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AN OVERVIEW
OF
CELLULAR TELECOMMUNICATIONS

by

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March, 1991

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The cellular telecommunications industry is one of the fastest growing segments in the international telecommunications domain. Many current communications systems will soon interface with cellular voice and data signals, and this interface will not be restricted to just vehicular cellular. In fact, cellular systems are now even replacing wireline telecommunications systems in certain applications. Today's communications managers and engineers should understand how cellular systems work, and how these systems might be put to work to solve communications requirements. The mobile, low-cost, tetherless characteristics of cellular systems make them ideal candidates for many military needs. This paper provides an overview of current cellular communications systems, and treats their history, theory and operation, applications, and limitations. Additionally, new experimental digital and micro-cellular systems will be introduced and described.

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An Overview of Cellular Telecommunications

by

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ABSTRACT

The cellular telecommunications industry is one of the fastest growing segments in the international telecommunications domain. Many current communications systems will soon interface with cellular voice and data signals, and this interface will not be restricted to just vehicular cellular. In fact, cellular systems are now even replacing wireline telecommunications systems in certain applications. Today's communications managers and engineers should understand how cellular systems work, and how these systems might be put to work to solve communications requirements. The mobile, low-cost, tetherless characteristics of cellular systems make them ideal candidates for many military needs. This paper provides an overview of current cellular communications systems, and treats their history, theory and operation, applications, and limitations. Additionally, new experimental digital and micro-cellular systems will be introduced and described.

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I. INTRODUCTION

A. PREFACE

The United States Cellular Radiotelephone industry has experienced phenomenal growth since the first cellular systems were introduced in 1983. Volatile, vigorous stock market trading in this new industry indicates the abundance of investor interest that exists in both the many new start-up companies as well as the traditional wireline carriers that offer cellular service. During a recent hearing before the Senate Communications Subcommittee, a spokesman for the National Telecommunications and Information Administration (NTIA) estimated the current total worth of the cellular industry to be between $66 and $88 billion [Ref. 1]. In 1985, the number of U. S. subscribers totaled 329,000; today, that number is nearly five million [Ref. 2]. The Cellular Telecommunications Industry Association (CTIA) has forecasted growth rates of 30% to 50% for the next few years [Ref. 3]; furthermore, the consulting firm, Booz, Allen, and Hamilton, Inc, has forecasted 18 million cellular subscribers by 1995 [Ref. 2], while a more recent survey conducted for NYNEX Mobile predicts up to 31 million U.S. cellular subscribers by that same year [Ref. 4].

Today, over 590 cellular systems are in operation throughout the United States [Ref. 5].

These statistics have been realized through the marriage of two technologies, radio and telephony. These two communication fields were brought together under a "cellular" architecture, and under this architecture, an industry has emerged. The synonymous terms "cellular radiotelephony", "cellular radio", and "cellular telecommunications" are all used to identify this new industry, and they will be so treated throughout this paper.

With initial visibility in the vehicular mobile telephone market, cellular telecommunications represents the first practical, wireless extension of the public switched telephone network (PSTN). Today, in addition to the ubiquitous "car phone", portable personal communication, using small, pocket-sized, lightweight transceivers is a commonplace phenomenon. These portable cellular units even provide modestly capable data communication with the addition of cellular modems. As military, industrial, and personal demands for mobile voice and data communications continue to grow, many other variations to the cellular architectures and systems will emerge using various portions of the radio frequency (RF) spectrum.

One of the key challenges facing the Federal Communications Commission (FCC) is the efficient allocation of spectrum as many new RF applications evolve. Spectrum "bandwidth" is the description for such allocation, and cellular architectures utilize this bandwidth in a highly efficient manner; that is, cellular schemes permit a relatively large number of users, or subscribers, for a given amount of bandwidth. With only a finite amount of RF spectrum available, this resource must be utilized as efficiently as possible to accommodate the increasing number of RF applications by the military and federal government, broadcast radio and television, fixed telephony (microwave and satellites), mobile services (radio paging, cellular, and specialized mobile radio (SMR)), and the burgeoning field of personal communications.

As the employment of cellular systems becomes more widespread, communications managers should understand the basic operating principles of cellular models, the potential for future cellular applications, and the theoretical and current limitations of cellular systems. While current analog cellular has been vastly more spectrum efficient than previous mobile radio methods, the analog frequency modulation (FM) technology is now preventing the current cellular architecture from becoming any more efficient. The reader will learn that each of the several new digital cellular transmission techniques portends tremendous increases in system capacity and efficiency. Hopefully, this thesis will serve as an introductory cellular reference guide, providing an overview of cellular telecommunications, and additionally providing some historical background on this exciting communications domain.

B. OUTLINE

In the next chapter, a brief history of the technological and regulatory developments that preceded the current cellular radio industry will be provided for the reader. Replete with major breakthroughs and blunders, the annals of cellular radiotelephony contain many worthwhile lessons learned.

In Chapters III and IV, the reader is introduced to cellular principles of operation and limitations of current cellular systems, respectively. Chapter V treats several predominant models for digital cellular telecommunications, and the following chapter introduces the reader to new, experimental, micro-cellular systems that are based on this new digital technology. Chapter VII follows with an overview of current cellular applications, both civilian and military, and the concluding chapter provides a forecast for future cellular systems.

II. HISTORY OF CELLULAR RADIO

A. PRE WORLD WAR II

To thoroughly trace the lineage of cellular telecommunications, one must pursue two branches of technology's family tree: telephony and radio.

The telephone originated from the telegraph. Telegraph networks appeared in the 1840s, and it is interesting to note in this increasingly digital age that the telegraph was in fact a digital device [Ref. 6]. Using Morse Code, named after Samuel Morse who devised the most widely used telegraph system, normal transmission speeds approximated 20 to 25 words per minute. Coast-to-coast telegraphy was in place by the 1860s, and the "district telegraph" was a principal communication format within metropolitan areas [Ref. 6:p. 9]. In 1872, Alexander Graham Bell, then a professor of vocal physiology at Boston University, commenced earnest efforts to develop a "harmonic telegraph". In 1875, Bell and his assistant Thomas Watson transmitted actual sounds for the first time, and on February 14, 1876, a telephone patent application was filed in Bell's name [Ref. 6:p.15]. The first distinct voice transmission using a telephone occurred on March 10, 1876.

Radio's genesis also took place in the late nineteenth century when Hienrich Rudolf Hertz discovered that invisible waves of some force seemed to emanate from an electric spark of sufficient energy, and that a proper receiver apparatus could capture this force [Ref. 7]. While Hertz's experiments were limited to only several meters of distance, Guglielmo Marconi was able to transmit these waves over several kilometers, and he gave this phenomenon the name "radio" [Ref. 7:p. 8]. It took quite some time before radio could be used to transmit the human voice. In fact, one of the true ironies in this day of optical fiber is that the first wireless transmission of human voice did not use radio but light! Calling it his greatest invention, Alexander Graham Bell invented the "photophone" in 1880, and he achieved successful wireless transmission of intelligible human speech over distances up to 700 feet [Ref. 7:p. 24]. Such a feat would not be performed using radio for another 25 years. Then, radio caught on because of its ability to penetrate moisture, foliage, and most buildings. In 1915, the United States War Department started a program to develop naval communications using radio. By 1929, commercial radio service had commenced to ships on the Atlantic [Ref. 7:p. 25].

As for telephone service, the first telephone exchange, or switch, in the United States became operational in 1878 [Ref. 6:p. 18]. Although this switch was manual, it replaced expensive physical connections that were required without it.

The big disadvantage, however, was that only a limited number of subscribers could be serviced since a switchboard operator had to personally connect and disconnect the lines. In 1891, this situation was considerably improved when Almon B. Strowger, a Kansas City undertaker, developed an automatic switchboard called the Strowger switch [Ref. 6:p. 21]. This switch has had tremendous impact on telephony; even in 1986, 38% of the switches in the PSTN were Strowger switches [Ref. 6:p. 22]. The Strowger switch and those that followed it, the panel and crossbar switches, made it possible for the telephone to be a feature of the majority of homes.

In addition to communications at sea, radio was also employed in the mobile vehicle environment for the Detroit Police Department [Ref. 8]. In 1921, this system was intended to provide one-way satisfactory voice communication to moving cars, but radio receiver technology had not yet been developed to render this truly practical [Ref. 7:p. 25]. Then, in 1928, Robert L. Batts developed a superheterodyne receiver that was able to withstand the rigors of the vehicular application, and the Detroit Police Radio System became the first operational mobile radio system [Ref. 7:p. 26].

Mobile transmitters were developed several years later, but the truly revolutionary breakthrough for radio came in 1935, when Edwin H. Armstrong invented frequency modulation [Ref. 7:p. 27]. Critical to mobile radio, FM required less power, performed well in an environment of both natural and man-made noise, and produced the desirable "capture effect", in which the receiver will recognize the stronger of two competing signals and reject the unwanted signal [Ref. 7:p. 28]. FM has enjoyed tremendous longevity as a radio technology, and much of its refinement came about during World War II.

B. POST WORLD WAR II

For telephony, the years that followed World War II included steady evolutionary progress. Improvements were made in telephone handsets, transmission wires, and switching. Telephony remained an analog territory until the 1960s when large businesses began using computers, and the demand for data communications emerged. Around this time, computers became reliable enough to control telephone switching, and hybrid analog/digital telephone exchanges, called Stored Program Control (SPC) switches, surfaced [Ref. 6:p. 44]. These switches have evolved into purely digital, programmable devices that are enabling networks to take on an "intelligence" of their own. Specialized "unswitched" networks, such as local area networks (LAN), now offer a number of alternatives to conventional telephony. Finally, the increasing practicality of communication through optical fiber rather than copper, and current efforts to implement a new set of public networking standards, the integrated services digital network (ISDN), promise a comprehensive new digital world for telephony [Ref. 6:p. 51].

During World War II, many colossal developments were realized in radio. Mobile radio systems were implemented in all major military vehicles, including aircraft and tanks. As a result of Armstrong donating his FM patents, the United States was the only fighting force to employ FM and reap the many advantages that this technology offered [Ref. 7:p. 28]. After the war, the U.S. was left with an extraordinary commercial FM manufacturing capability. This "forced" modernization of the radio industry paved the way for a viable mobile communication market in the United States [Ref. 7:p. 29].

Initial post-war improvements in radio were focused on two key objectives:

1. The reduction of transmission bandwidths.
2. The incorporation of automatic trunking into radio systems [Ref. 7:p. 29].

The official birth of mobile radio took place in 1949 when the FCC recognized it as separate class of service [Ref. 7:p. 30]. The service provided by mobile radio was never able to keep up with the demand for it, and blocking probabilities of 65% were common in these systems. By 1976, in New York, a total of 12 channels served 543 customers with 3,700 customers on a waiting list for a service known for expensive rates and low customer satisfaction. [Ref. 7:p. 31]

Mobile radio highlighted the difficulties of achieving the reduced transmission bandwidth objective using FM technology. The FM engineering tradeoff between noise and bandwidth had been known since Armstrong published his paper in 1936 titled, ***A Method of Reducing Disturbance in Radio Signaling by a System of Frequency Modulation*** [Ref. 9]. The excellent voice quality and low noise levels were achieved by increasing system bandwidth. This was the major disadvantage with FM compared to conventional amplitude modulation (AM) schemes:

> Each radio channel had to be wider, and the guardbands separating it from the next channel had to be wider, so that there could be fewer such channels carved out of a given portion of the radio spectrum [Ref. 7].

Over the years, transmission bandwidth requirements in FM systems were reduced, and by the 1960s, FM spectrum efficiency had essentially been quadrupled since World War II [Ref. 7:p. 32].

The next post-war technological improvement in radio was the implementation of automatic trunking radio systems. In non-trunked radio, communication took place over a dedicated channel for the transmitter and receiver. A specific fixed frequency was used for both transmitter and receiver so that if the channel served a group of users, they had to share it like a party line [Ref. 7:p. 32]. Under trunked radio, a set of channels was made available to group of users, and one of the channels was made available to a user, or subscriber, upon demand. Figure 1 depicts a comparison of these two methods.

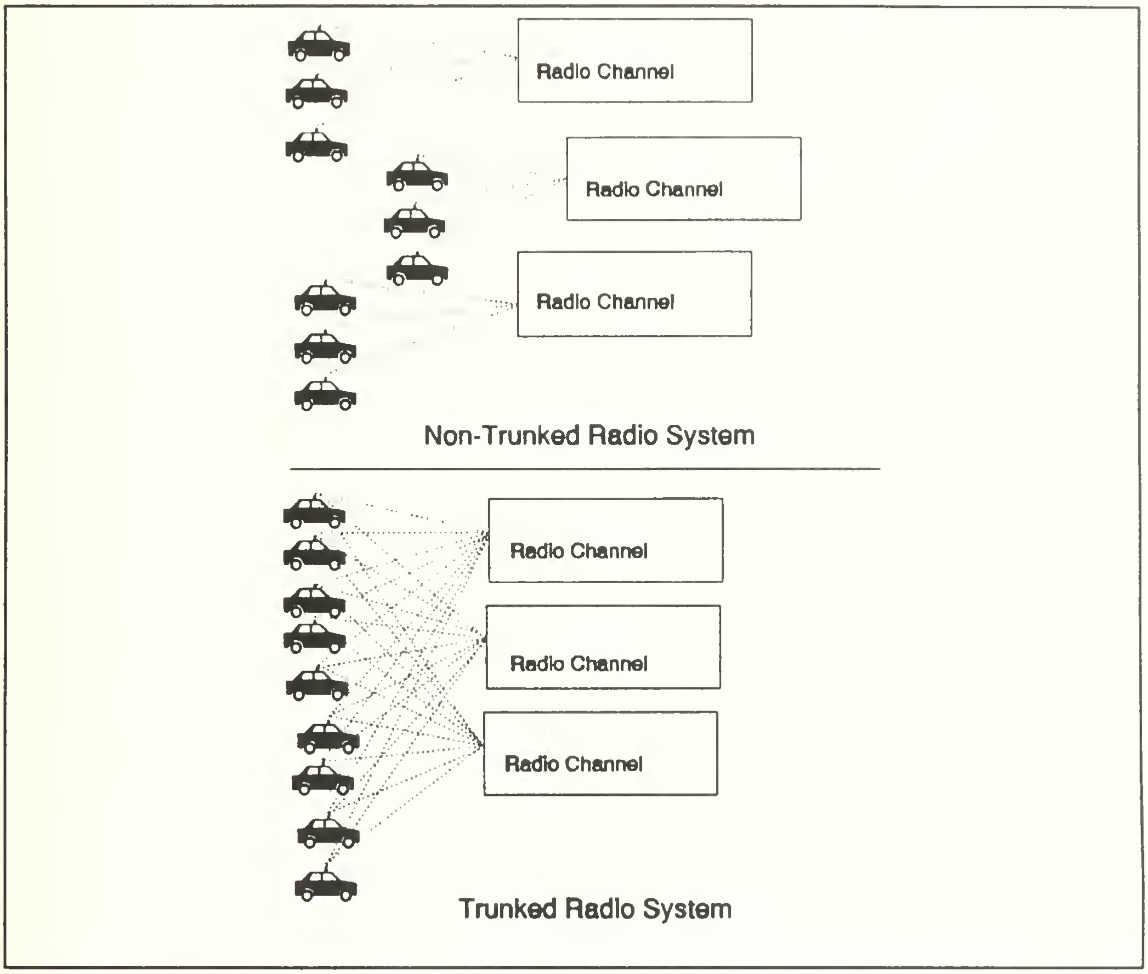

Figure 1. Comparison of trunked versus non-trunked radio [Ref 7: p. 33]

By trunking channels together so that any system user can have access to any available channel, many more subscribers can be serviced than if each channel was non-trunked. This is known as trunking efficiency [Ref. 7:p. 32]. Although trunking increased both system spectrum efficiency and capacity, it did so at the cost of expensive mobile units, or subscriber radio equipment.

During the late 1940s, suggestions of a cellular approach to radio began appearing in Bell proposals, such as FCC Docket 8658 of 1947 [Ref. 10]. However, at this time, the microprocessors and large-scale integration circuit technology needed to make cellular both technically as well as economically practical were not yet available [Ref. 11].

Until this technology was made available for future widespread application, a series of mobile telephone systems based on the broadcast radio model evolved. Known as Mobile Telephone Service (MTS) and later as Improved Mobile Telephone Service (IMTS), these systems offered poor service characterized by high blocking probabilities, limited capacity, and limited geographic coverage [Ref. 9:p. 2]. These limitations stemmed from the systems' broadcast-type design where one relatively high-powered base transceiver must serve a relatively large geographic area such as the New York metropolitan area that was mentioned earlier in the chapter. These systems were also spectrum inefficient since each radio channel could handle no more than one customer at a time.

C. EMERGENCE OF THE CELLULAR INDUSTRY

Cellular proponents wanted to divide the relatively large radio coverage areas of existing mobile systems into a series of small coverage areas, or cells. A low-powered transceiver would service each of these cells, and all of the transceivers for a particular service area would be linked to a switching center for interface with the PSTN or mobile-to-mobile interface. It was envisioned that frequencies could be reused from one cell to a non-neighboring cell, so that one channel would serve several, perhaps even many, users. As capacity limits were reached for a given architecture, the cells could be redrawn or "split" so a greater number of cells would cover the same area, but support more subscribers. However, one critical resource was required before this architecture could be employed: a sufficient allocation of frequency spectrum.

1. The Spectrum Search

Since 1949, broadcast television had enjoyed, and today still does enjoy, a generous spectrum allocation. For quite some time, a segment of the valuable ultra-high frequency (UHF) spectrum had remained idle. This 800 MHz region of spectrum was originally reserved for educational television channels, but several factors precluded this particular spectrum application.

First, the emergence of viable, widespread cable television service relieved some of the demand for "education" spectrum [Ref. 9:p. 5]. Secondly, television set manufacturers were initially reluctant to add UHF tuning components for fear that the required price increase would hurt sales [Ref. 7:p. 46]. Finally, demand for mobile services grew stalwartly, and the improved efficiency of radio trunking and channel narrowing added credibility to the concept of large-scale mobile telephony [Ref. 7:p. 46]. After receiving technical reassurances from Bell that the cellular concept was technically feasible, the FCC allocated 40 MHz of UHF spectrum in 1974 [Ref. 9:p. 5]. On July 24, 1986, this allocation grew by 10 MHz to a total of 50 MHz in the 800 MHz region.

2. Industry Composition

Originally, the FCC felt that the "natural monopoly" analysis used in telephony did not apply to the mobile radio market. This gave birth to the radio common carriers (RCC), later referred to as nonwireline carriers in cellular parlance, who were the independent providers of mobile radio equipment and service. In 1956, the RCCs were given real legitimacy in the mobile radio market, when the Consent Decree agreed to by the Justice Department and AT&T left AT&T's telephone monopoly intact, but required that Bell remove itself from the mobile radio manufacturing business [Ref. 7:p. 35].

AT&T independently developed the sophisticated Advanced Mobile Phone Service (AMPS) model, which was based on a cellular architecture. By 1970, only AT&T had the technical expertise that was needed to construct and operate such a system [Ref. 7:p. 50]. The key issue for the FCC was whether to consider this system as an extension of the public switched telephone network (PSTN) or as a radio system:

> Unfortunately, the easy assumption that AT&T would, and should monopolize wireless telephony as it then monopolized wireline telephony was contradicted by an obstinate fact: there had been head-to-head competition in the mobile telephone business for twenty years. Ever since the 1940s, there had been another side to the peculiar mobile industry: the RCCs [Ref 7:p. 51].

When the FCC allocated the UHF spectrum for mobile radio, it originally planned for one cellular system per market, and it appeared that this might come true. However, in its first cellular system test, AT&T excluded its former key partner, Motorola, a major manufacturer of mobile radio equipment, by using Japanese mobile radio equipment. This set an important precedent because Motorola joined an RCC's developmental efforts to demonstrate their own experimental cellular system. This successful alliance demonstrated that the RCCs were also technically capable of providing cellular service, and created skepticism for the concept of a mobile radiotelephone monopoly. [Ref. 7:p. 53]

The FCC now was forced to consider the issue of competition in cellular licensing, and under Docket 79-318, they considered three options:

1. Maintain a single-operator monopoly, which favored the wireline carrier (AT&T).

2. Allow open entry or perfect competition, by allowing any and all comers to compete in all markets.
3. Allow two carriers to operate in each market by splitting the frequency allocation in half.

In making this decision, the FCC had to balance the pressures for an efficient system, that of the single service provider, against the desire for competitiveness in this new industry. Both Motorola and AT&T had warned the FCC about the inefficiencies of smaller systems that would result from split spectrum; however, the FCC felt that the "public benefits of diversity of technology, service, and price", all of which the FCC believed would result from competition, would outweigh the benefits of efficiency arising from unsplit cellular markets. [Ref. 7]

In March of 1980, the FCC formally published its decision to split the spectrum in half for each market, to create a duopoly structure for each cellular market in which a wireline carrier would compete against a nonwireline carrier [Ref. 7:p. 58]. The operational effects that this decision had on the cellular industry will be discussed in chapter IV under the Economic/Cost Limitation section.

3. Synopsis

The impressive growth statistics cited in the preface to this paper mask some of the disabilities that the cellular industry currently experiences. Some of these problems are attributable to the FCC's regulatory efforts that were just covered. Consider the following comments published by the U.S. Department of Commerce:

> In retrospect, it can be argued that the regulatory process has been somewhat ad hoc and short-sighted...cellular regulation has in some ways delayed the implementation of nationwide cellular service and added to the uncertainties facing industry. [Ref. 12]

One source of cellular's hidden ills has been the FCC's prescription for duopoly market structure. When more than one carrier uses a given spectrum allocation, a degradation in trunking efficiency results. In order to maintain the same level of service, measured in terms of call blocking probability, the duopolist will be about 10 percent less efficient in his allocation of spectrum due to this trunking efficiency loss [Ref. 9:p. 7]. As quantity of service increases, the duopolist will have to resort to the more expensive techniques of cell splitting, which will be described in the next chapter, sooner than the monopolist would have to. The topic of market structure will be covered in greater detail in Chapter IV.

Moving from the issue of market structure to that of technology, while the selection of FM as a cellular standard promoted the existence of relatively affordable radio telephone and equipment prices, it has unfortunately also prevented the realization of any meaningful scale effect for operating costs. Although the prices for cellular telephones have continued to decrease, monthly cellular service charges still average over $130 per month and $1,000 monthly bills are not uncommon [Ref. 3: Part IV, page 4]. As mentioned earlier, some experts believe that substantial reductions in operating costs are impossible with analog FM as the radio transmission scheme. To realize such reductions, cellular must move to one of the digital radio methods, the topic of chapter V.

These facts are important because analysts believe that cellular end-user demand is highly inelastic at high prices, but will become highly elastic at low prices [Ref. 12:p. 32]. Indeed, 80% of U.S. cellular service is currently sold to the business sector [Ref. 13]. This has led to the quandary between cost and capacity that Dr. George Calhoun eloquently describes in his ***Digital Cellular Radio***. In many cases, cellular operators are unable to operate at a level that covers the high costs of operation. Yet, even if operating costs could miraculously be reduced, at the lower side of the demand curve, the current FM system would be incapable of providing the capacity to service this increased quantity of customers needed for profitable operations.

As these cellular problems are addressed through the experimentation of digital systems and alternative cellular architectures (treated in chapters V and VI respectively), the vexing issue of standards will have to be dealt with by the FCC. While many feel that standards are necessary for the viability of any telecommunications realm, there are those that believe the communications field should look to the computer industry, successful yet devoid of any hardware standards. In fact, some industry experts have questioned the overall requirement for standardization. Consider the following statement made by Hiroshi Kojima, head of the Japanese equivalent of the FCC:

> Standardization was initially a concept of the 19th Century age of mass production. However, we are now entering an era of customer-oriented standards. To put it in a nutshell, as long as networks can be linked up, they can be utilized according to how individuals wish to use them. This may sound strange, but I think standards may have to become "destandardized standards", that is to say, standardization will be based on user needs and shifted from single standards to sophisticated standards. [Ref. 7:p. 428]

Dr. George Calhoun argues against technological standardization, but for the establishment of standards of service. To date, the FCC appears to be in favor of "letting industry decide" what technologies are employed, and it seems to favor the elimination of technical standards.

This should foster a creative climate for experimentation of new digital radio technologies, which will probably be both very educational and exciting for users and managers of all wireless communications systems, especially those based on the cellular architecture. The next chapter will cover the theory behind cellular systems, and will introduce the reader to some of the concepts and terminology germane to cellular communication architectures.

III. CELLULAR THEORY AND OPERATION

A. BASIC TERMINOLOGY

Fundamentally, "cellular" implies a system architecture, not a specific radio transmission technique or technology. For today's analog cellular system in the United States, Advanced Mobile Phone Service (AMPS), many important technological issues, which will affect the next generation of mobile telephony, are being hotly debated within the industry. Some of these issues include digital radio schemes, and alternative network-level system designs and control structures, both centralized, like AMPS, and distributed.

Before these issues can be discussed in subsequent chapters, the reader should understand the basic concepts common to all cellular systems. The current AMPS cellular system will be used as a reference model to facilitate this introductory treatment of cellular operating principles.

1. Basic AMPS Information

Some of the historical information leading to the emergence of the U.S. AMPS cellular system was provided in the previous chapter. AMPS became a reality when the FCC granted a construction permit for the city of Buffalo, New York in 1982 [Ref. 8:p.3]. Under AMPS, the entire U.S. cellular market is comprised of individual cellular geographic service areas (CGSA), formerly known as metropolitan statistical areas or mobile service areas (MSA). Each CGSA is serviced by both a wireline carrier, one of the conventional telephone companies such as a regional Bell operating company (RBOC), and a non-wireline carrier, usually an RCC who previously specialized in paging or other specialized mobile radio (SMR) services. The non-wireline companies are referred to as "A" carriers, while the wireline providers are referred to as "B" carriers.

For each CGSA, both carriers divide their coverage areas into cells. It is important to note that each A and B carrier does this independently, and the resulting cells that each defines will probably not be the same for a given CGSA. Additionally, A and B carriers do not share the radio equipment associated with each cell site, so that for every CGSA in the U.S., there exist two independent providers of cellular service.

The FCC has allocated spectrum in the 850 MHz region for AMPS, with each wireline and non-wireline carrier receiving an equal aggregate quantity of bandwidth, 20 MHz [Ref. 14]. The channel bandwidth is a relatively wide 30 kHz to ensure adequate transmission quality with FM. Not all of these channels are used for voice transmission; some must be employed as control channels, a medium of exchange for important radio link parameters, such as signal strength. Currently, each carrier sets aside 21 channels for system control.

The adverse peculiarities of RF propagation of this frequency will be discussed in Chapter IV, but for now, the reader should understand that cellular engineers face a number of challenges when organizing cell boundaries.

2. Cell

In the cellular industry, the symbol for the individual cell, and perhaps for the industry itself, has become the hexagon because of its convenience in showing interlocking, non-overlapping area coverage. Figure 2 illustrates the coverage of seven interlocking cells.

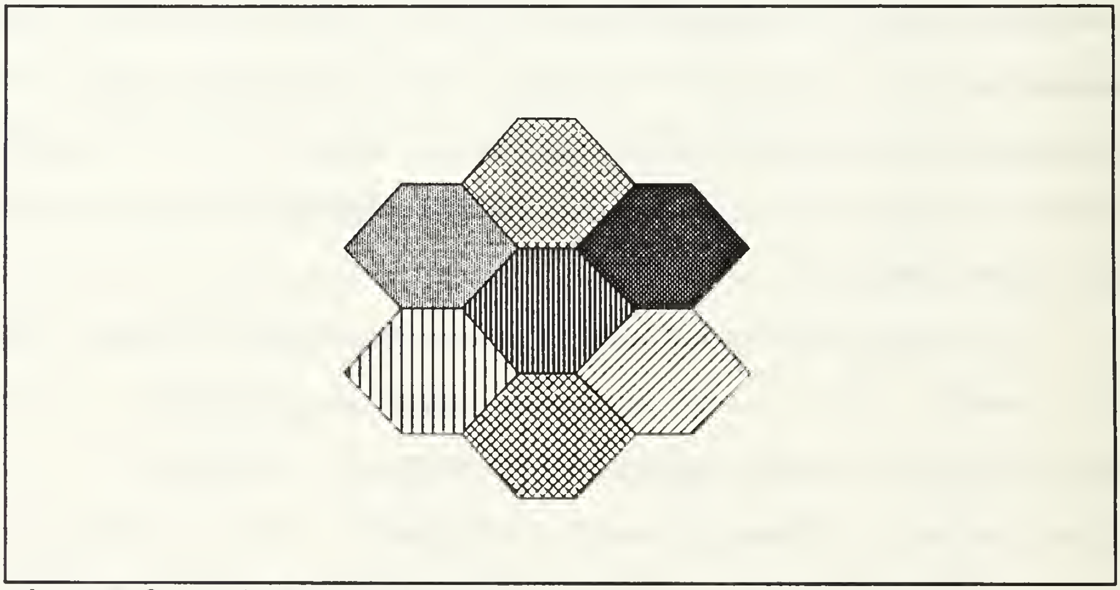

Figure 2. Cluster of Cells

The cell belongs at the root level of the cellular communication architecture. Each individual cell represents the coverage area for one particular cell site.

A cell site consists of the buildings, power plant, antennas, radio equipment, and data terminals that collectively form the interface between the switching center, called the mobile telephone switching office (MTSO), and the mobile units [Ref. 9:p. 8]. Cell sites coordinate, but do not control, the cellular functions of paging, handoff, and power control [Ref. 15]. Geography, zoning regulations, and RF propagation phenomena may preclude the cell site from being located in the exact center of a particular cell. In fact, the hexagon or the honeycomb-like structure of a group of hexagons is actually only a convenient symbol, some would argue a marketing symbol, and a mere approximation for the cell. Because of the difficulty in obtaining property on which to construct cell sites and because of the 850-MHz radio frequency (RF) propagation effects over undulating terrain, the actual coverage may be an irregularly shaped outline [Ref. 10:p. 22.7].

Generally, each cell is assigned a group or set of 50 to 70 channels subject to the restriction that adjacent cells must use different groups of channels to avoid interference [Ref. 16]. However, the channels in one cluster may be reassigned to another cluster some distance away thereby reusing spectrum.

In setting up a cellular system, it is assumed that the total cluster of cells for a given system is appropriate for use as a map of that system, and that each hexagon contains exactly one cell site [Ref. 10:p. 22.7]. The number of cells assigned to a given system depends on the RF propagation characteristics of the coverage area and the transmission quality objectives for the system. For example, a coverage area featuring uneven terrain and foliage will not permit cells as large as that of a flat, denuded area. As the reader will learn in chapter IV, foliage is a major attenuator of 850 MHz AMPS radio signals, and intervening hills produce shadow areas. All other parameters being equal, this sort of coverage area would require more cells that are smaller in size.

When actually defining cell boundaries, elevation databases, available from the Defense Mapping Agency (DMA), are used by computer programs to develop RF predictions for feasible service areas given a prescribed location of cell sites [Ref. 9:p. 132]. It's quite possible that the cell boundaries may not form a nice, neat hexagon, and in fact may contain holes or shadows inside its perimeter. Figure 3 presents such a case. The cross-hatched ellipse represents a shadow area, or "hole" that would result in the event that a prominent terrain feature was situated between it and the cell site. Such areas will have to be covered by an alternative cell site if practical, otherwise service degradation will result. The curved, dashed line, rather than the hexagon, defines the actual cell boundary that engineers must recognize for cellular system planning.

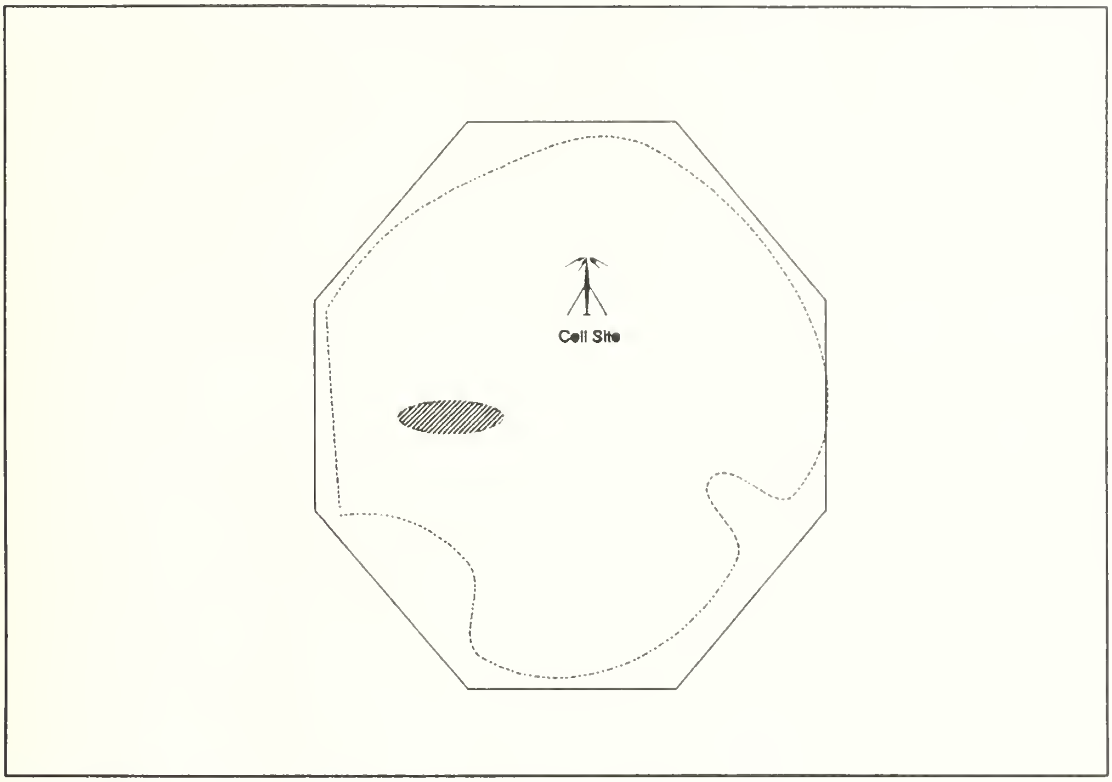

Figure 3. RF Prediction for a Cell

3. Mobile Set

The mobile set consists of a control unit, a transceiver, and an antenna system. Remarkably, these can all be packaged today in a stylish handset capable of fitting easily in a coat pocket. In cellular parlance, these small devices are referred to as "portables", whereas automobile cellular phones are called "mobiles", and the more common carrying case units are referred to as "transportables". Portables can access all of the channels that a mobile unit can, but portable units transmit at a maximum power level of

.6 Watts, while mobiles and transportables transmit at a maximum of 3 Watts [Ref. 9:p. 393].

The control unit portion of the mobile set is the subscriber's principal interface with the cellular system. It typically consists of the handset, pushbutton keypad, and information windows used to feed information to the subscriber [Ref. 18:p. 2-26].

The transceiver includes a full duplex, 850 MHz FM transmitter/receiver and accompanying logic circuitry. The radio will operate over 666 channels in the following frequencies:

1. To transmit: 825 to 845 MHz
2. To receive: 870 to 890 MHz

The analog logic circuits convert noisy analog signals into clear, clocked TTL binary signals for the processor, while the digital circuits make cellular call processing possible.

The antenna systems for mobile sets are simple, omnidirectional units for both mobiles and portables. The portable sets typically employ a short telescopic antenna providing zero antenna gain. The mobile automobile sets use a simple whip roof or glass-mounted antenna providing up to a 3 dB gain [Ref. 9:p. 171].

4. Mobile Telephone Switching Office (MTSO)

With the cell site as the coordinator, the MTSO controls the power levels of the mobile units by monitoring each of the control channels, which are interleaved among the mobile units. This power agility is necessary under AMPS to reduce the effects of interference, a topic that will be treated in greater detail in chapter IV. The MTSO can adjust the mobile units' power levels from between 3 to 8 discrete tiers [Ref. 17]. By maintaining a mobile power level just sufficient enough for adequate communication, the MTSO reduces the chance of interfering with the signal of another cell [Ref. 17:p. 55].

The physical connection between the cell site and the MTSO in Figure 4 can be made by telephone line (T1 carrier), fiber optic cable, or microwave radio link [Ref. 6:p. 108]. The MTSO also coordinates all switching functions, and is therefore also physically connected to the local telephone office for PSTN access. The MTSO requires a great deal of computing power, for in addition to monitoring the radio links, it must also handle customer billing activity.

The electronic switching system of the MTSO is characterized as the stored program type. The programs that are stored in the switching system's main memory provide the logic to control cellular operations. This switching mechanism connects the cell site trunks to the PSTN. [Ref. 18:p. 2-17]

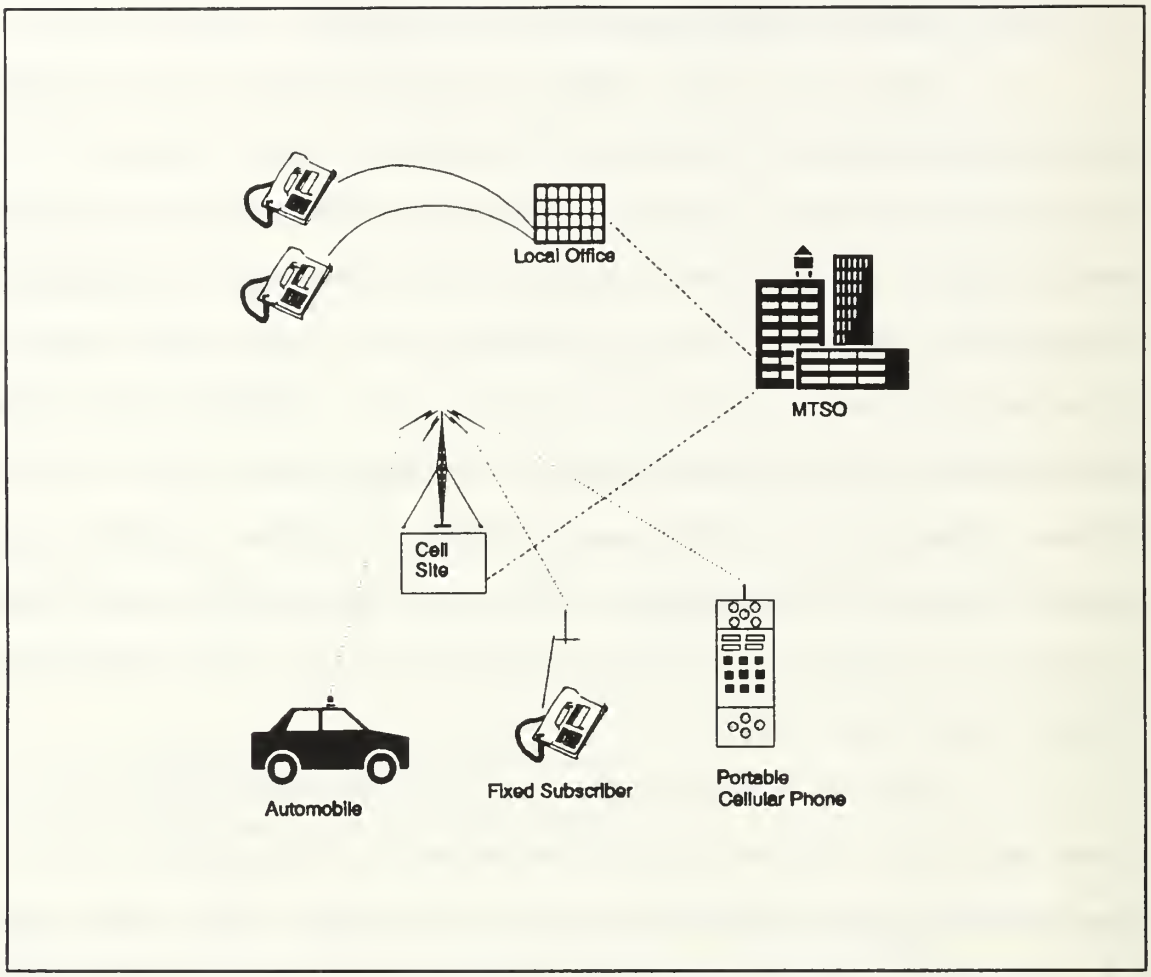

Figure 4. MTSO, Cell Site, and Mobile Sets

B. KEY FUNCTIONS AND CONCEPTS

In this section, the reader will be guided step-by-step through system operation during a typical cellular telephone call.

1. Call Setup

A mobile unit regularly scans the set of assigned control channels whenever the mobile unit is idle, a condition where the power is turned on, but the unit is not in active use. As the control channels are scanned, the mobile unit is marking and updating the strongest carrier found, and then decoding this carrier's signal to look for incoming calls. As the reader will learn, there are both *forward* and *reverse* control and voice channels. "Forward" denotes a channel used for transmission from a cell site to a mobile, while "reverse" means a channel used from a mobile unit to a cell site [Ref. 9:p. 67].

When someone calls a mobile subscriber from within the PSTN, the standard seven-digit telephone number is forwarded to the MTSO. The MTSO must then locate the subscriber by having all the cell sites transmit this identification number over the forward control channels. This is known as *paging*. After the subscriber's mobile unit detects its own identification number, it will respond an acknowledgment back over a reverse control channel to the cell site, which relays the response, or *page reply*, back to the MTSO. [Ref. 10:p. 22.2].

Next, *channel designation* occurs as the MTSO chooses an idle voice channel from those that are available at the cell site which relayed the page reply [Ref. 18]. This voice channel designation is forwarded back to the mobile unit over a special control channel referred to as the *forward setup channel* [Ref 18]. The mobile unit then tunes to this channel, and at this point, the mobile unit will ring, thereby notifying, or *alerting*, the user of the incoming call [Ref. 10:p. 22.2].

If the mobile user originates the call, then the telephone number that the user dialed into the mobile telephone is transmitted over the strongest carrier (control channel) to the cell site. This is referred to as *origination.* The cell site forwards this message to the MTSO, which designates a voice channel for the subscriber's desired conversation, and sends this information back to the cell site. The cell site transmits this voice channel identity to the mobile unit, which then tunes to it while the MTSO simultaneously forwards the desired PSTN number to the local telephone office. From this point, the call is processed as a landline phone call. [Ref. 10:p.22.2]

2. Supervision

a. *Supervisory Audio Tone (SAT)*

As each cellular call is in progress, continuous supervision is provided by one of three possible supervisory audio tones (SAT), which must be modulated on the carrier of the voice channel [Ref. 19]. These frequencies are: 5970, 6000, or 6030 Hz. One of these tones is added to the voice channel by the cell site. The mobile set will detect, filter, and modulate the transmitted voice carrier with this tone. In this way, the SAT is transponded back to the cell site. The return voice signal to the cell site should therefore be modulated by the same SAT that it sent to the mobile. If the cell site fails to detect a valid SAT, then the fade timer is started, muting audio for the subscriber. If this timer counts to its preset limit, usually from five to ten seconds, the mobile set's transmitter will automatically be shut down [Ref. 19:p. 2-18].

One specific SAT is allocated for use by each cluster of cells, and this SAT is used by each of the cell sites in that cluster to modulate the voice signals. This is a system mechanism to prevent cochannel signals from a like-numbered cell in one cluster from interfering with signals in the same-numbered cell of another cluster in the same cellular system. If the incorrect SAT is received continuously for the duration of the timer limit, then the call is terminated.

b. Signaling Tone

The signaling tone (ST) is a 10 kHz tone transmitted by the mobile set over the voice channel. It is transmitted when the mobile unit is initially activated by an incoming call, and this tone stays present until the subscriber's phone goes "off hook" [Ref. 18]. This tone is also transmitted for a period of 1.8 seconds by the mobile set when the subscriber chooses to terminate a call [Ref. 9:p. 77].

3. Call Handoff

During the course of a cellular telephone conversation, if the subscriber approaches one of the cell boundaries or one of the propagation "holes" described earlier, then a *handoff* of the call to another cell site may be required. The function that makes this process possible is that of *location*. Each cell site continuously monitors the signals of all calls that are in progress within its cell boundaries. Measured signal strengths near the threshold level, normally around -100 dBm, for the minimum required voice quality for cellular service, prompt the cell site to send a request to the MTSO for a handoff for that call [Ref. 9:p. 272].

After receiving this handoff request, the MTSO checks with nearby cell sites to determine which cell site receives the mobile unit's signal the strongest [Ref. 20]. As each of these nearby cell sites is queried by the MTSO, it looks for the mobile unit's signal, measures its signal strength, and reports this back to the MTSO. The MTSO uses these results to determine the handoff destination, required for construction of its handoff message.

The MTSO instructs the current cell site to send the handoff signal, a very brief data burst, over the forward voice channel. This process is referred to as "blank and burst", and the signal contains the new frequency that the mobile unit will automatically switch to upon its receipt, the SAT, and the appropriate power level to maintain after completing the handoff. The mobile set stores this data and sends a 50 millisecond ST, and turns off the current reverse voice channel [Ref. 18]. The mobile then tunes to the new voice channel, and transponds to the new SAT. Once the system detects the SAT, the former cell site channel is removed, and becomes available for another assignment.

During this entire process, the audio signal is muted for only 150 to 400 milliseconds, and normally goes unnoticed by the subscriber [Ref. 20:p. 50].

Handoffs may also be ordered by the MTSO to relieve congestion in particularly congested cells. In such a case, the MTSO would have the cell sites create "early" handoffs so that bordering cells could take some of the traffic of the crowded cell. [Ref. 9:p. 276]

4. Roaming

Roaming is defined as a mobile unit operating outside of its subscribed CGSA [Ref 17:p. 55]. In many cases, this is also transparent to the subscriber, except that a "roam" light will be illuminated on the control unit of his mobile, and the toll charges may increase.

As of 1987, roaming accounted for 13% of the total service revenue for the U.S. cellular industry. Roaming between systems is not always automatic, or transparent to the subscriber, and the CTIA has been working on a universal cellular dialing plan and a national roaming assistance number [Ref. 12:p. 21]. Currently, many cellular operators employ call-delivery clearing-house systems to handle roaming functions. One such example is Bell Atlantic Mobile Systems

"Follow Me Roaming" which is offered to cellular customers in 250 cities in both the United States and Canada. This service forwards all incoming calls to subscribers regardless of the city in which they are currently located [Ref. 21].

The Telecommunications Industry Association (TIA) is the manufacturers' industry group, and it continues to refine IS.41, which is the switch networking standard for inter-system handoffs, or roaming [Ref. 13:p. 13]. The current revision of IS.41, now being considered by the committee for approval, also includes a call delivery provision for the cellular subscriber. Also being considered for this standard is a call lock-out feature that would allow the roamer to specify in advance which phone numbers that he wanted to receive, and all other numbers would be blocked [Ref. 13:p. 14].

5. Call Release

As a mobile user hangs up, the signaling tone is sent to the system to release the telephone trunks and the base-station equipment. The modulation tone is also removed, eliminating any indications of an active call [Ref. 10:p.22.3].

C. SYSTEM STRUCTURE

One of the fundamental decisions that a radio engineer must make when establishing a cellular system is the selection of the frequency reuse pattern for the cellular architecture.

The engineer must decide how many cells to group to form one cluster. Each cluster of cells will employ the entire channel allocation available to the cellular carrier. Depending on the size of the CGSA, the type of terrain featured, and potential subscriber density, the CGSA may be service by one cluster of a prescribed number of cells, or it may require several clusters of cells.

In the U.S. AMPS systems, 12-cell reuse patterns were initially used, but subsequently both seven-cell and four-cell patterns have been employed [Ref. 7:p. 379]. Figure 5 illustrates how a seven-cell reuse pattern might appear. In this figure, seven clusters are shown with each containing seven cells. The clusters are outlined in bold lines, and each individual cell in each cluster is numbered. Although seven clusters are shown here for convenience, in reality, any number of clusters might exist, but all would contain seven cells apiece for a seven-cell reuse pattern.

1. Frequency Reuse Distance: D

Selection of the frequency reuse pattern is important because it is one of the principle determinants of the frequency reuse distance. This distance is that which must be provided between two cells of different clusters in order for the same frequency or channel to be used in each of these cells. If sufficient distance is not provided, the probability that interference will impinge on operations increases. This interference limitation will be described further in the next chapter; however, this distance requirement can be mathematically derived by the formula shown in Equation 1 [Ref. 9:p. 52]:

$$D = R \times \sqrt{3 \times N}$$

Equation 1. Frequency reuse distance

In this formula, the parameter of interest, D, is the required distance between cochannel cells. Cochannel cells each belong to separate clusters in a given cellular system, but each cochannel cell employs the same frequency channels. R is the radius of each cell in the cellular structure, and N is the number of cells in the reuse pattern, or frequency reuse factor, which is seven for the example shown in Figure 5.

For example, in Figure 5, the same channel that is used in cell "number 1" in the center cluster should theoretically be capable of being used in each of the other clusters' "number 1" cells as long as the required distance, D, is maintained between these like-numbered cells.

2. Frequency Reuse Factor: N

If one excluded the real estate constraints for building numerous cell sites, for a given system it might superficially appear desirable to have a large value of N and relatively few clusters. However, a tradeoff must be made.

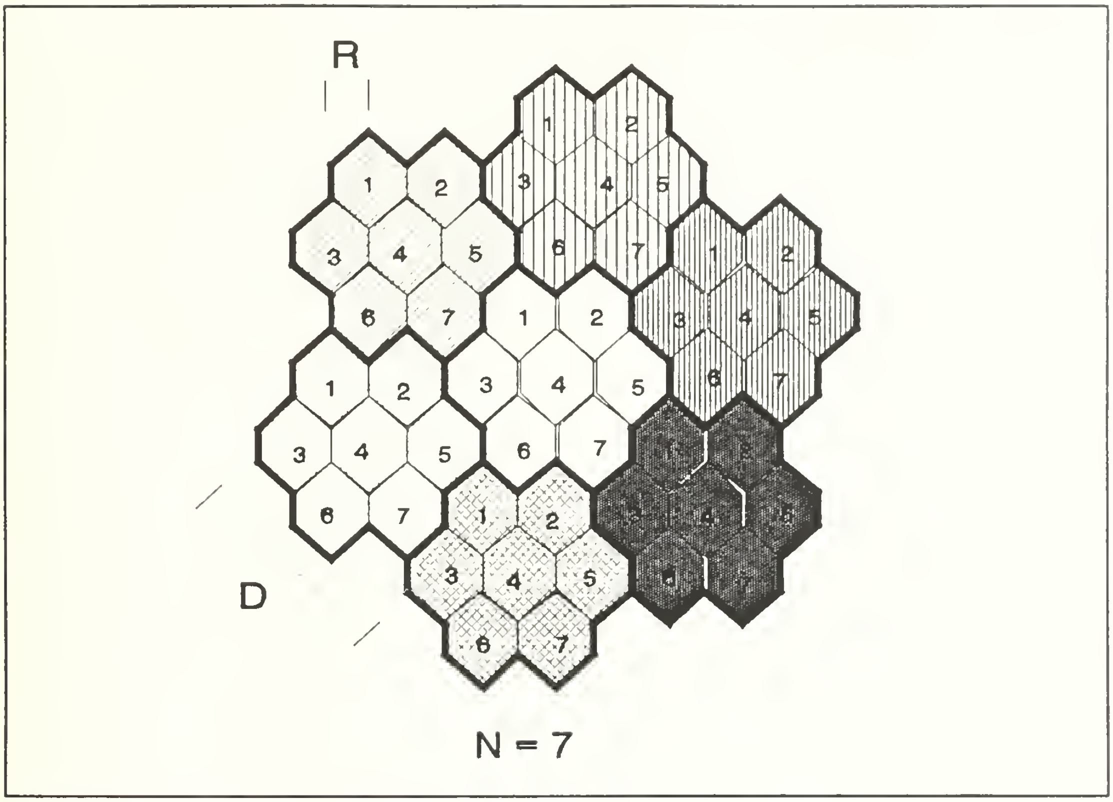

Figure 5. 7-Cell Reuse Pattern

With too many cells per cluster, under the AMPS analog FM system, the number of channels available for assignment to each cell becomes small, and this may be impractical for active, high-traffic systems. To avoid this trunking inefficiency, and therefore also to avoid conditions of spectrum inefficiency, the cellular engineer strives for the smallest number of cells per cluster which will still achieve adequate system performance. [Ref. 9:p. 53] The lower the N value, the more circuits that can be provided per square mile [Ref. 7:p. 379].

3. Cell Radius: R

The cell site's transmitter power largely determines the effective cell radius, R. From equation 1, the reader can see that for a large value of R, the required separation distance for frequency reuse will increase proportionally, and the system will be less efficient. On the other hand, a reduction in the value of R will lead to tremendous increases in spectrum efficiency. For example, if R is reduced by 50% for a given system, the number of circuits per megahertz per square mile will quadruple [Ref. 7:p. 41]. Lower powered cell site transmitters would be used for these smaller cells so that a desirably low frequency reuse distance could be realized.

The original AMPS architects envisioned relatively large cell sizes for the introductory cellular systems. As service demand increases and higher traffic capacity becomes a requirement, the cells would be "split" in size; that is, the cell boundaries for the system would be redefined so that a larger number of smaller cells would be prescribed for the original service area.

4. Cell Splitting

The innovative concept of cell splitting provided the key to congestion management, a chronic problem of the older IMTS system. As traffic in a cell area approaches the point at which service quality degrades to an unacceptable level, for example if high call blocking probabilities exist, then the cell must be split so that the frequency channels can be used more often [Ref. 9:p. 301]. The original cell will be split into a number of smaller cells, and capacity will increase by a factor equal to the number of new cells that were created [Ref. 7:p. 42]. Figure 6 illustrates this graphically. If demand for service had increased beyond capacity for the center cell in diagram A below, that cell could be split into smaller cells as shown in B. After splitting, a greater number of channels are available for the service area than before the cell splitting, and service capacity is increased for that area.

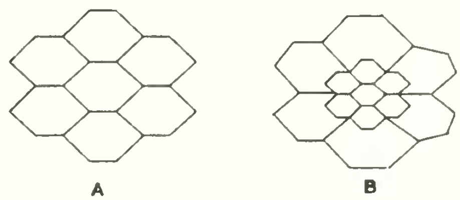

Figure 6. (A) Before Cell Splitting, (B) After Splitting

Cell splitting provides flexibility to the cellular engineer. The cellular architect is selectively able to boost system capacity through cell splitting to those areas that really needed the additional capacity. Additionally, the concept seemed to provide for a system that would be unbound by capacity limitations; indeed, the original AMPS engineers conceived of at least 3 rounds of cell splitting, but felt that the system could be split into even smaller cells [Ref. 7:p. 42]. Current cell site technology provides for minimum cell radii of about one kilometer [Ref. 22].

Cell splitting is the key cellular component that permits efficient utilization of the frequency spectrum and circumvents the system capacity problems of the previous radiotelephone systems. If the system is never split into the smaller-sized cells, then the spectrum efficiency will never be much greater than that provided by the non-cellular systems. Cell splitting is the capacity booster for the cellular system; however, as the reader will learn in the next chapter, cell splitting is extremely expensive for the system operator, so expensive that even though capacity does increase, the cost per channel may also increase [Ref. 7:p. 119].

IV. LIMITATIONS OF CELLULAR SYSTEMS

A. INTRODUCTION

Just as in the previous chapter, the U.S. AMPS cellular system will be used as a reference in this chapter to outline the performance limitations of cellular systems. So that the reader might be able to discern those limitations that are only AMPS specific from those that belong to cellular systems in general, one section in this chapter will focus on the inherent limitations of employing the analog FM architecture upon which AMPS is based.

Before introducing these limitations, the reader should understand the performance criteria for cellular systems. Dr. William Lee outlines three categories of performance criteria [Ref. 9:p. 9]:

1. Voice Quality
2. Service Quality
3. Special Features

A specific bit error rate (BER) for the voice channel can not be prescribed in an analog system like today's AMPS cellular. Subjective user opinion is required to measure the voice quality, and this is formally referred to as circuit merit (CM), the top two levels of which are "good" and "excellent", CM4 and CM5 respectively. Service quality is measured by evaluating the parameters of area coverage, call blocking probability, and number of dropped calls. The combined voice quality and coverage parameters for today's AMPS systems stipulate that 75% of the users must rate the voice quality between good and excellent in 90% of the served area for flat terrain, and for hilly terrain, the stipulation is that 90% of users must rate voice quality as good or excellent in 75% of the served area.

The specified blocking probability is two percent for the initiation of calls during the busy hour. [Ref. 9:p. 10] Obviously, the more special features, such as call forwarding, automatic roaming, and navigation services, that are offered, the greater the evaluated service performance.

In this chapter the reader will learn of the three categories of limitations that constrain the performance of cellular systems. The reader will understand the elements of each of these three categories, which include:

- RF-propagation limitations
- Analog FM architecture limitations
- Economic/cost limitations

B. RF-PROPAGATION LIMITATIONS

1. Natural Signal Attenuation

Natural propagation path loss is a characteristic that makes cellular radio practical. If signal strength did not attenuate as a function of distance, then it would be impractical to reuse a frequency channel in another cell of the system because the signals would interfere with each other. However, for relatively sparsely populated systems that might employ large-size cells with radii of up to ten miles, natural propagation path loss can be a limitation.

In free space, AMPS cellular radio signals will lose strength at the rate of 20 dB per ten miles. In a flat, open area on the surface of the earth, this figure is accelerated to a loss rate of 43.5 dB per ten miles. In the city environment of New York City, the rate of path loss is nearly 50 dB per ten miles. [Ref. 9:p. 102] In the larger cells, cell sites frequently transmit at a power level close to 40 Watts or 46 dBm, and most cellular mobile sets have a receiver threshold of -116 dBm. As the reader will learn in this chapter, there are many other possible factors that can act to attenuate the cellular radio signal, so natural propagation path loss can take away a large part of the signal power margin. This power margin is normally computed in a link budget, and it represents the gap between the receiver threshold and calculated power at the receiver after all signal propagation factors have been accounted for.

2. Foliage Loss

Foliage located along the point-to-point cellular radio path between the mobile and the cell site is a critical and complicated attenuation factor for 850 MHz RF propagation. Any branch, leaf, or vegetation stems can absorb RF energy, and the density of such foliage is directly correlated to the reduction in signal strength. This is especially true for needles and stems that are one-half the wavelength of 850 MHz signals. For example, trees that possess pine needles of about six inches absorb a great deal of energy of cellular radio signals. [Ref. 9:p. 115]

When planning a cellular system, foliage-covered terrain can pose uncertainties for the engineer. If particularly dense vegetation along a path is not accounted for, cellular communication may not be possible [Ref. 23]. Some types of vegetation will attenuate or absorb more energy than others, some trees will shed their leaves during winter seasons, and the density of foliage can be difficult to estimate. This means that foliage can make predicting RF signal coverage for cells very difficult. For relatively long mobile-to-cell site path lengths that include foliage, Dr. William Lee recommends using a value of 20 dB per decade in addition to the area path loss figure. [Ref. 9:p. 116]

3. Diffraction Loss

When the path between the cell site antenna and the mobile set antenna is obstructed, cellular radio communication is still possible, but a reduction in signal strength will result. Figure 7 represents an elevation contour diagram for the terrain between the Cellular One, Inc.'s cell site in Pebble Beach, California and the nearby Naval Postgraduate School (NPS) in Monterey. This elevation data was extracted from a DMA Chart, and antenna height was provided by Cellular One, Inc. [Ref. 24]. Since a direct line-of-sight path does not exist between these two points, a shadow or diffraction loss results.

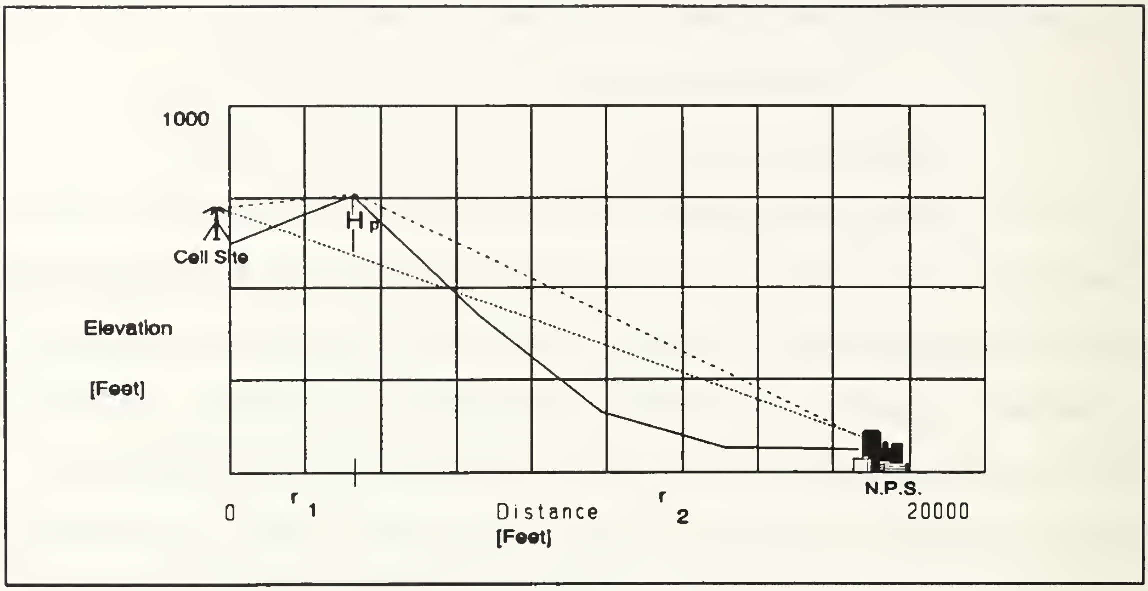

Figure 7. Diffraction Loss Parameters

Using Dr. William Lee's ***Mobile Cellular Telecommunications Systems*** as a reference, Equation 2 defines the relationship between the parameters associated with diffraction loss and the accompanying reduction in signal strength. For the Pebble Beach-NPS cellular radio link, H_p, the vertical distance between the obstruction's zenith and the imaginary line representing the line-of-sight (LOS) path between the two points, equals 150 feet; r_1, the distance from the cell site antenna to the obstruction's zenith equals 2,700 feet; r_2, the distance from the obstruction's zenith to the mobile set at NPS, equals 13,950 feet; *lambda*, the wavelength of the cellular signal, equals 1.16 feet; and the dimensionless parameter, v, equals minus 4.145. The calculated diffraction or shadow loss equals 25.31 dBm for this case.

$$v := -h_p \left[\left[\frac{2}{\lambda} \left[\frac{1}{r_1} + \frac{1}{r_2} \right] \right] \right]^{.5}$$

$$Diffraction_{loss} := 20 \log \left[\frac{-0.225}{v} \right]$$

Equation 2. Diffraction Loss Equation [Ref. 9]

In some obstructive cases, cellular radio communication may not be possible unless special hardware is employed. One such case is the Laguna Canyon in Laguna Beach, California. To provide cellular service to this high demand valley, PacTel had to use a solar-powered radio repeater to carry the radio signals through this "shadow" area. [Ref. 15:p. 138]

4. Adjacent Channel Interference

Adjacent channel interference occurs when energy from one channel bleeds over into an adjacent channel causing some degree of destruction to the message carried by the signal. Theoretically, this interference could be completely eliminated through filtering mechanisms in both the transmitter and receiver; however, this filtering adds costs to transceiver components. To promote low-cost mobile sets, the FCC specified loose filtering under AMPS. For this reason, adjacent channels may not be used within a given cell, and as a result, fewer frequencies are available for reuse than would be the case if tighter filtering had been specified. [Ref. 7:p. 242]

As a sidenote, equipment cost has not proven to be as important an issue for cellular market penetration as operating costs. It is the monthly operating costs that have prevented cellular from gaining greater use rather than the original concern of transceiver costs.

5. Cochannel Interference

Cochannel interference is the single most important constraint on cellular system frequency reuse [Ref. 7:p. 244]. It occurs when the transmitted energy from one particular cell site impinges upon the received signal of another distant cell site or mobile set that is using the same frequency. It is interference due to the common use of the same channel in different areas [Ref. 9:p. 51].

Cochannel interference comprises most of the denominator portion of the carrier-to-interference ratio (C/I), a fundamental calculation for cellular reuse [Ref. 7:p. 244]. Where filtering may be employed to reduce the effects of adjacent channel interference, no such mechanism can be employed for cochannel interference. The interfering signal by definition occupies the same bandwidth as desired signal. Cochannel interference is the driver for the requirement of maintaining a cellular reuse distance that is described in Equation 1 of Chapter III. However, the full effects of cochannel interference really can't be described until the concept of multipath fading is explained.

6. Multipath Propagation

The deleterious effects caused by multipath propagation are primarily observed in the mobile cellular environment, but can be found in all operating conditions. Multipath propagation occurs when radio waves reflect from obstacles, and sometimes even from the atmosphere. The result is a series of separate radio paths, instead of a singular path, between the cell site and mobile set. While these reflections permit non-LOS cellular radio links like the earlier example shown in Figure 7, multipath propagation also causes three very difficult challenges for radio engineers [Ref. 7:p. 213]:

1. Delay Spread of the received signal;
2. Rayleigh fading, which creates rapid fluctuations in the signal strength;
3. Doppler shifts, which cause random frequency modulation.

In this section, the manner in which each of these problems affects cellular operations will be described for the reader.

a. *Delay Spread*

Radio waves reflect from buildings, cars, and other objects with vertical features. These reflections, which may occur between the mobile set and the cell site, cause multiple radio paths of varying lengths. Since each radio wave travels at the same speed, multiple reflected radio paths will arrive at the receiver at different times. By the time a radio impulse is received, it has become a pulse with a spread width. It is this spread that is known as the *delay spread*. [Ref. 9:p. 22]

The effect of this delay spread is to smear the signal. The greater the duration of the spread, the greater the smearing or distorting effects. For indoor and office environments, the delay spread is typically 1 microsecond. The values are much higher for outdoor environments, especially in urban areas. [Ref. 7:p. 215]

b. *Rayleigh Fading*

While the phenomenon of delay spread retards the arrival of multiple radio waves and smears the received signal, *Rayleigh fading* is a condition where many very rapid, quick fades occur over time. These fades are the results of major changes to the phase and amplitude of the radio wave.

The moniker, Rayleigh, is prescribed because the fades fall under a statistical distribution called the Rayleigh distribution after the English physicist, Lord Rayleigh [Ref. 7:p. 216].

The variation in overall signal strength caused by Rayleigh fading is also caused by reflections from nearby buildings and other vertical structures [Ref. 9:p. 13]. However, rather than just smearing the signal, its strength undergoes rapid, deep fades which become particularly destructive when coupled with cochannel interference. What may happen to a cell site's receiver during these brief fading periods, is that it might capture the cochannel transmission of a distant cell site. Even though this Rayleigh fading induced cochannel interference would probably only last a brief time interval, the signal quality would diminish [Ref. 7:p. 219].

The mobile environment can complicate things even further because of the relative motion of the radio wave reflectors that results. As the vehicle speed varies, so too does the rate of fading [Ref. 9:p. 15]. In the 850 MHz region of AMPS cellular, any potential radio wave reflector within approximately 100 feet of the mobile set can induce this type of multipath fading.

One non-cellular, yet vivid, example of Rayleigh fading frequently occurs when an airplane, inadvertently serving as a radio wave reflector, flies at low altitude over a residential area and causes multipath propagation of television signals. The television viewer observes an accentuated picture flutter of the received video images. [Ref. 7:p. 219]

c. *Doppler Shift*

Named after the Austrian physicist, Christian Johann Doppler, *doppler shift* is the term used to describe the variations in frequency of the received signal. This frequency variation results from the movement of the mobile set relative to the cell site. For AMPS frequencies, a mobile set traveling at about 20 miles per hour can cause a doppler shift significant enough to induce noticeable distortion. This distortion develops because the entire power spectrum of the transmitted signal "shifts" to either increase or decrease the nominal center frequency of the received signal by the absolute amount of the doppler shift. [Ref. 7:p. 220]

7. Noise

In addition to interference, the cellular radio signal is also affected by *noise*. Noise, categorized as either internal or external, can be described as "any undesired signal in a communication circuit" [Ref. 25]. Noise is the result of random environmental processes that produce RF energy [Ref. 7:p. 204].

Internal noise represents sources, such as thermal noise, arising inside cellular communication components [Ref. 26]. However, in the cellular environment, external noise poses the most serious problems. This category of noise includes that caused by automobile ignition systems, electric motors, neon signs, and power lines [Ref. 26:p. 388].

One of the primary measures of cellular signal quality is called the signal-to-noise ratio (SNR), and thermal noise, amplifier noise, and the various external noise sources account for the value of the denominator in this measurement. The numerator of the SNR measurement is the signal strength. In the current AMPS cellular system, Dr. William Lee states that to obtain good quality at the baseband, an SNR value of 38 dB is a reasonable figure when both the deemphasis and diversity gains are accounted for [Ref. 9:p. 380].

Because of the impact of automobile ignition noise in the cellular environment, the noise level can vary just as vehicular traffic in an area varies. For this reason, cellular engineers are challenged by the requirement of achieving acceptable SNR measurements over a variety of operating conditions.

C. ANALOG FM ARCHITECTURE LIMITATIONS

1. Potential for Refinement

The FCC chose to exercise its regulatory authority in another facet of the cellular market, that of radio technology. As described earlier, cellular is an architectural concept and as such, it does not necessarily dictate a particular scheme of radio transmission. The analog scheme of FM has matured over the years and become nearly as efficient as is theoretically possible. Analog FM permits relatively noise-free, high quality transmission of voice under a variety of conditions. Access to FM technology has been widely available to all radio carriers for many years, and, in the eyes of the FCC, this fact made it suitable for consideration as a "standard" for the cellular industry.

To ensure that the spectrum allocation for cellular was employed efficiently, the FCC believed that a radio transmission standard was mandatory so that equipment and signals would be compatible nationwide. In large part due to the universal availability of FM technology to the carriers, the FCC specified analog FM as the radio transmission standard for cellular [Ref. 7:p. 71].

Despite the improvements that had occurred over the decades, FM still required a relatively large amount of bandwidth to achieve good performance. This is a less than ideal attribute when spectrum is scarce. An optimal level of spectrum efficiency, measured by the number of conversations per megahertz, is unlikely to be achieved with analog FM.

Figure 8 attempts to illustrate the different incentives for improvement between mature and new technologies. When the FCC specified FM, a very mature

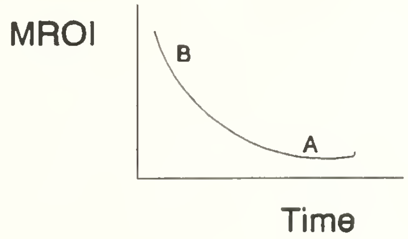

Figure 8. MROI Comparison

technology, it virtually guaranteed that very little research and development for radio transmission would ever be exerted in the cellular marketplace. In Figure 8, the abscissa represents time, and in the case of modern radio technology, a relevant span or interval might be as short as 5 years. The ordinate represents marginal return on investment on technological improvements, and FM technology is located at point "A" on the curve of diminishing marginal return on technology investment. "B" represents one of several newly emerging digital technologies that, at the time of the FCC's decision, may not have been quite ready for gainful employment with cellular radio, but were soon to be. With the FCC's standardization of FM for cellular, it virtually eliminated the incentives for and possibilities of future technical system efficiency increases. The FM "savings" account had already been virtually depleted [Ref. 7].

Some experts judge this technology choice more harshly, and predict effectively negative returns on FM investment:

> The costs of analog systems are likely to climb as the rest of the telephone network goes digital. Solutions to the problems of privacy and medium to high-speed data transmission, not to speak of ISDN compatibility, will *add* costs to analog systems. [Ref. 7:p. 275]

2. Single Channel per Carrier (SCPC)

The second problem with FM as a cellular radio transmission scheme is that it provides only a *single channel per carrier (SCPC)*. This means that each frequency channel must be entirely devoted to a single conversation; the channel can not be shared under FM. With current digital transmission schemes that will be described in the next chapter, eight circuits can be serviced under a single channel, and some of the newer digital systems may provide double this figure. Not only does this constrain system capacity, but the system cost per subscriber is much higher under analog FM. [Ref. 7:p. 82]

3. Security/Privacy

Under the analog FM AMPS system, any person with an 800 MHz radio scanner, like those available from Radio Shack, can listen in or eavesdrop on cellular calls. Industry analysts report that this has even become a hobby or "high sport" with some eavesdroppers, so that many businesses that are concerned about compromising proprietary or confidential information have been discouraged from using cellular communications [Ref. 15:p. 138].

Several companies offer an encryption system as a cellular value-added option. One such system is GTE Mobilnet's Commando 5000 system. This system employs "scramblers" which change frequencies more than 400 times per second, thus rendering eavesdropping impossible. The drawback is that both subscribers must have these scramblers for mobile to mobile transmission, and for mobile to landline transmission, the CGSA MTSO must also be equipped with this scrambler, so universal service may not always be available. These scramblers are currently being used by the U.S. Government, many local law enforcement agencies, and businesses requiring voice security.

4. Data Transmission

Analog FM is inherently ill-suited for data transmission since computers manipulate data in digital format. Just as for landline phones, most of which are still analog, modems are available for cellular phones. Unfortunately, because of the noise in most cellular environments and also the interruptions of the voice radio signal during a handoff, cellular data communication is extremely error-prone under the current analog system. As a result, error detection and correction schemes must be employed by cellular modems. For these reasons, the maximum usable throughput is about 1200 bits per second [Ref. 7:p. 112].

This problem will be magnified in the future as landline phones migrate to fully digital circuits, and the Integrated Services Digital Network (ISDN) becomes a reality. In this case, the 1200 bits per second data rate for analog cellular will be about 64 times slower than that permitted over ISDN circuits, and many users may be discouraged from even cellular for data transmission.

5. Centralized Control

The final limitation in this section does not concern the FM transmission technique, but rather the architecture of the current AMPS system. When the major features of AMPS were being developed in the late 1960s, the only option for system control was the large, centralized computer. Since microprocessors did not yet exist, the system was designed for centralized control by the MTSO; distributed control was not yet an option.

The MTSO provides all aspects of intelligence and control to the AMPS system. The drawback of such a system, as most military students learn, is that survivability is compromised and robustness is sacrificed when all the control functions are centrally located. Should the MTSO suffer some sort of failure, the entire MSA loses service.

D. ECONOMIC/COST LIMITATIONS

Some of the constraints listed in this section would be factors for all cellular systems, regardless of the market structure; however, when the FCC prescribed a duopoly, two carriers or operators per market, for AMPS cellular, several other limitations arose that may not have under a one-carrier-per-market structure. In this section, the reader will see that the intended "competition bonus" for the customer was most likely forfeited because of the economic inefficiencies that resulted from splitting each MSA between two cellular carriers.

1. Start-Up Costs

The start-up fixed costs are enormous for the operator commencing cellular service in an inaugural MSA. Real estate must be leased or purchased so that cell sites can be constructed, expensive radio equipment must be procured, and radio propagation analyses as well as extensive system testing must be performed. Even today, individual cell sites can cost nearly one million dollars to build, and an MTSO can cost $5 million or more [Ref. 27]. For any given MSA there are only a fixed number of suitable "zoned" locations that will provide effective radio coverage. When two carriers compete in one MSA for cellular service, the competition in obtaining this scarce real estate greatly increases, and the prices for this category of land will be queued upward. In some high density environments (Los Angeles counties), a supply of suitable land lots may not even exist for optimal-architecture service. In this case, the cellular architecture for such an area will have to be scaled down (more cells for a given coverage area), and more cell sites will have to be built to achieve full area coverage. In either case, the operator's marginal operations cost curve will shift upwards and also become steeper, the effects of which will be explained in the next section.

2. Duopoly Market Structure

Figure 9 portrays a hypothetical, graphical comparison between a CGSA duopoly structure and a monopoly market structure. Since a rigorous economic analysis falls outside the scope of this paper, the following assumptions have been made to illustrate that the individual cellular subscriber might be better served by a monopoly:

1. The demand curve facing the individual duopolist for cellular service in a CGSA will be exactly one-half that of the monopolist provider of cellular service in that CGSA.

2. Each duopolist will set price and quantity based on the intersection of the marginal cost and marginal revenue curves; gaming theories for price strategies will not be applied in this simplified comparison.

The following acronyms and the labels for the various curves are defined below:

$\underline{MC_M}$: marginal cost curve for monopolist

MC_D: marginal cost curve for duopolist

D_M: demand curve for monopolist

$D_D=MR_M$: demand curve for duopolist; monopolist's marginal revenue

MR_D: marginal revenue for duopolist

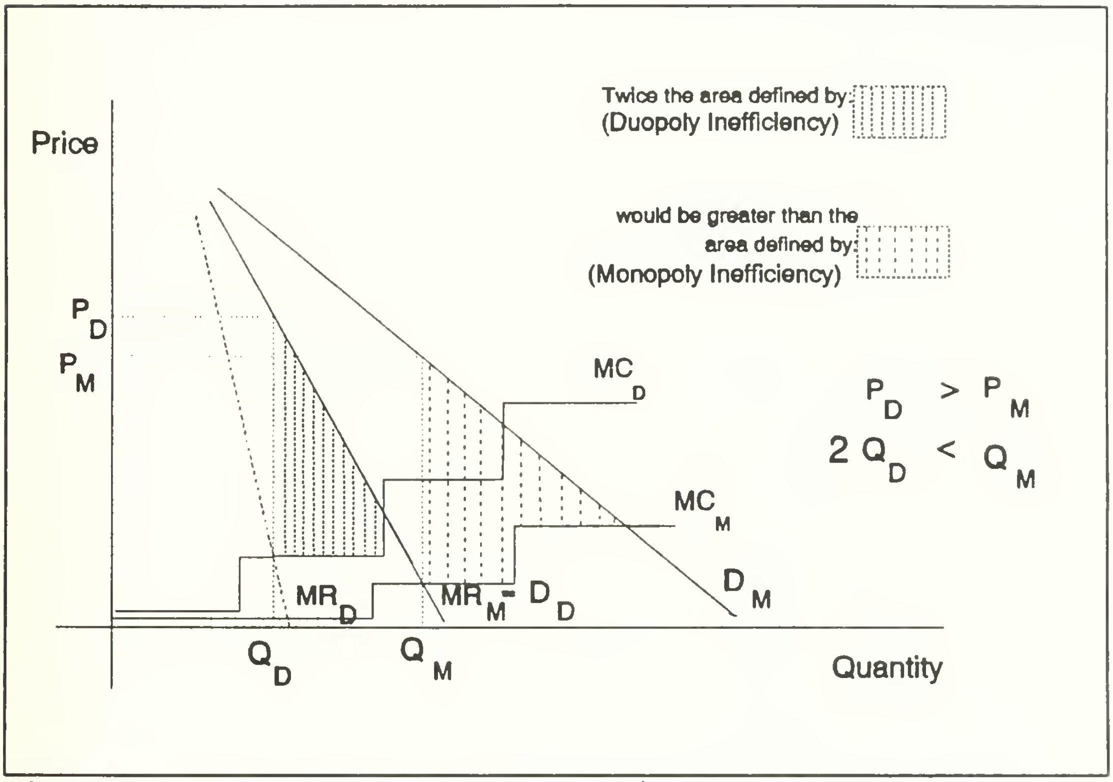

Figure 9. Hypothetical Monopoly/Duopoly Comparison

One of the factors that contribute to the duopolist's higher marginal cost curve is the degradation in trunking efficiency that results from two cellular service providers rather than one [Ref. 9]. In order to maintain the same level of service, measured in terms of call blocking probability, the duopolist will be about 10 percent less efficient in his allocation of spectrum due to this trunking efficiency loss [Ref. 9:p. 7]. As quantity increases, the duopolist will have to resort to the more expensive techniques of cell splitting well before the monopolist, and this causes his marginal cost curve to feature "steeper steps" as quantity increases.

The process of cell splitting accounts for the "stair-step" shape of both the monopolist's and the duopolist's marginal cost functions. When demand in one particular cell far outstrips its channel capacity, that particular cell is split into a group of smaller cells, as was described in Chapter III. Cell splitting is extremely expensive for cellular operators. The problem even becomes worse when the switching processors are considered. More cells mean that more "handoffs" will be required as the mobile user moves from one cell boundary to another. This places an increased load on the expensive computers that control this switching function, and upgrading them is very expensive. Perhaps one of the cellular industry's experts put it best:

> In practice, cell-splitting probably *increases* the cost per circuit. In addition, the processing (computer) overload problems...(and) smaller cells produce geometrically higher rates of hand-offs, requiring more switching and interconnecting trunks mean that the network costs of a small-cell system will be higher than for a large-cell system. [Ref. 7:p.119]

No really viable, long-term technique exists for adding just "a little", or marginal capacity. Instead, after cell splitting, a relatively large amount of unused capacity will exist for some level of additional quantity. As we stated earlier, the duopolist is forced into this situation sooner that the monopolist would be.

If we assume that the duopolist will set prices independent of the other provider's pricing behavior, then quantity should be set according to the intersection of the marginal revenue and marginal cost curves, and price should be set according to the projection of this intersection on their demand curve. In Figure 9, we identify this price level as P_D, and the quantity associated with it as Q_D. Note that the price charged by duopolist is greater than the monopolist's price, and twice Q_D is less than the quantity provided by the monopolist, Q_M.

Although difficult to perform without empirical marginal cost and demand function formulas, a comparison could also be made between the "areas of inefficiency" shown in Figure 9 for both cases. Twice the area labeled "Duopoly Inefficiency" in Figure 9 would be empirically compared to the area labeled "Monopoly Inefficiency." The inspection of Figure 9 suggests that the monopoly efficiency loss would be less than the total duopoly efficiency in this hypothetical comparison. The duopolistic market features higher prices and lower quantity of cellular service than under the single-provider market.

Perhaps the luxury of hindsight and the realities of the cellular market exaggerate the case against the duopoly market structure selected by the FCC. The FCC may also have been somewhat misled by the original AMPS communications engineers who touted the cellular architecture as a "spectrum engine" and underplayed or miscalculated the costs that would accompany cell splitting [Ref. 7:p. 114]. The outcome in the cellular market, however, provides a case that the technical communication inefficiencies associated with both a split market and split frequency spectrum have exceeded any competitive benefits that might have accrued from such a structure. Competition for the right to service the CGSAs is definitely desirable; wireline carriers as well as non-wireline carriers should be allowed to compete for service areas. However, for maximum efficiency, this simplified analysis seems to suggest that circumstances could possibly exist whereby each CGSA should be served by a sole carrier, whether it be wireline or nonwireline.

V. DIGITAL CELLULAR RADIO

A. INTRODUCTION

The exciting new field of digital radio is as technologically prestigious and newsworthy as that of high definition television (HDTV). Recently, Alfred C. Sikes, current chairman of the FCC, addressed the importance of properly regulating these remarkable developments:

> No longer is the promise of fiber optics, digital radio, advanced television and cordless personal communications networks a secret known only to industry insiders. Some business leaders in positions of influence are also beginning to ask how these promises might become reality. At the FCC, we are exploring ways to make the radio spectrum available for new uses....[Ref. 28]

Digital radio promises to ameliorate, or even eliminate, many of the cellular limitations that were delineated in the previous chapter. Even in non-cellular radio systems, digital radio techniques are much more efficient than FM in their use of the radio spectrum. Digital radio techniques are the most likely means through which personal communications services (PCS) might become universal throughout the country or perhaps even the world.

Some experts contend that the U.S. has fallen behind the international telecommunications community in advancing a digital cellular standard to replace the current AMPS system. In Europe, a new digital cellular system called Groupe

Speciale Mobile (GSM) is now being introduced. This Time Division Multiple Access (TDMA) system is intended to provide universal cellular service throughout all of Europe, including its rural areas [Ref. 29]. The European Economic Community (EEC) has already commenced a research project to establish a follow-on system to GSM. Referred to as the Research and development in Advanced Communications in Europe (RACE) project, its charter is to develop a mobile data and voice communications system that will accommodate ISDN by 1995 [Ref. 29:p. 20]. In Japan, a digital cellular standard has also been selected, and supply contracts for digital radio equipment have already been awarded to Motorola [Ref. 30].

During early 1989, the U.S. cellular industry was comparing TDMA against Frequency Division Multiple Access (FDMA) in field experiments. FDMA was originally favored by both AT&T and Motorola, but as of this writing, the CTIA currently favors TDMA technology, which has been successfully demonstrated for cellular application by International Mobile Machines (IMM). The CTIA has proposed the following requirements for the new digital cellular technology [Ref. 31]:

1. Ten-fold increase over analog system capacity
2. Long life and adequate growth of second-generation technology
3. Ability to introduce new features

4. Quality improvement

5. Privacy

6. Ease of transition and compatibility with existing analog system

7. Early availability and reasonable costs for dual mode radios and cells

Recent experiments in another digital system, Code Division Multiple Access (CDMA), have redirected the focus of industry interest [Ref. 32]. Despite the fact that CDMA developmental efforts for cellular are about one year behind those of TDMA, some analysts believe that this technology will provide the greatest long-term growth potential.

Superficially, it may appear that the U.S. has indeed fallen behind its international competitors in the digital radio field. However, the selection of a digital cellular standard involves many complex matters, and the newer CDMA technology possesses several potential advantages over TDMA.

Several excellent references are available that describe the fundamentals of digital radio; however, the details of the very issues that are currently being debated by industry are not so widely treated. These include the principles of multiple access for digital cellular radio.

In this chapter, the reader will learn that the terms, FDMA, TDMA, and CDMA, each describe a single dimension of digital radio, that of the multiple access technique (actually CDMA also implies a wideband channelization scheme). The next section will cover the fundamentals of multiple access for digital cellular, and the final section will provide a synopsis of the current status of each digital multiple access system. These multiple access alternatives comprise the crucial and contentious issues in selecting a digital cellular technology.

B. MULTIPLE ACCESS ALTERNATIVES

The concept of multiple access is closely related to that of multiplexing. Both describe the sharing of a fixed communications resource, such as the allocated RF spectrum. In multiplexing, the users' requirements are usually fixed, and the sharing algorithm is confined to a local site, such as a circuit board [Ref. 33].

Multiple access implies the simultaneous sharing of a resource, like a cell site, in a dynamic environment [Ref. 33:p. 476]. Multiple access schemes are also used in the fields of satellite and computer communications, as well as in packet radio networks. In each case, one of the goals of the multiple access system is to allocate bandwidth among the users in the most efficient way possible. To accomplish this, every user should be able to utilize any available channel or circuit in a fully trunked system [Ref. 7:p. 283].

In general, multiple access schemes can be divided into two broad categories: random access and fixed access. Random access protocols, used in packet radio and computer networks, include [Ref. 34]:

1. ALOHA/ slotted ALOHA
2. Carrier Sense Multiple Access (CSMA)
3. Busy-Tone Multiple Access (BTMA)

This section will focus on the set of fixed multiple access protocols identified in the introduction to this chapter:

1. FDMA
2. TDMA
3. CDMA

1. FDMA

FDMA is the access scheme used by the current analog FM cellular system. The frequency spectrum is divided into multiple segments, each of which is separated by guard bands as shown in Figure 10. These guard bands serve as buffer zones to prevent interference between adjacent channels [Ref. 33:p. 479]. The subscriber is assigned any one of the available frequency segments on a first-come, first-serve basis, and this channel is used until the call is terminated. At this time, the channel becomes available for use by another subscriber.

The most significant change in a digital FDMA system is the more narrow bandwidth or segment width, illustrated as

W in Figure 10. In 1989, Motorola and AT&T were testing digital FDMA systems with channel bandwidths of 10 kHz and 7.5 kHz, instead of the 30 kHz AMPS channel bandwidth [Ref. 2:p. 121]. The advantage of more narrow channel bandwidths is that system capacity increases.

Another advantage of an FDMA system is the low transmission overhead that is required. Since transmission through the channel is continuous, or non-bursty, relatively few bits must be inserted for synchronization, framing, and control. One estimate for the required bit-overhead rate of digital FDMA cellular is two percent, which is considered quite low. [Ref. 7:p. 368]

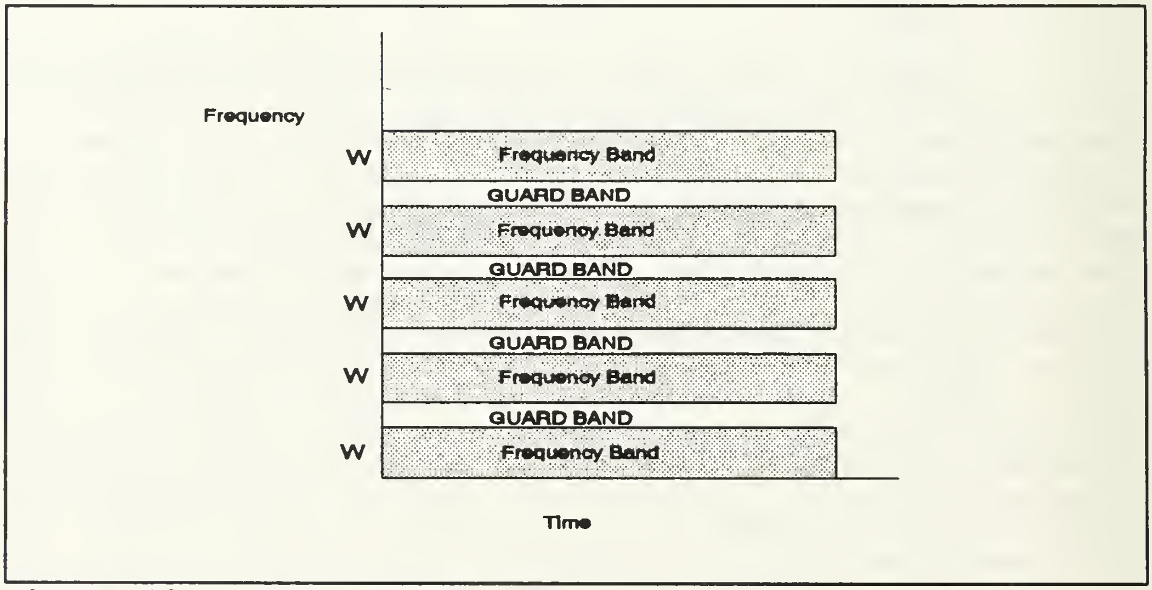

Figure 10. FDMA System [Ref. 33: p. 480]

On the other hand, digital FDMA is still SCPC, and as a result, considerably more equipment is required at the transceivers. Additionally, since both the receiver and transmitter operate simultaneously, FDMA mobile sets must employ duplexers so that the mobile receiver can function effectively [Ref. 7:p. 368]. The mobile unit must also feature frequency agility so that each can tune to all of the available frequencies [Ref. 7:p. 284].

2. TDMA

TDMA separates frequency channels into individual time slots and assigns these time slots to different subscribers on a fixed schedule. One general advantage of this system is that several subscribers' conversations can be transmitted over a given frequency channel. This means that the mobile set does not have to transmit continuously, so that transmitter power and RF spectrum are used more efficiently [Ref. 35].

Figure 11 portrays a simple example of a TDMA system [Ref. 33:p. 484]. The blank slots labeled "guard time" provide a buffer for potential time uncertainty between adjacent signals [Ref. 33:p. 484]. Depending on the particular TDMA system, a fixed number of time slots are combined to form a frame, and then each individual frequency channel is assigned a frame. The result is a frequency-time matrix like that shown in Figure 12.

To simplify the following analysis, the guard times and guard bands have been omitted from Figure 12. This figure models the European GSM digital cellular system, which employs

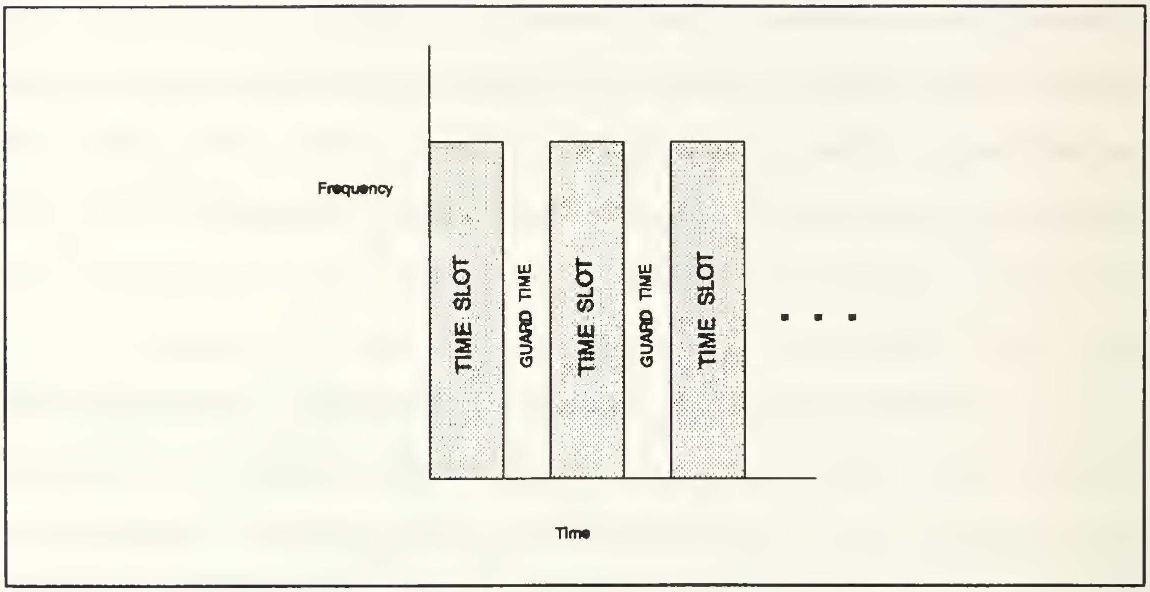

Figure 11. TDMA [Ref. 33:p. 484]

a voice coding technique known as residually excited linear predictive coding (RELP). The details of voice coding are beyond the scope of this paper; Figure 12 reveals the details of GSM's TDMA. In this system, eight slots compose a frame, and each frame has a bandwidth, W, of 200 kHz [Ref. 35:p. 20]. The overall frequency allocation would be divided by 200 kHz, and the quotient would be total number, N, of channels as shown below. Under GSM, the eight time slots, or circuits, of 30 kbps are multiplexed to achieve a total channel rate of 240 kbps, or nearly 1 b/Hz [Ref. 7:p. 370]. Actually, as the reader may notice, this system is a combination of FDMA and TDMA since subscribers have access to all available frequencies and time slots in the time-frequency matrix of Figure 12 [Ref. 7:p. 285].

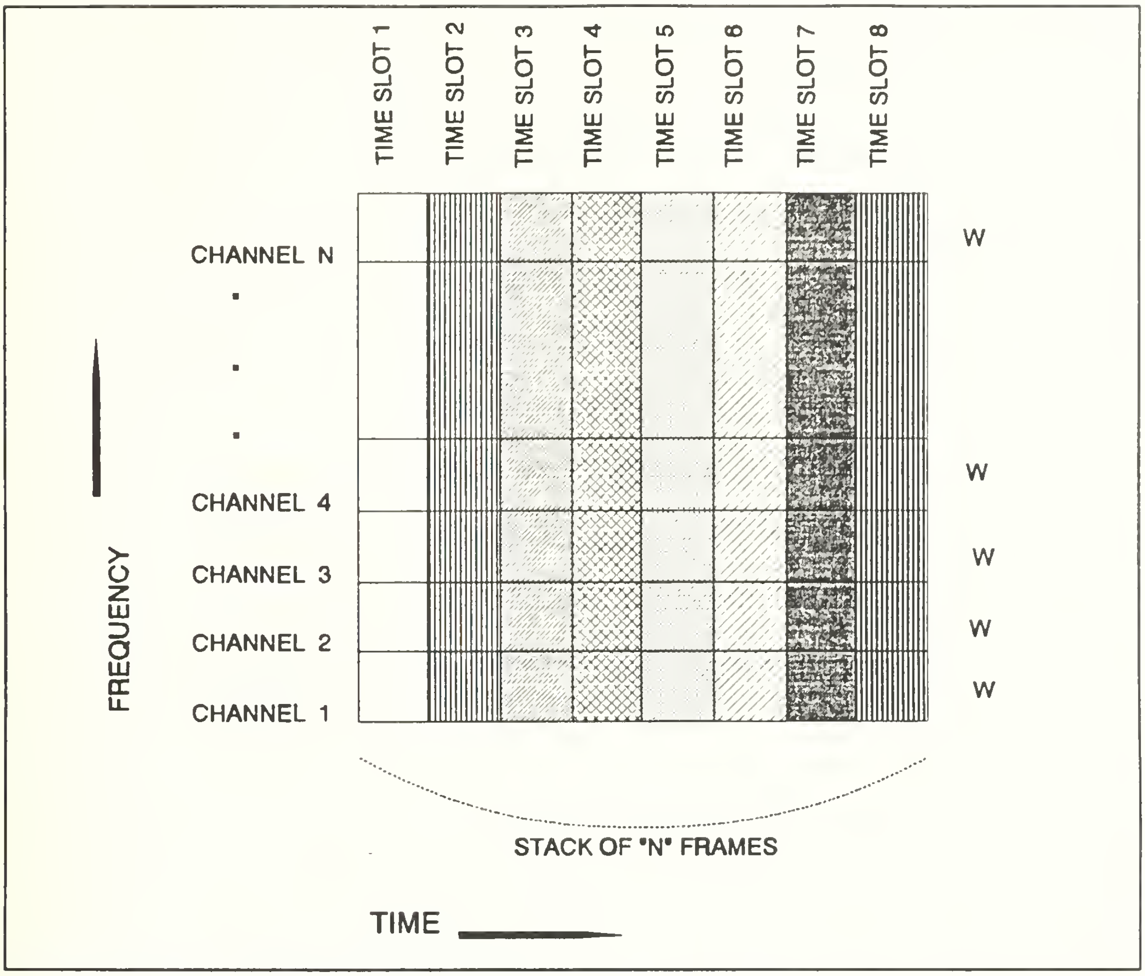

Figure 12. GSM TDMA System

Since TDMA transmission is not continuous, duplexers are not required for these systems. Instead fast switching circuitry alternately turns the transmitter and receiver on and off at the proper times [Ref. 7:p. 372]. Another TDMA advantage that integrated circuitry provides over FDMA is the ease with which this system can be reconfigured over time to accept advanced, lower bit-rate coding algorithms. In TDMA systems, this can be achieved through software upgrades. To similarly upgrade FDMA systems would require substantial investment in new hardware after frequency channels are redefined. [Ref. 7:p. 373]

A comparative disadvantage of TDMA is the large amount of overhead that is required for frame synchronization since the communication scheme is "bursty." Compared to FDMA's two percent requirement, TDMA usually requires from 20-30% of the total bits transmitted; however, IMM recently achieved success with only nine percent overhead, and rate should continue to drop, although it will always be greater than that of FDMA. [Ref. 7:p. 372]

Most analysts believe that the advantages of TDMA far outweigh its disadvantages, especially for application in the cellular environment where interference is encountered. TDMA promises better cochannel interference resistance than FDMA, and it should also yield much better adjacent channel interference performance. These advantages permit greater system capacity since the radio engineer has more freedom in channel assignment among all the cells for a given area. [Ref. 7:p. 408]

3. CDMA

CDMA is a multiple access scheme employed by spread spectrum communication systems. Spread spectrum techniques have been employed by military systems for many years, but only recently have they been applied to the realm of cellular radio. The key patents for this remarkable system were developed just after World War II by engineers from ITT. However, because of national security concerns, the patents had been suppressed until 1978 [Ref. 7:p. 341]. Today, most of the large cellular operators are currently experimenting with spread spectrum modulation using CDMA as the multiple access method. Its main advantages for cellular are large subscriber capacity, inherently high level of information security, and ease of transition when converting an analog system to a digital one [Ref. 36].

The two predominant categories of spread spectrum include frequency hopping and direct sequence. In both categories, the signal power is spread out over the entire assigned bandwidth, rather than channelizing the power into a specific band [Ref. 37]. Another characteristic of both categories is tremendous processing gain, which allows for the toleration of very low signal-to-noise ratio values [Ref. 7:p. 356].

In frequency-hopping CDMA, each user's signal is assigned a short-term frequency slot. It may be that only a few bits are transmitted during this brief interval, and then the system will assign a different frequency slot for the next time interval. Figure 13 portrays a simplified model of frequency-hopping CDMA (FH-CDMA). It would appear that the system is randomly assigning frequency slots over a very wide bandwidth to the subscribers, but actually, each subscriber has a pseudonoise code that dictates the frequency hopping assignments. Additionally, despite what Figure 13 might suggest, no time synchronization is required among the various subscribers [Ref. 33:p. 492]. The processing gain produced by FH-CDMA corresponds to the ratio of the total frequency bandwidth to the width of the frequency occupied during each hop.

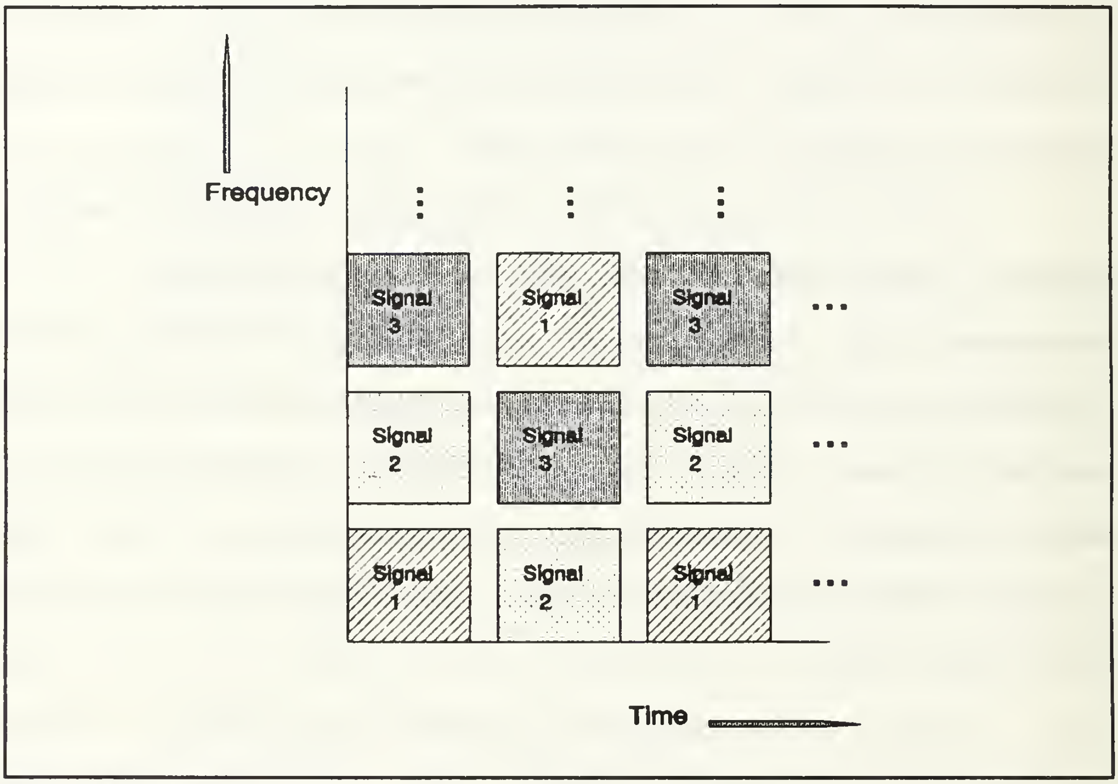

Figure 13. FH-CDMA [Ref. 33: p. 491]

FH-CDMA was originally devised for the purposes of communication jamming resistance, but the system also provides for several other advantages [Ref. 33:p. 493]:

1. *Flexibility.* Compared to TDMA systems, no time coordination is required among the various simultaneous users.

2. *Resistance to Fading.* Since a subscriber's signal never occupies one particular frequency band for any appreciable duration, it's very unlikely that quality will degrade even if fading conditions exist. Fading is usually a frequency-specific phenomenon, and it's unlikely that fading conditions will concurrently exist throughout the entire bandwidth that a particular signal is "hopping" within.

3. *Security.* FH-CDMA provides a reasonable degree of transmission privacy since the pseudonoise code is required to identify a particular signal.

4. *Capacity.* There is no fixed limitation on capacity in a FH-CDMA system. As the number of subscribers increases, the voice quality will gradually decrease, but no subscriber is ever "blocked." This feature is also known as a "soft capacity limit."

Direct-sequence CDMA (DS-CDMA) is the second category of spread spectrum multiple access to be considered in this section. This particular technique was developed by researchers at ITT to provide reliable, secure military voice communication [Ref. 7:p. 351]. DS-CDMA combines the subscriber's signal with another signal produced by a random-sequence generator to form a random, high-rate bit stream covering the entire assigned spectrum. As shown in Figure 14, each DS-CDMA signal shares the same frequency spectrum [Ref. 31]. At the receiver, this random sequence is separated using a correlator, and the subscriber's signal is available for processing.

Each subscriber's transmission occupies the entire bandwidth, but each also possesses its own code. Figure 14 illustrates this concept in both the time and frequency domains [Ref. 31]. The processing gain, which permits effective use of very low signal-to-noise ratio signals, can be calculated by computing the ratio of the channel bit rate to the information or voice-coding bit rate [Ref. 7:p. 355].

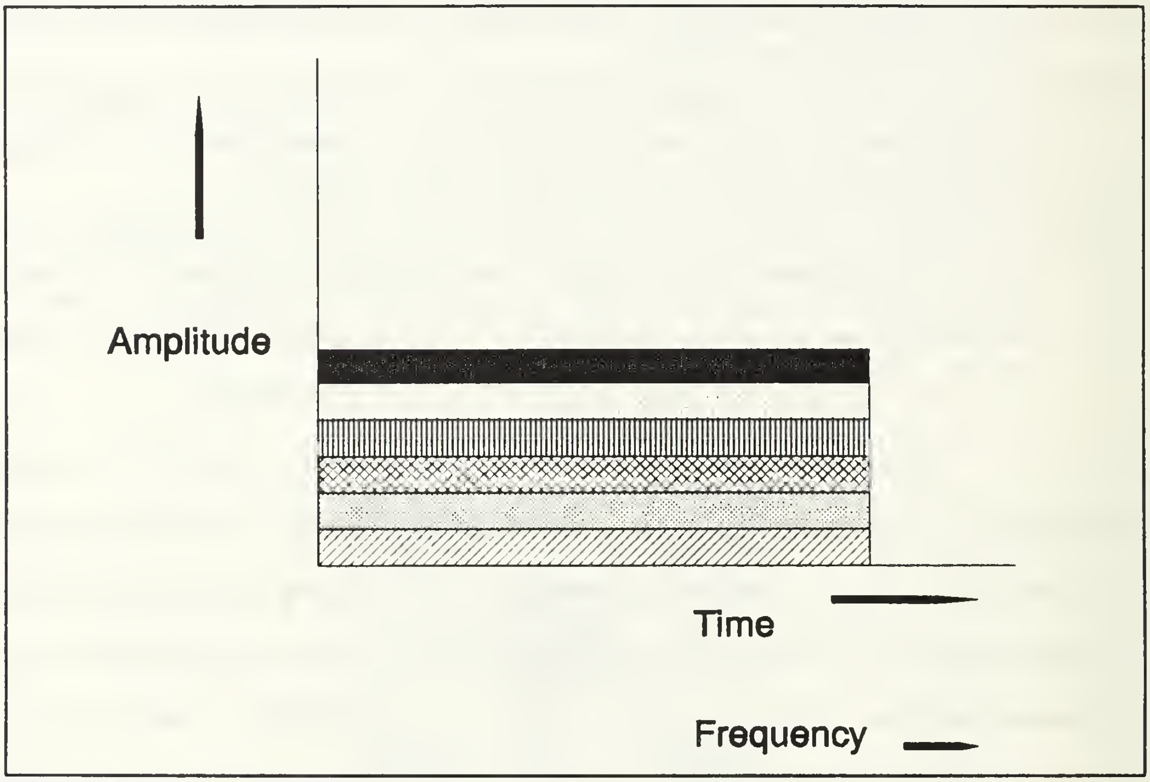

Figure 14. DS-CDMA [Ref. 31]

DS-CDMA systems enjoy the same benefits described earlier for FH-CDMA systems. Proponents project capacity limits 20 times greater than those of analog FM systems, and they feel that CDMA systems are capable of coexisting with current analog FM cellular systems. Additionally, the handoff procedure for CDMA systems is much simpler than in others. Synchronization of a frequency change is not required for CDMA systems. Because of the inherent CDMA processing gain, the transmitters for CDMA cell sites can be of much lower power levels. [Ref. 31]

One of the problems for cellular applications of DS-CDMA is the "near-far" phenomenon. Dr. Donald Schilling explains this by considering several users in a particular cell, each simultaneously transmitting to a particular cell site. The closer the user is located to the cell site, the larger the power received there; therefore, the closest user would be received most clearly, and the others would endure greater reception distortion as their distances to the cell site increased. To solve this, adaptive power control (APC) is employed so that each subscriber's transmitted power is adjusted, resulting in a nearly constant power received by the cell site. [Ref. 38]

C. SYNOPSIS

Today, FDMA is rarely mentioned as a serious alternative for digital cellular. The CDMA experiments that have recently commenced have shifted the focus from a TDMA versus FDMA debate to one between TDMA and CDMA. Industry inertia and politics probably favor TDMA at this writing, despite the potential of CDMA.

IMM has allied itself with Hughes Network Systems, a subsidiary of GM Hughes Electronics, for marketing its TDMA Ultraphone. This system is being used to provide Basic Exchange Telecommunications Radio Service (BETRS) for rural service areas (RSA) [Ref. 39]. The results have been successful with the Ultraphone digital radio yielding 80 simultaneous telephone circuits per megahertz of spectrum. This is 16 times more efficient than current analog FM cellular [Ref. 40].

Dr. George Calhoun, who is affiliated with IMM, states in his book, ***Digital Cellular Radio*** [Ref. 7:p. 357]:

> The era of spread spectrum techniques has not yet arrived for commercial mobile telephony. It is likely, however that with major continuing advances in digital-processor technology over the next ten years spread spectrum will command increasing interest from mobile-systems architects. It is likely, in my opinion, that spread spectrum concepts will be important in the third-generation systems that may begin to emerge in the latter part of the next decade.

However, experiments with CDMA may be progressing faster than Calhoun predicted. Qualcomm and PACTEL Cellular have been jointly experimenting with DS-CDMA, and their results so far support CDMA for cellular application. Qualcomm reports that recent CDMA field tests in San Diego, California, proved that CDMA can handle cellular handoffs and as well as the "near-far" problem [Ref. 41].

The CTIA currently has a CDMA study group with 9 carriers participating; however, recent remarks suggest that the CTIA would prefer to adopt TDMA now, and continue CDMA research for future applications. CTIA executive director Robert Maher recently commented, "It's time to shoot the engineers and go to market. [Ref. 32:p. 8]" Indeed, this is exactly the approach that the FCC has prescribed: promote experiments with new digital technology and let the market determine which is most appropriate. Because of the apparent momentum for TDMA, cellular analyst Herschel Shosteck predicts that it will be selected as the standard in mid-1992 [Ref. 32].

This does not imply that CDMA will be discarded for digital radio. The third-generation cellular systems that Calhoun referred to include new microcellular radio, and Personal Communications Services (PCS). Efforts are in full swing to bring these technologies to market as soon as possible. Additionally, NYNEX is testing radio alternatives to copper wire for access to the local loop. Trials, using CDMA technology, will start in both Boston and New York City during 1991 [Ref. 42].

The FCC and the NTIA have been reevaluating the frequency allocations for wireless communication in light of the rapid emergence of microcellular PCS. In the next chapter, the reader will be introduced to microcellular concepts and systems.

VI. PERSONAL COMMUNICATION SERVICES (PCS)

A. INTRODUCTION

The PCS concept is just now beginning to take shape. An exact definition of PCS has yet to materialize nor will a unique explanation surface until many regulatory and technological issues are more fully addressed. Consider the following PCS definitions recently taken from communication journals:

1. PCS encompasses a broad range of radio communications services that free individuals from the constraints of the wireline public switched telephone network and enable them to communicate when they are away from their home or office telephone. [Ref. 43]

2. With PCS, we can communicate from person to person, regardless of where we are physically located. While PCS as a class of services embraces a wide range of capabilities, from simple paging and telephony to more advanced functionality, the basic benefit is the ability to communicate from virtually anywhere to virtually anywhere else. [Ref. 44]

3. PCS is a service not a particular technology. PCS draws on the technologies of digital modulation, cellular and cordless telephones, and sophisticated network protocols. Most PCS proposals envision a portable lightweight instrument providing users with access to a ubiquitous public network. [Ref. 45]

4. PCS is a generic term referring to mobile communication services in which the user possesses a personal handset or cordless telephone that can be used in a number of pedestrian, office, and possibly residential and vehicular settings. [Ref. 46]

In the second section of this chapter, the terminology and key features of several different types of PCS proposals will be presented. The reader will gain an understanding of how the terms CT-2, CT-3, Digital European Cordless Telephone (DECT), Universal Personal Communications Service (UPCS), Personal Communications Network (PCN), Telepoint, and Business Cordless Telecommunications (BCT) relate to the overarching concept of PCS. In all cases, a digital radio link will serve subscribers in a microcell, or in the case of DECT, a picocell. The concept of PCS will become reality as these microcellular systems are attached in some way to a backbone network.

The FCC released its Notice of Inquiry (NOI) into the development and implementation of new personal communications services on June 28, 1990. In reply, over 100 companies filed comments [Ref. 47]. Respondents' opinions differ as to exactly how this new category of communication services should be regulated. Many dispute whether PCS should be regulated as a separate service or be included as part of the cellular regulatory environment. PCS providers must also find some portion of the valuable RF spectrum in which to operate. After some general PCS terminology is covered in the next section, these regulatory issues will be covered in the third section of this chapter.

In this chapter's concluding section, the regulatory questions, the technical issues, and the political forces will be considered collectively. The author will provide his opinion about the future of PCS as it pertains to communications planning and management.

B. TERMINOLOGY

1. CT-2

The moniker CT-2 is used to refer to the standard of second-generation digital cordless telephones developed by manufacturers in Great Britain. CT-2 telephones are small, relatively inexpensive handsets that can be used to make outgoing calls from the subscriber's home, office, or certain public access areas. When used from public access areas, the service is referred to as "Telepoint" [Ref. 43:p. 3].

The United Kingdom has licensed four telepoint service carriers who have just recently commenced operations. The United Kingdom's Department of Trade and Industry adopted a common air interface (CAI), MPT 1375, during May of 1989 so that CT-2 transceivers can operate in all licensed systems [Ref. 43:p. 5]. CT-2 employs FDMA as a multiple access scheme, and each of the four carriers operates in the 864-868 MHz region, which is comprised of 40 100 kHz channels [Ref. 46:p. 2]. The reader will recall from Chapter V that FDMA imposes serious adjacent channel limitations on system operators, and these limitations restrict the capacity potential of CT-2 systems.

Telepoint service is accomplished through base stations, or mini-cell sites known as public access points (PAP), that are constructed in high-traffic public areas such as airports, shopping malls, and restaurants [Ref. 46:p. 2]. Communication within a range of about 100 meters of the base stations is possible under CT-2, but the drawback of this system is that subscribers are unable to receive calls, merely place outgoing calls [Ref. 48].

Another disadvantage of the current CT-2 system is that cell-to-cell handoffs are not possible, so the subscriber is confined to a relatively small area during the course of the conversation [Ref. 49]. This renders the system virtually a wireless payphone, permitting the subscriber to make calls within the microcell boundaries of the telepoint base station. Of course, CT-2 differs from payphone service in that the calls are routed through the local exchange networks and subscriber billing is based on airtime usage as is done with cellular [Ref. 50]. To alleviate this shortcoming, some subscribers also carry a pagers, which inform them of the phone number of the person trying to establish voice communication. A subscriber who has been paged could then walk within about 100 meters of the nearest telepoint base station and call the party who paged him [Ref. 51]. Some CT-2 handsets are equipped with a built-in pager for this purpose, a feature referred to as "Meet Me."

In the United States, several companies are experimenting with CT-2 systems. Cellular 21 has applied for use of the 940-941 MHz bandwidth for a nationwide CT-2 system, and Bell Atlantic Mobile Systems has commenced a technical trial of CT-2 in Philadelphia [Ref. 52]. Cellular General was granted authority to experiment with CT-2 units near Deerfield Beach, Florida in late 1989 [Ref. 46]. However, the majority of U.S. interests rests outside of CT-2 in the proposals of CT-3/DECT and PCN.

2. CT-3/DECT

The European Telecommunications Standards Institute (ETSI), which has recently taken over the job of defining wireless European standards from the Conference Europeanne des Administrations des Postes et des Telecommunications (CEPT), has established DECT as the European standard for digital cordless telephones [Ref. 53]. DECT specifies a TDMA multiple access scheme where 12 subscribers share one carrier frequency [Ref. 54]. Before the marketplace sees full-fledged DECT systems, somewhat similar CT-3 systems will most likely be fielded, such as Ericsson's DCT900. CT-3 also uses TDMA; Table I compares the specifications for the CT-3 DCT900 system of Ericsson with those of DECT systems [Ref. 51:p. 8]. The major improvement with CT-3 compared to CT-2 is that two-way calling is supported, so the subscriber may also receive incoming calls. Some analysts have predicted that this feature alone may spell the demise for CT-2 if DECT/CT-3 service can be economically provided.

Table I. COMPARISON OF CT-3 AND DECT [Ref. 51: p. 8]

Parameter	DCT900 (CT-3)	DECT
Frame Length (time):	16 milliseconds	10 milliseconds
Number of Duplex Channels per Frame:	8	12
Number of Time Slots per Frame:	16	24
Overall Data Rate:	640 kbps	1152 kbps
Radio Channel Bandwidth:	1 MHz	1.728 MHz
Speech Data Rate:	32 kbps	32 kbps
Operating Frequency:	800-1000 MHz	1.88-1.9 GHz

DECT/CT-3 appears to be best suited for the wireless Private Branch Exchange (PBX) application where the individual coverage area is a picocell with a 30 to 100 meter radius [Ref. 51:p. 9]. The benefits associated with applying CT-3/DECT to the PBX environment include [Ref. 53:p. 3]:

1. No public network is required, since the subscribers will be using their own customer premise equipment (CPE).

2. From a marketing standpoint, the price entry barrier problem is minimized with PBX users.

3. A wireless PBX would solve the reconfiguration problems and costs that PBX managers face.

4. Mobility, important for most PBX users, is provided.

Such systems will be more sophisticated than CT-2; DECT systems will permit seamless handoffs among the numerous contiguous cells of the system. Ericsson describes the picocells in three-dimensional terms since many DECT systems will located inside multi-level buildings. Voice quality will be better than that of CT-2 since TDMA is used, and channel availability will be improved since dynamic channel allocation (DCA) is employed. DCA permits all available channels to be used in every cell so that the same channel can be used for different calls in adjacent cells. But, most importantly, CT-3 technology, through its wireless access to the PBX and its intelligence, will provide "find you anywhere, anytime if that is what you want" service [Ref. 51:p. 6]. Wireless PBXs as envisioned by Ericsson are also referred to as business cordless telecommunication (BCT) systems [Ref. 54:p.718]. CT-3 should support more than 150,000 terminals in one cubic mile of a three-dimensional area [Ref. 55].

Perhaps the biggest drawback to CT-3 and DECT compared to CT-2 is timeliness of availability. Some analysts believe that ISDN features may not be available in CT-3 for several years. The European Commission has stated that voice-only units could be introduced in short order, while adding the higher level capabilities at a later date [Ref. 56]. However, Colin B. Buckingham of Ericsson Paging Systems, states that CT-3 products employing DECT technology will be introduced during 1990, and will provide full wireless PBX capability. Additionally, he states that such products will also be available for telepoint service during 1990. The major difference between these products and DECT systems is the operating frequency. Full DECT systems will be operating in the 1.6 to 1.9 GHz range, while Ericsson's CT-3 systems will use the 900 MHz band [Ref. 53:p. 8]. Additional information regarding regulatory matters of CT-2, CT-3, and DECT will be included in Section C of this chapter.

3. PCN

One of the events that prompted the FCC's release of its PCS NOI of June 28, 1990 was the petition by PCN America, a wholly owned subsidiary of Millicom Incorporated, for the FCC to allocate radio frequency spectrum for PCN service. Millicom is a member of one of the three consortia that were recently awarded PCN licenses in the United Kingdom [Ref. 57]. This consortium, which is headed by British Aerospace, was awarded the first license to operate a national PCN in the U.K. In the U.S., the FCC has issued experimental licenses to PCN America, hereafter referred to as

Millicom, for the construction and operation of PCNs in both Houston, Texas and Orlando, Florida. The reason that these two cities were chosen is related to the innovative approach that this company has taken in search of RF spectrum. Millicom hoped to demonstrate that a spread spectrum DS-CDMA PCN can coexist in a frequency band already used by others without interfering with these existing users or have them interfere with the PCN [Ref. 38:p. 1]. The FCC selected Houston and Orlando for this Millicom experiment because these two cities already have a heavy volume of microwave traffic in the frequency region proposed by Millicom (1.85-1.99 GHz) [Ref. 58].

Millicom and SCS Mobilecom have recently formed a joint venture to develop and hold intellectual property rights for PCNs in spread spectrum technology with the overall objective of establishing the technological base for commercial, competitive PCNs in the U.S. The recent results of a detailed study undertaken by SCS Mobilecom, under the direction of Dr. Donald L. Schilling, indicate that PCN can successfully function on a co-primary basis with both present and future microwave licensees of the existing allocation of the 1.85-1.99 GHz band [Ref. 59]. The remainder of this section will be used to describe the PCN model proposed by Millicom.

Millicom's microcellular PCN system is the most sophisticated PCS proposal to date. Through the use of pocket-sized handsets, smart cards, and advanced signaling protocols like signaling system (SS-7), the PCN will provide integrated services including voice, data, and image delivery [Ref. 43:p. 6]. Millicom maintains that their PCN will be more than a wireless extension of the existing PSTN; PCN will be a self-contained intelligent network that is capable of offering voice and data services not possible under existing wireline and mobile communications networks [Ref. 37:p. 9]. Millicom designed their PCN around the following fundamental concepts:

1. The network should link persons, not stations.
2. The network should provide sufficient bandwidth for voice, data, and image transmission on demand.
3. The network should make the most efficient use of the RF spectrum.

Figure 15 depicts the structure of such a PCN [Ref. 37:p. 14].

The microcell base stations in Figure 15 are analogous to cell sites of the current AMPS cellular systems. In the PCN environment, these base stations might be located along pedestrian walkways, within residential neighborhoods, or on separate floors of office buildings. When serving mobile subscribers, the PCN will provide seamless handoffs between microcells. As in other cellular systems, the size of the microcell will depend on the density of the subscriber population, base station power level, and area propagation characteristics. Because the microcells will be much smaller

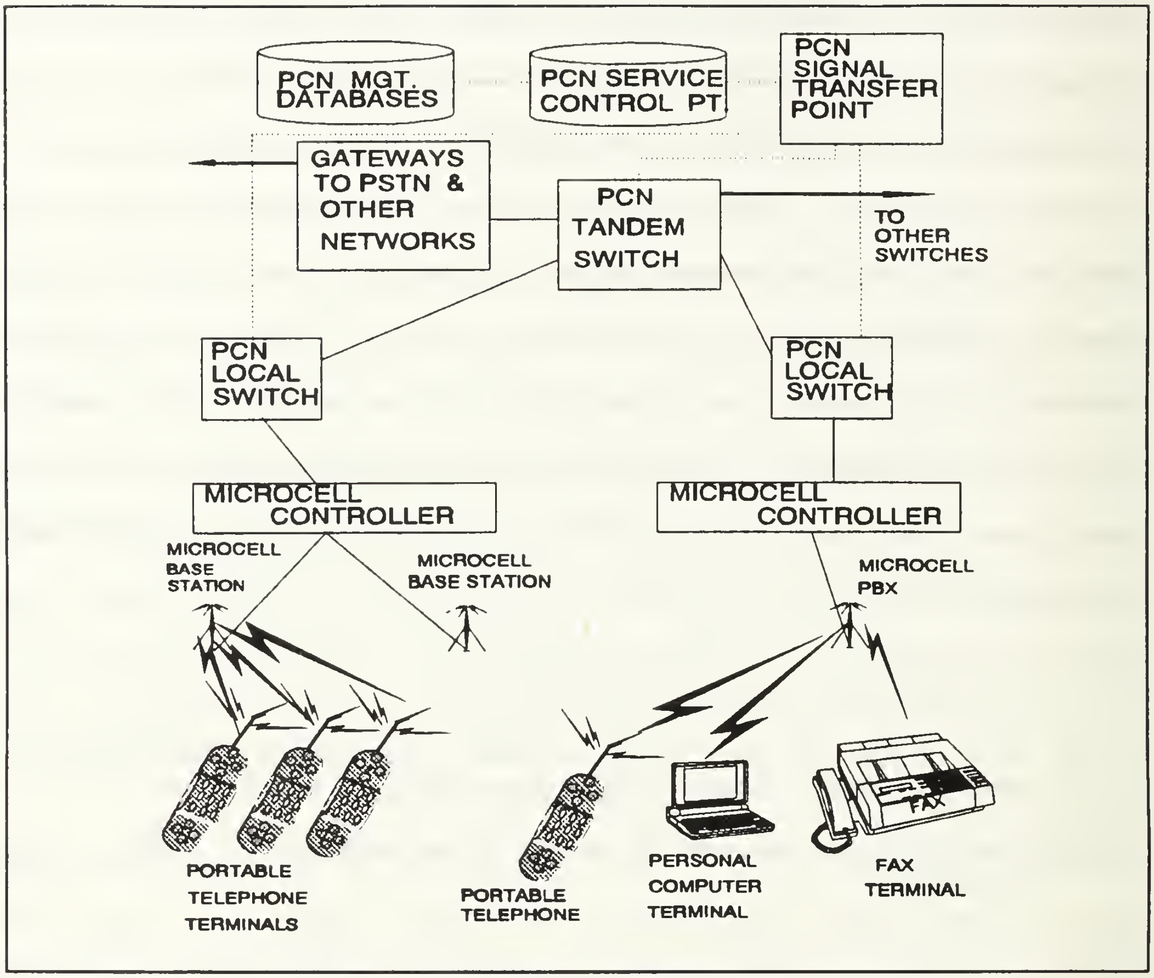

Figure 15. PCN Topology [Ref. 37: p. 14]

than cells of the current AMPS system, the radio handsets will require less battery power and should be cheaper than current AMPS mobile units. [Ref. 37:p. 11]

The dotted lines in Figure 15 represent control paths, while the solid lines are call paths. PCN system architecture will be based on a modified form of the SS-7 protocol so that PCN will be supported by SS-7's Application Layer [Ref. 37:p. 12]. SS-7 will permit features like selective call ringing and rejection, virtual private networks, wide-area Centrex, and ISDN capabilities. The "transaction capabilities part" of SS-7 gives the service provider access to a database for information on how to handle a call [Ref. 37:p. 12]. The "end user" part of SS-7 allows transmission of the information, such as calling party identity or billing data, through the network on an end-to-end or switch-to-switch basis. Millicom also envisions the use of "smart cards" that will be encoded with subscriber information. In this way, a subscriber can utilize *any* PCN handset, and the SS-7 features of PCN will provide the network with the location of that subscriber as well as the services and features that he rates [Ref. 37:p. 13]. Billing functions will be handled with SS-7 also.

The radio link between the subscriber terminal and the microcell base station is DS-CDMA, as described in the previous chapter. The microcell controller manages the functioning of the base stations and coordinates intercell handoffs. PCN network switches, which are supplied intelligence via an SS-7 overlay signaling network, transfer calls between microcell controllers. Management databases supply billing information and access data to the appropriate parts of the network via the signaling overlay. Although calls initiated on the PCN network can be terminated on the network, the PCN will also be capable of interconnecting with the PSTN as well as other voice and data networks. [Ref. 37:p. 15]

The SCS Mobilecom research cited above has shown that the PCN spread spectrum system can coexist with those point-to-point microwave facilities operating at 1.85-1.99 GHz as long as they are operating at data rates of T-1 (1.544 Mbps) or less. Dr. Schilling maintains that there is no realistic likelihood of harmful interference from PCN to any non-video microwave users in the proposed RF spectrum. His analysis assumes that PCN users would be operating at one milliwatt within a conservative 20 degree beamwidth of the microwave receiver. His study also revealed that 50 MHz minimum is required for transmitting and for receiving so that effective signal spreading can take place. [Ref. 59]

4. Other PCS

a. Personal Telephone Service (PTS)

Unrelated to efforts by Millicom, NYNEX recently announced another DS-CDMA PCN-type system, called Personal Telephone Service (PTS). This $100 million project slated for the Manhattan area of New York will use equipment from Qualcomm, whose CDMA experiments were mentioned in Chapter V [Ref. 60]. NYNEX is expected to offer the service in late 1991, and both subscriber equipment and calling charges are expected to be half those of conventional cellular. The network is intended for use by pedestrians using small, portable handsets [Ref. 61]. Some analysts have speculated that NYNEX's successful deployment of a CDMA system may "break the ice" for other CDMA applications.

b. Bellcore's Generic PCS

During March of 1990, Bellcore released its technical advisory, ***Generic Framework Criteria for Universal Digital Portable Communications Systems (PCS)***. Bellcore published this document both to inform the industry of its preliminary views on PCS and to solicit industry comments on these views [Ref. 62]. Bellcore advocates TDMA over both FDMA and CDMA for their plan, which includes the following details:

1. The frame period shall be 16 milliseconds with 40 independently assignable time slots per frame.
2. Bit rate shall be eight kbps per time slot.
3. Each time slot will contain 19 system control bits, 14 error detection and synchronization bits, two bits for differential encoding, and 128 bearer bits.
4. Total bits per time slot shall be 180.
5. The TDMA architecture will permit user selectable data rates up to 144 kbps, and the PCS will provide transparent data service to the user.

The Radio Port employing TDMA will provide the interface between the radio link and the fixed network facility. It will be capable of serving from 50 to 100 users per RF channel [Ref. 62:p. 33]. PCS services could be developed to operate anywhere within the .4 to 4 GHz region [Ref. 62:p. 3]. Bellcore believes that functionality can be provided either in the Ports or at the Network Interface Unit (NIU). Figure 16 portrays the PCS topology as envisioned by Bellcore.

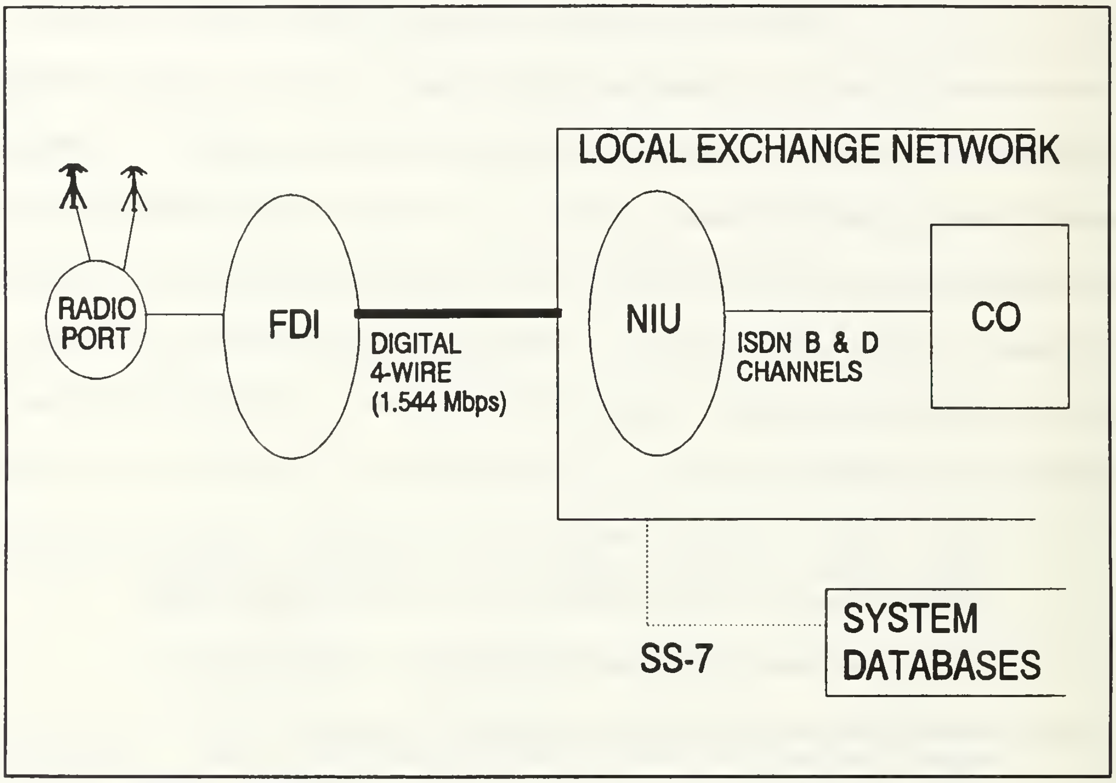

Figure 16. Bellcore PCS Standard Interfaces

In Figure 16, the Feeder Distribution Interface Unit (FDI) multiplexes 450 kbps Radio Port outputs to T-1 rate for transmission over cable, fiber, or microwave [Ref. 62:p. 39]. The FDI also provides DC power to the radio ports. The Network Interface Unit (NIU) demultiplexes between T-1 rates and the 450 kbps line rates, performs encryption and decryption to provide privacy between the Radio Port and the portable unit, performs dynamic call transfer or call rerouting, performs echo cancellation if necessary, and also performs maintenance and operation checks [Ref. 62:p. 40]. The central office (CO) is also depicted in Figure 16.

Bellcore states that the following architectural issues must be addressed before PCS can be offered to the public [Ref. 62:p. 40]:

1. Narrowband ISDN compatibility.
2. Billing.
3. Compatibility with International and North American numbering plans.
4. Minimizing disruption of both data and voice during automatic link transfer.
5. Providing service when away from the home area.

In their PCS technical advisory, Bellcore reminds readers that each Bellcore Client Company may have requirements or specifications different from the generic descriptions described above. The document is intended to initiate dialogue with the telecommunications industry on the preliminary aspects of PCS criteria.

C. REGULATION OF PCS

1. Industry Structure

One of the issues about which the FCC requested comments is "whether and how the (PCS) services should be regulated [Ref. 43]." To appreciate just how contentious this issue has become, consider the following responses from various industry officials:

1. From Richard J. Lynch, Vice President of Bell Atlantic Mobile Systems:

   It is Bell Atlantic Mobile Systems' view that PCN is not a separate service or technology or product, but simply a logical evolution, a later generation of cellular technology [Ref. 27:p. 56].

2. From J. Shelby Bryan, Chief Executive Officer of Millicom:

   In my view, PCN should be regarded as an alternate telephone network. This approach to PCN establishes the need for a policy debate on how the U.S. will define the provision of communications services...PCN provides the technological basis which will enable practicable competition at the local loop level [Ref. 63].

3. From Richard B. Snyder, AT&T's Cellular Business Development Director:

   I fundamentally believe that PCNs are going to be the first serious means of competition for local communications...The technology involved will someday threaten the existing monopolies of local telephone companies [Ref. 58].

4. From Ian M. Ross, President of AT&T's Bell Laboratories:

   It is premature for any government to determine what PCS-type services are needed. Given the multiple technologies and services being tested in the global marketplace, the public interest would be best served by allowing marketplace competition to determine the evolution of PCS [Ref. 49].

The four statements above indicate the four possible directions that the FCC could take in its regulation of PCS:

1. Regulate the emerging PCSs as natural extensions to cellular; that is, wait for the existing cellular carriers to offer the PCS features described in this chapter.

2. Create a separate, new industry for PCS as the FCC did in the early 1980s with cellular radiotelephony.

3. Regulate PCSs with local exchange carriers (LEC). Instead of copper wire to the residence, the LECs could employ digital radio tails.

4. Adopt a laissez-faire orientation; the FCC could apply a "hands off," pure free-market approach, and permit carriers to offer PCS service as the technology evolves.

Dr. Donald C. Cox, Division Manager of Radio Research at Bellcore, provides several reasons why the first option is inappropriate. First, he notes that even the coming digital cellular schemes are optimized for relatively high-power vehicular applications, and are not suitable for small, low-power, long-usage-time personal communicators [Ref. 64]. Cox also points out the lack of available spectrum for cellular operators to support both high-power and low-power users simultaneously. Even when technological advances in voice coding and multiple access are considered, he believes that the current cellular mobile radio spectrum will likely be "overstressed" just serving the vehicular market [Ref. 64:p. 19]. Nonetheless, responding to the NOI, the CTIA apparently disagrees [Ref. 27:p.56]:

> CTIA sees PCS [PCN] and cellular service as being indistinguishable. Any effort to portray PCS as a technically or commercially separate service from cellular is unrealistic and unlikely to succeed in the marketplace.

The second option of creating a new market segment for PCS providers has been discounted by those who believe that it is premature for any government agency to determine which PCS services and technologies are needed [Ref. 49:p.

41]. The author is reminded of criticism by some analysts of the FCC's past prescription of analog FM for AMPS cellular at a time when digital technologies were taking off [Ref. 7]. Even the FCC, under the leadership of Chairman Sikes, has publicly stated its desire to avoid impeding technological progress by imprudent regulation. The potential for "misregulation" may be reason enough to eliminate this option.

Recent announcements by NYNEX make the third option seem possible. NYNEX has requested experimental licenses from the FCC to test the use of digital radio communications for local telephone links [Ref. 65]. It plans to test both CDMA and TDMA technologies in the areas of New York City and Boston. Additional insight by Cox also supports LEC control of PCS. Since PCS will require intelligent networking, LECs may be very well suited to provide this network infrastructure [Ref. 64:p. 19]. The local exchange network is comprised of many central office switching centers and dense distribution networks that provide intelligent network services to telephone customers [Ref. 64:p. 19]. However, Millicom counters that telephone companies have been slow to deploy SS-7, and in many cases, SS-7 plans are still on the drawing board [Ref. 59:p. 7]. Millicom also points to the potential for competitive pressures to qualitatively enhance local telephone service if PCN is allowed to emerge separately from LEC regulation.

Some experts believe that free market approach may be in the best interest of the consumer in view of the current pace of digital radio technology. Some companies have conceived of innovative PCS ideas free from regulatory supervision. In addition to the PCN proposed by Millicom in this chapter, this company has signed an agreement with Cable TV Laboratories to explore the technical and economical feasibility of using the cable industry's infrastructure to develop and deploy PCN services in the United States [Ref. 66]. By letting the competitive forces determine the technologies and services, the optimal PCS systems will be developed over the long-run. Two possible weaknesses of this option are the requirements for interface standards and the potential for inefficient, rushed PCS development that may cause short-term growing pains as well as wasted resources.

Whatever regulation the FCC promulgates for PCS, the author hopes that calls for mandatory or "contrived" competition are economically analyzed. As the reader will recall from the last part of Chapter IV, the author believes that the duopoly market structure of AMPS cellular has caused higher subscriber costs than would have been set in a single-carrier-per-market structure. The author also believes the FCC should review its cellular licensing history before making any rulings, like holding lotteries for PCS licenses as it did for cellular radio. Comparative hearings would probably be more appropriate for determining PCS license allocations.

2. Spectrum Allocation

In the overall world of spectrum management, apart from the influence of just the PCS supporters, there is concern among many telecommunications officials that the American method of allocating RF spectrum is in dire need of change. Consider these recent comments from an NTIA administrator [Ref. 67]:

> NTIA would prefer to rely on incentives rather than administrative fiat, and we believe that the FCC could improve its performance in the same way. The right kinds of incentives would encourage licensees to consider not only their own equipment costs, but also society's opportunity costs, when they use radio spectrum.
>
> If both public and private radio licensees were given some form of property rights and authorized to sell their spare capacity, chances are that many of them would jump at the opportunity.

Those comments deserve consideration. Many mobile communications carriers are forced to use the most spectrum-efficient radio technology. While as much as 40% of the RF spectrum lies fallow, mobile radio carriers scramble for ways to squeeze more capacity in their existing allocation [Ref. 68]. To correct this, the NTIA official above recommends a market-oriented approach to RF spectrum allocation. Other recommendations include joint planning efforts between federal government agencies and the private sector [Ref. 40: p. 5]. Others suggest that the upcoming 1992 World Administrative Radio Conference (WARC) may allocate the 1.7 to 2.3 GHz band for PCN service, which is within the frequency region deemed appropriate for PCS by Bellcore. This allocation may work fine for countries like the U.K. where this part of the spectrum is not heavily used; however, in the U.S., that region is divided into five occupied bands [Ref. 69]:

1. The band from 1.710 to 1.850 GHz is allocated for government use.
2. The band from 1.850 to 1.990 GHz is allocated for private fixed microwave use.
3. The band from 1.990 to 2.110 GHz is allocated for auxiliary broadcast and cable television use.
4. The band from 2.110 to 2.200 GHz is allocated for public fixed microwave use.
5. The band from 2.200 to 2.290 GHz is allocated for government use.

Because of the delays that would be associated with attempts to provide PCS with a discrete or exclusive allocation, Millicom's proposal for sharing an allocation seems to hold some favor with FCC officials. Indeed, this may be the best short-term solution so that regulation does not further impede the progress of what is obviously a very high-demand market.

Telecommunications expert, Peter Huber, may hold the real, long-term solution. He believes that broadcast television should not occupy the RF spectrum since "couch potatoes sit still [Ref. 70]." He makes a compelling argument to free the spectrum for use by those who value mobile communications. The unmistakable trend has been for telephone service to take to the air while huge chunks of RF spectrum are held by "network television, determined to remain airborne when the forces of nature dictate otherwise [Ref. 70:p. 144]." Huber believes that the FCC should take the lead to encourage local airwave broadcasters to move their operations to cable, and perhaps even permit them to move into mobile telephony. Better, the author believes, to encourage and permit them to sell this RF spectrum after they move to cable. In the final chapter to this paper, the ramifications that future spectrum management efforts may have on government users will be treated.

D. CONCLUSION

While digital radio technological breakthroughs continually surface, the manner in which they might be incorporated in the PCS environment is difficult to predict. Recent studies indicate that consumer demand will support PCS applications. The Arthur D. Little consulting firm estimates that more than half of all U.S. households would like to purchase a "less expensive, cellular-like" telephone service by the year 2000 [Ref. 71].

This author believes that a DS-CDMA system, which shares RF spectrum with existing non-video microwave applications, currently offers the most promise; however, if European countries proceed with TDMA systems, or if these systems flourish in the U.S., truly universal PCS may be difficult to achieve. As VLSI advances keep shrinking the sizes of electronic components and their costs, perhaps it's not unreasonable to expect that future PCS handsets will be capable of operating in both CDMA and TDMA modes. As long as individual standards can be agreed upon for both CDMA and TDMA, truly affordable, universal PCS (UPCS) may be possible. Figure 17 provides two possible routes that might take us there [Ref. 71].

The target for both halves of Figure 17 is labeled UPCS for Universal Personal Communications Services. Analysts from Arthur D. Little believe that the flow chart shown in the top half of Figure 17 provides an accurate forecast for the evolution to UPCS by the year 2000. The author has used this model as a reference in deriving the diagram located in the lower half of Figure 17. Cellular-packet networks and satellite-cellular systems will be described in Chapter VIII.

Since both CT-3/DECT and PCN systems will be capable of providing cordless PBX services, a separate module for this application is not explicitly depicted, but is assumed to be implicit with the CT-3/DECT and PCN networks. Additionally, the microcell module listed in the Arthur D. Little flow chart

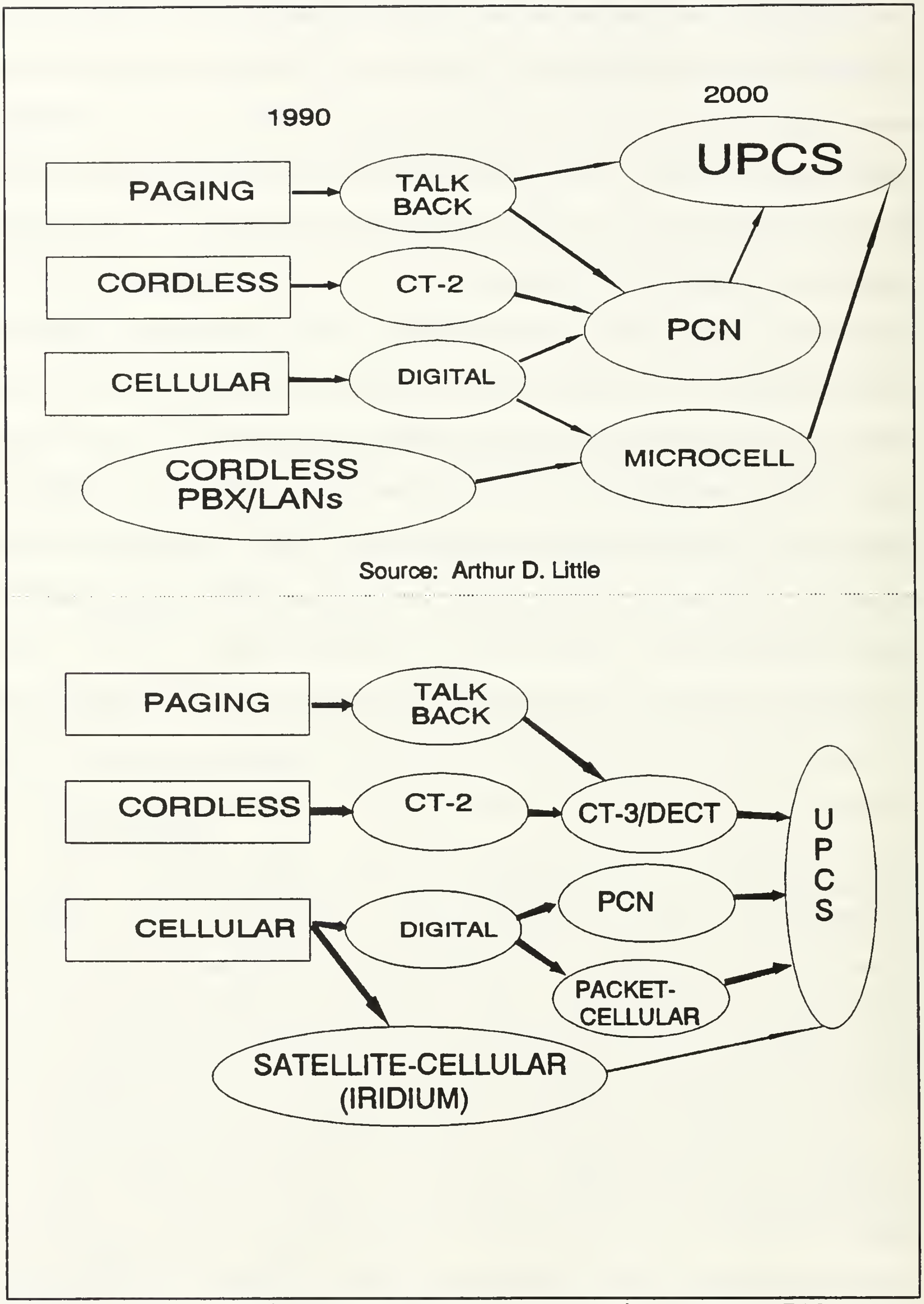

Figure 17. Possible PCS Market Evolution [Ref. 71]

is implicit with both CT-3/DECT and PCN networks, so it is not shown explicitly in the lower figure. The author believes that a single definition of the UPCS handset and communication system may never be seen; however, the distinction among the various PCS services and applications will continue to blur as time passes, making UPCS more like Virtual Personal Communication Services. As PCS services evolve, the handsets will shrink in size, and in this way, PCS evolution will eventually usher in full-feature, wristwatch-sized communication transceivers.

VII. CURRENT CELLULAR APPLICATIONS

A. MOBILE SYSTEMS

1. Voice

The majority of cellular subscribers and the predominance of the cellular industry's phenomenal growth rates described in Chapter I can be attributed to the vehicular cellular telephone market for voice communication. While it may appear natural that this would be the largest application area, several business practices have acted to hasten this already burgeoning market.

The prices of automobile cellular phones have dropped sharply since many dealers are now selling these phones below cost, and making their margin on the commissions that the carriers are paying them for cellular sign-up [Ref. 3:p. 4]. Rates have also dropped recently. In Southern California, the going rate for the automobile cellular user is a fixed $45.00 per month plus 45 cents per minute for calls. Cellular telephone systems will eventually provide mobile communications in 305 metropolitan areas and 423 less densely populated areas [Ref. 72]. Automobile cellular has become so pervasive that Hertz Rent-a-Car has installed 50,000 cellular phones in rental cars throughout the country, and

Chrysler has announced that selected 1991 Chrysler and Dodge automobiles sold in California will be available with cellular phones built into the sun visor [Ref. 73].

As of this writing, several companies offer portable cellular phones for less than $1,000. These devices have greatly expanded the mobile cellular voice field. Cellular portables fit easily in handbags, attache cases, and even shirt pockets, and as long as a subscriber travels within the boundaries of cell site coverage, he can initiate and receive phone calls on an uninterrupted basis. Portables may also be used as wide-area cordless telephones. Military and business officers who may be waiting for important calls can take these phones everywhere they go, whether it be to just another office in a building or to another city in the state. One disadvantage of these units is the lack of an interface to a cellular modem, so that data communication requires an acoustical coupler. However, at least one company has future plans to produce interfaces for two popular portables: the NEC P300 and the Novatel PTR800 [Ref. 74: p. 373].

A lower-priced alternative to the portable cellular unit is the "transportable." These units are typically packaged in a soft carrying case about the size of a small handbag. They are capable of transmitting at the full three-watt power level of vehicular cellular phones, and many offer an interface for a cellular modem. Since these units are also easily operated from vehicles without any special permanent installation, transportable cellular phones may be the best compromise solution for many users.

2. Data

Although data communication now accounts for only a small percentage of cellular traffic, this figure should grow, especially as portable computing becomes more popular and as the cellular industry prepares to implement digital technology, discussed earlier in Chapter IV. Current cellular modem sales figures suggest that only 15,000 subscribers are using cellular radio for data transmission [Ref. 74]. The primary reason for the relatively small amount of cellular data communication is that such transmission is relatively unreliable and, therefore, slow under the current analog system; nonetheless, for some special applications, cellular data communication can be practical using currently available cellular modems.

Problems encountered when transmitting data under the current AMPS system include noise, multipath fading, interference, and the brief interruption that occurs during the handoff process. While the human ear can barely detect the handoff, this hundred-millisecond or so blank period can destroy a large number of bits undergoing modulation. Robust error detection and correction schemes must be employed to compensate for this effect. The result is an effective data rate that is much lower than the modulation rate.

Spectrum Cellular, the first company to offer cellular modems, currently provides the following built-in error-correction protocols for its 2,400 baud cellular modem: SPCL, MNP 5, V.22, V.22bis, V.42, and V.42bis [Ref. 74:p. 366]. To connect any cellular modem or facsimile machine to a cellular phone, the RJ-11 phone plug and accompanying circuitry are required. Unfortunately, such cellular data interface units are still bulky and cumbersome to connect. The lone exception to this is Motorola's Cellular Connection, which weighs only 5 ounces and neatly attaches to the phone's handset cradle; however, this unit works only with Motorola cellular products. Industry experts cite this lack of standardization for cellular data-equipment connections as a major obstacle for the cellular data user [Ref. 74:p. 368]. Nonetheless, there exist a few applications where data transmission on the move is mandatory, and, in these cases, cellular may be the best answer. Several examples of these applications are listed in the remainder of this section.

a. *Emergency/Safety Communications*

During a recent experimental program by NYNEX Mobile Communications, a New Jersey ambulance crew was able to send electrocardiographs of a heart attack victim by cellular phone to Holy Name Hospital [Ref. 15:p. 138]. Insurance agents, serving customers in the aftermath of Hurricane Hugo on the eastern seaboard, used cellular modems and phones to expedite the processing of property damage claims. Some Northern California businesses successfully conducted cellular transfer of vital data after the San Francisco earthquake of 1990 crippled landlines and powerlines.

b. Mobile Office Systems

Spectrum Cellular Corporation is currently selling the LapPak portable office system, which consists of a laptop computer, cellular phone, and cellular modem; this entire package sells for under $5,000 [Ref. 15:p. 140]. A similar system to the LapPak, but one which is packaged in an attache case and capable of 9600 bps data rate, is available from Teleport Systems. One company, NovAtel, has taken the concept of a mobile office one step further. One of its main offices is a specially modified van equipped with five cellular phones, laptop computer, facsimile machine, and answering machine.

Facsimile (fax) transmission is often better suited for the cellular radio environment than standard data transmission because the Group III fax protocol was originally designed to operate over poor-quality phone lines [Ref. 74:p. 373]. This protocol lacks error correction capabilities, but fax documents are usually still readable with some lost data bits.

Intelligence Technology Corporation (ITC) offers a laptop computer with a built-in cellular modem, the only such model currently available. This modem uses a modified MNP 5 protocol using smaller block sizes that permit the many repeats necessary when transmitting over marginal radio conditions [Ref. 74:p. 376]. The user is spared the cumbersome chore of carrying an extra component and making additional connections when using this laptop.

B. FIXED SYSTEMS

In this section, no distinction will be made between cellular applications for voice and data. The data transmission limitations described in the previous section also apply to the fixed cellular environment, although multipath fading may be less of a problem since the subscriber is stationary.

1. Rural and Developing Area Applications

In some sparsely settled rural areas, cellular telecommunication is being used as an alternative to provide POTS [Ref. 75]. One example of such a system is the Total Access Communications System (TACS) that has been implemented in the United Kingdom and Ireland [Ref. 23]. TACS provides surprisingly high capacity, over 80,000 subscribers in a single service area, and when compared to low-density, wide-area, wire-based networks, the cost projections for cellular equipment are very attractive [Ref. 23:p. 518]. In China, Canada's Novatel Communications is installing a cellular system in the city of Chun King for approximately one-third the cost of a wireline system [Ref. 2:p. 123].

The United States is also using cellular for POTS in rural areas. On January 19, 1988, the FCC released its Report and Order on the provision of Basic Exchange Telecommunications Radio Service (BETRS) in place of conventional telephone service for rural areas [Ref. 39]. Fifty pairs of frequencies in the 800 MHz band were made available for this service, and the FCC also granted co-primary status in the 150 MHz and 450 MHz bands for BETRS. IMM's TDMA Ultraphone is being used for BETRS, and some experts believe that several million households will eventually benefit from this service [Ref. 40:p. 4]. IMM hopes to sell its Ultraphone system, the technical details of which were described in Chapter V, to both government and international customers.

In addition to the rural environment, areas suffering from inadequate communications systems that need prompt improvements may also be ideal candidates for cellular technology. Many developing countries fall into this category, including what was formerly known as East Germany. During a recent telephone interview, a Qualcomm representative reported that they were investigating the possibility of employing cellular technology for use in the local loop segment of that country [Ref. 41]. Cellular's prefabricated, modular components permit simple and quick installation at lower costs than those of wireline systems for overcrowded urban environments [Ref. 12:p. 49]. Cellular systems may also be attractive to developing countries because their flexibility permits progressive growth, thereby tailoring additional system upgrades to increases in system demand [Ref. 12:p. 49].

2. Contingency/Disaster Plan Applications

Some organizations have employed cellular phones as back-ups to the PSTN in their contingency or disaster plans. One organization, Sungard Recovery Services Inc., utilizes cellular phones as a vital part of the disaster recovery service that it provides to major U.S. corporations [Ref. 2:p. 123]. In the SunNet Cellular V service, if a fire or earthquake occurs and normal telecommunications service is lost, up to 50 cellular phones are made available to the victim, and incoming calls are routed to the disaster-struck company by Sungard using AT&T's call-forwarding service [Ref. 2:p. 123].

C. MOBILE SUBSCRIBER EQUIPMENT (MSE)

The U.S. Army's MSE program is designed to support the communications of a five-division corps covering an area of 150 km by 250 km. MSE's history can be traced back several decades when the Tri-Tac system was started. The Tri-Tac system was to provide tri-service tactical communication using existing analog components, but would also permit the use of digital technology as it became available by providing common standards [Ref. 76]. Under the original Tri-Tac plan, MSE was to be used only in forward areas; however, in 1982, the decision was made by the U.S. Army to use MSE from the corps headquarters down. A consortium led by GTE was awarded the MSE contract in 1985 [Ref. 76:p. 120].

Since MSE offers several features common to cellular systems, it is occasionally referred to as a cellular radio system; however, it is actually a circuit-switched network that includes optional packet switching capabilities [Ref. 77]. Since several technical journals have referred to MSE as a cellular system, it has been included in this section for the benefit of the reader. Some of the MSE features that are similar to cellular include:

1. Flexible voice or data communication to both fixed and mobile subscribers.
2. Automated frequency management and control analogous to that provided by cellular MTSOs.
3. Permanently assigned telephone numbers that remain valid for MSE subscribers no matter where they are connected to the network.

MSE will transmit voice, data, and image according to military specifications, with communications security provided on all radio channels [Ref. 78]. The equipment is divided into two categories: backbone equipment, which includes message switching and relay equipment, and user or subscriber equipment [Ref 78:p. 37]. MSE will be used to pass traffic through both existing U.S. and NATO communications systems.

Under MSE, a subscriber's telephone number is permanently assigned, and remains with that unit regardless of where that unit moves. MSE system control is provided by the Systems Control Center (SCC), which functions like cellular's MTSO. The SCC performs the following functions [Ref. 79]:

1. Systems engineering.
2. Frequency management.
3. Resource status monitoring.
4. Link and network monitoring.

The SCC provides the MSE system with the ability to locate a subscriber using a preset directory number; every subscriber's telephone number is stored in the SCC memory [Ref. 79:p. 3-33]. All frequency assignments for individual calls, including those on combat nets, are automatic and occur quickly.

MSE's counterpart to cellular's cell site is the Radio Access Unit (RAU), which provides the interface between subscribers and the MSE network [Ref. 80]. Each RAU is normally capable of supporting 25 subscribers who are able to call both fixed and mobile users without knowing their exact location on the battlefield. The subscriber's transceiver is called the mobile subscriber radiotelephone terminal (MSRT). If the user moves from one RAU's radio coverage area to that of another RAU, the user is automatically "reaffiliated" to the new RAU as long as a call is not in progress [Ref. 80:p. 14]. If radio communication is disrupted, a visual alarm on the MSRT as well as an audible handset tone alert the subscriber to the loss of contact condition. The system automatically "reaffiliates" with the nearest RAU within radio range [Ref. 80:p. 14]. Like the cell site, the RAU automatically limits the radiated power to a level just sufficient for effective communication, thereby reducing the probability of the transmission being detected by enemy sensors [Ref. 79:p. 3-53].

VIII. FUTURE OUTLOOK FOR CELLULAR

A. IRIDIUM

During June of 1990, Motorola announced its plans for a worldwide, digital, satellite-based, cellular personal communication system [Ref. 81]. Considered by many to be the most ambitious telecommunication project announcement of the year, this system is expected to cost over $2 billion to design and implement and is expected to be capable of serving up to five million subscribers [Ref. 82]. This satellite-cellular project was named "Iridium" by Motorola cellular radio engineer, Jim Williams, because its 77-satellite constellation reminded him of the 77 electrons encircling an atom, and the element Iridium has 77 electrons.

Each of the 700 pound satellites will orbit the earth at an altitude of 413 miles, an altitude far below the standard geosynchronous orbit of 22,300 miles, and each of the 77 satellites will operate 37 cells (arranged in a 7-cell reuse pattern) that will each span approximately 360 nautical miles in diameter [Ref. 82:p. 17]. Each cell is expected to be capable of supporting 150 simultaneous subscribers. This 413-mile-high orbit altitude was chosen for the following reasons:

1. Altitudes greater than 600 nautical miles would require expensive equipment shielding to protect the satellite from the radiation environment [Ref. 83].
2. The increased drag at altitudes lower than 200 nautical miles would cause excessive fuel requirements [Ref. 83].
3. The 413-mile orbit altitude reduces the deleterious effects of delay and echo, which are common to geostationary satellite systems.

The subscriber's signal is uplinked to the satellite at a frequency of 1.6 GHz, and downlinked to the base station at 1.5 GHz. Subscriber channel bandwidth is 8 kHz, and multiple subscriber access to the total available system bandwidth of 10 MHz is achieved through a TDMA architecture [Ref. 82:p. 17, Ref. 81]. Data transmission will be supported at a rate of 2,400 baud. Additional frequency spectrum is required for satellite-to-satellite "crosslinks" operating at approximately 20 GHz [Ref. 83].

When the Iridium subscriber places a call, the destination phone number and the subscriber's identification number are uplinked to the overhead satellite. This information is then "crosslinked" to another satellite, which downlinks the information to the base station, or "gateway," in the subscriber's home country. (Motorola expects to employ about 20 total gateways for the system, and these gateways will consist of standard cellular switches that will interface with PSTNs and local billing offices.) If the identification numbers are in order, the base station sends a message back to the second satellite, which crosslinks that message to a different satellite located overhead the destination party's country. This satellite then downlinks the radio signal into the gateway and then into the PSTN to the destination party. This destination could also be another Iridium subscriber, in which case the last satellite in the loop would downlink the radio signal directly to the destination party's Iridium handset. [Ref. 81]

Motorola does not intend for Iridium to be a substitute for existing cellular systems, nor does it expect it to become a local bypass system. It will most likely see application in parts of the world that are not covered by any mobile telecommunication system, and it will most likely see use by government officials, business executives, and field engineers [Ref. 81]. Iridium handsets are expected to cost $3,000, with monthly service charges of $50, and operating costs of three dollars per minute [Ref. 84].

Despite the forecasted $2 billion implementation costs, Motorola expects to financially break even with only 500,000 world-wide subscribers. Motorola has enlisted the support of several major satellite companies, including Inmarsat, the American Mobile Satellite Corporation, and Telesat Mobile Inc. Motorola is also negotiating with telecommunication operators in the U.K., Australia, Hong Kong, and Japan. Two demonstration satellites are expected to be launched in 1992, and full Iridium service is expected in 1996.

B. ISDN COMPATIBILITY

1. Cellular Access Digital Network (CADN)

In 1987, engineers from AT&T's Bell Laboratories proposed an architecture that would provide the signaling and control features of ISDN in a cellular radio network [Ref. 85]. They called this network the Cellular Access Digital Network (CADN), and it included a proposal for cellular ISDN standards at layers 1 (physical connection), 2 (data link), and 3 (messages) of the Open Systems Interconnection (OSI) model [Ref. 85:p. 23]. Layer 3 of the cellular ISDN would also have to accommodate the cellular functions of power adjustment and channel switching (handoff). The proposed cellular ISDN protocol for layer 2 would be analogous to ISDN's Link Access Protocol (LAP) on the ISDN D-channel, and would be called LAPC for Link Access Protocol for Cellular Control. The CADN proposal even includes a frame format for LAPC.

The physical connections of CADN would be comprised of "I" (information) channels and "C" (control) channels, analogous to "B" (bearer) and "D" (data) channels of ISDN. "I" channels would feature a data rate of 2 kbps, and "C" channels would have a data rate of .5 kbps. The authors of CADN propose that two "I" channels could be combined to form a V4 channel, capable of supporting 4 kbps transmission. Thirty-two "I" channels could form a V64 channel, which would be equivalent to ISDN's 64 kbps "B" channel. In the same fashion that ISDN defines multiple "B" channels forming an "H" channel, the authors of CADN propose that multiple cellular "I" channels would form a "V" channel. [Ref. 85]

To access the ISDN network, the CADN authors propose a digital MTSO. The network side of the CADN switch would have an information format conforming to the ISDN standards for "B" and "D" channels. Link termination on the CADN switch would provide translation between the radio transmission format and the public network format. The authors also describe the establishment of user-specific control (USC) channels for coordinating cellular functions and providing for ISDN features. These channels would be logically separate from the user information channels, and would be put into effect after call set-up to connect the subscriber's handset to the network. Subscribers whose handsets are idle would utilize common access and control (CAC) channels to communicate with the network for functions like paging and alerting. [Ref. 85:p. 25]

2. Cellular Packet Switching Network

Since 1987 when the CADN was first proposed, one of its authors, Dr. David J. Goodman, has recently proposed a different, "third-generation" wireless network architecture to correspond with ISDN. The proposed network is based on cellular packet switching, and the packet transmission method is referred to as packet reservation multiple access (PRMA).

Dr. Goodman notes that the second-generation cellular developments include three incompatible mobile telephone networks (the TDMA, CDMA, and FDMA systems described in Chapter V) and two incompatible cordless telephone systems. His cellular packet proposal reflects that his "vision of the third-generation is a unified mode of wireless access, merging today's cellular and cordless applications in harmony with twenty-first century information services [Ref. 22:p. 1272]." Decentralized control, accomplished with distributed network controllers instead of the single MTSO, and increased spectrum efficiency are two general rearrangements proposed for third-generation cellular networks. Five challenges of third-generation wireless systems are identified [Ref. 22:p. 1273]:

1. The capability to carry many information types.
2. The capability to serve a mass market in urban areas.
3. The efficient operation in sparsely populated rural areas.
4. The capability to operate indoors, outdoors, and within vehicles.
5. The capability to serve stationary as well as high-speed terminals.

Goodman's proposal is similar to CT-3 and PCN proposals in its emphasis on microcells of approximately 100 meters in diameter. It differs in its prescription of packet switching communication to support mixed information types, ease of information routing, and network evolution [Ref. 22:p. 1274]. The backbone of the cellular packet switch is the metropolitan area network shown in Figure 18.

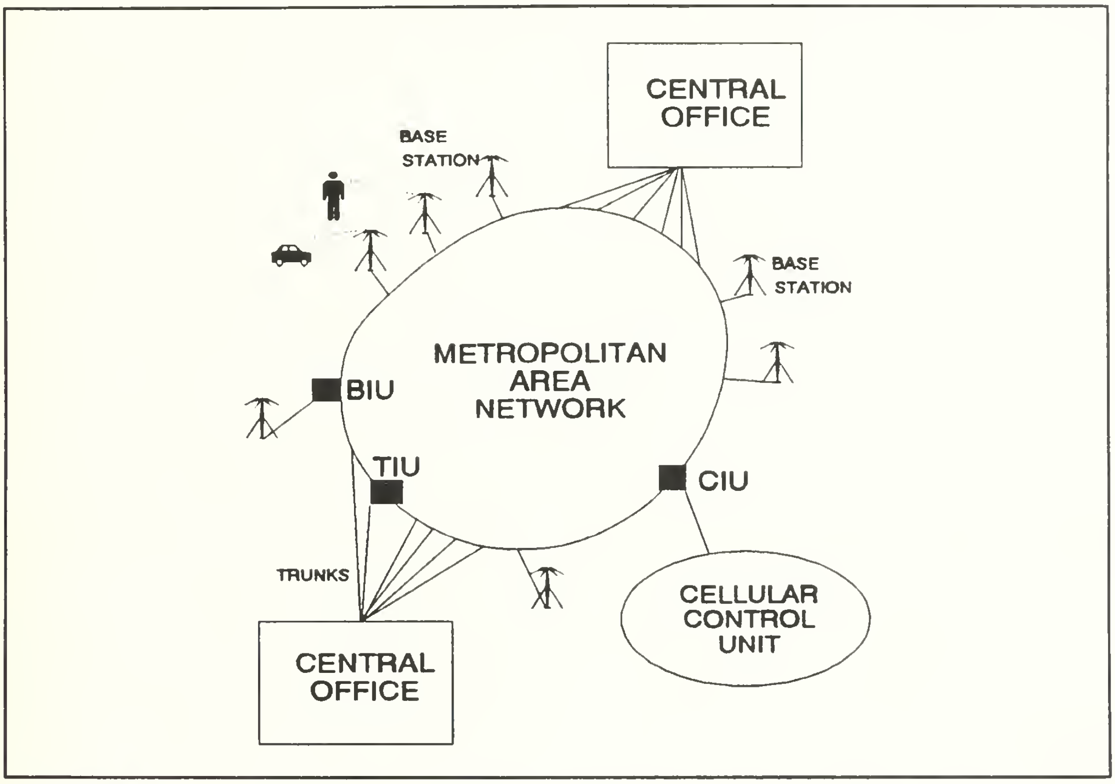

Figure 18. Cellular Packet Switch [Ref. 22:p. 1274]

The boxes labeled BIU, TIU, and CIU in Figure 18, correspond to base station interface units, trunk interface units, and cellular controller interface units, respectively. Each of these interface units performs network routing functions using the address field of each packet. Packets contain both a destination address and a source address. The TIU handles information in the standard format of the public network, and it contains a packet assembler and disassembler

(PAD). The TIU routes outgoing packets according to the base station identifier stored in its routing table. Virtual circuit identifiers are established for active subscribers by the cellular controller unit. [Ref. 22:p. 1274]

The Wireless Terminal Interface Unit (WIU) works like the TIU except that the WIU is connected directly to the information source. The WIU's packet assembler transfers packets to the radio transceiver via PRMA protocol processor control. The WIU accomplishes handoffs by monitoring channel quality to determine the base station identifier best able to serve the subscriber. The BIU acts as an information packet multiplexer for the packets sent to the radio transceiver, while the cellular control unit receives, processes and generates network control packets. [Ref. 22:p. 1275]

Since the cellular control unit is not involved in the handoff process, its performance is unaffected by the number of handoffs. As the reader will recall from Chapter VI, microcellular systems will require many handoffs. A handoff will only require that the TIU record a new base station identifier in its routing table. This feature should allow the cellular packet network to grow "gracefully" without straining its call management capability. [Ref. 22:p. 1279]

Dr. Goodman proposes that two TDMA architectures, GSM and DECT, be adapted for PRMA operation. Furthermore, he considers uniting PRMA with a distributed queue dual bus

(DQDB) of the MAN. PRMA is described as a combination of slotted ALOHA and TDMA:

> The channel bit stream is first organized in slots, such that each slot can carry one packet from a terminal to the base station. The time slots, in turn, are grouped in frames. Within a frame, terminals recognize each slot as being either *available* or *reserved* on the basis of a feedback packet broadcast in the previous frame from the base station to all of the terminals. As in slotted ALOHA, terminals with new information to transmit contend for access for available slots. At the end of each slot, the base station broadcasts the feedback packet that reports the result of the transmission. A terminal that succeeds in sending a packet to the base station obtains a reservation for exclusive use of the corresponding time slot in subsequent frames. [Ref. 22:p. 1276]

The entire DQDB packet would be transmitted over wireless channels, but in addition to the DQDB packet header, PRMA will also require additional bytes for synchronization overhead. Goodman then assumes two voice coding rates for each TDMA system, and he specifies a packet size of 69 bytes for each of the four configurations. The resulting data rate per channel is 270 kbps for each GSM system, and 672 kbps for each DECT system. His analysis suggests that these systems would achieve spectrum efficiency values 20 times greater than those of current AMPS systems. However, Goodman admits that a great deal of work must still be done to determine the following: how this architecture might serve a wide variety of information sources, what requirements will be imposed on the physical layer, and to what extent will it support the higher layers of advanced networks. [Ref. 22: p. 1279]

3. PCN for Wireless ISDN

Many of the third-generation network challenges identified by Dr. Goodman are being met, or at least they are actually being tested, by Millicom's PCN. The reader will recall from Chapter VI that the DS-CDMA architecture promises spectrum efficiency figures equal to the *predictions* of Dr. Goodman for PRMA. The difference between the two is that current PCN experiments have achieved data rates of 32 kbps, and 64 kbps is expected to be realistic for normal PCN service [Ref. 86]. Voice as well as data have successfully been carried over their PCN, and extensive testing will be conducted during the next few months in Houston, Texas, and Orlando, Florida.

The author believes that PRMA probably faces a long development road ahead. On the other hand, wideband CDMA PCN systems, like the one being developed by Millicom and SCS Mobilecom, utilize battle-proven spread spectrum technology, support ISDN basic rates, utilize the same microcellular concept proposed under PRMA, and perhaps, most importantly, are capable of sharing RF spectrum with existing microwave users. If the regulators permit PCNs to be offered on a commercial basis, the author believes that wireless ISDN requirements will be most immediately and practically satisfied by PCN, or even DECT systems.

C. WIRELESS NAVY BASE INFORMATION TRANSFER SYSTEM (BITS)

The Navy Data Communications Control Architecture (NDCCA) is the overall communication program designed to improve the effectiveness of current information transfer systems in the Navy [Ref. 87]. This program divides Navy communications into three sub-architectures: long-haul, afloat, and the Base Information Transfer System (BITS) [Ref. 87]. The BITS architecture will integrate existing, independent communications systems on Navy and Marine Corps bases through a backbone system to provide voice, data, imaging, and video communication services. The Naval Automation Command (NAVDAC) will develop Base Communication Plans (BCP) with the charter of identifying interbuilding, interactivity, base communications requirements for voice, data, video, and all other information requirements [Ref. 87:p. 1-2].

Interoperability problems at various levels of communication systems have prompted BITS planning. BITS also addresses the lack of centralized communications management for Navy bases. To solve these problems, the BITS program prescribes a transition to OSI protocol-based systems, in accordance with Government OSI Profile (GOSIP). Since the commercial telecommunications arena has also increased its awareness of OSI products and standards, BITS planners hope that future computer network purchases will be able to be accomplished on a commercial, off-the-shelf basis. This will give the Navy broader purchasing options at lower costs. Perhaps most importantly, the BITS program will usher in the capability of providing ISDN services at Navy and Marine Corps bases. Figure 19 illustrates the target BITS architecture published by the NAVDAC in the BITS Draft prepared by the MITRE Corporation [Ref. 87:p. 4-7]. The Network Management Center (NMC) will be the central facility that manages BITS. For communications between different bases, BITS will interface with the Defense Switched Network (DSN) to provide long-haul communications [Ref. 87:p. 4-1]. The box with the "Pier-Side" header represents the communication connections to Navy ships. The "Building" box containing the module "OUA/UA" represents the Organizational User Agent's and User Agent's access to the Defense Message System (DMS). This BITS architecture does not explicitly or directly address wireless/mobile access and services.

The author suggests that the NAVDAC also consider the increasingly important wireless/mobile communications services for Navy and Marine Corps bases. PCN technology might be one logical means of providing mobile features to base communications systems, while additionally bolstering the capability to provide ISDN services. Figure 20 illustrates one possible wireless-capable BITS architecture using PCN as a base-wide wireless network. The reader will recall from earlier chapters that PCN currently employs spread-spectrum, CDMA radio technology, which will facilitate encryption and

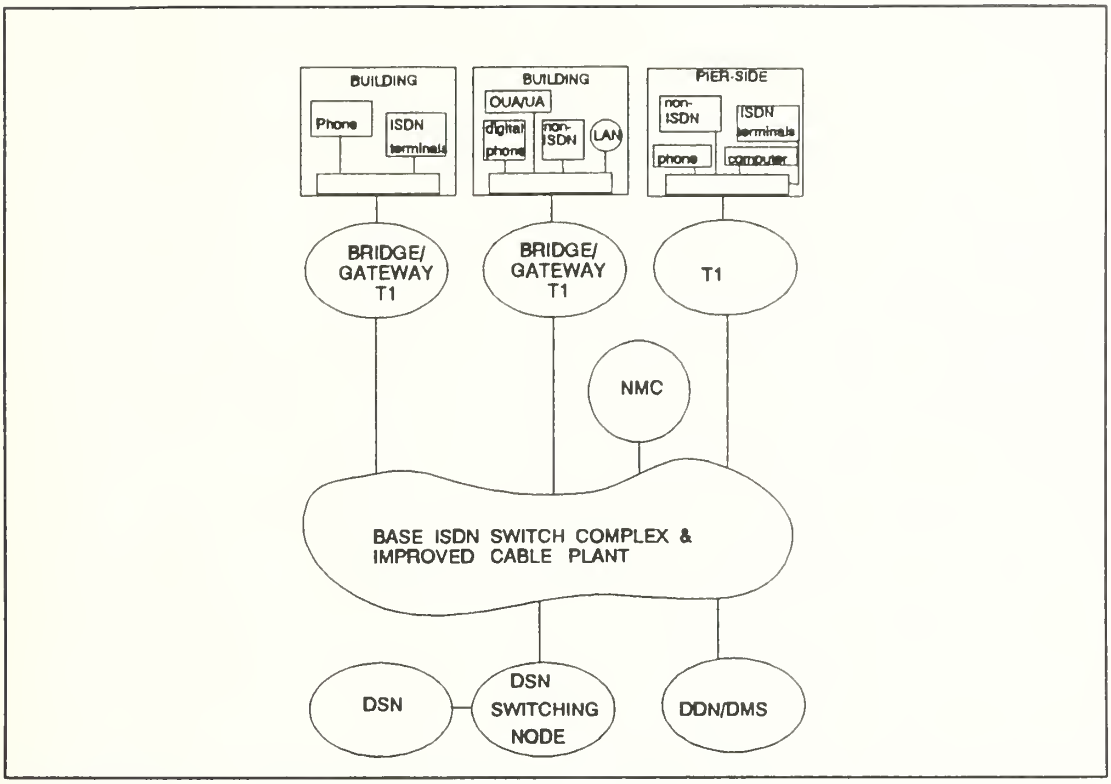

Figure 19. Target BITS Architecture [Ref. 87:p. 4-7]

security of the radio signals as well as providing for robust noise resistance and large subscriber capacity. For some bases, construction of an entire PCN may be uneconomical or impractical, and in these cases, conventional COTS cellular phones may satisfy mobile communications needs. Each BCP should address the wireless communication needs on a base-by-base basis. Cost-benefit studies might then be performed for each base to determine the most appropriate wireless system to satisfy each base's mobile requirements.

During a recent telephone interview, Dr. Schilling, President of SCS Mobilecom, stated that two months would probably be required for design of a base-wide PCN system, and that after a total of nine months, such a system would be ready for implementation and actual use [Ref. 88]. CT-3 systems would also be potential candidates as COTS-available wireless vehicles for mobile data and voice communication. Just how quickly these systems become available depends in large part on the regulators' ability to resolve the spectrum allocation issue. Because PCN may be allowed to coexist in currently allocated spectrum and because of the author's affinity for CDMA, PCN appears to be the most likely system to fill base-wide wireless communication needs.

D. CONCLUSION

Cellular systems have become important to communication managers, including those in the military, in some rather unexpected ways. Cable News Network's (CNN) military analyst, James Blackwell, stated in a news story about the air war against Iraq that Kuwait's sophisticated cellular network had been suspected of being utilized by Iraqi military officials to communicate with each other as well as with Iraqi Headquarters [Ref. 89]. Mr. Blackwell stated that the distributed nature of cellular systems with multiple cell sites makes them particularly difficult to disable from a targeting standpoint. The reader will hopefully realize the minor flaw in this analyst's reasoning; to disable one of today's cellular systems, one need only cripple the MTSO. However, as future cellular-based systems migrate from

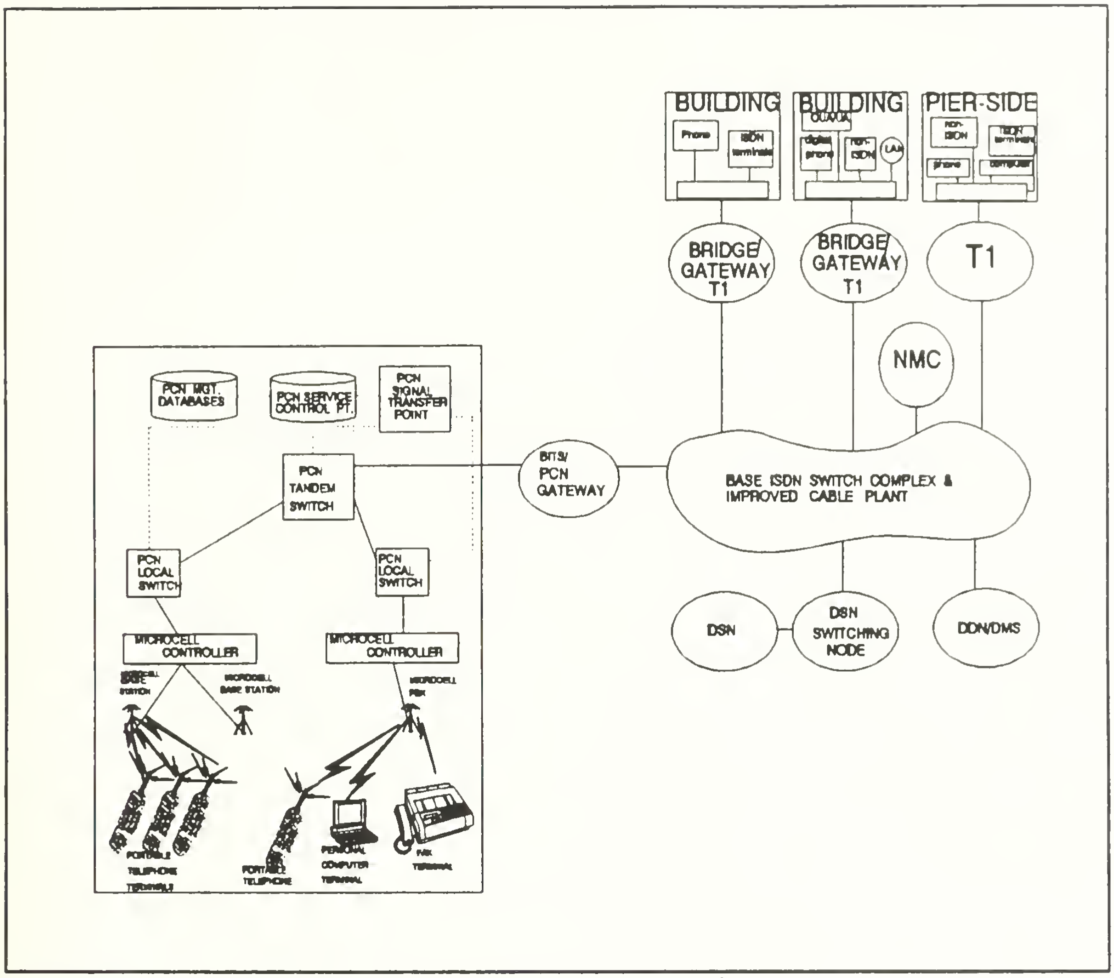

Figure 20. Target BITS Architecture/Wireless

centralized to distributed control with more intelligence at the cell sites, systems employing this distributed cellular architecture will indeed be quite survivable from a military perspective.

Voice recognition, enabling "hands off" dialing, is already a feature offered by after-market vendors for today's vehicular cellular subscribers. The author believes that this technology can be employed with future battlefield communication systems built around a cellular architecture.

The futuristic communications for the "Starship Troopers" of Robert Heinlein's science fiction novel might become reality sooner than most would believe possible. In that system, a soldier need only speak the name of the person with whom he needed to communicate [Ref. 90]. The transceiver, built-in to the soldier's helmet, would automatically channelize and alert the destination party. Simultaneous broadcast to multiple parties is also possible in this fictitious communication system. The author believes that advanced PCN-based systems will be able to provide such features for future warriors. Perhaps the biggest obstacle for such a system would be the capability to rapidly deploy a large number of mini-cell sites. For the high-speed maneuver environment, a high-power system may be required.

Of more immediate concern for the military and other government users of the RF spectrum is the quest, on the part of some legislators and lobbyists, for the "liberation" of government-allocated spectrum. Briefly mentioned in Chapter VI, the *Emerging Telecommunications Technologies Act of 1989* (H.R. 2965) seeks some 200 MHz of government-allocated spectrum. Demand for spectrum will continue to grow as PCS components become less costly, and legislators will likely seek even more in the future. Government communicators can best protect their communication interests from such action by employing systems that utilize spectrum in an efficient manner. Systems based on cellular architectures are very spectrum efficient when frequencies are reused. The author believes that a far more appropriate target to "liberate" is the 300 MHz block that is being held hostage by broadcast television. Some 80-90% of this allocation is unused [Ref. 40:p. 2].

The author does not intend to suggest that PCN developments, as well as other digital radio breakthroughs, will merely create challenges for communications managers from the government sectors. On the contrary, productive solutions are being offered with every new cellular-related development. This is especially true in the field of computer networking, where microcellular systems promise tetherless computer communication. One such system is the recently announced Wireless In-Building Network (WIN) by Motorola. This system, which has been named "Altair," uses 18 GHz radio waves to transmit data at 10 Mbps [Ref. 91]. Capable of penetrating most interior walls of buildings, this system eliminates the cumbersome cabling required for most computer networks, and it seems especially suitable for many administrative environments in the military where office spaces are constantly undergoing change. Other developments, including those mentioned previously in this paper, will continue to provide a broader range of communication solutions than is currently available.

As digital technology, especially that of spread spectrum, begins to permeate the radio link of today's cellular systems, and as sophisticated microcellular systems, such as PCN, become available on an almost COTS basis, communication managers will be provided with wireless alternatives for many communication requirements. Hopefully this paper will enable the reader to recognize and take advantage of them.

APPENDIX - LIST OF ACRONYMS

Acronym	*Full Term*
AMPS	Advanced Mobile Phone System
APC	Adaptive Power Control
BCP	Base Communication Plan
BCT	Business Cordless Telecommunication
BER	Bit Error Rate
BETRS	Basic Exchange Telecommunications Radio Service
BITS	Base Information Transfer System
BIU	Base Station Interface Unit
bps	bits per second
BTMA	Busy Tone Multiple Access
CAC	Common Access and Control
CADN	Cellular Access Digital Network
CAI	Common Air Interface
CCITT	Comite Consultatif Internationale de Telegraphique et Telephonique (International Telephone and Telegraph Consultative Committee)
CDMA	Code Division Multiple Access
CEPT	Conference Europeanne des Administrations des Postes et des Telecommunications
CGSA	Cellular Geographic Service Area
CIU	Central Office Interface Unit
CM	Circuit Merit
CPE	Customer Premises Equipment
CSMA	Carrier Sense Multiple Access
CT-2	Cordless Telephone, Second Generation
CT-3	Cordless Telephone, Third Generation
CTIA	Cellular Telecommunications Industry Association
dB	Decibels

dBm	Signal Output Referenced to an Input Signal of 1 milliwatt (1 mW)
DCA	Dynamic Channel Allocation
DECT	Digital European Cordless Telecommunication
DMA	Defense Mapping Agency
DMS	Defense Message System
DQDB	Distributed Queue Dual Bus
DS	Direct Sequence
DSN	Defense Switched Network
EEC	European Economic Community
EIA	Electronic Industries Association
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDI	Feeder Distribution Interface
FDMA	Frequency Division Multiple Access
FH	Frequency Hopping
FM	Frequency Modulation
GHz	Gigahertz (10^9 x Hertz)
GOSIP	Government Open Systems Interconnect Profile
GSM	Groupe Speciale Mobile
HDTV	High-Definition Television
IEEE	Institute of Electrical and Electronic Engineers
IMTS	Improved Mobile Telephone Service
ISDN	Integrated Services Digital Network
ISO	International Standards Organization
kHz	kilohertz (10^3 x Hertz)
kbps	kilobits per second (1,000 bits per second)
LAN	Local Area Network
LAPC	Link Access Protocol for Cellular Control
LEC	Local Exchange Carrier
MAN	Metropolitan Area Network
Mbps	Megabits per second (1,000,000 bits per second)

MC	Marginal Cost
MHz	Megahertz (10^6 x Hertz)
MR	Marginal Revenue
MROI	Marginal Return on Investment
ms	millisecond (1/1,000th of a second)
MSE	Mobile Subscriber Equipment
MSRT	Mobile Subscriber Radiotelephone Terminal
MTS	Mobile Telephone Service
MTSO	Mobile Telephone Switching Office
NAVDAC	Naval Automation Command
NDCCA	Navy Data Communications Control Architecture
NMC	Network Management Center
NOI	Notice of Inquiry
NTIA	National Telecommunications Industry Association
OSI	Open Systems Interconnect
PBX	Private Branch Exchange
PCN	Personal Communications Network
PCS	Personal Communications Services
PRMA	Packet Reservation Multiple Access
PSTN	Public Switched Telephone Network
PTS	Personal Telephone Service
RACE	Research and Development in Advanced Communications in Europe
RAU	Radio Access Unit
RCC	Radio Common Carrier
RELP	Residually Excited Linear Predictive Coding
RF	Radio Frequency
RSA	Rural Service Area
SAT	Supervisory Audio Tone
SCC	Systems Control Center
SCPC	Single Channel per Carrier
SMR	Specialized Mobile Radio
SNR	Signal-to-Noise Ratio

SPC	Stored Program Control
SS-7	Signaling System 7
ST	Signaling Tone
T-1	Digital Transmission at 1.544 Mbps
TACS	Total Access Communication System
TDMA	Time Division Multiple Access
TIA	Telecommunications Industry Association
TIU	Trunk Interface Unit
TTL	Transistor-Transistor Logic
UPCS	Universal Personal Communications Service
USC	User Specific Control
VLSI	Very Large Scale Integration
WARC	World Administrative Radio Conference
WIN	Wireless In-Building Network
WIU	Wireless Terminal Interface Unit

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