1985

Mobile telephone system and non-wire line network

Daniel Chi Man Cheung

Recommended Citation

Cheung, Daniel Chi Man, "Mobile telephone system and non-wire line network" (1985). Thesis. Rochester Institute of Technology. Accessed from

Rochester Institute of Technology

School of Computer Science and Technology

Mobile Telephone System and Non-wire Line Network

Daniel Chi Man, Cheung

A thesis, submitted to the Faculty of the School of Computer Science and Technology, in partial fulfillment of the requirements for the degree of Master of Science in Computer Science.

Date: 2 - 18 - 85

Approved by: Kenneth A. Reek
Professor Kenneth A. Reek (Chairman)

John L. Ellis
Professor John L. Ellis

Peter G. Anderson
Professor Peter G. Anderson

2/21/85

Title of Thesis: Mobile Phone System & Non-wire Line Network.

I Daniel Chi Man, Cheung hereby deny permission to the Wallace Library, of R.I.T., to reproduce my thesis in whole or in part.

CONTENTS

LIST OF FIGURES

Abstract

The need to communicate with non-fixed points without the use of wires led to the development of mobile telephone systems in the early 1920's. Since then, the expanding need for mobile phone service and resulting growth have led to the development of the Advanced Mobile Phone Service (AMPS) by the Bell System. This thesis describes the AMPS system and explains how service is provided to mobile units roaming in a typical area of up to 25 square miles.

A network is proposed to interconnect service areas to expand the coverage to a much larger geographic area. Efficient use is made of the limited bandwidth available for network communication. The network is able to manage mobile units that move from one service area to another during a call, and can efficiently locate mobile units throughout the network area.

1. Introduction

The need to communicate with nonfixed points without the use of wires led to the development of mobile phone systems in the early 1920s. Since then, the use of mobile phones has spread dramatically. The expanding need and resulting growth have led to the development of the Advanced Mobile Phone Service (AMPS) by the Bell System.

The cellular system concept embodied in AMPS makes large scale mobile phone service affordable to a sizable segment of the public. This cellular system concept calls for dividing transmission areas into "cells" to handle mobile phone traffic and, as traffic grows, subdividing those cells into smaller segments without increasing the amount of radio spectrum allocated.

This paper describes the AMPS mobile phone system. The concept of a proposed mobile telephone network is outlined, as are the objectives, evolution, design and testing, and maintenance considerations of the AMPS system.

1.1 Theoretical and Conceptual Development

Mobile phone service has remained a scarce luxury from the time of its inception to the emergence of key concepts. The most important one is the cellular concept which is also essential in the proposed network design of this paper (Section 4). Mobile telephone customers typically pay 10 to 20 times as much for mobile service as for residential phone service. But the primary factor that has hampered the spread of mobile service to the general public has been the unavailability of radio spectrum.

For a mobile service to be both pratical and economical, the following objectives must be met.

(1) Large Subscriber Capacity -

There must be capability of serving a large amount of traffic and many thousands of mobile users within a local service area, such as a greater metropolitan area, within a fixed allocation of several hundred channels.

(2) Efficient Use of Spectrum -

The scarcity of channels in the radio spectrum demands that they will be used responsibly and efficiently.

(3) Adaptability to Traffic Density -

The traffic density will differ from one point to another in any one area, as well as differing between points in different areas (for example, the center of a city and the more remote parts of it). Since all of these points will change with time, the system must be adaptable to these changing traffic patterns.

The realization of these objectives by the AMPS system is discussed later. The cellular concept and the fact that small cells with spectrum reuse could increase traffic capacity substantially, help to meet the first two objectives mentioned above. These make the more economical and widespread form of mobile-telephone service a reality.

Sections 2 and 3 show how a cellular system operating within a limited block of the frequency spectrum can meet the objectives of a large-scale mobile-telephone service. The key elements of the cellular concept, frequency reuse and cell splitting, will be explored. Certain mathematical properties of hexagonal cellular geometry will be described to aid the understanding of the cellular concept. Also, the basic structure and features of AMPS are explained to show how the cellular concept can be put into practice.

Section 4 presents the problems and possible solutions to the formation of a wireless mobile telephone network.

1.2 Key Words and Phrases

AMPS	Advanced Mobile Phone Service.
AT&T	American Telephone and Telegraph Company.

Cellular System Concept

Dividing transmission areas into "cells" to handle mobile phone traffic and, as traffic grows, subdividing those cells into smaller segments without increasing allocation of radio spectrum.

Land Telephone Network

The land telephone network is a system of integrated parts consisting of transmission and switching facilities, a control and signaling process, and associated operational support systems. It is engineered, installed, owned, and managed by a partnership of AT&T Long Lines, Bell System Operating Telephone Companies, and Independent Operating Telephone Comapnies. Its boundary is the location where the Network tariffed channel terminates on the customer's premises, or where carriers other than those comprising the Bell-Independent partnership are provided local access. Its principal function is to provide, on demand, a communication channel connecting any two communications terminal devices for the exchange of information in a variety of forms.

Locating and Handoff

The act of transferring from one channel to another is called handoff. "Locating" is a process for determining whether it would be better from the point of view of signal quality and potential interference to perform a handoff.

MSA

Mobile Service Area. A single AMPS system is designed to serve customers within a given MSA.

MTSO

Mobile Telephone Switching Office. The MTSO is a telephone switching office with capabilities for software control.

Paging and Access

The term "paging" is used in AMPS to describe the process of determining a mobile's availability to receive a given incoming call. The complementary function of beginning a call, performed by a mobile unit, is termed access.

RF

Radio Frequency.

1.3 Elements of the Mobile Telephone System

This section gives a brief introduction to the building blocks of the AMPS system. There are three major elements in a mobile telephone system:

(1) the Electronic Switching System (ESS);

(2) the cell site; and

(3) the mobile unit.

Each of these is controlled by its own processor and software. The mobile unit is controlled by a resident microprocessor. The cell site has a resident programmable controller and a low-powered transmitter. The ESS provides centralized control of the Mobile Telephone System. It is connected to all cell transmitters and the land based telephone line. It coordinates and controls the activities of the cell sites, interconnects the mobile telephone with the land telephone network, and maintains system integrity through automated maintenance.

Each cell transmitter constantly sends a special signal, and as a mobile unit moves from cell to cell, the mobile unit automatically tunes in the strongest signal. When a call comes in for a mobile unit, the ESS sends a signal containing the 10-digit phone number. When the mobile unit hears its phone number, it responds to the nearest cell transmitter, which in turn reports back to the Electronic

Switching System. The Electronic Switching System scans its list of vacant voice channels and assigns one for the conversation. The mobile unit tunes to that voice channel and the cell site rings the mobile unit.

2. The Cellular Concept

The mobile phone system must be capable of growing to serve many thousands of subscribers within a local service area, yet it must not be contingent on the enlargement of the allocated spectrum which is very limited. 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.

2.1 Basic Elements of The Cellular Concept

The two basic elements of the cellular concept are frequency reuse and cell splitting. The following sections will present these two concepts in detail.

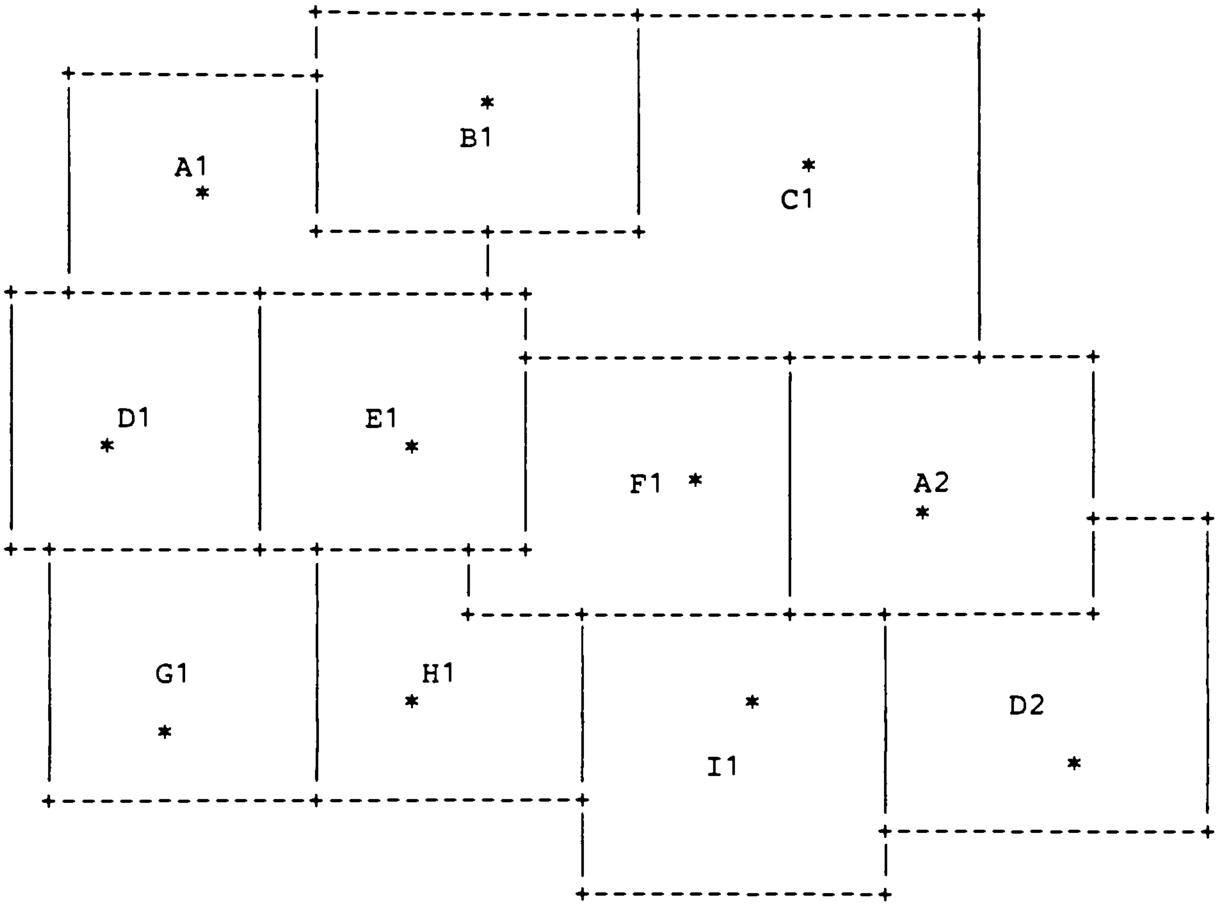
2.1.1 Frequency Reuse

Frequency reuse is commonly employed in entertainment broadcasting and most other radio services. The idea is to use radio channels on the same frequency to cover different areas which are separated from one another by sufficient distances so that co-channel interference is not objectionable. This is how radio stations in different cities can use the same radio frequency.

The same idea applies to the mobile telephone service with the exception that it is on a shrunken geographical scale. 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 transmitter then covers some nearby subarea, or zone, or "cell." A cell thus signifies the area in which a particular transmitter site is most likely to serve mobile telephone calls. In the overlapped area between two cells, a mobile telephone call can be serviced by either one of the two transmitters. How the mobile telephone system handles mobile units crossing from one cell to another in the middle of a conversation will be addressed later.

Figure 1 is 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 therefore has the additional significance that it is the area in which a particular set of channel frequencies is the most likely set to be used for mobile telephone calls. Cells sufficiently far apart, such as those



@i: iTH CELL USING CHANNEL SET @
where @={A,B,C,D,E,F,G,H,I}

*: TRANSMITTER LOCATION

Figure 1. Cellular layout illustrating frequency reuse

labeled A1 and A2, 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 system capacity depends on the total number of cells.

2.1.2 Cell Splitting

If the total allocation of C channels is partitioned into N sets, then each set will contain nominally S channels (where $S = C/N$). If one channel set of S channels is used in each cell, eventually the telephone traffic demand in some cell will reach the capacity of the 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. This is the process of "cell splitting."

Figure 2 illustrates an early stage of the cell-splitting process, in which the cell originally designated F1 (in Figure 1) has reached its capacity. The area previously treated as cell F1 now contains cells H3, I3, B6 and C6. If the demand in the area continues to grow, other larger cells will be split, and eventually, as in Figure 3, the entire region may be converted into smaller cells. Cell splitting is attractive because not all cells have to be split, only if the traffic demand in a cell has reached its capacity of S channels.

In practice, splitting a given cell may be less abrupt than the 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. In Figures 1, 2 and 3, the total allocation has been partitioned into nine distinct channel sets, labeled A through I. The figures show a progression from an initial stage (Figure 1), in which each allocated channel is available once within the region spanned by cells A1 through I1, to a later stage (Figure 3), 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

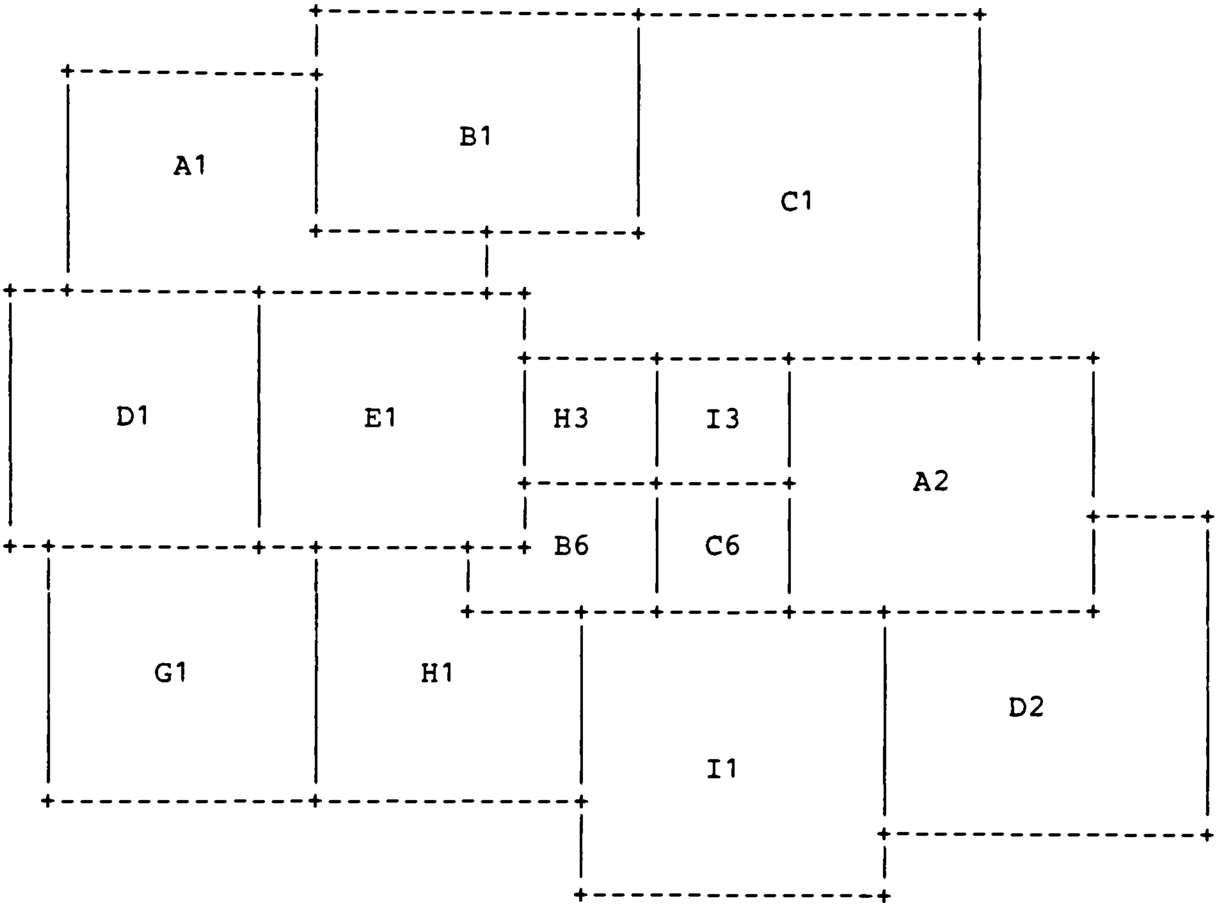


Figure 2. Cellular layout illustrating cell splitting - Early stage

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 (number of channels per square mile) to the spatial density of demand for channels (number of calls per square mile). This is because lower-demand areas can be served by larger cells at the same time that higher-demand areas are served by smaller cells.

2.2 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 (horizontal direction) gain pattern of the sites' antennas, and proper selection of a suitable site to serve every call.

The irregular land transmitter spacing and amorphous cell shapes shown in Figures 1, 2 and 3 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,

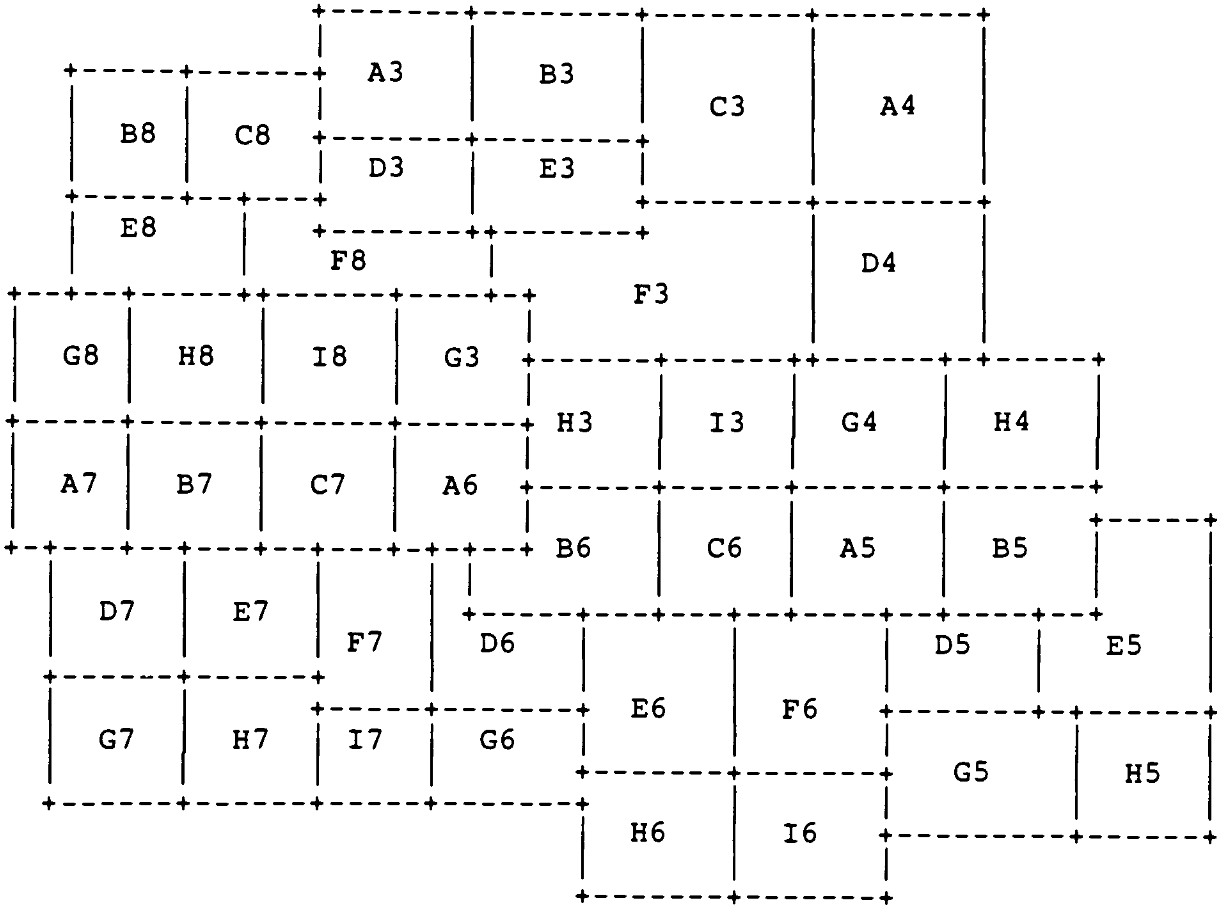


Figure 3. Cellular layout illustrating cell splitting - Later stage

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, it 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 to an extent and three types, the equilateral triangle, the square, and the regular hexagon, can cover a plane with no gaps or overlaps (Figure 4). A cellular system could be designed with square or equilateral triangular cells, but for economical reasons Bell Laboratories system designers adopted the regular hexagonal shape years ago.

To understand the economic motivation for choosing the hexagon, focus attention on the "worst-case" points in a cellular grid-the points farthest from the nearest land site. Assume a land site is 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. This is because the hexagon more closely approximates the circular pattern of transmitter coverage, thereby minimizing overlap of covered areas. 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 irregularities (for example, noise and distortion) it is not possible to precisely define a coverage area for a given cell site so 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 gives additional perspective on the later discussion of radio channel assignment in a cellular system. The following paragraphs explain how cells using the same channel set are oriented with respect to one another and how

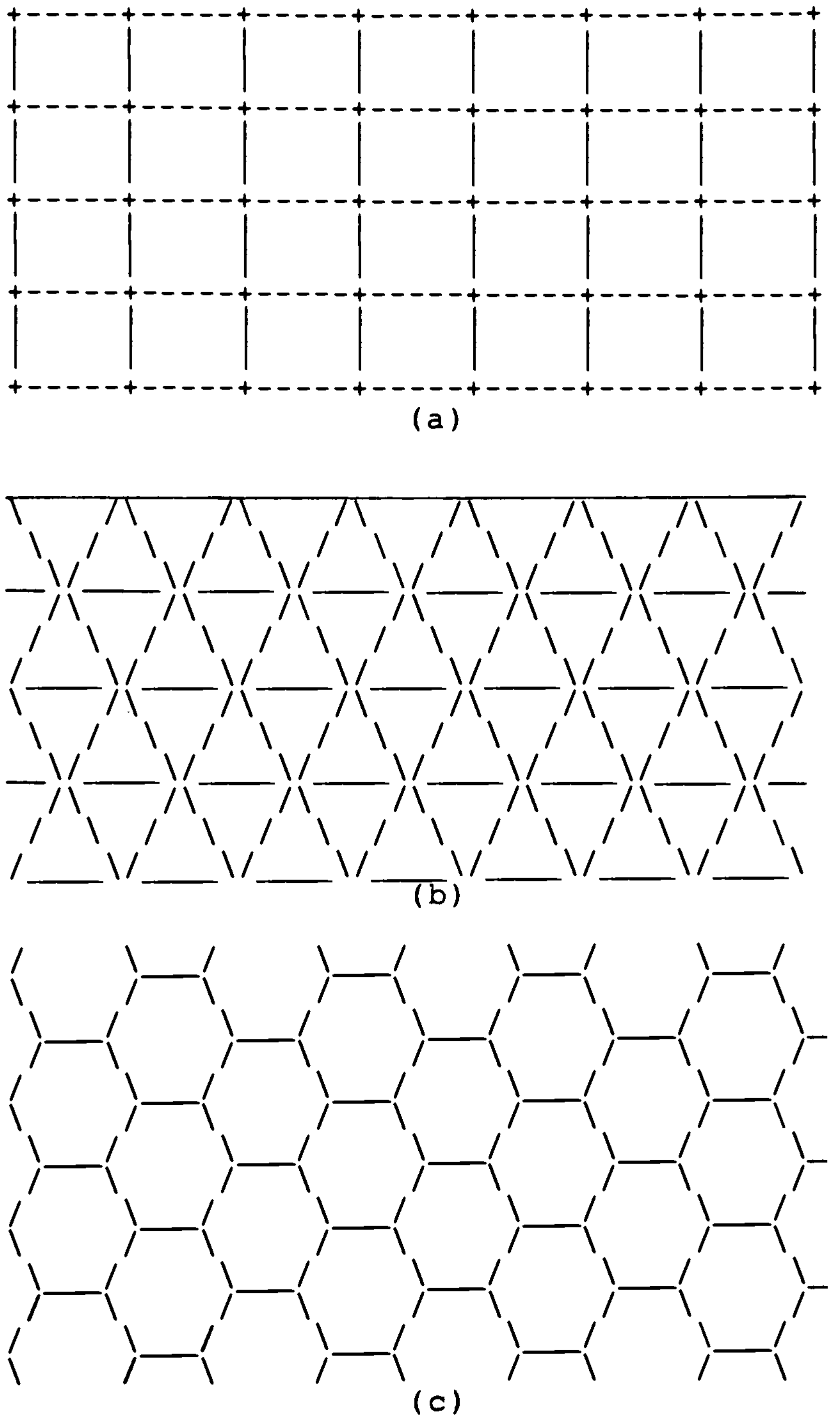


Figure 4. Regular polygons as cells. (a) Squares. (b) Equilateral triangles. (c) Regular hexagons.

cellular patterns and certain basic geometrical parameters are related to one another.

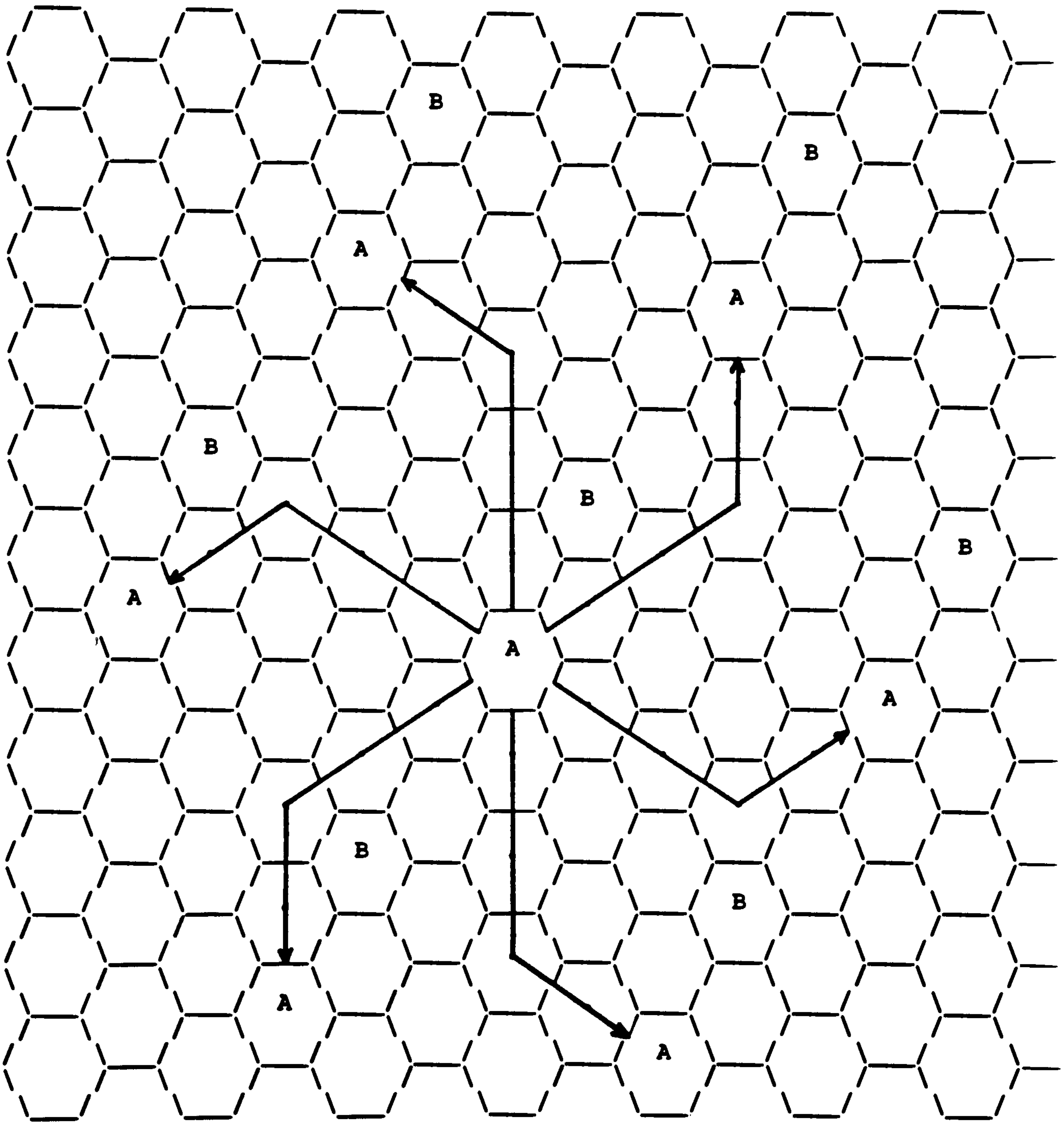
To lay out a cellular system in the sense of determining which channel set should be assigned to each cell, we begin with two integers i and j, where i >= j, called "shift parameters," which are predetermined in some manner (for example, i + j = the shortest distance in number of cells between any co-channel cells + 1). From the cellular pattern of Figure 5, note that six "chains" of hexagons emanate from each hexagon, extending in different directions. Starting with any cell as a reference, the nearest "co-channel" cells, that is, those cells that should use the same channel set, are located 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 jth 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 until all six sides of the reference cell are completed.

Figure 5 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 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. This is because the two clockwise configurations overlap with the two counterclockwise configurations of the adjacent chain in the clockwise



SHIFT PARAMETERS: $i = 3$, $j = 2$

Figure 5. Illustration of the determination of co-channel cells.

direction. 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, is

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

The next section 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:

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

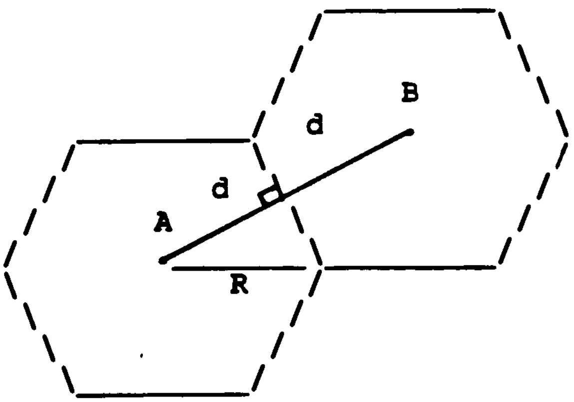
In a practical system, the choice of the number of cells per cluster is governed by co-channel-interference considerations. As the number of cells per cluster increases, the separation between co-channel cells increases, and consequently poor signal-to-interference conditions become less probable. A method for choosing the number of cells per cluster will be discussed next.

2.2.1 Fundamentals of Hexagonal Cellular Geometry

Some intriguing mathematical relations emerge from the hexagonal cellular geometry, yet there appears to be no published summary of all the basic relations with explanations of how they arise. This section is intended to fill the gap. It presents a novel algebraic method for using the coordinates of a cell's center to determine which channel set should serve the cell.

Figure 6 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. To prove this, let R be the radius and d the perpendicular distance from any sides of a cell to its center (refer to diagram below). Then the distance from A to B is as follows:

since d/R = cos 30 degrees
then d = (cos 30 degrees) R
= 0.8660254 R
therefore $2d$ = 1.7320508 R
and $2d$ = distance from A to B which equals to the unit distance along either axis in Figure 6.
$1.7320508 = \sqrt{3}$



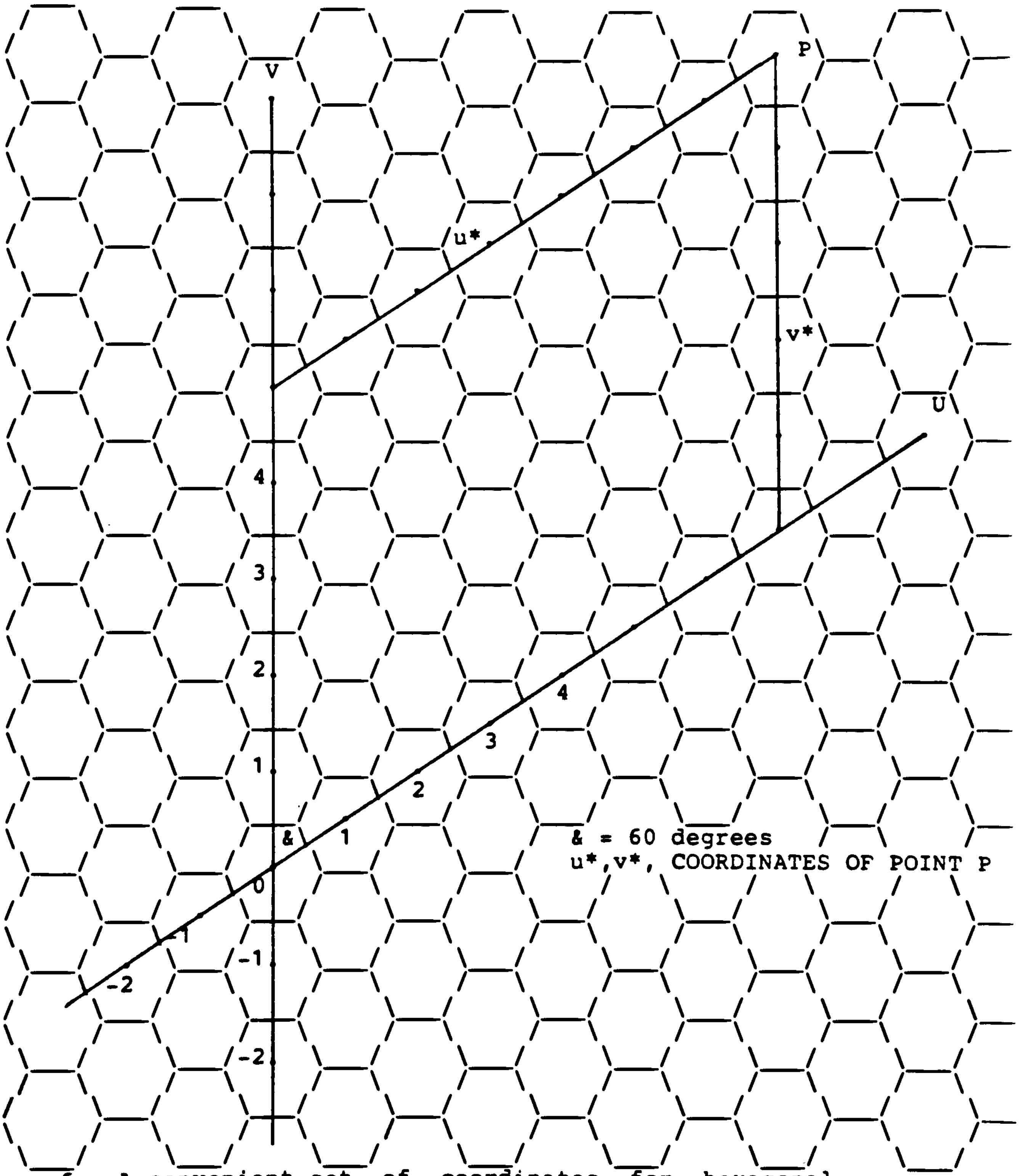


Figure 6. A convenient set of coordinates for hexagonal cellular geometry.

With these coordinates, an array of cells can 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 d12 between two points with coordinates (u1,v1) and (u2,v2), respectively, is the following:

$$d12 = \sqrt{(u2 - u1)^2 + (u2 - u1)(v2 - v1) + (v2 - v1)^2}. \qquad (3)$$

By definition, the distance between the centers of adjacent cells is unity and that the length of a cell radius R is

$$R = 1/\sqrt{3}. \qquad (4)$$

The number of cells per cluster, N, can be calculated by some heuristic reasoning. The directions given in the previous section 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." By equation (3), the distance D between the centers of these or any other nearest neighboring co-channel cells is

$$D = \sqrt{i^2 + ij + j^2}. \qquad (5)$$

Figure 5 illustrates the 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 Figure 7. The seven cells labeled A are reproduced from Figure 5. 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. Therefore, the area of the large hexagon equals the area of any valid cluster. This area can be deduced from results already presented. It is noted above that the distance between the centers of adjacent cells is unity. By equation (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 in the area of the large hexagon, is the square of this factor, namely

$$N = i^2 + ij + j^2. \qquad (6)$$

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

$$D/R = \sqrt{3N}. \qquad (7)$$

The rather cumbersome procedure described in the main body of these sections 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

$$L = [(i + 1)u + v] \bmod N. \qquad (8)$$

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

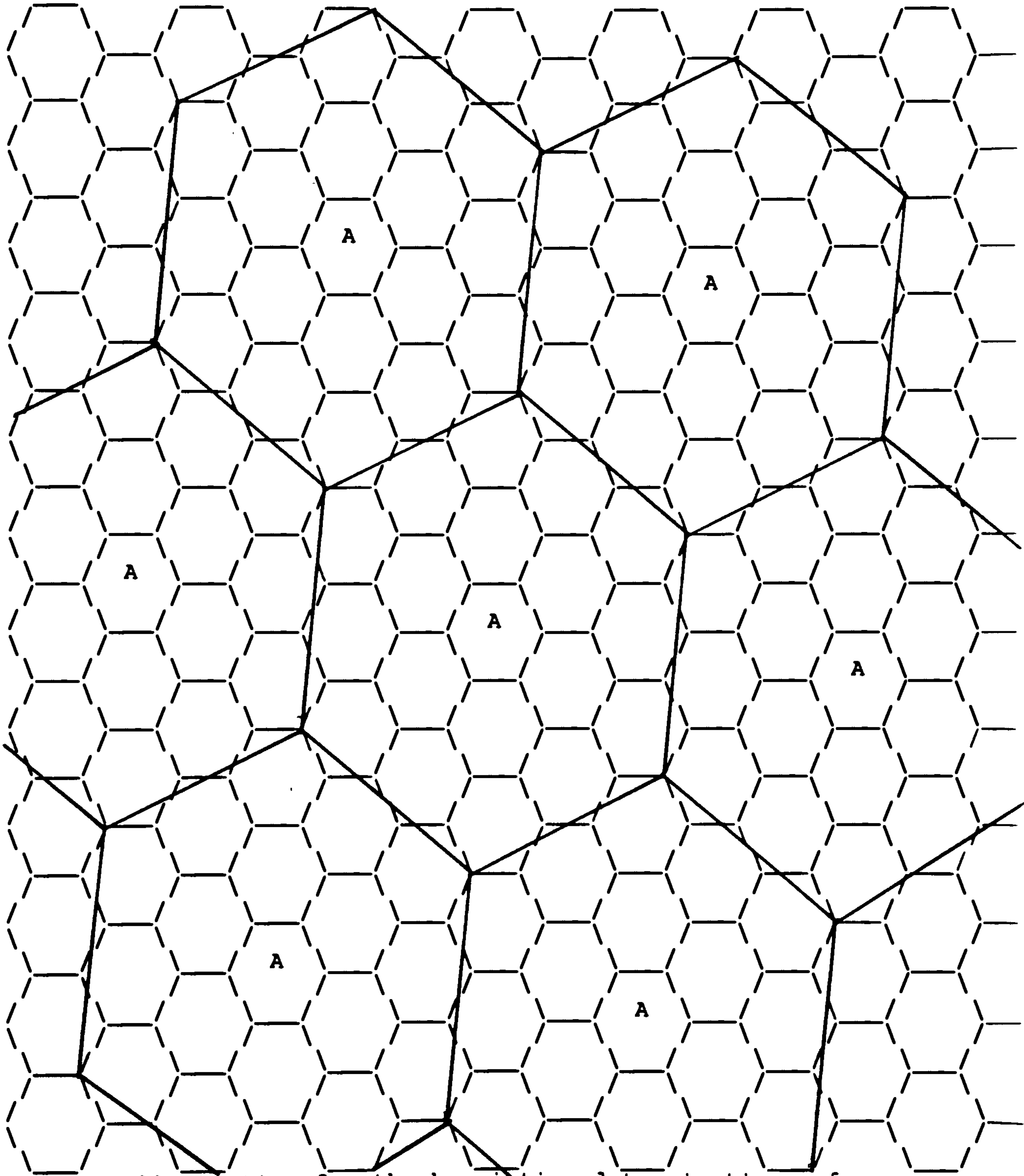


Figure 7. Illustration for the heuristic determination of the number of cells per cluster.

2.3 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 (*)s in Figure 8(a) 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 (Figure 8b), or

(ii) cells half of whose vertices fall on cell sites, "corner-excited" cells (Figure 8c).

In reality, it is seldom possible to position a cell site exactly at its geometrically ideal location.

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 action would clearly delineate any cell boundaries, but a 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.

2.3.1 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 pattern are omnidirectional in the horizontal plane. The use of omnidirectional antennas has

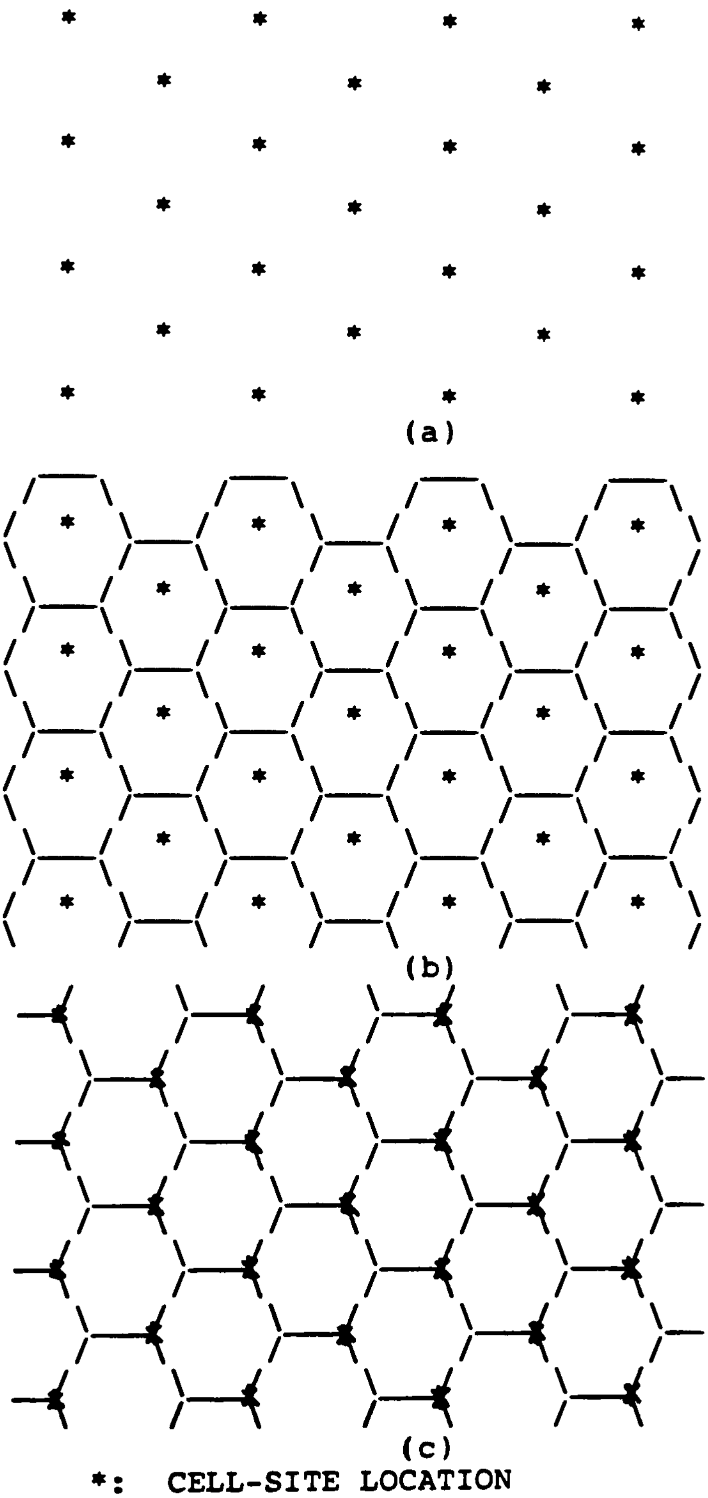


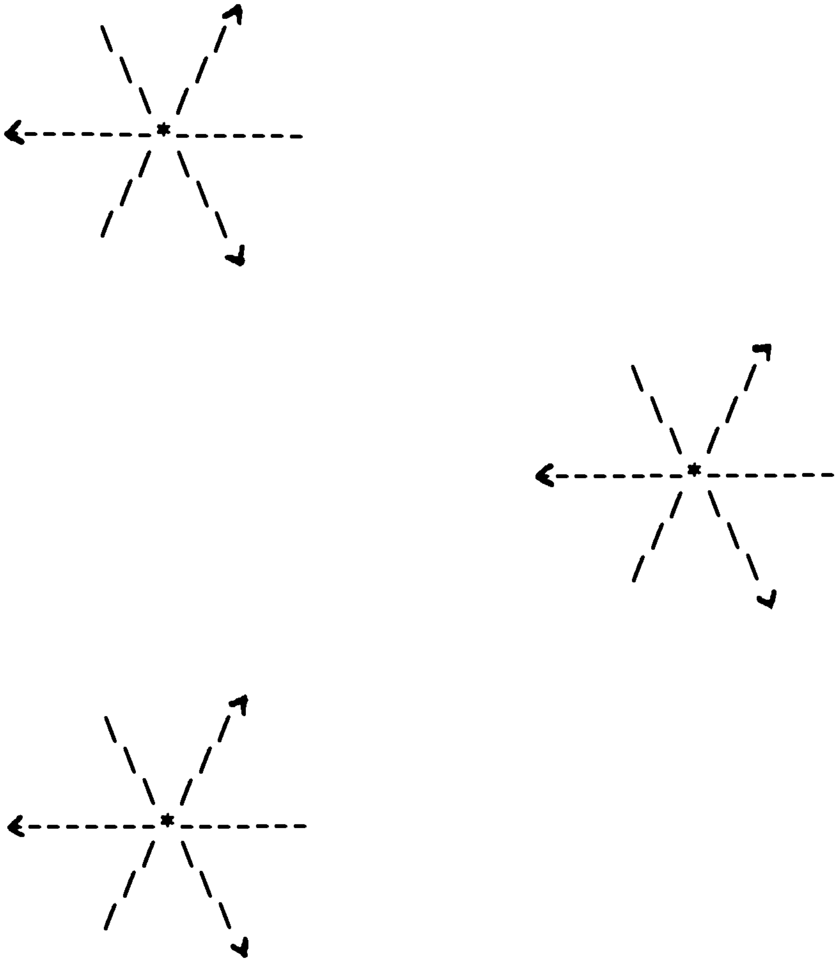
Figure 8. Cellular geometry with and without cells. (a) Cell-site lattice. (b) Center-excited cells. (c) Corner-excited cells.

traditionally been depicted by the center-excited cell pattern of Figure 8b. 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 Figure 9, so that extensions of the edges of the antennas' front lobes form the sides of hexagonal cells as in Figure 8c. 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 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 equation (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.



*: CELL-SITE POSITION

```
                          \
                           \<--NOMINAL EDGE OF FRONT LOBE
MAIN AXIS OF             & \
FRONT LOBE     <-------*
                         & /
                           /<--NOMINAL EDGE OF FRONT LOBE
                          /
              & = 60-degree
```

DIRECTIONAL ANTENNA
CHARACTERISTICS

Figure 9. Orientation of directional antennas at directional cell sites in AMPS.

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.

2.3.2 Functional Description of System Operation

This section offers a glimpse of the system control architecture, which will be discussed in greater detail in Section 3. 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 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 for better 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 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 (i.e., the identification number received matches its own), 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 (Seizure collision avoidance is described in Secion 3.4.3). 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 mobil 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. 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.

3. Control Architecture

The cellular concept used in the Advanced Mobile Phone Service (AMPS) system to achieve spectrum efficiency requires a complex and flexibly distributed system control architecture. Three major subsystems serve as the control elements:

(1) the mobile unit,

(2) the cell site, and

(3) the switching office.

System control functions are partitioned among these subsystems to handle the following AMPS control functions:

- interfacing with the nationwide switched telephone network,
- dialing from mobile units,
- supervising calls from mobile subscribers in the presence of noise and co-channel interference,
- performing call setup functions including paging and access, and
- locating and handing off mobiles between cell sites.

The following subsections explain the techniques used to achieve the control functions of the three major subsystems and the ways they in turn participate in control of the total AMPS system.

Figure 10 shows how the control functions are partitioned among the control elements.

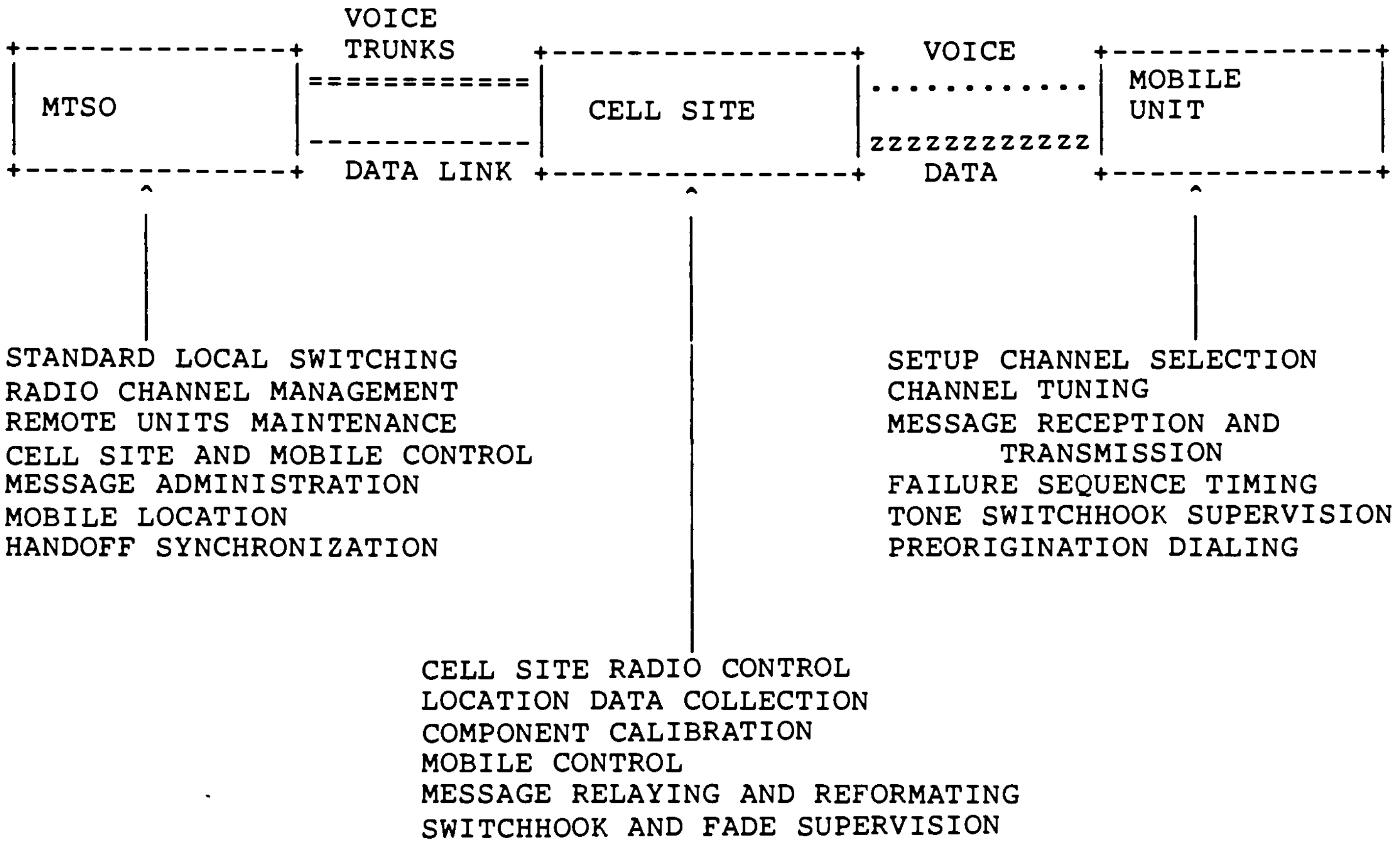


Figure 10. Partitioning of Control Functions Among AMPS Control Elements.

3.1 Introduction

The cellular concept, which achieves radio spectrum efficiency through the technique of frequency reuse, requires a grid of control elements (cell sites) distributed throughout a mobile coverage area to serve as the interface between the large numbers of moving customers and the nationwide switched telephone network. Meeting these requirements in a cost-effective manner and providing a framework for offering a variety of services to AMPS customers require a complex yet flexible control architecture.

Before proceeding to describe the system control architecture, it is helpful to look at some of the important system interfaces with the nationwide switched (wire-line) telephone network and with mobile users.

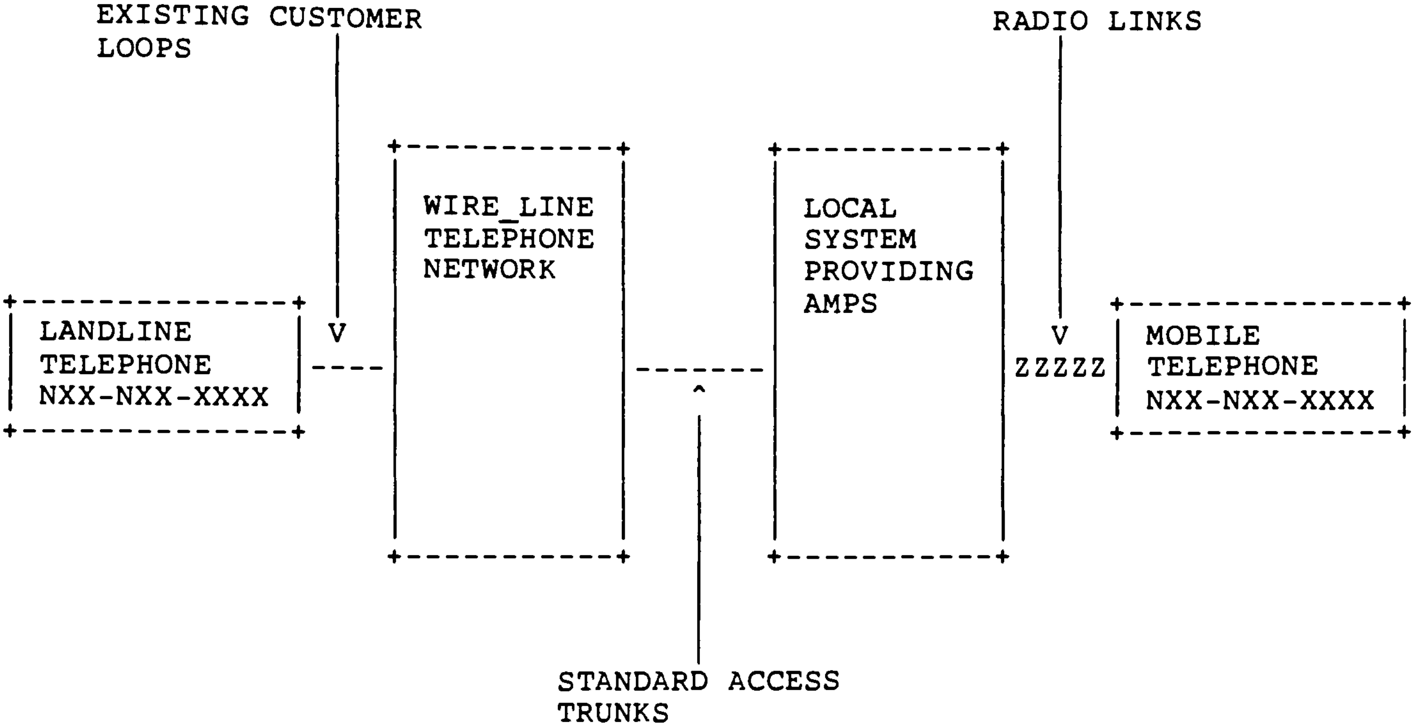
3.2 System Interfaces

There are two interfaces, the network interface and the user interface.

3.2.1 Network Interface

A single AMPS system is designed to serve customers within a given geographical area, known as a Mobile Service Area (MSA). This usually corresponds to a metropolitan area including a central city, its suburbs, and some portion of its rural fringe. However, it could encompass a portion of an extremely large metropolitan area or perhaps two or more cities located relatively close together.

Mobile customers are expected to subscribe to service in a specific MSA. While operating within its boundaries, a customer is termed a "home mobile." Outside this area, the customer is termed a "roamer." An objective of AMPS is to provide dial access between home mobiles and any other telephone (mobile or land-line) reached through the wire-line telephone network. Another objective is to provide access, as automatically as possible, to and from roamers. These goals are achieved by assigning each mobile customer a standard ten-digit telephone number composed of a three-digit area code plus a seven-digit directory number. This enables an AMPS system to interface with the wire-line telephone network using standard trunking methods (Figure 11) and permits calls to be handled with standard telephone routing and signaling techniques.



N = ANY DIGIT 2 THROUGH 9
X = ANY DIGIT 0 THROUGH 9

Figure 11. AMPS System Interfaces.

3.2.2 User Interface

AMPS radio links carry call control information in addition to voice communication. The customer's identification and the dialed digits (network address) are two call control items that must be supplied in a digital mode to the local system on every call from a mobile. Known as "preorigination dialing," the dialing sequence takes place before the mobile unit's first communication with the local system. This is not to be confused with the setup communication mentioned earlier. A mobile customer dials the telephone number of the party being contacted thus recording it in the unit's memory. The customer then initiates the communication with the land portion of the system according to calling procedures.

One major advantage of preorigination dialing is that a customer can dial at a slow rate without tying up a valuable radio channel. If a mistake is made, the customer can "erase" the dialed digits and redial the correct number. Only when the number is completely assembled and stored is the radio channel used, and then the number is sent as rapidly as possible in coded form along with other call-processing information.

The mobile telephone and the land portion of the system also exchange other information, such as the unit's supervisory state (for example, mobile on-hook/off-hook), the cell site being used, and the designated voice channel. These items are discussed in later sections.

3.3 System Control Elements

The three major system control elements are the mobile unit, the cell site, and the switching office.

3.3.1 The mobile unit

In addition to transmitting network address information, the mobile unit performs other control and signaling functions which are discussed in Section 3.4. The mobile unit is tunable on system command to any channel in the RF spectrum allocated to AMPS at any one of four power levels as pre-programmed. To perform these control and signaling functions, its design includes a microprocessor.

3.3.2 The cell site

To achieve the grid of small coverage areas from which the cellular concept takes its name, land-based radios are located at cell sites throughout the mobile coverage area. Each cell site processes the signals to make them suitable for transmission between the wire-line network and the radio network for all mobile telephones interfacing with it. This requires real-time control, which is accomplished with stored-program techniques. In addition, each cell site performs other control and signaling functions discussed below.

3.3.3 The Mobile Telecommunications Switching Office

The Mobile Telecommunications Switching Office (MTSO) serves as the central coordinator and controller for AMPS and as the interface between the mobile and the wire-line network. All information exchanged over this interface employs standard telephone signaling. Hence, standard switching techniques are required within the MTSO. In addition, the MTSO must:

(1) administer radio channels allocated to AMPS,

(2) coordinate the grid of cell sites and moving subscribers, and

(3) maintain the integrity of the local AMPS system as a whole.

These new switching functions require extensive use of stored-program technology within the MTSO.

3.3.4 Interconnection of Subsystems

Interconnection of the three major control elements is shown in Figure 12. The mobile telephone communicates with a nearby cell site over a radio channel assigned to that cell. The cell site, in turn, is connected by land-line facilities to the MTSO, which interfaces with the wire-line network. As Figure 12 also indicates, a considerable amount of data is exchanged between pairs of AMPS control elements. For instance, call setup data are exchanged between the mobile telephone and the cell site over radio channels reserved for this purpose. The voice channels also carry data to control and to confirm various mobile telephone actions. Between the cell site and the MTSO, separate facilities carry data to

```
TO WIRE-LINE
NETWORK
  |
  |    +--------------------+             +-------+          +-----------+
  |    |                    |=============| CELL  |<========>| MOBILE    |
  |    |                    |ZZZZZZZZZZZZZ| SITE 1|<ZZZZZZZZ>| TELEPHONE |
  |    |                    |             +-------+          +-----------+
  |    |                    |
  |    |  MOBILE            |             +-------+
  V    |  TELECOMMUNICATIONS|=============| CELL  |
<------|  SWITCHING         |ZZZZZZZZZZZZZ| SITE 2|
       |  OFFICE  (MTSO)    |             +-------+
       |                    |
       |                    |
       |                    |
       |                    |
       |                    |
       |                    |
       |                    |             +-------+
       |                    |=============| CELL  |
       |                    |ZZZZZZZZZZZZZ| SITE N|
       +--------------------+             +-------+

              LAND-LINE COMMUNICATION ------->|<---- RADIO COMMUNICATION


            ======== VOICE
            ZZZZZZZZ DATA
```

Figure 12. AMPS System Control Elements.

handle numerous call-processing and system integrity functions. All these functions are discussed below. Section 3.6 presents scenarios of call setup sequences. The next section presents some of the general techniques and requirements of AMPS control.

3.4 Control Techniques

This section describes several important control techniques required by the cellular concept. These techniques relate to the functions of supervision, paging and access, and seizure collision avoidance. Collision, as used here, means the loss of calls because of simultaneous arrival of two or more control messages.

3.4.1 Supervision

Classical land-line telephony defines supervision as the process of detecting changes in the switch-hook state caused by the customer. Mobile telephone supervision includes this process but has the additional task of ensuring that adequate RF signal strength is maintained during a call.

The AMPS system uses a combination of a tone burst and a continuous out-of-band modulation for supervisory purposes. These are known respectively as signaling tone (ST) and supervisory audio tone (SAT).

3.4.1.1 Supervisory Audio Tone (SAT)

Three SATs are set aside at 5970, 6000, and 6030 Hz. Only one of these is employed at a given cell site. The concept calls for using a SAT much as a land telephone uses dc current/voltage. A mobile unit receives a SAT from a cell site and transponds it back (i.e., closes the loop). The cell site looks for the specific SAT it sent to be returned; if some other SAT is returned, the cell site interprets the incoming RF power as being corrupted by interference, either in the land-to-mobile or in the mobile-to-land path. SAT is sent on each active voice channel at the cell sites.

Figure 13 shows how the use of three SATs effectively multiplies the D/R (co-channel reuse) ratio for supervision by $\sqrt{3}$. It is shown in Section 2.2 that D/R is proportional to $\sqrt{N}$, thus if N2/N1 = 21/7, then D2/D1 = $\sqrt{3}$. For example, given a voice channel reuse factor of N = 7, a cell site with both the same RF channel set and the same SAT is as far away as if N were 21. This three-SAT scheme provides supervision reliability by reducing the probability of misinterpreted interference (same SAT and same RF channel).

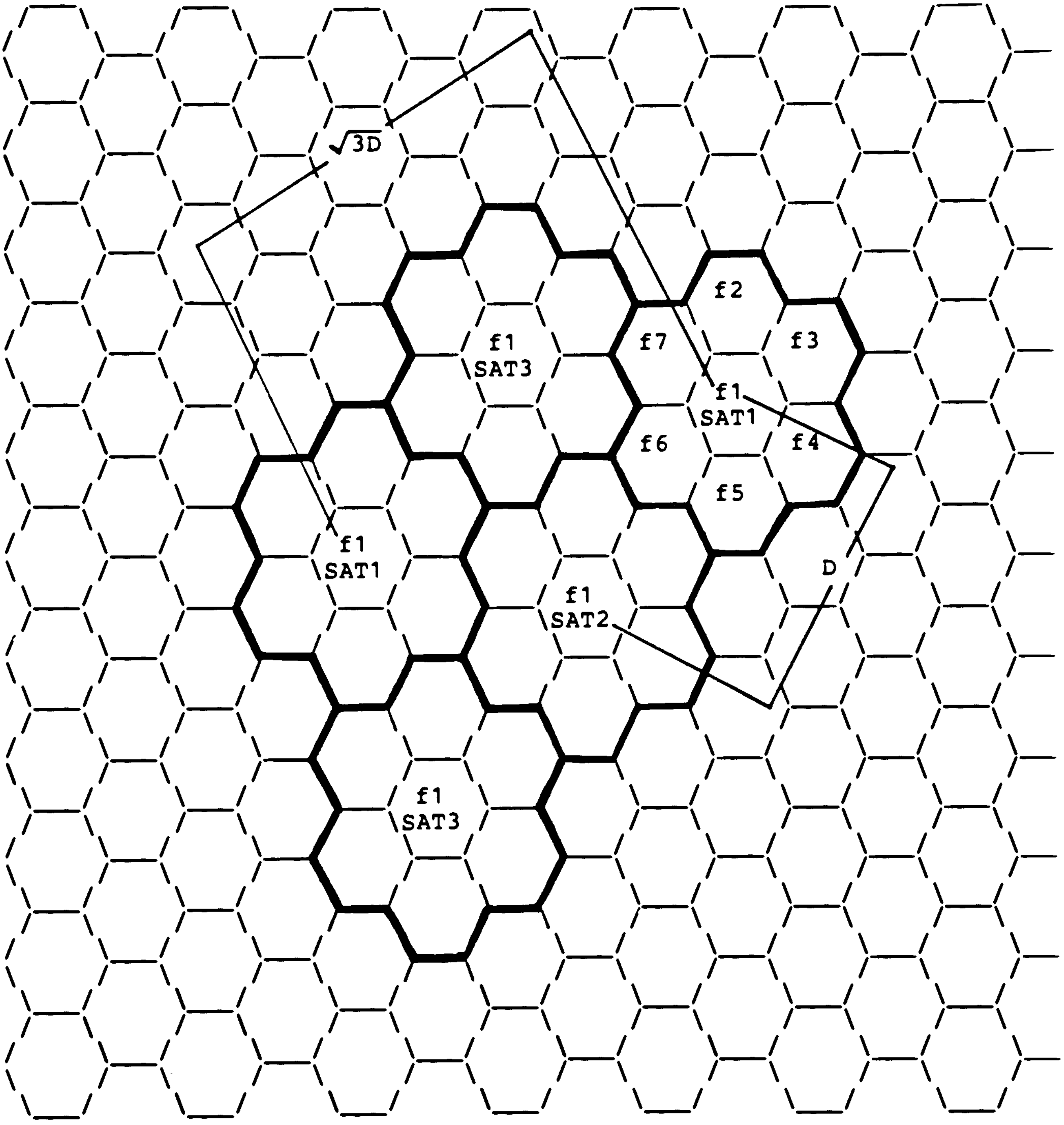


Figure 13. SAT Spatial Allocation.

3.4.1.2 Signaling Tone

Signaling tone (chosen to be 10 kHz) is present when the user is:

(1) being alerted,

(2) being handed off,

(3) disconnecting, or

(4) flashing for mid-call customer services (e.g., hold).

Signaling tone is used only in the mobile-to-land direction. Figure 14 tabulates the various supervision states of the mobile when on the voice channel, as detected by the land portion of the system.

3.4.1.3 Locating

Another aspect of supervision with no counterpart in land line telephony is the function of locating. Locating and handoff serve to keep the signal strength from a mobile unit at a high level during a call so that:

(1) the mobile's average S/I (signal-to-interference) ratio is adequate for its own good communication, and

(2) other active mobiles do not experience high co-channel or adjacent-channel interference.

The methodology for locating requires two measurements. One is a measurement of the RF signal strength on appropriate channels, made using a tunable logarithmic receiver located at each cell site. The other is a measurement of gross range (based on round-trip delay of SAT), made on each active channel using the voice channel radios at the cell sites. Analysis of this information at the MTSO determines whether a change of channels and/or cell sites (handoff) is required.

	SAT RECEIVED	SAT NOT RECEIVED
ST ON	MOBILE ON-HOOK	MOBILE IN FADE (MOBILE IS MOVING AWAY FROM THE CELL SITE) OR MOBILE TRANSMITTER OFF
ST OFF	MOBILE OFF-HOOK	

SAT = SUPERVISORY AUDIO TONE
ST = SIGNALING TONE

Figure 14. Supervision Decisions Made At Cell Site.

3.4.2 Paging and Access (Setup Channel Plan)

Seeking a called mobile unit that is at some unknown position in a service area is similar to the function performed vocally by persons called pages. Thus the term "paging" is used in AMPS to describe the process of determining a mobile's availability to receive a given incoming call. The complementary function of beginning a call, performed by a mobile unit, is termed access. This involves:

(1) informing the system of the mobile's presence,

(2) supplying the system with the mobile's identification and the dialed digits, and

(3) waiting for a proper channel designation.

Two techniques are available to perform these paging and access tasks:

(1) the special calling-channel method and

(2) the voice-channel method.

The latter method, employed by older land mobile systems presently in service, uses an "idle tone" to indicate which of several functionally identical channels is available to serve a new call, first for signaling, then for voice. The special-channel method, which dedicates channels either to the paging and access function or to the voice function, is used in the maritime and the air-ground services. In a cellular system with many thousands of users and hundreds of channels and where the mobile unit can be made to scan the dedicated channels rapidly, the special call-channel method is used. The AMPS control plan uses a set of special channels called setup channels for paging and access functions. These channels are distributed among the cell sites in an orderly way based on S/I considerations similar to those described in Section 2.

Paging and access place differing demands on the system. Paging information must be spread equally over the entire MSA. The information capacity requirements for paging will grow in proportion to the number of customers; however, splitting cells as described in Section 2 will not help to increase the capacity, since each point in the MSA needs all the paging information. The access requirements also increase with the traffic, but access capacity increases with cell-splitting since each cell in the MSA needs the access information only for mobiles in that cell.

3.4.2.1 Access Requirements

The following are the requirements on the access process:

(1) The capacity to handle access attempts must relate to the number of users. In areas saturated with access traffic, it is expected that the traffic is to arrive randomly at about one arrival per second (based on field statistics). This assumption should hold for cells of both the largest and the smallest radii. Furthermore, each user is expected to average 0.6 origination per hour, based on present-day usage statistics.

(2) It must not place undue demands on the real-time processing capabilities of either the MTSO or the cell sites.

(3) It must be accurate in the face of co-channel interference from other cells and collisions (the occasional arrival of two or more requests for service at the same time).

(4) It must be stable (i.e., some rare overload situation must not cause the system to enter a state from which it cannot recover quickly).

Since the setup channels represent an expense both in capital and in channel resource (i.e., they subtract from the total reserve of channels), it is important to use these carefully and flexibly even though future traffic loads for paging and for access are not accurately known.

3.4.2.2 Paging Requirements

Current assumptions concerning future paging requirements are that the process must:

(1) Be able to handle 0.8 page per user per busy hour, of which half go unanswered. (This estimate is based on a sample of present-day users).

(2) Provide complete number flexibility to permit nationwide roaming and to accommodate any of the ten-digit telephone numbers possible today. (This assumption requires a 34-bit binary number for mobile identification).

(3) Be capable of serving some unknown future demand (several hundred thousand users) while remaining economical in small cities with a user population of one thousand or less.

3.4.2.3 Setup Channel Plan

The plan that has evolved from these requirements allows paging and access functions, for the sake of economy, to be combined on the setup channels for the early years of growth when large cells with omnidirectional antennas are used. As the system grows, however, with cell splitting and the change to cell sites using directional antennas, more setup channels will be needed to handle the access function. The omnidirectional antennas would continue to handle the paging functions. Therefore, paging and access become separated when the first cell split occurs.

The paging messages themselves contain the binary equivalent of the mobile unit's directory number. Since a large amount of paging information has to be sent, efficient design suggests that the data be organized into a synchronous format (described later) of fixed-length words and synchronizing pulses. When paging is not needed, the cell site adds "filler text" in its place, merely to preserve the synchronous format.

Another type of message, called the "overhead word," is also sent periodically as part of the paging data stream to give the mobile certain descriptive information about the local system. The use of the overhead word permits flexibility in local system parameters (which are a function of local subscriber growth rates and traffic characteristics). These parameters can then be varied as actual field experience dictates. The overhead word includes:

(1) The MSA identification (called the Area Call Sign) to permit the automatic roaming feature.

(2) The cell site's SAT identification (5970, 6000 or 6030 Hz.).

(3) A parameter (called N) which specifies the number of setup channels in the repeating set (the frequency reuse factor).

(4) A parameter (called CMAX) which specifies the number of setup channels to scan when a call is to be made.

(5) A parameter (called CPA) which tells the mobile units whether the paging and the access functions share the same setup channels.

The highest 21 channels are always used for setup purposes; these are the channels all mobile units are pre-programmed to recognize as those containing the necessary system identification (overhead word) information, no matter where the unit makes a call.

During the early period of growth (typically to about 20,000 users in a single MSA), paging and access can be combined on the setup channels. After that, cell splitting occurs and new access capability is needed. The paging capability from the original sites, with omnidirectional antennas using the original number of paging channels, remains adequate. A second cell split, at roughly 60,000 users, requires even more access capability but is expected to leave paging on the original setup channels from the original sites.

At some point, the paging capacity of the original setup channels becomes saturated. Since each channel is limited to the order of 10,000 bits/second (b/s), and since high redundancy is required to combat the fading problem in areas of low S/I, only 1200 b/s of real information can be sent. Some of this is overhead information. Thus, a practical limit is about 25 messages per second (90,000 per hour) at 100 percent loading. Actual service experience, of course, will dictate the resulting customer loading allowed (depending on how many ineffective attempts there are), but a ratio of 90,000 customers for each paging stream is probably an upper bound. Beyond that size, which should be exceeded in only a few cities by the end of the century, more setup channel sets for paging will be needed at the original omnidirectional cell sites. Logic designed into the mobile unit must anticipate the use of these additional setup channels. Mobiles will be assigned to a specific paging channel set-either the primary (highest N channels) or one of the additional sets-for use when at home, much as land telephones are assigned to central office codes within an exchange.

3.4.2.4 Setup Channel Use

Mobiles use setup channels in the following sequence:

(1) When power is applied to a mobile unit, and about once a minute thereafter, it scans the top 21 channels and picks the strongest one on which to read an overhead message. This permits the mobile unit to determine if it is "home" and to retrieve the frequency reuse factor N. To receive its pages, it then rescans the approriate set of N channels to find the strongest channel. Since N can vary from city to city, it is read from the overhead message that is periodically being sent on all forward (cell site to mobile) setup channels.

(2) When a call is to be either originated from or completed to a mobile unit, the unit must repeat the scanning process to self-locate itself to the best cell site (i.e., the strongest signal) for access. In this case, it scans CMAX channels.

(3) The unit synchronizes to the word pattern on the chosen setup channel and determines if that channel is idle. If so, it attempts an access by transmitting the necessary information to the cell site:

    (a) If answering a page, its identification; or

    (b) If originating a call, its identification and the dialed digits.

The unit then turns its transmitter off but remains tuned and synchronized to the chosen setup channel.

(4) After the land portion of the system has processed the access information, it sends a channel designation message to the mobile unit, much as a page would be sent, on the setup channel which the mobile unit has used previously. Upon receipt of this message, the mobile tunes to the designated channel, and the voice portion of the call can proceed.

3.4.3 Seizure Collision Avoidance

The initiation of a call by a mobile unit is a random event in both space and time, as the land portion of the system perceives it. Since all mobiles compete for the same setup channels, methods must be devised to minimize collisions and to prevent temporary system disruption if collisions do occur. Several techniques are used for this purpose.

First, the forward (toward the mobile) setup channels set aside every 11th bit as a "busy/idle" bit. As long as a cell site perceives legitimate seizure messages directed toward it, it sees that the "busy/idle" bit is set to "busy."

Second, the mobile sends in its seizure message a "precursor," which tells the land portion of the system with which cell site it is attempting to communicate. The information provided in the precursor is the digital-encoded equivalent of the SAT mentioned earlier; the mobile unit, having read this digital code message in the forward data stream of the setup channel being used, transmits it back to the cell site on the reverse half of the channel.

Third, before the mobile attempts to seize (access) a setup channel, it waits a random time. This cancels the periodicity introduced into the mobile seizures by the format of the setup channel messages. Mobile units programmed with a smaller range of random numbers will have preference in seizing the channel.

Fourth, after a mobile unit sends its precursor, it opens a "window" in time in which it expects to see the channel become busy. If the idle-to-busy transition does not occur within the time window, the seizure attempt is instantly aborted.

Fifth, if the initial seizure is unsuccessful for any reason, the mobile unit will automatically try again and again at random intervals. However, to prevent continued collisions and hence system overload, a limit is placed on the number of automatic reattempts permitted. Whenever this limit is reached, the mobile unit terminates the call.

3.5 Data Requirement and Formats

As a result of the control techniques described in the preceding section, considerable amounts of data are exchanged between pairs of AMPS control elements. The radio interface channels (mobile unit to cell site) differ from land channels (cell site to MTSO) not only in capacity requirements but also in the way they must be handled because of the differing nature of the noise impairments. This section describes the data requirements and formats for the different AMPS interfaces:

(1) forward setup channel,

(2) reverse setup channel,

(3) voice channel, and

(4) land-line data link.

The following are common characteristics of the first three. One is the rapid fading experienced by signals as mobiles move through the complex RF interference pattern. To combat the burst errors caused by this fading, all data words are encoded and repeated several times at the source, and a bit-by-bit, 3-out-of-5 majority vote is taken at the receiver to determine the best-guess detected word to send to the decoder. The coding used on all radio channels is a shortened (63,51) BCH code [(40,28) in the forward direction, and (48,36) in the reverse direction]. BCH - Bose-Chandhuri-Hocquenghem, is a linear block systematic error coding scheme; (63,51) indicates that there are 63 bits transmitted, of which 51 are information and 12 are parity-check bits. This code has a Hamming distance of 3 and has the capability of correcting one bit errors while detecting two bit errors, without unreasonable complexity. This type of coding scheme, along with the majority-voting technique, provides a good balance between a low miss rate (probability of not detecting a message when one is sent) and a low falsing rate (probability of detecting the wrong message).

The philosophy used is to send the data at the fastest bit rate possible over the RF channel, consistent with its bandwidth, thus filling the channel as evenly as reasonably possible with energy. Channel capacity over and above the information needs is used up by redundancy, i.e., both by encoding and by repeating the message several times. Thus, a 10-kbs rate was chosen for the AMPS radio channels, to give a total maximum information throughput of 1200 b/s.

Another characteristic which these radio channels have in common is the pair of error requirements for information transfer:

(i) The miss rate for messages should be in the range of 10^3 at S/I = 15 db. Averaged over the entire service area, this implies a miss rate of about 10^4. This miss rate is very small compared to the probability that a call will be missed because a mobile is unattended. Furthermore, it is consistent with the requirement placed on mishandled calls in the wire-line telephone network.

(ii) The falsing rate (incorrect data interpretation) should be less than 10^7 for a given message. This stringent requirement is necessary because, for example, in a system where 90,000 users are assigned to a given paging data stream, up to 45,000 mobile units might be listening to every page (assuming that at least half the equipped mobiles are not energized at any given time); in this situation, the requirement implies that less than one transmitted page in 200 will elicit a false response (which the MTSO will be required to screen).

3.5.1 Forward Setup Channel

Data on this channel are transmitted continuously in a periodic format, so that idle mobile units can synchronize to the format to read a large volume of paging and local system information.

Figure 15 details the data format of the forward setup channel. The basic period of the bit stream is 463 bits, summed as follows:

```
              10bits 11bits       40bits              40
- - - --------+-----+-----+-----------------------+-----------------------+
LAST WORD B5  | BIT | WORD| WORD A1 (40,28) BCH   | WORD B1               |
              | SYNC| SYNC|                       |                       |
- - - --------+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
              ^     ^     ^     ^     ^     ^     ^     ^     ^     ^     ^
              |     |     |     |     |     |     |     |     |     |     |

              40                      40
        +-----------------------+-----------------------+------------ - - -
        |     WORD A2           |     WORD B2           |    WORD A3
        |                       |                       |
        +-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+ - - -
              ^     ^     ^     ^     ^     ^     ^     ^     ^     ^
              |     |     |     |     |     |     |     |     |     |

              40                 10    11          40
- - - --+-----------------------+-----+-----+-----------------------+ - - -
        |     WORD B5           |BIT  |WORD |    NEXT WORD A1       |
        |                       |SYNC |SYNC |                       |
- - - --+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+ - - -
        ^     ^     ^     ^     ^     ^     ^     ^     ^     ^     ^
        |     |     |     |     |     |     |     |     |     |     |
```

NOTES:

```
 ^
 |  =  POINT OF BUSY-IDLE BIT INSERTION (AFTER EACH 10 MESSAGE BITS
       AND AFTER BIT AND WORD SYNC)
```

Ai = iTH OF FIVE REPEATS OF WORD FROM MESSAGE STREAM A

Bi = iTH OF FIVE REPEATS OF WORD FROM MESSAGE STREAM B

INFORMATION CONTENT OF WORDS
PAGES
CHANNEL DESIGNATIONS
OVERHEAD WORDS
FILLER TEXT

Figure 15. Data Format (Forward Setup Channel).

200 bits - Word A (40 bits, repeated 5 times)
200 bits - Word B (40 bits, repeated 5 times)
10 bits - Bit sync
11 bits - Word sync
42 bits - Busy-idle bits
----
463 bits

The five repeats of words A and B are interleaved to provide spacing in time, which in turn ensures partial decorrelation of bit errors between repeats of the same word. Note that a given mobile unit is not required to decode both of the two message streams; it chooses the A or B stream depending on whether its identification is even or odd. This is determined by the last digit of its telephone number.

3.5.2 Reverse Setup Channel

On this channel, the mobiles act in a random and competitive way to initiate calls. Both signals and interferences are turned on and off in an uncorrelated fashion.

Details on the data format of the reverse setup channel are shown in Figure 16. A message is preceded by a 48-bit seizure precursor. Each message consists of 1 to 5 words of 48 bits each, repeated 5 times. The cell site performs a bit-by-bit, 3-out-of-5 vote to determine the 48-bit encoded word; it then uses a decoding algorithm to correct one error if necessary (or to reject the message as uncorrectable).

3.5.3 Voice Channel

This channel is used primarily for conversation. However, data messages (primarily handoff) are also required on this channel. Unlike the reverse setup channel, a transmitted signal is always available to provide "capture" and thus suppress interfering data messages. This is because the receivers are able to extract the stronger of two overlapping signals without error which is known as the "capture effect."

The technique used is "blank-and-burst"; that is, the voice signal is blanked and the data sent rapidly in a burst that uses a large part of the channel's bandwidth.

Details on the data format of the voice channel are shown in Figure 17. Note that messages are repeated 11 times in the forward direction but only 5 times in the reverse direction. The primary reason for this difference is that the handoff

```
   /  SEIZURE PRECURSOR   \
   |                      |

    30(bits)  11    7            48                     48
   +---------+-----+-----+----------------------+-----------------------+--
....|BIT SYNC | WORD|  *  | WORD A1 (48,36) BCH  | WORD A2               |
   |         | SYNC|     |                      |                       |
   +---------+-----+-----+----------------------+-----------------------+--


  48         48                      48                     48
- - - --+-----------------------+-----------------------+------------- - - -
WORD A3 |     WORD A4           |    WORD A5            |     WORD B1
        |                       |                       |
- - - --+-----------------------+-----------------------+------------- - - -


           48                      48
 - - - -+-----------------------+-----------------------+
        |     LAST WORD4        |    LAST WORD5         |.....
        |                       |                       |
 - - - -+-----------------------+-----------------------+


     * = ONE OF FOUR SEQUENCES TO IDENTIFY THE CELL SITE
         AT WHICH THE MESSAGE IS AIMED
```

Figure 16. Data Format (Reverse Setup Channel).

message, considered a critical function since false interpretation results in a mishandled call, is usually sent under atypically low S/I conditions.

3.5.4 Land-line Data Line

The capacity for information transfer between cell site and MTSO must be great enough to take care of a large number of functions and flexible enough to accommodate changes as the system matures. The choice of a 2400-b/s channel, with growth capability to two channels in large systems and the use of the data format to be described, satisfies these qualitative requirements.

The coding scheme chosen is a (32,26) BCH code, shortened from a basic (63,57) BCH code. Synchronization is via a preamble embedded at the start of each message. Subtracting the 6-bit parity check and the 3-bit synchronization leaves 23 bits for information.

Figure 18 is a sketch of the basic format. Each message has 16 bits for the actual data (specific commands, numbers to be transmitted, locating measurements, etc.) preceded by 7-bit routing item, which generally takes one of three forms:

(i) "Source" identification for message sent from cell site to MTSO, (e.g., setup receiver, locating receiver, voice radio)

(ii) "Destination" identification for messages sent from MTSO to cell site (e.g., setup transmitter, blank-and-burst data unit)

(iii) "AWC" (additional word coming) for multi-word messages in each direction.

3.6 Condensed Call Sequences (Single MTSO system)

Various control functions and the major control elements of the AMPS system have been described. The ways these elements work together to perform their control functions can be seen in perspective most effectively by describing rudimentary mobile call sequences. There are two basic types of mobile telephone calls - mobile-completed calls and mobile-originated calls. These are described next, in turn, to the point at which conversation occurs (talking state). Actions common to both call types are also discussed.

```
                          L1 (BITS LONG)      11    L2
                     +-------------------------+----+---------+---  -  -
...____VOICE______|         BIT SYNC          |WORD| WORD A1 |
                     |                          |SYNC|         |
                     +-------------------------+----+---------+---  -  -


    37       11        L2        37       11        L2        37      11    L2
- - ---------+----+---------+---------+----+---------+---------+----+----  -  -
 BIT SYNC |WORD| WORD A2 | BIT SYNC|WORD| WORD A3 | BIT SYNC|WORD|WORD A4
          |SYNC|         |          |SYNC|         |          |SYNC|
- - ---------+----+---------+---------+----+---------+---------+----+----  -  -


      11          L2         37       11    L2
- - ---------+---------+---------+----+---------+ *
     WORD    |WORD Ak-1| BIT SYNC|WORD| WORD Ak |_____VOICE________.......
     SYNC    |         |          |SYNC|         |
- - ---------+---------+---------+----+---------+
```

	FORWARD	REVERSE
L1 (BITS LONG)	100+-	101
L2 (BITS LONG)	40	48
K (REPEATS)	11	5

* NOTE: ON THE REVERSE CHANNEL, A SECOND MESSAGE (B) MAY FOLLOW WORD Ak

Figure 17. Data Format (Voice Channel).

3	7	16	6
SYNC	SOURCE OR	DATA	PARITY

(32,26) BCH

Figure 18. Data Format (Land-Land Data Channel).

3.6.1 Initialization

When the mobile telephone is energized, it scans the setup channels according to a program in its memory (as described in Section 3.4.2.4) and selects the strongest one. This channel will normally be associated with a nearby paging cell site. The mobile telephone continues to monitor the selected forward setup channel for paging messages. It repeats the initialization process at regular intervals or when needed because of poor signal at the mobile, or until it is involved in a call.

3.6.2 Mobile-completed Call

Figure 19 shows the actions required to process a mobile-completed call. These are:

(i) Paging:

From the calling party's central office, the call is routed by standard wire-line network routing procedures to the home MTSO of the mobile. The MTSO collects the digits, converts them to the mobile's identification number, and instructs the cell sites containing paging channels to page the mobile over the forward setup channels. In this way, the paging signal is broadcast over the entire service area.

(ii) Cell Site Selection:

The mobile unit, after recognizing its page, scans the setup channels used for access in the MSA, using parameters derived from the overhead word, and selects the strongest one. The selected channel will probably be associated with a nearby cell site (usually the nearest cell site).

(iii) Page Reply:

The mobile responds to the cell site it selected over the reverse setup channel. The selected cell site then reports the page reply to the MTSO over its dedicated land-line data link.

(iv) Channel Designation:

The MTSO selects an idle voice channel (and associated land-line trunk) in the cell site that handled the page reply and informs the cell site of its choice over the appropriate data link. The serving cell site in turn informs the mobile of its channel designation over the forward setup channel. The mobile tunes to its channel designation and transponds the Supervisory Audio Tone (SAT) transmitted over the voice channel. On recognizing the transponded SAT, the cell site places the associated land-line trunk in an off-hook state, which the MTSO interprets as successful voice channel communication.

(v) Alerting:

On command from the MTSO, the serving cell site transmits a data message over the voice channel to an alerting device in the mobile telephone which signals the customer that there is an incoming call. Signaling tone from the mobile causes the cell site to place an on-hook signal on the appropriate land-line trunk which confirms successful alerting to the MTSO. The MTSO, in turn, provides audible ringing to the calling party.

(vi) Talking:

When the customer answers, the cell site recognizes removal of signaling tone by the mobile and restores the land-line trunk to an off-hook state. This is detected at the MTSO, which removes the audible ringing circuit and establishes the talking connection so that conversation can begin.

3.6.3 Mobile-originated Call

Figure 20 depicts the various actions required to establish a mobile-originated call. These are:

(i) Preorigination:

Using the preorigination dialing procedures described earlier (in Section 3.2.2), the customer enters the dialed digits into the mobile unit's memory.

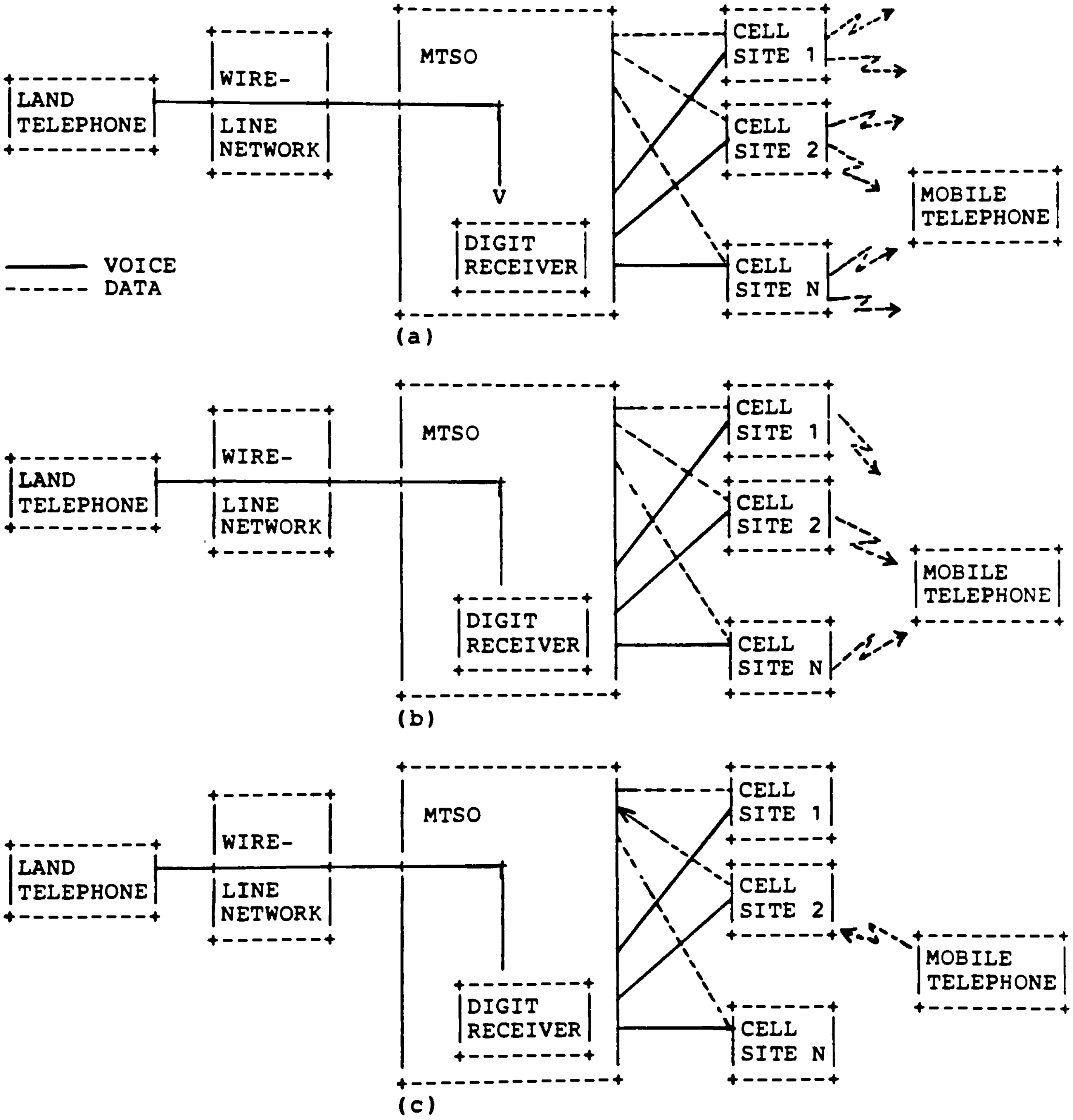
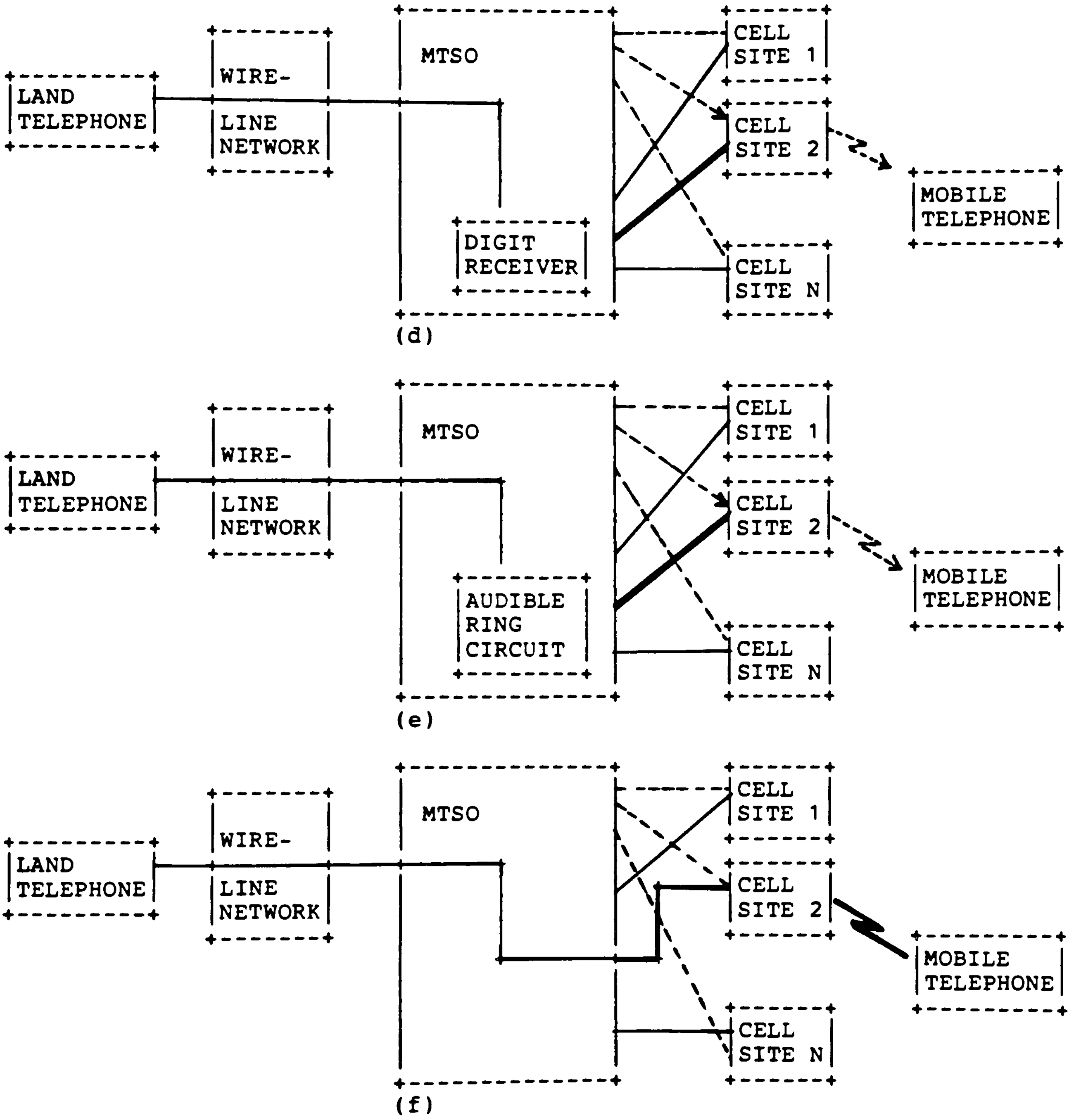


Figure 19. Mobile-Completed Call Sequence.
(a) Paging. (b) Cell site selection. (c) Page reply.
(Cont. next page ...)



(... Figure 19 Cont.)
(d) Channel designation. (e) Alerting. (f) Talking.

(ii) Cell Site Selection:

After the mobile unit is placed in an off-hook state, it scans the setup channels and selects the one with the strongest signal. The selected channel is associated with the nearest cell site. This process is similar to that described previously for the mobile-completed call (see item (ii) in Section 3.6.2).

(iii) Origination:

The stored digits, along with the mobile's identification, are transmitted over the reverse setup channel selected by the mobile. The cell site associated with this setup channel receives this information and relays it to the MTSO over its land-line data link.

(iv) Channel Designation:

As for a mobile-completed call, the MTSO designates a voice channel and establishes voice communication with the mobile. The MTSO also determines routing and charging information at this time by analyzing the dialed digits.

(v) Digit Outpulsing:

The MTSO completes the call through the wire-line network using standard digit outpulsing techniques.

(vi) Talking:

When outpulsing is completed, the MTSO establishes a talking connection. Communication between customers takes place when the called party answers.

3.6.4 Other Common Actions

Actions associated with handoff and disconnect are described next.

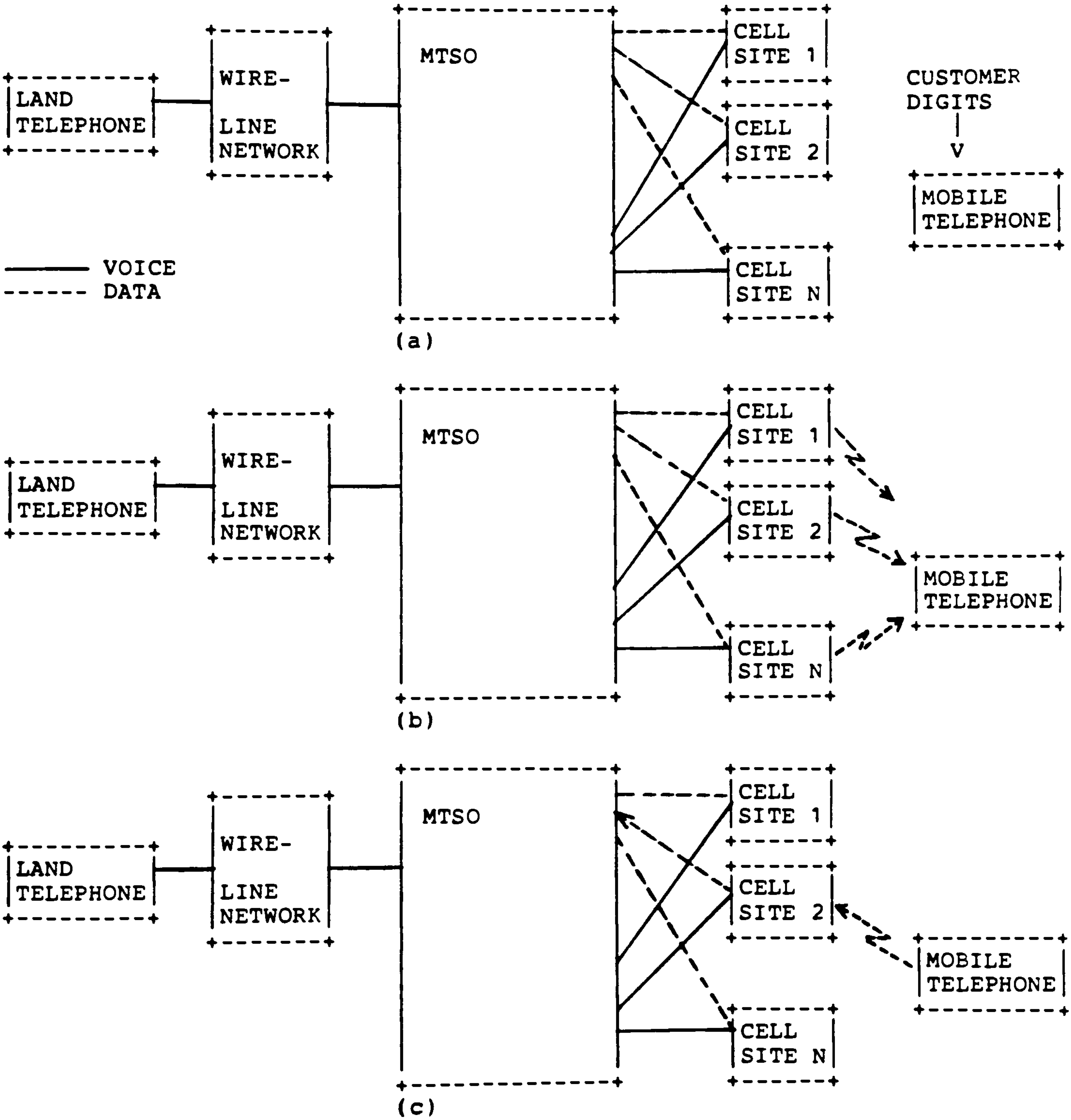
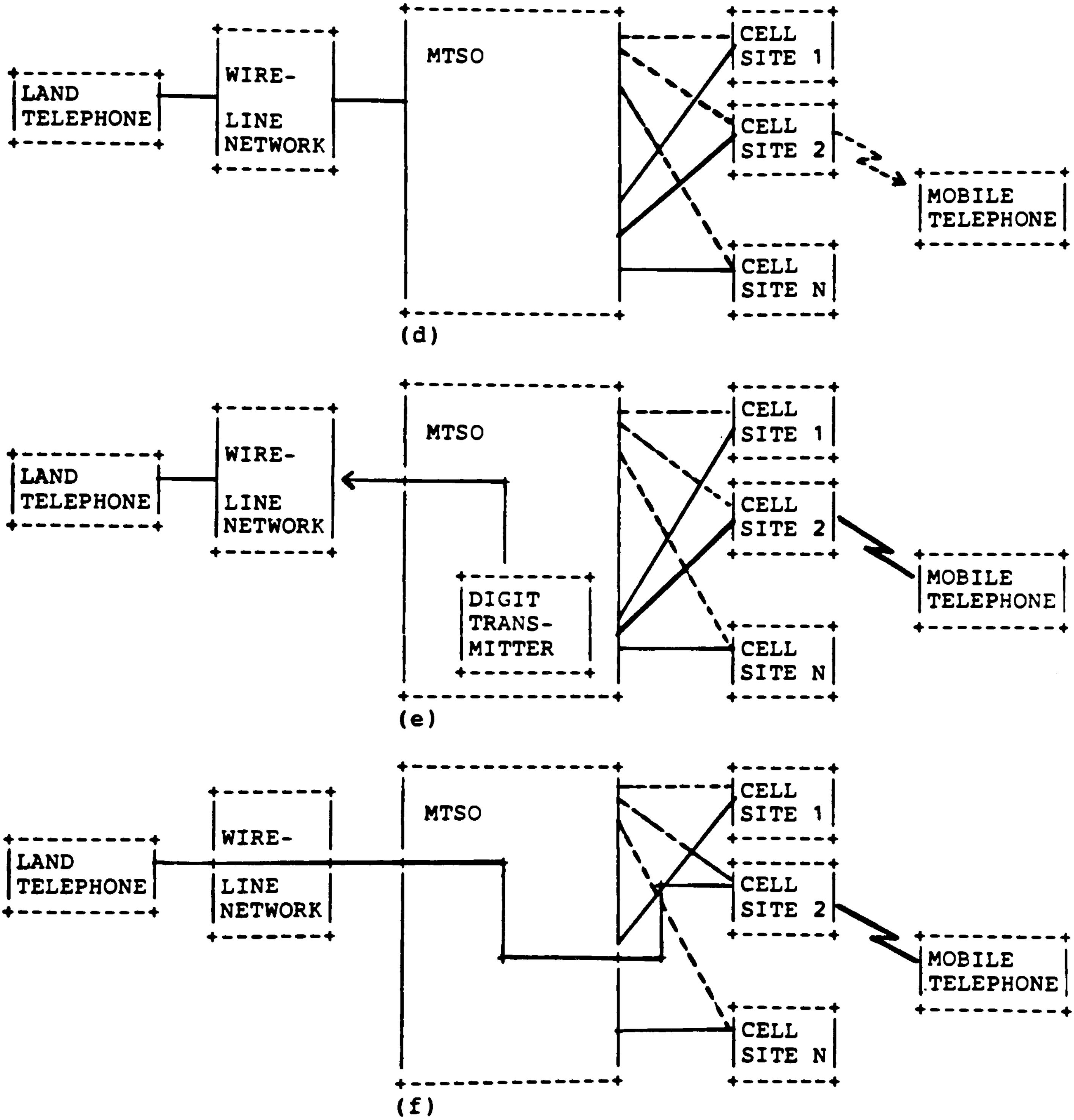


Figure 20. Mobile-Originated Call Sequence.
(a) Preorigination. (b) Cell site selection. (c) Origination.
(Cont. next page ...)



(... Figure 20 Cont.)
(d) Channel designation. (e) Digit outpulsing. (f) Talking.

3.6.4.1 Handoff

Figure 21 depicts the actions common to both mobile-originated and mobile-completed calls during the important process of handoff. These are:

(i) New Channel Preparation:

Location information gathered by the cell site serving the mobile, as well as by surrounding cell sites, is transmitted to the MTSO over the various cell site land-line data links. The data are analyzed by the MTSO, which decides that a handoff to a new cell site is to be attempted. The MTSO selects an idle voice channel (and an associated land-line trunk) at the receiving cell site and informs the new cell site to enable its radio. The receiving cell site turns on its radio and transmits its SAT.

(ii) Mobile Retune Command:

A message is sent to the current serving cell site informing it of the new channel and new SAT for the mobile in question. The serving cell site transmits this information to the mobile over the voice channel.

(iii) Channel/Path Reconfiguration:

The mobile sends a brief burst of signaling tone and turns off its transmitter; it then retunes to its new channel and transponds the SAT found there. The old cell site, having recognized the burst of signaling tone, places an on-hook signal on the trunk to the MTSO. The MTSO reconfigures its switching network, connecting the other party with the appropriate land-line trunk to the new serving cell site. The new serving cell site, on recognizing the transponded SAT on the new channel, places an off-hook signal on the associated land-line trunk. The MTSO interprets these two signals (off-hook on new trunk; on hook on old trunk) as a successful handoff. The customers should not experience any noticeable break in the conversation during a handoff.

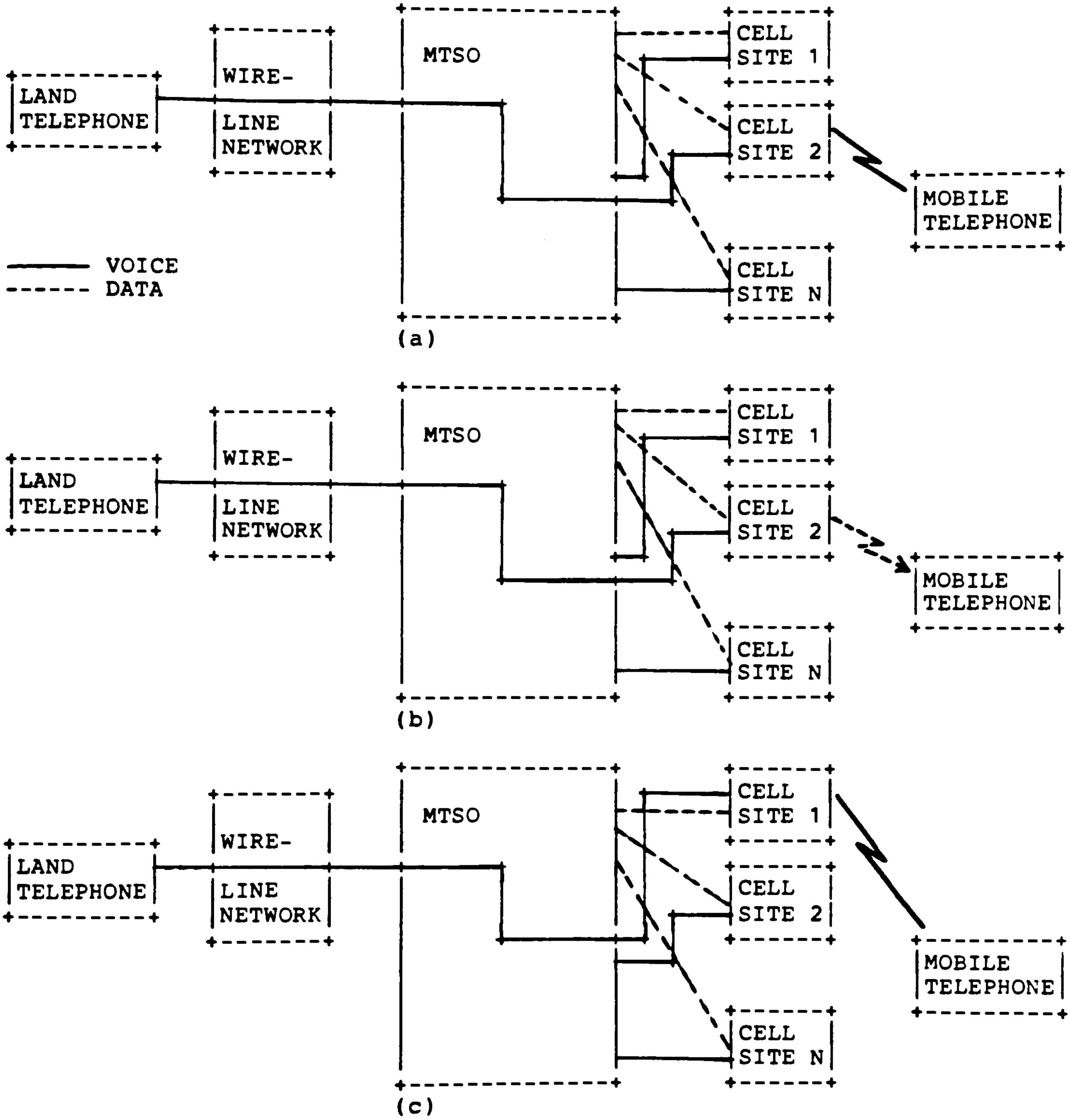


Figure 21. Handoff Sequence.
(a) New channel preparation. (b) Mobile retune command.
(c) Channel/path reconfiguration.

If no cell site can serve the mobile (for example, no idle voice channel available), the MTSO leaves the call undisturbed on the original cell site. If the mobile leaves the range of all cell sites served by the MTSO in a single system environment, then the call is terminated.

3.6.4.2 Disconnect

Figure 22 and 23 depict the actions common to both mobile-originated and mobile-completed calls during the call disconnect process. Disconnection can be initiated by either the mobile party or the land portion of the system (usually in response to an on-hook signal from a land party). The resulting actions differ somewhat.

3.6.4.2.1 Mobile-initiated disconnect

The actions occurring when the mobile party goes on-hook are:

(i) Release:

The mobile unit transmits signaling tone and turns off its transmitter. The signaling tone is received by the cell site, which places an on-hook signal on the appropriate land-line trunk.

(ii) Idle:

In response to the on-hook signal, the MTSO idles all switching office resources associated with the call and transmits any necessary disconnect signals through the wire-line network.

(iii) Transmitter shutdown:

As the final action in the call, the MTSO commands the serving cell site over its land-line data link to shut down the cell site radio transmitter associated with the call. All equipment used on this call may now be used on subsequent calls.

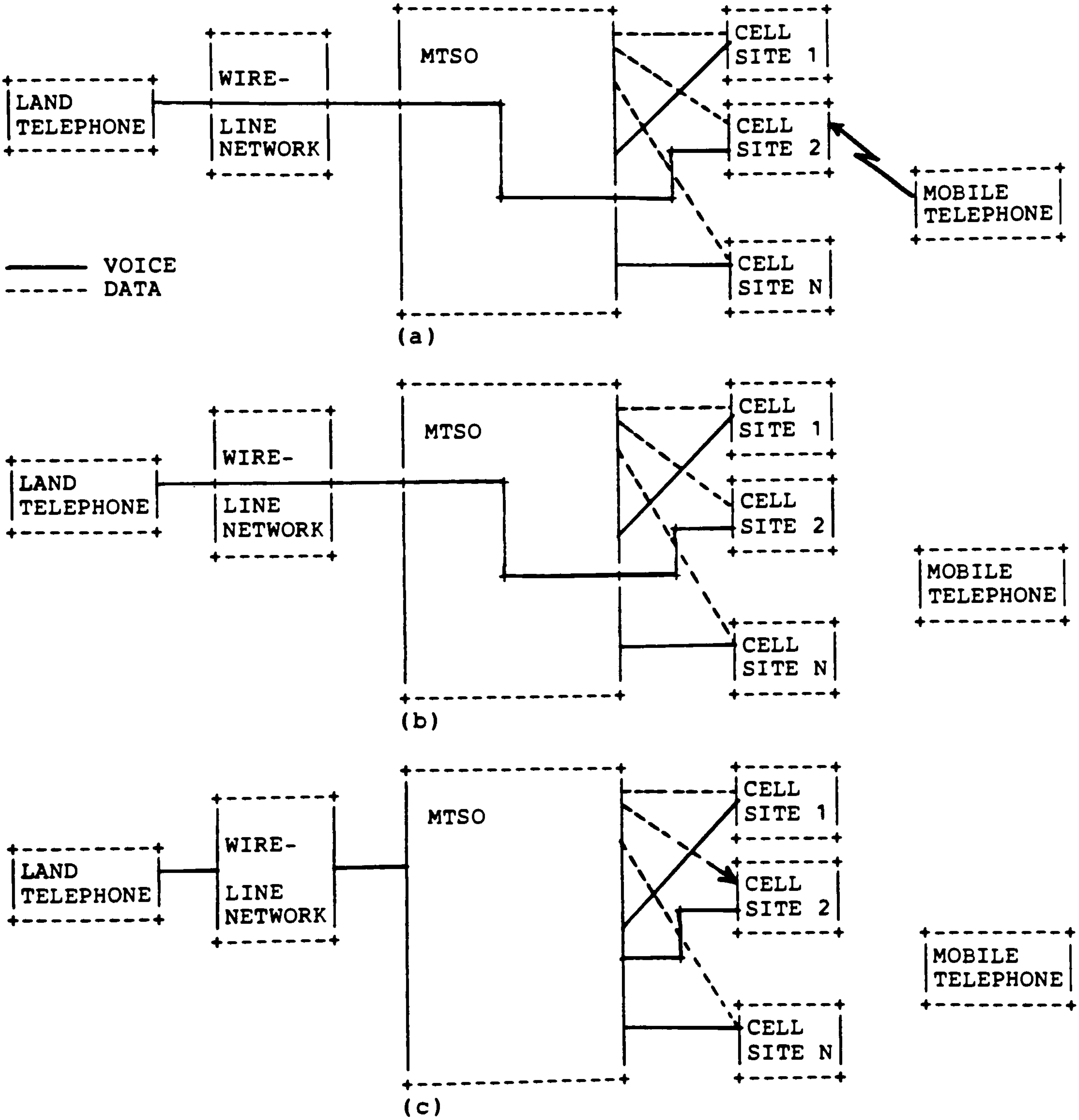


Figure 22. Disconnect Sequence (Mobile-Initiated).
(a) Release. (b) Idle. (c) Transmitter shutdown.

3.6.4.2.2 System-initiated Disconnect

The actions occurring when the land party goes on hook are:

(i) Idle:

In response to the disconnect signal received from the wire-line network, the MTSO idles all switching office resources associated with the call.

(ii) Ordered Release:

The MTSO sends a release order data link message to the serving cell site. The cell site transmits this command to the mobile over the voice channel. The mobile confirms receipt of this message by invoking the same release sequence as with a mobile-initiated disconnect.

(iii) Transmitter Shutdown:

When the MTSO recognizes successful release by the mobile (via an on-hook signal on the appropriate land-line trunk), it commands the serving cell site to shut down the radio transmitter as described previously.

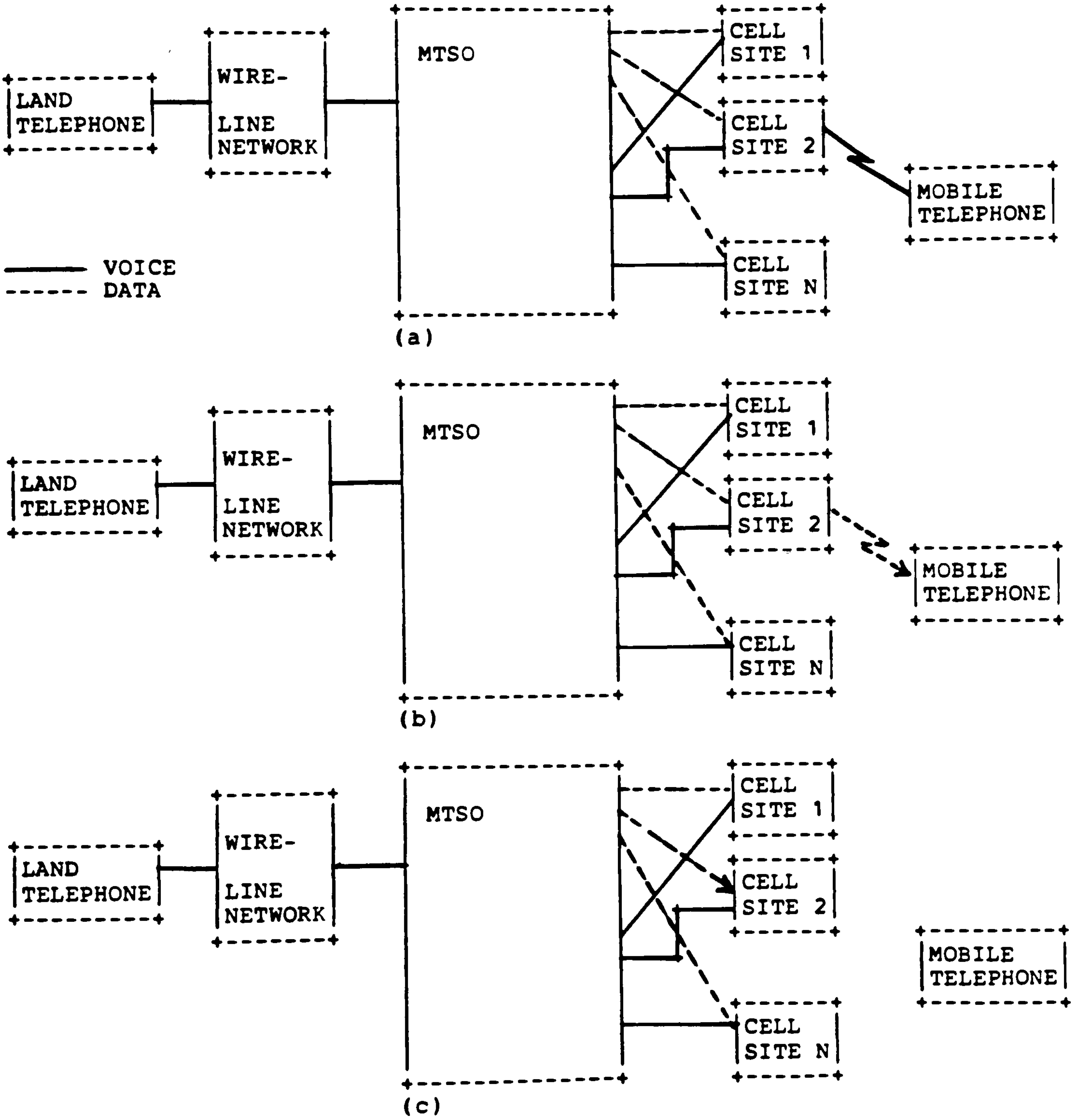


Figure 23. Disconnect Sequence (System-Initiated).
(a) Idle. (b) Ordered release. (c) Transmitter shutdown.

4. Mobile Telephone Network

The three major subsystems (the mobile unit, the cell site and the MTSO) of the AMPS system have been presented in the previous sections. The cellular concept and the control techniques performed by these subsystems are used to solve the problems associated with a proposed non-wire line mobile telephone network. This network differs from the existing mobile telephone networks which rely on the land telephone network for network communication. A non-wire line mobile telephone network uses the RF spectrum for network communication and control.

This proposed network interconnects service areas to expand the coverage to a much greater geographic area. Efficient use is made of the limited bandwidth available for network communication. The network is able to manage mobile units that move from one service area to another during a call, and can efficiently locate mobile units throughout the network area. The approach used in this proposed network can be generalized to apply to broadcasting network systems with non-stationary terminals.

The following sections present the problems associated with a non-wire line mobile telephone network and describe how the important control functions of routing, paging/access, locating and handoff are implemented in the network.

4.1 Problems Associated With A Mobile Telephone Network

The following problems are identified in a mobile telephone network configuration.

The two end points of a connection are not stationary (mobile to mobile). A mobile can move from one cell site to another or from one MSA to another during a conversation. The connection can extend over several MSA(s) and it is the responsibility of the network to setup and maintain such connection. The control techniques (handoff, paging, accessing, etc.) have to be modified to function properly in the network environment. Also the problem of routing within the network must be addressed.

The number of channels available for inter-MTSO communications is limited, which is the very same problem encountered by the mobile phone system (single MTSO system). This leads to the idea of applying the cellular concept in the network design.

Growth, in terms of the number of subscribers, cell sites, and MTSO(s) within the network, must be addressed in the network design.

Another problem is the reliability of the network. Failure in one MTSO or cell site should not impact the operation of the rest of the network.

Seizure collision avoidance, both in the MTSO level and the network level, must be addressed.

Proposed solutions for these problems are presented in subsequent sections.

4.2 Routing

Routing is one of the most important design questions of a point-to-point network like the mobile telephone network and it is addressed in the following sections.

There are two problems associated with routing in a mobile telephone network. The first one is how to setup a connection between two mobiles and the second one is how to maintain the connection during the entire call. There are also the considerations of cost and availability in routing. A least cost route will satisfy the customer, but in some cases such a route would cause blocking in traffic. This occurs if the last available channel in a mobile service area has to be taken in setting up the route, which results in local traffic congestion.

Paging process plays an important role in routing; therefore, it is described before the routing algorithms. Some of the paging functions required in a network are independent of the routing algorithm and they are presented in the following section.

4.2.1 Paging within the Network

When a mobile origination (mobile sent out some dialed digits) is detected by the MSA, the following functions are performed before paging takes place:

(1) The mobile ID of the origination mobile is validated. If it is a valid subscriber, then the next function is performed. A valid subscriber is one who has subscribed service in the MSA, or is allowed to have service if the MSA is not the home MSA of the mobile (valid roamer). Each MTSO keeps a list of local subcribers and a list of valid roamers. The call is terminated if this check failed.

(2) The dialed digits are validated. If insufficient digits are dialed or digits do not conform with NPA/NXX codes, then the call is terminated. Each mobile identification number corresponds to a 3-digit area or Numbering Plan Area (NPA) code and a 7-digit telephone number. The mobile NPA code conforms with the NPA codes of the land-line network for possible interface with the land-line network. The first 3 digits of the telephone number can be used as the MTSO identificaton number and the last 4 digits as a mobile identification number. This provides a maximum of ten thousand (0000-9999) mobile numbers per MTSO. If more mobile subscriptions are anticipated, the number of digits for the MTSO ID can be reduced to make room for mobile ids. Another approach would be similar to cell splitting by adding in new MTSO(s) to the same service area to increase the capacity. This is termed "MTSO" splitting. The choice of which approach to use will be based on cost and if necessary, both can be applied in the network.

Paging in a multi-MSA system would require the home MSA of the called mobile being paged first. If no response is detected, then paging information will be spread over the rest of the MSAs in the system. Since the probability of the mobile's being in its home MSA is high, it is likely that the mobile can be located in the first attempt. This results in a substantial amount of saved bandwidth. The home MSA of the mobile can be determined from the mobile's identification number.

A variation of the above approach is to page in all the adjacent MSAs and if no response, then corresponding adjacent MSAs will be attempted until the entire network service area has been paged, or the mobile is located.

Whenever a mobile is powered up, the MTSO will detect the presence of the mobile through the setup channels. The MSA can register all current active mobiles in its database. If the mobile to be paged is not registered in the list, no paging is attempted by the MTSO.

It is possible for remote MTSOs to send information to the home MTSOs about their roamers in the area. Another approach is to have a dedicated MTSO which keeps track of all the currently active mobiles in the network by having the MTSOs reporting to it whenever mobiles registered in the air. This special MTSO is the "Central/Control MTSO" presented later in this paper.

After the mobile is located, the system has to setup a virtual circuit between the orignating mobile and the terminating mobile. Therefore, routing becomes one of the design issues. The goals of routing are to locate the shortest available route and to consume the minimum resources in the routing process.

4.2.2 Possible Routing Algorithms

This section examines some of the routing algorithms used in broadcasting networks. The objective is to see if these can be applied to routing in a non-wire line mobile telephone network. The network consists of a number of MTSOs. Each MTSO can communicate with the other MTSOs via either intermediate MTSOs, radio repeaters or a combination of both. The radio repeater will use different frequencies for input and output. This is because repeater is also used for the voice path once routing is done and voice communication is asynchronous.

The packet radio system is used to present some possible routing algorithms and it is used only for channel setup. Gitman et al. (1976) have suggested three possible routing strategies for a packet radio system. The first algorithm is a modified version of flooding with two restraints. The first restraint is a hop counter, which is included in the header of each packet. Each time the packet is forwarded, the hop counter is decremented by one. When the counter gets to zero, the packet is discarded. This is to guarantee that no packet lives forever. The choice of the initial value of the counter is crucial. If it is too small, packets destined for outlying areas may never arrive. If it is too large, vast numbers of useless duplicates may be generated, wasting precious bandwidth. A second restraint that is needed to make flooding a practical algorithm is for repeaters or intermediate MTSOs to be able to recognize reruns of packets that they have recently forwarded. Consider the example of Figure 24. Suppose that the maximum number of hops for the destination shown is set at four(4). When the packet is initially transmitted, both A and B receive and forward it. Each of them hears the other's retransmission and retransmits it again. This goes on for a while until the hop count has been exhausted. The result is a large amount of wasted bandwidth.

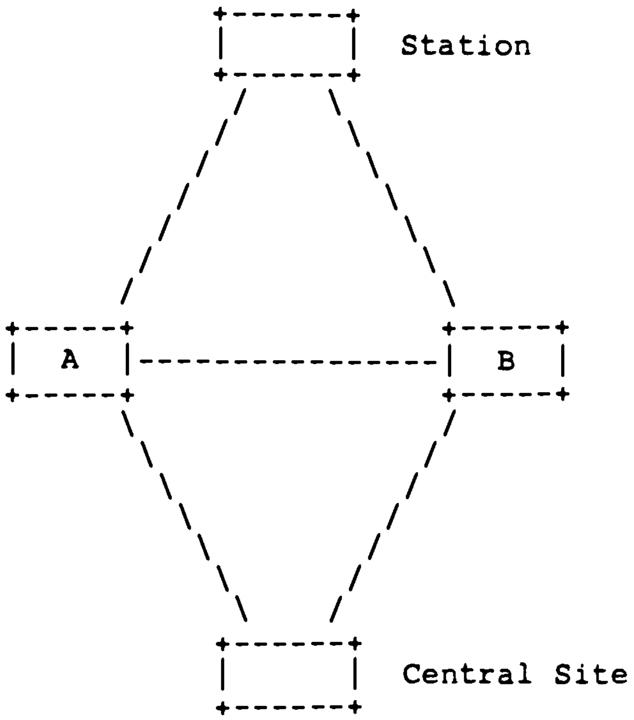


Figure 24. A Repeater Topology.

To alleviate this problem, each repeater can maintain a first-in first-out (FIFO) queue of the most recent M packets retransmitted. Whenever a packet comes in, it is checked against the available history and discarded if it is a duplicate. Each new packet causes the oldest one in the FIFO queue to be pushed off the end and lost. The mobile identification number of the destinated or originated mobile can be used as the unique identifier.

The second of the routing algorithms proposed by Gitman et al. is hierarchical routing. The repeaters are organized into a tree, with the central site at the root. This algorithm requires that the central site be aware of the complete topology. This information can be acquired by having the central site send broadcast probe packets periodically. Each repeater responds to a probe by sending an answer packet. When a repeater forwards an answer packet due to another repeater, it appends its identification to the packet. From the returned answers, the central site can easily determine the shortest path to each repeater. Upon learning the new topology, the central site then informs each repeater of its new label. A label is just a path description, as shown in Figure 25. In the case of multiple "central sites" like the multi-MSA system, each repeater will be assigned labels corresponding to the central sites.

Once the repeater tree has been formed, each data packet sent by the central site can contain the label of the repeater to which the station has been assigned. The packet must also contain a pointer telling which field in the label is the current one. When a packet arrives at a repeater, the repeater checks to see if it is named in the current field. If so, it advances the pointer by one field and forwards the packet. If not, it just discards the packet.

To see why this mechanism is needed, consider a packet directed to repeater 1310 in Figure 25. The central site initializes the pointer to the first 1 and broadcasts it. Repeater 1000 knows that it must forward it, and any other repeaters that hear the packet do not forward it. By the time repeater 1300 forwards the packet, the pointer is now pointing at the second 1. Were it not for the pointer, repeater 1000 might detect the packet, see that it was on the path, and forward it again.

In the third routing algorithm, a repeater only forwards a packet if it is closer to the destination than the last repeater that forwarded the packet. Each repeater is assumed to know its distance in hops from every other repeater. This information can be acquired by having each repeater broadcasts its distance table periodically. Each data packet

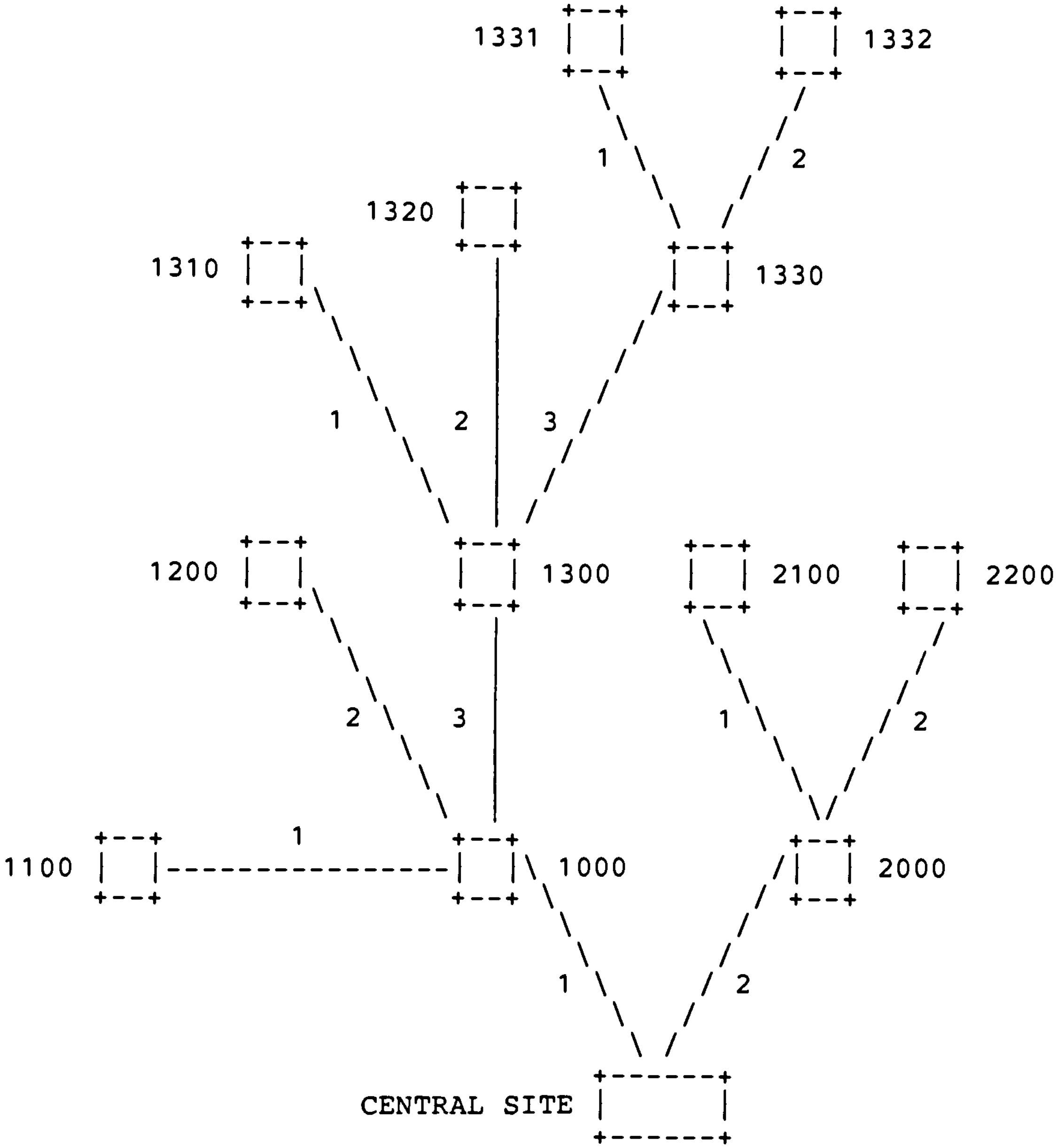


Figure 25. A Repeater Tree and Its Labeling.
The largest path is four hops, so labels have four fields, with trailing zeros if need be.

contains the identification of the destination and the sender's distance from that destination. At each hop there is a new sender, and hence a new distance. When a packet arrives at a repeater, the program checks to see if it is closer to the destination than the sender. If so, the packet is heading the right way and is forwarded. If not, the packet is heading the wrong way and is discarded.

As an example, consider Figure 26. When the central site sends a packet to A, it indicates that the distance is three(3) hops. Both J and K receive the initial transmission. J knows that it is only two(2) hops from A, so it forwards the packet, changing the distance in the header to two(2) hops. K knows that it is just as far away as the sender, so it discards the packet. The packet sent by J is received by F, G, H, and K. Of them, F and G are the only ones closer than two(2) hops, so they alone forward the packet, each one changing the distance in the header to 1. A will evetually get two copies of the packet. This algorithm always uses the shortest path, but it is more robust than the previous one, because it concurrently tries all alternate paths whose length are equal to the minimum length.

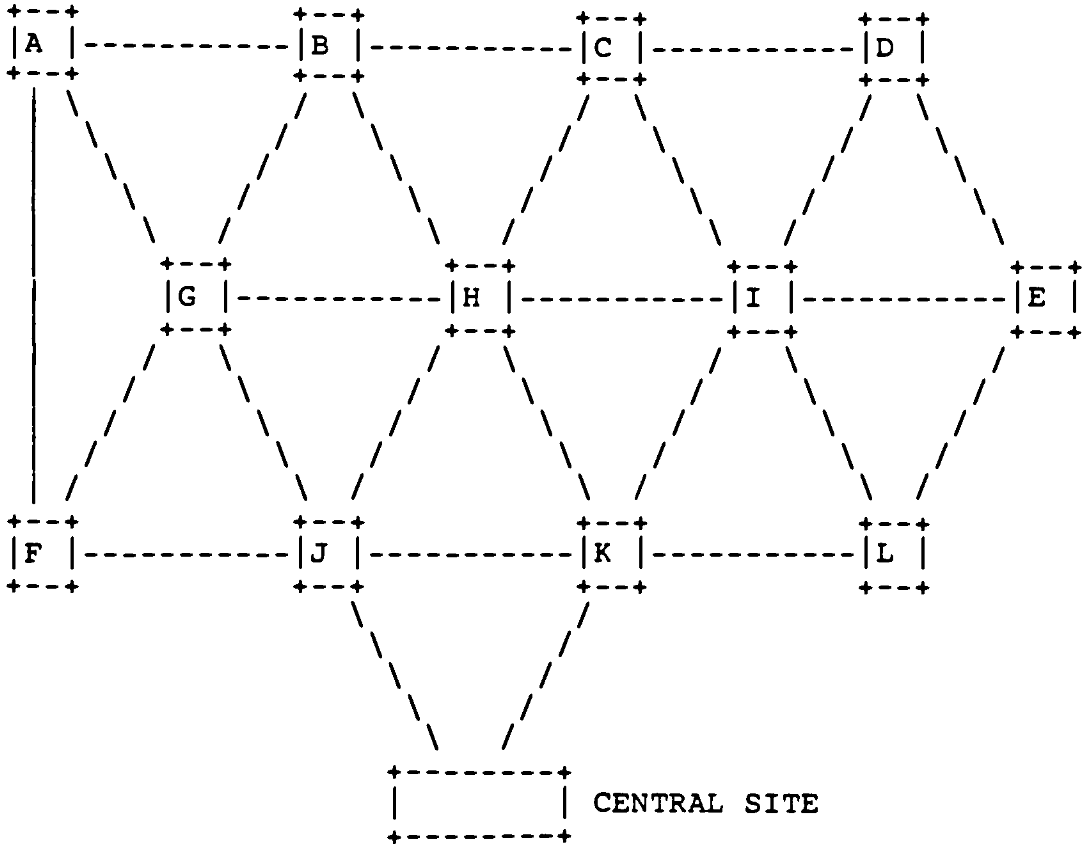
The modified flooding is a possible algorithm to use in a mobile telephone system where the stations have a high degree of mobility. It does not depend on any repeater knowing the location of any other one. Nor does it assume any fixed assignment of stations to repeaters. But the disadvantage is the large amount of bandwidth it consumes which makes it impratical for the mobile telephone system to adopt this routing algorithm.

The second algorithm requires that the complete topology of the repeater tree be known by the central site. This is under the assumption that stations and/or repeaters are stationary which is the contrary of the characteristic of the mobile telephone system. In a mobile telephone system, only the switching office and the cell site are necessarily stationary.

The third algorithm is adaptable to mobile repeaters/stations but it also consumes more bandwidth.

An applicable routing algorithm must satisfy the following conditions:

(1) Setup a virtual circuit between the mobiles with minimal amount of bandwidth;



The lines indicate which repeaters are in the range of each other.

Figure 26. A Repeater Network.

(2) be able to maintain the virtual circuit even if the mobiles migrate to other cell sites or MSAs; and

(3) be able to operate and grow within an allocation of a limited amount of bandwidth.

4.2.3 Proposed Routing Algorithm for The Mobile Telephone Network

Each MTSO and its associated MSA will be treated as a single independent unit in a multi-MTSO (multi-MSA) network. Each MTSO will be equipped with a high power directional antenna, which is used for network communication. The requirement is that it is powerful enough to reach the adjacent MTSOs and not beyond. This is to ensure no co-channel interference will occur between MTSOs. A special MTSO is needed to coordinate the traffic within the network service area. It is termed the Central/Control MTSO (CMTSO). It has dual responsibilities, to perform all the functions of a MTSO and to serve as the switching center of the network. All network traffic is routed through the CMTSO just as local traffic is routed through the MTSO.

The radio channels required for network communication can be derived by applying the frequency reuse concept (Section 2). Therefore, additional radio channels are not necessary in a multi-MTSO network environment and sometimes it is just not possible to allocate extra radio channels. Each MTSO will use a set of channel frequencies distinct from the ones used by its adjacent cell sites and MTSOs to avoid interference problems.

It is easier to understand if all the MTSOs are visualized as cell sites and the CMTSO being the MTSO. All "cell sites" are linked to the "MTSO" through radio channels instead of direct land line facilities. The radio channels are partitioned into voice channels and control channels to replace the functions of the data links. Figure 27 shows the partitioning of control functions among AMPS control elements in a network. The control channels are used in a FIFO manner while each voice channel is strictly dedicated to a call.

Paging, accessing and other control functions within a local MSA remain the same while the network control functions take on a new dimension.

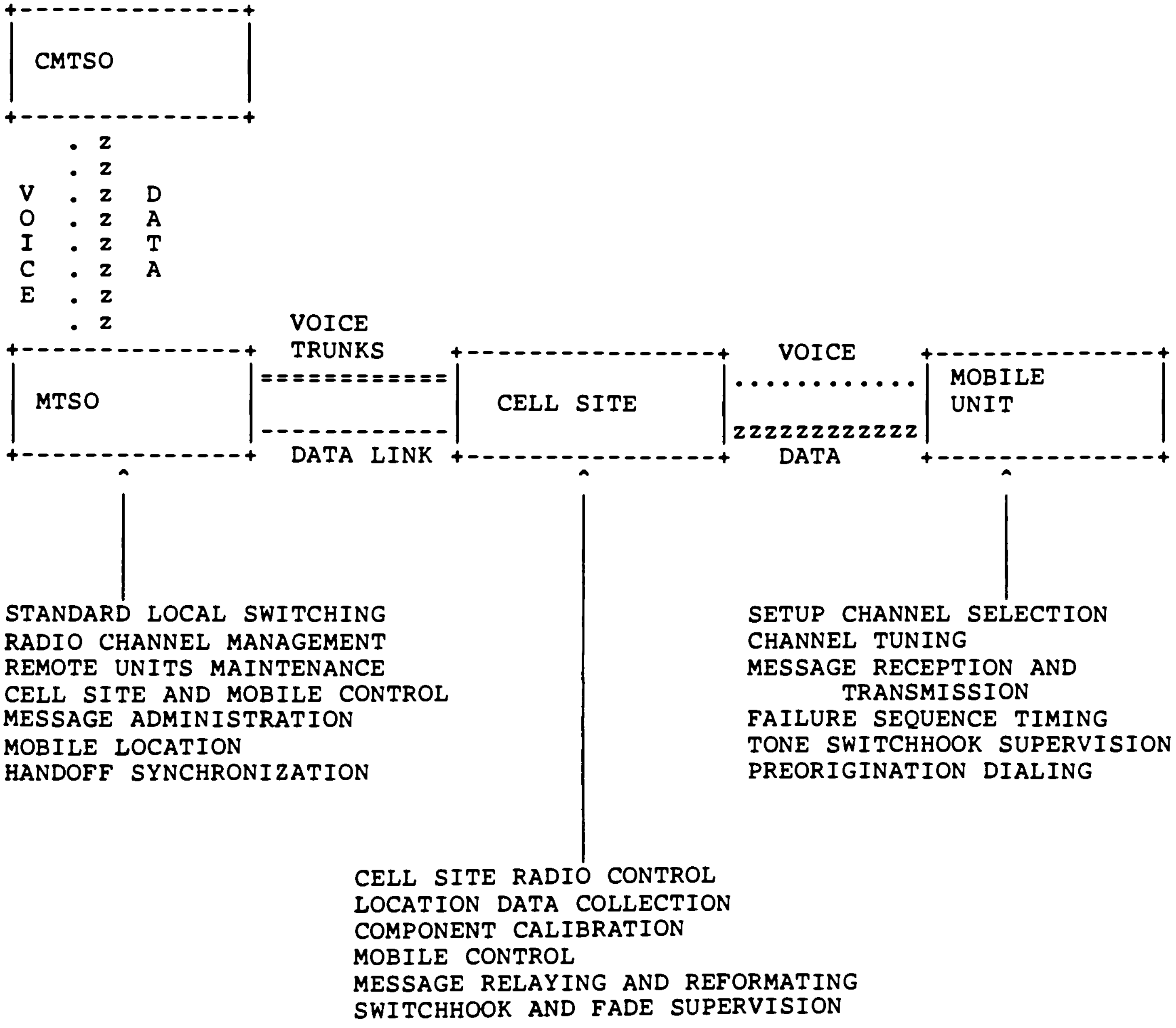


Figure 27. Partitioning of Control Functions Among AMPS Control Elements (Network).

Paging a mobile in another MSA requires a notification to the CMTSO which in turn sends a request to each of the remaining MTSOs in the network to inquire about the presence of the called mobile. If mobile is located in one, then the corresponding MTSO will respond with a confirmation message to the CMTSO, which then initiates a paging request message to the MTSO to perform the paging.

A typical geographic coverage of a MTSO is about 25 square miles. The CMTSO with its subordinate MTSOs can span an area of hundreds of square miles.

Accessing in an inter-MTSO call now has to go through the local MTSO and the CMTSO. The handling of seizure collisions is the same on both the MTSO and the CMTSO levels.

4.2.4 Growth

If the traffic volume of a MSA reached a certain threshold, the concept of cell splitting can be applied to handle the growth. This requires a second MTSO within the MSA and the original channel set is split between the two MTSOs. Therefore, with the same number of allocated channels, the number of simultaneous calls handled in the same coverage area is increased through MTSO splitting. The cost of setting up a new MTSO is more than a new cell site and this involves reconfiguring some of the cell sites to be connected to the new MTSO. The CMTSO has to be updated to include the new MTSO in its database and other related hardware modifications.

The total number of radio frequencies within the network area has to be shared between network traffic and local MSA traffic. The numbers allocated can be engineered parameters in system initialization or be made adjustable during normal system operation. This allows overload control in network and local traffic.

The cellular concept can be applied again to link different CMTSOs together into a new network. One CMTSO will be designated as the controlling CMTSO and the rest will be treated as "cell sites." This would be a two-level MTSO network. The number of levels is from the number of MTSOs between the cell site and the CMTSO, including the CMTSO. The limiting factors of the number of levels are the range of the radio frequencies used and the available bandwidth. This is because the channels used by the CMTSO cannot be used for local traffic.

The distance between the CMTSO and its subordinate MTSOs increases in direct proportion to the number of levels. The increase in distance will eventually render it impractical, due to cost-effective limitations, to increase the signalling power of the CMTSO. For example, the increase in coverage area is not directly proportional to the increase in signalling power.

The channel set used between the CMTSO and the subordinate MTSOs is excluded from local traffic usage in the same coverage area. This would make it impratical to setup a network in areas with a limited number of available channels.

Figure 28 depicts a one-level network.

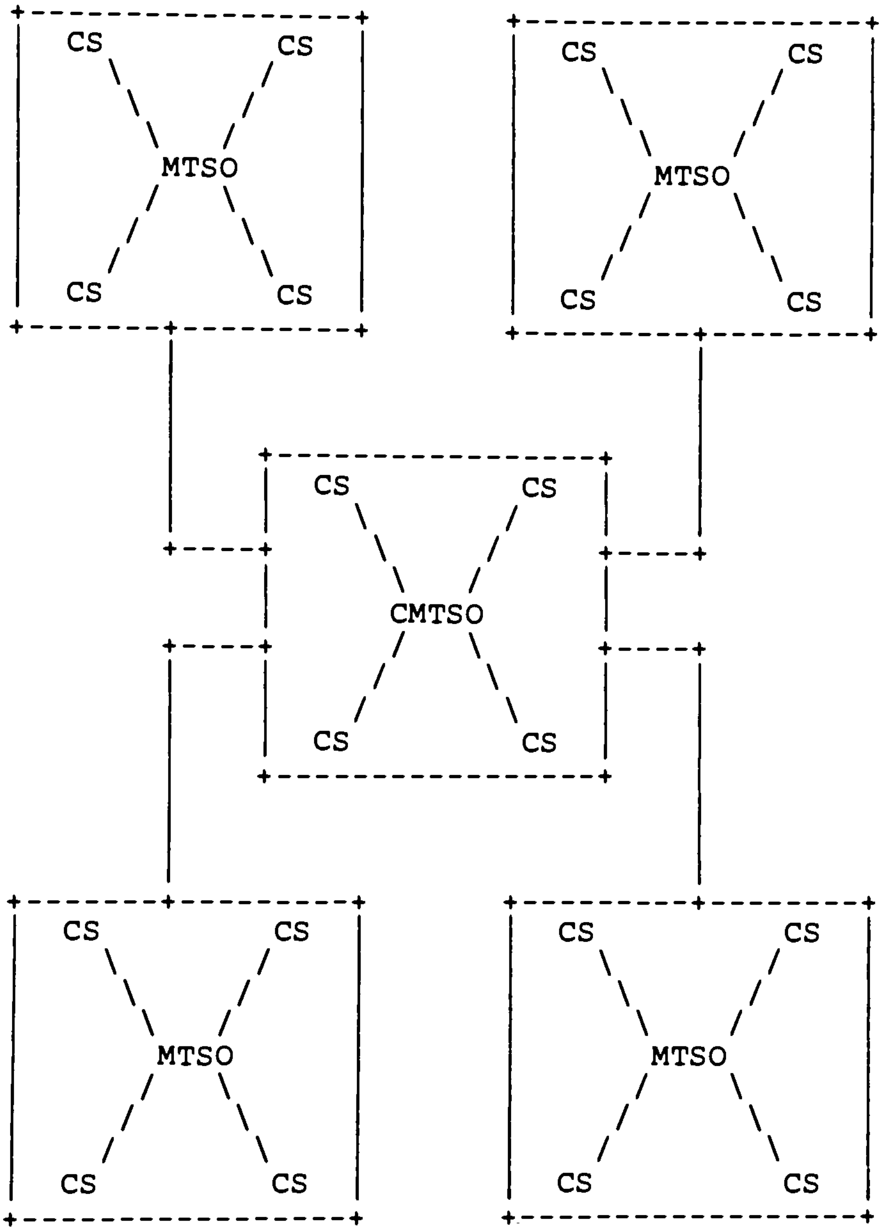
This approach is similar to a Hierarchial Network strategy. The local MTSO and its associated MSA can be viewed as the local access network and the CMTSO as the backbone, even though it will be a backbone of only one site.

4.2.5 Locating and Handoff within the Network

In a single MTSO system, the MTSO maintains in its database a list of adjacent cell sites for each cell site in the MSA. This is used in the handoff process to determine which cell site will handle the call when the old cell site can no longer maintain the signal strength of the mobile. In the network environment, the locating and handoff processes within each MTSO remain the same. But extra data are needed to process inter-MTSO handoffs. The list of adjacent cell sites will include cell sites in the adjacent MSAs. The MTSO ID to which each cell site is connected will be stored in conjunction with the adjacent cell site list in the database. When the system detects that a handoff is imminent and the new cell site is in another MSA, the following procedures take place:

(1) A message is sent via an available network communication channel to the central MTSO which in turn sends the message to the MTSO served by the new cell site. Network collision is treated and handled the same way as within a single MTSO system. The message is to inform the MTSO to prepare a channel to accept the call.

(2) After the channel preparation is completed, the MTSO sends a confirmation message back to the originating MTSO via the central MTSO.



CS - CELLSITE
MTSO - MOBILE TELEPHONE SWITCHING OFFICE
CMTSO - CENTRAL/CONTROL MTSO

Figure 28. A One-Level Mobile Telephone Network.

(3) If it is a negative confirmation, then the call is terminated. Otherwise, the originating MTSO will instruct the mobile to retune to the new channel and release the channel and other resources used by the mobile. At the same time, another message is sent to the central MTSO to reconfigure the channel/path to the new MTSO.

4.3 Call Sequences within the Network

The following actions are required to process a mobile-mobile call (call originated from another MSA):

(i) Preorigination:

The customer enters the dialed digits into the mobile unit's memory.

(ii) Cell Site Selection:

The mobile unit scans the setup channels used for access in the local MSA, using the parameters derived from the overhead word, and selects the strongest one.

(iii) Origination:

The stored digits, along with the mobile's ID, are transmitted over the reverse setup channel selected by the mobile. The cell site associated with this setup channel receives this information and relays it to the MTSO over its data-link.

(iv) Channel Designation:

The MTSO designates a voice channel and establishes voice communication with the mobile.

(v) MTSO Notification:

The MTSO sends a notification message to the CMTSO with the dialed digits.

(vi) Paging Setup:

The CMTSO sends request messages to remaining MTSOs in the network to inquire about the presence of the called mobile. The MTSO of the called mobile then responds with a confirmation message with the MTSO ID. The CMTSO then sends out a paging request to the corresponding MTSO. The MTSO then performs the paging function.

(vii) Voice Channel Allocation:

The CMTSO has to allocate an available voice channel from its network voice channel set for the call.

(viii) Cell Site Selection (Terminating Mobile):

Similar to item (ii).

(ix) Page Reply:

The mobile responds to the cell site it selected over the reverse setup channel. The selected cell site then reports the page reply to the MTSO over its data-link.

(x) Channel Designation:

The MTSO selects an idle voice channel in the cell site that handled the page reply and informs the cell site of its choice over the appropriate data-link. The serving cell site in turn informs the mobile of its channel designation over the forward setup channel. The mobile tunes to its channel designation and transponds the Supervisory Audio Tone (SAT) transmitted over the voice channel. On recognizing the transponded SAT, the cell site places the associated land-line trunk in an off-hook state, which the MTSO interprets as successful voice channel communication.

(xi) Alerting:

On command from the MTSO, the serving cell site transmits a data message over the voice channel to an alerting device in the mobile telephone which signals the customer that there is an incoming call. A signaling tone from the mobile causes the cell site to place an on-hook signal on the appropriate land-line trunk which confirms successful alerting to the MTSO. The MTSO, in turn, provides audible ringing to the calling party.

(xii) Talking:

When the customer answers, the cell site recognizes removal of signaling tone by the mobile and restores the land-line trunk to an off-hook state. This is detected at the MTSO, which removes the audible ringing circuit and establishes the talking connection so that the conversation can begin.

5. Conclusions

The cellular concept and the adaptation of it into the network design make it possible to serve a large number of moving customers in different mobile coverage areas with a limited amount of radio spectrum. Furthermore, the need to operate and grow within a fixed allocation of radio channels can be satisfied through the application of frequency reuse, cell splitting and/or MTSO splitting. The coverage area can also be expanded with the concept of a multi-level network system described in this papar.

The material presented in this paper may be applicable to other broadcast networks with non-stationary terminal stations or networks with similar characteristics and limitations. It provides an alternative to store-and-forward networks.

6. Bibliography

(1) Abramson, N.: "The ALOHA System - Another Alternative for Computer Communications," Proc. Fall Joint Computer Conference, 1970.

(2) Andrew S. Tanenbaum: "Computer Networks," ISBN 0-13-165183-8, 1981.

(3) AT&T: "The Bell System Technical Journal," ISSN0005-8580, January 1979, Vol. 58, No. 1, (Advanced Mobile Phone Service).

(4) AT&T: "Notes on The Network," AT&T Network Planning Division, Fundamental Network Planning Section, 1980.

(5) Chlamtac, I., Franta, W. R., and Levin, D.: "BRAM: The Broadcast Recognizing Access Method," IEEE Trans. Commun., vol. COM-27, August 1979.

(6) W. Wesley Peterson and E. J. Weldon, Jr.: "Error-Correcting Codes," ISBN 0 262 16 039 0, MIT, 1972.

(7) Shoch, J. F., and Stewart, L.: "Interconnecting Local Networks via the Packet Radio Network," Proc. Sixth Data Commun. Symp., 1979.