Standards for Personal Communications in Europe and the United States

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The research for this report was conducted during 1995, while I was a research associate at the Program, on sabbatical leave from Rutgers University.

Executive Summary

In the 1990s, cellular and personal communications have been among the most dynamic areas of the economy, both in terms of markets and technology. As in other branches of information technology, the technology of personal communications is embodied in published standards. Standards for personal communications systems, however, are exceptional in several ways. For example:

- They are directly influenced by government regulatory policy.
- They are created before the underlying technology is mature.
- Markets have accepted a proliferating number of standards rather than consolidating around one single standard.

This report chronicles the history of cellular and personal communications standards in Europe and the United States. It then analyzes the standards in the context of economic theories developed since around 1980, with an emphasis on changes that have occurred since the early 1980s, when the first cellular systems reached the market, and on the differences between government policies in Europe and the United States. European governments have increasingly worked together to guide the creation and deployment of standards, while the United States government has taken a less active role than it did in the early 1980s. It can be argued that in the mid-1990s, European industry and consumers have been better served by government policies than their American counterparts have been.

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Chapter One

Introduction

Since their birth in the early 1980s, cellular communications have proved a major success throughout the world. The public appetite for cellular telephones has consistently exceeded expectations of market analysts and fueled the rapid growth of service and equipment industries. Although the interplay of suppliers and consumers is common throughout the economy, two other factors have had an unusually strong influence on cellular communications: uncertainties about new technologies and government policy. As a consequence, the nature of cellular communications has been determined by the four factors illustrated in **Figure 1-1**, each of which influences all the others. This situation differs from other areas of information technology, for example video recording and personal computing, where the interaction of industry and consumers determines market growth in an environment of uniform government policy and predictable technology evolution. The situation portrayed in Figure 1-1 is complex. Moreover, the details of the interactions among the four factors are in a state of flux and differ considerably in different parts of the world.

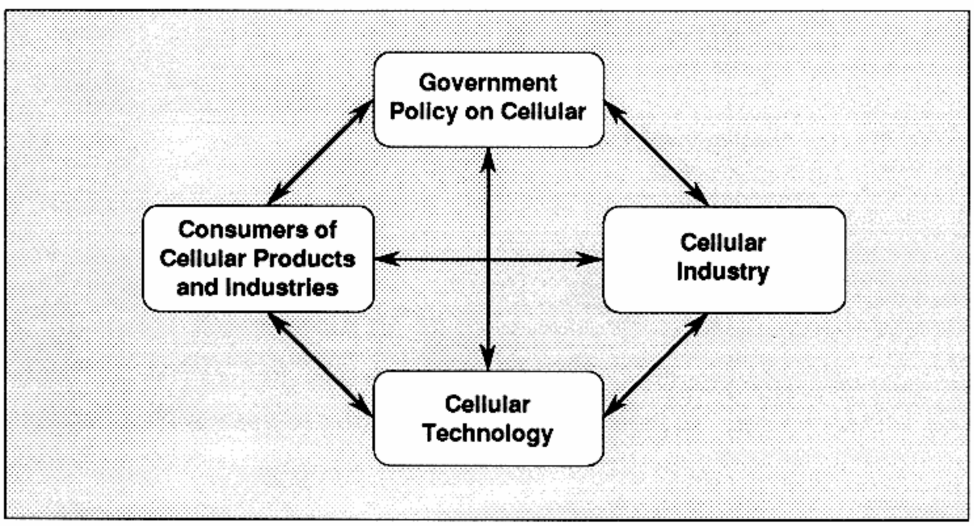

Figure 1-1

Four Factors in Cellular Communications

This report analyzes the relationship between government policy and the evolution in technology in Europe and the United States. The focus is on the standards that govern cellular communications and cellular's 1990s' counterpart, "personal communications." Usually, personal communications are referred to as PCS, in which "S" stands for services or systems. PCS is presented to the public as cellular telephone service with frills, such as paging, voice mail, and calling number identification. To government regulators, PCS refers to frequency bands in which telephones operate. The cellular bands are around 450 megahertz (MHz), 850 MHz, or 900 MHz, depending on national regulations. PCS bands are around 1900 MHz in the United States and Canada and around 1800 MHz in many other countries. For the most part, in this report the terms "cellular" and "PCS" are used as synonyms, because they share common technologies and in many respects are treated similarly by government regulators. In a few places (especially in **Chapter Four**), it is helpful to distinguish between services offered in the cellular and PCS frequency bands.

As in other branches of information technology, PCS equipment must conform to established standards, but the creation and adoption of standards for PCS differ substantially from procedures in other application areas. There are two major, interrelated differences:

- PCS standards were created before the conforming technologies were developed; and

- there are many competing PCS standards.

The striking effect of these differences is that the PCS industry, while mature commercially, remains a standards battleground, with an increasing, rather than decreasing, number of warring factions. This situation appears to be unique in information technology.

This report documents the status of PCS standards in the United States and Europe during the past fifteen years since roughly 1980. Many of these issues addressed here are identified in a body of literature that has grown steadily since the mid-1980s in response to a recognition of the increasing economic importance of information technology standards. Most of the standards literature falls into two categories: case studies, such as this one, and analyses based on abstract models. This report is a case study of PCS that refers to the abstract models in order to explain some of the economic forces guiding the evolution of PCS.

The report is aimed at two audiences. It offers members of the PCS community a context for analysis and decisonmaking relevant to the creation and adoption of standards. And to scholars with a general interest in standards, it offers another case study, distinguished in two ways: first, by the diversity of competing standards existing in a single industry, and, second, contrary to many other case studies, by describing issues still far from resolved. In this sense, PCS standards are a laboratory for examining hypotheses elsewhere deduced from abstract models or induced from retrospective case studies.

Chapter Two presents a framework for examining standards in general, with a focus on compatibility specifications. This framework, largely derived from the standards literature, emphasizes criteria for judging the merits of specific standards. **Chapters Three** and **Four** describe the history of first- and second-generation PCS systems in Europe and North America. The striking differences in the status of standards in these two continents is in itself surprising. Moreover, since 1988 the situation has flip-flopped so that the status of second-generation European standards resembles that of first-generation North American standards, and vice versa. **Chapter Five** uses the economics framework developed in Chapter Two to interpret the case studies presented in Chapters Three and Four. A principal conclusion is that, to date, the policies adopted in Europe in the 1980s have served consumers and industry better than policies in the United States.

Chapter Two

Compatibility Specifications

To establish a framework for examining PCS compatibility, compatibility specifications must first be placed in the general context of standards for products and services. There are many types of standards, each serving its own purposes. Compatibility specifications serve the purpose of interoperability. They insure that two or more products will function properly when part of the same system. Although the details of interoperability remain the fundamental purpose of compatibility specifications, specifications also address other goals that influence the value of standard products to their producers and consumers.

2.1 Standards in General

2.1.1 Types of Standards

Another author, introducing standards to his readers, explained that when he began his investigation, "Standards of every kind started to appear everywhere."[1] To prevent proliferation from obscuring the principal issues addressed here, this investigation begins with a definition that encompasses the scope of this report:

> Standards are formal rules that guide the manufacture of products and the delivery of services.

Although this definition excludes, in the words of that author, "the way my wife and I write phone messages,"[2] it still incorporates a wide variety of practices.

To appreciate the wide range of issues addressed by standards, it is helpful to identify categories that refer to the principal purpose of a standard:

1. Appearance, labeling
2. Dimensions, such as size and weight
3. Safety
4. Quality
5. Compatibility specifications

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[1]Yesha Y. Sivan, *Knowledge Age Standards: Present Scope and Potential Use in Education* (Cambridge, Mass: Harvard University Program on Information Resources Policy, P-96-1, March 1996), 7.

[2]Ibid.

All of them could be observed while I was recently examining a compact disc (CD) player in a store. Like other components of an audio system, the CD player was in a black cabinet (1). The controls were labeled with the same icons that appear on other CD players (1). The disc player has the same width and depth as other stereo components (2). It carries an endorsement from Underwriters Laboratories, certifying that it meets electrical safety standards (3). "Eight-times oversampling" in combination with an "18-bit digital-to-analog converter" indicate the quality of the audio signals (4). And, finally, the CD player is compatible with all my compact discs (5).

2.1.2 Why Have Standards? Benefits and Some Costs

Standards deliver a variety of benefits to industry and to the public at large. Appearance and labeling standards promote a company's image and help consumers understand the nature and function of a product. The benefits of safety and quality are obvious and inherent in the products and services they cover. Other benefits fall into the category of network economies and network externalities.[3] These are economic benefits that derive from wide adherence to standards, beyond the inherent benefits of the products and services to their users. Externalities can be positive or negative, depending on whether the total added benefit of one more unit is greater or less than the benefit to the person obtaining it.

Dimensional standards are useful principally because they produce network efficiencies. There is nothing inherently optimum in stereo components that are 44 centimeters (cm) wide and 29 cm deep. However, wide adherence to this convention produces efficiencies in storage and display for retailers. It also serves consumers by stimulating the availability of inexpensive, space-efficient audio equipment furniture. Dimensional conventions promote efficiency of service and repair facilities. Car maintenance would be even more expensive than it is if each model were to come with its own size of spark-plug threads.

Externalities can also be negative. For example, the batteries in portable electronic equipment increase the value of the equipment to its users but create disposal problems for the community at large. In some instances, the nature of the externality depends on how many similar products already exist. Citizens band (CB) radios at first had positive externalities. When there were few CB radios, the purchase of each new one gave existing owners new opportunities to communicate. But when the airwaves became congested, each new radio, although beneficial to its purchaser, added to the likelihood that other people would encounter congestion when they tried to use theirs.

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[3]In this context, the word "network" is used in the general sense of a collection of related goods and services. Elsewhere in this report the discussion refers extensively to communications networks consisting of electronic equipment that stores and transports information.

Even when they produce externalities that are positive in aggregate, standards can have negative side effects. By limiting variety, they can circumscribe efficiency and quality. Many stereo components could fit comfortably in boxes that are less than 44 cm wide and 29 cm deep. Smaller boxes would consume less metal for construction, and smaller boxes would be more economical to store and transport than standard ones. When standards become entrenched they can inhibit innovation. Someone may invent a better technique than Dolby for suppressing noise in audio tapes, but it would be hard to find a market for the new method in the presence of the "excess inertia"[4] associated with the millions of tapes and tape players that conform to the Dolby standard.

Some standards, such as the dimensions of audio equipment, embody a mixture of advantages and disadvantages. They are adopted when the pluses outweigh the minus. By contrast, compatibility specifications are often compelling. Whatever its color and size, a CD player that is incompatible with CD recordings would be useless. Similarly, compatibility of PCS system components is essential.

2.2 Compatibility

2.2.1 Methods of Achieving Compatibility

The word "compatibility" implies a relationship between two or more different things. Gabel's book[5] begins with an excellent discourse on the economic implications of compatibility. He points out that a standard is one way, but not the only way, of achieving compatibility. In some cases, compatibility is inherent in the relationship between separate properties of two things. He offers the example of tea and lemons. Other times, compatibility is achieved by means of an adaptor, which is an additional piece of equipment that allows two incompatible items to function together. To travelers, an electrical adaptor is a familiar means of making an appliance compatible with a local power source. Compatibility can also be achieved by gateways, which are products capable of conforming to more than one standard. An example of a gateway is a hair dryer that can be used with both European and North American electricity supplies. Gateway technologies, in the form of dual-mode cellular telephones, figure prominently among emerging cellular telephone products in North America.

The focus of this report is on products that conform to formal compatibility specifications. Sometimes a specification describes only one part of a system, such as a television transmitter. In doing so, it implicitly establishes rules for manufacturing compatible

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[4]Joseph Farrell and Garth Saloner, "Standardization, Compatibility, and Innovation, *Rand Journal of Economics* **16**, 1 (Spring 1985), 70-83.

[5]H. Landis Gabel, *Competitive Strategies for Product Standards: The Strategic Use of Compatibility Standards for Competitive Advantage* (London: McGraw-Hill, 1991), Chapter 1.

receivers. By contrast, a cellular phone standard typically contains rules for manufacturing groups of products that have to be mutually compatible.

2.2.2 The Growing Importance of Compatibility Specifications

Prior to roughly 1980, the creation of standards in telecommunications was, for the most part, a technical activity confined to experts within one company or to small teams of specialists nominated by their employers. In the telecommunications industry, standards were typically produced by representatives of national monopolies. When a single company produced a specification, the task of the experts was to formulate recipes for producing products that conformed to existing technology. Committees spanning several companies, usually from different countries, had the task of ironing out differences between similar, but not identical, approaches. In the late 1990s, this situation is rare. Standards groups today are battlegrounds where company representatives assert the interests of their employers and work to block competitors from gaining an advantage. Several circumstances explain this transformation.

Long-standing telecommunications monopolies are rapidly disappearing. Traditionally, companies like AT&T and government-owned post, telegraph, and telephone authorities (PTTs) set national standards. With their monopoly status gone, these companies no longer have the authority to dictate standards. Their competitors have a stake in the details of emerging standards, and often their interests are at variance with those of the former monopolies. This situation has opened the way for many more players in the standards arena, and for more contention, which together demand substantially more company resources. Twenty years ago, telecommunications standards were set by groups of experts working together to achieve a good technical solution. Today, standards are set by representatives of companies, each trying to obtain maximum advantage for their organizations.

In the 1970s, IBM derived enormous wealth and power from its ownership of mainframe computing standards. Today, Microsoft and Intel together hold a similar advantage in the realm of personal computing. It is an interesting paradox that their monopolies in software and microelectronics emerged concurrently with the eclipse of the world's telecommunications monopolies. This situation attracts the attention of everyone in the information technology industries who recognize the critical importance of standards to their businesses. It engages the U.S. government. The executive branch works to restrain Microsoft by exercising antitrust oversight, while the courts define the limits of the power Intel derives from its intellectual property rights.

Technologies have become increasingly complex and interdependent as the number and diversity of components that have to interact to produce an effective information system grow. In a system, the merits of each component depend not only on the quality of the particular component but also on how it functions in the presence of all the other components. Compatibility standards govern the interfaces between system components and critically influence the quality of a system. With the increasing complexity of a system, the task of producing a standard that promotes the quality of the system and advances the interests of a specific company requires more and more company resources. In contrast to issues of trade and industry structure, which have attracted increased government attention, technical complexity has in many instances had the opposite effect. Where the government once played a role in determining standards, officials and politicians have decided that the issues are too complex to be decided by administrative means. Instead, they leave standards setting to "market forces," which can assert themselves in various ways, depending on the technology involved.

The expansion of product markets to cover the entire world forces companies to be acquainted with standards beyond their home bases. They need to acquire expertise on existing standards and influence the creation of new standards that will govern their products. This situation also engages governments. Diplomats examine national standards ranging from the characteristics of rice to automobile pollution controls and argue about whether they really promote quality and safety or whether they serve as restraints to free trade.

The globalization of communications networks also commands increased attention to standards. For a long time, international communications accounted for a small fraction of information traffic. Under the auspices of the International Telegraphic Union (ITU), monopoly telephone companies collaborated to establish technical interfaces (adaptors) that reconciled differences between the national networks. Relative to compatible products throughout an international network, adaptors incur penalties in efficiency and quality, but these were of little consequence when there was little international traffic. Anticipating the growth of international communications, in the 1960s telephone industries moved toward product standardization for digital telephony. In the 1990s, with international calling a conspicuous growth area for telephony and the worldwide Internet expanding rapidly, global standards no longer are a side issue. All the other factors that lead to increased standards activity come together in the international scene, where their complexity is compounded by the need to reconcile differing national and regional interests.

2.2.3 The Economics of Compatibility

The academic community, recognizing the growing importance of compatibility specifications in an information society, has since the mid-1980s taken increasing interest in compatibility. Studies of compatibility fall into two categories, case studies and economic models. Many of the economic models focus on the effects of positive externalities. They address the question of whether markets with network externalities are "efficient," in the classical economists' sense of producing socially optimal characteristics.[6] Typically, a model describes a market containing products that conform to two or more competing standards, each with its own price. Owing to the presence of externalities, the value of a product to a consumer depends on the number of compatible products. Consumers choose among competing products on the basis of price and assumptions about the decisions of other consumers.[7] Other elements of mathematical models describe pricing policies of suppliers. Although the models differ with respect to details such as the nature of the information available to consumers,[8] they generally imply that in the presence of positive externalities, markets have multiple equilibrium points, including some that are suboptimal. An equilibrium point is the set of long-term marketshares of the competing products. Many equilibrium points of the mathematical models are characterized by a single product capturing the entire market. Videocassettes and operating systems for IBM-compatible computers are examples of markets that converged to a single standard.[9]

To economists, an important consequence of network externalities is that market forces cannot, in general, guarantee socially optimal results. This phenomenon differs from the classical economic situation, in which the "invisible hand" of the market produces a unique, efficient equilibrium point with an optimum balance of costs and benefits.[10] The reason that markets are inefficient in the presence of externalities is that they lack "coordination mechanisms" for inducing people to make decisions that take into account the long-term benefits of a large market for a single product. Another implication of these studies is that the actual equilibrium point achieved depends mathematically on initial conditions, or, in practice, on early decisions in the history of competing products. Peter Passell, in an article aptly titled "Why the Best Doesn't Always Win," refers to *path dependence*, "the idea that small random events at critical moments can determine choices in technology that are extremely difficult and expensive to change."[11]

These properties of the economic models have an important bearing on another variable of many models, the proprietary relationship of producers to the standard products. For

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[6]Paul A. David and Shane Greenstein, "The Economics of Compatibility: An Introduction to Recent Research," *Economics of Innovation and New Technology* **1** (1990), 33.

[7]Michael L. Katz and Carl Shapiro, "Technology Adoption in the Presence of Network Externalities," *Journal of Political Economy* **94**, 4 (1986), 822-841.

[8]Farrell and Soloner.

[9]Gabel (1991); for videocasettes, see Chapter 3, for computers, Chapter 2.

[10]Joseph Farrell, "The Economics of Standardization: A Guide for Non-Economics," in *An Analysis of the Information Technology Standardization Process*, edited by John L. Berg and Harald Schumny (Amsterdam, North-Holland: Elsevier Science Publishers B.V., 1990), 189-198.

[11]Peter Passell, "Why the Best Doesn't Always Win," *The New York Times Magazine*, May 5, 1996, 60-61.

example, some standards are "sponsored" in the sense that one supplier has property rights (typically a patent) to the technology embodied in the standard. In this situation, a sponsor can provide coordination by employing pricing strategies that affect the market equilibrium point. This strategy can lead to an inefficient result when the market converges to a single standard that is inferior to an alternative. That standard will remain in place when conversion costs make it undesirable to move to the alternative. In this situation, the market is said to possess "excess inertia." There are also models that exhibit "excess momentum," with consumers moving from one technology to an inferior one. Excess momentum is stimulated by the "bandwagon effect," which occurs in markets with positive externalities.

In addition to these aggregate properties of markets for products that require compatibility, economists have characterized the effects of adoption strategies on stakeholders. An important issue is the adoption strategy of a producer entering the market. A firm entering the market too early risks being "locked in" to an inferior technology. On the other hand, delayed decisions can result in "stranding" while the competition runs away with the market.

Generally speaking, the economic models of compatibility display the usual advantages and disadvantages of using mathematics to describe social phenomena. By distilling extremely complex phenomena into a manageable number of variables, they provide insights into the interrelated effects of major phenomena. Specifically, the papers on compatibility[12] shed light on the importance of the structure of the producer market and of timing in decisionmaking in the presence of the positive feedback produced by externalities. The degree of abstraction in the models, however, makes applying them quantitatively to real-world situations very difficult.[13] The best one can do is examine case studies of compatibility and look for the qualitative effects predicted by the economic models.

2.2.4 Examples of Compatibility

The other approach to understanding the effects of compatibility specifications is to study the history of specific products and industries in order to identify patterns of general relevance. Research in the 1980s examined historical examples, most prominently typewriter (and now computer) keyboards.[14] Later work concentrated on contemporary technology. Two excellent examples of recent work are H. Landis Gabel's *Competitive Strategies for Product Standards: The Strategic Use of Compatibility Standards for Competitive Advantage* (1991) and Martin C. Libicki's *Information Technology Standards: Quest for the Common*

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[12]David and Greenstein (1990).

[13]David and Greenstein (1990) conclude their excellent review with the comment that "the modelling exercises have run well ahead of the solidly established fact base."

[14]Paul A. David, "Understanding the Economics of QWERTY: The Necessity of History," in *Economic History and the Modern Economist* (Oxford: Blackwell, 1986).

Byte (1995).[15] Libicki's study focuses on computer software standards, while Gabel's discusses many different products, including videorecorders, computers, automobiles, and software. Gabel's analysis, embodied in twelve hypotheses,[16] focuses on markets and company strategies, the same phenomena addressed in the economic models. By considering the content of several standards with different histories, Libicki's analysis adds an important dimension not addressed by other research on standards. In asking "What makes a good standard?" Libicki examines a key issue considered only in an abstract way in the economic models.

Among all the studies of information technology standards, telecommunications products appear in only a few. The most detailed telecommunications study examines AM stereo broadcasting[17] in the United States. Until the 1980s, the Federal Communications Commission (FCC) mandated specific signal formats in radio broadcasting. With AM stereo, the FCC took a new approach that allows each broadcaster to choose from a menu of acceptable standards. This approach is now in effect for PCS. Another telecommunications case study,[18] of the workings of an international committee, addresses the strategies and influence of companies represented on the committee. The study closest to the subject matter of this report, however, is an analysis of the Telepoint industry (Telepoint is essentially a cordless payphone system) in the United Kingdom.[19] British industry pioneered a new technology for this service, and the government adopted a "hybrid" approach to standardization that mandates some properties of Telepoint and leaves the choice of others to individual firms. Grindley and Toker attribute the eventual failure of the Telepoint industry in part to the details of this policy. Grindley's conclusions can be stated in the vocabulary of the theoretical work cited in section **2.2.1**. In this context, Grindley and Toker can be said to assert that Telepoint suffered from insufficient market coordination and that the diversity of standards inhibited the externalities needed to make Telepoint viable.

2.3 Issues Addressed Here

This is the first case study of PCS compatibility specifications in the context of the general view of compatibility standards described in the preceding sections of this chapter.

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[15](Newton, Mass.: Butterworth-Heinemann, Digital Press).

[16]Gabel (1991) Chapter 6, 171-199.

[17]Federal Communications Commission, *In the Matter of AM Stereophonic Broadcasting, Docket 21313*, Report and Order, March 4, 1982.

[18]Martin Weiss and Marvin Sirbu, "Technological Choice in Voluntary Standards Setting Committees: An Empirical Analysis," *Economics of Innovation and New Technology* **1** (1990), 11-134.

[19]Peter Grindley and Saadet Toker, "Regulators, Markets and Standards Coordination: Policy Lessons," *Economics of Innovation and New Technology* **2**, 4 (1993), 319-342.

For each of seven standards, this report addresses four issues: the creation of the standard, the status of the standard, figures of merit, and adoption.

2.3.1 Creation and Adoption of Standards

The source of a standard can have a significant effect on its properties, its merits, and its adoption. Greenstein (1993) generalizes Adam Smith's metaphor of "an invisible hand" to establish a taxonomy of markets for products that conform to compatibility specifications. He refers to the classical economics market with many sellers and buyers as a situation with "too many hands." As Greenstein's image implies, this situation is undesirable, because in it no stakeholder has sufficient incentive to provide the coordination necessary to realize the benefits of externalities. At an early date, Hemenway (1975) pointed out that open standards are "public goods," in the sense that they benefit everyone in a market equally. As a consequence, individual firms lack an incentive to go to the expense of creating them.

Greenstein uses the image of "hand to hand combat" to describe the familiar situation in which a few sponsored standards battle to dominate a market. This situation, analyzed by Katz and Shapiro, is familiar in many information technology industries; for example, videocassette formats (Video Home System [VHS] versus Betamax) and microcomputers (IBM versus Apple). A third situation is "a strong hand," which is a market with a single standard sponsored by a dominant seller, which Greenstein refers as "the traditional market of telephone networks."[20] There are many examples of it in the cellular communications industry. Although this market has no coordination problem, monopolies, of course, produce other economic problems. There are several cellular telephone examples of strong hands.

Although too many hands, hand to hand combat, and strong hands all involve standards creation by individual companies, voluntary organizations with representatives of many organizations play a prominent role in creating information technology standards. Greenstein refers to such organizations as "invisible advisors." The standards produced by invisible advisors are public goods as described by Hemenway (1975), yet companies find strong incentives to participate in these organizations. Gabel puts forward a hypothesis that "a dominant firm will oppose and weak firms favor multi-firm standardization (open standards)."[21] Nondominant firms benefit from the existence of open standards even when they do not participate in their creation. These firms, however, often have incentives to influence the details of standards. Firms with a dominant market position can also be found participating in voluntary standards setting, sometimes to slow the process in order to

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[20]Shane M. Greenstein, Invisible Hands versus Invisible Advisors: Coordination Mechanisms in Economic Networks, University of Illinois, Champaign-Urbana, January 1993, 16 [unpublished].

[21]Gabel, 178.

postpone emergence of a new standard that would compete with prevailing ones. For examples of PCS standards created by voluntary organizations, see **Chapters Three** and **Four**. Greenstein does not offer a metaphor for them, but there are important examples, in the PCS industry and elsewhere, of markets in which a strong hand (sponsored standard) competes with an invisible advisor (standard from a voluntary organization).

2.3.2 Status of Standards

This report classifies PCS standards according to three criteria: statutory force, ownership, and scope. Some of the standards encountered in this report are *mandatory*, others are *voluntary*. Government regulations that mandate conformance to a specific standard provide a coordinating mechanism for realizing network externalities. Coordination was the approach taken by national authorities in the early 1980s, when the original cellular systems were introduced, and it has also been adopted on a continental scale for second-generation systems in Europe. In the United States, on the other hand, in the 1980s the FCC adopted the view that coordination is a commercial issue and outside the Commission's spectrum management responsibilities. Since 1990, in the United States PCS standards have been voluntary.

Another classification of a standard is based on whether it is *proprietary* or *open*. The standards literature examines the positions of stakeholders with respect to this property, pointing out that large companies can generally benefit from ownership of a proprietary standard, while small companies often favor open standards. In PCS, there are several intermediate situations in which there are published standards that specify technology covered by various patents and other intellectual property rights. Standards organizations have a variety of ways of dealing with this intellectual property. One way is to publish in the standards document a warning that organizations wishing to adopt this standard may be barred from doing so by the owner of the technology incorporated into it.[22] Another is to obtain in advance agreements from owners of the technology to license it on a nondiscriminatory basis to anyone adopting the standard. The European Telecommunications Standards Institute (ETSI) takes this approach to a controversial extreme by establishing procedures that strongly inhibit the adoption of standards covered by intellectual property that is not available on "fair, reasonable, and non-discriminatory terms."[23]

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[22]Telecommunications Industry Association, "Mobile-Station Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System," *Interim Standard 95*, July 1993.

[23]Frede Ask, "Interoperability and Intellectual Property," in *Standards Policy for the Information Infrastructure*, edited by Brian Kahin and Janet Abbate (Cambridge, Mass.: MIT Press, 1995), 405-409; also in Kahin and Abbate, William Ellis, "Intellectual Property Rights and High Technology Standards," 450-454; and Mark Shurmer and Gary Lea, "Telecommunications Standardization and Intellectual Property Rights: A Fundamental Dilemma?" 378-402. ETSI, "Rules of Procedure," Annex 6, Nov. 18, 1997.

The growing number of telecommunications standards covered in part by intellectual property rights has had a strong influence on the standardization process. It has played a major role in the transformation of standards organizations from forums of experts seeking consensus on technical issues into battlegrounds for the assertion of competing commercial interests.

The third property studied in the context of PCS is the scope of a compatibility specification. PCSs are complex networks. Each compatibility specification prescribes the details of one or more network interfaces. PCS standards vary widely in scope. Some are *comprehensive*, specifying many network interfaces in great detail. Others are *narrow*, leaving many characteristics of network elements and the interfaces between network elements to the discretion of equipment vendors. The scope of a standard can have an significant influence on the relative fortunes of the various PCS stakeholders. In their paper on Telepoint, a relative of PCS, Grindley and Toker attribute the failure of the Telepoint industry in the United Kingdom to the narrow scope of the compatibility specification.

2.3.3 Figures of Merit for Standards

There are several criteria for evaluating standards. Some are *intrinsic*, referring to the document that embodies the compatibility specification. Others are *extrinsic*, referring to how well the technology embodied in the standards meets the needs of its users. One example of an intrinsic figure of merit is whether the standard is well defined, in the sense that it is clear whether a piece of equipment conforms to it or not. The famous QWERTY typewriter standard ranks high on this intrinsic figure of merit. Yet QWERTY is inferior to other standards with respect the extrinsic criterion of typing speed.

In addressing the question of "What makes a good standard?" Libicki[24] refers only implicitly to extrinsic figures of merit. Stating that correct timing is important to the quality of a standard, he refers to an intrinsic quality and in doing so makes the point that good results are more easily achieved when the technology matures before the market. This situation has prevailed in telecommunications as well as other areas of information technology. It also applied to the original analog cellular systems, developed in the 1970s, using established radio transmission techniques. On the other hand, the digital cellular and PCS standards created since the 1980s, conform to Libicki's "hard case," in which the market matures before the technology and the standard is less likely to embody the best available technology. Compounding the difficulty of achieving good extrinsic results with immature technology is the complexity of the extrinsic figures of merit of cellular and PCS systems. I have identified

[24]Libicki, 14.

twenty figures of merit of a wireless communications system.[25] Each standard represents compromises among these twenty criteria.

This report summarizes these extrinsic figures of merit in three categories: *signal quality*, *bandwidth efficiency*, and *equipment costs*.

With respect to intrinsic figures of merit, *timing* is itself an important criterion in Libicki's hard case. All else being equal, a standard that is available early will satisfy pent-up demand better than a later one. Libicki refers to *extensibility* as a characteristic of a good standard that can mitigate the risks associated with adopting standards in an environment of technological uncertainty. An extensible standard can absorb technology advances without making existing equipment obsolete.

2.3.4 Adoption of Standards

Beyond extrinsic and intrinsic merits, a crucial issue for a standard is the extent of its adoption. Taking the view of the impresario who said, "Great opera is a full house applauding," the ultimate test of a standard may be the extent to which it is adopted. The literature on standards contains many theoretical models and case studies related to adoption decisions. Adoption involves two communities, vendors, that is, the equipment manufacturers, and users, the purchasers of services and equipment. In PCS, the vendor community can be divided into two further overlapping communities, manufacturers of infrastructure and manufacturers of consumer products. In addition, the user community is two-tiered, consisting of service providers (e.g., cellular telephone companies) and service subscribers. The adoption decisions of all four communities influence one another and together determine the extent to which a standard is *successful* by Libicki's criterion of market acceptance.

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[25] David J. Goodman, *Wireless Personal Communications Systems* (Reading, Mass.: Addison Wesley, 1997), Chapter 2.

Chapter Three

First-Generation Cellular Systems

3.1 The Cellular Idea

The cellular idea originated at AT&T in 1947,[1] reached technical maturity in the early 1970s, and went into commercial service in the United States in 1983. The original motivation behind cellular was the telephone industry's desire to extend its reach beyond homes and businesses—where it was approaching market saturation—to vehicles. The introduction of telephones into vehicles began in St. Louis in 1946 and quickly reached other large cities. Technically, the original radio telephone system resembled frequency modulation (FM) radio broadcasting. A single high-power radio station transmitted signals to vehicles in a geographical area extending as far as 50 kilometers (km). The same station received FM signals transmitted by radio telephones in the vehicles. Although technically sound, this method was severely limited, because the number of possible simultaneous telephone calls in a city could not exceed the number of two-way radio channels. That number started at six and increased gradually, thanks to technical advances and new radio spectrum allocations. But a system with a single radio station per city offered no prospect of increasing the number of channels to meet the growing needs of a mass consumer market.

Cellular operation overcomes this bottleneck. The key to the cellular idea is "channel reuse," which allows each radio channel to carry multiple conversations in the same city. Instead of covering an entire city, the range of each cellular radio transmitter is limited to a few kilometers; in densely populated areas, it is less than 1 km. A city contains hundreds of radio "base stations," each serving a small geographical area referred to as a "cell." A single radio channel carries dozens of conversations in different cells. The conversations do not interfere with one another, because each radio transmits at low power and there are gaps between cells using the same channel. By the time a signal reaches another cell using the same channel, it is too weak to cause interference to the remote conversation. Systems begin with a few large cells, to serve their original customers, and then install new base stations as the subscriber population grows. The process of adding base stations to increase capacity is referred to as "cell splitting."

Handoff is a key procedure in a cellular system. In order to serve a mobile population, the system has to be prepared for users to move through several cells in the course of a conversation. As this occurs, a sophisticated control system automatically hands the call from

[1]W. R. Young, "Advanced Mobile Phone Service: Introduction, Background, and Objectives," *The Bell System Journal* **58**, 1 (January 1979), 8.

one radio station to another. The locus of control is a mobile switching center (MSC), which routes calls to and from the public network and also manages the radio channels in as many as a hundred cells. The four principal ingredients of the cellular idea, according to Calhoun,[2] are the following:

1. Low-power transmitters and small coverage zones or cells
2. Frequency reuse
3. Cell-splitting to increase capacity
4. Handoff and central control

Every cellular system has three types of equipment, as shown in the configuration of a cellular system depicted in **Figure 3-1**: at least one MSC, several base stations (around 100 maximum) connected to the MSC, and mobile telephones.

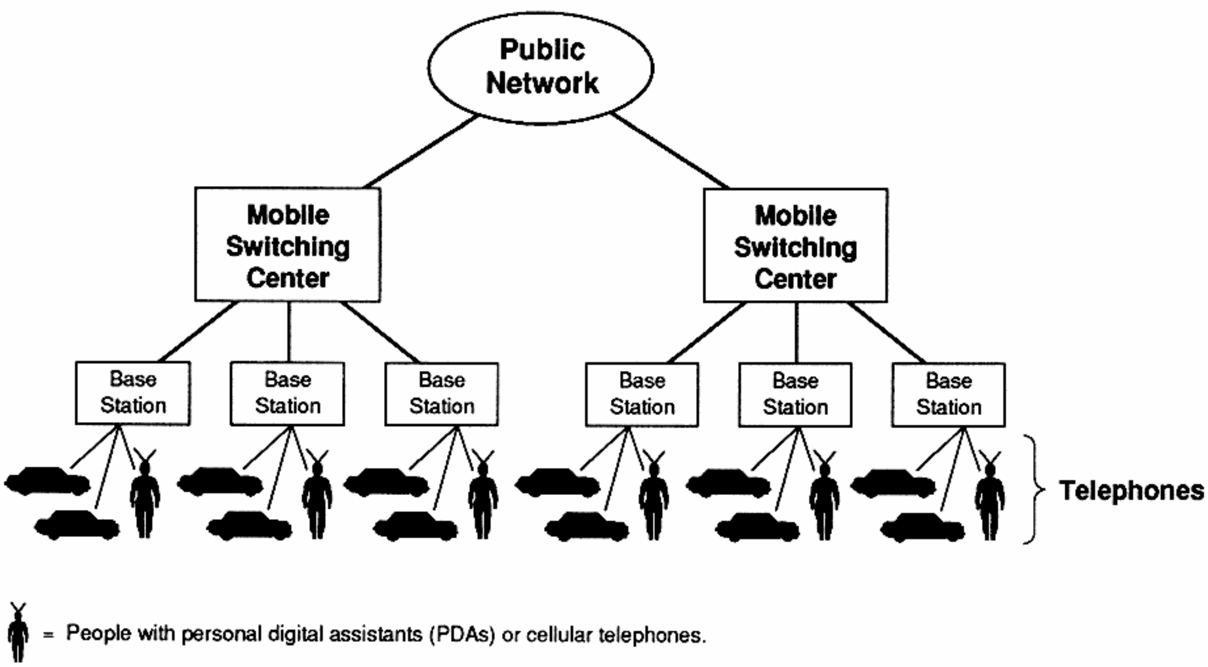

Figure 3-1

Elements of a Cellular System

[2]George Calhoun, *Digital Cellular Radio* (Norwood, Mass.: Artech House, 1988), 44.

3.2 Introduction of Cellular Service into the United States

Three processes account for the thirty-six-year gap between the origin of the cellular idea and the commercial introduction of cellular service in the United States in October 1983, all of which played roles in determining the status of cellular standards: technology development, radio spectrum allocation, and government deliberations about industry structure.

3.2.1 Technology

The two core technologies in a cellular system are mobile radio transmission and telephone switching. The leading U.S. companies in these industries, Motorola and AT&T, respectively, played active roles in system development. In the 1960s and 1970s, AT&T conducted the research and development necessary to transform the cellular idea into a practical system.[3] With the technical foundations of cellular systems established, both Motorola and AT&T produced system designs that formed the basis of technology trials performed in 1979 in Chicago (AT&T) and Baltimore–Washington (Motorola) which proved the feasibility of cellular operation. Their success led to the establishment of a standards committee within the Electronic Industries Association (EIA) which smoothed over the differences between the AT&T and Motorola systems and produced the advanced mobile phone system (AMPS), a compatibility specification adopted by the EIA as Interim Standard 3 (IS-3). In 1982, when the FCC issued the rules for commercial cellular service, IS-3 became a mandatory transmission standard, and it was eventually adopted by the American National Standards Institute (ANSI) as an American National Standard.[4]

The formal name of IS-3 is "Mobile Station–Land Station Compatibility Specification," and its stated purpose is to "ensure that a mobile station can obtain service in any cellular system."[5] Operationally, this means that base stations and mobile telephones built in accordance with the specification will be able to set up telephone calls to and from mobile telephones and maintain calls as the mobile phones move from cell to cell. The most prominent part of the specification is radio transmission by means of FM.

In addition to FM radio transmission, the standard requires elaborate coordination of network management operations at the three constituent parts of an AMPS system: the mobile switching center, the collection of base stations connected to the MSC, and thousands of mobile telephones. Although system coordination by the MSC is essential in AMPS, it is not

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[3]*Microwave Mobile Communication*, edited by W. C. Jakes (N.Y.: Wiley, 1974).

[4]*Mobile Station Land Station Compatibility Specification, ANSI* [American National Standards Institute]*/EIA/TIA* [Telecommunications Industry Association] *Standard 553*, Electronic Industries Association (1989), 398.

[5]Ibid., 399.

covered explicitly by the standard. Details of coordination, in particular the interface between switching centers and base stations, are proprietary to, and closely guarded by, each vendor of base-station and switching equipment. The result of this closed interface is that network operators must purchase all equipment in an AMPS system from the same source. Put another way, operators have no opportunity to mix and match base stations and switching centers.

In summary, every AMPS system operates with two compatibility specifications. One, governing the "air interface" between telephones and base station, is open. The other, between switching centers and base stations, is proprietary. This situation has led to the existence of two cellular equipment industries with different characteristics, an infrastructure industry that produces base stations and switches and a mobile telephone industry.

The most impressive AMPS innovations are incorporated into its network management operations, which allow computers at the MSC to keep track of the locations of mobile telephones, specify the channels they use, and control the power levels of their transmitters. The system maintains control by means of messages transmitted between network components. To carry many of these messages, AMPS dedicates a minimum of twenty-one radio channels to coordinating network control tasks. These "common control channels" are unavailable for carrying conversations.

3.2.2 Radio Spectrum

The common control channels place an overhead burden on an AMPS system that is relevant to radio spectrum allocation, a contentious issue during much of the thirty-six-year gestation period of AMPS. In the United States, the Communications Act of 1934 established the FCC as guardian, on behalf of the public interest, of access to the radio spectrum. After twenty years of wrangling between the broadcast television industry and the telephone industry, in 1974 the FCC established two 20-MHz spectrum bands for cellular services: 825–845 MHz for transmissions from mobile telephones to base stations and 870–890 MHz for transmissions from base stations to mobile phones. Originally, these bands had been allocated to ultrahigh frequency (UHF) television broadcasts in channels 70–83. According to the AMPS standard, the available spectrum is divided into 30-kilohertz (kHz) channels. A pair of channels carries one conversation or serves as a common control channel (see section **3.2.1**). Thus, the original AMPS spectrum assignment provided for 40 MHz $\div$ (2 x 30 kHz) = 666 two-way channels. In 1988,[6] the FCC added 10 MHz to the AMPS allocation, which brought the number of two-way channels to the present (1997) total of 832 and met AT&T's request for a number large enough to offset the overheads imposed by the presence of the common control channels.

[6]Asha Mehrotra, *Cellular Radio: Analog and Digital Systems* (Norwood, Mass.: Artech House, 1994), Table 1.2, 5.

3.2.3 Operating Companies

In addition to technology and spectrum allocation, the third major issue that occupied the FCC's attention through much of the gestation period of cellular was which companies would be granted licenses to operate cellular services. The main contender was AT&T, which regarded cellular as an expansion of its existing network. Opposing this view was that of the radio common carrier (RCC) industry, which had originated in 1949, when the FCC had allocated new spectrum to radio telephone service and licensed the new spectrum to operators outside the telephone industry. In regulatory nomenclature, a telephone company is a wireline common carrier (WCC). Under FCC guidance, the RCC industry grew in the number of mobile radios served at approximately the same rate as the WCC industry.[7] Although they operated with commensurate numbers of radio channels in aggregate, RCCs and WCCs differed dramatically in the nature of their operating industries. The WCCs were telephone monopolies, dominated by AT&T, while the hundreds of RCCs scattered around the United States were mainly small businesses.

Notwithstanding its dispersal and the small size of its constituents, during the years the FCC deliberated on cellular issues the RCC industry increasingly asserted its claim to operate cellular services. In doing so, it had the support of the Justice Department and of its most prominent equipment supplier, Motorola.[8]

The FCC's deliberations on the structure of the cellular industry took place in two dimensions, radio spectrum and geography, that is, the area covered by each cellular license. The FCC resolved the geographical issue by establishing no fewer than 733 licensing areas, with vastly different populations. The 308 largest are classified as Metropolitan Statistical Areas (MSAs); the other 425 are Rural Services Areas.

In the spectrum dimension, the question was whether to allocate all the AMPS channels to one operating company in each service area or a fraction of the channels to each of several companies. The issue was the conflict between efficiency and the benefits of competition. Efficiency here has two components: (1) the traditional economist's view, which considers economy of scale and natural monopoly concepts as applied to the telephone industry and other utilities, and (2) the aspect that telephone engineers call "trunking efficiency." According to the trunking principle, more customers can be served with a given quality of service if a system grants all of them access to all the channels, rather than segregating customers into groups with each group served by a fraction of the channels. (A post office applies this principle when it has one queue that leads to all postal clerks rather than separate

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[7]Young, Table II, 6.

[8]Calhoun, 52-53.

queues for each clerk.) Lee[9] demonstrates mathematically that trunking efficiency erodes quickly when the cellular spectrum is carved into smaller and smaller blocks of channels, with each block available to customers of a single operating company.

In its deliberations, the FCC gave high priority to promoting efficient use of the radio spectrum. Accustomed to dealing with a monopoly telephone industry, in 1974 the FCC announced a decision to assign all the channels in an area to a single operating company. Any company could apply for the license, but the assumption was that it would go to a WCC, rather than an RCC. The RCC industry challenged this decision, and, in 1982, the FCC succumbed to pressure from RCCs, the Justice Department, and a Federal Appeals Court to balance its interest in efficiency with the benefits of competition[10] and "cut the baby in half," assigning half the cellular spectrum (designated the "B band") in each area to a WCC and half (the "A band") to a nonwireline company.

Although this decision appeared to open the way for the entry of RCCs into the cellular industry, as a general rule that did not happen. The eventual structure of the cellular industry was determined by factors that played no role in the deliberations by the FCC that led bifurcation of the cellular spectrum. The first factor was the divestiture of AT&T into eight separate corporations, which occurred on January 1, 1984, less than three months after the initiation of commercial cellular service in the United States. AT&T's divestiture had two opposing effects on the structure of the cellular industry. The first effect was to fragment the WCC (B band) industry by replacing the single AT&T entity, which had covered 85 percent of the United States, with seven companies that have approximately equal slices of the original AT&T pie. The consent decree that governed AT&T's divestiture mandated that the cellular operating companies owned by AT&T's seven regional descendants (sometimes called "baby Bells") be operated as subsidiaries, separated from their monopoly telephone operations. This statutory isolation gave many of the Bell cellular operating companies the flavor of start-up operations in a new industry with corporate cultures far different from those of their parent companies that had seventy-five years of experience of prosperous monopoly operation.

To counteract this fragmentation of the B band, FCC regulations gave the baby Bells an opportunity to aggregate strength in the A band, reserved for nonwireline companies. The opportunity was derived from the classification of each of the baby Bells as a nonwireline

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[9]W. C. Y. Lee, *Mobile Cellular Telecommunications Systems* (N.Y.: McGraw-Hill, 1989), Figure 1.2, 7. The calculations do not take into account the effects of twenty-one dedicated control channels per operating company, but these make the case for confining spectrum allocation to the smallest possible number of companies even more compelling.

[10]Calhoun.

carrier outside its home region. Some companies seized on this status to pursue A-band licenses wherever they could get them.

The other event with a strong influence on industry structure was the FCC's decision to hold lotteries to issue A-band licenses in all regions except for the thirty largest MSAs. The lotteries replaced comparative hearings, which had favored established communications companies, as a basis for awarding cellular licenses. The effect was to open up a gold rush for cellular spectrum that attracted speculators from all parts of the economy. (There were 90,000 license applications for the 275 MSA licenses.) The first beneficiary of a lottery was the winner, often a limited partnership formed for the sole purpose of obtaining a cellular license. In many instances, the winner quickly sold its license to an aspiring system operator. The overall effect was a balkanized cellular industry, with hundreds of players of widely disparate backgrounds, sizes, and goals.

Industry fragmentation left the United States in a paradoxical state relative to other countries. From the outset, it had had a single standard (which in fact extended throughout Canada) governing interoperability of base stations and mobile telephones. The licensing arrangements and proprietary status of MSCs, however, made it difficult for a subscriber to use a cellular phone outside the local service area. Such use was expensive (exorbitant roaming surcharges were imposed) and, in many cases, awkward, because of the need to dial special phone numbers and signaling codes to initiate or receive calls. A further complication was the prohibition of the Bell companies from providing long-distance service, a condition of divestiture. The formal definition of "long distance" made it impossible for the cellular subsidiaries to maintain calls in progress when subscribers crossed service-area boundaries, even when two areas were served by compatible equipment operated by the same Bell company.

To overcome the technical and economic problems introduced by this fragmentation, the cellular industry in the 1990s has moved aggressively toward consolidation through mergers and acquisitions. Gustave Barth, in documenting this process, notes that by 1993, 92 percent of cellular subscribers were served by only eighteen operating companies, most of them large wireline telephone companies.[11]

3.3 Introduction of Cellular Service into Europe

Each country has a different story, but there were consistent patterns in most of Western Europe. The prominent theme was the establishment of national networks, with each operating company providing service throughout an entire country. Except in the United Kingdom, the

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[11]Gustave Barth, *Cellular Phones: Is There Really Competition?* (Cambridge, Mass.: Harvard University Program on Information Resources Policy, P-94-3, August 1994), 17.

government-owned monopoly telephone company[12] in each country also monopolized cellular services. In the U.K., two private companies (one half-owned by British Telecom, the dominant wireline carrier) shared the cellular spectrum.

With the exception of the five Nordic countries (Denmark, Norway, Sweden, Finland, and Iceland) with a common system, each country in Europe made its own decisions about radio spectrum and technology. Most systems operated in frequency bands around 450 MHz, others were around 900 MHz, and the French analog cellular system occupied some channels near 200 MHz and others near 450 MHz. By 1990, there were seven different radio transmission systems in place in Western Europe,[13] all incompatible, in that telephones designed for one system could not operate with base stations designed for another. In France, Germany, and Italy, the systems were confined in application to a single country. Two systems were adopted in a few countries distant from one another, but not always in the same frequency bands. The total access communications system (TACS), a close relative of AMPS, appeared first in the United Kingdom and later as a second system in Italy, Austria, and Spain. The Nordic Mobile Telephone System (NMT) went into service in Scandinavia in 1981, two years earlier than in the United States. It was later adopted in the Netherlands and Austria and eventually in France as a second system. NMT comes in two incompatible flavors, a 450-MHz version and a 900-MHz one.

The result, from a subscriber's point of view, was a national (regional, in the case of the Nordic countries) system that allowed full roaming within the borders of the home country. To enjoy mobile phone service while traveling elsewhere in Europe, however, the subscriber required an array of telephones and a separate subscription in each country entered.

3.4 Stakeholders in Europe and the United States

Table 3-1 summarizes the situation in 1990. The United States had a single technology standard operated by a host of companies, each serving a collection of service areas. Although every telephone was technically capable of operating with every base station, roaming outside the local service area depended on a patchwork of business arrangements that were unpredictable by subscribers. Roaming was inhibited also by the proprietary status of the communications links to each switch that controlled services in each operating area. Europeans enjoyed full roaming within each country but limited opportunities to use their telephones outside national (regional, in the Nordic countries) boundaries.

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[12]No distinction is being made here between a government-owned corporation and a telephone operating entity (PTT) that was a branch of government.

[13]T. S. Rappaport, *Wireless Communications Principles and Practice* (Upper Saddle River, N.J.: Prentice Hall, 1996), 548; M. Mouly and M.-B. Pautet, *The GSM System for Mobile Communications* (France: Palaiseau, 1992), 27.

Table 3-1

First-Generation Cellular Systems

	Europe	United States
Networks	National networks	733 separate service areas
Roaming	Full roaming within each country	Inconsistent, awkward roaming arrangements
Radio Transmission	Incompatible standards in different countries	Common standard throughout the U.S. and Canada
Operating Companies	National monopolies (duopoly in the U.K.)	Dozens of regional companies; duopoly in each service area

Although the table displays the stark differences between technologies and operating arrangements in the United States and Europe, one critically important element was common to both continents: a public appetite for cellular services that each year exceeded even the most optimistic predictions. As this appetite became apparent, it stimulated the active interest of governments and business communities. In the early 1980s, cellular service appeared to serve the convenience of telephone users with high budgets and special needs, but by the late 1980s, it was increasingly clear that cellular provided a new information service to a mass consumer market. Second-generation systems (see **Chapter Four**) apply advanced technology to meet the needs of a population with rising expectations of the benefits of personal communications.

Before considering the second-generation cellular PCS picture, it is helpful to describe the five categories of cellular stakeholders, which are identified in **Figure 3-2**, and the situation of each in 1990. As the figure shows, consumers obtain service, and in many places equipment, from operating companies, although in some places, they can obtain telephones from retailers. The operating companies purchase base stations and switches from infrastructure vendors. Governments influence the entire industry by regulating market entry, allocating radio spectrum, and setting technical standards for radio transmission. In first-generation systems, operating licenses were tied to mandatory radio-transmission standards.

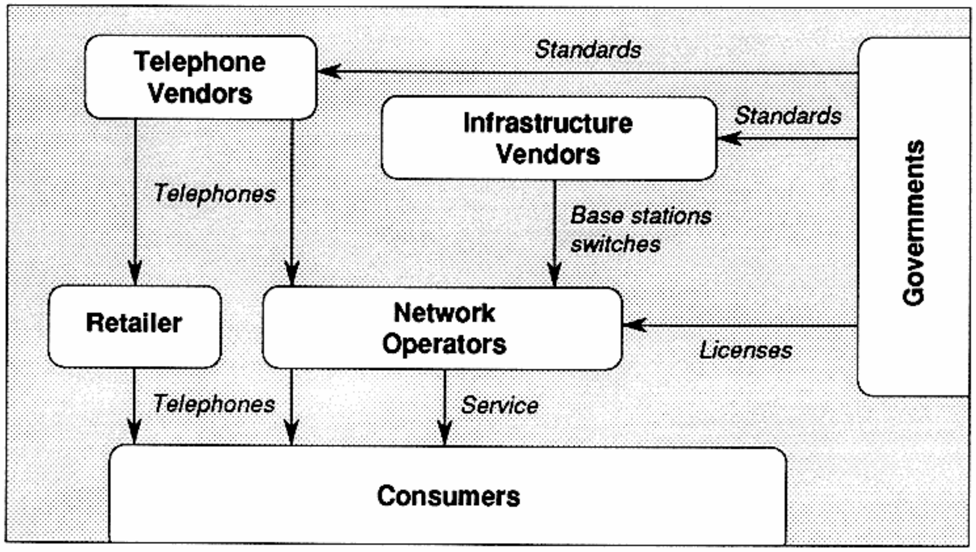

Figure 3-2

Cellular Stakeholders

3.4.1 Consumers

In 1990, the situations in the United States and Europe were different, but the salient characteristic of consumers was (and remains) their appetite for cellular services. Rapid adoption of cellular services created positive externalities, because the ability to reach people in transit increased the value of all telephones. It also produced economies of scale and network economies that benefited consumers. For example, there were more sources of cellular phones to choose from, and telephone prices fell steadily. A factor that influenced later developments was consumer preference for portable, hand-held, telephones, over vehicle-mounted units.

3.4.2 Network Operators

The distinctive characters of the operating industries in Europe and the United States had a profound influence on second-generation standards. In the U.S., the operating industry was fragmented, and there were many new companies. Another major component was the subsidiaries of regional Bell companies, which operated at arm's length from their owners. As a consequence, the cellular industry in the U.S. had a start-up flavor with expertise focused almost entirely on marketing, rather than technology. This focus placed the industry in a weak position to assert its interests in the creation of second-generation systems. By contrast, the established European telephone operating industry played a major, or exclusive, role in operating cellular services. Its technical expertise was in many countries focused in research organizations resembling Bell Labs, where the cellular idea had been born and nurtured, enabling the European operating industry to exert a major influence on the nature of second-generation cellular technology and standards.

3.4.3 Infrastructure Vendors

The core technologies of the two infrastructure components, base stations and switches, are very different, especially in first-generation equipment. Base stations consist for the most part of radio equipment. The radio technology adopted in the original cellular systems was based on FM, by 1970 a mature technique. Although the market leader for mobile radio equipment in the 1970s was Motorola, there were many other players, and the cost of entry to the FM radio equipment business was not high. By contrast, telephone switching equipment was software intensive, and, except for small systems, expensive to develop. The 1960s and 1970s saw consolidation in the worldwide telephone switching industry, which was eventually dominated by a handful of companies, including three in Europe (Siemens, Alcatel, and Ericsson) and two in North America (AT&T and Northern Telecom). The proprietary nature of the interface between switches and base stations in first-generation systems favored these companies over those with principal expertise in radio technology.

In the United States, four companies emerged with the lion's share of the infrastructure market: AT&T and Motorola, which had developed the first cellular systems, were the early market leaders, then the Swedish company Ericsson and Northern Telecom, based in Canada. Motorola obtained its switching equipment from Digital Switch Corporation and sold complete systems to operating companies. Ericsson made consistent gains as the business expanded, and Northern Telecom had a strong share of the market in Canada and a lesser presence in the U.S. Some European countries had long traditions of protecting telecommunications markets for domestic producers, and this carried into the cellular business. For example, in Germany, Siemens had a lock on the development and production of cellular systems based on the C-450 standard. Elsewhere, where markets were open, Ericsson and Motorola made strong showings. For example, of the two operating companies in the United Kingdom one (Cellnet) deployed Motorola infrastructure equipment while the other (Vodaphone) used Ericsson equipment.

3.4.4 Subscriber Equipment Vendors

As a consequence of the open air interface in cellular systems, the mobile telephone industry has many players. Some, Ericsson and Motorola most prominently, were also infrastructure vendors, while others, like Sony and Panasonic, are large consumer electronics companies. Nokia, a newcomer to mobile radio, has been a conspicuous success, achieving the second highest marketshare (behind Motorola) in worldwide cellular telephone sales. The highly competitive telephone market contributed to rapidly falling prices, which served the interests of other stakeholders. For example, the operating companies could use their purchasing power to drive telephone prices down, thus stimulating demand while maintaining high service prices.

3.4.5 Governments

As indicated in **Figure 3-2**, governments play two roles. As regulators of the airwaves, they influence the technology standards that govern infrastructure products and consumer products. They also regulate the structure of the operating industry. The traditional approach to licenses and standards has been prescriptive, with government regulators deciding not only who will have access to the airwaves but also what kinds of signals they will transmit. The traditional view of industry structure was that telecommunications is a natural monopoly subject to government ownership or tight government regulation. Around the time cellular arrived on the scene in the early 1980s, this approach began to change, moving toward liberalization and privatization, and since then the changes have accelerated. With cellular a new business, it was convenient in many places to apply the more liberal approach to cellular at the outset, in contrast to the fixed telephone network, with its enormous inertia. In both the United States and the United Kingdom, government opened the market to nontraditional companies from the outset. In other countries, competition appeared on the scene when second-generation systems arrived.

Even though both the United States and Europe moved toward liberalization of market entry (if not at the same speed everywhere), they marched in opposite directions regarding standards. Throughout the U.S. economy, the 1980s were years of government deregulation, and the FCC participated in the trend. The FCC narrowed its sights considerably concerning spectrum policy. Instead of overseeing four properties of a transmission technology—quality, efficiency, noninterference, and compatibility—it adopted a spectrum management policy of mandating only noninterference.[14] It determined that the other three issues were best left to the market to decide. The goals of the new policy were to encourage innovation and reduce the time to market of new products and services. In the mid-1980s, the FCC conspicuously applied its new policy toward compatibility to AM stereo broadcasting.[15] The policy had a profound effect on the future of cellular in the United States.

At the same time that the U.S. government was reducing its regulatory role, trends in Europe were moving in the opposite direction. The Conference of European Posts and

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[14]D. J. Goodman, "Government Regulation and Innovation in Information Technology," Chapter 4 in *Information Technology: The Public Issues*, edited by Raymond Plant, Frank Gregory, and Alan Brier (Manchester, U.K.: Manchester University Press; N.Y.: St. Martin's, 1988).

[15]Federal Communications Commission, "In the Matter of AM Stereophonic Broadcasting," Docket 21313, *Report and Order*, March 4, 1982.

Telecommunications (CEPT) Administrations initiated an effort to design a single, pan-European standard for mobile communications. Concurrently, in the ten countries of the European Community (since 1993, the European Union [EU]), regulatory authority moved from national governments to the European Commission in Brussels. Two goals of the Commission influenced cellular communications: promotion of both a unified European economy and a competitive advantage for European businesses. The first goal led the Commission to support uniform continental technology standards, a marked departure from the existing patchwork of incompatible national practices. (Electric plugs and sockets and telephone-calling conventions are examples all too familiar to tourists and international business travelers.) The other goal led the Commission to stimulate research and development in technology areas where it perceived an opportunity to gain an advantage for European companies over tough North American and Japanese competition. How these trends converged to propel PCS in Europe is the subject of the next chapter.

Chapter Four

Second-Generation Cellular and PCS

First-generation cellular technology originated in the United States and was adopted, with various local flavors, in Europe. To a large extent, second-generation technology flowed in the opposite direction. In 1982, when cellular was an infant in Scandinavia and Japan, and merely a fetus elsewhere, CEPT formed a standards organization, the Groupe Spécial Mobile (GSM), to plan a pan-European cellular system. Eventually, the system took the initials of the original planning group and came up with a new name: Global System for Mobile Communications. A corresponding North American effort started six years later.

4.1 Evolution of Technology in Europe

4.1.1 Motivation and Goals of GSM

The initial stimulus for GSM was the designation by the European Commission in 1978 of two frequency bands (890–915 MHz and 935–960 MHz) for mobile services in Europe. To exploit this spectrum allocation, in 1982 CEPT set out to promote a single standard to be adopted in all twenty member nations. This goal had obvious value to consumers in an increasingly integrated European Community. Another beneficiary would be the European manufacturing industry, which would have a large, unified market for second-generation products instead of the separate national markets that were emerging for first-generation equipment. As principal suppliers of equipment to CEPT members and participants in GSM from 1987 onward, European equipment vendors obtained a valuable head start over competitors in North America and Japan.

Before first-generation systems became a reality in the United States, government and industry spent almost four decades (1947–83) resolving three issues—technology, spectrum, and industry structure—with the most difficult decisions centered on the second and third. The second-generation situation was very different, both in Europe and in the United States. Spectrum bands were established first. The GSM committed itself to creating a technical standard that would allow each European country to establish its own industry structure. While that standard was being developed, liberalization of the European telecommunications industry proceeded at a steady pace, and the general pattern throughout Europe eventually was to award half the GSM spectrum to each of two national operating companies. Thus, if the structure of the industry is seen in terms of the dimensions of spectrum and geography, for spectrum, GSM, like AMPS in the United States, has a duopoly, while, for geography, separate national companies operate in each country.

For technology, the GSM, as a standards-creating consortium, found itself in uncharted waters. It began by developing a technology standard without the technology to be standardized!—a marked departure from the usual standards exercise, which is to adopt a preferred configuration of existing technologies. To navigate in this sea of change, the members of CEPT, GSM's parent, had the benefit of substantial technical expertise acquired in their long years as telecommunications monopolies. Thus, for the first years (1982–86), the principal task of GSM was to stimulate, monitor, and coordinate the research and development that would produce the technology to be standardized.

4.1.2 Technology Development by GSM

To perform its tasks, the GSM established three working parties.[1] Working Party 1 was responsible for defining the communications services to be provided by the new system; Working Party 2 addressed the most difficult technical issues related to radio transmission; and Working Party 3 was responsible for network architecture and signaling disciplines. Working Party 3 determined the elements of the GSM network and the flow of information between them. The entire GSM project was strongly influenced by the preoccupation of telecommunications planners in the 1970s and 1980s with integrated services digital networks (ISDN). By 1982, ISDN consisted of a set of standards ("Red Books," published by the ITU) that formed a blueprint for the evolution of separate national telephone systems toward a coordinated digital network carrying all kinds of information.

In formulating service definitions and network interfaces, Working Parties 1 and 3 adopted ISDN precedents, the most important of which were standard network elements with open interfaces between them (see **Figure 4-1**). Starting with the terminals, base stations, and switching centers of analog systems (see **Figure 3-1**), GSM broke base stations into two elements—controllers and transceiver stations. The transceiver stations contain the radio equipment. A controller, which can control several transceiver stations, consists mainly of computer equipment. The GSM architecture defined separate network elements that perform the functions of a single MSC in analog cellular systems. The corresponding GSM network elements are a mobile services switching center and three databases: a visitor location register, a home location register, and an equipment identity register. Perhaps the most important part of **Figure 4-1** is the open A interface, based on an established technology, Signaling System Number 7 (SS7), used by telephone companies throughout the world.[2]

Another important GSM innovation is the subscriber identity module (SIM), shown in Figure 4-1 in the mobile station. The SIM is a small electronic card that carries a subscriber's

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[1]Mouly and Pautet, 30.

[2]T. Ramteke, *Networks* (Englewood Cliffs, N.J.: 1994), Chapter 14.

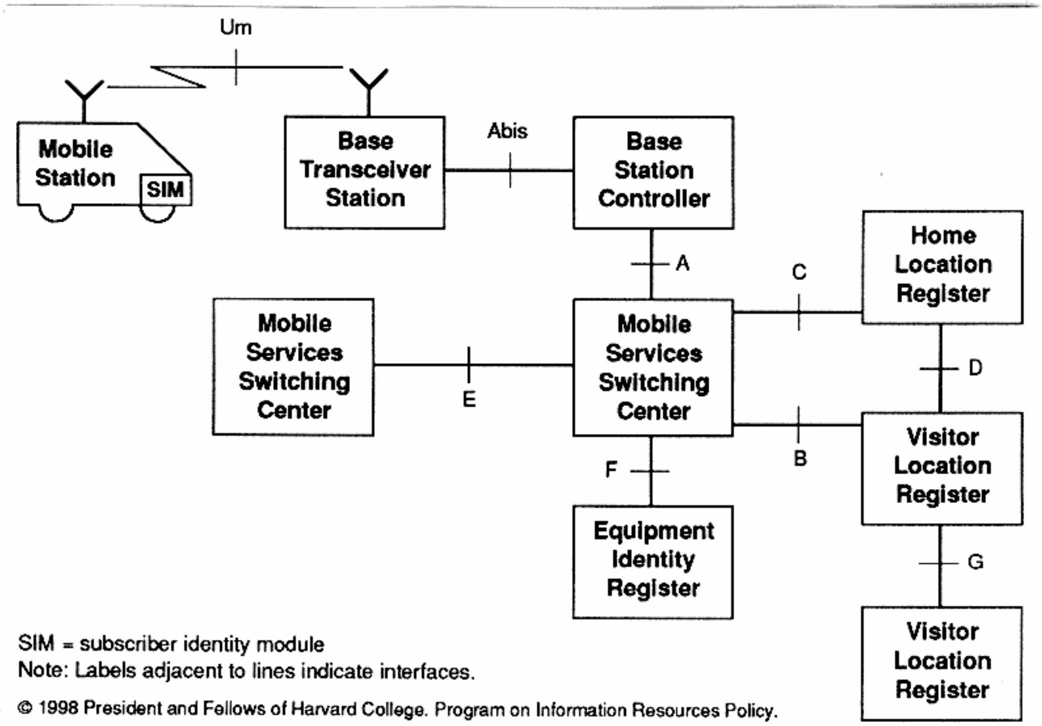

Figure 4-1

Global System for Mobile Communications (GSM) Architecture

telephone number and other information. To change telephones, a subscriber removes the SIM from one instrument and places it in another. Calls to the subscriber then arrive at the new terminal. This is in contrast to other systems in which each terminal has to be programmed by the telephone company before it can be used. The SIM facilitates international roaming.

The network elements in the figure are functional, not necessarily physical ones. It is still possible, and often the practice, to create a network infrastructure with combinations of two building blocks. Thus, one block incorporates the functions of one base transceiver station and one base station controller. The other incorporates the functions of the mobile services switching center, the home location register, the visitor location register, and the equipment identity register. The open GSM interfaces, however, created opportunities for specialized companies to supply infrastructure components. Some companies can concentrate on radio equipment, others on switching equipment, still others on database management. This flexibility favors the operating industry and new entrants, potentially at the expense of the large switching companies that dominate the first-generation infrastructure market.

With GSM infrastructure based on established ISDN technology, the new technology and difficult standards decisions of GSM were concentrated in the air interface between base transceiver stations and mobile telephones. This was a turnabout from first-generation systems, which had adopted mature radio technology and introduced novel network control concepts in its manufacture.

The only established technology for radio transmission when GSM began its work (1982) was analog FM used in all first-generation systems. To the technical community, FM appeared old-fashioned and restrictive at a time when fixed networks were moving rapidly toward digital speech transmission. The major GSM activities in the first four years were to stimulate, monitor, and evaluate the development of alternative digital transmission techniques. The work culminated at the end of 1986, when GSM conducted two technology evaluations (beauty contests). In Paris, CNET, the research and development unit of France Télécom, performed laboratory and field tests on several prototype digital radio transmission systems, while in Turin, CSELT, the corresponding research and development laboratory of in Italy, evaluated several prototype speech coders (which digitize speech prior to radio transmission). The prototype equipment for both these evaluations came from a variety of sources, including equipment vendors and the laboratories of network operators. Pointing the way forward, the evaluations established the feasibility of digital radio transmission in a cellular system and provided a basis for design decisions.

4.1.3 GSM's Decisions and Deployment

The key decisions came in 1987, at a GSM meeting in Madeira. With two dissenting votes (France and Germany), GSM adopted a plan based on time division multiple access (TDMA) radio transmission, a technique that divides the GSM radio spectrum into 125 bands, each spanning 200 kHz. Each band simultaneously carries eight signals from different telephones, with each telephone transmitting one-eighth of the time in its own "time slot." Eventually, Germany and, later, France, agreed to TDMA, and in May 1987 government ministers from France, Germany, Italy, and the United Kingdom met in London and mandated the GSM standard.

The basis for commercial deployment of GSM was established in September 1987, when telephone companies in thirteen countries signed a Memorandum of Understanding (MoU),[3] according to which the signatories were committed to a deployment schedule and technical and business arrangements, such as numbering plans and accounting procedures, that facilitate subscriber roaming among GSM systems. Since 1987, membership in the MoU has expanded dramatically. In 1997, it includes 256 companies in 110 countries.

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[3]Mouly and Pautet, 32.

Thus, by the end of 1987, GSM had fulfilled its main goals–but only on paper. Pressure exerted by the European Commission and national governments led to the consensus on technology and business arrangements necessary to make GSM a pan-European system. This status promised consumers the convenience of a telephone that could be carried everywhere in Europe and used in the same way, regardless of the subscriber's location. It insulated subscribers from the bewildering array of calling conventions and billing arrangements for conventional telephones that exists in different European countries. For the infrastructure industry, it aggregated a market and prescribed a new radio technology that was truly European in character. Because it was more advanced than anything existing elsewhere, it offered European industry an excellent opportunity for leadership in mobile communications.

In contrast to the GSM's solid political and commercial foundations in 1987, standards and equipment existed then only in preliminary form. The technology evaluations performed in 1986 in Paris and Turin used laboratory-grade equipment, far removed from commercial products, and the agreed-on standards resembled technical parameters, rather than precise compatibility specifications. To move from this situation to a working system within the deployment schedule of the MoU demanded intensive development within companies, and, concurrently, the creation of standards by multinational, multicompany teams of engineers. The result by 1992 was a system defined by more than five thousand pages of standards documents and operational equipment in place in fifteen European countries.

In terms of market acceptance, the GSM standard is highly successful. In 1997, the number of subscribers to GSM systems surpassed 50 million in more than 100 countries. GSM cellular systems operate in most parts of the world in the 900-MHz band (defined in section **4.1.1**). GSM technology is in use also in the 1800-MHz PCS bands in Europe and Asia and in 1900-MHz PCS bands in North America. GSM technology, coupled to the MoU binding GSM operating companies, makes it possible for subscribers to GSM systems to initiate and receive phone calls conveniently at any location in the world served by a GSM system.

4.1.4 Other European Wireless Telecommunications Standards

Two other mobile communications systems reinforced the strong technology base established during the development of GSM. A British standard, second-generation cordless telephone (CT2), provided the basis for the Telepoint (cordless payphone) products (see sections **2.2.4** and **2.3.2**). Although CT2 has a digital air interface, it follows first-generation cellular systems in adopting frequency division multiple access (FDMA) as a means of allocating radio resources to different communications sharing the same airwaves. Telepoint service was a commercial failure in the United Kingdom,[4] but Telepoint systems based on CT2 were introduced with some success in other countries, including Hong Kong, Singapore, and France. Northern Telecom also uses CT2 technology, in a wireless private branch exchange (PBX) product.

Digital European Cordless Telecommunications (DECT) is a more elaborate wireless technology based on TDMA with twelve signals sharing a 1.7-MHz frequency band. Created by a process similar to the one by which GSM was created, DECT is a European standard published by ETSI. Sometimes referred to as CT3, DECT forms the basis of private, indoor wireless communications products for voice and data transmission.

Although in 1997 CT2 and DECT lag far behind GSM in commercial importance, they are technically sound and, along with GSM, demonstrate the strong positions in wireless technologies established by European industry in the 1980s and early 1990s.

4.2 The Evolution of Technology in the United States

In marked contrast to the leading role played in the 1970s by U.S. industry in developing first-generation cellular communications, the subsequent development of technology proceeded slowly in the United States through most of the 1980s. The two U.S. leaders in first-generation systems, AT&T and Motorola, found themselves with limited motivation to create new technologies. AT&T's initial motivation in advancing cellular communications was to extend telephone services to vehicles. To enhance the prospects for mobile telephony, AT&T made cellular technology readily available to competing equipment manufacturers. Under the terms of AT&T's divestiture in 1984, the regional Bells inherited AT&T's claims to the WCC licenses issued by the FCC. That left AT&T in the role of a cellular equipment vendor, which it regarded as a minor niche in its information technology strategy. Its major strategic interests in the 1980s included protecting its market for conventional switching equipment, building its fiber-optic network, and invading the computer industry with a hostile takeover of NCR. Also in the 1980s, Motorola established a strong position in analog cellular infrastructure and cellular subscriber equipment throughout the world. With its dominant position in mobile communications reinforced by its success in cellular, Motorola stuck to its traditional policy of promoting gradual technology evolution within existing standards, rather than encouraging radical breakthroughs, which could disrupt prevailing markets.[5]

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[4]Peter Grindley and Saadet Toker, "Regulators, Markets and Standards Coordination: Policy Lessons from Telepoint," *Economics of Innovation and New Technology* **2**, 4 (1993), 319-342.

[5]This is an example of Gabel's observation that "A dominant firm will oppose...multi-firm standardization." See Gabel (1991), 178.

Just as the U.S. manufacturing industry in the 1980s had little appetite for technical innovation, the service industry lacked the technical competence to advance its technology base. The industry was fragmented by the FCC's licensing policy, and, by the terms of the 1984 divestiture, the cellular subsidiaries of the baby Bells were isolated from the technology expertise (residing largely in Bellcore) of their parent companies.

By 1988, as the commercial potential of cellular telephony became apparent, the operating industry became acutely aware that its ability to expand would be threatened by congestion of their licensed spectrum bands. When consumer demand saturates the capacity of a cellular system, there are three ways to expand: obtain new radio bands, split existing cells into smaller cells by installing new base stations, or introduce new technology to make more efficient use of existing bandwidth and base stations. When it expanded the cellular bandwidth allocation from 40 MHz to 50 MHz in the mid-1980s, the FCC indicated that no new radio spectrum would be available for cellular services. As the geographical density of a cellular system increases, adding base stations becomes an increasingly expensive means of expansion and, beyond a certain point, impractical. As cell dimensions become smaller and smaller in congested areas, the precise locations of new base stations become critical, and the opportunities for acquiring new sites in the necessary locations diminish.

The absence of new cellular spectrum in the United States, combined with the discouraging prospects for adding base stations indefinitely, left new technology as the main means for the cellular industry to realize its full commercial potential. The FCC encouraged this approach in 1990, when it narrowed the scope of its regulation of transmission techniques to enforcement of noninterference.[6] Thus, the FCC no longer mandated adherence to AMPS or any other air interface. License holders were now free to transmit any signals they chose, provided they did not interfere with the signals of other license holders.

4.2.1 NA-TDMA Development

Recognizing the need for new technology, the cellular service industry, through its trade association, the Cellular Telecommunications Industry Association (CTIA,) formed a committee for the purpose of stimulating the equipment industry to create new technologies. The CTIA challenged vendors to devise radio technology that would increase by a factor of 10 the capacity of each base station to handle telephone conversations. In response to the challenge, the EIA, which had formulated the AMPS standard, formed its own committee, within the Telecommunications Industry Association (TIA). Assuming the role played by GSM in Europe, this committee took responsibility for devising a bandwidth-efficient transmission technology to be introduced to AMPS networks. The TIA committee, with

[6]Federal Communications Commission, "Special Provisions for Alternative Cellular Technologies and Alternative Services," *Memorandum Opinion and Order Docket 87-390*, February 1990, 3.

representatives from a broad range of equipment vendors based in the United States, Canada, Europe, and Japan, solicited proposals for new technologies. The response was substantial, consisting of descriptions of many radio transmission techniques. All of the vendors proposed digital transmission of telephone signals. The proposals fell into two principal categories: (1) techniques based on FDMA, the analog cellular approach, which assigns different signals in a cell to different frequency bands, and (2) techniques related to GSM, a hybrid of FDMA and TDMA in which several signals occupy the same frequency band in a cell, sharing the band by transmitting short bursts of digital information at different times.

AT&T and Motorola, the AMPS market leaders, recommended the conservative FDMA approach. Most other vendors favored some sort of hybrid scheme. The issue was decided in January 1989, when the TIA voted to focus on a hybrid standard, generally referred to as TDMA. Here, it is referred to as North American TDMA, or NA-TDMA, to distinguish it from the GSM flavor of TDMA adopted in Europe. Although the decision to move to a TDMA standard represented a departure from the AMPS approach to multiple access, in the end the TIA stayed close to AMPS by deciding to retain the AMPS dimension of 30 kHz as the bandwidth occupied by each cellular signal. With NA-TDMA, three conversations share a 30-kHz band, which makes it possible for cellular operators to replace individual analog AMPS radio units with digital radios that handle three conversations simultaneously. Another decision was to introduce digital transmissions to AMPS as part of a "dual-mode" system, a gateway technology in which each NA-TDMA telephone is also capable of functioning as an analog AMPS telephone. The dual-mode standard favors the operating industry, which can gradually introduce high-capacity radios to congested areas and serve the same customers with existing AMPS equipment in other areas. This transition to new technology is in contrast to GSM, which requires an extensive new network to be in place before service can begin.

NA-TDMA technology is embodied in Interim Standard 54 (IS-54), published by the TIA. In 1994, the industry replaced IS-54 with Interim Standard 136, which enhances NA-TDMA by introducing new types of common control channels that make it possible for portable terminals to conserve battery power. They also make it possible for networks and terminals to exchange short text messages, a service anticipated in the GSM standard.

The cellular industry adopted the NA-TDMA technology without benefit of the kinds of experiments and technology trials performed by the developers of GSM. With the standard formally adopted, vendors set out in earnest to develop conforming equipment, but they encountered technical difficulties that had not been anticipated by the engineers who had drafted the standard. Practical experience with NA-TDMA showed it was more vulnerable to time-varying channel impairments than GSM, and this vulnerability made reusing the NA-TDMA channels as intensively as the original designers had hoped impossible. Less aggressive reuse translates into lower capacity. The capacity gain of NA-TDMA relative to

AMPS is approximately a factor of 3, corresponding to the replacement of an AMPS channel carrying one analog signal by an NA-TMDA bitstream composed of three digital signals. NA-TDMA has not realized the operating industry's goal of a capacity gain of a factor of 10.

Most of the innovations embodied in NA-TDMA are in radio transmission technology. Operating with the same 30-kHz-per-channel frequency plan of AMPS, NA-TDMA retains the major portion of AMPS switching and network control technology. As a consequence, the equipment development cycle of NA-TDMA was relatively short.

4.2.2 The Development of Code Division Multiple Access (CDMA)

While the TIA was establishing the details of the NA-TDMA standard, Qualcomm, a young company, announced the development of a proprietary cellular technology that would exceed the capacity goal set by the operating industry. The gap between this ambitious goal and the achievement embodied in NA-TDMA drew attention to the new technology. At the heart of this technology is the code division multiple access method of introducing multiple signals to the same transmission medium. CDMA is a form of "spread spectrum" communications in which the bit rate of a transmitted signal is significantly higher than that of the original information signal. In the Qualcomm system, the transmitted bit rate is 1.2288 megabits per second (Mbps) and that of a speech signal is 9,600 bps. The ratio of the two bit rates, 128, is the processing gain of the system, which provides each signal with a high immunity against interference from other signals. This gain allows the entire spectrum band occupied by CDMA signals to be reused in each cell. This intensive reuse is the source of the high capacity anticipated for cellular CDMA.

In a CDMA system, each transmitter has its own binary code, which it transmits repeatedly, modulated by the information signal. For example, when the information is "1," it transmits the original code. When the information is "zero," it inverts the code, replacing "1's" with "zeros" and vice versa. A receiver, by tuning to the code of one transmitter, extracts the information signal. As the number of simultaneous transmissions increases, the job of each receiver becomes more difficult, and the receivers make an increasing number of detection errors, generating "1's" when "zeros" were transmitted and vice versa. A digital communications system is designed to withstand a certain error rate and still meet signal quality objectives. In CDMA, capacity measures are based on the number of simultaneous transmissions that can occur within a given error-rate criterion—for example, one error per 1,000 bits transmitted by a source. This is referred to as "soft capacity," because it does not impose a firm limit on the number of signals that can be transmitted. If the number of transmissions exceeds capacity, some signals will experience excessive distortion, a condition often tolerable for short periods. The soft capacity of CDMA is in contrast to the "hard" capacity of FDMA systems, such as analog cellular, and TDMA systems, such as NA-TDMA and GSM. In FDMA and TDMA, the number of frequency bands or time slots available is fixed so that when all are occupied the system has no way to admit another signal.

The soft nature of CDMA capacity, combined with many exotic technical innovations created by Qualcomm, complicate the task of predicting the capacity of a practical CDMA system and comparing it to the capacity of alternate technologies. Another complicating factor is the statistical nature of the interference in CDMA. The quality of each signal depends on the aggregate of many small effects produced by all the other signals in an extensive service area. This dependence on many small effects makes it difficult to conduct laboratory experiments or field trials that could lead to accurate predictions of the capacity and quality of a large system. Qualcomm initially claimed that CDMA could produce a capacity gain of a factor of 20 relative to analog cellular, thus surpassing by a factor of 2 the goal of the operating industry. Although subsequent calculations performed by Qualcomm and other organizations moderated these estimates, the consensus (by no means unanimous) is that CDMA has the potential to increase system capacity by a factor of 5 to 10 relative to AMPS.

Capacity estimates, combined with the operational and economic advantages claimed for CDMA, along with an elaborate technology demonstration staged by Qualcomm in San Diego in 1991, convinced a significant fraction of the U.S. operating industry to deploy CDMA technology in dual-mode systems. Pactel Cellular (now AirTouch) was an early (1989) partner of Qualcomm in CDMA technology development and evaluation. The San Diego experiment, as well as other trials, used Pactel's frequency bands and cellular infrastructure. The cellular subsidiaries of other regional Bell companies joined Pactel in expressing enthusiasm for CDMA, as did GTE, which holds numerous WCC cellular licenses.

In addition to the merits of CDMA technology, the availability of CDMA infrastructure and CDMA telephones is a major consideration affecting deployment. To stimulate the creation of products that incorporate the technology, Qualcomm entered into licensing agreements with equipment vendors, including Motorola, AT&T Technologies (now Lucent Technologies), and Northern Telecom, all major infrastructure suppliers in North America. Qualcomm also drafted a CDMA compatibility specification, adopted in July 1993 by the TIA as Interim Standard 95.

In contrast to NA-TDMA, dual-mode CDMA systems require extensive modifications to AMPS base stations and switching centers. Because of this requirement, as well as the novelty and complexity of the technology embodied in IS-95, development and installation of CDMA equipment have taken considerably longer than for NA-TDMA. Operating companies in the United States began to install commercial CDMA equipment as early as 1994, but it was only in mid-1996 that AirTouch became the first operating company in the U.S. to make dual-mode CDMA service available to customers on a commercial basis.

4.2.3 Intersystem Operations

In contrast to GSM, which specifies many open network interfaces, compatibility in AMPS and in dual-mode CDMA and NA-TDMA is limited to the air interface between base stations and telephones. Originally, the interfaces between base stations and switching centers, and those between pairs of switching centers, were proprietary. This situation, combined with the geographically fragmented licensing arrangements in the United States, made it difficult to serve customers outside their home areas and created the paradox that even though every cellular phone in the United States is compatible with every base station, subscribers were uncertain of obtaining cellular service unless they were close to home.

To ameliorate this situation, the industry adopted TIA Interim Standard 41, a compatibility specification for coordinating operations between systems controlled by different MSCs. The network architecture and many network control operations parallel those of GSM. IS-41 allows subscribers to make and receive calls in all service areas where network operators have adopted the standard. It also makes it possible to maintain a call in progress when subscribers move between two adjacent service areas served by infrastructure equipment from different manufacturers.

The development by the TIA of IS-41 and its adoption by equipment vendors and network operators was accomplished without the uncertainty and controversy associated with GSM, NA-TDMA, and AMPS, for four reasons: (1) IS-41 is an adapter technology[7] added to existing equipment; (2) its adoption does not directly alter the market positions of stakeholders; (3) and it relies on established technologies; and (4) it offers all adopters the benefits of widely recognized positive externalities.

4.2.3 Narrowband AMPS (NAMPS)

Motorola developed narrowband AMPS[8] in response to uncertainties about both the relative merits of the two digital standards and when they would be available in commercial products. Operating companies can use NAMPS technology to provide a short-term solution to capacity problems and then introduce the preferred digital standard after uncertainties are resolved. NAMPS gains its capacity advantage over AMPS by dividing the frequency band occupied by an AMPS channel into three narrow channels, each occupying 10 kHz. Each narrow channel uses analog FM to carry one telephone conversation. Although the TIA published the NAMPS compatibility specification as Interim Standard 88, Motorola remains the only vendor to produce NAMPS telephones and infrastructure equipment: NAMPS has

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[7]Gabel (1991), 5.

[8]Telecommunications Industry Association, "Mobile Station Land Station Compatibility Standard for Dual-Mode Narrowband Analog Cellular System," *Interim Standard 88*, January 1993.

been adopted by many of Motorola's operating-company customers while they get ready for commercial deployment of CDMA. Because Motorola decided not to produce NA-TDMA infrastructure equipment, its customers who decide to use this technology have to convert entire networks to equipment of other vendors—Ericsson, Lucent Technologies, or Northern Telecom.

4.2.4 PCS

In 1995 and 1996, the FCC awarded, by auction, hundreds of spectrum licenses to provide PCS services. The auctions attracted many aspiring network operators. The winning bids aggregated to $18 billion for three spectrum bands, each comprising 30 MHz in the vicinity of 1900 MHz. (Cellular systems occupy a total of 50 MHz, centered at 850 MHz.) Although license holders have considerable latitude in the services they can offer, the early applications were all focused on mobile telephony and all license holders intend to build networks based on digital speech transmission. Many licenses were purchased by existing cellular operators that plan to extend their service footprints to cover larger portions of the United States. These companies will adopt the same digital technology in the PCS bands (either NA-TDMA or CDMA) that they introduce to their cellular systems. Several new PCS license holders that do not operate cellular systems have adopted GSM technology; others have chosen CDMA. In all, the new PCS bands will be occupied by GSM, NA-TDMA, and CDMA signals, commanding substantial marketshares.

4.3 Stakeholders in Europe and the United States

Markets for cellular and personal communications have expanded rapidly in the 1990s, and the pace of technical change has been swift. As a consequence, the positions of stakeholders described (section **3.4**) in 1997 are very different from what they were in 1990. In examining second-generation systems and services in 1997, official terminology is helpful to distinguish between cellular and personal communications. In the following paragraphs, the term "cellular" refers to services offered in the 900 MHz GSM frequency band in Europe and the 850 MHz AMPS frequency band in the United States. "Personal communications" refers to services offered at 1800 MHz in Europe and at 1900 MHz in the United States.

Just as **Table 3-1** summarizes the status of first-generation cellular systems in 1990, **Tables 4-1** and **4-2** summarize the status of second-generation cellular and personal communications systems in 1997. A comparison of Tables 3-1 and 4-1 reveals significant changes in the cellular picture, more in Europe than in the United States. In both, the situation for roaming subscribers has improved considerably. Roaming throughout Europe and in dozens of non-European countries has become a reality in 1997 for tens of millions of GSM subscribers. In the United States, the proliferation of IS-41 technology for intersystem

Table 4-1

Digital Cellular Systems in 1997

	Europe	United States
Networks	Two competing national networks in each country	733 separate service areas, two operating companies in each area
Roaming	Full roaming throughout Europe and beyond	IS-41 and dual-mode equipment facilitate roaming
Radio Transmission	A single Continental standard: GSM	Two competing standards: NA-TDMA and CDMA
Operating Companies	More private operators than in 1990	Fewer companies than in 1990

CDMA = code division multiple access
IS = Interim Standard
GSM = Global System for Mobile Communications
NA-TDMA = North American time division multiple access

operations has significantly improved services to roaming subscribers. With respect to the operating industry, the diversity in Europe is greater in 1997 than in 1990. In contrast to the original monopoly on analog cellular networks in most countries, two national operating companies offer GSM service in 1997. Mergers and acquisitions in the United States, on the other hand, have led to a consolidation of the service industry. Relative to 1990, there are fewer operating companies with larger geographical footprints on average. The trend toward consolidation documented by Barth in 1994 has continued in the years since then.[9]

In 1997, the market penetration of digital cellular technology is much lower in the United States than in Europe, for several reasons. In the United States, digital cellular service is offered in the context of dual-mode systems that incorporate both first- and second-generation technology. With dual-mode subscriber equipment capable of operating in all cellular service areas, U.S. cellular companies have introduced second-generation technology only when it has become profitable to do so. Typically, digital technology is introduced where demand overtakes the capacity of analog technology. In Europe, operating licenses and the GSM MoU commit companies to specific schedules for building their networks and offering services. Because GSM subscriber equipment is not capable of operating with analog infrastructure equipment, to attract subscribers network operators must establish as quickly as possible an extensive digital infrastructure. The existence of two competing standards in the

[9]Gustave Barth, *Cellular Phones: Is There Really Competition?* (Cambridge, Mass.: Harvard University Program on Information Resources Policy, P-94-3, August 1994).

Table 4-2

Personal Communications Systems in 1997

	Europe	**United States**
Networks	National networks planned in an increasing number of countries	Hundreds of service areas, three operating companies offering or planning services in each
Roaming	National roaming in Germany and the United Kingdom	Limited roaming because services are offered in specific locations
Radio Transmission	A single Continental standard: GSM	Three competing standards: NA-TDMA, CDMA, and GSM
Operating Companies	Competing private operating companies in each country	Dozens of operating companies, including many cellular companies

CDMA = code division multiple access
NA-TDMA = North American time division multiple access
GSM = Global System for Mobile Communications

United States also has slowed the spread of digital service. Operating companies hesitate to invest heavily in either technology until the relative positions of CDMA and NA-TDMA are clearer. In addition, CDMA systems are more complex to install and operate than either GSM or NA-TDMA. As a consequence, it took until mid-1996 for U.S. equipment vendors and operating companies to acquire the expertise necessary to introduce CDMA technology to subscribers. At about the same time, operators of NA-TDMA dual-mode cellular systems increased their efforts to market second-generation services.

In 1997, activity rapidly accelerated in frequency bands officially allocated for personal communications ("Personal Communications Services" in the United States and "Personal Communications Networks" in Europe). Table 4-2 summarizes the status of these frequency bands. Although regulators have placed personal and cellular communications in separate categories, the distinction between them is, for the most part, hidden from the public. In promoting subscriptions, U.S. companies have used the term "personal communications" to describe a collection of service features, such as voice mail and the delivery of short messages. Second-generation technologies deliver these features in both the cellular and the personal communications bands.

In the personal communications frequency bands, the longest established services operate in the United Kingdom and Germany. Other European countries are in the process of awarding licenses to operate in these bands, generally to two companies in each country. In

1995 and 1996, the U.S. government auctioned operating licenses in the personal communications bands to a diverse collection of companies, including new companies, established cellular operating companies, cable television companies, and wireline telephone companies. With substantial sums invested in spectrum licenses, these companies are under pressure to build networks and begin generating revenues. Each company has selected technology embodied in one of three digital cellular standards.

In contrast to the dual-mode telephones available to cellular subscribers, subscribers to services in the personal communications bands obtain digital telephones that operate only with a single standard. Some digital telephones have a "dual-band" capability to operate in either the 850 MHz cellular band or the 1900 MHz personal communications band. With an all-digital telephone, a subscriber's roaming opportunities in a specific location depend on the introduction of service in that location by a company that has adopted the same technology as the subscriber's home company. In Europe, many network operators in the 1800-MHz PCS band are required to provide national coverage. Elsewhere, operating companies provide service at 1800 MHz only in areas of high demand. There is only one PCS standard in Europe—GSM—and there are plans to produce "dual-band" subscriber equipment enabling people to roam with one mobile phone between 900 MHz GSM systems and 1800 MHz systems. GSM roaming is further facilitated by the SIM feature (see section **4.1.2**). For example, a subscriber to a 1900-MHz system in the United States can install his or her SIM in a 900-MHz GSM cellular telephone and use the U.S. phone number to initiate and receive phone calls in dozens of countries throughout the world.

4.3.1 Consumers

Although the number of consumers benefiting from second-generation technology is smaller in the United States than in Europe, the situation for consumers in the United States will improve in the period 1997–2000, as more services come on line in the personal communications frequency band. Soon, most people will be able to choose among five service providers (two cellular companies and three personal communications companies). It is likely that all three second-generation technologies will eventually have national footprints. At that point, U.S. consumers will, like their European counterparts, have the benefits of an information system that they can use throughout most of the continent. Cellular and personal communications services, however, comprise a market with many equilibrium points (see section **2.2.3**), including equilibrium points in which one or two of the technologies do not survive or are limited to isolated areas in the United States. Although the demise of one or two technologies would leave many consumers with equipment of little value, consumer equipment does not represent a significant investment, and the cost of switching to a surviving technology would be moderate.

4.3.2 Network Operators

In the cellular operating bands, there are two major differences between the positions of European and U.S. network operators. In Europe, spectrum licenses open up new frequency bands. In some countries, part of the 900 MHz cellular band is used for analog cellular transmissions, and network operators begin GSM services in the other parts of the frequency band and eventually displace analog channels as GSM markets grow. Elsewhere in Europe, the entire GSM band is available from the start to the operating company. In the United States, on the other hand, there is no new spectrum for digital cellular operation. Digital cellular channels have to displace analog channels from the start.

The other major difference in the positions of operating companies is that European licenses prescribe the GSM standard while U.S. cellular operators have to select one of two competing standards for second-generation operation. The single standard in Europe gives operating companies full benefits of externalities and economies of scale. In addition, the open interfaces in the GSM standard allow operators to obtain network infrastructure equipment from a variety of sources. In the United States, the proprietary nature of the interface between switching equipment and base stations locks operators who adopt NA-TDMA or CDMA into a single source for most infrastructure equipment.

The U.S. industry has approved seven compatibility standards for operation in the personal communications band, and in early 1997, operating companies made significant commitments to three: GSM, NA-TDMA, and CDMA. In addition to the burden of choosing among technologies with uncertain prospects, U.S. personal communications operating companies had to purchase operating licenses from the government. The service areas available to each company and the prices paid were established in auctions conducted in 1995 and 1996 by the FCC. European personal communications operating companies do not need to pay heavy fees to obtain spectrum licenses. Governments issue licenses on the basis of the merits of competing applications. Like their cellular counterparts, personal communications operating companies in Europe have the benefits of a prescribed single standard, GSM.

4.3.3 Infrastructure Vendors

European equipment manufacturers participated in the creation of the GSM standard, thereby gaining a head start in product development and manufacturing. Because the standard is mandatory, they benefit from a large market for their equipment. In many countries, they have also taken advantage of their positions as preferred suppliers to monopoly telephone companies that also operate GSM networks. The large European telecommunications switching companies—Alcatel, Ericsson, and Siemens—all enjoy large markets for GSM cellular and personal communications infrastructure equipment. Nokia is unique among infrastructure vendors in that it entered the telecommunications equipment market by offering cellular products. Nokia markets GSM infrastructure equipment in both the cellular and personal communications bands. Among North American companies, Motorola has had a modest success selling GSM cellular infrastructure equipment. The two large switching companies, Lucent Technologies (formerly a division of AT&T) and Northern Telecom have gained direct access to European markets. Eventually, these two companies entered the picture by purchasing subsidiaries of established European vendors in Germany (Lucent) and France (Northern Telecom).

In the U.S. market, infrastructure vendors have to establish technology adoption strategies in the face of uncertainty. In doing so, they face two risks. Companies making an early decision risk being "locked in" to an unsuccessful technology, while companies that wait too long to adopt a winning technology can be stranded with very little marketshare. The four largest vendors in the United States are Ericsson (GSM and NA-TDMA), Lucent Technologies (CDMA and NA-TDMA), Motorola (CDMA), and Northern Telecom (CDMA, GSM, and NA-TDMA). Those adopting CDMA license intellectual property from Qualcomm, and Northern Telecom has a joint venture with Qualcomm to manufacture CDMA base stations. Except for Motorola, the largest infrastructure vendors in the United States have accepted the burden of developing and marketing two or three product lines, rather than taking the risk of relying entirely on one of them.

4.3.4 Subscriber Equipment Vendors

The market for second-generation consumer equipment is similar in many respects to that of the first-generation (see section **3.4.4**). Two European companies, Nokia and Ericsson, have strengthened their market positions in the 1990s, offering GSM and NA-TDMA telephones. A joint venture of Sony and Qualcomm, the owner of most CDMA intellectual property, emerged in 1996 and 1997 as the leading supplier of CDMA terminals. Among infrastructure vendors, Motorola is a significant manufacturer of GSM and NA-TDMA terminals, while Lucent Technologies began producing terminal equipment in 1996. In addition, digital telephones are marketed by a wide variety of consumer electronics companies.

4.3.5 Government

The different pictures of cellular and personal communications in Europe and the United States are largely due to government policies. In both of the roles indicated in **Figure 3-2**, governments in the United States and Europe take radically different approaches to regulation of cellular and personal communications. European regulators mandate conformity to a single compatibility specification, GSM, while the U.S. government regards compatibility as a commercial issue to be decided in the marketplace.

In regulating industry structure, the EU has opened all telecommunications markets in member countries to competition. Government-owned telephone companies have been privatized, and monopolies are gradually giving way to competition in Europe. In contrast to wireline telephony, where the inertia of one hundred years of monopoly operation has retarded competition, new operators of cellular and PCS are able to establish significant market positions quickly. Typically, European governments award two national operating licenses in the cellular band and two licenses in the personal communications band.

In the United States, the FCC, in awarding personal communications operating licenses, established geographical boundaries that differ considerably from the 733 cellular licensing areas (see section **3.2.3**). In one set of auctions (1995), the FCC divided the United States into 51 "major trading areas" and sold two licenses (A-band and B-band licenses) to operate in each area. The total purchase price for the 102 licenses was $7.8 billion. In a later (1996) auction, the FCC issued 493 (C-band) licenses, each covering a "basic trading area." The aggregate fee for these licenses exceeded $10 billion. Each of the 595 personal communications licenses covers 30 MHz of radio spectrum near 1900 MHz. In addition to establishing the different sizes of geographical service areas and selling expensive tickets of admission to PCS, the government influenced the structure of the operating industry by setting rules on the nature of the companies eligible to participate in spectrum auctions. One important decision was to allow local telephone companies to operate PCS in the A and B bands. In 1984, these companies had been excluded from cellular operations by the terms of the AT&T divestiture. Another regulation, restricting access to C-band licenses, made it possible for many new, smaller companies to enter the personal communications operating industry.

In addition to their policies on standards and licensing procedures, in the 1990s European governments strongly influenced technology creation. Through the EU, they financed research and development of third-generation personal communications technology through two programs: Research in Advanced Communications in Europe (RACE) and its successor, Advanced Communications Technology and Services (ACTS).[10] These programs bring together dozens of European companies and universities in design and demonstration projects in all areas of mobile communications technology. Perceiving the success of GSM in giving European companies the lead worldwide in second-generation technologies, the EU has invested heavily in these projects (24,000 person months of effort in the 1994–98 funding cycle) to maintain this lead in the next century. By contrast, in the United States, advanced technology is created by individual companies pursuing separate commercial interests and by isolated university projects with modest funding from industry and government. The only

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[10]J. S. Da Silva, B. Arroyo, B. Barani, and D. Ikonomou, "European Third Generation Mobile Systems," *IEEE Communications* **34**, 10 (October 1996), 68-83.

significant program that attempts to unite the strengths of industry and universities in the United States is the Global Mobile Communications (GloMo) program funded by the Department of Defense. The aim of GloMo is to create technologies of direct use to the military sector and in size it is but a small fraction of the European programs.

Given these different approaches to technology creation, the next generation of PCS probably will, like the second generation, see European industry and governments moving ahead with a common technology that has been examined and tested in extensive research and development projects. The prospect in the United States is for various possibilities offered by competing companies, with the destiny of each to be determined in the marketplace. Regardless of their technical merits, these differences will place European technology in an advantageous competitive position.

Chapter Five

Analysis of PCS Standards

Chapter Two presents a general discussion of issues related to technology standards, and **Chapters Three** and **Four** describes the creation and deployment of compatibility specifications for personal communications systems. This chapter examines seven of these standards in the context of issues raised in Chapter Two. In personal communications, as compared with case studies of other technologies, extreme diversity is manifest in three dimensions: technology, geography, and time. In the technology dimension, the number of standards is large and continues to grow. The policies governing adoption of standards, as well as governing the standards themselves, are different in different places. The whole situation is fluid, with uncertainty liable to remain past 2005.

The analysis in this report has been limited to standards widely adopted in the United States and Europe. **Table 5-1** lists two standards of European origin, NMT and GSM, and others of U.S. origin. With the exception of NMT, all are embodied in PCSs in service in the United States.

5.1 Creation of Standards

As indicated in the table, of the seven standards considered in this chapter, four were created by "strong hands." With the exception of AMPS, the companies that created them remain market leaders in equipment production. The NAMPS situation is the simplest. Motorola is the exclusive producer of infrastructure and terminal equipment. In the case of NMT, Ericsson dominates in the supply of infrastructure equipment, but the terminal market is more diverse. Qualcomm, the sponsor of CDMA technology, maintains its strong position by exercising intellectual property rights to the technology embodied in the standard. While Qualcomm leads the market for telephones, the infrastructure and terminal market is shared by several vendors under license from Qualcomm. Although AT&T and Motorola, as the originators of AMPS, have strong positions in the AMPS infrastructure market, they do not dominate it. Ericsson and Northern Telecom also play major roles. For AMPS terminal equipment, Motorola is the market leader among many successful vendors, while AT&T plays a minor role.

The three other standards are the products of "invisible advisors." The two North American standards, NA-TDMA and IS-41, were produced by teams of vendor representatives, unlike the organization that produced GSM, which was dominated by the operating industry. In the absence of proprietary constraints on these three standards, several vendors produce conforming equipment.

Table 5-1

Standards Widely Adopted in the United States and Europe

Name of Standard	Description	Origin
AMPS	Analog air interface	AT&T, Motorola
NMT	Analog network	Ericsson and Swedish Telecom
NAMPS	Analog air interface	Motorola
GSM	Digital network	Operating company consortium
NA-TDMA	Digital air interface	Vendor consortium
CDMA	Digital air interface	Qualcomm
IS-41	Infrastructure signaling system	Vendor consortium

AMPS = Advanced Mobile Phone System
CDMA = code division multiple access
GSM= Global System for Mobile Communications (originally Groupe Spécial Mobile)
IS-41 = Interim Standard 41 (Telecommunication Industry Association)NAMPS = Narrowband AMPS
NA-TDMA = North American time division multiple access
NMT = Nordic Mobile Telephone (System)

5.2 Status

This section reviews the scope of the standards, their statutory force, and the status of intellectual property rights pertaining to them (see section **2.3.2**). Four standards are limited to the air interface that defines communications between base stations and terminals. Two standards of European origin, NMT and GSM, specify entire networks, including the signaling system that links base stations with switching centers. IS-41 specifies communications between pairs of switching centers and communications between switching centers and databases. The comprehensive scope of NMT and GSM reflects the importance of operating companies in their creation. The open interface between base stations and switching equipment, and, in the case of GSM, an additional open interface between components of a base station system, provide network operators with valuable flexibility in infrastructure procurement. In the other systems, operators need to obtain switching equipment and base stations from the same source.

Perhaps the most striking difference between the situations in Europe and North America is the statutory force of the standards. Because GSM is mandatory in Europe, it is the only digital personal communications system in commercial service there (see section **4.1.3**). Deployment of GSM is governed by an MoU signed by all European companies with operating licenses in the 900 MHz and 1800 MHz spectrum bands of GSM. An important part of the Memorandum is a provision for roaming that assures all GSM subscribers of service in any area covered by a GSM system.

At the outset (1983) of cellular operation in the United States, the AMPS air interface was mandated by the FCC, which later liberalized its rules, so that since 1990, AMPS has been voluntary. Nevertheless, all cellular phones and all base stations in the U.S. continue to conform to the AMPS specification. With no regulatory enforcement of compatibility in the U.S., NA-TDMA, NAMPS, CDMA, and GSM all have been adopted by segments of the U.S. operating industry. With the exception of GSM, they are gateway technologies that create compatibility with AMPS by means of dual-mode equipment (see section **4.2.1**). Each dual-mode telephone is capable of operating according to the AMPS specification, and with one other technology (either NAMPS, CDMA, or NA-TDMA).

With respect to proprietary status, AMPS, NA-TDMA, GSM, and IS-41 are essentially in the public domain. At the opposite extreme, NAMPS is the property of one company, Motorola, which produces all the NAMPS infrastructure and terminal equipment. In the case of CDMA, Qualcomm holds strong intellectual property rights, which it asserts through licensing agreements with an array of equipment vendors. Ericsson maintains a dominant, but not exclusive, role in NMT equipment markets.

5.3 Figures of Merit

5.3.1 Extrinsic Figures of Merit

The three extrinsic criteria described in section **2.3.3** are signal quality, efficiency, and complexity. An examination of the six air interface standards (**Table 5-1**) indicates the strongest distinctions between the two original systems, AMPS and NMT, and the four later ones, GSM, NAMPS, NA-TDMA, and CDMA.

In general, the advanced technologies embodied in the digital systems and in NAMPS deliver improved bandwidth efficiency over the original analog systems, AMPS and NMT. This efficiency leads to reduced infrastructure costs per subscriber. With respect to signal quality, the performance of the digital systems is more uniform geographically than that of the three analog systems, which are more vulnerable to location-dependent transmission impairments. The speech-coding technology embodied in the standard has a strong influence on the quality of communications in a digital system. Every speech coder represents a compromise among spectrum efficiency, signal quality, and equipment complexity. Initial versions of the digital standards emphasized spectrum efficiency and low complexity. As a result, the quality of digital signals is inferior to that of analog cellular signals in the absence of transmission impairments. To rectify this situation, the standards have been extended to incorporate higher quality speech coders, which will bring speech quality in digital systems up to that of analog systems operating in ideal conditions. In the case of CDMA, the price of higher quality is reduced spectrum efficiency. GSM and NA-TDMA obtain quality improvements by means of more complex equipment. Progress in digital electronics has made it possible to incorporate complex signal processing into small portable telephones. The relative merits of the three digital systems will become clearer as their markets grow. The quality of each will vary, however, from one set of operating conditions to another and will change over the years, as the technology evolves.

The digital systems achieve their efficiency and quality at the expense of complexity, which imposes burdens on the design and manufacture of PCS consumer equipment. These burdens are offset by advances in integrated circuits and by details of the digital system designs that help conserve battery power and thus reduce the size of the batteries in portable phones. The complex relationships between consumer equipment costs and service costs in many PCS markets makes any precise assessment of the relative costs of telephones that incorporate the different technologies difficult. Looking at the situation in Europe, where production of GSM equipment is more mature than that of CDMA and NA-TDMA in the United States, it appears that consumers will gain the operational advantages of digital technology without paying much for the added complexity of the telephone equipment.

Among analog technologies, NMT, with slightly narrower radio channels, has a slight edge in efficiency over AMPS, but its advantage is purchased at the expense of signal quality in marginal operating environments. NAMPS achieves higher efficiency than the earlier analog systems by means of added complexity introduced to overcome greater vulnerability to channel impairments.

Owing to the complexity of the three digital systems and their different operating histories, ranking them with respect to extrinsic figures of merit is difficult. CDMA is the newest of the digital technologies, and its initial attraction was the promise of a strong advance in bandwidth efficiency over earlier technologies. The fulfillment of that promise awaits further operational experience. The second digital system, chronologically, NA-TDMA, offers somewhat higher bandwidth efficiency than GSM. Of the three systems, CDMA is the most complex, followed by GSM, with NA-TDMA somewhat simpler. All three technologies appear on paper to be capable of delivering comparable signal quality. The quality of practical networks depends on engineering decisions of network operators and on local environments. A general comparison of the quality actually delivered by the three digital technologies must await more operational experience.

5.3.2 Intrinsic Figures of Merit

The two intrinsic figures of merit identified in section **2.3.3** are timing and extensibility. Although AMPS is the product of the earliest cellular technology development, NMT was the first of the original systems to be deployed commercially. Its early arrival was a factor in its adoption in many countries outside Europe and the United States.

Among the four later systems, GSM and NAMPS were both deployed in the early 1990s, NA-TDMA arrived next, and CDMA was the latest of the six air interfaces to be standardized and deployed. All other things being equal, early deployment of a technology is an advantage. Abetted by favorable government policies in Europe, GSM has taken full advantage of early arrival. To overcome CDMA's handicap of being last to market among the three digital cellular technologies, its proponents have asserted its technical superiority in terms of extrinsic figures of merit. This strategy was effective in retarding the progress of an NA-TDMA bandwagon in the United States.

Extensibility is not an issue with NAMPS and NMT. From the outset, NAMPS was created as a stopgap technology to provide greater bandwidth efficiency than AMPS, while North American network operators deliberated over strategies for introducing digital technology. By the early 1990s, operators of NMT systems anticipated that the analog cellular market would gradually yield to digital systems, and, in consequence, made no effort to introduce new technologies to extend the capabilities of NMT and NAMPS.

The AMPS situation is different. The gateways to AMPS incorporated in CDMA and NA-TDMA, coupled with uncertainties about the future of digital cellular technologies in the United States, promote the likelihood of a long-term future for analog cellular operation. Given this prospect, the industry has introduced to AMPS a packet-switched data capability, Cellular Digital Packet Data. It has also extended AMPS to incorporate "local control" options, which allow individual operating companies to introduce their own service options. Examples include improved security measures to prevent unauthorized use of a network and a technique that enables specially manufactured telephones to function as residential cordless phones in coordination with domestic base stations owned by subscribers.

Although these extensions to AMPS involve modifications to the standard not anticipated when it was created, the four digital cellular standards and IS-41 were developed with "hooks" for introducing new technology in an efficient manner. Extensions to the air interface technologies include accommodation of new speech coders, transmission techniques for nonspeech sources, such as facsimile (fax) and electronic mail (e-mail), and access to digital transmission channels at a variety of bit rates. Provisions for extending the standard reside in the network control technology, which allows terminals and base stations to exchange information about their configurations and capabilities. With respect to the technical properties of the three digital air interface standards, NA-TDMA is the least capable of gracefully introducing a range of new communications services, because its time-division signals are confined to 30-kHz frequency bands, which have limited capacity. By contrast, GSM, a time-division system with signals occupying 200 kHz, can accommodate a richer mixture of services. CDMA also has a wide bandwidth and inherent flexibility. However, no consensus yet exists on how best to introduce new services with high bit-rate requirements.

5.4 Adoption

In a PCS market with duelling standards, three communities of stakeholders face adoption decisions: equipment vendors, network operators, and subscribers. Each community faces the issues of when to make an adoption decision and which technology or set of technologies to adopt.

5.4.1 Equipment Vendors

The issues addressed by manufacturers of PCS infrastructure and terminal equipment closely resemble the situations addressed in the theoretical literature. Early adopters risk being stranded with a standard that, in the end, has an insignificant marketshare. On the other hand, early adoption of a winning standard offers a vendor the advantages of riding the bandwagon produced by positive externalities. Deferred adoption reduces the risk of stranding but opens up the possibility of a firm missing the bandwagon and finding itself confronted with major barriers to entering a market already dominated by competitors.

To demonstrate the complexity of the technology adoption deliberations, the remainder of this section examines the positions taken with respect to North American and European analog and digital infrastructure equipment by four major companies: AT&T, Ericsson, Motorola, and Northern Telecom, all with significant shares of the North American analog market. As the original sponsors of the AMPS standard, AT&T and Motorola enjoyed the benefits of a head start over competitors. AT&T produces complete systems, while Motorola, originally a mobile radio company, acquires its switching equipment from the Digital Switch Corporation (DSC). By contrast, Northern Telecom gained its foothold by building on its position as an established vendor of switching equipment, especially in Canada. To do so, it adapted its DMS line of switching equipment to cellular operation and acquired base-station equipment from outside sources. Eventually, Northern Telecom developed its own radio manufacturing competence and produced complete analog systems. Ericsson, with no prior North American market in either telephony or mobile radio equipment, entered on the basis of early experience catering to roaming subscribers in the analog cellular system that spans the Nordic countries. A substantial contract with McCaw Cellular (now AT&T Wireless Systems), signed in 1991, marked Ericsson's major step into the AMPS market. By then, McCaw had acquired many RCC licenses with a large geographical span. By installing Ericsson infrastructure equipment throughout most of its coverage area, McCaw was able to offer subscribers at an early date the advantages of automatic roaming over much of the United States.

With respect to analog cellular standards, AT&T and Northern Telecom have confined their infrastructure offerings to AMPS equipment and, thus, have no analog equipment markets in Europe. Motorola, on the other hand, has been a major player in markets for TACS equipment, most notably in the United Kingdom, where it shares the TACS market with Ericsson. In addition to playing a major role in AMPS and TACS, Ericsson is the dominant supplier of NMT analog cellular equipment.

Although all four of the vendors considered here offer GSM equipment, only Motorola and Ericsson are prominent in European markets, and their success there is the result of early adoption decisions. AT&T and Northern Telecom decided later to offer GSM equipment and so missed the bandwagon in Europe. As with analog cellular, Ericsson, AT&T, and Northern Telecom produce complete GSM systems. Northern Telecom's base stations are produced in France.

The four companies all have different approaches to the three duelling digital standards in North America—CDMA, NA-TDMA, and GSM. As just mentioned, all four offer GSM equipment, but Ericsson and Northern Telecom are off to an early lead in the new GSM market in the North American 1900-MHz PCS band. All the companies, except Ericsson, have succeeded in selling CDMA systems. AT&T produces complete systems; Motorola produces base stations and obtains switching equipment form DSC; and Northern Telecom produces CDMA switches and obtains base stations from Qualcomm. With respect to NA-TDMA, Motorola is the one company with no infrastructure market position. The three other vendors all offer customers the opportunity to replace analog channel units (each capable of carrying one conversation) in a base station with digital units (each capable of carrying three conversations). With TDMA equipment available a few years earlier than CDMA, Motorola introduced NAMPS in order to retard the progress of a possible NA-TDMA bandwagon. By converting some of its channels to NAMPS operation, network operators gain some relief from channel congestion while they wait for CDMA technology to mature.

5.4.2 Operating Companies

Standards adoption by operating companies depends on a combination of policy and commercial factors. For the analog and digital generations of PCS systems, the situations in Europe and the United States have flip-flopped. In the U.S. and Canada, AMPS was the mandatory technology for all analog systems. Rules established by the FCC fragmented the operating industry that shares a single cellular technology. In Europe, with usually one operating company (in a few cases two) per country, each country made its own analog technology adoption decision. Given the preponderance of government-owned telephone companies there in the 1980s, in many countries government policies and commercial considerations merged. The result was by 1990, a patchwork of analog cellular technologies, with NMT and TACS, a derivative of AMPS, holding major marketshares.

In the digital generation, the volume of mandatory GSM service enjoys steady growth. In the United States, the FCC, in 1990, stopped regulating PCS compatibility, so technology adoption now depends entirely on commercial considerations. Because of the geographical fragmentation of the U.S. industry and the proliferation of spectrum licenses in each area, there has been a wide variety of technology adoption patterns. In the 850-MHz cellular band, the competition between CDMA and NA-TDMA standards has retarded adoption decisions by many companies. By comparison with the pace in Europe, the slow migration to digital has been exacerbated by problems with the CDMA technology. In 1994, CDMA systems were installed by U S West in the state of Washington and by AirTouch in California, but commercial service was delayed until mid-1996.

Several companies, mainly AT&T Wireless Systems and Southwestern Bell (SBC), have deployed NA-TDMA equipment in congested areas. As of mid-1996, there were NA-TDMA cellular systems in commercial service and several CDMA systems undergoing technology trials. On the basis of announced adoption decisions, the market appears evenly split between NA-TDMA and CDMA, with some companies still taking a wait-and-see position. Those with Motorola infrastructure equipment have adopted NAMPS as a stopgap technology, to relieve capacity problems to some extent as the digital systems mature.

License holders in the 1900-MHz PCS spectrum bands auctioned by the FCC in 1995 and 1996 have not had the luxury of operating profitable AMPS systems in these bands while deliberating the relative merits of digital technologies. Because their spectrum license fees represent substantial investments in new networks, they are under pressure to set up the networks in order to initiate a revenue stream to offset the investments. Operation in the 1900-MHz band will be entirely digital, and a survey of announcements by companies that won spectrum licenses in the 1995 auctions of A- and B-band licenses indicated approximately equal division among GSM, NA-TDMA, and CDMA. The technology decisions among cellular companies that obtained PCS licenses in areas not covered by their cellular operations match those adopted for 850-MHz operation. These companies will certainly promote subscriber equipment capable of operating with both 850-MHz and 1900-MHz channels. Initially, some telephones will probably be triple-mode devices, capable of digital operation at 850 MHz and 1900 MHz and also of analog AMPS operation, assuring their owners of service throughout the United States and Canada.

By contrast, the GSM telephones operate only with that technology in the 1900-MHz band. The first 1900-MHz commercial system in the United States, operated by American Personal Communications with the Sprint Spectrum brand name, opened for business in November 1995. Press reports indicated that it is a success both commercially and technically. Initially, subscribers could obtain service only in the Baltimore–Washington area, but GSM deployment decisions in many parts of the United States promise a rapid expansion of service availability.

5.4.3 Subscribers

Subscribers make technology adoption decisions when they purchase telephones and sign service contracts with network operators, but they are far less conscious than equipment vendors and operating companies of the issues addressed in this study. This is true primarily because, to consumers, network and equipment alternatives appear to be choices between pricing plans, coverage areas, roaming opportunities, and service features, rather than as technology alternatives. In addition, the nature of the PCS service markets in North America and some parts of Europe makes it easy for subscribers to change equipment and service providers frequently. The low cost of nullifying an adoption decision insulates subscribers from the principal risks faced by vendors and service operators: stranding and missing a bandwagon.

5.5 Relation of This Study to Theoretical Studies of Standards

The academic literature on compatibility focuses on the effects of externalities. There are two broad categories of analysis: inductive studies based on case histories and deductive studies based on mathematical models. Even though the models contain numerical parameters, their main use has been to demonstrate qualitative phenomena, rather than to predict quantitatively the effects of specific actions in a practical setting. Two important conclusions of these studies are (1) that markets with externalities require coordinating mechanisms to arrive at desirable results, and (2) that a variety of possible results can evolve from specific market conditions.

In telecommunications, government policies have traditionally provided the coordinating mechanism. In analog cellular communications in the United States in the 1970s the FCC mandated interoperability. It also regulated signal quality and spectrum efficiency. It judged AMPS the best available technology to satisfy these criteria, and until 1990 all cellular transmissions, by decree, conformed to the AMPS standard. In Europe, where no such coordinating mechanism existed to achieve the positive externalities of Continental compatibility, a geographic mosaic of incompatible analog cellular standards resulted. Although from the outset AMPS equipment vendors have benefited from the compatibility of telephones and base stations throughout North America, the restricted scope of the AMPS standard has prevented subscribers from realizing the full benefits of externalities. In particular, roaming arrangements and handoff possibilities have, until recently, been limited by the proprietary nature of AMPS infrastructure signaling. Only with the widespread adoption in the mid-1990s of a standard for intersystem signaling (IS-41), did a majority of subscribers gain the advantages of convenient roaming throughout the United States.

By mandating a single digital standard, in the late 1980s the European Community (as it was then) provided a coordinating mechanism similar to that provided by the FCC a decade earlier. Although the European Community had followed the FCC's earlier example of mandating compatibility of all digital systems in the 900-MHz cellular band, it did not take on the difficult task of assessing efficiency and signal quality of technology alternatives. Instead, it relied on an industry organization to develop the GSM specification. Because GSM specifies an entire system, including many infrastructure interfaces, the growing number of GSM subscribers enjoy the benefits of both base station-telephone compatibility and easy roaming in all GSM service areas.

Although the European Commission assumed this coordinating role, U.S. authorities decided that market forces could do a better job than regulators of sorting out the relative merits of technology alternatives. At present, market forces are at work, arranging the relative positions of three digital PCS technologies. In the absence of a national standard, dual-mode gateways insure compatibility between telephones and base stations for the majority of subscribers. At present, it appears that this standards battle will go on for years.

Although it is beyond the scope of this study to answer the basic economic question of which, if any, markets will converge to an efficient operating point, the current PCS situation provides an opportunity for economists to examine the predictive power of mathematical models by applying them to the future of PCS markets. In performing this analysis, interested parties will identify early events that can lead to each possible outcome in the path-dependent environment of PCS markets, and their analyses will suggest strategies for stakeholders to adopt in order to obtain the most favorable results for themselves.

Awaiting such deductive assessments, this study offers inductive judgements of the effects to date of PCS standards activities:

• European vendors and subscribers enjoy the full effects of externalities in digital cellular and PCS. It remains to be seen whether they are locked into a suboptimum technology in terms of quality and efficiency. Mitigating this risk is the extensibility of GSM, which appears sufficient to narrow any disadvantages it might have relative to other technologies.

• U.S. vendors are at a disadvantage relative to European ones. On a global basis, markets for their products will for a long time be smaller than markets for GSM. Although the U.S. market remains divided among GSM, NA-TDMA, and CDMA, with various gateways in place, subscribers will also be denied the full externalities of a national standard.

• Even with the U.S. market in a position to determine the final outcome of the duel, the market's path dependence offers no guarantee that the final result will be the most efficient one. As Passell's title states, "The best doesn't always win."[1]

5.6 Implications for Public Policy

PCS stands at the intersection of three types of government activity: radio spectrum regulation, which determines the structure of broadcasting and other industries; monopoly regulation, which determines the structure of telecommunications industries; and technology creation, which determines the nature and ownership of new technologies. With all three activities in flux globally, PCS is in a particularly volatile situation. Cellular communications arrived during a period of strong regulation of radio spectrum in each country, which produced national compatibility specifications that extended in some cases to clusters of countries. In North America, the cluster covered the whole continent, while in Europe, the largest cluster was the Nordic countries. With respect to industry structure, Europe at first followed the traditional telecommunications model of national monopolies, except the United Kingdom, which from the outset has had two national cellular networks. By contrast, the United States adopted a decentralized approach that combined the post-divestiture telecommunications industry structure with the traditional U.S. broadcasting model of a myriad of local licenses.

In formulating the policies that governed the introduction of second-generation technologies, authorities in the United States and Europe adopted new approaches that addressed different issues. The European Community's policies were aimed at producing externalities of Continental proportions, while U.S. policies aimed to stimulate technical innovation. Although both sides can reasonably argue that their aims were achieved, as of early 1997 it seems that European stakeholders have been better served by their governments' policies than those in the United States. Owing to the stable, mature nature of GSM technology, vendors in Europe have a global marketplace for their products, and subscribers enjoy the benefits of economies of scale and roaming opportunities in a growing number of countries throughout the world. Neither of these benefits yet exists in the United States, where government policies have allowed operating industry and subscribers to choose among several

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[1]Peter Passell, "Why the Best Doesn't Always Win," *The New York Times Magazine*, May 5, 1996, 60-61.

different technologies with the possibility, but by no means the assurance, that the best choice, when it can be determined, will be the most widely adopted.

In my view, the European approach has to date been on balance more successful than the U.S. one. Indeed, the U.S. policy for regulating high-definition television technology more closely resembles the European approach to PCS than its own approach to PCS. The FCC has encouraged proponents of competing television technologies to reach a consensus on a standard that incorporates the best features of their separate proposals. In adopting a spectrum management policy for high-definition television, the FCC compelled the industry to reach a consensus on technology. In doing so, it followed the European approach to PCS standards.

With respect to industry structure, Europe continues in its traditional mode of issuing national licenses on the basis of the merits of the applicants as perceived by government agencies. The United States, by contrast, has adopted auctions for issuing thousands of spectrum licenses that cover a wide range of frequency bandwidths and geographical areas. In the current environment of change throughout all telecommunications industries, this approach offers the promise of allowing consumers diverse service choices, many of which will bundle PCS with other telecommunications services, such as cable television, local telephone service, long-distance telephone service, and even Internet access. I view this diversity as beneficial to consumers and industry in the United States.

In technology creation for PCS, there are profound differences between the policies of the EU and the U.S. government. The EU has invested hundreds of millions of dollars to establish the technical basis for the next generation of personal communications. It encourages the formation of broadly based consortia of industry and academia to produce a consensus in advance of commercial deployment. In contrast, the U.S. government leaves technology creation to separate competing companies and relies on market forces to decide among alternatives. Economic theory suggests that in a market with externalities, a coordinating mechanism is necessary to produce the benefits of the externalities and that, in the end, as said above, the "best doesn't always win" (see section **2.2.3**). Coupled with spectrum management regulations, the European approach to creating technology for the next generation of PCS provides a coordinating mechanism and a likelihood that the technology that emerges from it will succeed regardless of its merits relative to competition from U.S. companies.

Acronyms

AMPS	advanced mobile phone system
ANSI	American National Standards Institute
CB	citizens band
CD	compact disc
CDMA	code division multiple access
CEPT	Conference of European Posts and Telecommunications Administration
cm	centimeter
CT2	second-generation cordless telephone
CTIA	Cellular Telecommunications Industry Association
DECT	Digital European Cordless Telecommunications
e-mail	electronic mail
EIA	Electronic Industries Association
ETSI	European Telecommunications Standards Institute
EU	European Union
FCC	Federal Communications Commission
FDMA	frequency division multiple access
FM	frequency modulation
GloMo	Global Mobile Communications
GSM	Groupe Spécial Mobile; now Global System for Mobile Communications
IS	Interim Standard
ISDN	integrated services digital networks
ITU	International Telegraphic Union
kHz	kilohertz
km	kilometer
Mbps	megabits per second
MHz	megahertz
MoU	memorandum of understanding
MSA	Metropolitan Statistical Area
MSC	mobile switching center
NA-TDMA	North American TDMA
NAMPS	narrowband AMPS
NMT	Nordic Mobile Telephone System
PCS	personal communications services or systems
PBX	private branch exchange
PTT	post, telegraph, and telephone

RCC	radio common carrier
SBC	Southwestern Bell Co.
SIM	subscriber identity module
TACS	total access communications system
TDMA	time division multiple access
TIA	Telecommunications Industry Association
UHF	ultrahigh frequency
VHS	Video Home System
WCC	wireline common carrier