DISCUSSION AND CONCLUSIONS

Novel antenna configurations for cellular digital radio systems are introduced and analyzed in this paper. Two key ideas are presented. The first is designing new cells by keeping the base-station locations in conventional cellular systems and rearranging the antenna patterns. Basically, merging conventional cells into larger, novel cells improves trunking efficiency. The local availability of channels is increased. The second idea is transmitter-power weighting. The base-station transmitters in the novel cells have different roles depending on the exact location. The center stations and the corner stations contribute differently to the cochannel interference. Thus, the signal-to-cochannel interference ratio can be improved by proper weighting of the transmitter-power levels.

Many unsolved problems remain. The analysis above (as that in Refs. 1 and 3) is based on idealized assumptions about the selection of the serving base station and on very simple and idealized channel and interference models. More refined analysis and simulations will be necessary. The analysis above was carried out under the idealized assumptions of flat fading. Uniform transmission conditions were assumed for all cells. No delay spread was considered. Perfect timing and synchronization was assumed with coherent detection and ideal maximal-ratio combining. It was furthermore assumed that perfect synchronization for the time-division retransmission scheme was established. The analysis was confined to local-mean values of signal and interference at isolated points. Consequently, the effects of shadow fading were not taken into account, and no results were obtained for overall signal-to-interference statistics throughout entire cellular areas. The effect of channel occupancy (the fraction of time that a channel is in use) on interference was not considered. All of the above problems and others have to be taken into account in a refined system analysis.

Some of the aspects of choosing a modulation scheme for digital cellular mobile radio systems are dealt with in Refs. 6 and 8. Adjacent-channel interference in cellular systems is calculated in Ref. 6 for some bandwidth-efficient constant amplitude modulation schemes.

Further work should be devoted to the traffic-carrying aspects of cellular systems based on the novel cells. Detailed comparisons with dynamic channel assignment schemes with conventional (and novel) cells should be made.

V. ACKNOWLEDGMENTS

Thanks are due to the reviewers, who pointed out the trunking efficiency aspects of the novel cells and the relationship with dynamic channel assignment.

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APPENDIX

Details of Cochannel-Interference Calculations

This appendix contains some details about the calculations of the signal-to-cochannel-interference ratios given in Tables I to III in Section 3.1 above.

Figure 13 shows the worst-case location for the desired mobile unit for the case of transmission from base to mobile with $N = 1$, $\alpha = 3$, and 120-degree base stations in all corners and in the center (cell e).

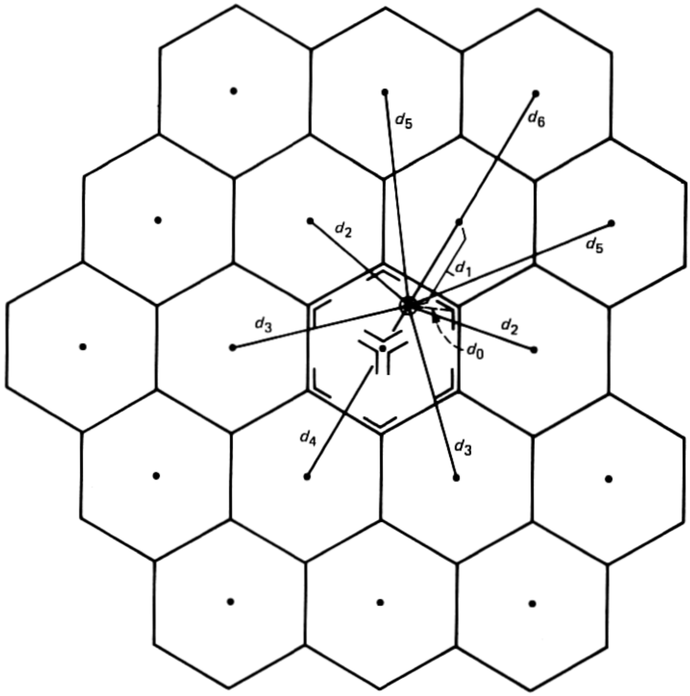

Fig. 13—Worst-case location for the desired mobile unit for worst-case base-to-mobile transmission $N = 1$, $\alpha = 3$, cell e. This location of the desired mobile unit is referred to as location A.

Assume that the base stations in nearby cells are serving mobile units in interfering frequency slots in such a way that the base station in a particular cell is as close as possible to the desired mobile unit, thus contributing maximally to the cochannel interference. Thus, the worst-case interference power to signal power is given by the distance relationships[1,3]

$$\frac{P_I}{P_S} = \left(\frac{d_0}{d_1}\right)^3 + 2\left(\frac{d_0}{d_2}\right)^3 + 2\left(\frac{d_0}{d_3}\right)^3 + 2\left(\frac{d_0}{d_5}\right)^3 + \left(\frac{d_0}{d_4}\right)^3 + \left(\frac{d_0}{d_6}\right)^3 + \text{terms from cells further away.} \quad (11)$$

The worst-case position above is given by the location where the mobile unit is as far away as possible from the nearest base station in the cell. Thus $d_0 = r_0\sqrt{3}$, where r_0 is the cell radius (of cell e) (see Fig. 8).

The dominating term in eq. (11) is

$$\left(\frac{d_0}{d_1}\right)^3 = \left(\frac{r_0/\sqrt{3}}{2r_0/\sqrt{3}}\right)^3 = \left(\frac{1}{2}\right)^3. \tag{12}$$

Compare the dominating term in the $N = 1$ schemes with centrally located base stations or corner stations only in Refs. 1 and 3. In this case, this term is 1, independent of α. For the above case, the cochannel-interference noise suppression improves with the propagation constant α.

Taking into account contributing terms from the 23 interfering cells closest to the cell with the desired mobile unit we have (see Table I)

$$\frac{P_S}{P_I} \approx 4.4 \text{ dB}. \tag{13}$$

This is the signal-to-interference ratio for base-to-mobile transmission with the worst-case location of the desired mobile unit. All the interfering base stations are assumed to be in a worst-case mode of operation too. The propagation exponent is $\alpha = 3$, and the frequency plan is such that all cells use the total number of frequency slots, $N = 1$. We have assumed that each cell has 120-degree base stations in each corner and in the center, cell e.

Figure 14 shows the location of the desired mobile unit in the cell where the worst-case relationship is between the distance to the nearest transmitter in the cell and the distance to the nearest interfering base station in the adjacent cells. In this case, the interference-to-signal ratio is

$$\frac{P_I}{P_S} = \left(\frac{d_0}{d_1}\right)^3 + 2\left(\frac{d_0}{d_2}\right)^3 + 4\left(\frac{d_0}{d_3}\right)^3 + 2\left(\frac{d_0}{d_4}\right)^3$$
$$+ \text{ terms from interfering cells further away.} \tag{14}$$

The dominating term is now given by $d_0 = r_0/2$, $d_1 = r_0\sqrt{3}/2$, thus

$$\left(\frac{d_0}{d_1}\right)^3 = \left(\frac{1}{\sqrt{3}}\right)^3. \tag{15}$$

This term is, of course, larger than eq. (12). However, the other terms in eq. (14) are smaller than their counterparts in eq. (11) because d_0 is smaller in Fig. 14 than in Fig. 13. Thus, it is not immediately evident which location, A or B, is generally the worst-case location for the desired mobile unit.

Carrying out the calculations in eq. (14) with the same number of terms as in eq. (11), we have the signal-to-distortion ratio

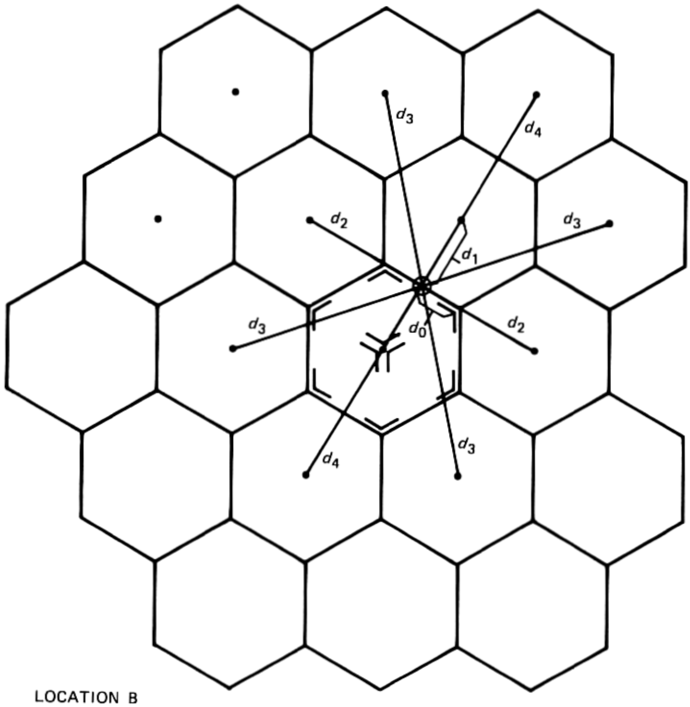

Fig. 14—Location of the desired mobile unit where (d_0/d_1) is maximum. Otherwise, same case as Fig. 13. This location of the desired mobile unit is referred to as location B.

$$\frac{P_S}{P_I} \cong 4.5 \text{ dB} \tag{16}$$

for the worst case in Fig. 14, for $\alpha = 3$. Thus, the location in Fig. 13 is slightly worse for the $N = 1$, $\alpha = 3$ case.

It is even conceivable that some location between that in Figs. 13 and 14 is the worst case for $\alpha = 3$. We do not expect more than a very small (if any) deviation from eq. (13), however.

We have also carried out the calculations of the base-to-mobile worst-case signal-to-cochannel-interference ratio for the cases in Figs. 13 and 14 for the propagation exponent $\alpha = 4$. For this case, the dominating term for location A is

$$\left(\frac{d_0}{d_1}\right)^4 = \left(\frac{1}{2}\right)^4, \tag{17}$$

and for location B,

$$\left(\frac{d_0}{d_1}\right)^4 = \left(\frac{1}{\sqrt{3}}\right)^4. \tag{18}$$

Carrying out the calculation of eqs. (11) and (14) for $\alpha = 4$ for the locations A and B we have, for $\alpha = 4$,

$$\frac{P_S}{P_I} \approx 9.2 \text{ dB location A},$$

$$\frac{P_S}{P_I} = 8.3 \text{ dB location B}.$$

Thus, in this case ($\alpha = 4$), location B is the worst case. This is what might be expected from the formulas above. For large α's, the first term [in generalizations of eqs. (11) and (14)] will play an increasing role.

Above, we have calculated the signal-to-interference ratio for the worst-case base-to-mobile transmission where we assumed worst-case conditions, i.e., that the desired mobile unit is in the worst location and that the mobile units in neighboring cells are all in such positions that the interference from all cells is maximum. This is, of course, a very pessimistic assumption. Next, we will calculate the average interference power when it is assumed that all positions of a particular mobile unit in a cell are equally probable. Thus, the probability that a mobile unit is served by a particular 120-degree base station is 1/5 in configuration e (see Fig. 5e). Note that it is still assumed that the desired mobile unit is in its worst location. Other positions for the desired mobile unit will yield better signal-to-interference ratios. With the assumptions above, we have the contributions to the average interference-to-signal power ratio for the closest cell,

$$\frac{P_I}{P_S} = \frac{1}{9}\left(\frac{d_0}{d_1}\right)^3 + \text{other smaller terms within the cell}$$
$$+ \text{ terms from other interfering cells.} \tag{19}$$

Note that the contribution from each base station is scaled with either 1/9, when it is pointed towards the desired mobile unit, or 0, when it is pointed in a different direction. The worst-case term $(d_0/d_1)^3$ is now scaled down with a factor of 1/9. Continuing the calculation in eq. (19) and including all the cells included in the calculation of eq. (11), we have the approximate average signal-to-cochannel-distortion ratio with the desired mobile unit in the worst location A for the $\alpha = 3$, $N = 1$ case with 120-degree base stations in all corners and in the center of the cell,

$$\frac{P_S}{P_I} \approx 10.6 \text{ dB}. \tag{20}$$

This is significantly better than the worst case [eq. (13)] of 4.4 dB for the worst-case location for the desired mobile unit. The large improvement is, of course, due to the fact that the surrounding interfering cells only use the interfering antennas that are closest to the desired mobile unit part of the time. Sometimes, there is no interference from a particular cell, because the mobile unit served on the same frequency channel in that particular cell is served by an antenna that is not pointed in the direction of the desired mobile unit.

Figure 15 shows the worst-case mobile-to-base cochannel interference for the 120-degree corner base station in a cell with 120-degree base stations in all corners and in the center. The desired mobile unit is assumed to be in its worst position, A, on distance $d_0 = r\sqrt{3}$ from the serving base station (see Fig. 13). Mobile units on interfering frequency channels are all assumed to be in the least favorable position in their cells (see Fig. 15). With straightforward calculations like those earlier in this appendix, we arrive at the signal-to-interference ratio of approximately 2.9 dB for $\alpha = 3$ (see Table I).

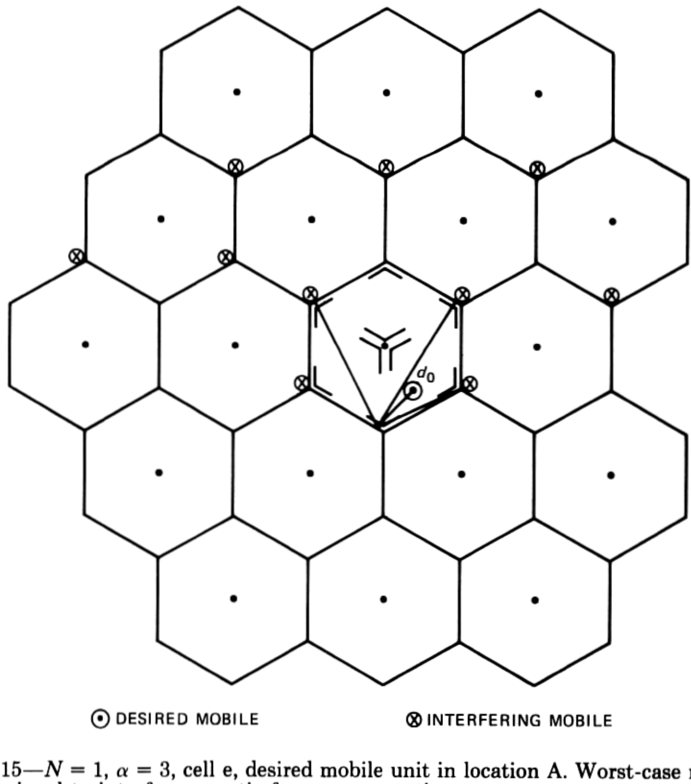

Fig. 15—$N = 1$, $\alpha = 3$, cell e, desired mobile unit in location A. Worst-case mobile-to-base signal-to-interference ratio for a corner station.

The center base station is more sensitive to worst-case mobile-to-base cochannel interference that the corner base stations in Fig. 15. Figure 16 shows this. The worst locations for interfering mobile units are closer to the base station serving the desired mobile unit in this case. The signal-to-interference ratio for this worst case is approximately 2.0 dB.

It is clear from Fig. 16 that an ominidirectional center antenna is very sensitive to mobile-to-base cochannel interference. The lack of directivity forces it to receive interference from all directions, while the desired mobile unit is in a particular direction. Thus, it is advantageous to use 120-degree antennas rather than omnidirectional antennas. Further improvements are obtained by using 60-degree antennas (see Fig. 7 and Table I).

The worst-case base-to-mobile cochannel interference is the same for omnidirectional, 120- or 60-degree center antennas (see Table I).

The assumption that all interfering mobile units are in their worst positions in their respective cells is, of course, a very pessimistic one. It is more realistic to calculate an average interference, where the mobile units are assumed, with equal probability, to be in any position

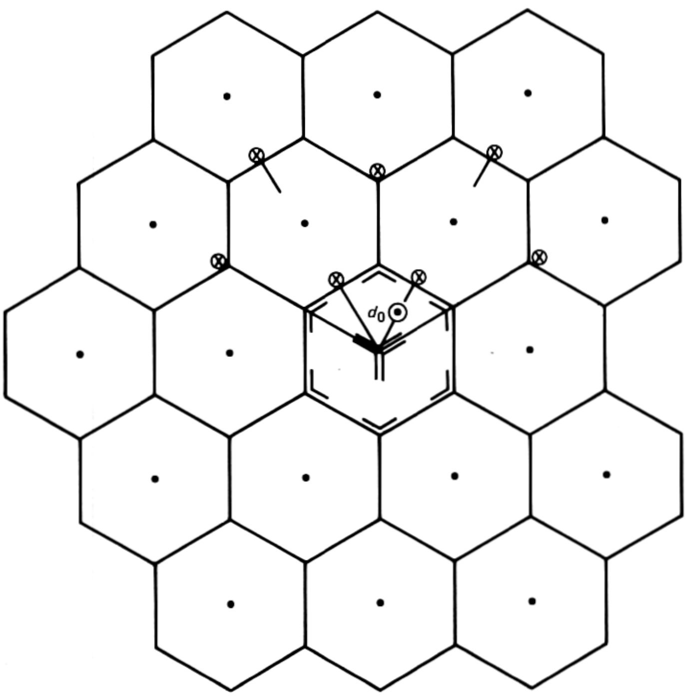

Fig. 16—Same as Fig. 15 for a center station.

within a cell. Using the averaging technique, described in detail in Ref. 1, we obtain the average signal-to-interference ratios for mobile-to-base transmission in Tables I to III in Section 3.1.

By using 60-degree antennas, the interference above is reduced by a factor of two. Since the center base station is the most sensitive one, it is, of course, conceivable with a hybrid scheme with 120-degree antennas in all the corners and 60-degree antennas in the center locations (see Fig. 5g).

The cochannel-interference calculations behind the remaining signal-to-cochannel-interferences ratios in Tables I to III above are carried out with the same techniques as above. The averaging technique for the mobile-to-base cochannel interference in Ref. 1 is easily extended to the propagation exponent $\alpha = 4$. Location A is the worst case for $N = 3$, $\alpha = 3$ with cell e.

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