

Air Interface Standards for Digital Mobile Cellular Systems in the U.S., Europe and Japan

by

Rohit Sakhuja

Submitted to the Department of Electrical Engineering and Com-
puter Science in partial fulfillment of the requirements for the
degrees of

Bachelor of Science and Masters of Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Abstract

As deregulation of cellular markets in the U.S., Europe and Japan proceeds, technical standards for cellular systems are being developed and refined in each of these regions. Both the process of standard setting and the outcome of the process have differed in these three regions. This thesis will explore these differences. It focuses in particular on the air interface standard for second generation digital mobile cellular systems. Based on this analysis, conclusions are drawn concerning how the standard setting process might be improved in each part of the world.

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This thesis is a story about the people who made the standard setting decisions. The only way to really understand these decisions is to meet with the people directly involved. The number of people makes it impossible for me to mention them all here. Without their cooperation, however writing this thesis would have been impossible.

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Chapter 1

Introduction

As deregulation of cellular markets in the U.S., Europe and Japan proceeds, technical standards for cellular systems are being developed and refined in each of these regions. Both the process of standard setting and the outcome of the process have differed in those three regions. This thesis will explore these differences. It focuses in particular on the air interface standard for second generation digital mobile cellular systems. Based on this analysis, conclusions are drawn concerning how the standard setting process might be improved in each part of the world.

1.1 Why are standards necessary?

In the last ten years governments around the world have been privatizing and deregulating telecommunications markets. During the regulated-monopoly era there was typically a single government-owned service provider and a small group of national equipment manufacturers who sold to that operator. The service provider developed the technical standard in accordance with all government regulations, and the national equipment manufacturers produced according to the standard. In this environment no formal standard-setting infrastructure was necessary.

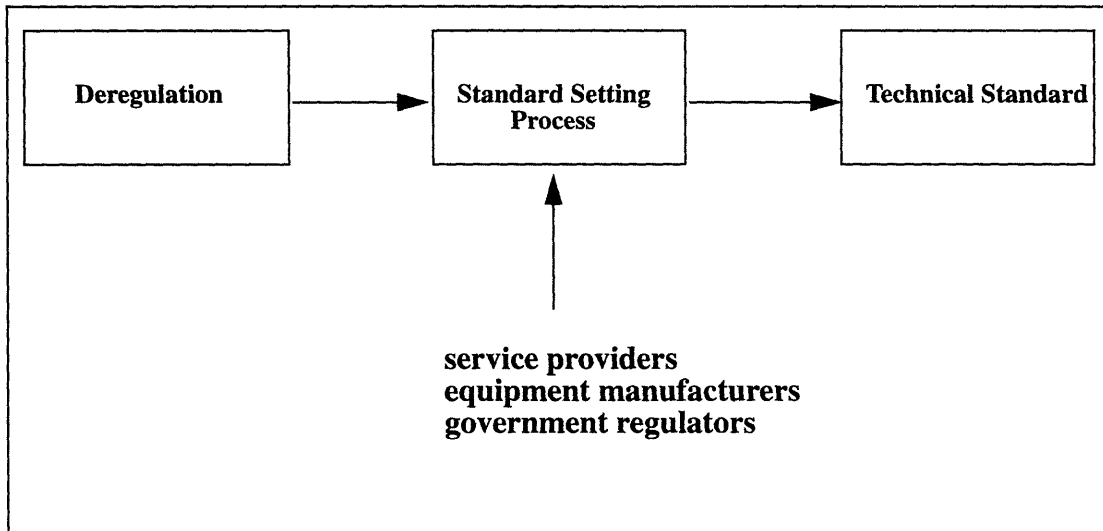


Figure 1.1: Standard setting in a deregulated environment

However, partly as a result of changes in the economics of telecommunications over the last decade, governments around the world have been deregulating their telecommunications markets. One consequence of deregulation is the emergence of competition amongst service providers for the different segments of the telecommunications industry. In addition, trade barriers around the world have been falling, creating major new international opportunities for equipment manufacturers. For example, in 1994 Ericsson Radio generated 96% of its revenue internationally.¹ Even in the Japanese market, traditionally one of the most closed industrial markets in the world, Motorola, Ericsson and AT&T are successfully selling telecommunications equipment. Figure 1.1 shows how deregulation creates the need for a new standard setting process which accommodates the increasing number of service providers and equipment manufacturers. As we will learn in this thesis, the standard setting process has evolved very differently in the U.S., Europe and Japan.

1. Interview with Jan Uddenfeld, Ericsson Radio Systems, Stockholm.

1.2 Thesis Focus

The focus of this thesis is a comparison of the technologies and the standard setting processes for second generation digital mobile cellular systems in the U.S., Europe and Japan. To provide additional focus, five key air interface decisions are analyzed including i) whether or not to adopt a single standard, ii) spectrum allocation and partitioning, iii) channel spacing and number of users per channel, iv) voice codec systems, and v) transmission technology.

1.2.1 Why second generation systems?

	1st generation analog standards	2nd generation digital standards	3rd generation digital standards
United States	AMPS	D-AMPS, E-TDMA N-CDMA	N-CDMA or DCS-1800
Europe	TACS NMT-450 / 900	G.S.M.	D.C.S.-1800
Japan	N.T.T. analog J-TACS N-TACS	P.D.C.	

Table 1.1: Different Cellular Standards in the U.S., Europe and Japan

Table 1.1 lists the cellular standards which have emerged in the U.S., Europe and Japan. The first set of cellular standards was introduced into the market in the late 1970's and early 1980's. These systems were analog, already by then a well developed field of radio communications. However, as the demand for mobile communications grew, it was apparent that digital systems could provide improved spectral efficiency, and hence could help alleviate capacity constraints in large metropolitan areas. Therefore digital solutions

were researched and proposed in various standard setting bodies in the U.S., Europe and Japan. By the early 1990's, a second generation of mostly digital services had been introduced in many countries around the world. In regions such as Portugal, India, and Germany, which do not have a well-established analog infrastructure, the penetration rates of digital systems are higher than in regions where analog service is still a viable solution. An example of the latter is the United States where there are currently 25 million users of analog AMPS telephones and less than 1 million users of digital telephone service. More recently, the U.S. and Europe have also allocated spectrum for third generation digital services. These systems are expected to provide additional functionality and improved spectral efficiency.

This research focuses on second generation digital cellular technologies which emerged in each region: i) Digital American Mobile Phone Service (D-AMPS) in the U.S., ii) Groupe Speciale Mobile (GSM) in Europe and iii) Personal Digital Cellular (PDC) in Japan. The comparison between these three systems is particularly interesting because the goals of the decision makers in each region were very different. This thesis also includes some discussion of Qualcomm's N-CDMA technology which is a strong contender for the second and third generation digital mobile systems in the U.S. and potentially overseas. Because multiple technologies were not permitted in Europe or Japan for second generation systems, and because CDMA technology was not mature enough when these second generation standards were set, a CDMA solution does not yet exist in either region. These technical and policy decisions have thus put cellular technology on different trajectories in each part of the world.

1.2.2 Why the U.S., Europe and Japan?

The U.S., Europe and Japan have the most advanced high technology industries and research facilities in the world and the standard setting bodies and corporations in these three parts of the world are consequently the most prolific developers of technical standards. Countries with less advanced technological industries typically do not develop their own standards, but rather adopt foreign technologies. They do this primarily for two reasons. First, they do not have the same research and development capabilities and therefore are not as well positioned to develop strong technical standards. Second, economies of scale mean that equipment costs will generally be lower for equipment manufacturers adhering to standards developed for large markets. In fact, all of the cellular standards used in the world today were developed in one of these three parts of the world.

A study of the specific decision making process for the air interface standard in the U.S., Europe and Japan will lead us to a better understanding of both the motivations and goals of the policy makers in these regions, and the different processes used to carry those decisions out.

1.2.3 Air interface versus network standards

Within a cellular system, technical standards are required for both the air interface (the communication over the radio link between the handsets and the base stations) and the telephone switching system. A focus on either standard would yield insight into the different processes for standard setting in the three different parts of the world. However, the air interface standard affects the design of the base station, the mobile station and the switch-

ing system. It defines the algorithms for doing multiplexing, coding, interleaving, modulation, framing, synchronization and transmission and reception. Because of the broad scope of the air interface standard, and the author's technical background, this was chosen as the focus of the research.

1.2.4 Why these particular air interface decisions?

The five aspects of the air interface standard discussed here involve political, economic and technical issues.

Number of standards

The decision regarding whether or not to establish a single standard is a case study in how interactions between policy makers, service providers and equipment manufacturers have differed in the three parts of the world. This decision set the stage for the different technological trajectories which have been pursued in the U.S., Europe and Japan.

Spectrum Allocation and Channel Spacing

Two other important decisions concerned the allocation and partitioning of spectrum between the different service providers, and the channel spacing used within that spectrum. The allocation of virgin spectrum for digital mobile cellular services in Europe provided engineers with an additional degree of freedom relative to the situation in the U.S. and Japan. Allocating virgin spectrum forces service providers to invest in new infrastruc-

ture, but also gives them the flexibility to provide new more advanced services. The channel spacing decision also affects the flexibility of the system.

Access Method and Voice Coding

The access method and voice coding decisions are particularly interesting because they illustrate two important points. The former illustrates the differences in the standard setting goals and processes in the three regions. The latter illustrates some of the advantages of being the last to set a standard. Because the Japanese were able to incorporate and improve upon the technology in the European and the American standards, the Japanese PDC standard the most spectrally efficient of the three. However, as we will see there are also many disadvantages of being the last to set a standard. In the conclusion, we will address issues concerning optimal timing in standard setting.

Summary

In general by comparing the standard setting process for several digital mobile cellular systems in the three regions of the world - how the process was organized, who the key participants were, the technologies that emerged and the current state of cellular technology - it is possible to reach conclusions regarding the strengths and weaknesses of each process. Based on these conclusions recommendations are made concerning how telecommunications standards should be set in the future.

Chapter 2

Technical Standards

Policy makers and industry leaders have debated the benefits and drawbacks of setting technical standards. A technical standard requires manufacturers to adhere to a particular set of technical requirements in order to implement a particular product or service. According to the Office of Technology Assessment, standards help “determine the efficiency and effectiveness of the economy, the cost, quality and availability of the products and the services and ensure the nation’s health, safety and quality of life.”¹ Clearly, technical standard setting can provide benefits for the consumers, equipment manufacturers and the national economies. This chapter will present some of the benefits and drawbacks to setting technical standards and will examine some international differences in mechanisms and approaches to setting standards.

2.1 Trade-offs in implementing Technical Standards

In this section we will consider the advantages and disadvantages of technical standards from three perspectives: i) equipment manufacturers, ii) consumers and iii) national governments. Many of these advantages, such as reduced costs, and increased total volumes, actually benefit all of these groups.

1. Davidson, Alan. p. 12.

2.1.1 Equipment Manufacturers

Technical standards allow equipment manufacturers to develop a single product to serve a particular market rather than develop multiple products to interface with different companies' standards. Not only does this save development costs, but the manufacturers can also take advantage of economies of scale to produce products at a lower cost. For example, all consumer electricity outlets in the United States are at 110 volts. Any manufacturer producing a product which requires electricity must meet that specification. Implicitly, this single standard increases the value of an item such as a lamp because the customer knows that all U.S. electric outlets will accommodate it. By adhering to a single standard, and increasing the value of the lamp to customers, manufacturers can also attain larger volumes.

Technical standards also have potential disadvantages from the perspective of equipment manufacturers. First there is the possibility that the standard will stifle the further development of technology. Standards require manufacturers to lock into technologies which may not be state-of-the-art for the entire lifetime of the product; they may force manufacturers to produce technology which is not as cost-effective.

Second, equipment manufacturers may be forced to accept technologies embodied in the standard which they do not believe are optimal from the outset. Third, they may not be in the best competitive position to manufacture to the standard. For example, as will be explained later in the thesis, AT&T and Motorola were forced to adopt a Time Division Multiple Access Technology (TDMA) standard for the D-AMPS digital mobile cellular standard, even though they were both best positioned to manufacture equipment based on Frequency Division Multiple Access (FDMA) technology. To gain the advantages of man-

ufacturing to the Telecommunications Industry Association (TIA) standard, they would in all likelihood have manufactured Frequency Division Multiple Access (FDMA) technology and would have had products on the market much sooner.

Fourth, the coordination between various parties in the industry that is required to develop technical standards takes time and typically delays the introduction of a product. Clearly, delays in product introduction will adversely affect both the service received by consumers and the industry's profits. The greater the number of participants in the standard setting process, the more difficult it is to reach consensus; hence the longer the product introduction will take and the greater the cost will be to the consumers and the manufacturers.

Traditionally, manufacturers who are able to set a de-facto market standard because of their strong technical and/or marketing capabilities do not support technical standards because these reduce the barriers to entry for their competitors. For example, Microsoft gained a huge advantage in the marketplace by establishing the D.O.S. operating system as the market standard. Once D.O.S. became successful, most computer manufacturers sold their hardware with the D.O.S. operating system and most software vendors wrote all of their code to run on the D.O.S. Other companies tried to introduce alternative technologies, but in most cases were not able to gain the support of the computer manufacturers and software vendors. Microsoft established D.O.S. as the market standard.

Smaller manufacturers, on the other hand, often prefer technical standards, because they provide all manufacturers with a common technology base and guaranteed compatibility with other products.

2.1.2 Consumers

Consumers benefit from technical standards primarily in two ways: lower prices and increased choice and flexibility. Consumers enjoy lower prices primarily because the manufacturers can exploit economies of scale and pass on some of the cost savings. As noted earlier, standards level the playing field and increase the overall level of competition, thereby allowing consumers to enjoy a larger product range with lower prices. For example, with common standards and well-defined interfaces, one could imagine buying all of the different components of a system from different manufacturers. This would allow retailers to mix and match various components of a system to provide consumers with the best quality systems. On the other hand, if one company used proprietary technology to establish a de facto market standard, consumers would be forced to purchase the entire system from that company at whatever price the company demanded.

Standards also increase the flexibility with which consumers can use and operate various products. For example, with a common electrical outlet, the same hairdryer can be used anywhere in the United States. Common standards, therefore, allow consumers to use products in a greater number of places, which increases their value to the consumer.

On the other hand, although there may be more manufacturers producing the same product, consumers have fewer technical solutions to choose from to fulfill a particular need. Consumers lose this freedom because a technology standard forces consumers to use a product which is often a combination of different manufacturers' technologies, rather than being able to choose between different products, each of which uses a different technology. In many cases these alternative solutions will never actually be introduced on the market because manufacturers are required to adhere to a different standard.

2.1.3 National governments

Technical standards also provide government with a way to improve the efficiency of the economy, stimulate the level of competition in an industry, and promote the interests of domestic manufacturers abroad. Technical standards can also provide a more advanced infrastructure for a country. Today a single analog standard allows Americans with cellular telephones to use these telephones almost anywhere where there is analog cellular coverage. By establishing a common standard and allowing people to use a product anywhere, the efficiency with which tasks can be accomplished. Imagine a situation in which all of the Regional Bell Operating Companies had disparate telephone networks which could not be linked together. No telephone calls would be able to travel between Boston and Chicago because the NYNEX and Ameritech networks would not be linked. This would make it virtually impossible to do business or keep in contact with people outside of one's local region.

As discussed earlier, common standards can also be a way for governments to reduce the barriers to entry for new competitors, with the intent of promoting more open competition.

A third reason for governments to promote technical standards is for trade policy reasons. First, governments can use national standards to protect their domestic industries. By having the domestic equipment manufacturers and service providers work together to create domestic standards, the government can give the domestic equipment manufacturers a competitive advantage in the marketplace. Second, establishing national standards provides an opportunity for national industries to establish their standards internationally. This gives equipment manufacturers a competitive advantage in new overseas markets

because they have developed the technology and have more expertise in manufacturing and better opportunities to exploit economies of scale.

For example, many developing countries have adopted GSM, the pan-European digital cellular standard.

One such country is India, where telecommunications services are growing at a faster rate than in any developed country, at 50-100% per year. In New Delhi, there is a 5-year waiting list for telephone service. Wireline and cellular infrastructure is therefore needed as quickly as possible. Indian telecommunication service providers do not have the technical expertise to develop their own technologies; consequently, they have been considering solutions from abroad. Recently the Indian government agreed to adopt GSM as its cellular standard. 70-80% of GSM the market for base stations and handsets is held by European equipment manufacturers.¹ Motorola is the only non-European player which has a significant share of the GSM market. If European equipment manufacturers are as successful in India as they have been in Europe, they could have an additional 14 - 24 million customers from the Indian market alone by the year 2000.²

G.S.M. has been set as the standard in 80 countries today. These additional markets are generating additional profits for European manufacturers, and giving the European governments additional influence within the technical and business communities.

Technical standards may, on the other hand, reduce the motivation for industries to invest in research and development and to develop more advanced technology. For example, if a common digital standard had been established in the United States, Qualcomm may never have developed commercially available CDMA (code division multiple access)

1. Data provided by European Mobile Communications

2. This is based on analyst estimates that India will have cellular market penetrations of 2-3% (20-30 million people) by 2000 and my estimates that European equipment manufacturers will capture 70-80% of the GSM market in India.

technology, because all of the cellular telephones manufacturers would have been required to use the older, less sophisticated TDMA technology. As of April 1995, nine of the twelve service providers in the U.S., had agreed to adopt CDMA in the 800 MHz band.¹ Today Qualcomm's CDMA is arguably the strongest potential competitor to Europe's DCS-1900 technology for future mobile communications services in the United States.

Advantages	Disadvantages
economies of scale	stifles technology
promotion of national equipment manufacturers overseas	longer development time
protection of domestic market	
interoperability	

Table 2.1: Summary of trade-offs in standard setting

To summarize, standardization has many advantages from the perspective of the growth of an industry. It gives firms an opportunity to cut costs, provides interoperability, promote a nation's equipment manufacturers and promote a more open competitive atmosphere. Timing, however, is critical. If standards are determined too early, the industry may be forced to lock onto an obsolete technology. If standards are set too late, there is a risk of weakening the industry and reducing its overall growth potential. The next section describes two mechanisms by which the standard setting process could work.

1. This information was provided by an official at Qualcomm.

2.2 Standardization Mechanisms

There are two different mechanisms which can be used to develop technical standards. These include a de facto market mechanism and a government mandated standard. In either case the government can regulate participation in the process and therefore influence the outcome of the technology. This issue has been handled differently in the U.S., Europe and Japan.

2.2.1 Market mechanisms

In a completely open competitive environment, no standard is set by the government or industry trade organizations and all corporations are encouraged to introduce their products on the open market. Consumers decide through their purchasing decisions which technology becomes the market standard. Perhaps the most famous example of a market determined standard is the V.H.S. standard for video cassette recorders. Both V.H.S. recorders and Beta-max recorders were introduced on the market at approximately the same time. Initially video cassette manufacturers produced both blank and pre-recorded tapes for both standards. In time, however, the market determined that V.H.S. recorders were the choice of consumers. Tape manufacturers slowed their production of Beta-max video tapes and increased their production of V.H.S. tapes. Today we clearly have one standard for V.C.R.'s - the V.H.S. standard.

In general, a process which results in multiple competing standards stimulates better technology than a because the different players must continually adopt develop and adopt better technologies to stay ahead of their competitors. Having multiple standards in a market may also increase the total market penetration of the product because it increases con-

sumers awareness of the product. Perhaps the VHS VCR standard was more successful in the end because it had to compete with the Beta-max standard before it established itself as the market standard. However, permitting multiple standards in the market can also cause confusion because consumers do not know whether to purchase products manufactured to the current standard or to wait for a more advanced or cost-efficient solution to be introduced. Many consumers may not commit to purchasing products today.

2.2.2 Government mandated standards

In this case the government mandates a single technical standard. The government can either set the standard itself, or can organize a process in which other participants such as the equipment manufacturers and service providers work together to set the standard. The government may choose this option if it believes the industry is so fragmented that it is incapable of establishing a single standard. Governments may also be reluctant to yield authority to private organizations. In Japan, for example, the government ministries, with some input from industry and the trade associations, specify the high level requirements for all high-technology products. Manufacturers then design their products according to these specifications. It is virtually impossible for a company in Japan to introduce a high technology product without the government's blessing.¹

Part of the goal of this thesis is to develop a set of principles which policy makers can use to design a successful standard setting process. One of the issues which will be addressed later in the thesis is whether the government should mandate a single standard

1. Interview with Noly Morimoto, I.B.M. Japan, April 1995.

for future cellular technologies. The next section how the process has evolved in the three parts of the world.

2.3 The Evolution of the Standard Setting Process for Cellular

2.3.1 U.S.

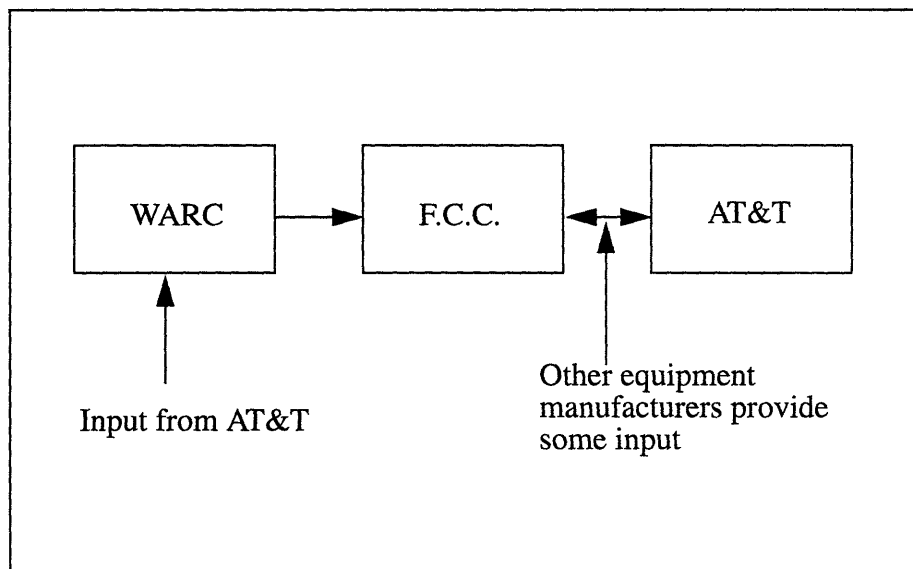


Figure 2.1: The U.S. standard setting process (pre 1984)

The regulated monopoly era (Pre 1984)

Figure 2.1 illustrates how the standard setting process in the U.S. worked before 1984. First, the World Association Radio Committee (WARC) would allocate certain frequencies in North America for land mobile services. The Federal Communications Commission (FCC), the United States government agency responsible for the regulatory aspects of

radio communication in the United States, would then allocate spectrum for cellular, determine the licensing procedures, and set certain other technical specifications to ensure that the different radio services would not interfere with each other. Before the breakup of AT&T in 1984, AT&T was the single telecommunications service provider in the United States. Therefore, AT&T would develop all technical telecommunications standards for the United States. For example, the analog American Mobile Phone Service (AMPS) standard was developed at AT&T research laboratories over the course of 10 years.

New Deregulated Model for Standard Setting (1984 -)

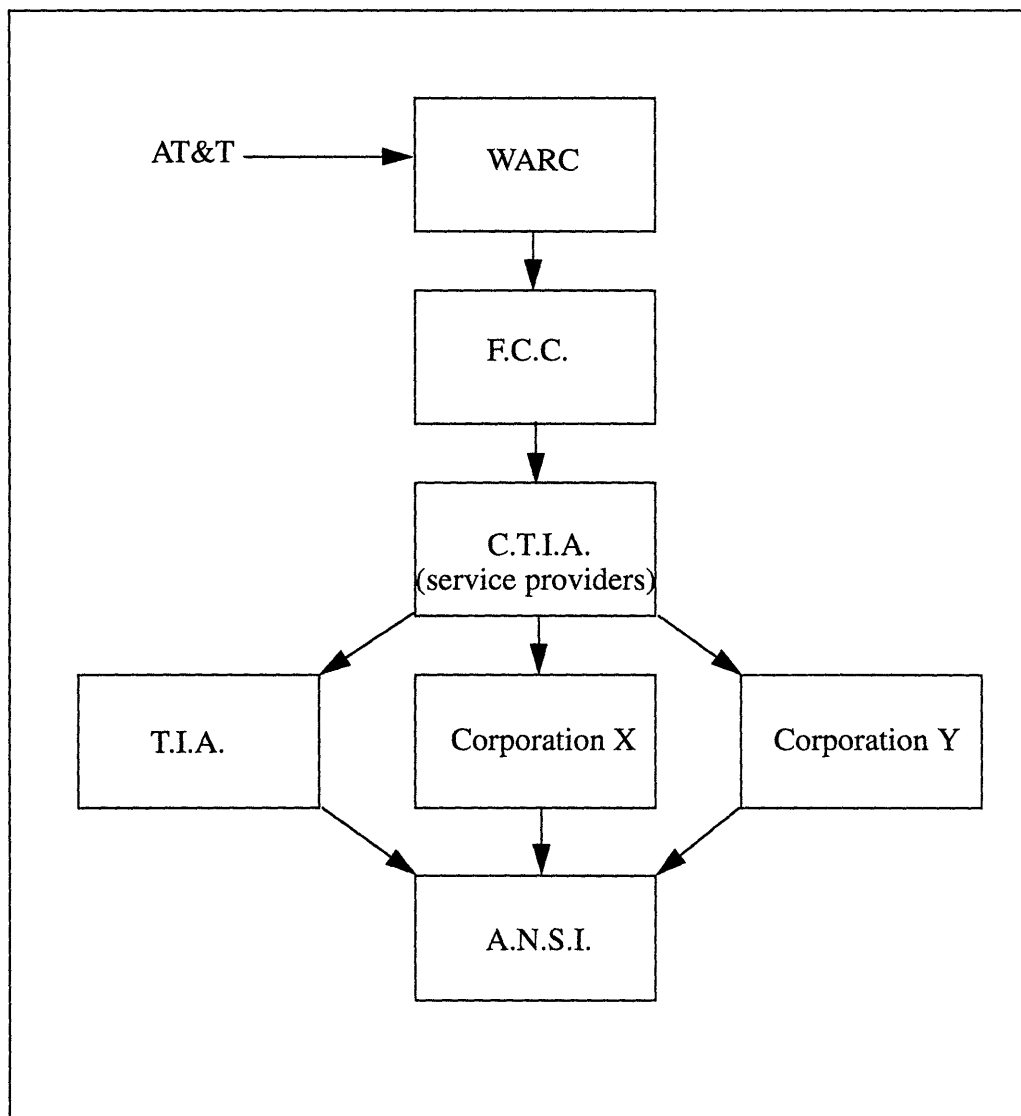


Figure 2.2: U.S. standard setting process (1984 -)

As figure 2.2 illustrates in the United States standards today are set by multiple organizations. WARC and the F.C.C. still play the same role as before by allocating spectrum and setting technical requirements to ensure that the different services do not interfere with each other. Unlike the European and Japanese governments, the mandate of the

F.C.C. is to act as a mediator and to ensure “the fairness and effectiveness of the standard setting process” rather than to be a proponent of particular national industrial policy objectives.

After the F.C.C. has set the technical requirements, the Cellular Telephone Industry Association (CTIA), a voluntary group of cellular operators, may then set additional specifications which its members believe are in the best interests of all of the service providers. For example, in 1988 the CTIA mandated that all digital mobile telephones were required to be backward compatible with analog AMPS service to reduce the overall infrastructure costs for implementing digital cellular systems. After the CTIA sets its requirements the industry players are then free to set technical standards. Many corporations work together to set common technical standards through the Telecommunications Industry Association (TIA), an industry trade group. Qualcomm has chosen to develop CDMA on its own and then has recently had it set by the TIA as an official alternative to D-AMPS standard in the 800 MHz band. All standards must then be approved by the American National Standards Institute (ANSI), a government organization.

The Results

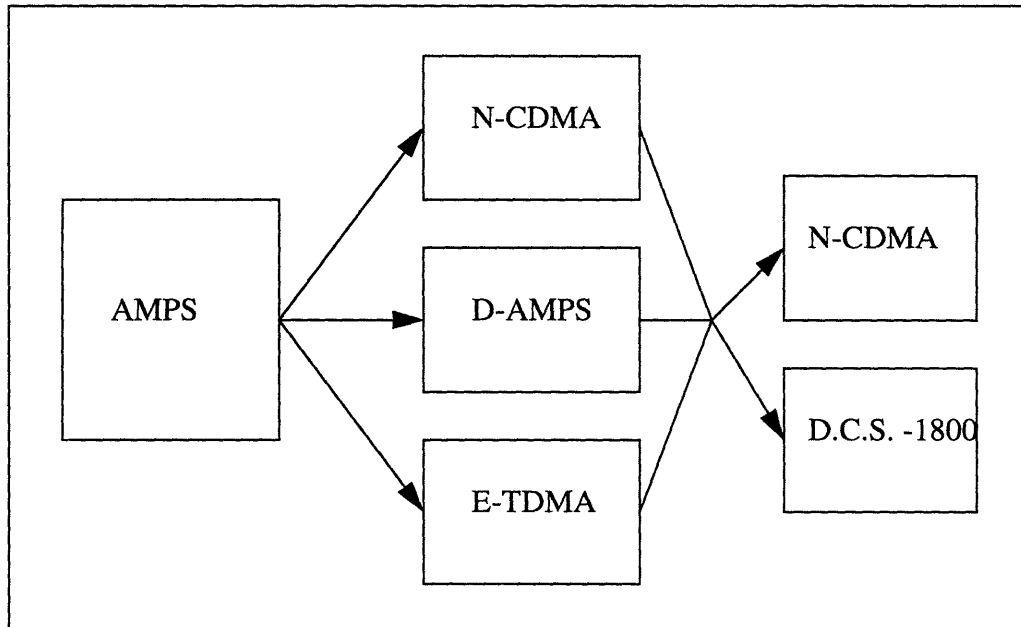


Figure 2.3: 1st, 2nd and 3rd generation cellular standards in the United States

Figure 2.3 shows the standards which have emerged in the U.S. In the United States, AT&T developed the American Mobile Phones Service (AMPS) standard. AMPS has been by far the most successful analog standard in the world and is today deployed in 42 countries. The second generation technologies which have emerged since include the Digital AMPS service, developed by the Telecommunications Industry Association, and a narrowband CDMA solution. Motorola also developed an advanced analog service (N-AMPS) with improved spectrum efficiency relative to the existing analog systems. Auctions were recently held for licenses for third generation mobile services called Personal Communication Services (P.C.S.). The two competing standards for third generation digital cellular services are Qualcomm's N-CDMA solution and the European D.C.S. 1900

solution, which is a derivative of the GSM technology. These services will be deployed in the 1800-1900 Mhz region.

2.3.2 Europe

The Regulated Monopoly Era (pre 1982)

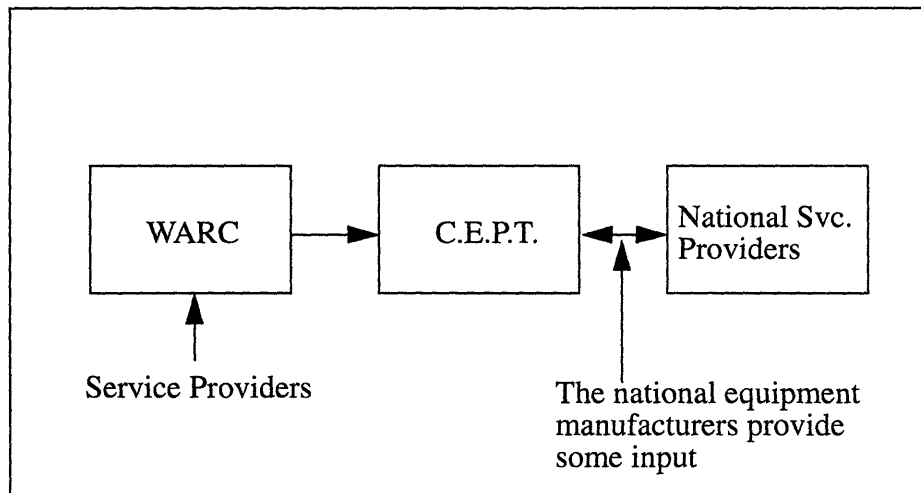


Figure 2.4: The European standard setting process (pre 1982)

Figure 2.4 illustrates the interactions between the regulatory bodies, the service providers and the national equipment manufacturers during the regulated monopoly era in Europe. First, WARC would allocate the frequencies for land mobile services in Europe. The Conference Europeen de Poste et Telecomm (C.E.P.T.), the group of European government owned operators, would then handle regulatory issues such as harmonization of services in the different frequency bands to prevent interference between neighboring countries. The technical standards would then be developed by the individual operators in each country with the help of national equipment manufacturers. This explains why there are a number of different technical analog standards in Europe.

The C.E.P.T. era (1982-1988)

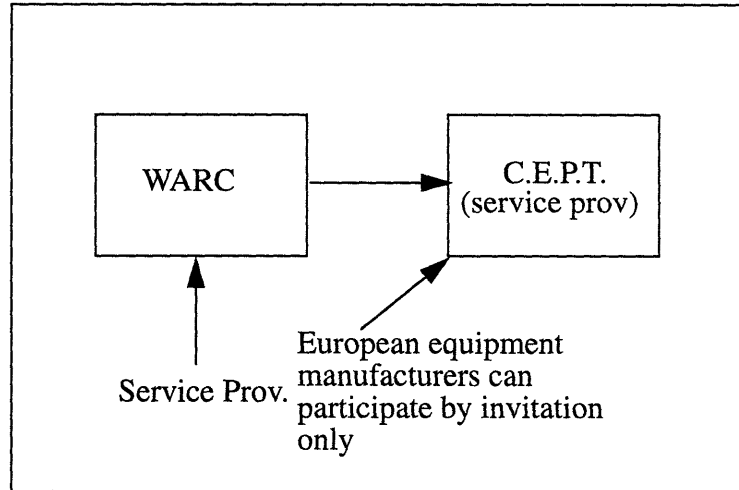


Figure 2.5: The European standard setting process(1982-1988)

Figure 2.5 illustrates the European standard setting process between 1982 and 1988. In 1979 the WARC allocated additional spectrum for land mobile services. In 1982 the Nordic countries proposed that rather than having each country set its own technical standards, the C.E.P.T. should handle technical standardization issues. The European operators all agreed to work together to set a common pan-European cellular standard. European manufacturers have traditionally had a very close relationship with their national operators, and therefore could be expected to contribute their input indirectly through the latter.¹ At times when their expertise was necessary they were invited to the meetings. Non-European manufacturers and operators were not permitted to participate in the standardization process.

1. Interview with Mats Nilsen, Ericsson.

The E.T.S.I. Era (1988 -)

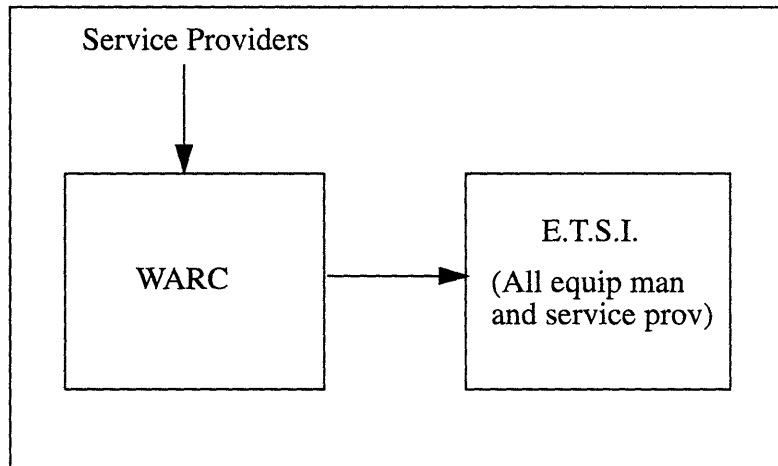


Figure 2.6: European standard setting process (1988 -)

Figure 2.6 illustrates the European standard setting process after 1988. In 1986 the European Commission issued a directive to open up the standard setting process in telecommunications to all domestic and foreign equipment manufacturers with a European address. This led to the formation of the European Telecommunications Standards Institute (ETSI). ETSI was formed to develop single pan-European telecommunications standards. The rules of participation in ETSI are based on the U.S. model. All interested parties with a European address are permitted to participate. When E.T.S.I. was created in 1988, the G.S.M. standards activities which had been initiated in 1982 were moved from C.E.P.T. to E.T.S.I.

The Result

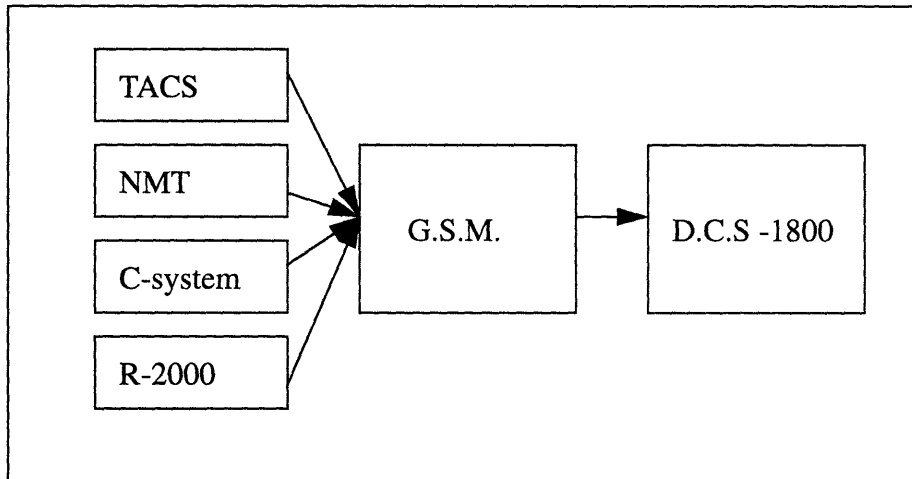


Figure 2.7: 1st, 2nd and 3rd generation digital mobile cellular services in Europe

Figure 2.7 shows the cellular standards which have emerged in Europe. In Europe, several different analog standards were initially developed including NMT-450 and later NMT-900 in the Nordic countries, TACS in Britain, C system in Germany and a Matra Radio 2000 standard in France. All of these were being deployed in the early 1980's. Between 1982 and 1991 the European operators jointly developed G.S.M. (Groupe Special Mobile). The European operators also set aside spectrum in the 1800 Mhz range for a more advanced G.S.M. service called DCS-1800 to be introduced in the late 1990's.

The Deregulated Era (1987 -)

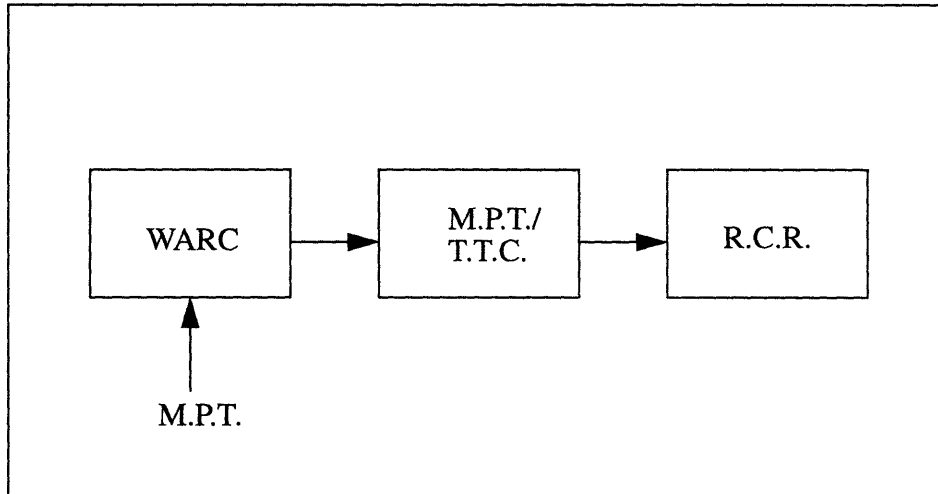


Figure 2.9: Standard setting in Japan (1987 -)

Figure 2.9 illustrates the standard setting process in the current deregulated cellular market. WARC and the M.P.T. continue to set the technical requirements and allocate spectrum for cellular systems. However, with multiple service providers and equipment manufacturers, the M.P.T. has organized a committee, the Research and Development Center for Radio Systems (R.C.R.) to bring these players together to develop technical specifications for radio standards for Japan. Only radio standards developed by RCR can be used commercially. The participants in the R.C.R. committee are primarily domestic service providers and equipment manufacturers; however, AT&T, Ericsson and Motorola were able to participate in the Japanese standard setting process for the Personal Digital Cellular Standard as an outcome of high level trade negotiations between the Japanese government and the U.S. government.¹

1. Though the Swedish government may have also been involved in these negotiations, the most likely explanation is that the United States government opened the door for the best positioned foreign equipment manufacturers, one of which was Ericsson.

The Result

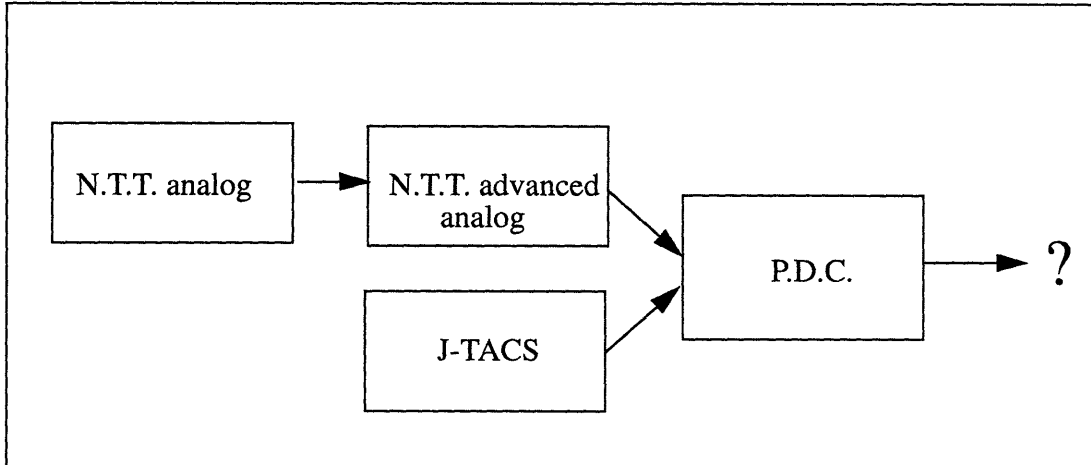


Figure 2.10: 1st, 1.5, and 2nd generation standards in Japan.

Figure 2.10 illustrates the various cellular services which have emerged in Japan. N.T.T. developed an analog standard¹ and began deploying analog cellular service in 1979. A more advanced analog standard with better spectral efficiency was introduced in the mid-1980's. In the late 1980's, Motorola was granted access to the cellular markets in the Kansai and Nagoya regions and introduced a variation of the TACS standard, which, unlike the AMPS standard, was consistent with the 25kHz channel spacing in Japan. The M.P.T. then decided that Japan must have a single standard for digital mobile cellular services. The Japanese Personal Digital Cellular is being introduced in the 800-900 Mhz range and the 1.5 GHz range.

1. This was the first commercial cellular system in the world.

Chapter 3

Characterizing the Goals of the Standard Setting Process

With this background on why standards are set and who was involved in making the standards decisions in each part of the world, we will now examine the goals and motivations of the various players in establishing cellular standards.

In this chapter, I will argue that decision makers in the U.S., Europe, and Japan balanced the needs of government, industry and consumers in very different ways in defining the goals and making high level decisions for digital cellular systems.

	U.S.	Europe	Japan
Consumers	**	*	
Equipment Manufacturers	***	**	**
Service Providers	*****	***	*****
Government		*****	*****

Table 3.1: Whose perspectives were important?

Understanding the motivations of the decision-makers and the context within which these decisions were made is critical to understanding how the process worked in the three parts of the world. Table 3.1 summarizes the relative importance of the service providers, the equipment manufacturers and the consumers in the decisions which were made.

3.1 The U.S.

In the United States in the late 1980's, the cellular service providers in the large cities were running up against capacity constraints and were requesting that the F.C.C. do something to allow them to meet the growing demand for service. Analog technology (AMPS) had been available in the United States since 1984, but many predicted that it would be unable to meet capacity needs in coming years. Spectrum was scarce and the service providers needed new technologies which more efficiently utilized the allocated spectrum for cellular.

The Reagan administration was philosophically predisposed to deregulation. Many of its policies were designed to reduce the role which the Federal government played in determining the course of industries. The basic approach to standards was laid out in the document, OMB-Circular 119, which required the Federal government to rely on voluntary commercially set standards whenever possible. The three F.C.C. Commissioners who were appointed by President Reagan, Mark Fowler, Dennis Patrick and Al Sikes also shared many of these views.

The general view within the F.C.C. was that it should minimize its role in the development of digital cellular technology. There were a number of reasons for this view. First, the F.C.C. did not believe it had the technical expertise to make this decision and was not willing to risk hurting the industry. Only two years earlier, in 1988, the F.C.C. had chosen a standard for A.M. stereo which had poor voice quality and stifled the growth of the industry. (In 1992, the F.C.C. reversed its earlier decision and chose the Motorola standard, which arguably would have been chosen by the market a few years earlier.) The F.C.C. did not want to take responsibility again for stifling the growth of an industry by making the wrong technical choice.¹ The members of the F.C.C. believed that even if it

did not mandate a single standard for digital cellular, in the long run the market would converge to a common standard.¹

Second, the F.C.C. believed that the technology was not yet mature enough to make a decision so that it was important for the market to test multiple solutions. When analog technology was being developed in the 1960's and 1970's, AT&T, the regulated monopoly, was arguably the only company with the research capabilities to develop a technical standard. However, analog cellular services were initially introduced as a duopoly in 1984 with licences granted to a regional Bell company and a competitor in each region. By the late 1980's with multiple service providers and equipment manufacturers in the business, there were a number of players in the industry who were capable of developing the winning future digital technology. By letting the market determine the standard, the F.C.C. would not limit any technology from coming to market.

A third reason is that the F.C.C. had a reputation for taking a very long time to make standards decisions, in significant part because its decision-making procedure is so open. Industry believed that it could establish technical standards much more quickly and therefore bring products to market more quickly. The Commission did not want to be responsible for causing delays in the introduction of digital cellular products to the market.

A final reason for the F.C.C.'s reluctance to mandate a single standard is because different cellular markets had different technological and capacity requirements. In cities like New York, Chicago and Los Angeles, cellular service providers were reaching full capacity and needed either additional spectrum or more spectrally efficient technology. On the other hand in rural areas, no new technology was necessary since analog technology could

1. Conversation with an F.C.C. official (From prev page).

1. Conversation with an F.C.C. official.

continue to meet subscriber needs for the next ten years. Market driven standards would allow carriers to use the technology that best met their market needs.

The FCC's Office of Plans and Policy put forth an economic rationale for technical flexibility. It argued that the fairest allocation of spectrum for different technologies could best be determined by the market.¹ Digital technology should be allocated as much spectrum as the market deemed necessary as the F.C.C. had no way to determine that allocation in advance.² The market should also determine the technologies that would most efficiently use the allocated spectrum and meet subscribers' radio communications needs. In 1988 the F.C.C. issued a document allowing carriers to use alternative technologies in their allocated spectrum. The 5 F.C.C. Commissioners were unanimously in favor of this policy. It would allow the gradual introduction of new technologies and would allow multiple technologies to come to market, as the service providers continue to dedicate some spectrum to conventional services. The market must determine the technologies which efficiently use the allocated spectrum to meet subscribers needs.

The main counter argument to letting the market determine the standard was that multiple technical standards would fragment the market, preventing roaming between various regions of the country and therefore stifling the growth of the industry. The F.C.C. discounted these arguments for the case of the digital mobile cellular because in the U.S., unlike any other part of the world, roaming capabilities were already available with the AMPS standard. To ensure that these would be preserved, the F.C.C. mandated that cellular service providers dedicate some of their allotted spectrum to AMPS technology. All digital handsets would be required to operate using AMPS. operational using either analog or digital technology. Even if each part of the country did not have a common digital stan-

1. Conversation with John Williams, Office of Plans and Policy, F.C.C., January 1995.

2. Conversation with Mike Ferante, F.C.C., October 1994.

dard, a user could always fall back to using AMPS analog service anywhere where there is cellular coverage. Therefore, the immediate market need for roaming capabilities with digital cellular systems were not as great, and the cellular industry could afford to experiment with different technologies to determine the optimal digital cellular technology.

Both the F.C.C. Commissioners and staff of the Office of Plans and Policy believed that the government should minimize its role in the development of cellular standards. Whose perspectives were most important in this process? I would argue that the service providers played the most influential role in the standard setting process in the U.S. The service providers had different capacity needs in different regions and therefore needed different technologies to ensure that they could meet the needs of their customer base. In some rural areas some of the spectrum could be used for other land mobile services including paging. Giving service providers this flexibility allowed them to maximize their use of the spectrum. In addition service providers did not need to worry about interoperability because they had the authority to mandate that all telephones be dual-mode and be backward-compatible with the analog AMPS standard. Therefore the service provider was a clear winner. 75% of the service providers have decided to continue to deploy analog technology until CDMA systems become commercially available at the end of 1995.¹

The response of the equipment manufacturers to the initial government proposal, on the other hand, was very mixed. Some supported the idea because they believed it would give them the flexibility to develop the technology of their choice. Others opposed the idea because they wanted a single standard to reduce risk and to enable them to take advantage of economies of scale. Equipment manufacturers also feared that with multiple standards in the U.S. marketplace, it would be difficult to sell a second generation American products overseas.

1. Conversation with Jim Madsen, Director of P.C.S., Qualcomm Inc., April 1995.

Almost all of the service providers supported the FCC decision. Table 3.2 summarizes the reasons the U.S. policy makers allowed multiple standards in the marketplace. By letting the market decide the standard, the F.C.C. was acting on its belief that a market determined standard would offer consumers the best quality service at the lowest cost. For this reason, there are a number of competing digital technologies either on the market today or soon to be introduced to the market, including the D-AMPS (TDMA) standard, a Hughes E-TDMA standard and Qualcomm's N-CDMA standard.

Perhaps Qualcomm's CDMA technology would not be the potential solution for P.C.S. services that it is today if the F.C.C. had simply worked with two or three incumbent equipment manufacturers and service providers to establish the future digital cellular standard and not allowed CDMA to be introduced in second generation systems.¹

Primary motivations for allowing multiple digital standards in the U.S. market
Technology not mature enough to make a decision
Different markets have different technological requirements
Roaming capability already available with AMPS
Mandating a single standard takes more time to create consensus

Table 3.2: Summary of the goals for introducing digital standards in the U.S.

1. Conversation with Kevin Kelley, Qualcomm Inc. January 1995.

3.2 Europe

The context and goals in Europe for the establishment of a digital cellular standard were quite different from those in the United States. The idea for a pan-European cellular standard arose in 1982. At that time, several different analog networks were being developed in Europe including the TACS standard in the United Kingdom, the C-450 standard in Germany and the NMT-900 system in the Nordic countries. The Nordic countries had a long history of working together and had already realized the benefits of a common standard. They wanted to extend international roaming to all of the European countries. At the XIth Plenary meeting of the European Telecommunications Commission, the Nordic operators proposed a harmonized system in the 900 MHz band that had been allocated for land mobile radio in Europe. This proposal was met with great enthusiasm by the operators in the CEPT countries and by their respective governments. In November 1982 the CEPT then decided to establish a working group to investigate the details of a potential pan-European standard.

The benefits that the politicians and operators saw in a pan European standard were as follows:

First, a pan-European standard would improve the overall efficiency of the telecommunications infrastructure in Europe and would offer consumers value added services that could not be offered today. Moreover, all of the European nations who chose to adopt this standard would reach the same level in terms of cellular services offered. Part of the goal of the European politicians in creating the European Union was to reduce the disparity in the standard of living between the various nations in Europe.¹ A common pan-European

1. Conversation with Thomas Haug, leader of the G.S.M. Committee, Stockholm, Sweden March 1995.

digital cellular standard would improve the quality of telecommunications services in Europe.

Second, a pan-European standard would support the European equipment manufacturers. By establishing a common European standard, European equipment manufacturers would clearly have a competitive advantage in selling their equipment both in Europe and overseas. Non-European manufacturers were not able to influence this standard and were not privy to the information until the air interface standard was completed. By protecting the home market, European manufacturers were also given the opportunity to catch up technologically and assert themselves as a prominent force in the information industry in the telecommunications industry. In addition, this pan-European cellular standard would increase the market volume for all consumers, bring costs down and therefore benefit everyone involved. Without this invisible trade barrier, the European manufacturers were at a greater risk of losing market share to the United States and Japanese manufacturers who both had larger home markets, and better economies of scale than any single European country. In addition, the Europeans also recognized that if they were the first to establish a digital cellular standard, European manufacturers could offer this standard to developing countries around the world, giving European manufacturers huge new markets.

Third, a pan-European standard would be a symbol of European political unity. Government officials in England, France, Germany and Italy wanted to establish a precedent for working together to reach common decisions. The policy makers hoped that this would be the first of many collaborative efforts by the European countries in the high technology arena.

Finally, this standard would reduce the barrier to entry for competitors. By establishing a single standard, service providers would compete not on technology, but on market-

ing and distribution capabilities. The argument was that even if the incumbent cellular service providers contributed more to the contents of the standard, the competitors would have equal access to the technology. In the European view this was the “fairest” way to open up the telecommunications market to new competitors. This is in contrast to the decision made in the United States, where the law-makers believed that by allowing different carriers to use multiple technologies would maximize the opportunity for non-incumbent companies to introduce technologies and promote competition in the cellular marketplace.

Clearly the operators and the manufacturers saw very strong benefits to having a common standard. However, the main challenge in designing a common standard was that the different countries’ operators had different requirements for this new pan-European system. In the United Kingdom, the operators were capacity constrained and wanted a spectrally efficient solution to be deployed as quickly as possible. The operators were already implementing one of the most spectrally efficient analog systems and therefore wanted a system which would either be more spectrally efficient or would provide more advanced services than the current TACS system. Of all of the European nations the United Kingdom was probably the most market driven. In France, the analog system Radio Comm 2000, gave very poor voice quality. Therefore the French primarily wanted a system with reasonable voice quality. The French and German governments saw manufacturers such as Ericsson, Motorola and Nokia as having a very strong advantage in the current generation of analog systems and welcomed the chance to establish a standard which would promote their own equipment manufacturers.¹ In the United Kingdom and the Scandinavian countries, the visionaries saw this system not being limited to telephones for automobiles but rather saw a handportable future. Therefore a technical standard which lent itself to a

1. Conversation with Phillipe duPuis, formerly of France Telecom, Paris, France, March 1995.

lightweight system with a long battery lifetime would be critical. In addition, these operators wanted to ensure that the system would be cost efficient to implement in rural areas.

Despite these different interests, the members of the CEPT believed that the benefits of a single European standard far outweighed the drawbacks of being forced to make technical compromises. As we will see, these compromises involved finding efficient technical solutions as well as balancing the interests of European manufacturers, operators and governments from the CEPT countries. The goal was to design and implement a standard at all costs. However, in 1984, as capacity needs continued to grow in many of the developed European countries, a number of them could not wait until the G.S.M. standard had been completed and therefore adopted a range of then-available analog cellular technologies. The pan-European cellular standard would be designed as to be as forward looking and scalable as possible.

By the end of 1984, after the CEPT's GSM Committee had met a few times, it was agreed that this solution should be digital. There were several reasons for this. First, a digital solution could have better spectral efficiency and therefore support more users in a band. Second, the public switched network was being digitized and operators wanted to facilitate the interconnection of cellular to the public switched networks. Third, the CEPT wanted all of the manufacturers to start from a level playing field. Adopting one of the existing analog systems would inevitably give the manufacturers already producing those systems a competitive advantage in the marketplace.

For all of these reasons, therefore, the operators in the CEPT agreed to adopt a digital standard. To ensure that any new standard was technically better than the existing analog systems, Stephen Temple of the Department of Trade and Industry in the United Kingdom put forth the requirement that for a system to be adopted it needed to match the current analog systems in 5 of the following 6 criteria for evaluation and be superior in one of

these areas.¹ The criteria for evaluation were spectral efficiency, voice quality, hand-portability, infrastructure costs, handset costs and data transmission. All systems were tested to ensure that they met this criteria.

In the rest of this thesis we will tell the story of how some of the compromises were made, and how the European leaders came to unprecedented agreement on a pan-European cellular standard.

In summary, this standard was designed with the interests of European politicians and government officials, European industry and the European consumers in mind. It would facilitate European governments working together on joint technology development projects and serve as a symbol for European unity. Establishing a single standard would also give European equipment manufacturers an advantage in Europe and potentially internationally. Table 3.3 summarizes the goals of the G.S.M. standard.

Motivation for a single standard in Europe
establish interoperability all over Europe
promote European equipment manufacturers domestically and internationally
economies of scale

Table 3.3: Motivations for the Europeans to establish a single European digital cellular standard

3.3 Japan

In the late 1980's the Ministry of Post and Telecommunications (MPT) and the Ministry of International Trade and Industry (MITI) saw the profits of Japanese equipment manufacturers falling and wanted to create new markets for them.² Although Japan was not

1. Conversation with Stephen Temple, Department of Trade and Industry U.K., March 1995.

facing the same capacity constraints as the United States, we can speculate that the Japanese also wanted to ensure that they developed a digital cellular standard to keep up with the development of technology in the U.S. and Europe, build a market for the equipment manufacturers in Japan and compete abroad.¹ Traditionally, the members of the M.P.T. and N.T.T. and the large Japanese equipment manufacturers would work together in setting the national telecommunications policy. Unlike the United States, no telecommunications technology can be brought to the market in Japan without the support and backing of the M.P.T.² This is one example of the very strong role which the Japanese government plays in Japanese industrial policy. Typically, the Japanese have not been the first to develop a new technology, but rather seek to master the art of manufacturing currently available technologies.

In the early 1980's, much like the United States, Japan had only one telecommunications operator, Nippon Telephone and Telegraph, which was the single source of expertise on all telecommunications standards. In all areas of telecommunications, the Ministry of Post and Telecommunications would request N.T.T. in cooperation with the various equipment manufacturers to draft a standard, which N.T.T. would proceed to do. N.T.T. has rarely adopted foreign standards, partly out of concern that it would undermine its role and reputation as the driver of Japanese telecommunications technology.³ Typically N.T.T. alters foreign standards to create unique Japanese technical standards.⁴ In 1985, however, given the deregulatory trends occurring all over the world, the M.P.T. also introduced competition into the marketplace. Just as AT&T was no longer the sole source for tele-

2. (from prev page page) Telephone Interview with an official at Nippon Motorola.

1. Interview with John Stern, American Electronics Association, Tokyo, Japan, July 1994.

2. Interview with Norishige Morimoto, I.B.M. Japan, April 1995.

3. Interview with an official at Nippon Motorola.

4. Interview with Keith Henry, MIT Japan Program, Tokyo, Japan, August 1994.

communications technology in the United States, N.T.T. was no longer the sole telecommunications power in Japan.

Because of its influence within the Japanese bureaucracy, NTT did manage to maintain control of the P.D.C. standardization process. It selected the 6 manufacturers, NEC, Fujitsu, Matsushita, Mitsubishi, Japan Radio Comm and Motorola, who would be permitted to submit proposals for the future digital mobile cellular standard. After the proposals were submitted, the RCR Committee would together come to a consensus on the detailed specifications of the standard. Therefore despite the increased openness of the process, N.T.T. still had much more influence than the equipment manufacturers or the competing service providers. This process incorporates these new participants, but preserves the authority of the Ministry of Post and Telecommunications and the primary cellular operator, NTT.

As in Europe, the Japanese equipment manufacturers supported the idea of establishing a single digital mobile cellular standard. They believed that the advantages of interoperability, shared development costs, and promotion of competition outweighed the disadvantage of locking into a single technology and stifling the potential advancement of technology. In the analog development process, the Japanese had experienced a somewhat fragmented market as a result of the trade concession which permitted Motorola to offer the TACS standard. The M.P.T. was convinced of the need for uniform digital cellular standards throughout Japan. In addition, because the United States and Europe already had working digital designs and because digital radio technology was more mature when the Japanese digital standard was set and there was even less of a risk of choosing a potentially ineffective technology than there was when the Europeans adopted digital for GSM.

Motivation for a single standard in Japan
support the Japanese equipment manufacturers
provide nationwide roaming capabilities
Reduce cost of equipment

Table 3.4: Motivation for the Japanese to establish a single common standard

Table 3.4 summarizes the reasons for establishing a common standard in Japan, of which the most important was to support the Japanese equipment manufacturers.

Country	Primary Motivation for a Digital Standard
U.S.	provide service providers with additional capacity
Europe	establish a pan-European cellular standard
Japan	support the Japanese equipment manufacturers

Table 3.5: Summary of Primary motivations for a Digital Cellular Standard

Finally, table 3.5 summarizes the primary arguments in each region for implementing a digital standard for second generation systems. In the United States, it was to help the service providers use technology to meet the growing capacity needs. In Europe it was to establish a pan-European cellular system. In Japan it was to help bolster the falling profits of the Japanese equipment manufacturers in the domestic market.

Chapter 4

Cellular Technologies

Traditionally, telephone conversations have been transmitted by wire. When the user speaks into a telephone, his or her voice is captured by an micro-phone, transmitted across a wire through a switched network, and projected by a speaker on the other end. Thus, all telephone calls originate in a specific place and arrive at another specific place. Cellular technology offers a caller the ability to reach a cellular subscriber in any location where there is cellular coverage compatible with the subscribers handsets, using a single telephone number. This is achieved by using a radio transmission link between a mobile handset and a base station. The base station is in turn connected to mobile telephone switching office (MTSO) that provides access to the Public Switched Network. The MTSO adds the functionality to route a call to the appropriate base station. This allows users to roam between base stations and have their calls “handed off” as they move from cell to cell. This chapter explores the different interfaces and components in a cellular radio system and describes some of the relevant trade-offs involved in the design of these systems.

4.1 Functionality within a Cellular System

The infrastructure required to implement a cellular telephony system includes the handsets, the base stations, the base station controllers, and the mobile switching capabilities. Figure 4.1 shows how these components interact with each other in a cellular system.

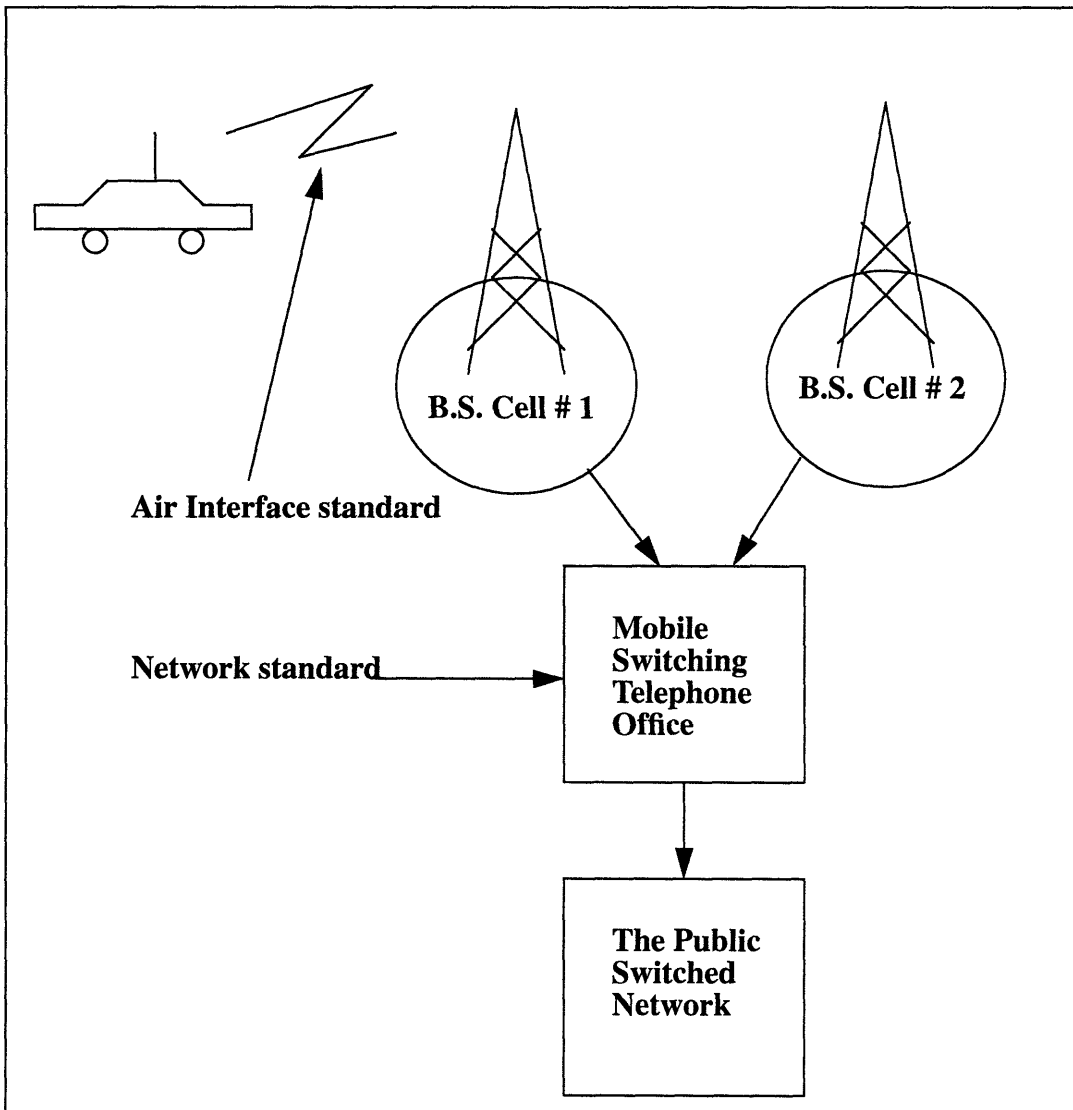


Figure 4.1: Block diagram of a cellular system ¹

4.1.1 Handsets

The handsets are designed to receive and transmit information to the base station over a radio channel. The two major components of a handset in a digital cellular system are the transceiver and a digital signal processing chip. The transceiver receives and transmits

1. Figure taken from Lee, Mobile Cellular Telecommunications Systems. pg 8.

all information to the base station. The digital signal processing chip performs the necessary processing steps to prepare the voice signal for transmission on a radio channel and to demodulate and process the received signal.

4.1.2 Base station

Base stations in a cellular system connect the wired network with the radio channels. Base stations have a region of coverage known as a cell. All mobile users operating in this base station's cell space must connect to the network by establishing a radio connection with this base station. In most transmission schemes each signal is received by two antennas at the base station to achieve diversity and therefore improve performance. To ensure that the best pair of antennas is always connected to every receiver, the base station monitors the link between each antenna and the mobile user. Typically each base station will support 20-30 traffic channels.

4.1.3 The Base Station controller

The base station controller controls all of the base stations within a particular sector. It communicates all of the signals and messages to and from the subscribers in the network through the base stations. One such function is monitoring the air link quality information of each of the handsets and the base stations to determine when hand-off should occur.

4.1.4 The Mobile Telephone Switching Office (MTSO)

The Mobile Telephone Switching Office handles all of the routing and switching for the cellular system. To locate mobile users, the mobile switching center has access to the visiting location register, the home location register and the authentication center. The home location register and the visiting location register are a distributed data base which contain the information on the location of all of the subscribers in the network. Each mobile station will have entries in at least one home location register and at least one visiting location register. The visiting location register is typically near the most recently used base station and caches relevant information including the services available to that user, and the last location of the user. The authentication center ensures that unauthorized users do not gain access to the system. On an outgoing call, after a user is authenticated to use a particular service, telephone calls can be appropriately routed through the switches at the mobile switching center to the Public Switched Network. On an incoming call, the MTSO must use the home and visiting location registers to locate the user's current cell, and then route it accordingly. The base station then establishes a radio link with the mobile user.

4.2 Important Factors to Consider in the Design of a Cellular System

In the development of second generation systems, the designers used several criteria to evaluate the different proposals for the air interface standard: spectral efficiency; infrastructure costs; handset costs; flexibility of the system; handportability; and voice quality. Different standard setters prioritized these issues in different ways and therefore arrived at different conclusions in setting each of these standards.

Criteria for Evaluation
spectral efficiency
infrastructure cost
handset cost
flexibility of the system
handportability
voice quality

Table 4.1: Criteria for evaluation for air interface standards

4.2.1 Spectrum efficiency

Spectral efficiency determines how many users are sharing the spectrum allocated for cellular. The greater the number of users sharing a channel, the more spectrally efficient the system is. Radio engineers have long realized that for mobile telephony to be a mass market technology, they needed to find ways to improve the spectral efficiency of these systems. There are two ways to improve spectral efficiency in radio systems: reduce the required amount of spectrum per channel, or reduce the required level of co-channel interference which radio signals cause each other, thereby allowing nearby cells to re-use the same frequencies for different voice conversations. The design of the air interface standard affects both of these parameters.

4.2.2 Infrastructure Costs

A second important goal for service providers in designing new systems is to reduce infrastructure costs. Infrastructure consists primarily of two components, the base stations and the MTSO's. The total cost of implementing the system is a function of the costs of each unit and the number of units required to serve the entire system. The design of the air interface standard affects both the number of base stations required to serve an area and the cost of each individual base station.

4.2.3 Handset Costs

One of the biggest factors limiting the penetration of cellular technology is the cost of the handsets for the consumers.¹ Handset costs depend primarily on two factors. First, the cost is a function of the complexity of the digital signal processing unit and the analog transceivers and filters. The design of the air interface standard clearly affects the complexity of both the digital and the analog components of the handset. The more complicated these functions the higher the cost of the handset. Second, the cost of the handset also depends on the penetration rates of the handsets because of manufacturing scale economies. The higher the penetration rates for cellular, the lower the costs of the handset.

4.2.4 Flexibility of the System

Different regions have very different capacity requirements and therefore need a system which is as flexible as possible. In the inner cities, for example, the system needs to

1. In the U.S. these costs are subsidized by the service provider, but are indirectly passed along to the consumer through increased service costs.

have extremely small cell sizes so that the cell-reuse factor is as high as possible and the system can accommodate as many users as possible. On the other hand, in rural areas where systems rarely reach their maximum capacity, the most cost effective system is one which covers as large an area as possible. The larger the difference between the maximum and minimum cell radius the more flexible the system is. As will be explained in chapter 7, the channel spacing decisions directly affect the maximum cell radius which can be used.

A second important aspect of flexibility is the ease which a system can utilize the spectrum allocated to it. In this respect narrowband systems are more flexible and can fit into many more different spectrum blocks than can wideband systems. As we will see this is one reason why wideband systems were not adopted for most second generation cellular services.

4.2.5 Handportability

A fifth important criterion for air interface design is to have handportable systems. The simpler the processing algorithms and the smaller the cells, the less power dissipated in the handsets and the more conducive it is to handportability. As we will see later, the choice of channel spacing and access scheme strongly influence the power consumption in the handset, and therefore its size and handportability. The greater the power consumption, the larger the required power source within the handset and the less conducive the handset design is to handportability.

4.2.6 Voice quality

The final criterion which is important in the design of cellular systems is the voice quality. The voice quality is primarily a function of the effectiveness of the speech and channel coders. In all air interface standards there is a trade-off between the quality of the speech and the amount of spectrum each voice channel takes up. The greater the spectrum allocated per user, the better the speech quality. However, as technology improves fewer bits are required to transmit a signal of acceptable voice quality.

4.3 Towards a digital solution

There are two methods for processing and transmitting information in a radio system: analog modulation and processing and digital modulation and processing. In an analog system, the signals are transmitted, received and processed as continuous waveforms. The voice signal enters a system, is modulated up to the appropriate frequency band and is then transmitted. In a digital system all information is sensed at the microphone and is sampled and quantized such that it can be represented as a combination of zero's and ones. The series of bits are then modulated onto a radio carrier using any number of digital modulation techniques.

Digital methods of transmission have a number of advantages over analog technologies. First, digital technologies make very accurate reproduction of the original signal possible. In a digital system there are ways to improve the quality of the signal and minimize the distortion which is unavoidable in an analog system. Finer levels of quantization or error detection and correction techniques can be used in order to improve the level of reproduction of the signal. Error correction technologies, which are further explained in

the appendix, are used to eliminate channel errors due to imperfections in the radio transmission and amplification process and therefore allow a receiver to more accurately reproduce a transmitted signal.

The main motivation for service providers to use digital cellular technology is because it provides better spectral efficiency. Digital technologies allow manufacturers to use compression techniques and to exploit redundancies in voice patterns to use fewer bits to express the same information, therefore reducing the channel capacity requirements for transmission of a voice signal. The trade-off is that voice compression requires time and computational power to produce the output signal. These issues must be addressed in the design of a digital air interface standard. Another advantage of digital systems is that digital transmission is becoming the common language of information transfer. Therefore these cellular systems could easily be designed not only to transmit voice but also digital data.

4.4 Spectrum Efficiency

There are three ways to use digital technology to improve the spectral efficiency of the system: increase the spectrum re-use factor, decrease the spectrum required per channel, or improve the efficiency of the modulation scheme.

4.4.1 Spectrum reuse

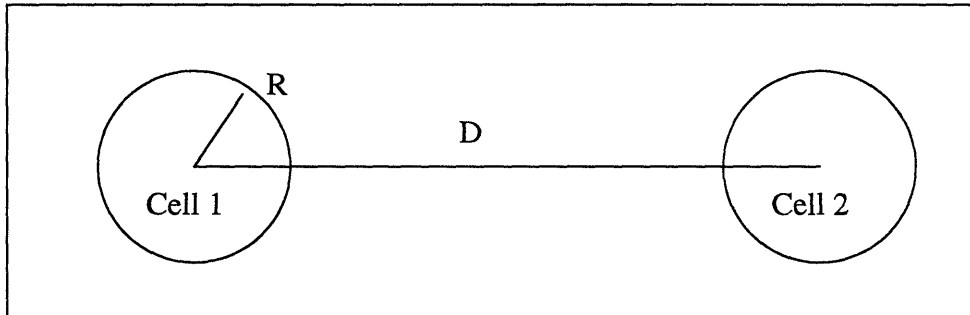


Figure 4.2: The cell reuse factor can be measured by the ratio D / R .¹

The first mobile telephone systems built in the 1950's consisted of a single large antenna, which could transmit within a 50 mile radius. One transmitter was traditionally used in each metropolitan area. This approach had two problems. First, the transmitters and receivers used large amounts of power to transmit over such a large radius. Second, the capacity of these systems was limited. In these systems, using high power transmitters prevented channels from being reused in the same metropolitan area because interference levels were too high. To put more users on a system, additional spectrum was necessary.

In 1947, the critical concept of spectrum reuse was conceived at Bell Labs. To improve spectral efficiency, coverage regions are split into small cells, each of which uses a less powerful base station transmitter. Using smaller cells reduces the amount of power required for transmission and therefore reduces the amount of interference in neighboring cells, allowing spectrum to be reused in non-adjacent cells. Figure 4.2 illustrates the spectrum reuse concept. As long as the cells are a sufficient distance from each other, the same frequencies can be used in cells 1 and 2. The goal of radio system designers is to minimize

1. Figure taken from Macario. Personal and Mobile Communications. pg. 195.

the ratio of D / R . This can be done by reducing the co-channel interference levels in the system which can be measured by the carrier to interference (C / I) ratios. The lower the required carrier to interference ratio is, the higher the spectrum re-use factor and the more spectrally efficient the system is. The cell re-use factor in a system can be increased by a number of different techniques.

Power levels

One technique to increase the cell re-use factor is to reduce the power level at which the signal is being transmitted. Power level drops with a factor of d^2 . Therefore by lowering the power level, the ratio D / R decreases. Intuitively, the lower the power level, the less interference it will cause users and the more frequently spectrum can be reused. This technique, however, requires smaller cell sizes. Smaller cell sizes increase the number of handoffs and the total network traffic and overhead in the system. Therefore system designers must determine the optimal minimum cell size. The minimum cell size in the D-AMPS, G.S.M. and P.D.C. standards is .5 km.

Another way to increase the cell reuse factor is to make the transmitted signal more robust to the interference. Techniques for improving the robustness of the signal include error correction coding, antenna diversity, spread spectrum and frequency hopping. These will now be discussed briefly.

Channel coding

Channel coding involves sending redundant bits which are a function of the transmitted signal. The receiver can detect and in many cases correct errors due to imperfections in the channel. Although channel coding increases the bit rate, it can be used to reduce the overall level of interference.

Antenna Diversity

Antenna diversity requires that a signal be received by 2 antennas at the mobile station and / or the base station to provide the receiver with additional information to more accurately reproduce the transmitted signal. Antenna diversity masks fading that results from the cancellation of signals which follow multiple paths as they travel from the transmitter to the receiver.

Frequency hopping

Frequency hopping requires the base station to frequently change the channels over which a user is transmitting or receiving and therefore prevents a user from transmitting on a bad channel for long periods of time. As a result, frequency hopping masks long burst errors which can be present on a single channel.

All of these techniques make the signal more robust to imperfections in the channel, but also add cost and complexity to a system.

4.4.2 Required Bit Rate

A second method of improving the spectral efficiency is to reduce the required bit rate of a voice channel. The number of bits transmitted is a function of the speech coding and the channel coding and the overhead. By reducing the number of bits required for any of these functions, spectral efficiency can also be improved. In this section, we will look at how the speech coding and channel coding techniques affect the required bit rate.

Speech Coding

The speech coder uses a compression algorithm to reduce the number of bits required to express each voice signal. The various algorithms for speech coding will be explained in further detail at the end of this chapter. As compression technologies improve and fewer bits are required per voice channel, less total spectrum is required per voice channel. This increases the overall spectral efficiency of the system. Today digital cellular systems are being designed such that as speech coding techniques improve, new coder technologies can be inserted in place of the old coder technology improving the spectral efficiency of the system.

Channel Coding

As explained earlier, the channel coder adds redundancy bits to increase a transmitted signal's robustness to noise. The greater the number of channel coding bits, the more spectrum required per voice channel and the less spectrally efficient the system is. The designer therefore must balance the added benefits of improved spectral re-use from channel coding with the associated cost of the additional spectrum required.

4.4.3 Modulation techniques

A third way of improving the spectral efficiency of digital systems is to use more advanced digital modulation techniques. For example, with the GMSK (Gaussian Mean Shift Keying) modulation scheme used in G.S.M. it is possible to transmit 1.35 bits / Hz. With the QPSK (Quadrature Phase Shift Keying) modulation scheme used in the Digital AMPS standard and the P.D.C. standard in Japan, it is possible to transmit 1.62 bits / Hz. By transmitting more total bits in a single cycle, the user needs less spectrum to transmit a voice signal, and therefore has a more spectrally efficient system.

As we can see, improving the spectral efficiency is quite complicated because of the many different interdependencies in the system. It is the system designer's job to balance these trade-offs to maximize the capacity of the system without compromising the voice quality.

4.5 Digital Cellular Access Schemes

This section discusses how the allocated spectrum can be divided up amongst the various users in a digital cellular system. In a frequency division scheme, a narrow slice of the spectrum referred to as the channel's frequency is allocated to each user. In a time division scheme, a number of users share the same frequency channel. Multiple users on a single channel can be distinguished either by assigning each user a designated time interval to transmit its data (Time Division Multiple Access - TDMA). Similarly, in a code division scheme, a single channel is shared by assigning each user a code word which allows only its receiver to demodulate its signal (Code Division Multiple Access). Typically, a TDMA

channel is narrower and is shared by fewer active users than a CDMA channel. The trade-offs in choosing between these systems will be addressed in chapter 6.

4.5.1 Frequency Division Multiple Access (FDMA)

As figure 4.3 illustrates, a Frequency Division Multiple Access system the spectrum is sub-divided into narrow channels, each of which can each carry one voice channel. As digital compression technology improves, channel sizes are decreasing because each user requires less spectrum. The smaller the channel size, the more users can be accommodated in a given frequency band. Implementing an FDMA system requires mainly radio system expertise to do the appropriate frequency splitting and filtering. Guard bands in frequency are used to minimize co-channel interference.

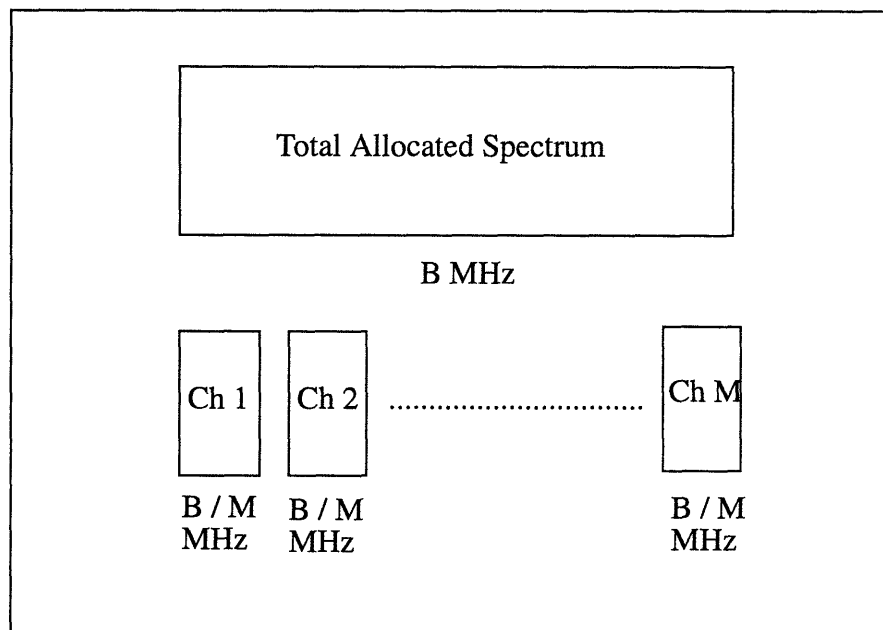


Figure 4.3: Multiplexing in an FDMA system

4.5.2 TDMA (Time Division Multiple Access)

As figure 4.4 illustrates, a Time Division Multiple Access requires channel splitting in both frequency and in time. First the spectrum is divided into smaller channels as in FDMA. Each channel in a TDMA system, however, supports multiple users. Users on the same channel distinguish themselves from each other by alternating in time. To support multiple users, channel sizes in TDMA systems are larger than they are in FDMA systems. Furthermore, a user on a TDMA system must transmit its data at N^{-1} times the transmission rate in an FDMA system, however each user is only using the channel for $1/N$ th of the time. As digital compression technologies improve, more users can be fit on the same size channel. Implementing a TDMA system requires radio engineering expertise to do frequency splitting, and digital multiplexing and synchronization capabilities to do the time division multiplexing within a channel.

1. N in the case refers to the number of users on a TDMA channel. The TDMA channel spacing will be approximately N times the FDMA channel spacing assuming these systems are using the same compression technology.

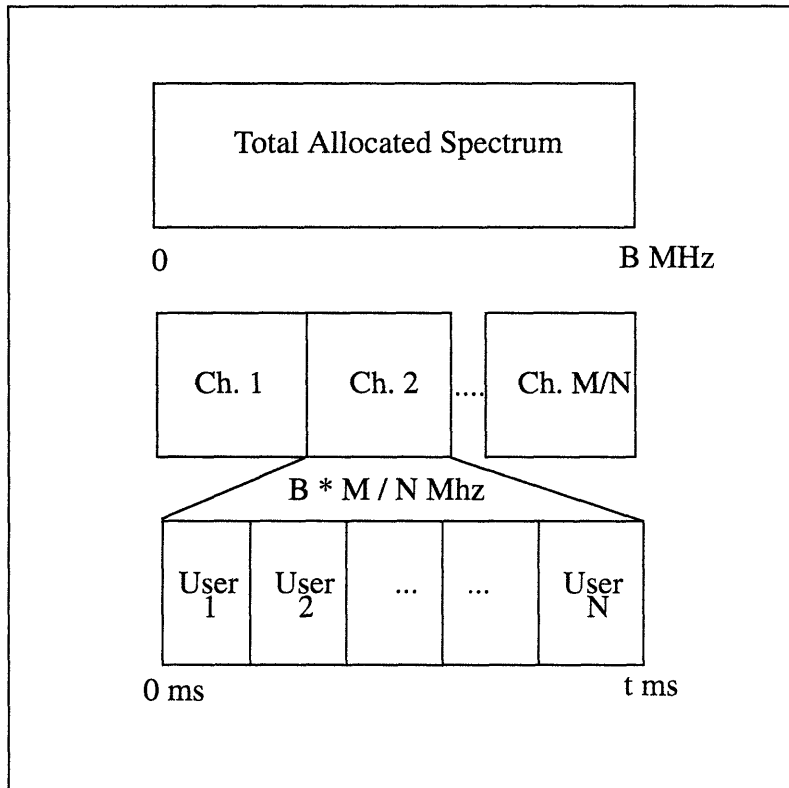


Figure 4.4: Multiplexing in a TDMA system

4.5.3 Code Division Multiple Access (CDMA)

As in TDMA and FDMA, CDMA also requires that the spectrum be divided into channels.¹ Within each channel, users distinguish themselves from each other by using different psuedo-random codes. Each voice signal is then modulated using that codeword and its energy is spread over the entire channel. The original signal is then recovered on the other end by demodulating the transmitted signal with the same code. All of the other signals using the same bandwidth appear to a user as noise, therefore the quality of each

1. The channel sizes in CDMA are typically much larger than the channel sizes in FDMA or TDMA though there have been some proposed wideband TDMA systems which have had larger channel spacings than Qualcomm's N-CDMA technology.

user's link degrades as the number of users on the system increases. Because CDMA uses lower power levels than either FDMA or TDMA, spectrum can be reused in adjacent cells. Consequently, CDMA systems have improved spectrum efficiency over FDMA and TDMA solutions.

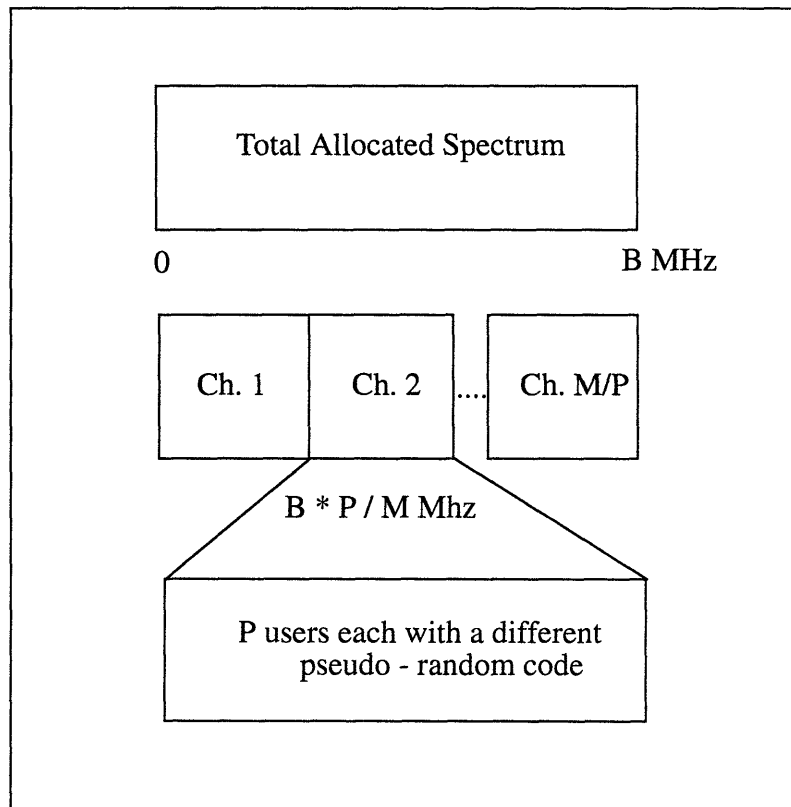


Figure 4.5: Multiplexing in a CDMA system

4.6 Speech Coder technologies

There are three speech coders which are commonly used for compression: vo-coders, waveform coders, and hybrid coders.

4.6.1 Vo-coders

Vo-coders use a technique called linear prediction, to estimate future data using past and current data using an inherent model of the speech process, which is illustrated in Figure 4.6. Figure 4.7 illustrates the encoding and decoding process. At the encoder, there are two sets of parameters which need to be determined, the characteristics of the source of the signal and the coefficients of the filter. Once the appropriate source and filter coefficients have been determined and sent to the receiver, the voice message can be coded and sent across the channel. The receiver will then regenerate the speech by using the filter coefficients and the source signal. Vo-coders can use either short term predictors (each sample is calculated from the last 10-20 samples) or long term predictors (each sample is calculated from the last 40-120 samples).

The decoder performs the same functions in reverse. The more efficient the coding, the fewer bits required to communicate a message. The trade-off, however, is that the calculation of the future bits using the model takes time and adds to the overall delay for transmission.

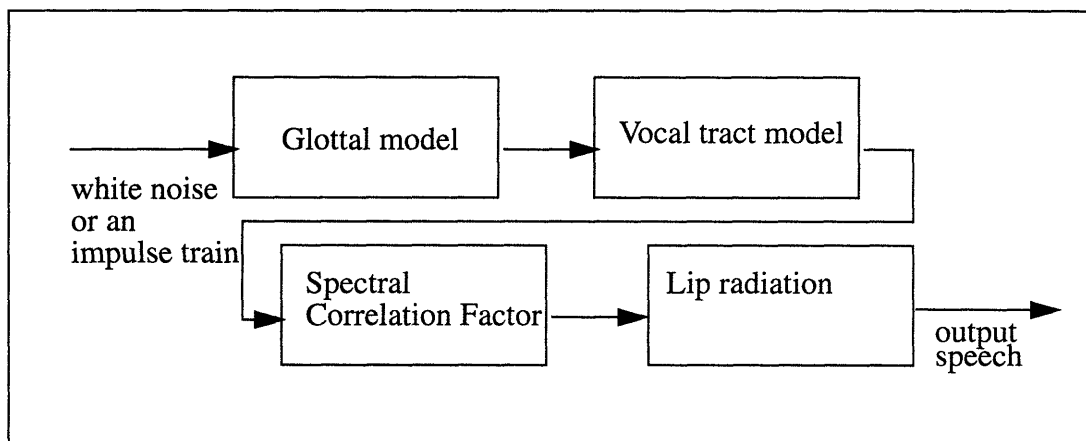


Figure 4.6: The source / filter model for generating the speech ¹

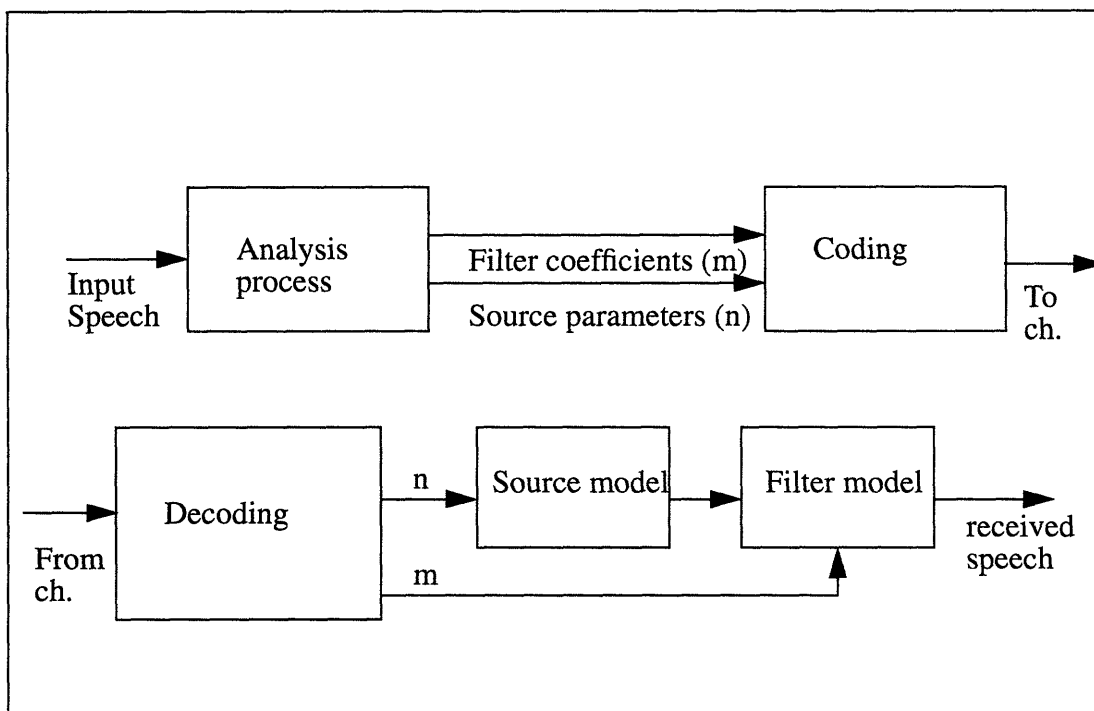


Figure 4.7: Encoding process at the transmitter and decoding process at the receiver for a vo-coder¹

4.6.2 Waveform coding

These sets of algorithms use various quantization and sampling techniques to reproduce the signal as accurately as possible. One technique for reducing the number of bits required to reproduce the signal is to dynamically allocate quantization bits to the different frequency bands. The number of these bits are allocated in proportion to the signal energy and the highest frequency of the signal in the band.² Therefore, fewer bits can be used to express low frequency and low energy information, reducing the required bit rate of a voice signal. A second technique for reducing the number of bits required per voice chan-

1. Figure taken from Macario. Cellular Radio Principles and Design. p. 150.

1. Figure taken from Macario. Cellular Radio Principles and Design, p. 151.

2. The Nyquist criteria states that in order to reproduce a signal accurately, the signal must be sampled at twice the highest frequency

nel is to represent each sample as the previous sample plus an error term. Since the error term is relatively small compared to the signal, fewer quantization bits can be used to represent the signal.

4.6.3 Hybrid coders

Because the quality of speech of vo-coders were often not at an acceptable level, engineers designed coders which were a combination of both waveform and vo-coder technology. In a hybrid coder the system codes a low frequency signal which is transmitted along with the filter and source coefficients. This baseband signal flattens and broadens the excitation signal to improve the quality of the speech. However, these coders require several extra kbps to code the baseband signal.

One example of this technology is Codebook Excited Linear Prediction. Codebook parameters are generated randomly by an independent identically distributed Gaussian process with a mean of 0 and a variance of 1. The best set of available parameters is then used to provide the excitation to the system.

4.7 Challenges in Cellular System Design

4.7.1 Power control

In order for a cellular system to be effective the base station and the mobile handset must have efficient power control mechanisms so that the power level can be adjusted depending on the network conditions. Higher power levels allow a signal to travel further with an acceptable level, but also result in greater co-channel interference for other users.

A further disadvantage of using higher power levels is that they result in greater power dissipation in the handset and therefore shorter battery lifetimes. CDMA requires even more extensive power control. The base station and the mobile station adjust their power levels depending on the distance between them, to ensure that mobile stations close to the base station do not drown out the signals from mobiles which are far away.

Higher power levels are necessary for sparsely populated regions with large cell sizes, and lower power levels are necessary for urban areas where it is necessary to re-use frequencies as often as possible to meet capacity requirements. with other subscribers using the same frequencies in nearby locations.

In TDMA systems with multiple users per channel, the power control may be adjusted each time a different user begins transmitting. Figure 4.8 shows how power can be adjusted in the system. In the G.S.M. system, for example, there are 16 power levels from 20 mW to 20 W.

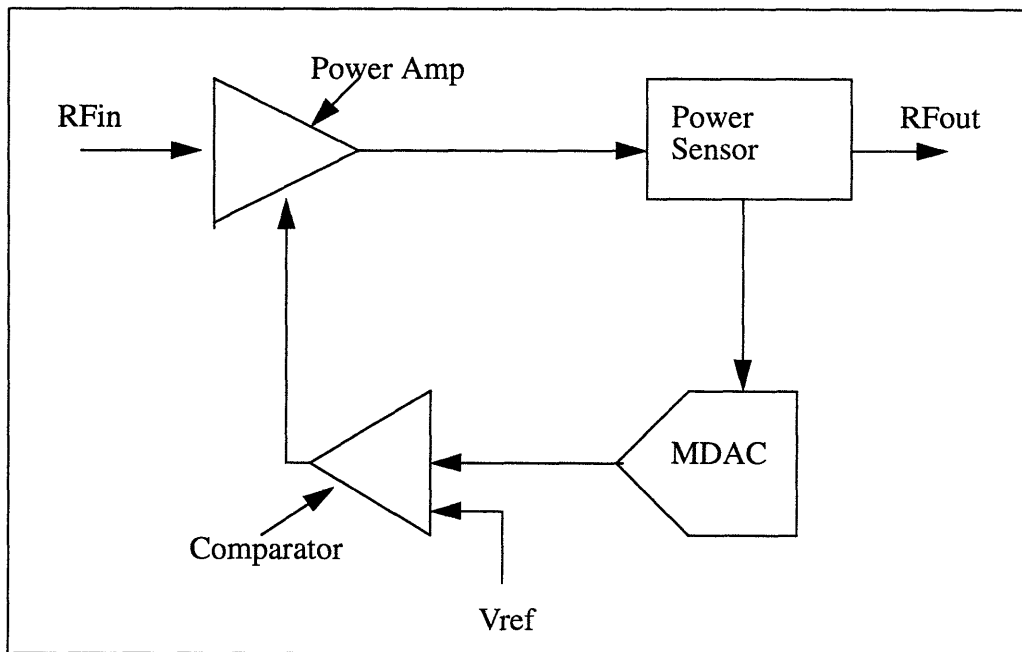


Figure 4.8: Power control mechanism used in both cellular handsets and the base stations

The voltage controlled amplifier shows how the output is modified by a multiplying digital to analog converter (MDAC). The output of the comparator will change until the system is stable again. Therefore the output will follow the control signal. A similar power control mechanism can be used in the mobile station.

4.7.2 Multipath Fading

One other important issue which must be addressed in the design of cellular systems is robustness to multipath fading. Multipath is the result of a signal traveling from the source to the destination by more than one path. This occurs because a signal can reflect off buildings, mountains or the ground and reach the receiver at a later time. As a result the received signal may not be equal to the transmitted signal and processing is necessary to minimize the error between the received signal and the transmitted signal. Figure 4.9 illustrates this problem.

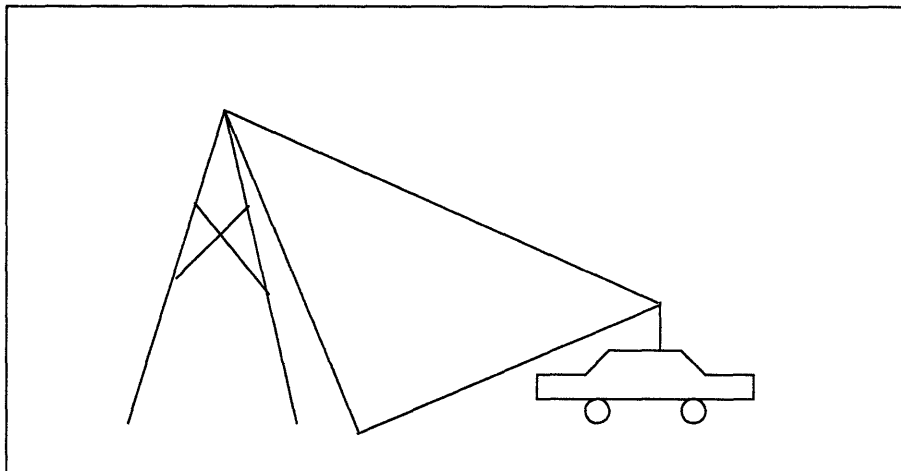


Figure 4.9: An illustration of the effects of Multipath fading¹

1. Taken from Macario, Personal and Mobile Radio Systems, p. 284.

Because the transmission time between the mobile and the base station can vary significantly, each received bit will correspond not only to the associated transmitted bit but also to the sum of scaled consecutively transmitted bits transmitted before that bit. One goal of a receiver designer is to minimize this difference between the transmitted signal and the received signal. In a digital cellular system this can be done using an equalizer. An equalizer is designed to use the synchronization bits to calculate the coefficients $c_1 - c_n$ in the equation below using regression techniques by comparing the synchronization data received over the channel (the output) with the actual transmitted signal (the input) which is known by the receiver. The coefficients of the equalizer reflect the channel characteristics and must be updated very frequently because these characteristics are constantly changing.

Fading occurs when a signal is received with too low of a power level. This can occur when two signals propagate and arrive at the receiver out of phase and therefore cancel each other out. Multiple antennas at the base station and / or the mobile station effectively combat that problem because with multiple receivers, the system can ensure that two signals can cause constructive interference making the received signal more powerful and reducing fading effects.

$$X_{trans}[n] = c_1 * X_{rec}[n] + c_2 * X_{rec}[n-1] + c_3 * X_{rec}[n-2] + c_4 * X_{rec}[n-3]...$$

Minimizing the complexity of the equalizer reduces the power consumption in the handset. The lower the bit rate, the more time there is between samples and the fewer the number of samples that will be corrupted in the set period of time. As a result lower bandwidth systems are usually less complex and dissipate less power in the handset.¹

4.8 The interfaces

Now that we understand the different components in the system and some of the issues involved in designing these components we can examine the interfaces in a cellular system. There are two important interfaces in these systems: the air interface between the handset and the base station, and the mobile switching network. The air interface handles the interaction between the mobile station and the base station over the radio link. The mobile switching network handles the routing of all data within a cellular network.

4.8.1 The air interface standard

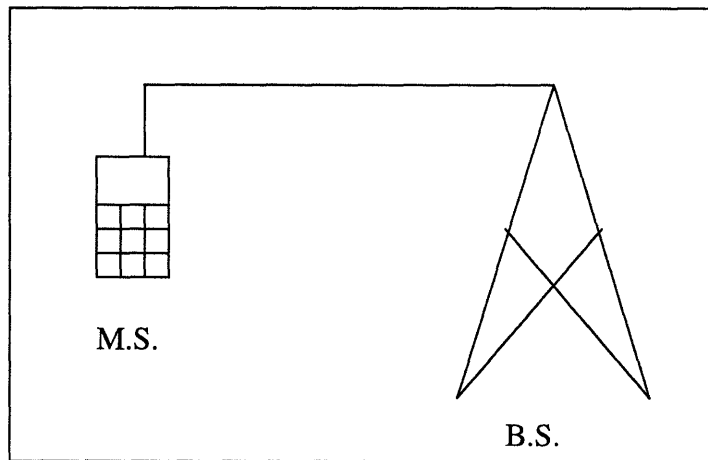


Figure 4.10: The air interface in a cellular system

As shown in figure 4.10, the air interface standard defines how the base station and the mobile station will communicate with each other over the radio channel. The air interface determines to a large extent how efficiently the allocated spectrum will be used for cellular

-
1. Standard setters usually set a time interval by which time 99% of all multipath signals have arrived at the receiver. In Europe it is set at 16milisec and in the U.S. it is set at 40 milliseconds.

services. As explained earlier the fewer the number of bits used for speech and channel coding, the more efficient the use of the spectrum, but the less accurately the voice signal is reproduced.

Defining the air interface standard includes defining the techniques for speech compression and decompression, channel coding, interleaving, signaling and control protocols, modulation and framing. Each of these elements plays an important role in determining the final balance between spectral efficiency and voice quality.

Figure 4.11 indicates the process by which a frame is prepared for transmission across a link. The speech input is first sampled at the appropriate rate. The speech coder then uses certain algorithms to reduce the number of bits necessary to represent the signal. The channel coder adds redundant bits to give the system error correction capabilities and makes it more robust to potential channel errors. In some digital systems interleaving is also done to make a voice path more robust to burst errors in the channel.¹ Interleaving involves transmitting a user's data in bursts so that a single user is not as susceptible to burst errors.² Extra control and signaling bits are added to ensure that all appropriate information for call setup and handoff³ is communicated between the base station and the mobile station. The signal is then modulated onto the radio carrier and transmitted.

-
1. Interleaving is really one more technique which system designers can use to reduce the required C/I ratio by improving the robustness of the link on the channel.
 2. Burst errors are a result of the propagation of a single bit error. Burst errors are common in digital radio transmission.
 3. Handoff occurs when a mobile travels from one cell's region to another cell's region.

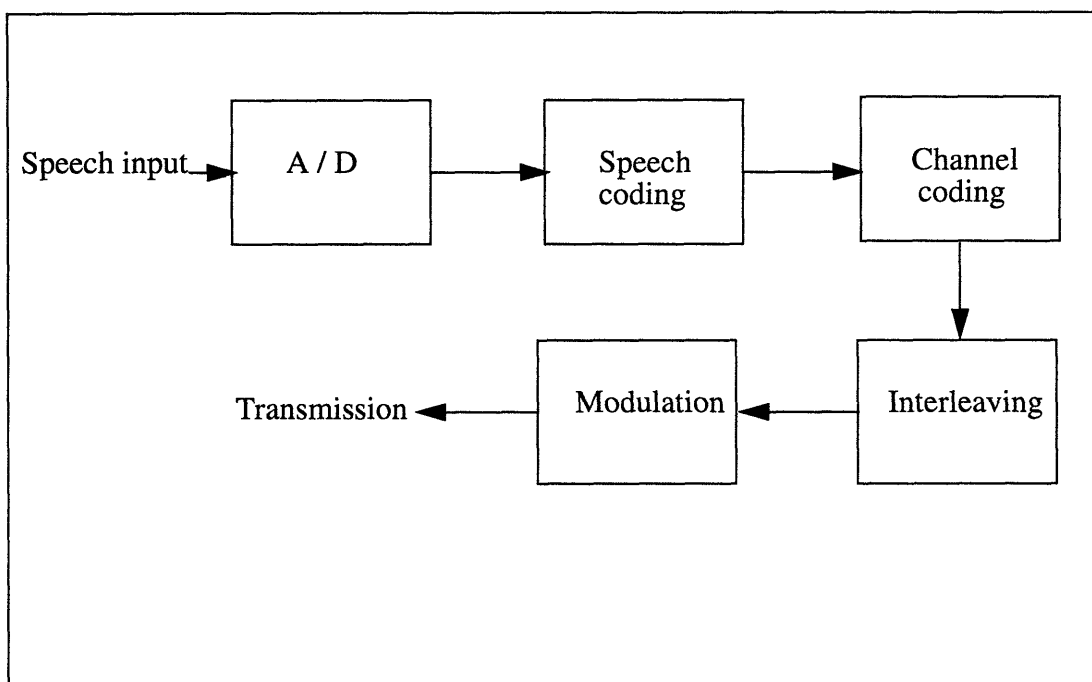


Figure 4.11: Processing required in a digital cellular transmitter

As figure 4.12 illustrates, the transmitted frame consists of header bits, control and signaling bits, encoded traffic bits and guard bits. Header bits are used to distinguish users from each other. Control and Signaling information is used to set up or terminate a channel and to send link quality information between the base station and the mobile station. Traffic information is then sent across the channel with additional parity bits to minimize the bit error rate. Frames are separated by guard bits to protect users from interfering with each other.

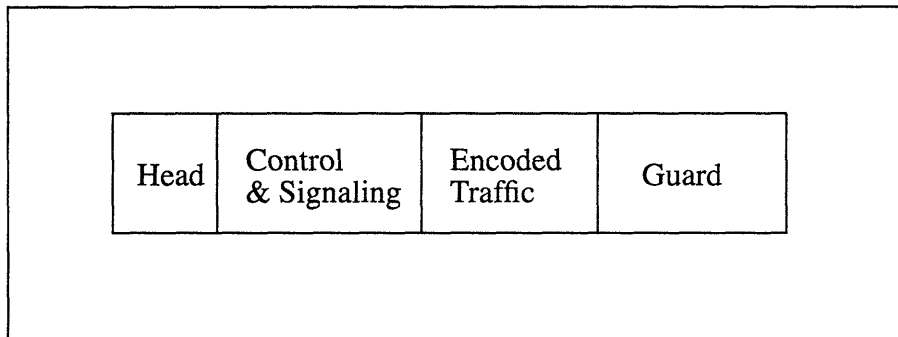


Figure 4.12: The frame structure for a generic user

The Handshaking Protocols (Signaling)

The handsets must also ensure that all signaling information exchanged between the mobile station and the base station is actually received by the other. This includes building frames, requesting acknowledgment during transmission, reconstructing frames and sending acknowledgments in receive mode. Although the specific protocols described in this section are actually used in analog cellular systems, the interaction between the different elements of digital systems is similar.

Figure 4.13¹ shows how a mobile station initiates a connection with the cellular and the public switched network. First, the mobile sends the data containing its own MIN, the ESN, and the called telephone number. The system then checks to see whether this mobile is valid or not and authenticates it to the system. The Mobile Switching Center then makes a connection with the public switched network. The system then sends a message back to the user to allocate a channel for the conversation and a sends a supervisory auditory tone (SAT). The mobile acknowledges it has received the information from the base

1. Figure taken from Macario, p. 97.

station by sending the same supervisory auditory tone back to the base station over the voice channel. The connection has then been established.

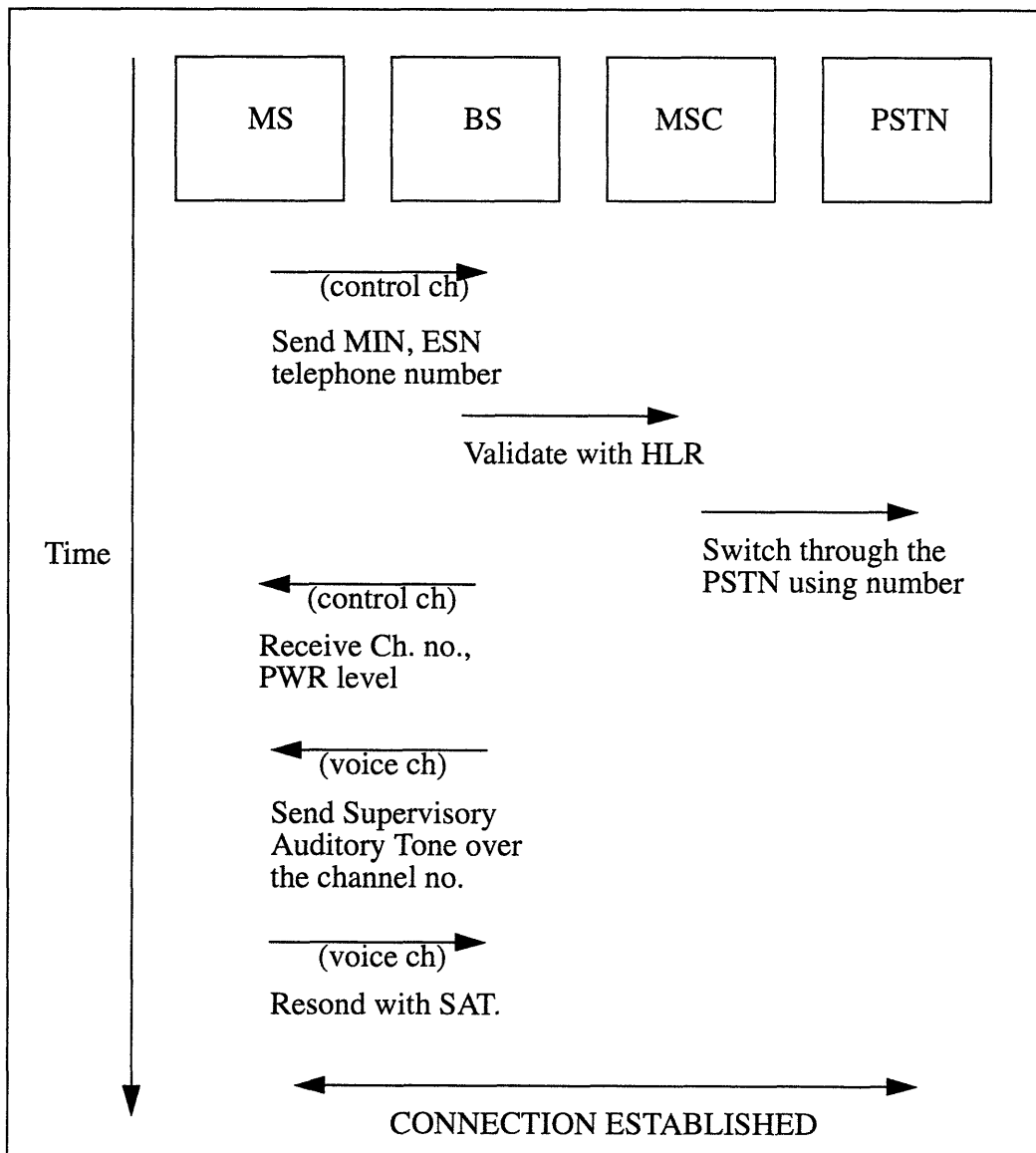


Figure 4.13: Cell set-up for a mobile initiated phone call

Figure 4.12¹ shows the connection is made when a mobile call is received. First the cell site of the mobile is looked up in the home and visitor location registers and the call is

1. Figure taken from Macario, p. 98.

routed to the correct base station in the system. The base station then transmits the page over the control channel to the mobile. The mobile then acknowledges the page and sends the Mobile Identification Number and the Electronic Serial Number back to the base station. The base station then allocates a channel, and sends the appropriate supervisory auditory tone on the voice channel. The handset then acknowledges the receipt of this tone, and a connection is established.

Figure 4.13¹ shows how handoff occurs in a cellular system. First the base station indicates that the quality of the air link has dropped below a certain level. The base station and the base station controller then use the information from neighboring base stations and the handset to determine if hand-off should occur. If a stronger signal is found, a free channel is allocated by the new base station, and the new control information is sent to the mobile station. The old base station releases control. The new base station then sends its SAT on the new channel, the mobile acknowledges this new base station on the respective voice channel and the conversation can continue.

All of these appropriate control bits must then be incorporated into the packets which the base station and mobile station are sending to each other.

1. Figure taken from Macario, p. 99.

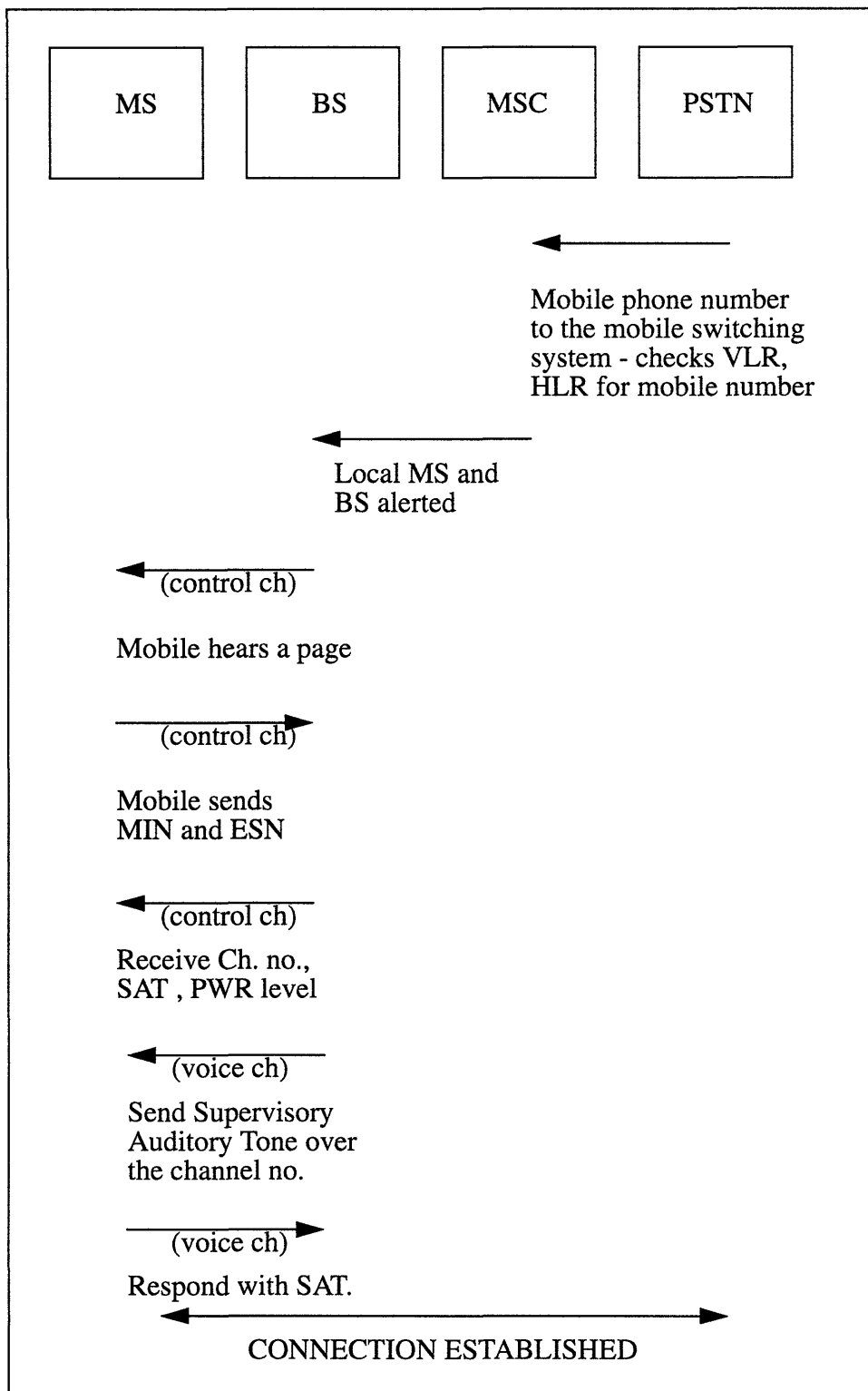


Figure 4.14: Call setup for a system initiated telephone call ¹

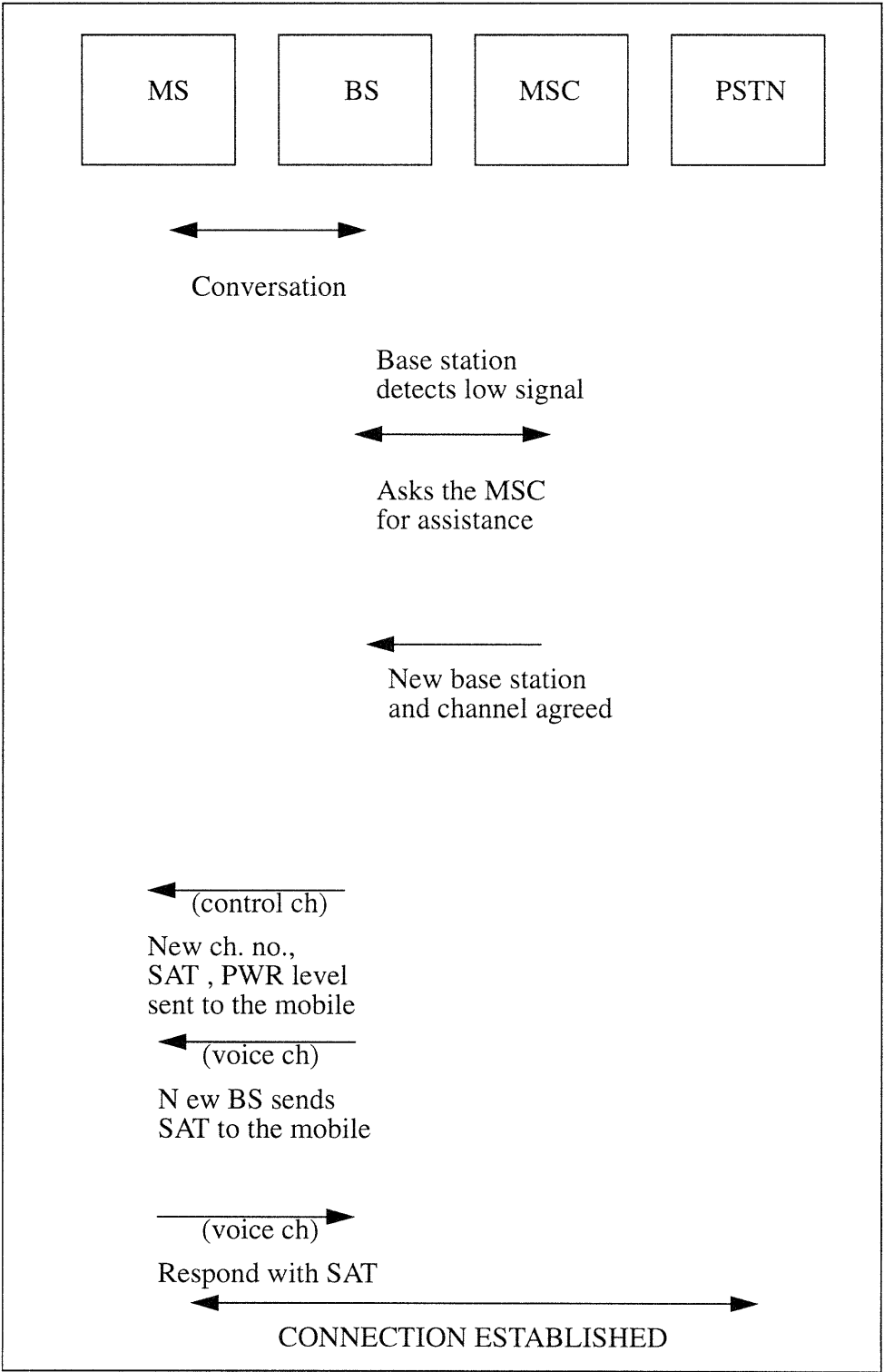


Figure 4.15: Handover protocol

1.

4.8.2 Network interfaces

A second set of important interfaces is between the various mobile switching components including the base stations, the MTSO, the Visiting Location Registers, the Home Location Registers and the Public Switched Telephone Network. Together these components form a fully integrated network wireless and wireline network. Figure 4.16 illustrates the overall architecture.¹

The following table is a guide to the abbreviations in each of the boxes.

Abbreviation	Function
PSTN	Public Switched Telephone Network
TSC	Transmission Switching Center
VLR	Visiting Location Register
HLR	Home Location Register
EIR	Equipment Identity Register
MSC	Mobile Switching Center
BSC	Base Station Controller
BS	Base Station
MS	Mobile Station

Table 4.2: Reference Table for Figure 4.9

1. This information is provided for background and is not the focus of this thesis.

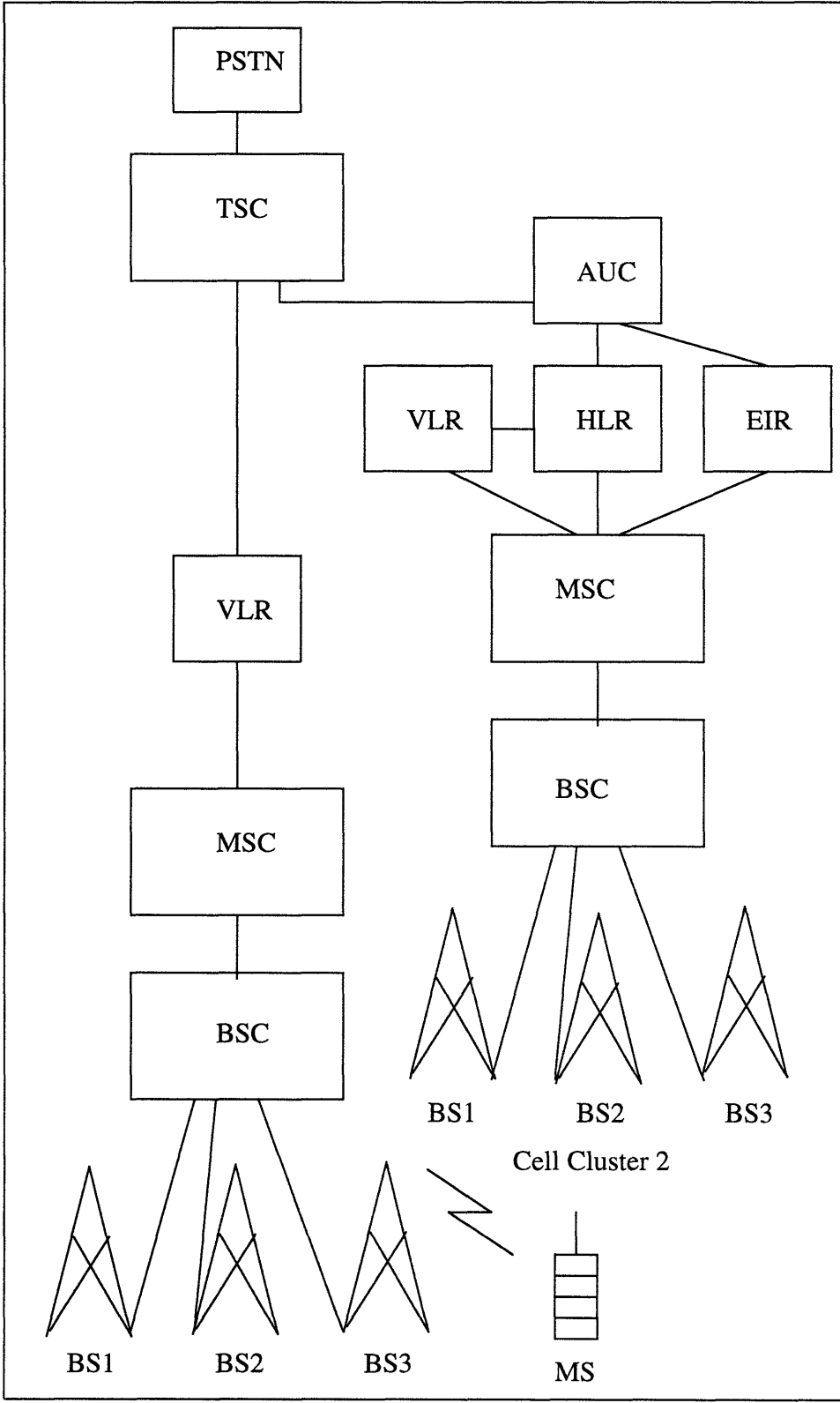


Figure 4.16: Cellular network architecture

This chapter has provided the reader with a technical framework to understand the decision making process which occurred in these three parts of the world. As we will see, it was the interaction of these technical issues with a host of political and business issues which led to the particular technologies which emerged in the U.S., Europe and Japan. The next four chapters address the regulatory and technical decisions which were actually made. In the conclusion we will attempt to understand whose perspectives were most important and what standard-setting process actually worked best in the three parts of the world.

Chapter 5

Spectrum Allocation

Spectrum allocation among service categories and partitioning among the service providers of each service are both extremely important in cellular systems. They determine the number of competing systems which will exist, and the capacity of each of these systems. Allocating more spectrum for a service increases the capacity of each system. Allocating new spectrum for a service, as the C.E.P.T. did for G.S.M. in Europe, maximizes the technical freedom with which the service could be implemented because the technology does not need to be backward compatible with older technologies. The division of spectrum between the service providers can also constrain the type of technology which can be used in a particular band: wideband systems are generally less flexible than narrowband systems because their channel spacing is larger.

U.S.	Europe	Japan
0%	100%	62%

Table 5.1: Percentage of spectrum allocated for digital which was not previously allocated for analog cellular services

5.1 The U.S.

The history of spectrum allocation in the United States dates back to 1957, when AT&T requested 75MHz of spectrum for land mobile telephony. AT&T was required to demonstrate to the F.C.C. that it would have the capability to implement this technology and that it would also have a viable market. In 1964 the F.C.C. outlined three possible

ways of assigning spectrum for land mobile services; a reallocation of the lower U.H.F. television channels; a reallocation of the upper U.H.F. channels or a sharing of the U.H.F. channels. Because no one ever wants to lose spectrum this led to a six year fight between AT&T and the broadcasters. In 1970, 13 years after the initial request, the F.C.C. Commissioners voted 3-2 to reallocate the upper 14 channels 70-83 of spectrum for cellular services. The F.C.C. reversed itself a couple of times and in the end decided to reduce the allocated spectrum to 40 MHz with an additional 10 MHz to be held in reserve.

	Frequency allocated (MHz)
Operator 1 (M.S. - B.S.)	824 - 835, 845 - 846.5
Operator 1 (B.S. - M.S.)	869 - 880, 890 - 891.5
Operator 2 (M.S. - B.S.)	835 - 845, 846.5 - 849
Operator 2 (M.S. - B.S.)	880 - 890, 891.5 - 894

Table 5.2: Spectrum allocated for analog and digital cellular in the U.S.

The F.C.C. decided that AT&T and one non-wireline carrier should each be granted spectrum in every market. AT&T claimed that by splitting the available spectrum between two service providers, the cost of running each network would increase by 30%. The F.C.C. decided, however, that it was important to stimulate competition to bring prices down for consumers. It feared that allowing more than two carriers would be too spectrally inefficient and that each of the carriers would end up reaching capacity constraints very quickly.¹ If there were more than two operators using the system, each licensee would not be able to service enough users within each region, increasing the probability of blocking and decreasing each system's overall performance. The F.C.C. decided that

1. Interview with John Williams, F.C.C., January 1995.

licensing two operators was the optimal trade-off between introducing competition into the market and designing an efficient system.

In 1984, in response to carrier demands for additional spectrum, the F.C.C. allocated the reserve spectrum to help cellular providers meet the expected growth in demand. By the mid-1980's it was clear that the demand for cellular services was growing extremely quickly and that service providers in the large metropolitan areas using the existing technology and existing bandwidth would soon run out of capacity. However, the F.C.C. did not reallocate spectrum from the other radio services for the use of cellular operators.

According to the F.C.C. no other spectrum was available for advanced cellular technologies, but there are at least two other possible factors which may have influenced the F.C.C.'s decision. First, candidate advanced technologies were not mature enough at this time to warrant specific dedicated spectrum. The F.C.C. policy was designed to use the 800 MHz band to test out the various new digital technologies before allocating new spectrum. Second, the F.C.C. typically responds to requests from industry and one F.C.C. official speculated that the incumbent cellular providers may not have even requested any additional spectrum out of a fear that the F.C.C. would license a third carrier in each region instead of giving them the additional spectrum.¹

Given this constraint, the only way for service providers to increase capacity was to use more advanced technologies which would fit into the current channel spacing. In 1988 the F.C.C. therefore allowed carriers the technical flexibility to implement advanced cellular services on a portion of their allocated bandwidth. Therefore they could develop and utilize technology according to their own specific market needs. The two digital solutions which are today competing in the 800 MHz band are the D-AMPS solution and Qualcomm's N-CDMA solution. The D-AMPS technology is designed to have the same chan-

1. Suggested by an F.C.C. official in the Office of Plans and Policy

nel spacing as analog systems such that channel-by-channel replacement is possible for cellular service providers. Qualcomm's N-CDMA system, on the other uses 42 analog channels to make one spread spectrum CDMA channel.¹

Because the reserve spectrum was allocated later, the spectrum is partitioned in such a way that one operator has an 11 Mhz block and a 1.5 MHz block and another operator has a 10 Mhz block and a 2.5 Mhz block. This limits the types of digital technologies which can be used in this spectrum. Qualcomm's N-CDMA system with a 1.25 Mhz bandwidth will waste .25 Mhz of spectrum if it is used in the 1.5 MHz block and 1Mhz in the 11 MHz. By partitioning the system in a non-traditional manner, the flexibility of the system is limited.

One consequence of not allocating any new spectrum in the U.S. was that many service providers have used advanced analog techniques rather than introducing digital technology in the 800 Mhz band. As a result, digital penetration of cellular telephones in the U.S. is still only 1% of analog penetration. On the other hand, by allocating new spectrum for P.C.S. services, the F.C.C. is forcing service providers to commit to either the N-CDMA or DCS-1900 technology since they are required to begin deploying systems next year.

5.2 Europe

The birth of G.S.M. can be traced back to the spectrum allocation decision made by the World Association for Radio Committee which performs radio coordination tasks for the three major developed regions of the world. This coordination of frequency utilization

1. E-TDMA was also introduced by Hughes in 1992, but is not being considered by a majority of the service providers in the U.S.

is primarily an attempt to ensure that all spectrum in neighboring countries is being used for the same purposes, to prevent interference. In 1979, WARC allocated a part of the European 800 and 900 MHz band for land mobile services. A subset of that band would be allocated for pan-European digital cellular services by the CEPT.

	Spectrum allocated for digital cellular in Europe
M.S. - B.S.	890 - 915 MHz
B.S. - M.S.	935 - 960 MHz

Table 5.3: Spectrum allocated for G.S.M. service in Europe

When the idea for a pan-European standard arose, the members of the CEPT realized that the spectrum allocated by WARC would be ideal for G.S.M. If the same frequency band were available for service in all European countries, a pan-European cellular system would be realizable as long as all regulators could clear this band exclusively for cellular services. However, some countries such as the United Kingdom were capacity constrained. Since this allocated spectrum was the only spectrum available for cellular, countries that were unable to hold off and wait for the development of the G.S.M. standard had to use some of the allocated spectrum for 1st generation analog technologies such as TACS.

To ensure that some of the remaining spectrum was allocated for digital cellular technologies, members of the E.C. were required to sign a Memorandum of Understanding drafted by Stephen Temple of the Department of Trade and Industry in the U.K. This document required that all member countries would begin G.S.M. in July 1991 and would use this allocated spectrum for G.S.M. services. All EEC countries were required to reserve

the frequency bands 905-915 and 950-960 MHz exclusively for pan-European services after 1991. The rest of the allocated spectrum could temporarily be used for either analog or digital cellular services. Member states were also required to produce plans showing how they planned to use the entire allocated band for pan-European cellular radio services. According to the Memorandum of Understanding, any country which wanted to participate in E.T.S.I. and have a role in the development of pan-European telecommunications standards would be required by European law to use the allocated spectrum in this way.¹

The E.C. also passed a directive stating that all European cellular markets have at least two competitors by 1998. It is, however, up to the individual countries to determine the actual bandwidth partitioning for digital cellular services. In both England and Germany, competition has already been introduced into the marketplace for G.S.M. services.

As in the United States, the technical flexibility of G.S.M. was also limited; in the United Kingdom, only 5 Mhz was available for the uplink of G.S.M., because the rest of the allocated spectrum was used for TACS analog technology to meet immediate and growing capacity needs. Any solution with a channel spacing greater than 5Mhz was not viable in England. The 6 Mhz wideband TDMA proposal put forth by Alcatel and S.E.L. would not fit in the 5 Mhz band. Therefore, the technical and policy leaders in the United Kingdom convinced 13 of the 15 participants to join the narrowband TDMA camp. Only France and Germany objected. However, as we will learn later, both subsequently agreed to a narrowband solution.

G.S.M. is today being deployed in 80 countries in Europe and overseas. Part of the reason for G.S.M.'s success is that the E.C. forced member countries to allocate the same band for G.S.M. and TO provide only G.S.M. service in this spectrum. By forcing the European Community by law to converge upon a single standard, the Europeans were able

1. Conversation with Stephen Temple, Department of Trade and Industry, U.K. March 1995.

to establish G.S.M. as one of the most prominent digital standards in the world. Some analysts have suggested that with the markets in India and China G.S.M. may reach penetration levels of 40-50 million telephones by the year 2000.

5.3 Japan

In Japan the Telecommunications Technology Council of the M.P.T. allocated two sets of new frequencies to digital mobile cellular services: 20 MHz in the 800 Mhz range and 48 MHz in the 1.5 GHz range. In addition the T.T.C. foresaw that all cellular services in Japan would soon be digital, and therefore mandated the same channel spacing for digital systems as existed for analog systems (as the F.C.C. did in the United States) to ensure that the analog systems could later be gradually converted to digital systems. The M.P.T. allocated Nippon Ido Tsushin Corporation (IDO), DDI Corporation (DDI) and NTT spectrum for digital services in the 800 MHz region. In addition, the M.P.T. also allocated NTT and two new consortia of companies, Digital Phone Group, led by Japan Railway Corporation, and Tu-Ka Cellular Group, led by Nissan Motor Company, spectrum for digital cellular service in the 1.5 Ghz range.

	Spectrum allocated
(M.S. - B.S.)	810 - 830 1477-1489 1501-1513
(B.S. - M.S.)	940-960 1429-1441 1453-1465

Table 5.4: Spectrum allocated for digital cellular services in Japan

An interesting aspect of spectrum allocation in Japan is that the T.T.C. combined the approaches of the frequency managers in Europe and the U.S. Like the D-AMPS system, the P.D.C. system is constrained to work within the analog system's channel spacing, but like the European system new frequencies have also been allocated.

5.4 Comparison

Of the three regions of the world, Japan allocated the most additional spectrum for second generation cellular services. It is also the only country which allocated spectrum in the 1.5 Ghz region for second generation services. In the United States and Europe, regulators were planning on allocating additional spectrum for advanced cellular systems, since second generation systems were regarded as an interim solution and were only needed to meet capacity needs until third generation digital mobile cellular services became available. In Japan, however, the P.D.C. system was the long term cellular solution. Therefore we can speculate that more spectrum was necessary in Japan because P.D.C. had to meet longer term market requirements.

	U.S.	Europe	Japan
Additional Spectrum allocated for 2nd generation Digital Cellular Services	0	50 Mhz	88 MHz
Number of competitors / region	2	1 - 2	4

Table 5.5: A comparison of the spectrum allocation and band partitioning decisions in the U.S., Europe and Japan

The additional services to be offered on third generation PCS and Personal Communication Networks (PCN) networks¹ such as FAX or wireless e-mail were not seen as being as important in Japan. As a result, I would speculate that Japanese equipment manufacturers are not very likely to have very high market shares in equipment for PCS services in the U.S. or PCN services in Europe because they are not developing that expertise at home in Japan.²

1. PCN networks are the third generation services in Europe. DCS-1800, a derivative of GSM will be used for those services.

2. Japan is developing an additional wireless technology, the Personal Handiphone Service. This, however, will be designed to be more like a cordless telephone with limited coverage rather than a network with more sophisticated functionality.

Chapter 6

Access Type - TDMA victorious everywhere (for now)

6.1 Technology Explanations

As explained in Chapter 3, standard setters could select from three main digital access schemes: Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA).

6.1.1 FDMA (Frequency Division Multiple Access)

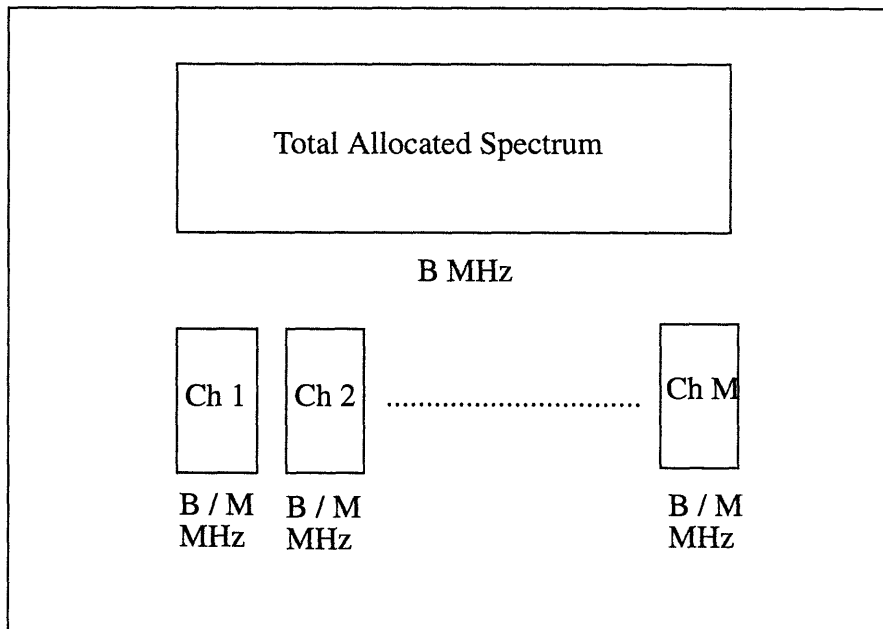


Figure 6.1: Multiplexing in an FDMA system

As figure 6.1 illustrates, a Frequency Division Multiple Access system divides the spectrum into narrow channels, each of which can each carry one voice channel. As digital compression technology improves, channel sizes are decreasing because each user requires less spectrum. The smaller the channel size, the more users can be accommodated in a given frequency band. Implementing an FDMA system requires mainly radio system expertise to do the appropriate frequency splitting and filtering. Guard bands in frequency are used to minimize co-channel interference.

One of the main advantages of an FDMA system is that it is an intermediate solution between analog systems and TDMA systems. Radio engineers have had years of experience in dividing a spectrum in frequency, but the multiplexing called for in TDMA is a concept with which engineers have less experience. The only aspects of an FDMA system which are more complex than an analog system are the compression technologies and the finer receivers used to accommodate the requirements of the smaller channel spacing.

Another advantage of the lower bit rate of FDMA systems compared to the other digital solutions is that fewer bits are corrupted by multipath fading effects. As explained in chapter 4, FDMA is less sensitive to multipath fading effects because the time period between bits is longer than in TDMA systems. As a result equalizers are either not necessary or can be made very simple to compensate for the effects of multipath fading. This reduces the power dissipation and greatly simplifies the design of the handsets.

One disadvantage of using an FDMA system is that unlike a TDMA system, a user is transmitting or receiving information almost all of the time. As a result average power levels are higher in an FDMA system than in a TDMA system. This has two negative consequences. First, this increased power dissipation more than outweighs the decrease in power due to the absence of an equalizer; consequently, battery lifetimes in FDMA systems are shorter. Second, co-channel interference levels are higher¹, decreasing the cell re-

use factor and the overall spectral efficiency of the system. Because of the change in the cell re-use factor, the cellular network needs to be completely re-engineered. As a result, FDMA is not a particularly attractive transition solution in cases where service providers want to convert gradually from analog to digital.

6.1.2 TDMA (Time Division Multiple Access)

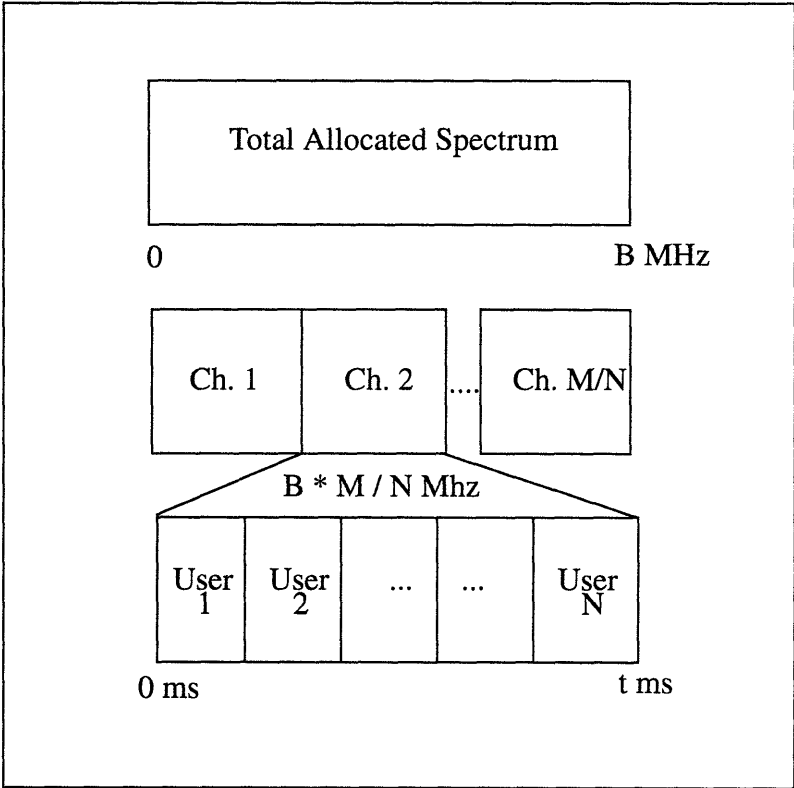


Figure 6.2: Multiplexing in a TDMA system

1. The filters used in the receivers are imperfect, allowing power to leak from one channel to a neighboring channel.

As discussed in chapter 4, Time Division Multiple Access (TDMA) requires channel splitting in both frequency and in time. First, the spectrum is divided into smaller channels as in FDMA. Unlike FDMA however, each channel in a TDMA system supports multiple users. Users on the same channel distinguish themselves from each other by alternating in time. To support multiple users on a channel, channel sizes in TDMA systems are larger than they are in FDMA systems. A user on a TDMA system will typically transmit its data at N times the transmission rate in an FDMA system, however each user will only use the channel for $1/N$ th of the time. As digital compression technologies improve, more users can be fit on the same size channel. Implementing a TDMA system requires both radio engineering expertise to do frequency splitting and accurate timing and switching capabilities to do the time division multiplexing within a channel.

Unlike FDMA, in TDMA systems each user is only transmitting or receiving information on the channel for a fraction of the time. This has two advantages.

First, the mobile can use the remaining time to monitor air channel links with other base stations to determine whether or not handoff is necessary. The greater the number of timeslots¹, the more time the mobile station has to monitor its air link with other base stations. For example, in G.S.M. there are a total of 8 time slots, 1 is used to transmit, 1 is used to receive, and 6 are used to monitor air links with the 6 nearest base stations to determine whether or not mobile assisted handoff is necessary.

A second advantage is that TDMA also allows a mobile to shut off and not dissipate power while the mobile is not transmitting or receiving information on the channel. Therefore as noted earlier the average power dissipated in the handset is less than that of an FDMA system, making TDMA systems more conducive to handportability. In addition, a

1. The trade-offs involved in selecting in the number of timeslots for a TDMA system will be addressed in the next chapter.

TDMA system can be designed to have approximately the same overall level of co-channel interference as an analog system; consequently, the cellular system can be engineered with the same cell re-use patterns as an analog system, making it very convenient for service providers to make a gradual transition between analog and digital systems.

Base station costs for TDMA systems are also lower than for FDMA systems. This is because an FDMA system requires each sub-channel to have its own transceiver. In a TDMA system, on the other hand, a number of users share a single channel and therefore share a single receiver. Therefore base stations for TDMA systems require fewer receivers per voice channel and cost less than base stations for FDMA systems.

A final advantage of TDMA systems is scalability. Because TDMA systems have a higher bit rate, a TDMA system can support higher data rate applications than an FDMA system because multiple timeslots can be used by one user. The maximum data rate which the system can support increases as the number of timeslots increases.

FDMA Advantages	TDMA Advantages
Design of system simpler	No cellular system reengineering necessary
Equalizer not necessary	Scalable to other higher data rate applications
	Lower infrastructure costs
	Power dissipation lower Easier to design handportable systems
	Mobile Assisted Handover possible

Table 6.1: Summary of the Advantages and Disadvantages of TDMA and FDMA systems

6.1.3 CDMA - Code Division Multiple Access

Code Division Multiple Access (CDMA) involves spreading a signal over a fairly wide channel. However, as discussed in chapter 4, the frequency band must first be separated into channels. Each voice within a channel gets assigned a different pseudo-random code. The signal is then modulated using that codeword and its energy is spread over a much larger bandwidth. The signals are distinguished from each other by using a correlator which only accepts signal energy from one codeword. All of the other signals using the same bandwidth and different codes generate signals which appear to the user as noise. Therefore each additional user degrades the voice quality for every other user.

One advantage of CDMA systems is that it provides inherent discrimination against multi-path fading. Any delay spread greater than 1 microsecond will not be correlated because correlator codes will change. This eliminates the need for a costly, power consuming equalizer and makes CDMA handsets more conducive to handportability.

One key challenge in implementing CDMA systems is to have an effective power control system. Power control in CDMA systems is particularly important because power levels used in CDMA are a fraction of those used in TDMA or FDMA. The power levels in CDMA depends on two factors. First, as explained in chapter 4, it depends on the number of users sharing a channel. The greater the number of users sharing a cell, the higher the noise level in the cell, therefore, the lower the power level of each handset to ensure an acceptable level of voice quality for each user. Second, power control must depend upon the distance between the mobile station and the base station. With effective power control, all signals when received by the base station would have approximately the same spectral

energy. This eliminates the near-far problem where mobiles close to the base station drown out the signal energy from the mobiles further away.

The primary advantage of CDMA technology is that the capacity of these systems is expected to be 10 times the capacity of AMPS.¹ This is for two reasons. First less spectrum is required per user due to improved speech and channel coding techniques. Second, the cell re-use factor is significantly higher in CDMA because the power used for transmission by each mobile is a fraction of what it is in FDMA or TDMA technologies. As a result, all of the frequencies to be reused in adjacent cells. CDMA will be deployed in the U.S. in second generation cellular systems, and is being seriously considered by service providers in the U.S. for third generation mobile services of Personal Communications Services (P.C.S.).

1. This figure is according to Qualcomm's estimates.

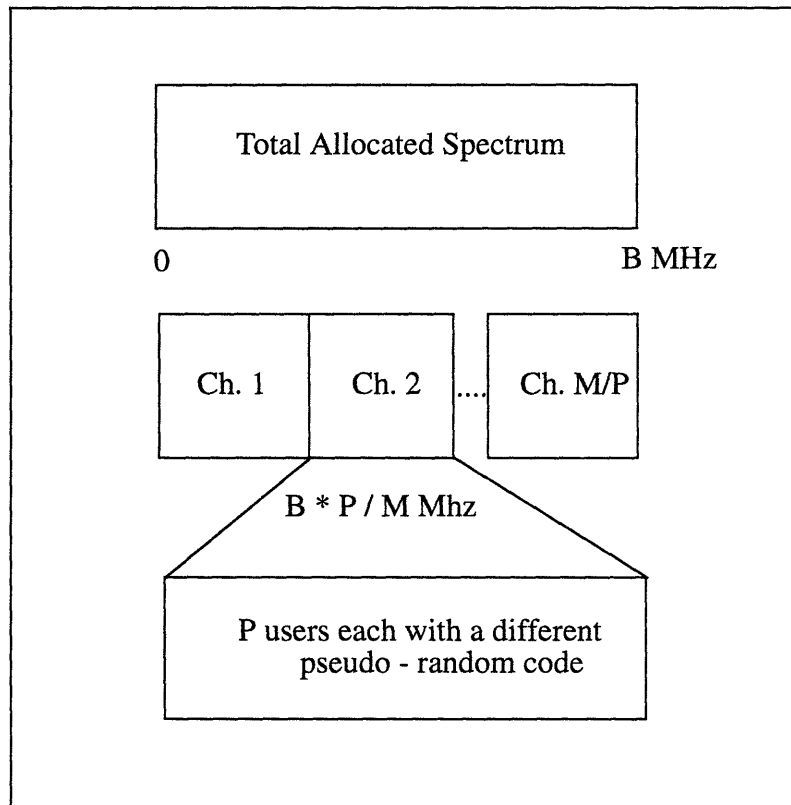


Figure 6.3: Multiplexing in a CDMA system

6.2 Decision Making Process

6.2.1 Europe

In 1984, when the GSM initiative was well underway, the leaders in the GSM group of the CEPT requested that the European manufacturers and operators submit test systems. These systems would then be evaluated based on their voice quality, spectrum efficiency, flexibility, base station cost, infrastructure cost and hand portable viability. After the systems had been evaluated, the participants in the CEPT would then determine the technical

characteristics by incorporating the best aspects of all of the systems submitted. Eight test systems were submitted, four by Franco-German manufacturers and operators and four by Scandinavian manufacturers and operators.¹ Of these systems five were pure TDMA, two were a mixture of CDMA and TDMA, and one used an FDMA system on the uplink and a CDMA/TDMA system on the downlink. These systems were constructed simply as technology demonstrators.

In January 1987 trials of these systems were conducted in Paris. At this time CDMA technology was deemed not to be mature enough. For the level of spectrum efficiency required, the voice quality of the CDMA systems was not yet at an acceptable level. The CDMA system was also much less flexible because each channel required 4 MHz² blocks rather than 200-300 kHz blocks for narrowband TDMA. In fact spectrum in Europe was not available in blocks of 4 MHz. The decision then boiled down to a TDMA system versus an FDMA system. As explained earlier, TDMA systems were considered to be more scalable, have lower infrastructure and mobile costs, and have more viable handportability. The FDMA system was seen as being less risky.

However, the biggest advantage which the engineers saw in TDMA over FDMA systems for G.S.M. was the ability to do mobile assisted handovers. As explained in chapter 4, mobile-assisted handoff allows the system to reduce the time required for handoff, therefore decrease the minimum cell size, and increase the cell reuse factor and the spectral efficiency. Mobile assisted handoff also decentralizes the handoff control and reduces the amount of network traffic per handoff. An FDMA system would not give the user enough time to do mobile assisted handoff because there is no idle time when the mobile is not either transmitting or receiving data.

1. Conversation with Alain Maloberti, Chairman of the GSM Radio Sub-system Committee. Paris, France. March 1995.

2. Channel sizes in proposed CDMA systems range from 1.25 Mhz to 8Mhz.

We can also speculate that another political reason why TDMA might have been adopted in Europe over FDMA is because the Europeans wanted to choose a technology which they believed would give the European equipment manufacturers a competitive advantage in manufacturing relative to American and Japanese equipment manufacturers. Many European equipment manufacturers felt that mobile communication manufacturing capabilities were more advanced in Europe than in any other part of the world. It was therefore important to leverage those capabilities by adopting a standard which was as technically advanced as possible.¹ As explained earlier, TDMA is a more complicated advanced technology than FDMA.

After the trials and the technical discussions, the CEPT Committee unanimously decided to support a TDMA system on both the uplink and the downlink.

6.2.2 The U.S.

After the F.C.C. passed a motion to allow carriers technical flexibility in the use of their available spectrum and the C.T.I.A. mandated that all phones must be dual-mode to work on both digital and analog systems, a number of the industry players and service providers decided to come together and develop a digital cellular standard, D-AMPS, in the Telecommunications Industry Association (TIA). This standard would be one of the competing standards for second generation digital mobile cellular services in the U.S. Just as in Europe, CDMA was not a viable option in the U.S. for the D-AMPS standard. First it was not compatible with the existing analog system channel spacing and therefore is not amenable to channel by channel replacement.² Second the technology was not mature enough to design a working system in 1988. Therefore, CDMA had to be put on the back-

1. Speculated by an engineer at a European P.T.T. who requested anonymity

2. This will be discussed in further detail in chapter 7.

burner and would be further developed for third generation digital mobile cellular technologies. Just as in Europe, the access scheme debate for the TIA standard was between the FDMA and TDMA. As we know, however, Qualcomm has developed CDMA over the last 4 or 5 years and is expecting to bring products to market by the end of 1995. CDMA will therefore be a competing standard for both second and third generation services.

The FDMA Camp

The strongest two supporters of FDMA technology were AT&T and Motorola. AT&T and Motorola were the two leading producers of analog AMPS equipment as well. AT&T claimed that several narrowband channels were more resistant to interference than one wider band TDMA channel because less noise will travel through a narrowband channel. In addition AT&T and Motorola both argued that an FDMA system requires a less complex equalizer because each channel is transmitting at a lower bit rate. Neither AT&T nor Motorola would be affected by the additional costs associated with reengineering the cellular network for use with FDMA technology. These were the arguments which both AT&T and Motorola put forth in the TIA meetings.

We can speculate here that AT&T and Motorola may have also supported FDMA technology because they believed it would give them the greatest competitive advantage in the digital cellular equipment market relative to their competitors. Both companies believed that their core competencies were in radio system design rather than in switching.¹ An FDMA standard would leverage AT&T and Motorola's strengths in radio system design

1. For Motorola there was a very clear decision because it has always specialized in products for radio systems. AT&T, however, has more well-balanced capabilities. Nonetheless according to a participant in these meetings because AT&T had been manufacturing products for the AMPS standard it believed it could be more successful manufacturing products based on FDMA technology.

more than a TDMA system would. In 1988 AT&T presented a demonstrator model at the Cellular Telephone Industry Association convention based on FDMA technology.

The TDMA Camp

The strongest supporters of TDMA in the United States were Ericsson, Northern Telecom, Hughes, and General Electric. Ericsson of course had already developed TDMA expertise from its GSM activities in Europe. General Electric was in the data transmission business and therefore wanted a standard which would be scalable to higher data rates.¹ Northern Telecom was already a large player in the switching business and therefore supported a TDMA system such that they could leverage their switching expertise in doing multiplexing in time. Most of the service providers also supported a TDMA solution because it would minimize the required reengineering of the systems. The technical arguments put forth for a TDMA system were similar to those explained earlier. TDMA was seen as a longer term scalable solution. Many also argued that by adopting FDMA as the digital standard, the U.S. would in effect be conceding the lead in mobile communications technology to the Europeans, who had already adopted a TDMA standard. FDMA was seen as a shorter term solution for meeting the growing demand for cellular systems as quickly as possible.

No consensus could be reached on this issue. The chairman of the committee even suggested drawing sticks out of a hat to resolve the debate since no other solution seemed possible. Finally, the T.I.A. committee decided to hold a three day conference in Denver,

1. G.E. and Ericsson later formed a joint venture to manufacture to the D-AMPS standard.

in November 1989, after which a vote would take place. The results of the vote were: TDMA 72%, FDMA 28%.¹ Once the vote took place, AT&T and Motorola agreed to support the TDMA efforts wholeheartedly and the two companies continued participating in the standardization process. The support of AT&T and Motorola was critical to completing a successful standard.

6.2.3 Japan

In 1987, when the T.T.C. began studying a digital mobile cellular system in Japan, it was clear that the models of the standards in Europe and the U.S. would receive much attention. Because the goals of the Japanese digital cellular system were to define a standard that was easily manufacturable, members of the T.T.C. thought that FDMA may be the best potential solution because it was the simpler than TDMA, the other solution being considered. CDMA was not being considered for the same reasons it was not adopted in the D-AMPS and GSM standards.

Why, then, did the Japanese choose TDMA technology? First, by the time TDMA was chosen in the United States, the Japanese standard-makers realized that technologists and policy makers around the world were coming to the same conclusion: TDMA was the access scheme of the first digital generation for mobile communications (2nd generation cellular systems). Japan could not afford to be left behind. A second advantage of adopting the same access scheme as the U.S. and European standards is that it would be easier for Japanese electronic manufacturers to make products compatible with those standards and sell them in the U.S. and European markets.

1. Conversation with Peter Nurse, Chairman of the D-AMPS Committee.

Country	Access Scheme Decision	Primary Reason
U.S. (D-AMPS)	TDMA	adopt the most advanced, scalable technology possible
Europe (G.S.M.)	TDMA	minimize the amount of re-engineering required by the service providers
Japan (P.D.C.)	TDMA	ensure that Japan does not fall behind in cellular technology

Table 6.2: Summary of the reasons for choosing the access scheme

Although the same decision was made in the three parts of the world, the motivations in each case were very different. The next chapter addresses the wideband / narrowband decision.

Chapter 7

Wideband versus Narrowband Systems

Once a TDMA access scheme was chosen, the next issue was to determine the number of users multiplexed on each channel and the channel spacing to be used. Although there is no strict definition, wideband TDMA systems are generally considered to have at least 30 users per channel and have channel spacings greater than 1 MHz. Narrowband TDMA systems are traditionally those with less than 10 users per channel and have a channel spacing of less than 300 kHz.¹ Systems with channel spacings between 300 kHz and 1 MHz can be classified as either narrowband or wideband systems.

7.1 Trade-offs

There are two main advantages to narrowband systems. First narrowband systems can fit into a larger class of frequency bands, because the spectrum is broken up into smaller channels. They are, therefore more flexible. Narrowband systems also require less complicated equalization algorithms, because they are lower bit rate systems which have fewer bits potentially corrupted by multi-path fading. As a result less power is dissipated in the handset from the equalizer. Although in wideband TDMA systems, power is dissipated in a handset for a smaller percentage of the time than handsets designed for narrowband TDMA systems do, according to test results of the European systems in Paris, the narrowband TDMA systems dissipated less total power in the handsets than the wideband TDMA systems.²

1. Narrowband and wideband CDMA systems which are not discussed in this section are classified differently from narrowband and wideband TDMA systems. Narrowband CDMA systems have typically channels spacings smaller than 1.5 MHz and wideband CDMA systems have channel spacings greater than 5 MHz.

Narrowband systems can also have larger maximum cell sizes. This is because wideband systems have more noise in the channel since noise passing through a channel is proportional to the channel size. As a result, a signal can travel further in a narrowband system than in a wideband system before it is too heavily degraded and is not of acceptable quality. Consequently, maximum cell size in a wideband systems is less than that of a narrowband system. The higher the bandwidth of the channel, the lower the maximum radius of the cell. As a result, narrowband systems are more cost-effective for rural areas where the system is rarely used to capacity since fewer base stations are required for coverage.

Wideband systems, on the other hand, are more scalable. With higher rates per channel it is much easier to anticipate using a single channel for a high bandwidth data application in the future. Second, wideband systems have fewer receivers per base station because more users share one channel which only requires one receiver, base station costs are lower. Narrowband TDMA and wideband TDMA solutions both typically have the same minimum cell size and require the same number of base stations in densely populated areas. Wideband systems are therefore more cost-effective for the cities and narrowband systems are more cost-effective for rural areas.

2. Narrowband TDMA systems also dissipated less power in the handset than FDMA systems, which is consistent with the discussion in the previous chapter.

Advantages of a wideband system	Advantages of a narrowband system
Lower cost of base stations - more cost effective for cities	Large cell sites possible - more cost efficient for rural areas
Scalable for higher data rate applications	Less complicated equalization algorithms - more conducive to handportability
	Flexibility in fitting into a variety of different frequency bands

Table 7.1: Trade-offs between using narrowband and wideband system

7.2 Decision Making Process

	U.S.	Europe	Japan
Constraints on the system	30 kHz (D-AMPS) < 1.5 MHz (N-CDMA)	None	25 Khz

Table 7.2: The constraints on different cellular systems

7.2.1 Europe

The narrowband / wideband decision was most difficult technical decision to gain consensus on in Europe. The main wideband proposal was submitted by the joint S.E.L. / Alcatel consortium. In 1984 the French and German governments had decided to invest approximately \$25 million in joint research efforts to produce future cellular systems. The two governments wanted to leapfrog analog systems such as NMT and TACS that other developed countries had already introduced. Once the GSM initiative began the French

and German policy makers realized that instead of using their results for just a Franco-German standard, these systems could be the basis for the future pan-European digital cellular standard. Policy makers in France and Germany saw this as an opportunity to give their manufacturers an edge in the European common market.

Narrowband systems were developed by both the Scandinavians and the Franco-German alliance.

As manufacturers were developing these systems, it became clear that the various European P.T.T. operators had very different visions for the set of requirements which an implemented system should meet. For example, the British and the Scandinavians wanted a system with the capability of having very large micro-cells, to meet the mobile telephony needs of the rural north in a cost-effective way. Therefore the Scandinavians and the British were vehemently against the wideband proposal because they wanted to provide cellular coverage in the rural area as a substitute for wireline telephony. The French and the German proponents of a wideband system did not envision this system being used in the rural areas but wanted to have a system which could be operated on the Autobahn, or on high speed trains operating at 250 km/hr. Reconciling these different requirements was one of the big challenges in the wideband TDMA / narrowband TDMA debate.

After all of the systems were tested in Paris, it became clear that narrowband systems had a number of advantages. First, the proposed narrowband TDMA systems were more spectrally efficient than the wideband TDMA solutions. The proposed wideband TDMA systems used more spectrum per user and even though the required Carrier to Interference ratio was lower, not all of the lost capacity was regained due to spectrum reuse. A second advantage for the narrowband TDMA systems was that the overall infrastructure cost for an entire country is lower.

A third advantage of the narrowband system in Europe was their flexibility in being accommodated in the available frequency band. This was a critical constraint in places where analog systems were already being used in part of the 900 MHz region. The initial wideband proposal was for a 6MHz channel spacing, but in the United Kingdom only 5MHz channel spacings were available.

After the tests were completed, it seemed clear that narrowband TDMA was the appropriate solution. A further advantage of the narrowband approach was that it did not favor any national equipment manufacturer, unlike a wideband approach. However, the night before the vote the French and German ministers telephoned their representatives in Madeira where the vote was taking place to instruct them to try to block the narrowband TDMA decision. This was for industrial policy reasons. Clearly Alcatel and S.E.L. wanted to see their wideband adopted system and put pressure on their individual governments to block this particular vote. The vote eventually came out 13-2 in favor of narrowband TDMA. The C.E.P.T. adopted an 8 users per channel TDMA solution as a working assumption, a preliminary solution which could later be modified.

The 8 user per channel solution provides for scalability and time for mobile assisted handover but still also allows for hand-portability and is a cost-effective solution in both the cities and the rural areas. The standard makers stuck to a working assumption of a 200-300kHz channel spacing and stated that the final channel spacing would be resolved when the details of the standard was determined by one of the working groups. Because the G.S.M. system had to be designed for the worst case scenario, a relatively large amount of overhead is used to ensure the system is robust in many different operating environments. Figure 7.1 shows the frame and multiframe structure in GSM.

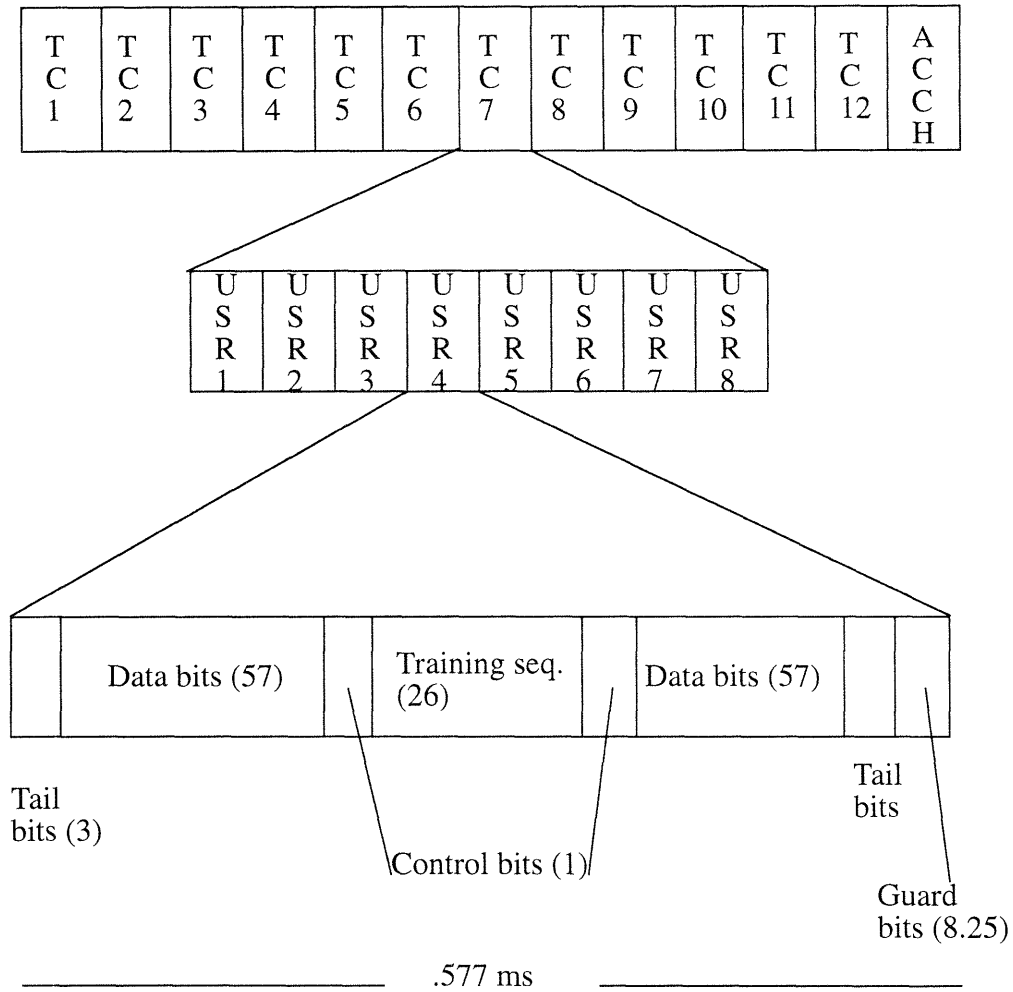


Figure 7.1: Frame and Multiframe structure in the G.S.M. system ¹

1. Partially taken from Shosteck. Technology Analysis. p. 124

	Bit Rate (kbps)
Speech Coder	13.0
Channel Coder	9.80
SAACH (used for mobile assisted handoff)	.95
Guard Time	10.1
Total	33.85

Table 7.3: Bit Rates for GSM system

Traffic channels consist of encoded data, and a training sequence to determine the coefficients for the equalizer. The SAACH bits are used to communicate air link quality information from the mobile to the base station. The guard band is to separate users in time from interfering with each other.

With these specifications and selected a GMSK modulation scheme (1.35 bits / Hz), a 200kHz channel would support 8 users per channels.

The next task was to get the French and the Germans to agree to this decision. Members of the CEPT and the European equipment manufacturers met in Bonn in March 1987 to convince the French and German ministers of the advantages of a narrowband system over a wideband system. The narrowband TDMA proposal also incorporated frequency hopping which had been proposed by the French and forward error correction channel coding. Both of these techniques improve the quality of the air interface link and therefore lower the required carrier to interference ratio to 9 dB from 11 dB, increasing the cell reuse factor and improving the spectral efficiency of the system.

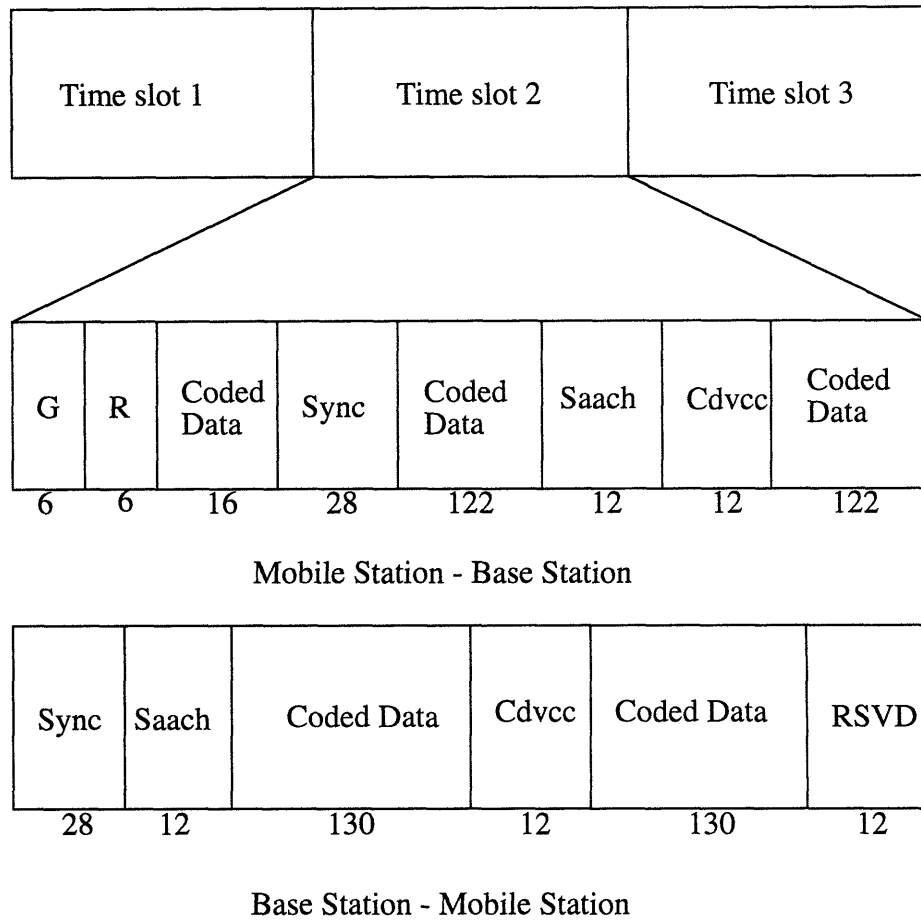
Although the engineers in France and Germany agreed that this new system was better than the wideband system, they were instructed not to voice their opinions. In the end, however, the French and German ministers had no choice but to support the pan-European narrowband system. Not doing so would increase development costs and the national equipment manufacturers sales and profitability. In May 1987, the British, French, German and Italian ministers signed an agreement to adopt narrowband TDMA for the G.S.M. systems.

7.2.2 The U.S.

In the United States the decision makers based their choice of the channel spacing on very different factors. Instead of determining a certain set of requirements and then designing a system to match those specifications, the D-AMPS system was mandated by the Cellular Telecommunications Industry Association (CTIA) use the existing analog channels. This was to ensure that all cellular service providers are able to do gradual channel by channel replacement of analog base stations with digital base stations. This requirement also minimized the amount of reengineering needed because the cell-reuse patterns of D-AMPS and AMPS could be designed to be the same.

Qualcomm's N-CDMA solution combines 42 analog channels to make one narrowband (1.25 Mhz) CDMA channel, which is shared by 20-30 users. Qualcomm's N-CDMA system is not as conducive to channel by channel replacement as the D-AMPS solution. This is because a service provider must replace 42 (1.26 Mhz) analog channels with a single digital channel. However, Qualcomm and nine of the U.S. service providers believe that the increased spectral efficiency and lower costs of N-CDMA outweigh the disadvantages of the loss of flexibility of using a wideband solution.

a



G - Guard Time Cdvcc - Digital Color Code
 R - Ramp up time Saach - Slow Associated Cnl. Ch.
 RSVD - Reserved Bits

Figure 7.2: The American Digital Cellular Air Interface Characteristics

Figure 7.2 illustrates the contents of the transmitted and received frames for the D-AMPS standard. Unlike G.S.M., all of the control and signaling information is interleaved with the traffic information in the same time slot. The guard band is used to separate the different users sharing the same channel from each other by a set time interval. The Saach

is used to communicate air link quality information between the handset and the base station. The synchronization bits are used to sent to select the appropriate equalizer coefficients.

	Bit Rate (kbps)
Speech Coder	7.95
Channel Coder	5.05
SACCH	.60
Guard Time	2.6
Total	16.2

Table 7.4: Bit rates in the D-AMPS standard

Each channel is 30 kHz which supports 48.6 kbps using the Quadrature Phase Shift Keying modulation scheme (1.62 bits / Hz). Therefore each 30 kHz channel can support 3 users per channel.

Because D-AMPS uses a narrower channel spacing and a lower bit rate than G.S.M., it requires a less complicated equalizer. However, it is also not as scalable to higher data rate applications. Unlike the designers of the G.S.M. standard in Europe, scalability was not as important to the designers of the D-AMPS standard because they saw D-AMPS as an interim solution, which would be replaced by more advanced technology in the future.

7.2.3 Japan

The M.P.T. also wanted to ensure that digital services could gradually replace all analog services in Japan. To facilitate channel-by-channel replacement, the Japanese required the spacing of digital systems to be a multiple of 25kHz, the analog channel spacing.

Both narrowband and wideband solutions were presented in the T.T.C. One reason the narrowband approach was chosen was because it minimized the complexity of the system. First, like the Scandinavians and the British, the Japanese wanted to design a standard which was conducive to handportability. Therefore an important design requirement was to minimize the power dissipation in the handsets to make the phones as light as possible. Using a narrowband system makes an equalizer unnecessary in the Japanese standard, and therefore reduces the power consumption in the system and increases the battery lifetime of the system. Furthermore, because a narrowband system was less complicated it would reduce the equipment manufacturers time to market and therefore generate more revenue for the equipment manufacturers.

One disadvantage of adopting a low bandwidth system is that it is not scalable to higher bit rate applications. However, the penetration of computers in Japan is significantly lower than in the rest of the developed world and the use of a high bandwidth system to support higher data rates was therefore not given as high priority as it was in Europe.

I speculate, however, that a narrowband system may also have been chosen for trade policy reasons. By selecting an air interface standard which was similar to the U.S. D-AMPS standard, the Japanese equipment manufacturers could use the expertise they had developed from manufacturing D-AMPS terminals, and reduce their time to market in Japan. On the other hand, by selecting an air interface which was different and ensuring that P.D.C. was a unique Japanese standard, the Japanese could more easily protect its own national equipment manufacturers. Only three foreign equipment manufacturers are manufacturing for P.D.C. today, AT&T, Motorola, and Ericsson. If G.S.M. or D-AMPS had been chosen as the Japanese technical standard, many more foreign equipment manufacturers would have been vying for market share. This would have put even more pressure

on the Japanese government to open up the market. Establishing a unique Japanese standard reduced the number of foreign manufacturers interested in selling telecommunications equipment in the Japanese market.

One question which remains is why the Japanese did not choose to model their air interface standard after G.S.M. I speculate that this is because the Japanese understood the D-AMPS technology better than G.S.M., because they had actively participated in the air interface standard setting process in the U.S. whereas only the European operators and equipment manufacturers had participated in the G.S.M. standard setting process.¹

Of the three second generation systems which I compared, the Japanese system is the most spectrally efficient. This is primarily because a more efficient speech coder is used because the system was developed later.

	bit rate (kbps)
Speech Coder	5.95
Channel Coder	5.25
SAACH / overhead	2.0
Total	14.2

Table 7.5: Bit rates for the Japanese P.D.C. standard

Table 7.6 summarizes the channel spacing decisions and the associated reasons. The next chapter compares the speech coding technologies.

1. It is interesting to note that the networking protocols in P.D.C. are actually very similar to those in G.S.M. Part of the reason for this might be because these were determined in ETSI when the standard setting process open to foreign equipment manufacturers.

Chapter 8

Speech Coders

8.1 Technology

As discussed in chapter 4, the speech coder is designed to reduce the number of bits required to represent a voice signal. As technology improves speech coders are able to use fewer bits to represent a signal with an acceptable level of voice quality. There are three main types of speech coders, linear predictive coders which use predictive algorithms to estimate certain future data based on past and current data, waveform coders which sub-sampling the signal in the different frequency bands and hybrid coders which combine LPC and waveform coding techniques. These are described in detail in chapter 4.

8.2 Decision Making Process

8.2.1 Europe

In 1985, the CEPT decided to hold a contest to determine the algorithm to be used for the speech coder. Each country was permitted to submit one design with a gross bit rate of 16 kbps. This was later lowered to 13kbps. Waveform coders were submitted by Norway, Italy, Sweden and the U.K. Germany and France submitted the predictive coders. The results of the tests in Turin, Italy in October 1986 were 1) the German P.K.I. coder, 2) the French (I.B.M.) coder, 3) the Swedish coder and 4) the British Telecom (British) coder.¹ The Italian and Norwegian coders did not have an acceptable level of voice quality so they were both disqualified from the competition.

1. Interview with Hans Hermanson, Stockholm Sweden, March 1995.

The GSM Committee then used the test results to determine the final standard by combining the best aspects of the remaining 4 coders rather than just adopting the best coder. The French and the Germans then collaborated and developed a hybrid source coder, the Regular Pulse Excited Long Term Predictor (RPE-LTP), which combines the P.K.I. and the I.B.M. technology. This proposal combines the short term predictor and the regular pulse excitation aspects of the P.K.I. coder with the long term predictor aspect of the IBM coder.¹ As shown in figure 8.1, the short term predictor uses the average harmonic and tonal component using 8 digital filter coefficients. Sample predictability is expressed in a correlation coefficient. The long term predictor estimates pitch and gain at 5 millisecond intervals by using the past 65 samples to estimate each sample point. Time information is then expressed in a residual excitation sequence which is fed in as the source to the short term and long term filters.

The British and the Swedish responded by making plans for a joint Anglo-Swedish waveform coder to compete with the Franco-German coder. However, after the Madeira meeting in February 1987, Stephen Temple of the Department of Trade and Industry in the U.K., orchestrated a compromise that involved adopting narrowband TDMA technology and the Franco-German voice codec. This would make it easier for the French and German ministers to join the narrowband TDMA camp. Therefore the Anglo-Swedish coder was never actually developed.

1. The other aspects of the I.B.M. coder were protected under an AT&T patent and therefore were not used in the standard since the committee members wanted to avoid dealing with intellectual property issues.

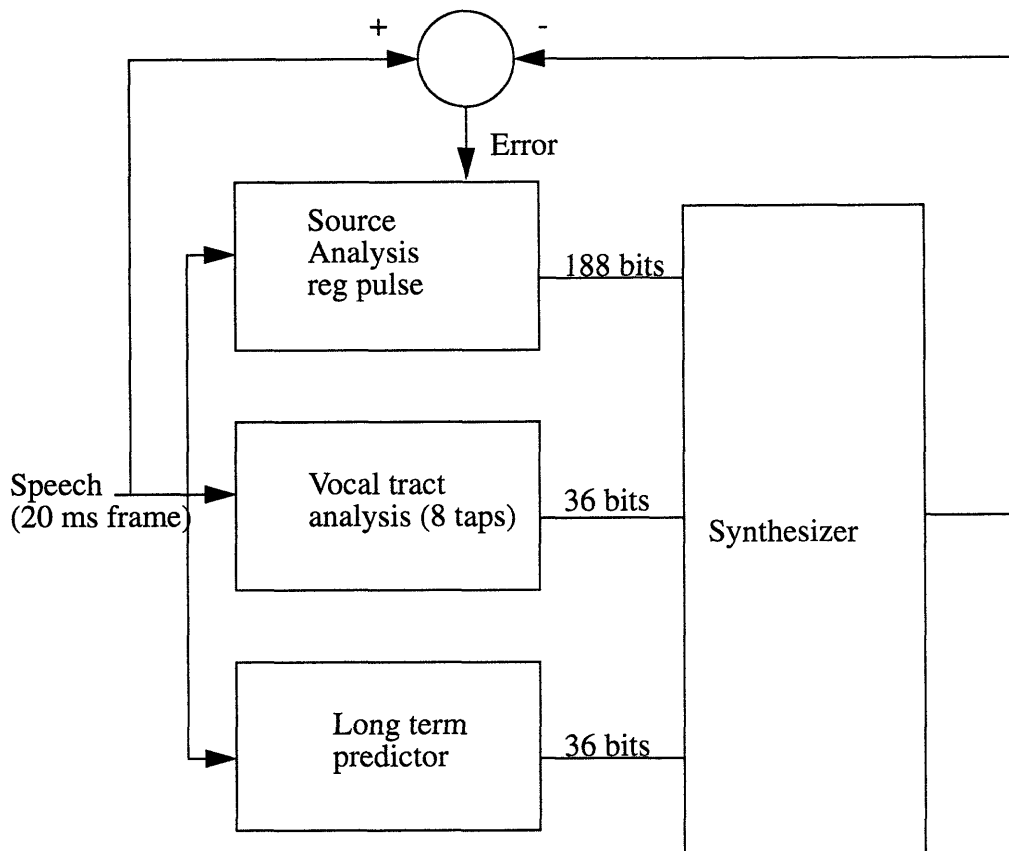


Figure 8.1: The speech coder algorithm for G.S.M.

8.2.2 The U.S.

In the United States there was a straight competition to determine the best voice codec for the D-AMPS standard. Unlike the European model, the speech coder decision was made independent of the other air interface decisions and was not a part of any higher level compromise.

By the U.S. standards, the voice coder in the G.S.M. system was not efficient enough to meet the growing capacity needs of many of the U.S. cellular service providers. Before

the competition the participants jointly decided to have a 13kbps channel for both speech and channel coding.¹ The criteria for evaluation of the codecs were primarily the voice quality and the complexity of the system (because using cost would have violated an anti-trust law).² Voice coders were then submitted by Northern Telecom, Ericsson, Hughes, PCSI, Motorola, AT&T, I.B.M., N.E.C. and G.E. Sample tests were conducted at Bell Northern Research and Simon Frazer University. The codecs from Motorola, Ericsson, Northern Telecom and General Electric all had acceptable levels of voice quality. However, the participants agreed to adopt the technology with the highest score on the test. Therefore the Motorola technology was selected as the D-AMPS voice codec standard.

The Motorola technology used an algorithm called vector sum excited linear prediction algorithm. There are several differences between the G.S.M. coder and the D-AMPS coder. First, the excitation used is a form of codebook excited linear prediction rather than a regular pulse excited predictor. Second, a greater number of taps is used on the short term filter in the D-AMPS standard. The main difference, however, is the efficiency of the speech coder. The output of the speech coder for G.S.M. is 13 kbps whereas the output for the D-AMPS standard is 7.95 kbps. This is primarily because the codec for D-AMPS was designed 2-3 years after the codec was designed for G.S.M. Because the rate of change of speech coding technology is high, a lower bit rate could be used increasing the spectral efficiency of the system.³

Qualcomm has also developed its own set of voice coders for its CDMA system which have bit rates from 4kbps to 13 kbps.

1. G.S.M. used 22.8 bits for speech and channel coding.

2. Interview with Howard Lester, G.E., January 1995.

3. Because G.S.M. has a less efficient speech and channel coding and modulation scheme, G.S.M. requires 25 kHz / voice path (200 kHz / 8 voice paths) where as D-AMPS only requires 10 kHz / voice path (30 kHz / 3 voice paths).

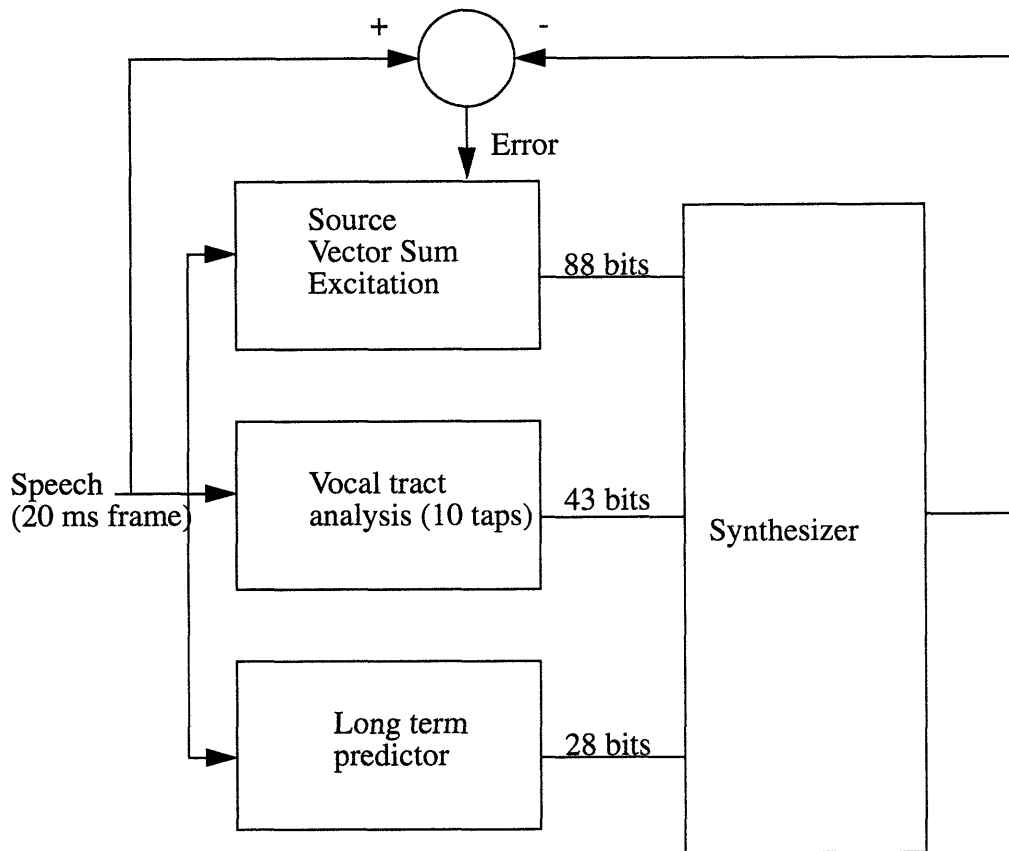


Figure 8.2: The speech coder algorithm for D-AMPS

8.2.3 Japan

The Japanese also decided to use a competition to determine the appropriate voice codec standard. Codecs were submitted to Research Center for Radio Systems (RCR) by NEC, Ericsson, Motorola, Toshiba, NTT, Matsushita, Mitsubishi Electric, and Fujitsu. The evaluation criteria were also modeled after that set by the Telecommunications Industry Association in the U.S. Motorola repeated its voice codec victory in the Japanese competition with a vector sum excited linear predictor (VSELP), a similar algorithm to that used in the United States with a bit rate of 5.95 kbps. VSELP technology uses code book

parameters to generate the both the source and the filter information. This method, uses less total memory and provides improved error tolerance relative to code book prediction techniques. Because speech coding technology has been improving over time, and the Japanese were the last to set their speech coding standard, the Japanese used a lower bit rate than both G.S.M. and D-AMPS standard in the U.S.¹

Motorola's victory in this contest market marked the first time any foreign technology had been directly incorporated into a Japanese standard. This gave Motorola both an additional prestige factor as well as a competitive advantage in selling digital phones on the market, because its product development time was shortened. As a result Motorola has gained approximately 30% of the digital handset market in Japan.

	Year standardized	Bit rate (kbps)
Europe (G.S.M.)	1987	13.0
United States (D-AMPS)	1989	7.95
Japan (P.D.C.)	1991	5.95

Table 8.1: The correlation between the timing of the standard and the bit rate of the speech coders

As described in table 8.1, there is a clear correlation between the rate of the speech coder and the time at which it was developed. This chapter illustrates the advantages of being a late-mover in standard setting. The later a technology is standardized the more advanced the technology will be. However, in the next and final chapter I will argue that for a technology to be successful it must be introduced as early as possible. I will argue that the benefits of early standardization outweigh the drawbacks of locking into an older technology.

1. The P.D.C. standard uses 8.33 kHz / channel and therefore is the most spectrally efficient of the three systems

Chapter 9

Conclusion

	U.S.	Europe	Japan
Consumers	**	**	
Equipment Manufacturers	**	**	**
Service Providers	****	**	****
Government		****	****

Table 9.1: Whose perspectives were important?

	U.S.	Europe	Japan
Single versus multiple standards	Government	Government	Government
Spectrum Allocation	Government	Government	Government
Channel Spacing	Service Providers / Manufacturers	Service Providers	Government / Service Providers
Access Scheme	Manufacturers / Service Providers	Service Providers / Manufacturers	Government / Service Providers
Voice Coder	Manufacturers	Manufacturers	Manufacturers

Table 9.2: Who made the decisions?

9.1 What is a successful standard setting process?

How can we evaluate the relative success of the standard setting process in each part of the world? I would argue that a successful process is one which continually produces standards with high domestic and international market penetrations. Equipment manufacturers generate more revenues from increased sales both domestically and internationally. Consumers gain the advantages of interoperability and can purchase handsets at lower prices because of economies of scale. Service providers have more domestic customers using their network and therefore generate larger profits and can also offer customers lower prices. Although the service providers only directly benefit from domestic market penetration, national equipment manufacturers directly benefit from higher international market penetration levels as well because it provides an additional source of revenue.

However, the standard setting process must be designed such that it not only promotes high market penetration of a nation's standards today but it also promotes high penetration of a nation's standards in the future. This requires that equipment manufacturers and service providers are in a position to not only work with the current standards but also develop future technologies which exploit technological improvements. Achieving both of these objectives requires a nation's service providers and equipment manufacturers to set a standard as quickly as possible to gain a first mover advantage, but also use the time between standards to monitor the technologies around the world to ensure that they are in the best position to adopt the most advanced technology in the next generation systems. If that technology is developed abroad, the service providers and equipment manufacturers must find a way to import it and use it in the next generation of standards. This strategy

will ensure that a nation’s equipment manufacturers, service providers and consumers can exploit the advantages of standardization, but also ensures that a nation does not fall behind by locking into obsolete technologies. The governments in each part of the world must adopt a process which ensures that both of these objectives are met.

Criteria for a Successful Standard Setting Process
high market penetration rate of the current standard
high market penetration rate of future standards

Table 9.3: Criteria for a successful standard setting process

9.2 The U.S.

In the United States, D-AMPS technology was introduced in 1992. Today it has 250,000 subscribers or 1% of the analog market penetration rate. Qualcomm will also introduce the N-CDMA technology at the end of this year, which nine of the twelve service providers have indicated they will adopt in the 800 MHz band. Although we do not yet know how successful N-CDMA will be for cellular services, D-AMPS clearly has not yet proven to be successful. The next section describes the effect of the F.C.C.’s technical flexibility ruling on the equipment manufacturers, the service providers and the customers.

9.2.1 The Service Providers

In the United States, the technical flexibility ruling was favored most by the service providers. Before the D-AMPS specifications were defined the Cellular Telephone Indus-

try Association (CTIA), the trade organization of U.S. service providers, mandated that all digital telephones be dual-mode to ensure backward compatibility with analog systems. Under the technical flexibility ruling, cellular service providers could use different technologies in different markets depending on the capacity constraints. The CTIA also mandated that the channel spacing for the D-AMPS standard be the same as the analog AMPS channel spacing. Service providers could also easily make the transition between AMPS and D-AMPS systems because the cell reuse factor was designed to be the same. Many service providers, however, decided to wait until a more cost effective technology emerged and used advanced analog systems to meet the capacity constraints in the meantime. In the end, introducing a number of competing digital solutions has caused confusion in the market. As a result, service providers in the U.S. have not been able to exploit the capacity advantages of digital cellular since its introduction.

9.2.2 Equipment Manufacturers

Most U.S. equipment manufacturers also did not benefit from these decisions. Equipment manufacturers have had to manufacture equipment to meet multiple standards. As of today, equipment manufacturers have not been able to sell large quantities of digital cellular equipment based on U.S. standards either in the U.S. or overseas. This is partly a consequence of the CTIA mandate that the handsets be dual-mode, making the cost of a digital handset 20-30% higher than the cost of an analog handset.

The only equipment manufacturer which may have benefitted from this decision is Qualcomm because it gained the opportunity to develop CDMA technology for second and third generation services. We can speculate that if Qualcomm had tried to sell CDMA as the access scheme standard in the T.I.A., the other equipment manufacturers might have

opposed it. In addition, CDMA technology was not mature enough to be adopted as a technical standard when the TIA decisions were made in 1989 and 1990. CDMA could become the world wide standard for future radio services, and is not being commercialized by any European or Japanese equipment manufacturer. As of April 1995, CDMA has been sold as a cellular standard in 5 countries.¹

9.2.3 Customers

Customers have clearly not yet benefited from second generation digital cellular services. Digital telephones are more expensive, and have not yet provided the customer with any additional value added functions. For example, digital voice quality is not better than analog voice quality. Eventually, however, customers may benefit from CDMA if it turns out to offer more value added services at a lower cost. The jury is still out on this.

9.3 Europe

In Europe G.S.M. has been the most successful standard to date, with over 5.5 million users of the system world wide. However, the success of G.S.M. has not been uniform throughout Europe. G.S.M. has been most successful in places with poor analog networks such as in Germany or Portugal. 40% of G.S.M.'s 5.5 million subscribers are in Germany. On the other hand, in England, where TACS networks are very well developed, only 8% of Vodafone's² subscribers use G.S.M. Internationally, however, G.S.M. has been quite

1. Telephone Interview with Jim Madsen, Director of P.C.S. Services, Qualcomm, April 1995.

2. Vodafone is one of two British cellular service providers in the 900 Mhz region and one of three cellular service providers in the 1800 Mhz region.

successful. Today G.S.M. has been sold or will be sold in 80 countries including India and China (2.2 billion people).

9.3.1 Service Providers

However, as of May 1995 European service providers have had mixed results with G.S.M. As noted earlier, service providers in countries with strong analog networks have not benefitted as much from G.S.M. as the service providers in countries without analog networks at this time. However, European law has mandated that by the end of the century G.S.M. and D.C.S.-1800 will be only the cellular services offered in Europe. Service providers gain the benefits of increased revenues from a pan-European system, but are locked into a particular technology. For example, CDMA is not being offered as a solution in Europe. If CDMA is actually a much more cost-effective solution, the European service providers will miss out on CDMA for the next two generations of cellular services. They also probably will not be in a position to adopt CDMA for other wireless standards either because they have not developed it in their research laboratories.

9.3.2 Equipment Manufacturers

However, by establishing a pan-European system, The European equipment manufacturers have probably benefited most from these decisions because of the relatively large size and expected growth of the market both in Europe and overseas. GSM is selling successfully in overseas markets primarily because it was the first digital solution to be offered in the marketplace. In Europe, the only solution being offered is the one developed by the European equipment manufacturers and service providers. As a result, the Euro-

pean equipment manufacturers have 73% and 80% of the G.S.M. base station and handset markets. If G.S.M. can reach a penetration level of 2-3% in India and China alone, this will generate an additional 40-50 million subscribers of G.S.M. equipment. I speculate that 60-70% of the market will be captured by European equipment manufacturers. Being the first mover in digital cellular will continue to create additional markets overseas and generate large profits for the European equipment manufacturers.

However, European equipment manufacturers are not well positioned to manufacture CDMA if it becomes a world standard, because their expertise is in TDMA. Therefore they will in all likelihood lose out to Qualcomm and Motorola in all markets which adopt CDMA as the standard.

9.3.3 Customers

The customers in Europe have also benefitted from G.S.M. because it is now possible to be reached with one telephone number anywhere in Europe. Costs of G.S.M. service are approaching costs of analog service in Europe as penetration rates have been increasing.

9.4 Japan

In Japan, P.D.C. service has begun only recently and we do not yet know how successful the Japanese P.D.C. standard will be there. What we do know, however, is that the standard has not been adopted anywhere outside of Japan and is not likely to be in the future, primarily because it was introduced 2-3 years after D-AMPS and GSM and does not offer a significant improvement in spectral efficiency over either of these standards.

9.4.1 Service Providers

In Japan the service providers, primarily NTT, have benefited from the process because they have been able to control the outcome of the technology and maintain power and influence within the Japanese political sphere. By agreeing to adopt foreign standards, service providers would have abdicated their power and influence to the foreign standard setters and therefore would not have been able to play as strong a role in setting the direction of the telecommunications industry in Japan. Because the service providers and the M.P.T. still have such close ties, this is not likely to change in the near future.¹ The service providers are also not adversely affected by the failure of Japanese manufacturers to sell PDC internationally. Although the Japanese service providers like the Europeans have no plans to deploy CDMA in the near future, I speculate that it is more important for the Japanese service providers to maintain their role as the developers of telecommunications technology in Japan. Therefore I would argue that they are achieving their goals through the current process.

9.4.2 Equipment Manufacturers

The Japanese equipment manufacturers, on the other hand, have not fared as well as the service providers. One of the MPT's goals in introducing PDC was actually to help support the Japanese equipment manufacturers. The result, however, was the opposite. Within Japan, P.D.C. was just recently introduced so it is difficult to tell how successful equipment manufacturers will be in Japan. Japanese equipment manufacturers will probably capture 60-70% of this market.²

1. Interview with an N.T.T. official, May 1995. This comment was just his speculation.

However, in overseas markets the Japanese equipment manufacturers have not been successful at all. The Japanese equipment manufacturers do not have any of the G.S.M. base station or handset market share in Europe. In the U.S. they have captured a fraction of the D-AMPS handset market and have not been successful at all in the D-AMPS base station market. Traditionally, Japanese manufacturers have been late comers to the market, but have mastered the art of manufacturing those technologies. In technologies where the lifetimes of the products and the standards is long such as consumer electronics, this strategy has worked quite well. However, in industries where the rate of change of technology is very high, being a last-mover in standard setting prevents Japan from selling its standards overseas and forces it to compete in foreign markets using other nation's standards. By the time the Japanese equipment manufacturers master the current generation technology, a new set of standards has emerged in the market. I speculate that if CDMA succeeds in the United States as many analysts expect it will, the Japanese equipment manufacturers will be even less successful in the U.S. market because other companies such as Qualcomm have much stronger expertise in the technology.

In addition, the Japanese air interface standard was chosen to be similar to D-AMPS to help the Japanese equipment manufacturers leverage in the United States. However, D-AMPS will only be adopted for cellular services in the 800MHz band in the United States. Had the Japanese picked to model their standard after GSM, which is now being sold around the world, the Japanese equipment manufacturers would have been larger players in many more foreign markets where GSM is being sold.

2. This is my speculation based on market share data information for analog and the participants in the standard setting process. There were 10 active participants in the P.D.C. technical standard setting process of which 70% were Japanese equipment manufacturers.

9.4.3 Consumers

The Japanese consumers have also not fared well. Handset cost are 5 -7 times what they are in the United States and costs for service are 2 -3 times the cost in the U.S.

9.5 Recommendations

What can be learned from this experience that would help policy analysts in each part of the world improve their standard setting process? Our goal is design a process which maximizes the probability of high international market penetration in current and future standards. Mandating a single standard for each service maximizes the probability of success of the current standard. As noted earlier a single standard gives all of the benefits of interoperability and economies of scale. The nation which is able to introduce effective technologies early and aggressively market them overseas will most likely have the most successful standard for that generation of services. Both AMPS and GSM, the most successful first and second generation standards were mandated by the U.S. and European authorities to be single common standards.

However, we also need to ensure success of future standards. If the F.C.C. had mandated that there be only a single digital standard in the U.S., service providers would not have had the opportunity to use more spectrally efficient CDMA technology in the 800 MHz band. However, the next generation of services typically emerges within 4-5 years, making the current generation of services obsolete by that time. The government must mandate a single common standard today to maximize the current market penetration of the standard. The process must also ensure that improvements in technology can be incor-

porated into either the next generation cellular system or another wireless standard which perhaps was not designed to be scalable.

Recommendation	Justification
Set a single standard	Economies of scale, Roaming, Avoid market fragmentation
Set standards quickly	Exploit first mover advantage overseas
Bring in foreign technologies into the process	Ensure that a nation does not get stuck using obsolete technology

Table 9.4: Recommendations for Policy Makers

These three recommendations may seem to be contradictory, however must all be incorporated into the proposed solution to ensure the success of current and future standards. I would propose that all nations consider adopting dual-mode standards for the future. Dual-mode standards would allow a nation to exploit the advantages of standardization but also ensure that the process provides an incentive for companies to bring new technologies to the market as the second standard. One of these new technologies will be adopted as the next generation standard. The government must set a target date for when the next generation system will be standardized. Once again other companies can then introduce dual-mode products. This process will continue to repeat itself.

In the U.S. today dual-mode telephones cost about 30% more than analog telephones. As technology improves, this incremental cost of operating a system with multiple standards is decreasing. This will further increase the number of competing standards and will ensure that the best technologies come to market. Adopting dual-mode standards is one effective way of meeting both of our objectives.

This section describes the specific recommendations I have for each region's policy makers.

9.5.1 The U.S.

The strength of the U.S. process is that it stimulates the best technologies to come to market. The weakness is that having competing technologies confuses the market and stifles its growth. Adopting a dual-mode standard in the United States would continue to bring new technologies to the market, but would also allow consumers, service providers and equipment manufacturers to gain the advantages of standardization.

9.5.2 Europe

The European operators have been quite successful at implementing a single standard in Europe and aggressively selling it overseas. GSM will probably be the most successful second generation standard. However, the European operators and equipment manufacturers need to ensure that they adopt standards with the most advanced technology. Dual-mode standards would provide an incentive for domestic or foreign companies to introduce new technology.

CDMA technology either needs to be developed in the European equipment manufacturers' laboratories or it needs to be imported from the U.S. One effective way of importing it would be for a European equipment manufacturer to form a joint venture with Qualcomm. This would give the a European equipment manufacturer expertise in CDMA to establish a future CDMA standard in Europe if not for cellular for some other wireless

service. In addition the European manufacturers would be able to sell CDMA equipment overseas. Another way would be to allow Qualcomm to play a large role in the next wireless standard developed by ETSI. This would ensure that the Europeans are not left behind if CDMA becomes the world standard.

The European process needs to be altered such that it creates an incentive for new technology to be introduced in Europe. The dual-mode standard provides such an incentive. This technology does not necessarily need to be used in the next generation cellular system, but it can be used for other wireless services which require standards.

9.5.3 Japan

The M.P.T. in Japan has also been quite successful at ensuring that Japan has a single standard. However, like the Europeans the Japanese have not been very successful at stimulating new technology. I would recommend that the MPT and N.T.T. ensure that the Japanese equipment manufacturers gain access to CDMA because of its market potential for radio services in Japan and overseas. Perhaps NTT could do this by forming a joint venture with Qualcomm to develop CDMA technology for another wireless standard. A dual-mode standard would provide the opportunity for new players to test these new technologies. A dual mode standard would allow the Japanese to become experts in a number of different technologies rather than be forced to try to pick a winner.

I would also recommend that Japan attempt to introduce its standards either at the same time as or before the U.S. and Europe introduce their standards. Doing so would give the Japanese equipment manufacturers a chance to sell their standard in developing countries before the Americans and the Europeans have already sold their standards.

	Mandating single standard	Promoting new technology	Being a first mover
U.S.		****	**
Europe	****	*	****
Japan	****		

Table 9.5: How well are the players doing now?

In summary, the government must do three things to maximize the probability of having a successful standard. First, it must mandate a single standard. Second, it must ensure that all technologies from around the world are being considered so that the best possible technical standard. Third, it must set the standard as quickly as possible and help its national equipment manufacturers sell the standard overseas. Introducing dual-mode standards addresses all three of these issues. National standards from governments which follow these principles will be most likely to succeed.

Appendix A

Spectral Re-use Factors

The minimum C / I ratios required to maintain sufficient voice quality, varies from one system to another because of the different coding and error correction techniques that are used in each case. For example, G.S.M. uses a 22.8 kbps channel (voice and coding) and D-AMPS uses only 13 kbps (voice and coding). Although G.S.M. requires more digital capacity per channel it has a higher spectrum re-use factor because it is a less sensitive to bit errors and higher levels of interference. In addition, other techniques in digital systems can be used to reduce the required C / I ratio such as frequency hopping, antenna diversity, and interleaving in time. All of these techniques either provide redundancy at the receiver or distribute the information in frequency or time making the information less susceptible to burst errors due to fading.

System	Required C / I ratio with antenna diversity (db)	Required C/I ratio without antenna diversity (db)
D-AMPS	12	16
G.S.M. (frequency hopping used not antenna diversity)	9	11
Japanese Digital Cellular	13	17
AMPS	N/A	18

Table A.1: C/I ratios for different digital cellular systems

In G.S.M. cell sector size is 3 cells / sector and in A.D.C. and J.D.C. it is 4 -7 cells per sector and AMPS also has 7 sector reuse. The cell sector size is proportional to the mini-

mum carrier to interference ratio required. The effectiveness of cell reuse can be measured by the number of cells in a sector because the fewer the number of cells in a sector, the more the same frequencies can be reused. A more effective cell reuse pattern creates a more spectrally efficient system. Over time, engineers have developed techniques for reducing the time required for hand-off and reducing the level of co-channel interference. As a result, cell site sizes have gotten smaller, allowing for greater spectral reuse and more spectrally efficient systems.

The following data shows how efficiently spectrum is used in the G.S.M., A.D.C., and the P.D.C. standard. Both the amount of bandwidth per channel and the sector reuse factor are factored into the spectrum efficiency calculation.

	Channel Spacing	Number of Voice paths / channel	Cell reuse factor	Number of voice paths in 25 Mhz
A.M.P.S.	30 Khz	1	7 cells	119
G.S.M.	200 Khz	8	3 - 4 cells	250 - 333
A.D.C.	30 kHz	3	4 - 7 cells	357 - 625
P.D.C.	25 kHz	3	4 - 7 cells	428 - 750

Table A.2: Relative spectral efficiency

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Interviews

Many of the stories told in this thesis were not written anywhere. To tell these stories, I went to each of the three regions, the U.S., Europe and Japan and met with the following people. The following list consists of both the telephone and personal interviews conducted.

U.S.

Jim Madsen - Qualcomm
Kevin Kelley - Qualcomm
Barry Kratz - Ericsson
Krister Raith - Ericsson
Peter Nurse - AT&T
John Marino - AT&T
Howard Lester - G.E.
Tony Akers - Motorola
Mike McGlauglin - Motorola
Bill Blackburne - Northern Telecom
Paul Coverdale - Northern Telecom
Peter Pitsch - F.C.C (formerly)
Mike Ferrante - F.C.C.
Steve Markendor - F.C.C.
John Reed - F.C.C.
John Williams - F.C.C.
Lex Felcher - F.C.C. (formerly)
Donna Cutshaw - CTIA
Erik Schimell - TIA
Barry Yumansky - National Association for Broadcasters (NAB)
Hershall Shosteck - Hershall Shosteck Associates

Europe

Mike Short - Director of MOU
David Hendon - Department of Trade and Industry (DTI), U.K.
Stephen Temple - DTI, U.K.
Armin Silberhorn - Ministry of Telecommunications, Germany.
Christopher Corbett - ETSI
Alan Cox - Vodaphone, U.K.
Phil White - Vodaphone, U.K.
David Barnes - Cellnet, U.K.
Robin Potter - Mercury 1-1, U.K.
Phillipe du Puis - France Telecom (formerly)
Alain Maloberti - France Telecom
Thomas Haug - Telia Mobile Research, Sweden
Osten Makitallo - Telia Mobile Research, Sweden
Gunnar Fremin - Telia Mobile Research, Sweden
Mats Nilsen - Telia Mobile Research, Sweden
Per Bjorndandal - Ericsson
Jan Uddenfeldt - Ericsson
Gunnar Sandegren - Ericsson
Hans Hermanson - Ericsson
Hokan Ericson - Ericsson
Mats Nilsen - Ericsson
Nygel Cawthorne - European Mobile Communications
Julian Herbert - European Mobile Communications

Japan

Masayoshi Wakao - RCR
Kohei Habara - TTC (formerly)
Takeo Ohgane - MPT (formerly)
Kohei Satoh - NTT Do Co Mo
Nobuo Nakajima - NTT Do Co Mo
Yutaka Kodaira - NTT
Norishige Morimoto - IBM Japan

David Hytha - Nippon Motorola
Katsushi Oshiden - Mitsubishi Research Institute
Seichi Sampei - Professor Osaka University
Keith Henry - MIT Japan Program - Tokyo
Akira Kowase - Gemini Consulting
John Stern - American Electronics Association
Jeff Camp - Jardine Fleming Securities

