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Advanced Mobile Phone Service:

The Cellular Concept

By V. H. MAC DONALD

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This paper shows how a cellular system operating within a limited block of frequency spectrum can meet the objectives of a large-scale mobile-telephone service designed with attention to cost restraint. It explores the key elements of the cellular concept—frequency reuse and cell splitting—and describes certain mathematical properties of hexagonal cellular geometry. A description of the basic structure and features of AMPS *shows how the cellular concept can be put into practice.*

I. INTRODUCTION

The preceding paper in this issue[1] noted that Bell System planners were already looking ahead to a more economical and widespread form of mobile-telephone service when early mobile telephone systems were being installed in the 1940s. Since then, system designers have recognized that a substantial block of radio-frequency spectrum, equivalent to hundreds of voice channels, is a prerequisite for a large-scale mobile service. This spectrum was provided by the FCC's reallocation of a portion of the former UHF television band for mobile service in Docket 18262. This paper cites the system objectives adopted over the years, explores the cellular concept which evolved in response to these objectives, and describes many aspects of a practical embodiment of the cellular concept—the Advanced Mobile Phone Service (AMPS) system.

II. OBJECTIVES FOR LARGE-SCALE MOBILE-TELEPHONE SERVICE

Over the years, system designers have set various objectives for large-scale mobile-telephone service, based on the interests of the public, mobile-telephone customers, and mobile-telephone operating companies. The first paper in this issue[1] cited the following basic objectives:

- (*i*) Large subscriber capacity.
- (*ii*) Efficient use of spectrum.
- (*iii*) Nationwide compatibility.
- (*iv*) Widespread availability.
- (*v*) Adaptability to traffic density.
- (*vi*) Service to vehicles and portables.
- (*vii*) Regular telephone service and special services, including "dispatch."
- (*viii*) "Telephone" quality of service.
- (*ix*) Affordability.

Various systems might be devised to satisfy all the above objectives, except for the first two. The system must be capable of growing to serve many thousands of subscribers within a local service area, such as the environs of a single city, yet the provision of service must not be contingent on the continual enlargement of the allocated spectrum. The need to operate and grow indefinitely within an allocation of hundreds of channels has been the primary driving force behind the evolution of the cellular concept.

III. BASIC ELEMENTS OF THE CELLULAR CONCEPT

The two phrases *frequency reuse* and *cell splitting* summarize the essential features of the cellular concept.

3.1 Frequency reuse

Frequency reuse refers to the use of radio channels on the same carrier frequency to cover different areas which are separated from one another by sufficient distances so that co-channel interference is not objectionable. Frequency reuse is employed not only in present-day mobile-telephone service but also in entertainment broadcasting and most other radio services.

The idea of employing frequency reuse in mobile-telephone service on a shrunken geographical scale hints at the cellular concept. Instead of covering an entire local area from one land transmitter site with high power at a high elevation, the service provider can distribute transmitters of moderate power throughout the coverage area. Each site then primarily covers some nearby subarea, or zone, or "cell." A cell thus signifies the area in which a particular transmitter site is the site most likely to serve mobile-telephone calls. Figure 1 is a sketch of a cellular map or "layout." In principle, the spacing of transmitter sites does not need to be regular, and the cells need not have any particular shape. Cells labeled with different letters must be served by distinct sets of channel frequencies to avoid interference problems. A cell

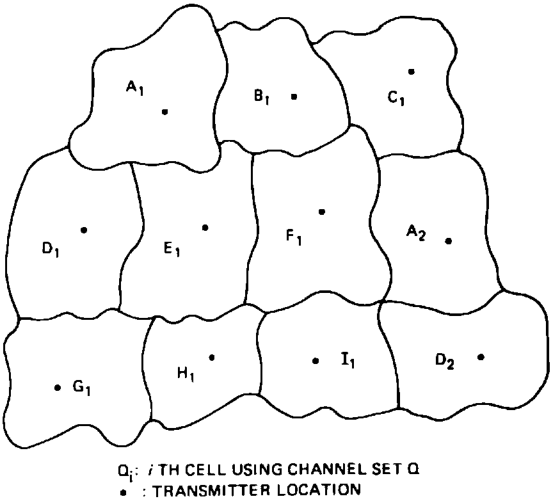


Fig. 1—Cellular layout illustrating frequency reuse.

therefore has the additional significance that it is the area in which a particular channel set is the most likely set to be used for mobile-telephone calls. Cells sufficiently far apart, such as those labeled A_1 and A_2, may use the same channel set.

Through frequency reuse, a cellular mobile-telephone system in one coverage area can handle a number of simultaneous calls greatly exceeding the total number of allocated channel frequencies. The multiplier by which the system capacity in simultaneous calls exceeds the number of allocated channels depends on several factors, particularly on the total number of cells.

3.2 Cell splitting

If the total allocation of C channels is partitioned into N sets, then each set will contain nominally $S = C/N$ channels. If one channel set is used in each cell, eventually the telephone traffic demand in some cell will reach the capacity of that cell's S channels. Further growth in traffic within the cell will require a revision of cell boundaries so that the area formerly regarded as a single cell can now contain several cells and utilize all these cells' channel complements. The process called "cell splitting" fills this need.

Figure 2a illustrates an early stage of the cell-splitting process, in which the cell originally designated F_1 (in Fig. 1) has reached capacity. The area previously treated as cell F_1 now contains cells H_3, I_3, B_6, and C_6. If the demand in the area continues to grow, other larger cells will be split, and eventually, as in Fig. 2b, the entire region will be converted into smaller cells.

In practice, splitting a given cell may be less abrupt than our

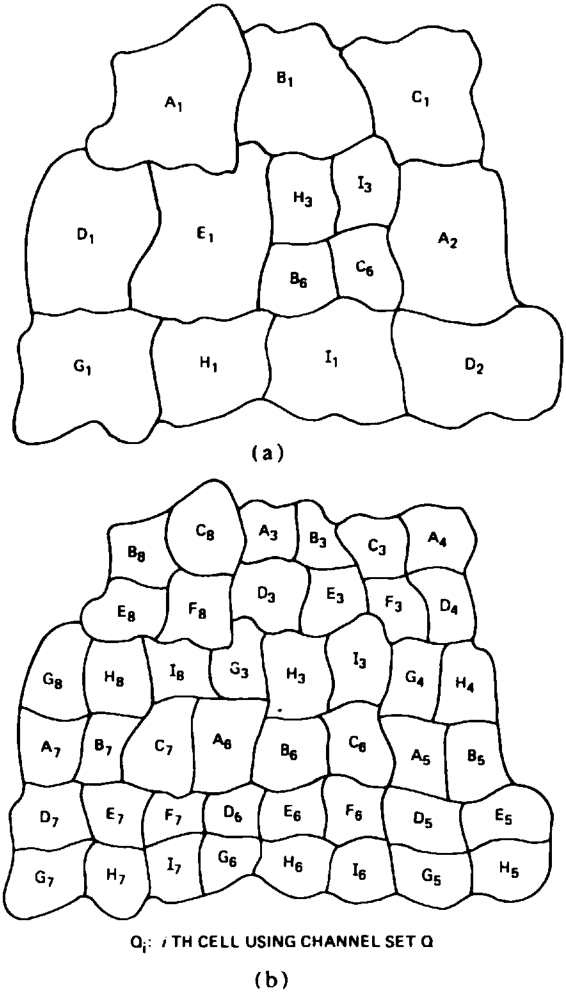


Fig. 2—Cellular layout illustrating cell splitting. (a) Early stage. (b) Later stage.

illustration implies. It is often sufficient initially to superimpose just one or two smaller cells onto a larger cell, so that the larger and smaller cells jointly serve the traffic within the area spanned by the smaller cell(s). The larger cell disappears at a later time, when all its territory becomes covered by smaller cells. We discuss this aspect of system growth in Section 7.3. In Figs. 1 and 2, for illustration the total allocation has been partitioned into nine distinct channel sets, labeled *A* through *I*. The figures show a progression from an initial stage (Fig. 1), in which each allocated channel is available once within the region spanned by cells A_1 through I_1, to a later stage (Fig. 2b), in which each channel is available in four different cells within that same region.

Successive stages of cell splitting would further multiply the number of "voicepaths," i.e., the total number of simultaneous mobile-telephone calls possible within the same region. By decreasing the area of each cell, cell splitting allows the system to adjust to a growing spatial traffic demand density (simultaneous calls per square mile) without any increase in the spectrum allocation.

The techniques of frequency reuse and cell splitting permit a cellular system to meet the important objectives of serving a very large number of customers in a single coverage area while using a relatively small spectrum allocation. Cell splitting also helps to meet the objective of matching the spatial density of available channels to the spatial density of demand for channels, since lower-demand areas can be served by larger cells at the same time that higher-demand areas are served by smaller cells.

IV. PROPERTIES OF CELLULAR GEOMETRY

The main purpose of defining cells in a mobile-telephone system is to delineate areas in which either specific channels or a specific cell site will be used at least preferentially, if not exclusively. A reasonable degree of geographical confinement of channel usage is necessary to prevent co-channel interference problems. Having defined a desired cellular pattern in concept, system planners achieve that pattern in the field through proper positioning of land transmitter sites, proper design of the azimuthal gain pattern of the sites' antennas, and proper selection during every call of a suitable site to serve the call.

The irregular land transmitter spacing and amorphous cell shapes shown in Figs. 1 and 2 might be acceptable in a system where the initial system configuration, including the selection of transmitter sites and the assignment of channels to cells, could be frozen indefinitely. In practice, however, the absence of an orderly geometrical structure in a cellular pattern would make adaptation to traffic growth more cumbersome than necessary. Inefficient use of spectrum and uneconomical deployment of equipment would be likely outcomes. A great deal of improvisation and custom engineering of radio, transmission, switching, and control facilities would be required repeatedly in the course of system growth.

Early in the evolution of the cellular concept, system designers recognized that visualizing all cells as having the same shape helps to systematize the design and layout of cellular systems. A cell was viewed as the coverage area of a particular land site. If, as with present-day mobile service, omnidirectional transmitting antennas were used, then each site's coverage area—bounded by a contour of constant signal level—would be roughly circular. Although propagation considerations recommend the circle as a cell shape, the circle is impractical for design purposes, because an array of circular cells produces ambiguous areas which are contained either in no cell or in multiple cells. On the other hand, any regular polygon approximates the shape of a circle and three types, the equilateral triangle, the square, and the regular hexagon, can cover a plane with no gaps or overlaps (Fig. 3). A cellular system could be designed with square or equilateral triangular cells, but, for economic reasons, Bell Laboratories system designers adopted the regular hexagonal shape several years ago.

To understand the economic motivation for choosing the hexagon, let us focus our attention on the "worst-case" points in a cellular grid—the points farthest from the nearest land site. Assume a land site located at the center of each cell, the center being the unique point equidistant from the vertices. The vertices are in fact the worst-case points, since they lie at the greatest distance from the nearest land site. Restricting the distance between the cell center and any vertex to a certain maximum value helps to assure satisfactory transmission quality at the worst-case points. If an equilateral triangle, a square, and a regular hexagon all have the same center-to-vertex distance, the hexagon has a substantially larger area. Consequently, to serve a given total coverage area, a hexagonal layout requires fewer cells, hence fewer transmitter sites. A system based on hexagonal cells therefore costs less than one with triangular or square cells, all other factors being equal.

With our present understanding of cellular systems, we recognize that, because of propagation vagaries, it is not possible to precisely define a coverage area for a given cell site in the sense that the site never serves mobile units outside the area and always serves mobile units within the area. Nevertheless, the concept of a cell remains valid in the context of an area in which a certain land site is more likely to serve mobile-telephone calls than any other site.

A familiarity with some of the basic properties of hexagonal cellular geometry will give the reader additional perspective on subsequently

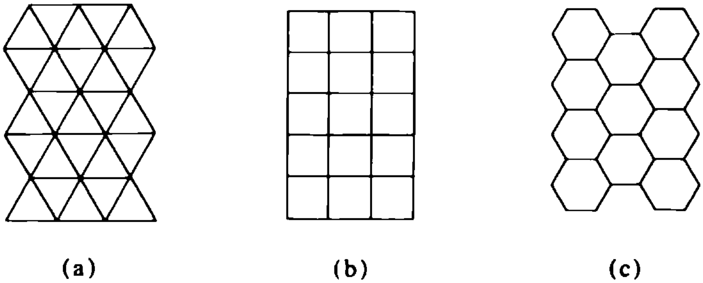


Fig. 3—Regular polygons as cells. (a) Equilateral triangles. (b) Squares. (c) Regular hexagons.

discussed details of radio-channel assignment in a cellular system. We now explain how cells using the same channel set are oriented with respect to one another and how cellular patterns and certain basic geometrical parameters are related to one another.

To lay out a cellular system in the sense of determining which channel set should be assigned to each cell, we begin with two integers i and j ($i \geq j$), called "shift parameters," which are predetermined in some manner. From the cellular pattern of Fig. 4, note that six "chains" of hexagons emanate from each hexagon, extending in different directions. Starting with any cell as a reference, we find the nearest "co-channel" cells, that is, those cells that should use the same channel set, as follows:

> Move i cells along any chain of hexagons; turn counter-clockwise 60 degrees; move j cells along the chain that lies on this new heading.

The *j*th cell and the reference cell are co-channel cells. Now return to the reference cell and set forth along a different chain of hexagons using the same procedure.

Figure 4 illustrates the use of these directions for an example in which $i = 3$ and $j = 2$. A cell near the center of the figure is taken as a reference and labeled A. As each co-channel cell is located, it is also

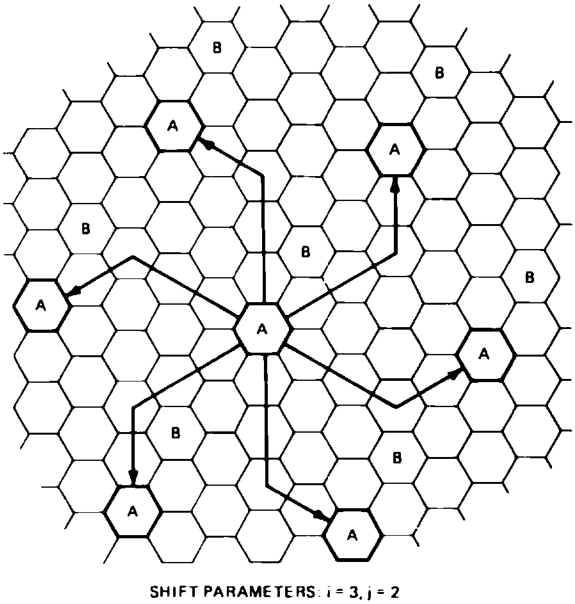


Fig. 4—Illustration of the determination of co-channel cells.

labeled A. To continue the cellular layout, one could choose another label, such as B, for a cell close to the reference cell and find this cell's nearest co-channel cells. However, once the position of all the cells labeled A is determined, it is not necessary to work through the procedure described above for subsequent labels. The pattern of cell labels built up around the reference A cell is simply replicated around all the other A cells by translation without rotation.

Co-channel cells could also be located by moving j cells before turning and i cells afterwards, rather than vice versa, or by turning 60 degrees clockwise instead of counterclockwise. There are four different ways of describing the procedure, and two different configurations can result. Each configuration is just the reflection of the other across an appropriate axis.

When a sufficient number of different labels has been used, all cells will be labeled, and the layout will be complete. The cells form natural blocks or clusters around the reference cell in the center and around each of its co-channel cells. The exact shape of a valid cluster is not unique; all that is required is that it contain exactly one cell with each label. The number of cells per cluster is a parameter of major interest, since in a practical system this number determines how many different channel sets must be formed out of the total allocated spectrum. The number of cells per cluster, N, turns out to be

$$N = i^2 + ij + j^2. \tag{1}$$

(The appendix to this paper derives this result and presents additional information on hexagonal cellular geometry.) The fact that i and j must be integers means that only certain values of the number of cells per cluster are geometrically realizable.

The ratio of D, the distance between the centers of nearest neighboring co-channel cells, to R, the cell radius, is sometimes called the "co-channel reuse ratio." This ratio is related to the number of cells per cluster, N, as follows:

$$D/R = \sqrt{3N}. \tag{2}$$

In a practical system, the choice of the number of cells per cluster is governed by co-channel-interference considerations. As the number of cells per cluster increases, the relative separation between co-channel cells obviously increases, and consequently poor signal-to-interference conditions become progressively less probable. Section 6.4 discusses a method for choosing the number of cells per cluster.

V. AMPS: A PRACTICAL REALIZATION OF THE CELLULAR CONCEPT

This section describes the physical structure of the AMPS system and provides a glimpse of its basic control algorithms to show how cellular operation can be effected in a working system.

The implementation of the cellular concept in a practical system requires the construction of an essentially regular array of land transmitter-receiver stations, called "cell sites" in AMPS. The design abstraction of an array of cells is embodied in the physical reality of the cell-site array. The dots in Fig. 5a symbolize an idealized AMPS cell-site array, consisting of a lattice of regularly spaced cell sites. For this idealized array of cell sites, an accompanying pattern of regular hexagonal cells can be visualized in at least two different ways: (*i*) cells whose centers fall on cell sites, "center-excited" cells (Fig. 5b), or (*ii*) cells half of whose vertices fall on cell sites, "corner-excited" cells (Fig. 5c).

Section 6.1 acknowledges the practical reality that it is seldom possible to position a cell site exactly at its geometrically ideal location and discusses the degree to which the actual location may deviate from the ideal.

Center-excited cells exemplify the previous practical definition of a cell as the area in which one particular cell site is more likely to be used on mobile-telephone calls than any other site. On any single call, neither the mobile unit's nor the system's actions would clearly delineate any cell boundaries, but a protracted study of system behavior would reveal the presence of center-excited cells satisfying the above pragmatic definition. Because of random propagation effects, any real cell only approximates the ideal hexagonal shape but, for purposes of design and discussion, it is appropriate to visualize cells as regular hexagons. The practical meaning of a corner-excited cell will be explained in conjunction with the ensuing discussion of directional cell sites.

5.1 Omnidirectional and directional cell-sites

The AMPS plan envisions that, at the inception of the system in any locality, the cell sites will use transmitter and receiver antennas whose patterns are omnidirectional in the horizontal plane.[3] The use of omnidirectional antennas has traditionally been depicted by the cen-

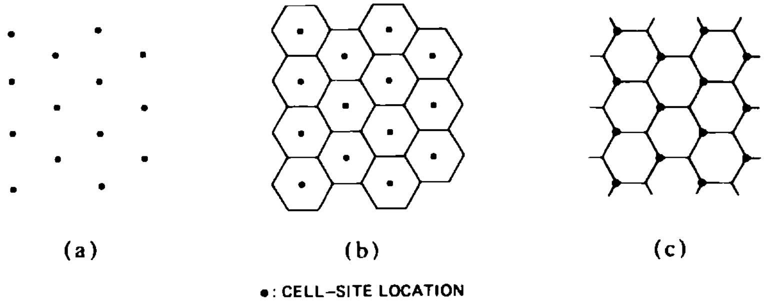


Fig. 5—Cellular geometry with and without cells. (a) Cell-site lattice. (b) "Center-excited" cells. (c) "Corner-excited" cells.

ter-excited cell pattern of Fig. 5b. The phrase "omnidirectional cell site" refers to a site equipped with omnidirectional voice-channel antennas.

In mature systems, cell sites will have three faces, that is, each voice channel in a cell site will be transmitted and received over one of three 120-degree sector antennas, rather than over an omnidirectional antenna. The antennas will be oriented as shown in Fig. 6, so that extensions of the edges of the antennas' front lobes form the sides of hexagonal cells as in Fig. 5c. These are the "corner-excited" cells that have customarily been employed to suggest the tri-directional coverage of AMPS cell sites in mature systems.

Cell sites are very expensive investments. The initial cost of a site, before installation of any voice-channel transceivers, is much greater than the incremental cost of each subsequently installed voice channel. At the inception of a system, the number of sites is governed strictly by the need to span the desired coverage area. At this stage, omnidirectional sites are used because the initial cost of an omnidirectional site is lower than that of a directional site. In mature systems, however, the potential, explained below, for cutting cost by reducing the total

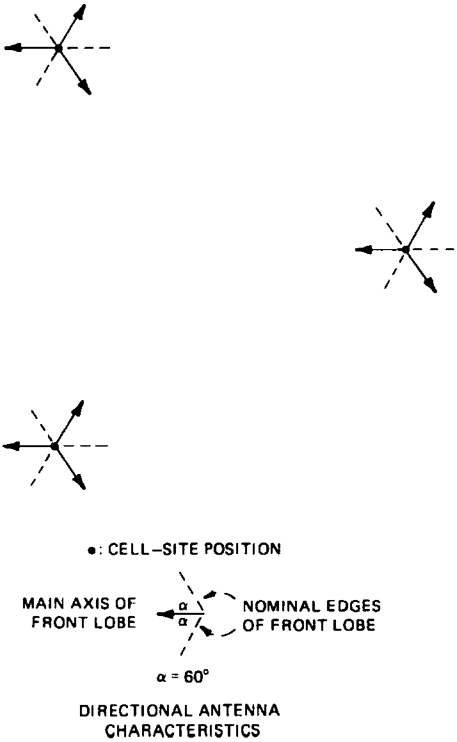


Fig. 6—Orientation of directional antennas at directional cell sites in AMPS.

number of cell sites needed to serve the existing telephone traffic load is the chief motivation for using directional cell sites.

In comparison with an omnidirectional land transmitting antenna, a directional antenna can deliver the same signal level in the region that it serves while causing substantially less interference within co-channel cells which lie outside the 120-degree wedge which the front lobe illuminates. Similarly, a directional land receiving antenna substantially attenuates interference received from mobile units at bearings not spanned by the front lobe. If omnidirectional systems and directional systems are to have comparable radio-frequency signal-to-interference statistics, the directional system can operate with a smaller co-channel reuse ratio, that is, a closer spacing between co-channel sites. By eq. (2), the smaller co-channel reuse ratio is equivalent to a smaller number of cells per cluster, or, more to the point, a smaller number of channel sets. Since the total number of channels is fixed, the smaller number of sets means more channels per set and per cell site. Each site can carry more traffic, thereby reducing the total number of sites needed for a given total load.

The use of three faces at each site with the orientation described above leads to certain convenient symmetries and relationships in the system design. A hexagonal cellular system could be designed, however, for a different azimuthal orientation of the directional antennas or for some other number of faces at each site.

5.2 Functional description of system operation

This section offers the reader a glimpse of the system control architecture, which is discussed in greater detail in Ref. 4. The main entities of an Advanced Mobile Phone Service system are the Mobile Telephone Switching Office (MTSO), the cell sites, and the mobile units. The central processor of the MTSO controls not only the switching equipment needed to interconnect mobile parties with the land telephone network, but also cell-site actions and even many of the actions of mobile units through commands relayed to them by the cell sites.

The MTSO is linked with each cell site by a group of voice trunks—one trunk for each radio channel installed in the site—and two or more data links, over which the MTSO and cell site exchange information necessary for processing calls. Every cell site contains one transceiver for each voice channel assigned to it and the transmitting and receiving antennas for these channels. The cell site also contains signal-level monitoring equipment and a "setup" radio, whose purpose is explained below.

The mobile equipment consists of a control unit, a transceiver, a logic unit, and two antennas. The control unit contains all the user interfaces, such as a handset, various pushbuttons, and indicator lights. The transceiver uses a frequency synthesizer to tune to any allocated channel. The logic unit interprets customer actions and system commands and controls the transceiver and control units. A single antenna is used for transmission; two antennas together are used to provide space diversity for reception.

A few allocated radio channels serve as "setup" channels rather than voice channels; these channels are used primarily for the exchange of information needed to establish or set up calls. Applying the frequency-reuse concept to setup channels minimizes the number of channels withheld from voice use. Ordinarily, each site has one such channel. Whenever a mobile unit is turned on but the user is not engaged in a call, the mobile unit simply monitors a setup channel. The unit itself chooses which one of the various channels to monitor by sampling the signal strength on all members of a standard group of setup channels. The mobile unit then tunes to the channel which yields the strongest measurement, synchronizes with the data stream being transmitted by the system, and begins interpreting the data. Ordinarily, the mobile unit will remain on this channel; in some cases, the received data will indicate that the mobile unit should sample the signal strength on another set of channels before making a final choice. The mobile unit continues to monitor the chosen setup channel unless some condition, such as poor reception, requires that the choice of a channel be renewed. The setup-channel data words include the identification numbers of mobile units to which calls are currently being directed.

When a mobile unit detects that it is being called, it quickly samples the signal strength on all the system's setup channels so that it can respond through the cell site offering the strongest signal at the mobile unit's current position. The mobile unit seizes the newly chosen setup channel and transmits its page response. The system then transmits a voice-channel assignment addressed to the mobile unit, which, in turn, tunes to the assigned channel, where it receives a command to alert the mobile user. A similar sequence of actions takes place when the mobile user originates a call.

While a call is in progress, at intervals of a few seconds the system examines the signal being received at the serving cell site (the site that is handling the call). When necessary, the system looks for another site to serve the call. When it finds a suitable site, the system sends the mobile unit a command to retune to a channel associated with that site. While the mobile unit is changing channels, the MTSO reswitches the land party to the trunk associated with the new channel's transceiver. The periodic examination of a mobile unit's signal is known as "locating." The act of changing channels has come to be called "handoff."

The sole purpose of the locating function is to provide satisfactory transmission quality for calls.[5] In this context, the term "locating" is really a misnomer. The term was coined in the early stages of the evolution of the cellular concept, when system designers supposed that it would be necessary to know the physical position of the mobile unit accurately.

VI. SELECTION OF KEY SYSTEM PARAMETERS

This section discusses the current recommended values for some key system geometrical parameters and the methodologies which led to them. The most important objectives in the setting of parameters are cost restraints, good transmission quality, and a large ultimate customer capacity. In some contexts, conflicts appear among these objectives, and tradeoffs must be made so that no one objective is seriously undercut to benefit another.

6.1 Cell-site position tolerance

Previous sections have alluded to perfectly regular spacing of hexagonal cell sites. In practice, however, the procurement of space for cell sites may be one of the most difficult practical hurdles in engineering and installing cellular systems.

The current design permits a cell site to be positioned up to one-quarter of the nominal cell radius away from the ideal location. The site position tolerance has far more impact on transmission quality than on cost or capacity. Consequently, an analysis was made of the effect of the cell-site position tolerance on the overall probability distribution of the RF signal-to-interference ratio (S/I) on voice channels in mature systems. For simplicity and concreteness, the analysis focused on the value of RF S/I ratio which falls at the tenth percentile of the overall S/I distribution. This level decreased gradually as the cell-site position tolerance increased from 0 to about one-fourth of a cell radius, but it decreased rapidly beyond this break point. The tolerance was therefore set at a quarter radius to allow system administrators as much leeway as possible in positioning sites without significantly degrading the transmission quality.

6.2 Maximum cell radius

Setting the maximum cell radius, which is to be used in a system at its inception, is part of the general problem of achieving a satisfactory compromise between the objectives of low cost and good transmission quality. The maximum cell radius has only an indirect effect on the system objective of a large ultimate capacity.

Transmitter power is another important element in the overall reconciliation of low cost with high-quality transmission. In present-day mobile-telephone systems, the transmitter power of mobile units is smaller by an order of magnitude than that of the land stations. To provide adequate reception of mobile transmissions emanating from any place where mobile units receive land transmissions, satellite receiver sites are deployed throughout the coverage area. A cellular system might be designed in this manner. However, the AMPS system designers consider a "balanced" system with comparable transmitter power in mobile units and cell sites to be a more economical design, because satellite receiver sites would represent a substantial fraction of the cost of full-fledged cell sites, yet possess far fewer capabilities.

When a system is first established, there is normally little frequency reuse. Since each initial cell is relatively large, the total number of cells needed to span the desired coverage area does not greatly exceed the number of channel sets into which the total allocation is partitioned. Even though two or more cell sites may be assigned the same channel set, mutually exclusive subsets can be used in the co-channel sites until a certain amount of growth in telephone traffic has occurred. For an initial period, therefore, the main channel impairment to contend with is ambient noise, both inevitable receiver thermal noise and man-made environmental noise.

In a startup system, an increase in land and mobile transmitter power, all other system parameters being held constant, would improve transmission quality by raising RF signal-to-noise (S/N) ratios, but it would also raise the system cost. From a broader perspective, however, increased transmitter power could be used to reduce system cost rather than to improve transmission quality. Increased power would permit the use of a larger initial cell radius for the same level of transmission quality, which in turn would allow fewer cell sites to cover the desired area. If an extra expenditure on transmitter power yields a greater cost saving in cell-site construction, the expenditure is desirable. At some level, however, additional transmitter power ceases to pay for itself. Not only does the incremental cost per decibel mount, but eventually practical considerations of feasibility and reliability also enter in. Furthermore, the relatively high level of transmitter power that is beneficial in the startup phases of cellular systems is largely superfluous in mature phases, since each stage of cell splitting essentially halves the mean distance between mobile units and their serving cell sites.

The chosen value of 10 watts delivered to the transmitting antennas is based on an evaluation of the cost, reliability, and power drain of present-day transmitters in the 800- to 900-MHz range. To supply approximately 10 watts of power at the antenna terminals, the system design requires 12 watts from mobile transmitters and 40 watts from cell-site transmitters to compensate for cable and combiner losses.

Cell-site antenna elevation and gain (in any vertical plane) influence the tradeoff between cost and transmission quality in much the same way as transmitter power. As with transmitter power, the selected figures for antenna gain and elevation are the largest values normally achievable without excessive costs. The expected range of antenna gain is 6 to 8 dB relative to a dipole; the expected range of elevation above the ground, 100 to 200 feet.

Assuming that transmitter power and cell-site antenna gain and elevation are already established, the tradeoff between cost and quality in the early stages of AMPS growth is governed by the value chosen for the cell radius. Since increasing the radius both decreases cost and degrades transmission quality, the transmission-quality objective allows a controlled level of imperfection for the sake of economy.

The sound quality of AMPS calls is intended to be comparable in acceptability to the sound quality on calls over the land telephone network, but setting system parameters requires that this general guideline be reduced to more concrete terms.

The maximum cell radius depends on both subjective and statistical factors. To meet the sound-quality objective, designers required information both on customer opinions of mobile-telephone channels at 800 to 900 MHz and on the propagation of energy at these frequencies. In a subjective testing program,[6] subjects rated the quality of simulated and actual mobile-telephone channels subjected to the rapid Rayleigh fading encountered in UHF mobile communications. The test results showed that at an RF S/N ratio of 18 dB, most listeners considered the channel to be good or excellent. The system designers concluded that the S/N ratio in a working system should exceed 18 dB with high probability. The AMPS transmission-quality objective was therefore quantified for design purposes as a requirement that this S/N value be exceeded in 90 percent of the area covered by any system.

Our knowledge of propagation is based largely on an extensive measurement program performed by Bell Laboratories in Philadelphia in the early 1970s and in Newark more recently.[7] These measurement results corroborate studies performed in Tokyo,[8] New York,[9] and suburban areas of New Jersey.[10] All these investigations and others[11] show that, for a given distance r between transmitter and receiver, the probability distribution of the path loss (attenuation) in decibels is approximately Gaussian. The mean of the distribution (in decibels) is approximated by a function of the form $k + 10n \log_{10} r$, in which k is a constant for a given transmitter-receiver pair and n is known as the path-loss exponent. The standard deviation amounts to several decibels. The bodies of data associated with different transmitter sites yield different numerical results for all these parameters, but the values which emerge from the total ensemble of Philadelphia and Newark measurements are a path-loss exponent n on the order of 4 and a standard deviation of roughly 8 dB.

At Bell Laboratories, a computer simulation was written to predict many aspects of the behavior of a cellular system, including the overall statistics of received signal level. This simulation incorporates a propagation model based on the Philadelphia measurements, and it also models vehicle movements and the details of the locating algorithm.

The results of this simulation show that in an environment similar to Philadelphia a cell radius of 8 miles allows the system to meet the requirement that the S/N ratio be above 18 dB over 90 percent of the coverage area. Somewhat different values of maximum cell radius may be appropriate for situations in which any of the relevant parameters, such as the path-loss exponent, environmental noise, antenna gain, or antenna elevation, differ substantially from the assumed values.

6.3 Minimum cell radius

In the AMPS system, additional cell sites needed to relieve the telephone traffic demand on existing sites will be positioned midway between adjacent old sites. This simple procedure cuts the distance between adjacent sites in half and therefore cuts the cell radius by a factor of 2 and the cell area by a factor of 4.

The minimum cell radius, which is the cell radius after the final stage of cell splitting, has little effect on the system cost per customer or on transmission quality, but it plays a vital part in setting the ultimate system capacity. Each stage of cell splitting multiplies the number of cell sites in the desired coverage area by a factor of about 4. The system's total traffic-carrying capacity is also increased by essentially the same factor. In principle, the cell-splitting process could be repeated an indefinite number of times, but system designers cite a 1-mile cell radius as a practical minimum. If start-up cells have an 8-mile radius, three stages of cell splitting are possible. There is no insurmountable physical barrier to having smaller cells, but the greatest practical obstacles are the cell-site position tolerance and the burden of frequent handoffs. As previously stated, cell sites should be positioned within a quarter of a cell radius of their ideal locations. A tolerance of a quarter mile (corresponding to a 1-mile radius) is probably the most stringent requirement that can be contemplated. The mean distance traveled between handoffs is bound to decrease as the cell radius decreases. In a system composed of many cells with a radius of much less than one mile, handoffs would consume a significant fraction of the MTSO central processor's capacity.

6.4 Co-channel reuse ratio

The discussion of directional cell sites explained the economic incentive for minimizing the ratio of D, the distance between co-channel cell sites, to R, the cell radius. The co-channel reuse ratio (D/R) also has an impact on both the transmission quality and the ultimate customer capacity of the system. The influence on transmission quality arises because the D/R ratio materially affects co-channel interference statistics. Since this ratio determines the number of channels per channel set, it sets a limit on each site's traffic-carrying capacity, which in turn limits the ultimate system capacity.

The allowable minimum value of D/R was set in much the same way as the maximum cell radius. Making D/R as small as possible serves the objectives of low cost and large capacity. On the other hand, making D/R as large as possible benefits transmission quality. As in the determination of the maximum cell radius, a compromise among objectives is achieved through the kind of transmission-quality objective described in the discussion of maximum radius.

The subjective testing program mentioned previously included an evaluation of the effect of co-channel interference on listeners' opinions. The results indicated that most of the subjects considered the transmission quality of a channel to be good or excellent at an S/I of 17 dB. To satisfy the AMPS quality objective, a system must provide an S/I of 17 dB or greater over 90 percent of its coverage area. The system simulation mentioned above shows that, in an environment similar to Philadelphia or Newark, a system meets the S/I requirement if the separation between co-channel sites is 4.6 cell radii when 120-degree directional antennas are used and 6.0 cell radii when omnidirectional antennas are used. These co-channel reuse ratios correspond, by eq. (2), to 7 cells per cluster (equivalently 7 disjoint channel sets) for directional sites and 12 cells per cluster for omnidirectional sites.

VII. DEFINITION AND DEPLOYMENT OF CHANNEL SETS

A complete description of a plan for deploying channels in a coverage area requires that some additional facts and procedures be specified. The degree of foresight with which channel sets are defined and used can materially affect the system's transmission quality, cost, and ease of adaptation to growth in telephone traffic.

7.1 Reduction of adjacent-channel interference

The design of a mobile-telephone system must include measures to limit not only co-channel interference but also adjacent-channel interference. Although the IF filters of both the cell-site and mobile-unit receivers significantly attenuate signals from the channels adjacent in frequency to the desired channel, it is advisable to avoid circumstances in which the received level of an adjacent channel greatly exceeds that of the desired channel.

This situation would arise at a cell site, for example, if one mobile unit were many times farther away from its serving cell site than another mobile unit being served by the same site on an adjacent channel. With a distance ratio of 10, for instance, the received level of the adjacent channel at the cell site could easily be 40 dB higher than the level of the desired channel. In the presence of fading, severe adjacent-channel interference would result unless the receiver IF filter could greatly attenuate the adjacent channel. In general, a substantial spectral guard band would be required between channels to permit IF filters to reject the interference adequately.

Fortunately, in a cellular system, since only a fraction of the allocated channels belong to any one channel set, it is possible to avoid the use of adjacent channels in the same cell site, thereby keeping the probability of severe adjacent-channel interference low. Since stringent IF attenuation of adjacent channels is not essential, no guard band is needed.

AMPS voice channels have an FM peak deviation of 12 kHz and a spacing of 30 kHz.[12] With this spacing, 666 duplex channels can be created out of a 40-MHz spectrum allocation. The use of adjacent channels at the same site would require a larger channel spacing, and fewer channels would be available from the allocation. In the AMPS system, the largest possible frequency separation is maintained between adjacent members of the same channel set. Suppose that channels are numbered sequentially from 1 upward and that the frequency difference between channels is proportional to the algebraic difference of their channel numbers. If N disjoint channel sets are required, the nth set ($1 \leq n \leq N$) would contain channels n, $n + N$, $n + 2N$, etc. For example, if $N = 7$, set 4 would contain channels 4, 11, 18, etc.

In some cases, system designers can also prevent a secondary source of adjacent-channel interference by avoiding the use of adjacent channels in geographically adjacent cell sites. Figure 7 shows a cell-site pattern for 12 disjoint channel sets (12 cells per cluster). This pattern can be used in startup phases of AMPS, during which all sites will be equipped with omnidirectional voice-channel antennas. Only sets with adjacent set numbers (including 12 and 1) contain any adjacent channels. In the figure, each site is labeled with the number of its channel set. Center-excited cells are drawn in to aid in visualizing the nominal area in which each set is most likely to be used.

As previously discussed, when 120-degree directional cell-site antennas are employed in AMPS, transmission-quality considerations call for seven cells per cluster. In this case, it is impossible to avoid having adjacent channels at adjacent sites, because if there are only seven channel sets, any site plus its six neighbors constitute a complete cluster in which every channel may be assigned exactly once. With 120-degree directional antennas, however, it is possible to subdivide the seven channel sets and deploy the subsets geographically in such a way that the received adjacent-channel interference, at both the mobile units and cell sites, is usually attenuated by the front-to-back ratio of the cell-site directional antennas. (An example below illustrates this effect.) The AMPS plan subdivides each of the seven channel sets

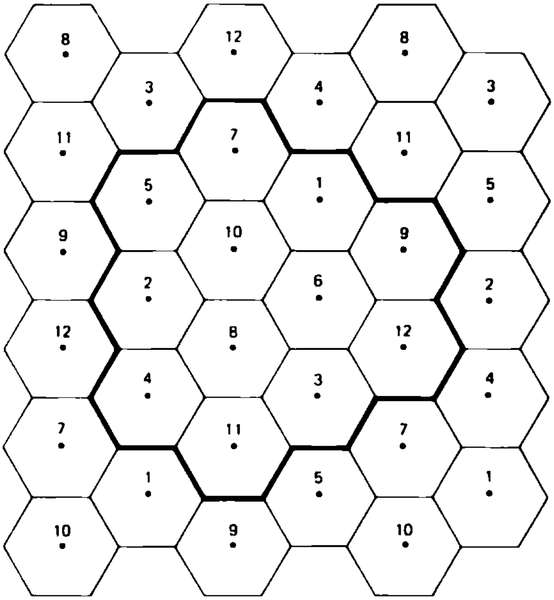


Fig. 7—Channel-set deployment pattern for 12 cells per cluster.

into three subsets. For example, set 4, containing channels 4, 11, 18, 25, 32, 39, 46, 53, 60, etc., subdivides into subset 4a with channels 4, 25, 46; subset 4b with channels 11, 32, 53, etc.; and set 4c with channels 18, 39, 60, etc. The notation is simplified if we simply number the channel subsets from 1 to 21, so that set *n* is subdivided into subsets *n*, *n* + 7, and *n* + 14.

Figure 8 shows one acceptable pattern for assigning channel subsets to cell-site faces. (The appendix to this paper describes a simple algorithm for assigning channel sets to cells; this algorithm would produce a differently labeled but equally acceptable pattern.) In Fig. 8, corner-excited cells are shown whose sides are projections of the edges of the antennas' 120-degree front lobes. Subsets with sequential subset numbers contain adjacent channels and are assigned to faces in such a way that they do not cover the same corner-excited cell, even though they may reside in adjacent sites. This procedure attenuates adjacent-channel interference by the cell-site antenna's front-to-back ratio in situations which otherwise would cause problems. For instance, in Fig. 8, suppose that a channel of subset 6 is serving the mobile unit at point *M*. The adjacent-channel interference that exists in both directions between the mobile unit and the cell site using subset 7 is attenuated by the front-to-back ratio of the directional antennas which transmit and receive subset 7.

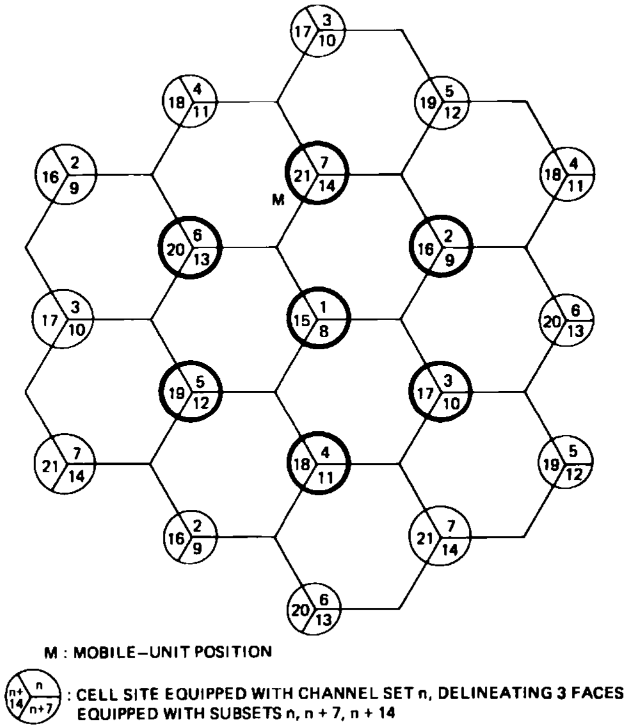
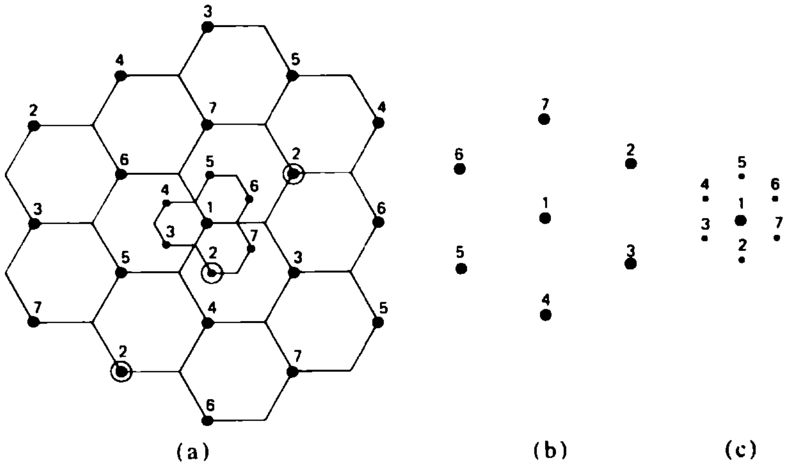


Fig. 8—Channel-subset deployment pattern for seven cells per cluster and three faces per cell site.

7.2 Cell splitting

The practical significance of cell splitting is that the distance between adjacent cell sites is cut in half, and through the action of the locating algorithm, the nominal coverage area of newly established cell sites is reduced to a quarter of the nominal area previously covered by existing sites. Conversely, wherever cell splitting occurs, it quadruples the cell-site density. The AMPS cell-splitting plan sets the ideal location for new sites at points midway between neighboring existing sites, although the actual position may be anywhere within a distance of one-quarter of a (smaller) cell radius. The previously existing cell sites together with the new ones form a hexagonal cellular lattice.

In the transition from a system based on 12 channel sets and omnidirectional cell-site antennas to one based on 21 channel subsets and directional antennas, a gradual alteration may be necessary in the assignment of channel frequencies to cell sites. Once directional operation is established, however, splitting does not cause any further alteration of existing channel assignments. Figure 9 shows an array of directional cell sites identified by single set numbers. In one area, six new cell sites have been established. The channel set assigned to any



● : PREVIOUSLY EXISTING OR "OLD" CELL SITE
• : "NEW" CELL SITE INSTALLED DURING CELL SPLITTING

Fig. 9—Channel-set deployment pattern for seven cells per cluster, with multiple cell sizes. (a) Overall cell-site pattern. (b) Orientation of cluster of cell sites in larger-cell pattern. (c) Orientation of cluster of cell sites in smaller-cell pattern.

new site is determined by observing that the new site lies midway between two co-channel sites, each one situated a little more than one (larger) cell diameter away from the new site, both of which use the same channel set. This is the channel set which should be assigned to the new site. The sites labeled 2 in Fig. 9a are circled to illustrate this geometrical relationship. Figures 9b and 9c extract from Fig. 9a the channel-set patterns of the cell-site clusters at different stages of cell splitting. Successive stages of cell splitting preserve the internal geometrical relations within the cluster, but each stage causes the cluster to be rotated counterclockwise 120 degrees.

7.3 The overlaid-cell concept

In a coverage area where two or more sizes of cells exist simultaneously, special care must be taken to guarantee the correct minimum distance D between cell sites equipped with the same voice channels. As previously discussed, a certain co-channel reuse ratio D/R must be maintained, but when a system includes multiple cell sizes, the radius R has different values for different sites.

Figure 10 illustrates some unusual situations that arise whenever groups of cells of different sizes abut. Site A_1 lies within a group of larger cells. For a cellular pattern of seven cells per cluster, the nearest co-channel sites within the group of larger cells, such as sites A_2 and A_3, should be separated from site A_1 by a distance of 4.6 larger-cell radii. Within the group of smaller cells, co-channel sites such as sites A_4 and A_5 are separated from each other by a distance of 4.6 smaller-

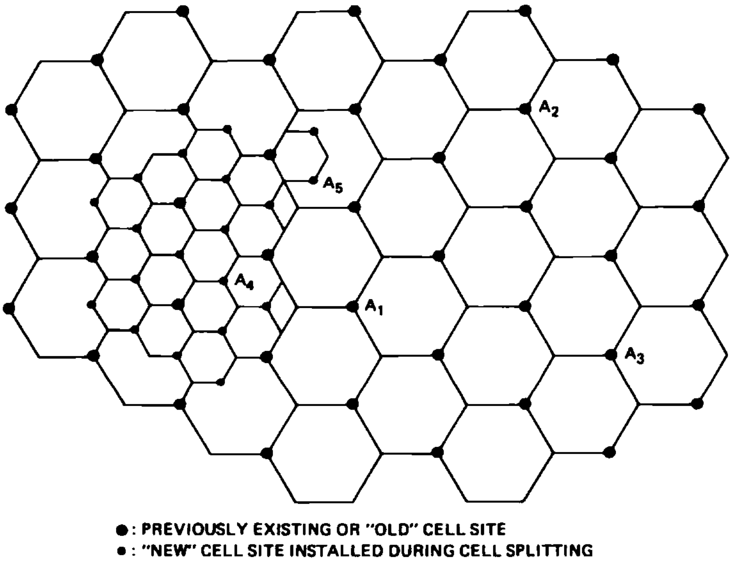


Fig. 10—Illustration of mixed cell sizes for discussion of overlaid-cell concept.

cell radii, or 2.3 larger-cell radii. Site A_1 is also in the correct position to be a nearest co-channel neighbor of sites A_4 and A_5. The D/R ratio is satisfied for sites A_4 and A_5 because the appropriate value of R for these sites is the smaller-cell radius. Channels installed in site A_1 would cause no undue co-channel interference on calls served by sites A_4 and A_5, because a mobile unit being served by one of these latter sites would tend to be within a range of about one smaller cell radius.

The troublesome questions pertain to calls served by site A_1. If this site is to serve a larger-cell area, then it cannot use any of the same channels as sites A_4 and A_5, because the co-channel reuse ratio (D/R) would not be satisfied for site A_1 if the larger-cell radius is taken as the appropriate value for R. This ratio would be satisfied if the smaller-cell radius could somehow be made applicable to site A_1, but restricting site A_1 to serving only a smaller-cell area could mean inadequate coverage for some areas further removed from the site.

The dilemma affecting site A_1 is resolved by invoking the overlaid-cell concept. This concept recognizes that, when multiple cell sizes coexist, the cellular pattern is best viewed as the superposition of a fragmentary smaller-cell pattern on top of a complete larger cell pattern. The underlying larger-cell pattern does not disappear in a given region until the overlaid smaller-cell pattern is complete in that region.

Implementing the overlaid-cell concept requires that, in a region where cells of two sizes are present, the channel subset assigned to any cell-site face must be further subdivided into a larger-cell group and a smaller-cell group. Each face of an older, previously existing site will use some of its channels to continue coverage of the same larger cellular area as before. The remainder of the channels assigned to the face will be restricted to covering a smaller area, corresponding to the smaller cell size. The subdivision of a subset into larger- and smaller-cell groups for an existing site is governed by the channel requirements of its new co-channel neighbors. For example, in Fig. 10, any channel installed in site A_4 or A_5 must be restricted to smaller-cell use in site A_1. The way that a channel is restricted to smaller-cell use is simply to reassign the channel in software to a channel group which is treated as if it were serving a smaller cell. When appropriate, a call being served by a smaller-cell channel will be handed off to a neighboring new site if there is one, or otherwise to a channel belonging to the larger-cell group of the same face on which the call is already being served. As the telephone traffic loads grow in the new sites, reassignment of more and more channels in the old site to a smaller-cell group must follow, thereby reducing the capacity of the older site to serve the larger-cell area. For this reason, not only the local growth in telephone traffic around any older site but also the growth in traffic carried by that site's new co-channel neighbors can force cell splitting around the older site.

The various procedures described in this section for channel-set definition and deployment and for cell splitting allow the system to grow gradually and, on the whole, gracefully in response to a growing telephone traffic load. When an existing site reaches its traffic-carrying capacity, new sites are added around it one by one, only as needed, while the older site makes a gradual transition from larger-cell operation to smaller-cell operation.

VIII. SUMMARY

The FCC's allocation of a relatively large block of spectrum for public mobile communications has made a large-scale, economical mobile-telephone service feasible. The need for a method of serving many thousands of customers in a single local coverage area, while using a limited spectral allocation equivalent to several hundred voice channels, has spurred the evolution of the cellular concept. In practical terms, a cell is the area in which one particular group of channels is more likely to be used for mobile telephone calls than any other group. The essential elements of the cellular concept, frequency reuse and cell splitting, allow a cellular system to use spectrum efficiently, to grow gradually, and to supply service in response to a geographical pattern of demand.

In the AMPS system, the lattice of cell sites is designed to create a pattern of hexagonal cells. In the initial growth phase of a system in a given locality, cell-site voice-channel transmitters and receivers connect to omnidirectional antennas. In later stages, cell sites have three faces, equipped with 120-degree directional antennas. The omnidirectional plan minimizes the startup costs for new systems, whereas the directional plan confines costs in mature systems by reducing the total number of sites required to serve a given offered load.

The key geometrical parameters of AMPS were chosen primarily to satisfy the objectives of moderate cost, good transmission quality, and a large ultimate customer capacity. In some cases, tradeoffs must be made among these joint objectives.

The ways in which channel sets are defined and distributed among cell sites in AMPS keep co-channel and adjacent-channel interference within acceptable bounds. The procedure for assigning channels to new cell sites introduced during cell splitting promotes graceful growth in response to increasing demand. As new sites are added, previously existing sites make a gradual transition from larger-cell operation to smaller-cell operation.

IX. ACKNOWLEDGMENTS

During three decades, many people have contributed to the definition of a mobile-telephone system structure capable of realizing the promises of the cellular concept. We shall mention just a few. W. R. Young and J. S. Engel helped to crystallize the overall system objectives. The cellular geometry of AMPS and the techniques for deploying and utilizing channel frequencies largely reflect the contributions of R. H. Frenkiel and P. T. Porter. In particular, the overlaid-cell concept, which governs system growth procedures, is the work of R. H. Frenkiel. M. A. Castellano also worked out many of the geometrical details of channel-set deployment. J. A. O'Brien and G. D. Ott contributed to the iterative process of proposing and evaluating the details of the locating algorithm.

APPENDIX

Fundamentals of Hexagonal Cellular Geometry

Certain intriguing mathematical relations emerge when one deals with hexagonal cellular geometry, yet there appears to be no published summary of all the basic relations with explanations of how they arise. This appendix is intended to fill the gap. We also present a novel algebraic method for using the coordinates of a cell's center to determine which channel set should serve the cell.

Figure 11 shows the most convenient set of coordinates for hexagonal geometry. The positive halves of the two axes intersect at a 60-degree angle, and the unit distance along either axis equals $\sqrt{3}$ times the cell radius, the radius being defined as the distance from the center of a cell to any of its vertices. With these coordinates, an array of cells can

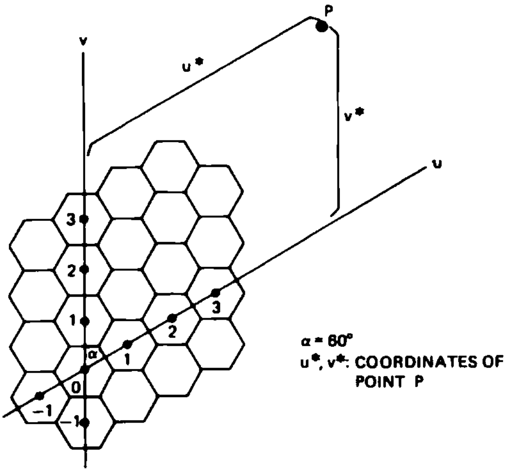


Fig. 11—A convenient set of coordinates for hexagonal cellular geometry.

be laid out so that the center of every cell falls on a point specified by a pair of integer coordinates.

The first useful fact to note is that, in this coordinate system, the distance d_{12} between two points with coordinates (u_1, v_1) and (u_2, v_2), respectively, is

$$d_{12} = \sqrt{(u_2 - u_1)^2 + (u_2 - u_1)(v_2 - v_1) + (v_2 - v_1)^2}. \tag{3}$$

Using this formula we can verify that the distance between the centers of adjacent cells is unity and that the length of a cell radius R is

$$R = 1/\sqrt{3}. \tag{4}$$

We can calculate the number of cells per cluster, N, by some heuristic reasoning. The directions given in Section IV of this paper for locating co-channel cells result in a co-channel relationship between the reference cell with its center at the origin and the cell whose center lies at $(u, v) = (i, j)$, where i and j are the integer "shift parameters," with $i \geq j$. (See Fig. 4 for an illustration.) By eq. (3), the distance D between the centers of these or any other nearest neighboring co-channel cells is

$$D = \sqrt{i^2 + ij + j^2}. \tag{5}$$

Figure 4 illustrates the universal fact that any cell has exactly six equidistant nearest neighboring co-channel cells. Moreover, the vectors from the center of a cell to the centers of these co-channel cells are separated in angle from one another by multiples of 60 degrees. These same observations also hold for any arbitrary cell and the six cells immediately adjacent to it. The idea presents itself to visualize each cluster as a large hexagon. In reality, the cluster, being composed of a group of contiguous hexagonal cells, cannot also be exactly hexagonal in shape, but it is nevertheless true that a properly visualized large hexagon can have the same area as a cluster. For proper visualization, refer to Fig. 12. The seven cells labeled A are reproduced from Fig. 4. The center of each A cell is also the center of a large hexagon representing a cluster of cells. Each A cell is imbedded in exactly one large hexagon, just as it is contained in exactly one cluster. All large hexagons have the same area, just as all clusters have the same area. The large hexagons cover the plane with no gaps and no overlaps, just as the clusters do. We therefore claim that the area of the large hexagon equals the area of any valid cluster. This area can be deduced from results already presented. We noted above that the distance between the centers of adjacent cells is unity. By eq. (5), the distance between centers of the large hexagons is $\sqrt{i^2 + ij + j^2}$.

Consequently, since the pattern of large hexagons is simply an enlarged replica of the original cellular pattern with a linear scale factor of $\sqrt{i^2 + ij + j^2}$, then N, the total number of cell areas contained

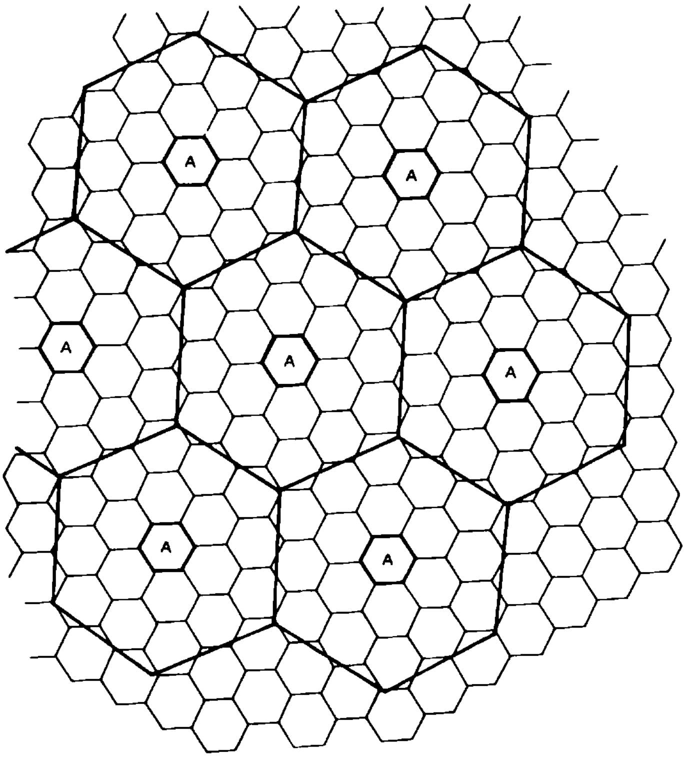


Fig. 12—Illustration for the heuristic determination of the number of cells per cluster.

in the area of the large hexagon, is the square of this factor, namely

$$N = i^2 + ij + j^2. \tag{6}$$

By combining eqs. (4), (5), and (6), we obtain the classical relationship between the co-channel reuse ratio D/R and the number of cells per cluster N:

$$D/R = \sqrt{3N}. \tag{7}$$

The rather cumbersome procedure described in the main body of this paper for performing a cellular layout can be replaced by a simple algebraic algorithm in certain cases of practical interest, namely those cases in which the smaller shift parameter j equals unity. (A pattern of 7 cells per cluster falls into this category.) For these cases, it is convenient to label the cells by the integers 0 through N-1. Then the correct label L for the cell whose center lies at (u, v) is given by

$$L = [(i + 1)\, u + v] \bmod N. \tag{8}$$

The application of this simple formula causes all cells which should use the same channel set to have the same numerical label.

REFERENCES

1. W. R. Young, "AMPS: Introduction, Background, and Objectives," B.S.T.J., this issue, pp. 1–14.
2. Richard H. Frenkiel, "A High-Capacity Mobile Radiotelephone System Model Using a Coordinated Small-Zone Approach," IEEE Trans. Veh. Technol., *VT-19*, No. 2 (May 1970), pp. 173–177.
3. Bell Laboratories, "High-Capacity Mobile Telephone System Technical Report" (December 1971), submitted to FCC.
4. Z. C. Fluhr and P. T. Porter, "AMPS: Control Architecture," B.S.T.J., this issue, pp. 43–69.
5. Gary D. Ott, "Vehicle Location in Cellular Mobile Radio Systems" IEEE Trans Veh. Technol., *VT-26*, No. 1 (February 1977), pp. 43–46.
6. V. H. MacDonald, "Subjective Voice-Circuit Quality Measurements in the Presence of Multipath Fading," Symposium on Microwave Mobile Communications, Boulder, Colo., 1972.
7. G. C. DiPiazza, A. Plitkins, and G. I. Zysman, "AMPS: The Cellular Test Bed," B.S.T.J., this issue, pp. 215–248.
8. Y. Okumura, E. Ohmori, T. Kawano, and K. Fukuda, "Field Strength and its Variability in VHF and UHF Land Mobile Service," Rev. Elec. Comm. Lab., *16* (September 1968), pp. 825–873.
9. W. Rae Young, Jr., "Comparison of Mobile Radio Transmission at 150, 450, 900, and 3700 MC," B.S.T.J., *31*, No. 6 (November 1952), pp. 1068–1085.
10. D. C. Cox, "Time-and-Frequency Domain Characterizations of Multipath Propagation at 910 MHz in a Suburban Mobile-Radio Environment," Radio Sci., *7* (December 1972), pp. 1069–1077.
11. W. C. Jakes, Jr., ed., *Microwave Mobile Communications*, New York, John Wiley, 1974.
12. G. A. Arredondo, J. C. Feggler, and J. I. Smith, "AMPS: Voice and Data Transmission," B.S.T.J., this issue, pp. 97–122.