INTRODUCTION BY THE EDITOR

The article following, written by one of the lead engineers in the project, describes the development of AMPS, the first cellular telephone system in the United States. As noted, the project ran for over 12 years and required the services of a "vast number" of engineers at AT&T's Bell Labs. The hundreds of millions of people currently using cell phones, smart phones, and all the other mobile wireless equipment available in the United States, as well as everywhere else in the world, often take these devices and the infrastructure behind them for granted. We tend to forget that, not too many years ago, the spectral environment over which our mobile systems operate on a regular basis was not well understood. Until the cellular concept was recognized, it wasn't clear that many mobile phones could simultaneously share the same channels in a local area. With the cellular concept agreed on, problems such as tracking of cell phones and handoff from cell to cell had to be resolved. Computerized base stations had to be designed and tested. A myriad other important development and design issues and problems had to be resolved. Dick Frenkiel very clearly describes the various engineering problems that had to be solved, step by step, sometimes quite painstakingly. He gives credit to the many teams of Bell engineers who worked on this project. He also points out policy issues involving the FCC that had to be resolved. Competition for scarce radio spectral space was fierce. Competing engineering companies and telephone operators had to be assuaged. Getting from the initial concept to successful implementation of a trial system in Chicago took massive funding and assignment of multiple large teams of engineers by AT&T. But the job was finally accomplished. My own personal feeling is that this project, like a number of other massive projects requiring hundreds of engineers, could only have been undertaken at that time by a company with the resources of AT&T. But that's another question for anther day. In the meantime, I urge you to read on through this exciting description of the genesis of cellular telephony in the United States.

—Mischa Schwartz

CREATING CELLULAR: A HISTORY OF THE AMPS PROJECT (1971–1983)

RICHARD H. FRENKIEL

INTRODUCTION

I have attempted in this brief history to capture the rich mix of technical and political challenges that shaped the development of the Advanced Mobile Phone System (AMPS), the first cellular system in the United States, between 1971 and 1983. Earlier work was described in an article written for this column by Joel Engel [1]. I have also written a more detailed and personal view of these events within a manuscript titled *Cellular Dreams and Cordless Nightmares; Life at Bell Laboratories in Interesting Times*, which is available for download from http://www.winlab.rutgers.edu/~frenkiel/dreams [2].

The cellular concept emerged at Bell Labs in the late 1940s, in proposals by Rae Young and Douglas Ring. Some modest additional studies were conducted over the next two decades, including a conceptual system plan that Phil Porter and I produced in 1966. The attraction of cellular systems was their ability to reuse channels many times in a local area, and to provide service over very large areas with low-power radios, but a cost-effective cellular system required a large number of channels. Channels for all radio systems were in very short supply until the mid-1950s, when advances in radio design made frequencies up to about 1 GHz practical for consumer applications. This essentially doubled the available spectrum and led to competing proposals for a variety of purposes, including AT&T's cellular system and an expansion of TV broadcasting. After some deliberation the FCC used this huge block of new spectrum to create more than 80 new TV channels. TV was a relatively new and very popular medium at the time, and there was an expectation that this expansion would launch an era of cultural and educational programming.

The results of that experiment fell short of expectations, and in 1968 the FCC opened an "inquiry and proposed rule-making" to consider the reassignment of 14 of those UHF TV channels, near 900 MHz, for mobile telephone and private mobile radio systems. This would produce well over 1000 new mobile radio channels, and because these channels were considered to be a limited and valuable national resource, the FCC added the expectation that their inquiry would lead to more "spectrum efficient" systems.

The cellular system met the criterion of spectrum efficiency very well, but early plans for these systems had been limited in scope. Little was known about radio performance at 900 MHz, for example, or about the cost and ultimate capacity of a practical cellular system. To fill in these details, a large team was assembled at Bell Labs to prepare a "feasibility study and system plan" for the FCC. The core of this activity was Joel Engel's cellular systems engineering group under Rae Young, to which Phil Porter and I moved in 1968, and a cellular radio development department under Bob Mattingly. The latter were radar experts who had recently returned from a long assignment on Kwajelein Island in the Pacific, and included many who would be key contributors to the AMPS project. Radio research engineers under Bill Jakes contributed new ideas in radio propagation theory and receiver diversity that Jakes would later compile in a landmark text. [3] Zack Fleur, representing switching systems engineering, provided expertise on the switching systems that would be modified to become AMPS system controllers.

The resulting cellular plan was delivered to the FCC on December 20, 1971 [4], and AT&T committed its vast resources to the creation of a nationwide cellular network. In anticipation of FCC approval (and perhaps to encourage that approval) AT&T immediately launched a full-scale development project, estimating that cellular service could be offered within about five years. Sadly, this prediction proved overly optimistic. The development went smoothly, but intense controversies over the role to be played by the AT&T monopoly would delay commercial service until 1983.

At that time there were many small independent telephone companies, but the AT&T monopoly (often called the Bell System) provided more than 80 percent of the local and long-distance telephone service in the United States. Moreover, most of the equipment for the nationwide telephone network was designed by Bell Labs and built by Western Electric (AT&T's manufacturing arm). In contrast, the mobile tele-

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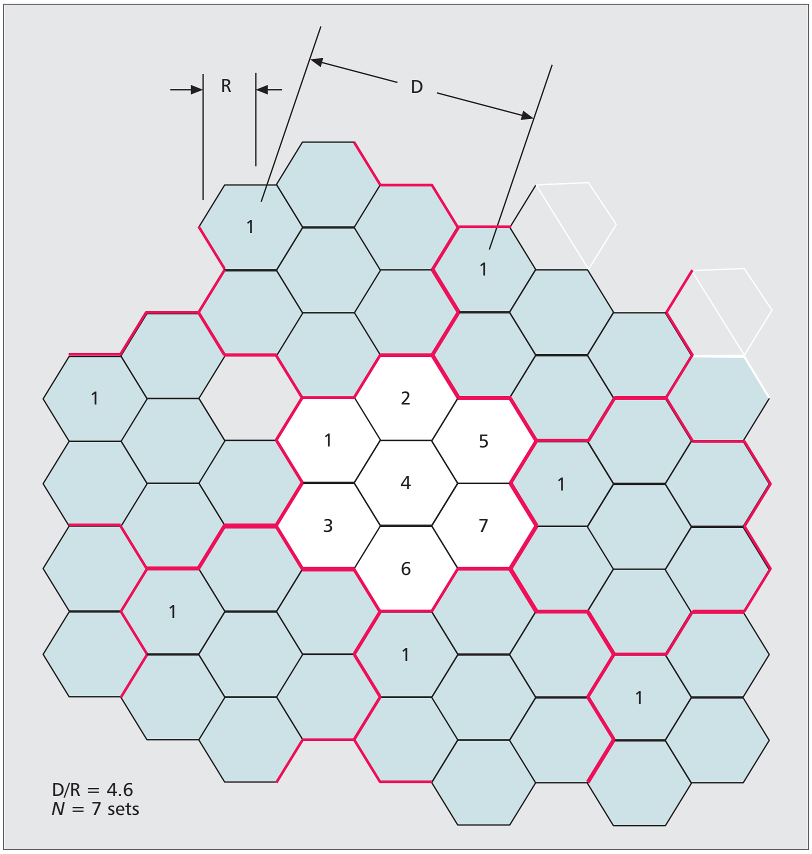

Figure 1. *A 7-cell channel reuse pattern (from AT&T's 1971 proposal to the FCC).*

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phone and private mobile radio markets were relatively open and competitive. Small businesses called radio common carriers (RCCs) operated half of the mobile telephone systems in the United States, and a number of radio manufacturers provided equipment for both mobile telephone systems and private mobile systems.

Both the RCCs and the radio manufacturers had reason to be concerned about the cellular proposal. The RCCs were generally small businesses, and would have difficulty installing and operating complex and expensive cellular systems, even if they were to get access to an adequate number of channels. The radio manufacturers expected to lose the market for mobile telephone equipment to Western Electric, and also worried that cellular service would weaken the demand for private systems. Their concerns were shared by the antitrust division of the Department of Justice, which had sought to limit AT&T's monopoly power for most of the century. The stage was set for a bitter and long-term confrontation.

In an attempt to lessen the fears of its monopoly power and gain wider support for its proposal, AT&T announced that it would not manufacture cell phones, and that Bell Labs would help cell phone manufacturers create the new radio designs these phones would require. This concession gained the support of some manufacturers, but important concerns remained. There might be a large new market for cell phones, but a standardized cell phone would attract new international competition and give AT&T great buying power. The high-margin market for private, custom-designed, turnkey systems might be replaced by a low-margin market for cell phones. The largest of the radio manufacturers, Motorola, would remain strongly opposed to the AT&T proposal.

Among the many opponents of AT&T's cellular proposal, Motorola was perhaps the most effective. Its opposition was always energetic, often creative, and occasionally rather witty. An amusing audio simulation, for example, contrasted a long and rambling telephone conversation with the brief and businesslike transmissions of a fleet dispatcher, to suggest that "efficiency" had some non-technical dimensions. Other challenges involved complex calculations of spectrum efficiency, and led to prolonged and confusing public debates between Bell Labs and Motorola engineers that did little to resolve the issues and much to delay the project.

THE PERVASIVE ISSUE OF SPECTRUM EFFICIENCY

Because base stations are very expensive, cellular system designers and operators must always focus on spectrum efficiency — if only to maximize the number of subscribers that share the cost of each base station. The modern FCC practice of auctioning new spectrum has resulted in some very high prices, which has only served to intensify the economic incentive to use spectrum efficiently. In the 1970s, however, radio spectrum was seen as a free but limited national resource, to be allocated by the FCC for the greatest public good. This cast a strong and almost moralistic light on the issue of spectrum efficiency: it was the means by which one could serve the greatest number of people with any given amount of precious spectrum.

Perhaps the most significant issue in determining the spectrum efficiency of a cellular system is the separation between cells that use the same channels —the so-called reuse distance. This, in turn, determines the number of cells requiring different channels, and thus the number of channels per cell. [5] Using an example based on AMPS, if one has 350 channels and can reuse channels at a distance of 4.6 cell radii (Fig. 1), the result is a 7-cell repeating pattern with 50 channels per cell.

For an AMPS call blocking objective of 2 percent and an estimated traffic load of 90 s/subscriber/busy-hour, a cell with 50 channels will serve about 1600 subscribers. In a hexagonal grid of 1-mi cells, this represents a capacity of about 600 subscribers/mi^2. If twice this reuse separation were required, however, a 28-cell repeating pattern would result, and the same 1-mi cells would serve only about 100 subscribers/mi^2 (fewer channels per cell with smaller, less efficient server groups). The capacity of a cell (and a system) would be reduced by 83 percent, and the cost per user would increase sharply.

This calculation requires only a few seconds and an Erlang B calculator, but with limited propagation data and no operating experience, our task in esti-

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mating reuse distance was a complex and time-consuming process. We needed to set an objective for voice quality and then determine what design parameters would meet that objective. This required an experimental program to map the relationship between subjective voice quality and objective signal-to-interference ratio, where both signal and interference could be fading at various rates (i.e., for different vehicle speeds). To conduct any such voice quality experiments we needed to specify a particular radio design, and to convert these laboratory results to a reuse distance we needed propagation data at 900 MHz from a variety of environments.

A massive program of propagation measurements in typical U.S. environments was carried out by a team led by Gerry DiPiazza, one of those radar experts from Mattingly's department who were so important to the AMPS project. Gerry's propagation models were then processed in computer simulations, to determine the signal-to-interference performance of different cell grids. The largest of these simulations, called MultiCell, was designed by Jim O'Brien and could simulate thousands of calls in a mature system configuration. For many years, Jim's MultiCell simulation was our best window into the reality of an operating cellular system. It was used to study a wide variety of issues, from the variation of signal and interference during a typical call, to the performance of locating algorithms, to the logistics of cell splitting and the ultimate capacity of a system.

Inevitably, the design of those experiments and the interpretation of their results involved an element of subjectivity. Methods and conclusions were often challenged, leading to time-consuming public debates. Moreover, improvements in spectrum efficiency were a double-edged sword. They demonstrated the value of cellular systems but supported the argument that such systems could be built with fewer channels.

Despite a variety of such controversies, the system design gradually took shape [6]. FM channels with 12-kHz frequency deviation were shown to provide good voice quality in an interference-limited environment. "Companding" (the compression of the dynamic range of a voice signal before transmission and its compensating expansion after reception) and the use of a "knee" in the expander curve to reduce background noise were shown by Gaston Arredondo to improve voice quality significantly. Two-branch receiver diversity, proposed and demonstrated by Bill Jakes' researchers, was adopted at base stations to further improve radio performance.

Based on listening tests using these advances, it was determined that "90% good-to-excellent" voice quality would require a signal-to-interference ratio of at least 17 dB over 90 percent of the cell. Based on propagation measurements and computer simulations, this initially implied a 12-cell reuse pattern, but Phil Porter's proposal to use directive antennas at base stations reduced interference enough to allow a 7-cell reuse pattern.

LOCATING AND HANDOFF

Of all the design issues created by cellular, none was more symbolic of the new technology than the need to locate the vehicle to a particular cell and to "hand off" a call to a new cell when the subscriber's location changed. The signal and interference conditions could change very quickly for a fast-moving vehicle in a small cell, so the locating process needed to be performed every few seconds for each call. The resulting handoffs could be frequent and needed to be performed without annoying clicks or gaps in speech that would be objectionable to the subscriber.

The goal of the locating and handoff process was first seen as preventing interference by constraining calls to use the nearest base station. Using one of the first simulations of a mobile unit in a cell grid, however, Gary Ott demonstrated that the best approach was simply to use whichever base station could provide the strongest signal. The result, of course, is that the actual service areas of cells are quite irregular, although we continue to draw them as ideal hexagons. Jim O'Brien's MultiCell simulation was later used to select a measurement rate for sampling signal level at nearby base stations, and a decision rule for handoff that balanced signal quality and processing load.

Achieving a "clean" handoff without dropped calls was also a challenging design problem. Out-of-band signaling was slow and unreliable, so it became necessary to interrupt the voice channel for this function. The audio would be muted during this operation, but it was determined in voice tests that a gap of more than one-quarter second in the audio path would be objectionable. A signaling method called "blank and burst" was proposed by Reed Fisher, in which the audio was "blanked" while a brief "burst" of heavily coded data was sent to the mobile. Reed was also the primary designer of the fast frequency synthesizer, which allowed the cell phone to change channels during that same brief period. Although AT&T would not manufacture cell phones, Reed was a major contributor to cell phone technology. The central switch would transfer the call to the new cell while the mobile was changing channels, and the subscriber would hear only a minor "click."

SIGNALING AND CONTROL

To carry out functions such as call setup and handoff, the cellular system would need to exchange a good deal of information between base stations and mobiles. A 10-kb/s digital signaling rate was introduced for this purpose. This was a high signaling rate for mobile radios in that period and would require extensive testing for error performance in the cluttered, interference-limited cellular environment.

The various signaling functions used in the AMPS system presented a variety of different coding problems. [7] As discussed above, the blank-and-burst function for handoff was carried out on voice channels. It required high reliability in a short time, to prevent dropped calls while causing only a brief gap in conversation. Other channels were only used for signaling purposes. Sets of one-way "paging" channels, for example, were used to alert mobiles throughout the system to incoming calls. All the mobiles in the system that were not engaged in calls would be listening for incoming calls, so a "false positive" rate of even 1 percent on the paging channels would lead to hundreds of false responses to each incoming call and put a heavy load on the system processor.

There were also channels that were used by the system to identify mobiles and exchange information such as telephone numbers for setting up calls. The "dial-then-send" operation for outgoing calls that is now so familiar for cell phones was another of Phil Porter's innovations, to make the dialing operation less hurried (and therefore safer) and to save the channel time that would have been lost during dialing. With a bit of additional innovation, this clever idea would enable modern text messaging. One of the original creators of the AMPS architecture, Phil was responsible for some of its most novel features.

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Compared to today's complex digital cellular systems, such innovations may seem rather ordinary, but at the time we were breaking new ground. A few years earlier, the dialing of a call from a car without operator assistance was a breakthrough. Now we were bringing mobile telephony into the modern age of communications. This required a powerful and flexible system controller that could behave as a telephone central office, interface with base stations, and control the locating and handoff processes.

Fortunately for the AMPS project, the Electronic Switching System (ESS) became widely available in the late 1960s. Pioneered by Bell Labs, this software-controlled switch offered a flexible and cost-effective platform for adding new cellular capabilities. It is difficult to imagine a successful AMPS project without the ESS, or without the large and talented team of Indian Hill software developers who converted the 1A ESS into the AMPS Mobile Telephone Switching Office [8].

AMPS would also require a cell phone smart enough to play its part in the choreography of call setup and handoff, and once again a new technology presented itself. Early in the project it was assumed that the cell phone logic would be realized in complex and specialized integrated circuits, but with the emergence of the microprocessor in the early 1970s we inherited a powerful and flexible tool with which to implement cell phone logic. In retrospect, the earliest proposals for cellular in the 1940s were well ahead of their time. To those early visionaries the radio technology must have seemed almost within reach, but it would take another quarter century to achieve the computer technologies that made a practical cellular system possible.

As a result of the size and complexity of the system, the AMPS base station (or "cell site") [9] was different from anything found in earlier systems. It incorporated separate radios for locating measurements and call setup, and multiple frames of voice radios. Amplifiers of that period could not provide the power and linearity needed to combine many transmitters onto a single antenna without creating spurious out-of-band signals, so transmitters were amplified individually. Groups of 16 transmitters were then combined with circular arrays of tuned cavity filters that were affectionately called "radial engines" because of their resemblance to World War II aircraft engines. A data frame controlled overall base station operations, and a maintenance and test frame monitored its health. There was a line supervision frame for incoming wireline connections to the switch and a power plant with battery backup. Even the monopole mast and antennas were new designs. This massive development effort was the responsibility of a large and talented team at our laboratory in Whippany, New Jersey, many of whom had arrived with Bob Mattingly in 1968 and would remain through the long project.

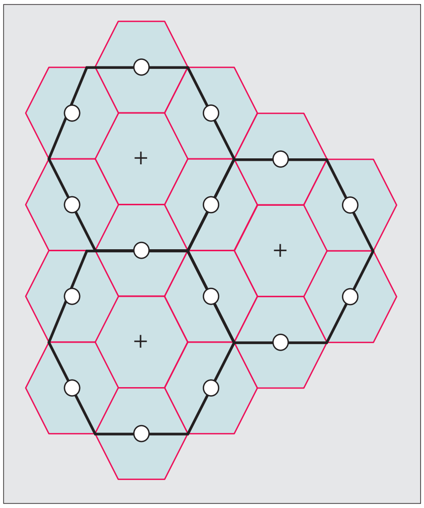

Figure 2. *Cell splitting that preserves the old base stations (+) in the new grid of smaller cells (o) (from AT&T's 1971 proposal to the FCC).*

The design of the switch and base stations was separated between New Jersey and Illinois, and there were multiple cell phone manufacturers as well. It was therefore important not only to write clear functional and interface specifications (a role that involved many of the systems engineers in my department), but also to make sure that those specifications were understood and accepted across the project. This latter role often fell to Stu Tartarone and Phil DiPiazza, who had a particularly broad grasp of the system architecture and could identify important new opportunities. Stu was the first to recognize, for example, that improvements in minicomputer technology could be used to create a smarter base station within a more distributed and flexible control structure.

Selling such ideas across the entire AMPS team required diplomacy, perseverance, and a willingness to travel quite a lot. Phil would continue this "commuter" role for many years, as the system entered its trial phase and was readied for commercial service. He would later "commute" between New Jersey and Illinois, overseeing the final system tests in Chicago, and would make the decision that the first cellular system in the United States was ready for commercial service.

Overall management of the AMPS project was the responsibility of Frank Blecher, whose ability and energy proved equal to the enormity of the task. During the field trial in Chicago he would use every opportunity to perform his own "system tests," and we became used to his early morning and late night cellular calls from one of the Chicago test vehicles. He kept the morale of our large and far-flung team high through delays and disappointments, and much of the credit for the success of the project can be attributed to his leadership.

THE LOGISTICS OF CELL SPLITTING

The key to the cost-effective startup and large final capacity of the cellular system is the process of cell splitting. In the AMPS system cells as large as 5–10 mi in radius (depending on terrain) could be used at startup to minimize cost. Through the process of cell splitting, these would gradually be reduced in size to increase system capacity. Because base stations are very expensive, however, it is necessary to retain existing base stations in the new grid as cells split. Figure 2 shows the splitting pattern used in AMPS. New cells are 1/4 of the area of the previous cells, so each round of cell splitting will increase the system capacity by a factor of four. The smallest cell size (and thus the ultimate system capacity) is limited by practical issues of base station placement and frequency of handoff. The smallest practical cell was thought at the time to be about 1 mi in radius, but much smaller "microcells" are used today.

Even with the original base stations incorporated into the new cell grid, however, cell splitting presented some significant challenges. The central region of the system had to be covered with a continuous grid of the new smaller cells, and more than one-quarter of the channels would have to be moved into the smaller cells simply to achieve the same capacity that had existed before the split. Since these channels were no longer available in the nearby grid of larger cells, the capacity of the large-cell grid would be reduced, and additional cells would be forced to split.

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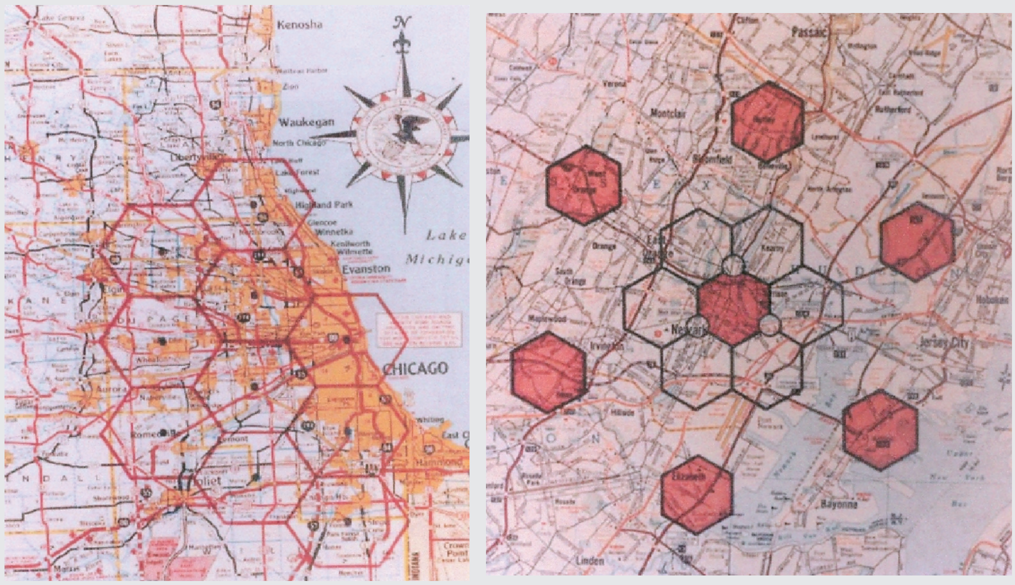

Cellular Service Trial — Chicago

Cellular testbed — Newark

Figure 3. *Coverage maps for the Chicago and Newark trials.*

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Dozens of new base stations would have to be installed and cut into service at the same moment. Hundreds of radios in the old base stations would have to be moved and retuned. It was a costly, labor intensive process and promised to be very difficult logistically.

While drawing such a configuration, it occurred to me that this massive disruption was being created to achieve an incremental increase in system capacity. At that moment, the larger cells were serving almost the entire traffic demand. If we retained the existing cells as a continuous "underlaid" grid providing almost all the needed capacity, we could add a few "overlaid" smaller cells "here and there," with only a few channels, to provide the small amount of incremental capacity we needed. Those few channels could continue to be used at the original base stations for mobiles that were in the inner portion of the cell (in effect, for a smaller cell that was co-sited with the larger cell). Calls that left these new isolated cells could be handed off to the underlaid grid, which would still provide geographically continuous coverage. Over time, more new base stations would be added, and more channels would gradually be moved into those new base stations until the old grid was finally replaced, but the process would be gradual and manageable. This eliminated the logistic problems of cell splitting and reduced the number of cells that were needed at most points in growth rather dramatically. Simulations using Jim O'Brien's MultiCell simulation showed that the average number of cells in a growing system (and thus the average system cost) were reduced by more than 50 percent. That simple idea later became one of AT&T's most sought after patents in cross-licensing agreements [10].

SYSTEM TRIALS AND COMPATIBILITY STANDARDS

As the system design progressed toward completion, it became necessary to demonstrate that AMPS would provide both the excellent service and the spectrum efficiency that had been promised. This sort of demonstration would be a feature of any development program, but amid the political debates of the time it led to new controversies and delays. To demonstrate real service, we would need a large coverage area, and to demonstrate the proper working of the system for the largest capacity we would need to use small cells. Putting the two objectives together would create a trial with hundreds of cells, which was economically infeasible, so AT&T proposed to separate the demonstration into two trials. The Chicago Service Trial would demonstrate real service in a startup configuration, with production equipment and several thousand subscribers. A cellular testbed in Newark would simulate operation in a few 1-mi cells, surrounded by six interfering cells several miles away. The coverage maps for the Chicago and Newark trials are shown in Fig. 3.

Objections were raised to the proposed trials, in particular because they would not demonstrate production equipment in the smallest cells. The FCC agreed with the objectors and denied permission for the trials. AT&T appealed, and the FCC eventually reversed their decision, granting approval for the Chicago and Newark trials on March 10, 1977, but a full year was lost in the appeal process.

The FCC also granted approval to Motorola to operate a trial in the Washington, DC/Baltimore area. A Motorola team led by Marty Cooper had created the first truly portable handheld cell phone, called Dyna-TAC, and service for portable handsets would be the focus of that trial. Dyna-TAC was large and heavy by modern standards (about the size and weight of a brick), but it represented a significant breakthrough in portability. It was a major step in the evolution of cellular from a telephone in a car to the truly "personal" communication service we enjoy today.

Installation of the equipment and facilities for AT&T's Chicago trial [11–13] was the responsibility of a large team led by Jim Troe. The system used 10 cells to cover 3000 mi^2, with a switching center at Oak Park and an opera-

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tions center at Elmhurst where cell phones manufactured by Motorola, E. F. Johnson, and OKI were installed in vehicles (the Chicago system was also used to prove-in the cell phone designs of several other manufacturers). On July 1, 1978, the system began a 12-h/day equipment test with 25 test vehicles, and on December 20, 1978, it began full-time service to paying customers. It was a large-scale and fully operational cellular system, but in the absence of a final FCC ruling it would remain a "trial" for five long years, capped at about 2000 customers, while commercial cellular systems were being introduced around the world.

The cellular testbed in Newark [14] was built by a team led by Gerry DiPiazza. It used a heavily equipped test van to test all the signaling and control functions required for small-cell operation while simultaneously gathering data on signal, interference, and audio quality in a densely populated urban center. The thousands of hours of data it provided were a final confirmation that the promise of cellular would be kept.

Data from the two trials was compiled by Ray Pennotti into a series of "90-day reports" to the FCC. [15] Over a period of several years, those reports demonstrated that Chicago customers were happy with the service and that system performance could be maintained within the smallest cells. We were approaching the finish line, but the trials continued, and the issue of standards remained.

The FCC had decided, by the late 1970s, to split the proposed spectrum between cellular and private systems. The cellular spectrum would be further divided between two competing systems in each service area, one to be operated by the local telephone company and the other by a private competitor. This final compromise, which mirrored the pre-cellular licensing process, was proposed by Lou Weinberg of AT&T's Federal Regulatory organization. It made the field sufficiently competitive to satisfy the FCC, while allowing each competitor sufficient channels to design a cost-effective system. Lou would later go on to create the AMPS corporation, a separate subsidiary created by AT&T to plan and implement a nationwide cellular network, in the brief but euphoric period between FCC approval and the breakup of the AT&T monopoly.

By 1980, it was clear that the proposed system would work as promised, but the FCC demanded agreement on a single nationwide "compatibility standard" that would allow any cell phone to operate in any system. This work fell to an ad hoc committee of the Electronics Industries Association. A draft was prepared for the committee by Tom Walker, based on the AMPS design (as demonstrated in AT&T's Chicago and Newark trials). After some modifications within the committee, the proposed standard was submitted to the FCC. The record was complete, and on April 9, 1981, the FCC issued a final ruling in their long inquiry. On October 13, 1983, AT&T's Chicago Service Trial became the first commercial cellular system in the United States, but the expansion of cellular to other cities was delayed for several additional years by a cumbersome and litigious licensing process.

POSTSCRIPT

The market, of course, turned out to be much larger than even our most optimistic predictions, but AT&T would watch the first decade of that rapid growth from the sidelines. In 1984 the Justice Department's long anti-trust case against AT&T finally ended with the breakup of the AT&T monopoly. AT&T agreed to divest itself of its local telephone operating companies (which would operate the cellular systems), and thus lost the cellular networks it had fought to create. We had planted the seeds for a revolutionary new service, but they would take root and flourish in a transformed telecommunications industry we had never imagined.

The Bell Labs engineers who designed AMPS would remain with AT&T, and would later become part of the spinoff to Lucent Technologies. Within Alcatel-Lucent, a few members of our original team are still at work — designing complex digital cellular systems that make AMPS seem rather simple by comparison.

In this brief history I have been able to name only a few of the hundreds of Bell Labs engineers who poured their creativity and energy into that long project. A few others are named in the references and within the referenced papers, but these short lists fail to capture the contributions of many others. Perhaps the larger truth is that the project was its own reward. We had an opportunity to work with enormously talented people, on problems that were both challenging and important. I suspect that most of us remember the AMPS project as the best period in our careers, and look with justifiable pride at its profound results.

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BIOGRAPHY

RICHARD FRENKIEL [F] received his B.S. degree in mechanical engineering from Tufts University in 1963 and his M.S. degree from Rutgers University in 1965. At Bell Labs, his involvement in cellular systems began in 1966 and lasted until 1983. He was one of the authors of AT&T's 1971 cellular proposal to the FCC and the inventor of an efficient method for cell splitting during cellular growth. He became head of Mobile Systems Engineering in 1977, and served on the EIA committee that proposed the nationwide compatibility standard for cellular. In 1983 he became head of R&D for AT&T's cordless telephone business unit, where he led the team that designed the very successful 5000 series of cordless telephones, and he was responsible for their initial production in Singapore. Following his retirement from Bell Labs in 1993 he joined the Wireless Information Networks Laboratory at Rutgers, where he still teaches a course in wireless business strategy. In 1999 he served as Mayor of Manalapan Township, New Jersey. For his work on cellular systems and cordless telephones, he has received a number of awards, including the National Medal of Technology (1994), the Alexander Graham Bell Medal of the IEEE (1987), and the Achievement Award of the Industrial Research Institute (1992). He is a member of the National Academy of Engineering.