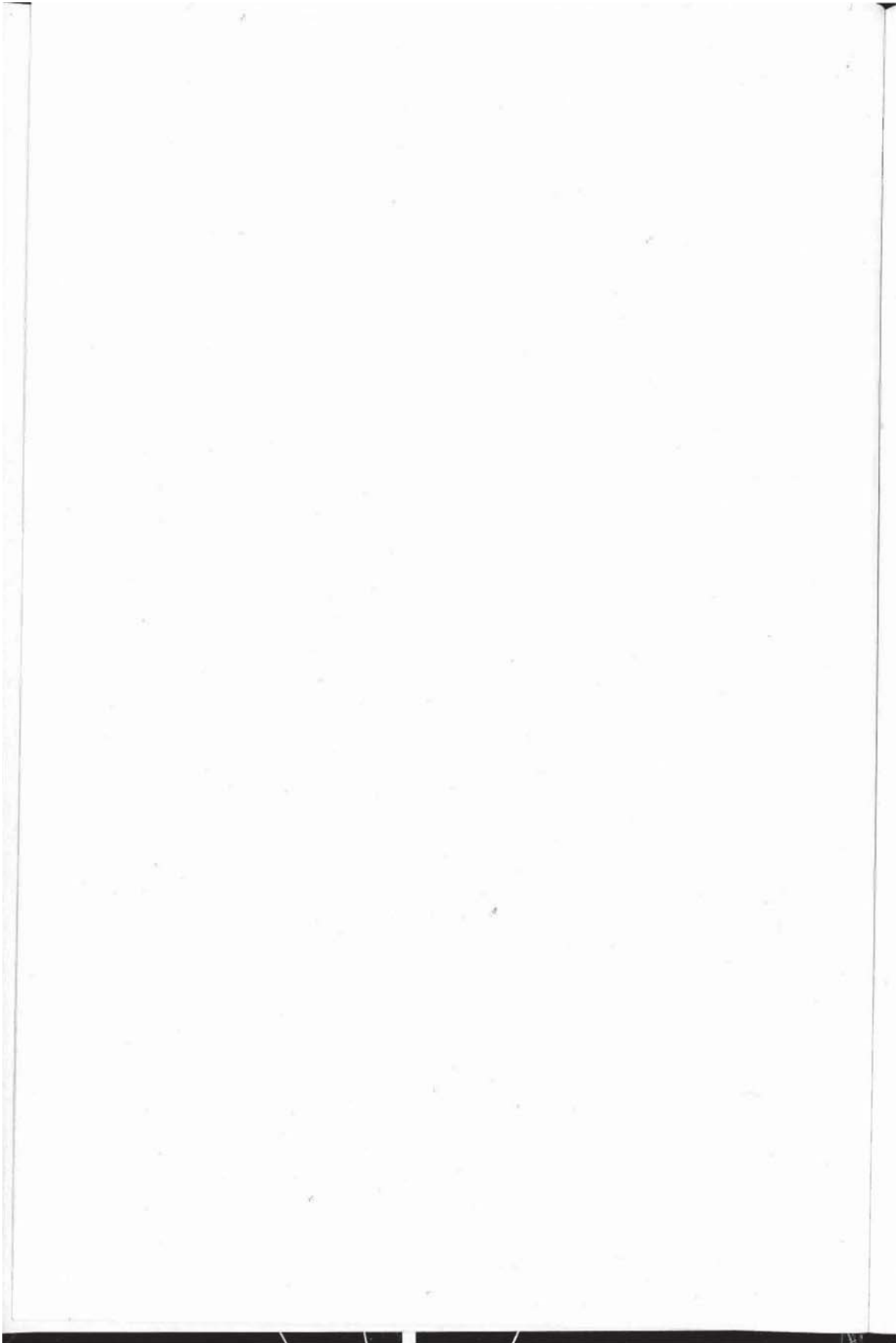


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Contents

Preface	xi
Acknowledgments	xiii
Part I Introduction	1
CHAPTER 1 THE UNCERTAIN FUTURE OF MOBILE TELEPHONY	3
1.1 Marconi <i>versus</i> Bell	3
1.2 The Unique Failure of Mobile Telephony	7
1.3 The Cellular "Disaster"	12
1.4 The "Digital" Panacea	17
Part II The Age of FM	21
CHAPTER 2 MOBILE RADIO BEFORE CELLULAR: 1921-1968	23
2.1 The Pioneer Phase: 1921-1945	23
2.2 The Commercial Phase: 1946-1968	29
CHAPTER 3 THE CELLULAR IDEA: 1947-1982	39
3.1 The Evolution of the Cellular Idea	39
3.2 The Struggle for Spectrum: 1947-1970	45
3.3 Industry Politics: 1970-1982	49
3.4 Competition and the Changing Regulatory Agenda: 1970-1982	54
CHAPTER 4 CELLULAR REALITIES	63
4.1 The Cost Syndrome	68
4.1.1 Mobile Equipment Economics	68
4.1.2 Cellular System Economics	72
4.1.2.1 System Overhead Costs (Hardware)	74
4.1.2.2 Start-Up and Operating Costs	83
4.1.2.3 Cellular Pricing	86
4.2 The Performance Syndrome	92

4.2.1	Coverage Problems	93
4.2.2	Call-Processing Problems	98
4.2.3	Privacy and Security	103
4.2.4	Data Transmission	111
4.3	The Spectrum Efficiency Syndrome	113
4.4	The Licensing Syndrome	120
4.4.1	The Comparative-Hearings Phase	121
4.4.2	The Lottery Phase	124
4.4.3	Speculation	129
4.5	The End of an Era	134
Part III Digital Communication: The Basics		141
CHAPTER 5 THE REEMERGENCE OF DIGITAL COMMUNICATION		143
5.1	The Analog Revolution	143
5.2	The Digital Resurgence	146
CHAPTER 6 THE DIGITAL VOCABULARY		151
6.1	The First Coding Stage: A/D Conversion	154
6.1.1	Sampling	154
6.1.2	Quantization	158
6.1.3	Coding	160
6.2	The Second Coding Stage: Modulation	164
6.3	Transmission and Signal Processing	168
6.3.1	Regeneration: The "Conquest of Distance"	170
6.3.2	Control of Intersymbol Interference: Recovery of the Physical Code	174
6.3.3	Error Control: Recovery of the Logical Code	177
6.3.4	Multiplexing	178
CHAPTER 7 THE ADVANTAGES OF DIGITAL COMMUNICATION		185
7.1	The Digital Network	187
7.2	The Digital Network Is Robust	188
7.3	The Intelligence of the Digital Network	190
7.4	The Flexibility of the Digital Network	192
7.5	The Digital Network Is Generic	192
7.6	The Efficiency of the Digital Network	193
7.7	Security and the Digital Network	193
7.8	The Digital Network Is Dynamic	194
7.9	The Integrated Digital Network	195
Part IV Design Challenges for Mobile Telephony		197
CHAPTER 8 DESIGNING FOR THE MOBILE ENVIRONMENT		199

8.1	The Vocabulary of Radio	202
8.2	The Fate of the Radio Wave	206
8.2.1	Free Space Loss	206
8.2.2	Blockage (Attenuation)	207
8.2.3	Multipath	212
	8.2.3.1 Delay Spread	214
	8.2.3.2 Rayleigh Fading	216
	8.2.3.3 Doppler Shift	220
8.3	Effects on System Performance	221
8.3.1	Path Effects	221
8.3.2	System Effects	222
8.4	Traditional Countermeasures	225
8.4.1	Fade Margins	225
8.4.2	Diversity	226
8.4.3	Supplementary Base Stations	229
8.5	Digital Countermeasures	229
8.5.1	Robust Voice Coding	231
8.5.2	Robust Modulation	232
8.5.3	Adaptive Equalization	232
8.5.4	Error Correction	235
CHAPTER 9 DESIGNING FOR FREQUENCY REUSE		239
9.1	The Engineering Implications of Frequency Reuse	240
9.2	Interference-Limited Systems	242
9.3	Cochannel Interference and the Mobile Environment	244
9.4	The Relationship Between Geographical Separation and the Reuse Factor	249
9.5	The Effect of Reduced C/I Requirements for Digital Systems	251
CHAPTER 10 OTHER DESIGN CONSIDERATIONS		255
10.1	Designing for Modularity and Geographical Flexibility	256
10.1.1	Example: Adjacent Channel Utilization	257
10.1.2	Example: Modularity and Growth	259
10.2	Designing for Low Cost	259
10.3	Designing for Compatibility with Future Network Services	260
10.4	Designing for a Competitive Marketplace	262
10.4.1	Future Proofing	262
10.4.2	Competition Among Operators	263
Part V Technological Alternatives for the Next Generation		265
CHAPTER 11 THE BROAD TECHNOLOGY ALTERNATIVES		267
11.1	The Flexibility of Digital Design	268
11.2	The Flexibility of Digital Formats	269
11.3	Analog <i>versus</i> Digital	274

11.4 Wideband <i>versus</i> Narrowband Systems	276
11.5 Multiplexing and Access Technique: FDMA <i>versus</i> TDMA <i>versus</i> CDMA	283
11.6 System Control Structures: Centralized <i>versus</i> Distributed Control	290
11.6.1 Nets	290
11.6.2 Interface Point	294
11.7 Summary of General Directions of the Next Generation	294
CHAPTER 12 ALTERNATIVES FOR THE RADIO LINK	297
12.1 Analog Techniques	298
12.1.1 Narrowband FM	298
12.1.2 Single-Sideband Modulation	299
12.2 Digital Techniques	303
12.2.1 Digital Modulation for Mobile Radio	304
12.2.1.1 Spectral Efficiency and Multilevel Modulation	304
12.2.1.2 Narrow Power Spectrum	309
12.2.1.3 Intersymbol Interference	312
12.2.1.4 Modulation Strategies	316
12.2.2 Voice Coding for Mobile Radio	317
12.2.2.1 Coding Strategies	318
12.2.2.2 Representative Coding Techniques	321
12.2.3 Interdependence of Coding and Modulation	334
12.2.3.1 Interdependent Design	334
12.2.3.2 Interdependent Performance	336
12.3 Spread-Spectrum Techniques	339
12.3.1 The Great Unknown	339
12.3.2 The Background of Spread Spectrum	343
12.3.3 Frequency-Hopping Spread Spectrum (FH/SS)	344
12.3.4 Direct-Sequence Spread Spectrum (DS/SS)	351
12.3.5 Performance of Spread-Spectrum Techniques	355
12.3.6 Application to Mobile-Telephone Systems	356
CHAPTER 13 ALTERNATIVE SYSTEM ARCHITECTURES: CELL LEVEL	363
13.1 FDMA Architecture	365
13.2 TDMA Architecture	369
13.3 CDMA Architecture	373
CHAPTER 14 ALTERNATIVE SYSTEM ARCHITECTURES: NETWORK LEVEL	377
14.1 Frequency Plans	378
14.2 Growth Plans	381

14.3	Cochannel-Interference Reduction Measures	381
14.4	Traffic and Service Objectives	383
14.5	Roaming and Related Issues	384
14.6	Interface to the Wireline Network	385
14.7	Control: Centralized <i>versus</i> Distributed	389
CHAPTER 15 CHOOSING THE FUTURE: EVALUATING THE ALTERNATIVES		393
15.1	Spectrum Efficiency	394
15.1.1	Spectral Efficiency (Information Density)	394
15.1.2	Circuit Spectrum Efficiency: Circuits per Megahertz	395
15.1.3	Geographical Spectrum Efficiency: Circuits per Square Mile	396
15.1.4	Economic Spectrum Efficiency: Cost per Circuit (per Megahertz per Square Mile)	398
15.1.5	Communication Efficiency: Improved Individual Communication Utility	398
15.1.6	Allocation Efficiency: Improved Social Utility of Communication	401
15.1.7	Improving Spectrum Efficiency	403
15.1.8	Summary	409
15.2	Cost	410
15.2.1	System Cost Comparisons	410
15.2.2	Mobile-Unit Cost Comparisons	414
15.2.3	Operating Cost Comparisons	415
15.3	Other Criteria: Modularity, Digital Compatibility, Openness to New Technology	415
15.3.1	Modularity and Geographical Flexibility	415
15.3.2	Digital Network Compatibility	416
15.3.3	Openness to New Technology	417
15.4	Summary	418
Part VI Managing the Transition		421
CHAPTER 16 A LOOK AHEAD		423
16.1	The Question of Standards	426
16.2	Looking Backward: Compatibility of the Next Generation with the Installed Analog Base	432
16.3	Looking Forward: Openness to Future Technological Change	437
16.4	Competition	438
16.5	A Modest Proposal	442
Index		445

Chapter 8

DESIGNING FOR THE MOBILE ENVIRONMENT

Designing a mobile radio system is arguably the most demanding technical challenge in all of telephony. No communication channel is more variable, or more uncontrollable, than the radio link to and from a moving vehicle. For example, a representative signal-to-noise ratio objective on an analog wireline link (short-haul) is about 46 dB, according to a standard text: in other words, the speech signal should be 40,000 times stronger than the noise level [1]. Every effort is made through quality control on materials and careful facilities engineering to ensure a relatively stable electrical environment within the cable-transmission facility. Short-term fluctuations in the basic signal-to-noise ratio of more than 1 or 2 dB for a short-haul circuit are generally taken as an indicator of something abnormal. Over a longer period of time, measured in years, wear and tear may induce a gradual degradation by as much as 10–15 dB, at which point plans are generally made to rebuild the transmission facility [2].

By contrast, it is quite normal for a mobile radio channel to experience *fades* — sudden decreases in signal strength — of 40–50 dB (a reduction by a factor of 10,000 to 100,000) in a fraction of a second. In fact, a mobile telephone in a fast-moving automobile in an urban environment may expect to experience dozens of significant fades (20 dB down or more, a factor of at least 100) per second [3]. The receiver is fighting not only noise but interference from other transmitters on the same channel or nearby channels. During a fade, the desired signal may suddenly become vastly weaker than an undesired, interfering signal from a distant cell-site operating on the same channel, and the receiver may lock in on the undesired signal.

The impact on conventional FM is severe. Without fading, the capture effect of FM, its ability to reject a competing signal as strong as 1 or

2 dB below the desired signal, can essentially suppress cochannel interference. According to one of the most authoritative studies of mobile propagation, however, "this rapid fading [of the mobile channel] alters the signal-to-noise performance markedly, washing out the sharp threshold and capture properties of FM [4]." The impact on other analog modulation schemes is even greater:

Rapid Rayleigh fading generally has a disastrous effect on single-sideband (SSB) and AM communication systems . . . The distortion introduced by fading is larger than the output signal, independent of how much the transmitter power is increased [5].

In a digital system, the effect of noise and interference in the mobile channel is a startling increase in the bit-error rate. The BER in the mobile channel may typically run up to 1,000,000 times higher than in nonmobile point-to-point digital radio. It is very different from the virtually error-free digital transmission which can be engineered in a wireline environment. Voice coders, modulators and demodulators, and synchronization schemes, which work well enough on wireline digital systems like T-1 trunks or point-to-point microwave radio systems, may simply disintegrate in the mobile channel. The challenge of maintaining acceptable transmission under such severe conditions is the continental divide between technological alternatives that may work for mobile telephony and those that will not.

The *mobile environment*, as it is often referred to, has been the subject of an enormous amount of theoretical analysis and field experimentation, and a great deal is known about its peculiar characteristics, some of which can be stated in seemingly precise mathematical or statistical terms [6]. The problems, however, are of sufficient complexity that mobile systems designers are still highly constrained by performance uncertainties in different types of setting. Indeed, it should be noted that there is no such thing as a single mobile environment, describable with uniform characteristics or statistics. The mobile environment in a large city with a great many tall, man-made structures is very different from the mobile environment in flat, open farm country. The important variables that define the mobile environment for a particular area include:

1. Physical terrain (mountainous *versus* hilly *versus* flat or land *versus* water);
2. Number, height, arrangement, and nature (construction materials) of man-made structures;
3. Foliage and vegetation characteristics;
4. Normal and abnormal weather conditions;
5. Man-made radio noise.

In addition, the importance of these factors is greatly influenced by the radio frequency at which the system is designed to operate. Finally, the effects are related to the behavior of the mobile subscriber — especially the speed of travel. Slow-moving or stationary automobiles face quite different problems in the mobile environment than those moving at highway speeds.

The complexity of the mobile environment can seem overwhelming to engineers who are used to the stable conditions of wireline telephone transmission. Electricians and physicists began modeling the electrical environment of metallic conductors as long ago as Lord Kelvin's mathematical depictions of the transatlantic telegraph cable in the 1850s. Today it is possible to describe, indeed to specify, the wireline transmission environment with a high degree of precision. Even conventional nonmobile radio engineering is relatively easy: most microwave links are engineered over a clear line-of-sight path where propagation takes place well above terrain irregularities. In contrast, the mobile propagation path quite often involves intervening terrain or structural blockages, which cannot be predicted with any precision; the mobile receiver is very close to ground level and is constantly moving into different settings. The mobile environment must be addressed through statistical treatments, which necessarily involve drastic simplifications of assumptions about user behavior and microvariations in terrain, foliage, and building patterns. Published studies can create an aura of certainty which is misleading. There is still disagreement over the mathematics for modeling a single transmitter-receiver propagation path in rough terrain [7]. Different models offer various predictions about the performance of specific systems. Most mobile engineers would agree that mobile system engineering is frustratingly imprecise and that to find out actually how a particular system is going to perform in a given physical setting it is necessary to build it, operate it, and modify it as shortcomings appear. The procedure is costly, and still may be unsatisfactory: Jakes *et al.* write "the testing of mobile radio transmission techniques in the field is time-consuming and often inconclusive, due to uncertainty in the statistical signal variations actually encountered [8]." The following conclusion of a recent study of propagation in nonurban areas, quoted virtually in its entirety, is typical:

This investigation has revealed unexpected and widespread variations [of mobile signal characteristics] which cannot be simply related to the environment or the seasons. There is no simple explanation to give at this moment but it can be conjectured that one is dealing with the results of a complex scattering phenomenon occurring in the environment consisting chiefly of trees and other types of vegetation. To describe scattering by trees according to type, season, or temperature

one would certainly require a major experimental undertaking even for one frequency [9].

Conceptually, the mobile systems engineer must understand three things:

1. The way in which the radio signal may be altered or degraded in the mobile channel;
2. The effects that these alterations can have on link quality and system performance, given a specific radio-link technology;
3. The countermeasures that are available to combat these effects.

8.1 THE VOCABULARY OF RADIO

A radio wave is a form of electromagnetic energy, propagating at the speed of light, which may be visualized as a sine wave. (See Figure 8.1.) For our purposes, the wave has three important characteristics:

(Insert Figure 8.1 hereabouts!)

1. *Amplitude*. The magnitude or height of the sine wave crests and troughs;
2. *Frequency*. The number of crests that occur in one second; the basic measure of frequency is the *Hertz*, named for Heinrich Hertz, which is defined as one cycle, one crest-to-crest event. Most radio frequencies are measured in thousands or millions of cycles per second, *kilohertz* (KHz) or *megahertz* (MHz), respectively. (*Wavelength* is the inverse of frequency — the distance between two crests; it is measured in terms of meters, millimeters, or feet and inches, and so forth.)
3. *Phase*. The particular angle of inflection of the wave at a precise moment in time. It is normally measured in terms of degrees.

As we shall see, all three of these parameters may be used to carry information in a radio transmission.

Most radio transmission utilizes a continuous wave of a fixed frequency, called the *carrier*. The frequency of this carrier is stated as so many MHz (in the range of interest here). For example, the cellular carrier frequencies are generally about 800 MHz. Different carrier frequencies define different regions of the spectrum. For mobile communication, the range of carrier frequencies that are of interest is between about 1 MHz and, say, 3000 MHz (or 3 *gigahertz*, 3 GHz). Different carrier frequencies interact in different ways with the physical environment; thus the carrier frequency determines many of the most important characteristics of mobile propagation.

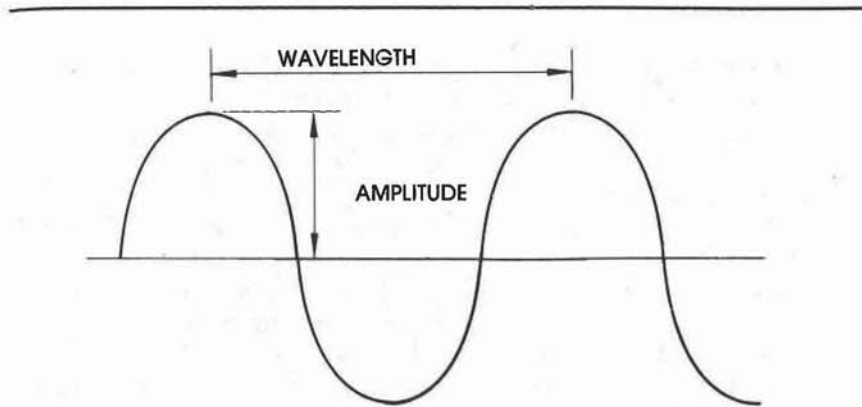


Figure 8.1 Idealized Radio Wave.

The modulated carrier — i.e., the carrier with the information, the voice signal, impressed upon it through slight changes in either its amplitude, frequency, or phase — actually occupies a narrow region of the spectrum around the nominal or unmodulated carrier frequency, sometimes called the *center frequency* in this context. (See Figure 8.2.) The width of this region — the *occupied bandwidth* — is also measured in KHz or MHz. This is what is commonly referred to as a radio *channel*. The *carrier spacing* is determined by the channel bandwidth, as well as the necessary guardbands.

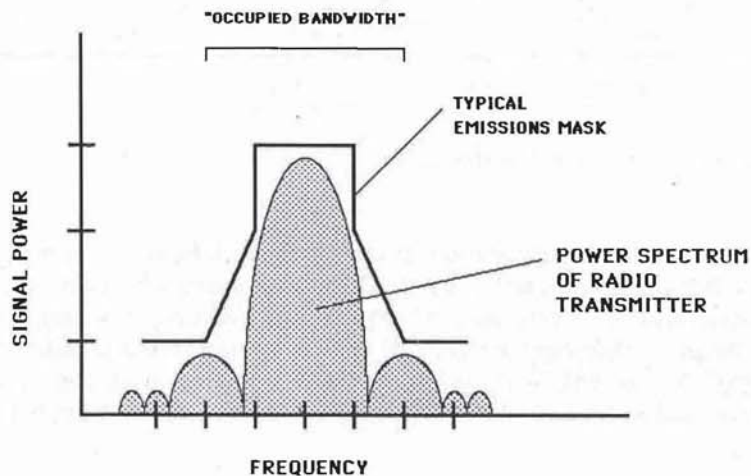


Figure 8.2 Emission Characteristics and Channel Definition.

The radio signal in a given channel is affected by *noise* and *interference*. Noise is considered to be the result of random environmental processes which produce radio energy such as lightning or automobile ignitions, or of thermal noise in the receiver itself. The ratio of the signal strength to the noise level is called the *signal-to-noise ratio* (SNR) and is the first fundamental measure of signal quality. Interference is the result of other man-made radio transmissions. There are two types of interference: *adjacent channel interference*, which occurs when energy from the carrier spills over into the adjacent channels (see Figure 8.3), and *cochannel interference*, which occurs when another transmission on the same carrier frequency impinges upon the receiver (see Figure 8.4). The ratio of the carrier to the interference (from both sources) is called the *carrier-to-interference ratio* (C/I).

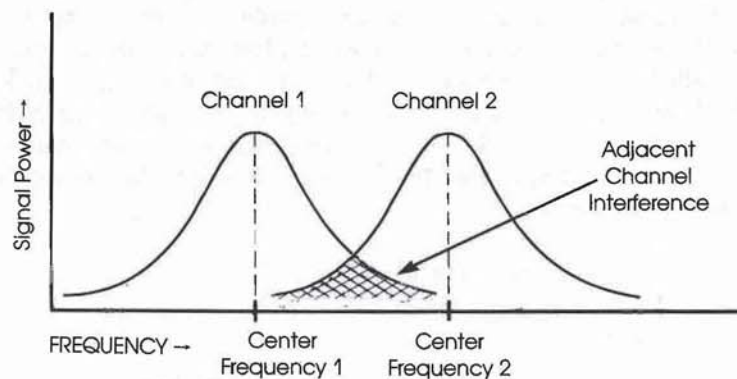


Figure 8.3 Adjacent Channel Interference.

The final basic propagation concept is the *link budget*, which defines the quality of the radio link, measured in terms of *decibels* or dB (or more precisely, dBm — where the “m” stands for milliwatts) of signal power. In a simple link-budget analysis, there are certain factors which “add decibels” to the link, such as the transmitter, the gain on the receiver antenna, and so forth, and others which “subtract decibels” from the link,

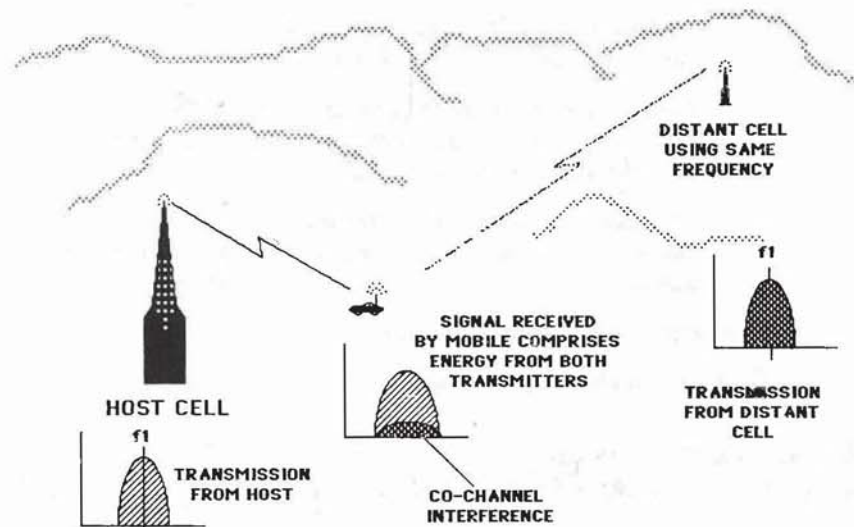


Figure 8.4 Co-Channel Interference.

like blocking terrain or fades. If enough dBs are left after the link budget has been constructed, the signal will get through with sufficient quality. A typical link budget is given in Figure 8.5. It should be noted that this is an extremely simplified propagation analysis.

$$G_s = L_p + F + L_t + L_m + L_b - G_t - G_r$$

where G_s = system gain in decibels

L_p = free space path loss in dB,

F = fade margin in dB

L_t = transmission line loss from waveguide or coaxials
used to connect radio to antenna, in dB

L_m = miscellaneous losses such as minor antenna
misalignment, waveguide corrosion, and increase in receiver
noise figure due to aging, in dB

L_b = branching loss due to filter and circulator used to
combine or split transmitter and receiver signals in a single
antenna

G_t = gain of transmitting antenna

G_r = gain of receiving antenna

Figure 8.5 Simplified Link Budget.

Source: David Smith, *Digital Transmissions Systems*.

8.2 THE FATE OF THE RADIO WAVE

Several things happen to a radio wave transmitted to or from a moving vehicle.

8.2.1 Free Space Loss

First, as the signal radiates in all directions, assuming for the moment an omnidirectional antenna, the power of the signal at any given point steadily diminishes as a function of the distance of the receiver from the transmitter. In a vacuum, in free space, the signal strength would diminish as the inverse of the square of the distance — the famous *inverse square law*. In free space, if the received signal is 100 watts at 1 mile, it will be 25 watts at 2 miles ($\frac{1}{4}$ the power), 4 watts at 5 miles ($\frac{1}{25}$ the power), and 1 watt at 10 miles ($\frac{1}{100}$ the power), assuming the same antenna. (See Figure 8.6.)

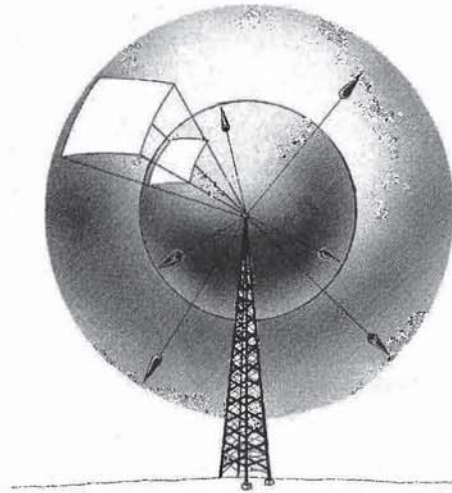


Figure 8.6 Free Space Radiator.

In practice, since mobile telephone systems are not set up in outer space, the path loss is *more severe* than the inverse square law would predict. Path loss for mobile systems may be evaluated as the inverse of the cube of the distance, or of some higher exponent up to the 5-th or 6-th power. Such statements reflect averaging of terrain, atmospheric, and other real-world effects. If the inverse of the 6-th power of distance is assumed, then the 100-watt signal level at 1 mile from the transmitter will decline to about 1.5 watts at 2 miles. (See Figure 8.7.)

The additional path loss is highly dependent upon frequency and upon assumptions about antenna design and other aspects of the physical locale. It is useful only in a very general way to indicate feasible transmission limits. It is, however, important to emphasize that even so fundamental a transmission parameter as the average rate of attenuation with distance must often be derived empirically for new frequency bands on the basis of field experience.

8.2.2 Blockage (Attenuation)

The second hazard facing the radio wave in the transmission path is the possibility that it may be partially blocked, or absorbed, by some feature of the environment. The degree of attenuation and the specific

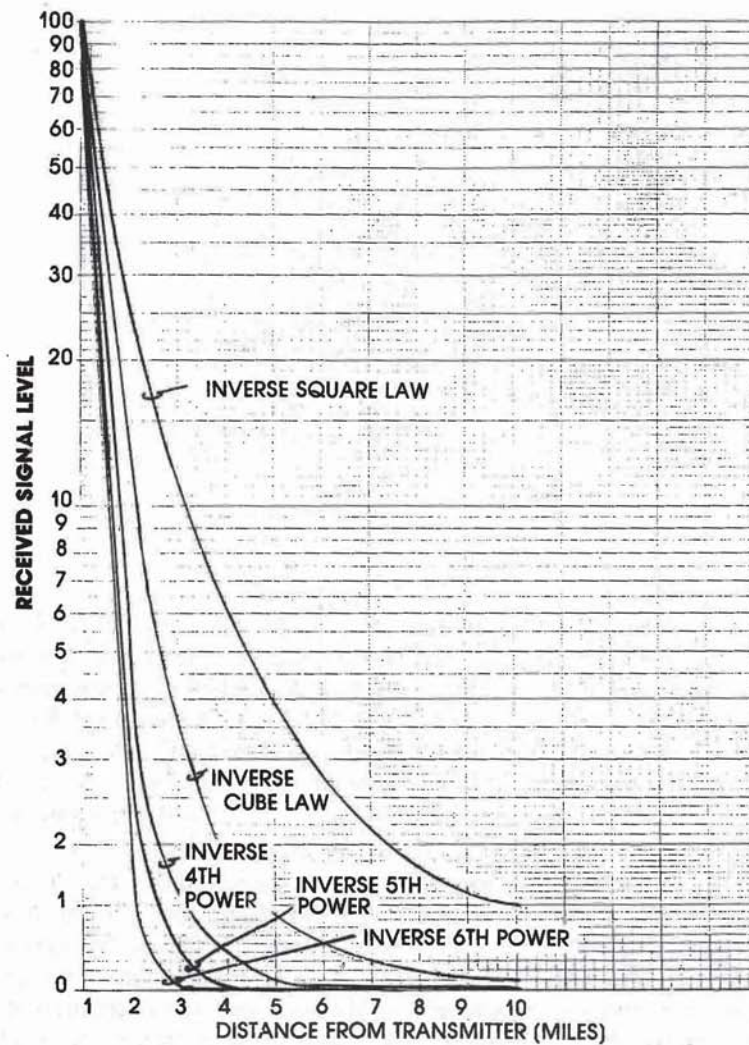


Figure 8.7 Path Loss as a Function of Assumed Inverse Power Law.

factors that may cause attenuation depend chiefly upon frequency. For example, frequencies below 1 GHz (1000 MHz) are essentially unaffected by rain or atmospheric moisture. Frequencies above 10 GHz are often severely affected, and frequencies above about 30 GHz are basically unusable over lengthy outdoor paths. (See Figure 8.8.) The general rule is that the lower frequencies have much greater penetrating power and will

propagate farther. The higher the frequency, the greater the attenuation, the more power needed at the transmitter, and the shorter the radius of effective transmission. For example, for TV transmission at the lower VHF band (50–90 MHz) the Federal Communications Commission authorizes maximum transmitter power of 100 kilowatts. For UHF stations, operating at 500–800 MHz, the FCC authorizes station power of up to 5000 kilowatts to achieve approximately the same quality over the same range.

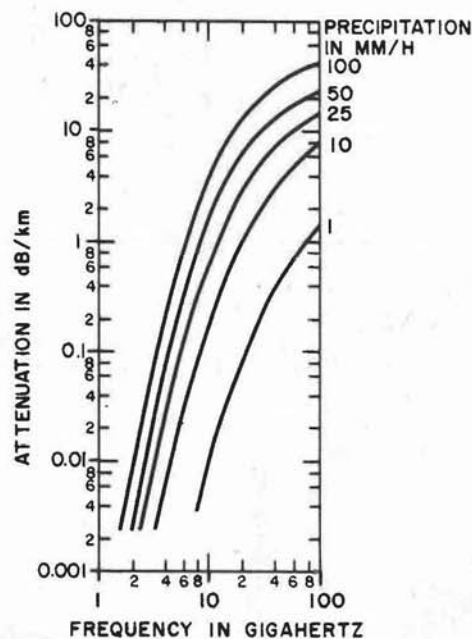


Figure 8.8 Rainfall Attenuation as a Function of Frequency.

Source: William C. Jakes, *Microwave Mobile Communications*, p.89.

Around 3–5 GHz, the attenuation becomes so great that the inverse power law results in impractically short transmission distances for omnidirectional transmitters. Highly directional antennas must be employed to concentrate the energy along a fixed point-to-point path. By focusing the radio waves in a narrow beam, analogous to a beam of light from a flashlight, the attenuation can be overcome for usable distances. These are called *point-to-point* systems and are characteristic of long-haul microwave telephone systems, which typically involve single hops of 10–50 miles. (See Figure 8.9.)

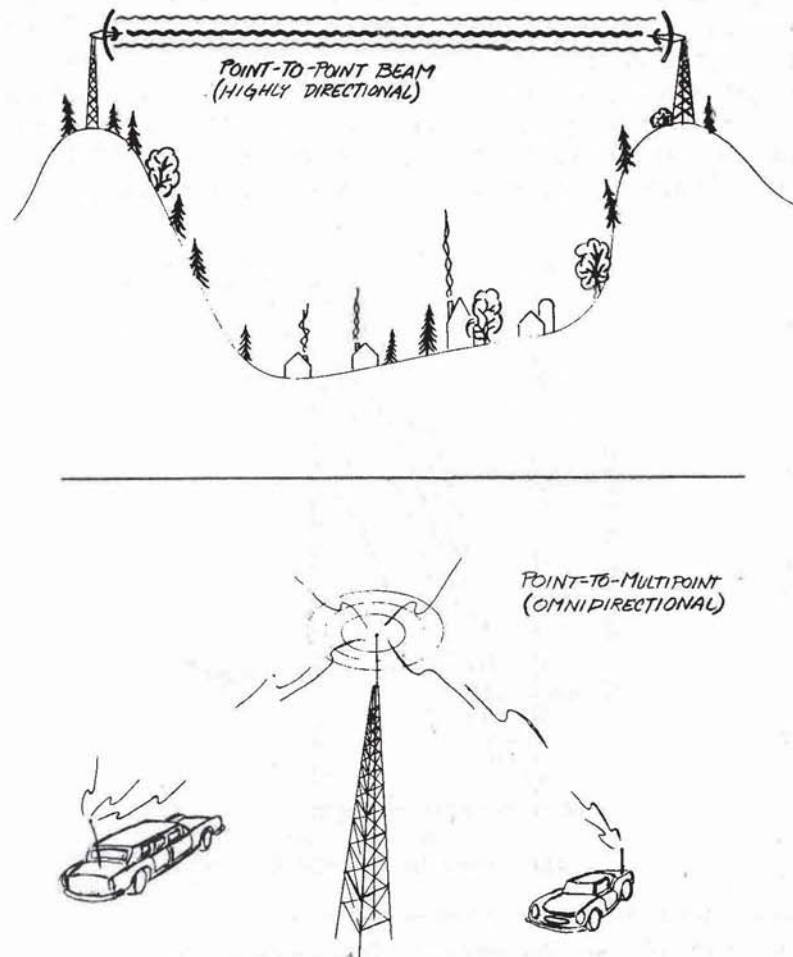


Figure 8.9 Point-to-Point versus Point-to-Multipoint Transmission.

It becomes more difficult to implement *point-to-multipoint* mobile systems at higher frequencies. Indeed, one of the principal concerns in the development of cellular radio was the fear that the radio link at 800–900 MHz would prove to be significantly less robust than the older IMTS systems at 150 MHz and 450 MHz. In practice, the transmission radius and effective coverage achieved by 800-MHz systems is significantly less

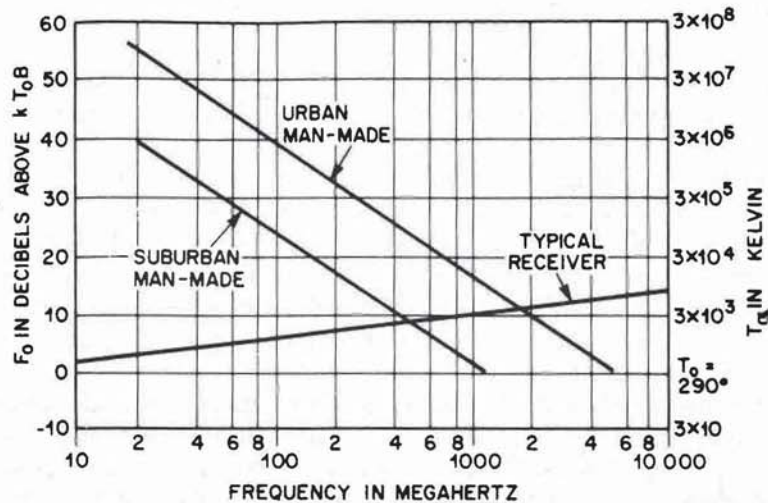


Figure 8.11 Environmental Radio Noise.

Source: William C. Jakes, *Microwave Mobile Communications*, p.298.

The fading effects produced by shadowing are often referred to as *slow fading*, because from the perspective of a moving automobile the entrance and exit to and from such a shadow takes a fair amount of time, since the area of the fade is large (many feet or hundreds of feet across).

8.2.3 Multipath

The radio wave may also be *reflected*, from a hill, a building, a truck, an airplane, or a discontinuity in the atmosphere; in some cases, the reflected signal is significantly attenuated, while in others almost all the radio energy is reflected and very little absorbed.

The effect is to produce not one but many different paths between the transmitter and receiver. (See Figure 8.12.) This is known as *multipath propagation*; it is the two-edged sword of mobile telephony. On the one hand, reflection and multipath propagation allow radio waves to "bend around corners," to reach behind hills and buildings and into parking garages and tunnels. (See Figure 8.13.) Reflection is the obverse of penetration. High frequencies reflect better, generally speaking, than lower frequencies, which tend to penetrate. For example, VHF frequencies (150 MHz) do not propagate well in long tunnels, but higher 800-MHz frequencies follow the tunnel like a waveguide and do considerably better [15].

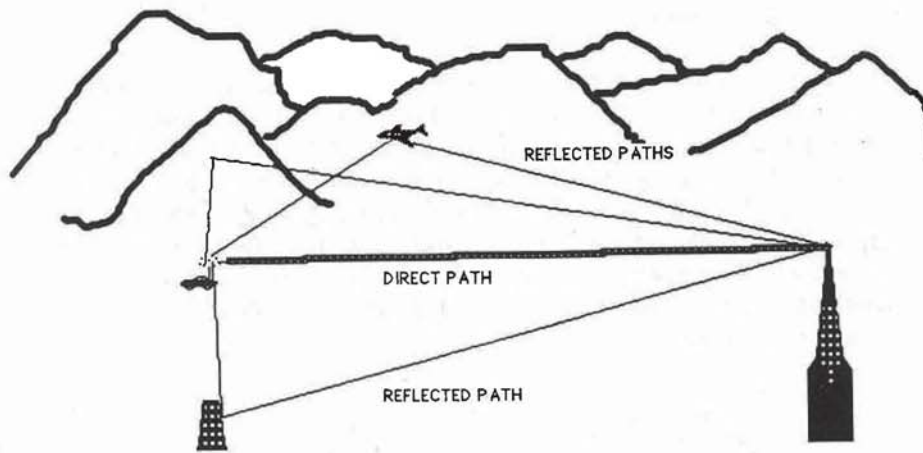


Figure 8.12 Multipath Propagation.

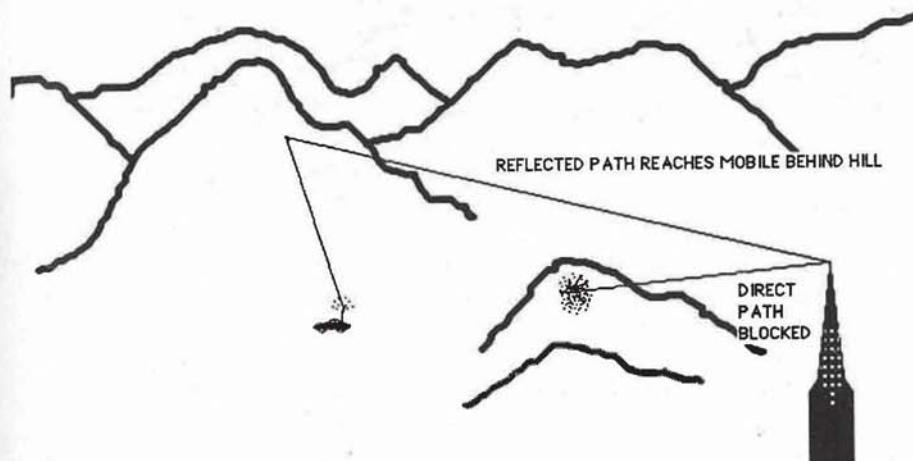


Figure 8.13 Multipath Allows Propagation around Obstacles.

On the other hand, multipath propagation creates some of the most difficult problems associated with the mobile environment. The three most important multipath issues for the digital designer are:

1. The delay spread of the received signal;
2. Random phase shift which creates rapid fluctuations in signal strength known as Rayleigh fading;
3. Random frequency modulation due to different Doppler shifts on different paths.

8.2.3.1 Delay Spread

Because the signal follows several paths, and because the reflected paths are longer than the direct path, if there is one, the multiple signals arrive with a slight additional delay. (See Figure 8.14.) Because different paths result in slightly different times of arrival, the effect is to smear or spread out the signal; for example, a single sharp transmitted pulse will appear to a receiver as indicated in Figure 8.15 [16]. In a digital system, particularly one operating at a high bit rate, the delay spread causes each symbol to overlap with preceding and following symbols, producing *inter-symbol interference*.

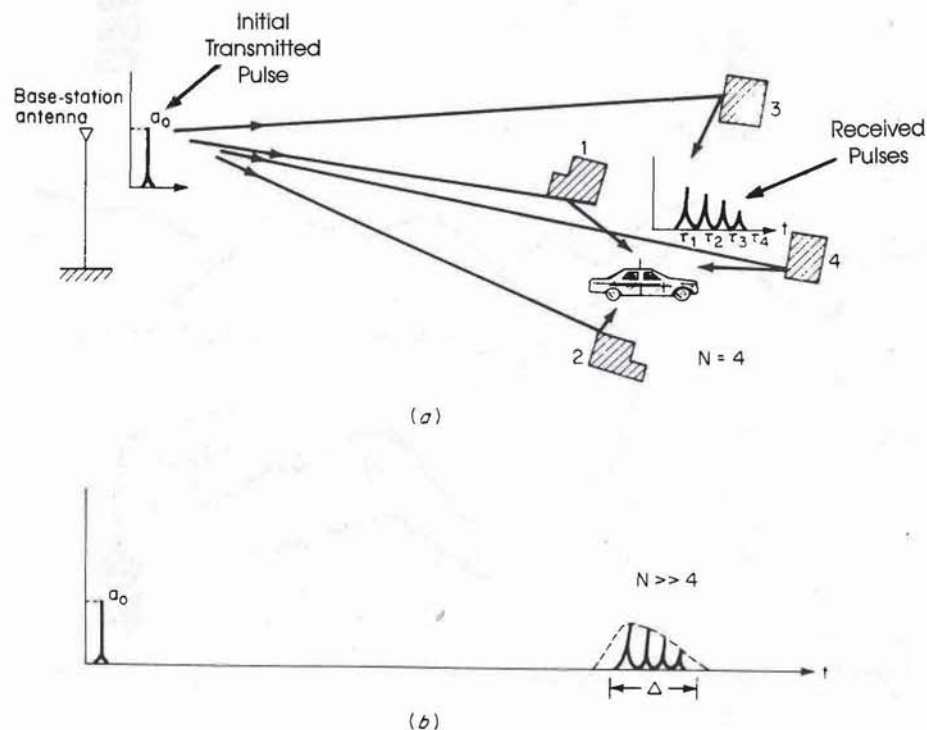


Figure 8.14 Illustration of Delay Spread.

Source: William C.Y. Lee, *Mobile Communications Engineering*, p.40.

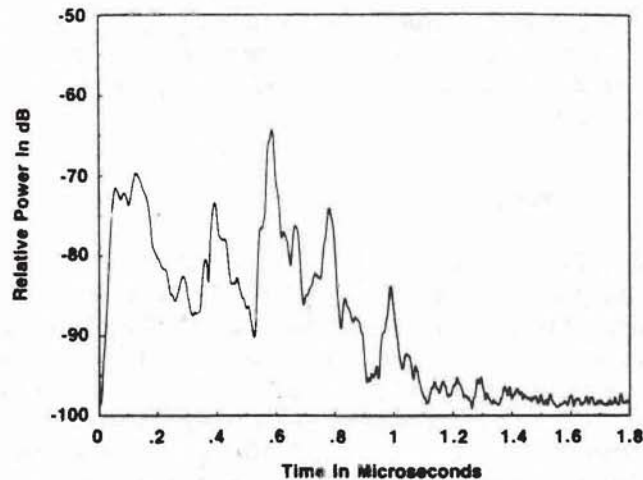


Figure 8.15 A Measured Profile of Average Received Power *versus* Time Delay at 850 MHz.
 Source: Cox, et al., *IEEE Proc.*, 1987, p.767.

The delay spread is fixed, depending upon frequency. Therefore, the degree of intersymbol interference from this source is dependent upon the transmission bit rate and the modulation level, which sets the symbol time. If the bit rate is high and the symbol time is similar in magnitude to the average delay spread, the rate of intersymbol interference can be quite high. In effect, delay spread sets a limit on the transmission symbol rate in a digital mobile channel. One study found that a delay spread of 1 μ s was typical for indoor office and work environments at 800 MHz [17]. Assuming 4-level modulation, or 2 bits per symbol, and a rate of 200 kilosymbols per second (equal to 400 kilobits per second), each symbol would occupy about 5 μ s. This would imply an average symbol overlap of up to 20%. (Note that this is a statistical property; some percentage of delay spreads would be significantly greater than this.) The study concluded that for these frequencies in these environments, this was the maximum intersymbol interference that could be tolerated without adaptive equalization.

In outdoor environments in which a mobile telephone would have to operate, both direct paths and reflected paths may be significantly longer, and delay spreads may range up to several microseconds or more [18]. The longer delay spreads are typically found in more urban areas,

where there are more reflectors. (Office buildings are usually excellent reflectors.) Longer delay spreads mean either that the symbol rate must be reduced or that adaptive equalization must be employed (see Section 8.5.3), which adds cost.

8.2.3.2 Rayleigh Fading

The second chief effect of multipath propagation is that the reflected radio wave may undergo drastic alteration in some of its fundamental characteristics, particularly phase and amplitude. The phase of the reflected wave may be rotated such that it arrives out of phase with the direct-path signal. If the two signals, assuming for the moment that there are only two, are exactly 180° out of phase, they will cancel each other out at the receiver. The signal effectively disappears. Other partial out-of-phase relationships among multiple received signals produce lesser reductions in measured signal strength.

The concept of a *fade* is therefore a *spatial* concept. Assuming the transmitter is stationary, at any given spot occupied by the receiver the sum of all direct and reflected paths from a transmitter to a receiver produces an alteration in signal strength related to the degree to which the multipath signals are in phase or out of phase. This signal strength may be somewhat more — or considerably less — than the expected signal strength, which can be defined as that which would be expected on the basis of the direct path alone, based solely on free-space loss and environmental attenuation. If the actual measured signal is significantly weaker — say 20 dB or 100 times weaker — than the expected signal level, we may conceive of that spot as a *20-dB fade*, for *that frequency* and for *that precise transmitter location and precise configuration of reflectors*. As long as we hold these factors constant, if we place our antenna in this spot we will lose 20 dB of signal strength.

What can we say about the number, the spacing, and the depth of these fades? There has developed a body of statistical knowledge which can be used with some success to characterize the incidence of fades in the environment.

The fades are said to fall within a statistical distribution known as Rayleigh distribution (after Lord Rayleigh, the great turn-of-the-century English physicist), and for this reason the phenomenon is often referred to as Rayleigh fading. The mobile environment is often called, from this perspective, the Rayleigh environment. The Rayleigh environment is pep-

pered with fades of varying depths. The depth and spacing of the fades is related to the radio frequency: at microwave frequencies (800 MHz) the maximum fades occur every few inches. These maximum fades are very deep: the signal strength is reduced by 10,000 to 100,000 times down from its expected value. In between are thousands of shallower fades. It is as though, from a radio point of view, the static world we have created is full of countless holes of varying depths. (See Figure 8.16.) The radio signal cannot reach into the bottoms of these deep holes, which means that if our receiving antenna is inside one of these holes at any instant in time it will not receive the transmitted signal. The individual holes are small: moving the antenna a couple of inches will take it out of a deep fade and restore a good signal.

Now imagine an automobile antenna moving through this strange Swiss-cheese radio world at 60 miles per hour, 88 feet per second. The antenna passes through hundreds of holes of varying depths every second, causing the signal strength to fluctuate very rapidly between normal levels and fades ranging up to 40 dB or more. An amplitude monitor on a mobile receiver will draw a graph like Figure 8.17. This is the way Rayleigh fading is usually experienced and portrayed.

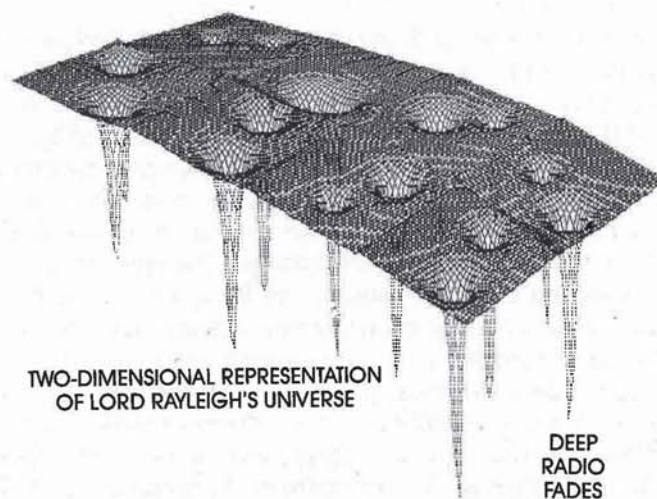


Figure 8.16 Lord Rayleigh's Universe.

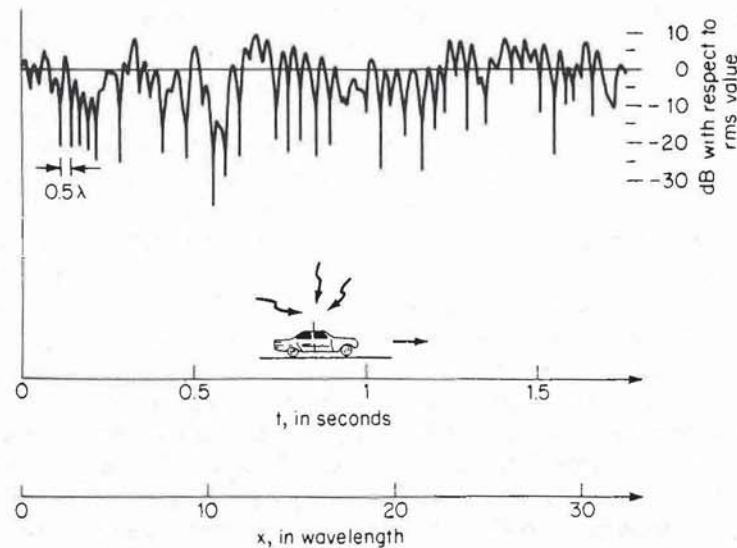


Figure 8.17 Typical Fading Signal Received While the Mobile Unit Is Moving.
 Source: William C.Y. Lee, *Mobile Communications Engineering*, p.46.

These signal amplitude fluctuations constitute far and away the most difficult challenge of the mobile environment. Rayleigh fading is the dominant design challenge for any digital mobile-radio proposal. It is a characteristic of the environment and cannot be directly altered by the mobile systems engineer. Although there are several available countermeasures (see Sections 8.4 and 8.5), all involve additional cost and complexity.

Multipath fading is the great destroyer of mobile-radio signals. It overwhelms AM and single sideband systems. The great advantage of FM when it was applied to mobile radio in the 1930s was due to the fact that the FM receiver suppresses (ignores) amplitude modulation, and thus the degradation due to amplitude fading is greatly reduced [19].

Rayleigh fading, however, poses an additional problem for cellular architectures. A second transmitter in a different location will create an entirely different spatial pattern of fades, because the relative positions of the reflectors are different. The strengths of the received signals from two cell-site transmitters are not correlated. Chances are that, at a given instant in time, if a mobile is in a fade with respect to the correct base station transmitter, it is not in a fade from a distant "incorrect" base station transmitting on the same frequency in another cell. In an FM system, the capture effect is lost; actually, FM capture works against us: "When Rayleigh fading is included in the analysis, most of the interference is caused when the receiver captures on the interfering stations, even if it is for a

very short time [20].” Consider a hypothetical chart of the signal levels received from two competing transmitters for a mobile moving through two superimposed Rayleigh environments, one for each transmitter. (See Figure 8.18.) The more transmitters there are in the general area operating on the same frequency, the more complex the Rayleigh patterning.

Another complicating factor is that some of the reflectors are also in motion, changing the Rayleigh characteristics over time irrespective of the movement of the mobile subscriber. Atmospheric reflectors, inversion layers, and so forth, are obviously transitory. Large trucks and buses can be significant reflectors for nearby mobile receivers. Indeed, one of the commonest demonstrations of multipath propagation occurs when an airplane — an excellent reflector — flies low over a housing area and creates a new and rapidly changing set of multiple paths for TV broadcast signals, causing the rhythmic flutter in the picture. (See Figure 8.19.)

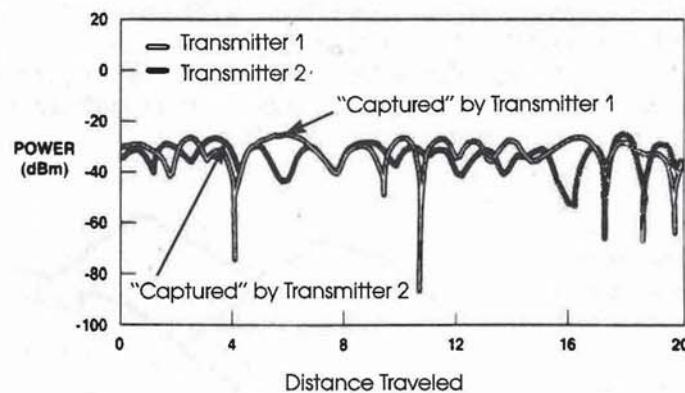


Figure 8.18 Rayleigh Patterns from Two Co-Channel Transmitters.

Source: derived from Cox, et al., *IEEE Proc.*, p. 768.

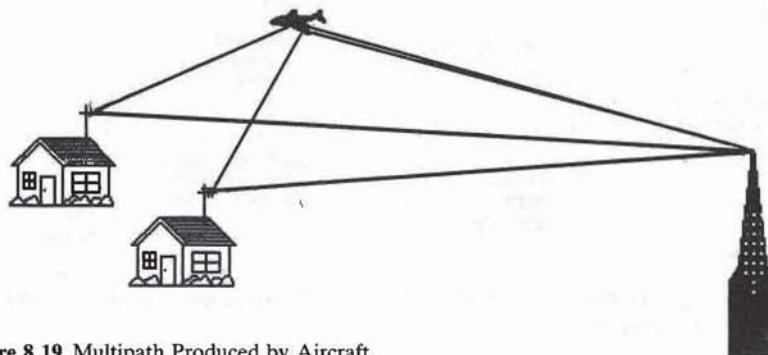


Figure 8.19 Multipath Produced by Aircraft.

8.2.3.3 Doppler Shift

Another aspect of the mobile channel is caused by the movement of the vehicle relative to the transmitter. This is the variation in the frequency of the received signal known as the *Doppler shift* (after Christian Johann Doppler, a nineteenth-century Austrian physicist who first called attention to frequency shifts caused by relative motion). Much as the sound of a horn on a moving car appears to the stationary observer to be slightly higher in pitch when the car is approaching rapidly and slightly lower when the car is receding, so radio transmissions are frequency shifted due to the relative motion of the vehicle. This frequency shift varies considerably as the mobile unit changes direction, speed, and is handed off from one cell to the next, and it introduces considerably random frequency modulation in the mobile signal. Moreover, the Doppler shift affects all multiple propagation paths, some of which may exhibit a positive shift, and some a negative shift, at the same instant. (See Figure 8.20.) Roughly speaking, Doppler-induced random FM is correlated with vehicle speed for a given frequency. At 22 miles per hour and 900 MHz, the median Doppler offset is about 30 hertz, which under certain conditions can be sufficient to "introduce distortion objectionable to the ear [21]."

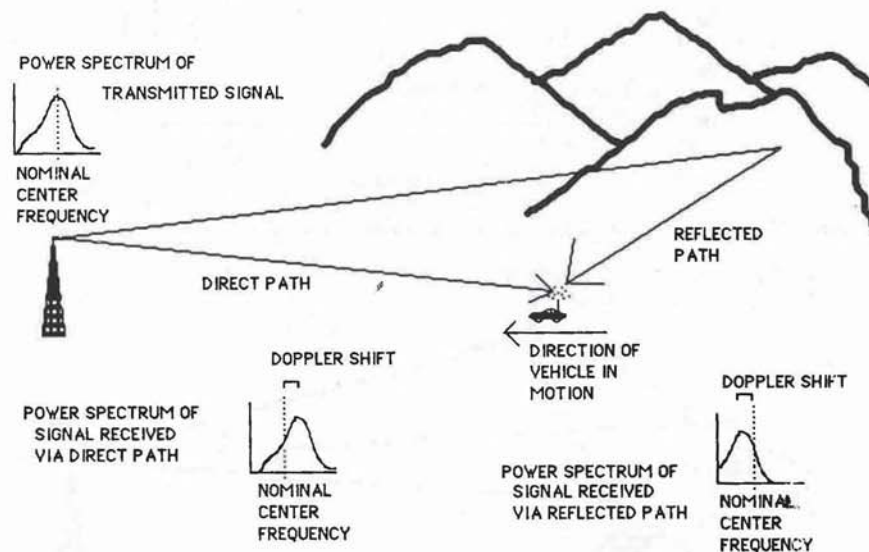


Figure 8.20 Idealization of the Doppler Effect on Received Signals in a Mobile Multipath Environment.

8.3 EFFECTS ON SYSTEM PERFORMANCE

The influence of the mobile environment on system performance has two aspects:

1. Effects on the quality of the individual radio link and the voice channel;
2. Effects on overall system performance.

8.3.1 Path Effects

The deleterious effects of the mobile environment on the radio signal have already been enumerated. Signal strength fluctuates rapidly and severely due to fast Rayleigh fading, and the time-averaged signal level also fluctuates due to shadowing or slow fading. In addition to multipath-induced variations in amplitude and phase, Doppler shifts induce random frequency variations. In short, every important parameter of the radio signal is subject to violent, sudden, and unpredictable alteration. Whatever modulation scheme is utilized — based on amplitude, frequency, or phase — the information-bearing parameter will be attacked.

In digital systems, all forms of signal degradation are converted into a common measure: the bit-error rate. The digital systems designer does not really care whether the source of a bit error was an amplitude fade produced by phase cancellation (Rayleigh fading), intersymbol interference due to delay spread, or signal attenuation caused by ice buildup on the antenna. The digital mobile-radio system must be able to tolerate a very high BER. In wireline digital systems, BERs of 10^{-8} or better are routine. In mobile applications where reuse is required, channel error rates of 10^{-2} or worse must be anticipated. In other words, from a digital point of view the mobile environment is more than a million times dirtier than the normal wire circuit. In fact, systems developers often simulate error rates of 5% to 25% to evaluate the bounds of system performance. Certain military digital mobile communication systems are designed to survive a 50% BER — one out of every two bits in error!

Strictly speaking, the BER is controllable by the system engineer. That is the liberating principle of digital communication, as we saw in Chapter 6. In the mobile radio circuit, however, it is generally not feasible to use multistage signal regeneration as is done on wireline T-carrier trunks, for example. Moreover, the bandwidth-limited character of radio transmission limits the engineer's ability to improve the BER by using less efficient but more robust coding and modulation techniques. As we shall see in Chapter 12, the digital mobile system designer is driven toward

higher-level modulation schemes which are inherently more susceptible to errors at a given signal-to-noise ratio than lower-level modulation. For example, for a signal-to-noise ratio of 12 dB (actually the reference here is to the energy-per-bit to noise density ratio, which Bellamy suggests as the most appropriate measure for measuring signal-to-noise in a digital system) a 2-level phase modulation scheme will produce a BER of about 10^{-8} , while a more bandwidth-efficient 16-level phase modulation suffers a BER between 10^{-2} and 10^{-3} [22]. In practice, given the other design constraints of the mobile system, high error rates are inescapable.

A second important path-related effect, already touched upon, is the limit imposed by the average delay spread upon the rate of digital transmission in a digital mobile channel. As we shall see, there is a wide range of proposals as far as the channel bit rate and symbol rate are concerned, and for many architectures this becomes a very significant limit.

8.3.2 System Effects

The most serious effect of the mobile environment on cellular system performance in a cellular architecture is the creation of fuzzy cell boundaries. The signal strength contour — the idea upon which traditional mobile engineering is based — is actually only a convenient idealization of what turns out to be a very messy reality. Consider the actual signal strength received at a moving automobile as it moves away from the cell-site transmitter. Figure 8.21 is adapted from actual measurements, reproduced here with permission of William Lee [23]. Figure 8.22 presents a finer-grained version of a hypothetical small portion of this signal record. Under such conditions, *there is no signal contour*: any criterion signal level will actually be crossed many times over a wide fuzzy boundary zone. Moreover, two mobiles following the same path at different times will experience generally similar *but specifically distinct* signal-level patterns. The characteristics of the mobile environment are constantly changing.

The cell boundary becomes a statistical property, rather like the position of the quantum mechanical electron. It cannot really be known; we can only state a confidence level associated with a particular estimate of its value at a particular location. The instantaneous unpredictable actual value, however, may differ from our estimate by as much as a factor of 100,000 or more. (See Figure 8.23.)

In Chapter 4 we discussed the effect of fuzzy cell boundaries on the hand-off decision. The system controller in today's cellular architecture knows nothing except the strength of the signal it is receiving from the mobile, which is subject to the same multipath fluctuations. Called upon

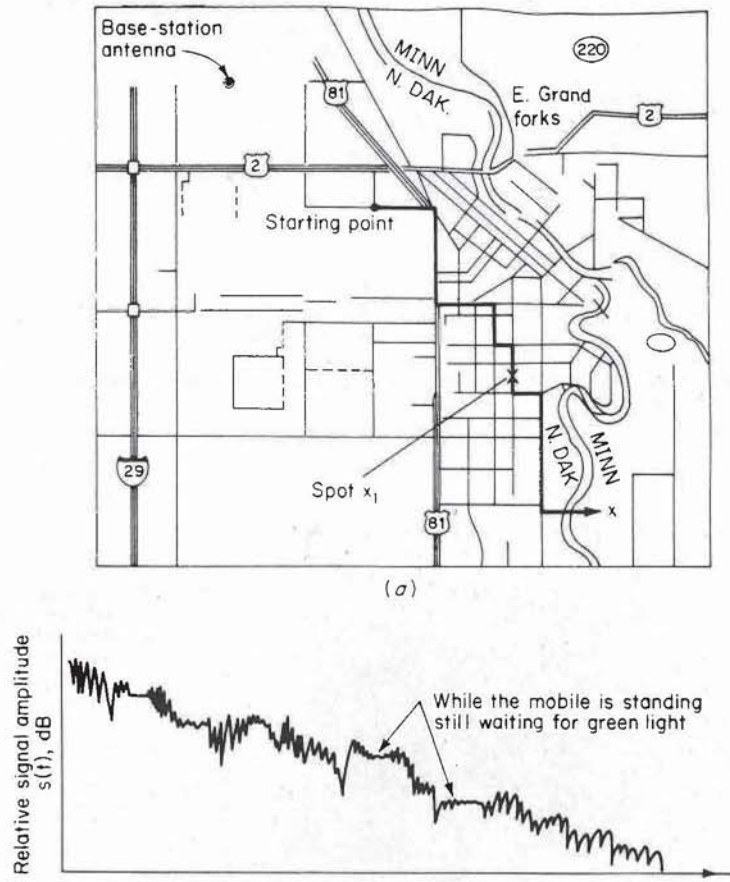


Figure 8.21 Actual Measured Signal Strength as Mobile Moves Away from Transmitter.
 Source: William C.Y. Lee, *Mobile Communications Engineering*, p.17.

to make a decision as to whether a hand-off is necessary, a short-term average of the signal strength is used to determine whether the criterion level, the cell boundary, has been reached. Because of the inherently high variability in the signal levels due to the multipath phenomena, a high rate of false hand-offs may be obtained, especially where (1) the mobile unit is moving slowly or in a stop-and-go mode and (2) where it is moving parallel to a cell boundary.

The fuzziness of the cells poses a more fundamental problem for cellular operations, however. It tends to undermine the cellular architec-

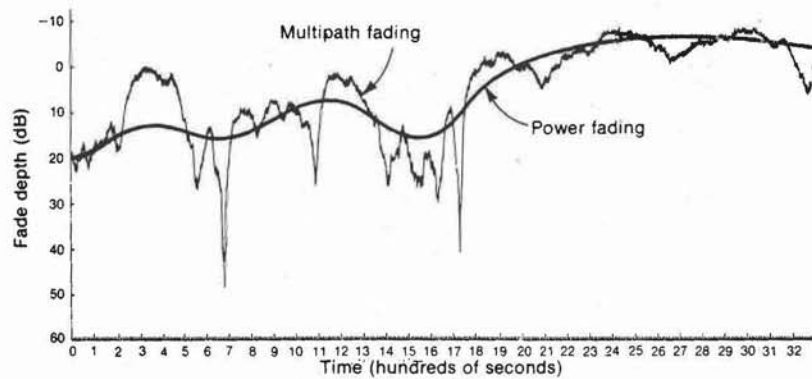


Figure 8.22 Signal Levels for a Radio Receiver in Motion, Reflecting Multipath and Power Fading.

Source: David Smith, *Digital Transmission Systems*, p.380.

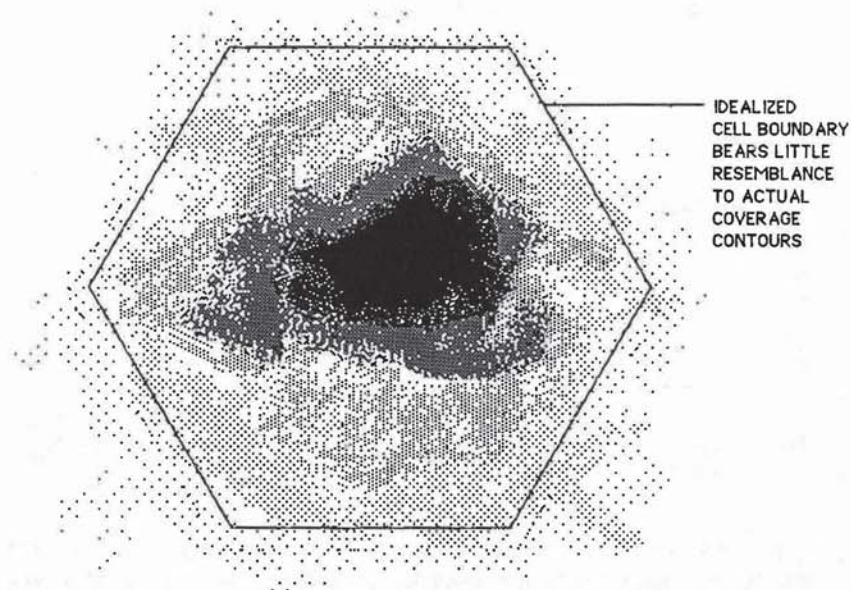


Figure 8.23 The Reality of Fuzzy Cell Boundaries.

ture at its foundation. Cellular engineers are beginning to realize that there is no such thing as "a cell." Instead, there may be one size cell for mobiles, another for portables, based on different antenna and power characteristics and different average antenna heights above the ground. (The fading characteristics are three-dimensional; the pattern of fades at four feet above street level will be very different from that at nine feet up.) According to

informal industry reports, the cell boundary for trunk-mounted antennas is significantly different than the cell boundary for glass-mounted antennas. Optimizing the overall system — sometimes called balancing the cells — is tremendously complicated by these irreducible statistical uncertainties (see Chapter 9).

In short, the mobile environment is so severe that it may well defeat the cellular architecture itself, at least in some of the more ambitious extensions such as very small cells to gain truly high spectrum efficiency.

8.4 TRADITIONAL COUNTERMEASURES

The strategies for dealing with the problems of the mobile channel may be divided into two groups: those that are, so to speak, conventional — those which have been applied fairly widely in mobile systems to date, including analog cellular — and those that are based upon robust digital signal-processing techniques, which require a digital architecture and, therefore, have not been as widely applied. Among the conventional countermeasures, the most important are:

1. The use of fade margins;
2. Various types of diversity;
3. Supplementary base stations.

8.4.1 Fade Margins

The concept of a fade margin is straightforward: extra power is added to the transmission to overcome potential fading [24]. If a system needs a signal-to-noise ratio at the receiver of x dB, and the maximum likely fade is calculated to be y dB, then the way to ensure a received signal of x dB is always to transmit enough power to produce a normal received signal of $x + y$ dB. (See Figure 8.24.) The fade margin is normally equal to the maximum expected fade. Most propagation studies call for a fade margin of about 40 dB [25].

In an analog system, the fade margin is strictly a function of transmitter power. For example, large fade margins are built into all radio broadcast signals, which is why we generally do not hear the effects of multipath fading on car radios. (Such effects are, however, quite audible in fringe areas, often as a fluttering or picket-fence effect, analogous to the wavering of the TV picture when the airplane flies over.) Broadcasters are not concerned with frequency reuse *per se*. They can simply blast out their signal and let the curvature of the earth take care of isolation from the next town. In mobile radio systems, however, the use of large fade margins complicates the implementation of frequency reuse, since trans-

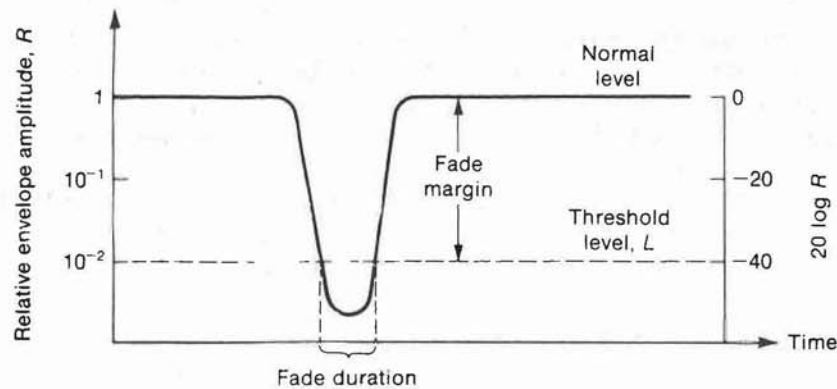


Figure 8.24 Fade Margin.

Source: David Smith, *Digital Transmission Systems*, p.382.

mitters are consistently running hotter than necessary for the average reception conditions and are transmitting farther, pushing out the distance at which the frequency is available for reuse. (Actually, reuse distance is not strictly related to transmitter power, but to the ratio between cell radii and the distance between transmitters. See Chapter 9.)

8.4.2 Diversity

Diversity refers to any of several techniques for sampling the received signal more than once and, by either combining these signals or selecting the best of them, improving the signal-to-noise ratio at the receiver. Of course, to counteract the fading problem the samples must be taken in such a way that the fading characteristics of the different samples are uncorrelated.

For example, the most common form is known as *space diversity*, which in layman's terms means simply having two or more antennas separated by a minimum of half a wavelength (several inches at 800–900 MHz) [26]. Two antennas so separated will show uncorrelated fading patterns; if one antenna is in a deep fade it is quite likely that the other antenna is not in a fade. (See Figure 8.25.) The radio circuitry can be programmed to select the antenna *branch* with the better signal. The more branches, the better the average signal. (See Figure 8.26.)

Many types of antenna-combiner systems, capable of producing space diversity, have been analyzed. Jakes *et al.* report that an eight-branch diversity system at the mobile unit — that is, eight separate antenna elements — is capable of ensuring that the received signal will be within 3

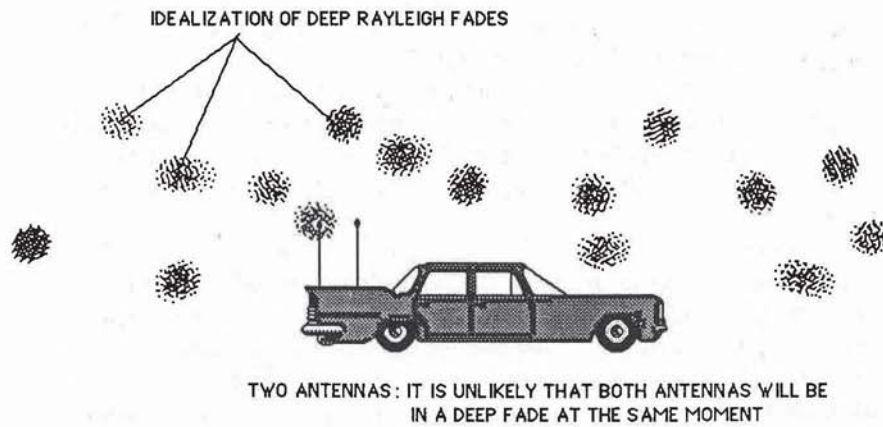


Figure 8.25 Idealization of Space Diversity.

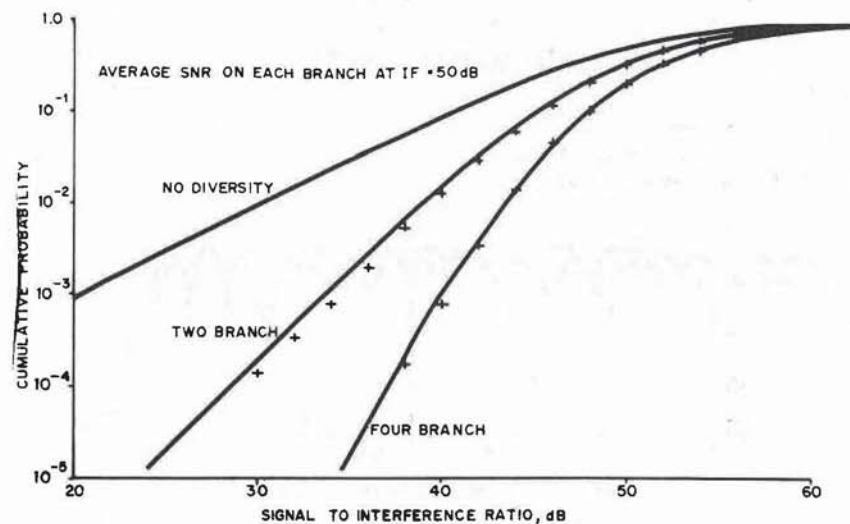


Figure 8.26 Effects of Spatial Diversity: Two-Branch and Four-Branch.

Source: William C. Jakes, *Microwave Mobile Communications*, p.363.

dB of its normal value 95% of the time [27]! This is clearly a tremendous improvement over the raw statistics of the Rayleigh channel. In other words, it is possible through multiple-antenna systems to reduce the effect of fast Rayleigh fades below the magnitude of slow, shadow-induced, fading which multiple antennas do not help. Another important benefit of

diversity may be that it significantly reduces cochannel interference by reducing FM capture of the interferer [28].

On the other hand, the cost of the equipment and the increased complexity of the circuitry necessary to deal with eight separate antenna inputs constitute additional overhead. Consumers have been unwilling to employ diversity techniques that might turn their automobiles into antenna farms.

Polarization diversity is another option, potentially an attractive one. It has been shown that the same signal transmitted with both a horizontal polarity and a vertical polarity exhibits uncorrelated fading statistics and can be used for diversity. This may be considered a special case of space diversity, since there are two antenna elements at the receiver. Cox *et al.* have shown the results of measurements taken on two orthogonally polarized signals at 800 MHz [29]. As the chart shows, if the receiver is designed to select the better of the two, the maximum fade would be about 10–15 dB, as opposed to almost 60 dB if the vertically polarized signal alone were considered. (See Figure 8.27.)

RECEIVED SIGNAL LEVELS

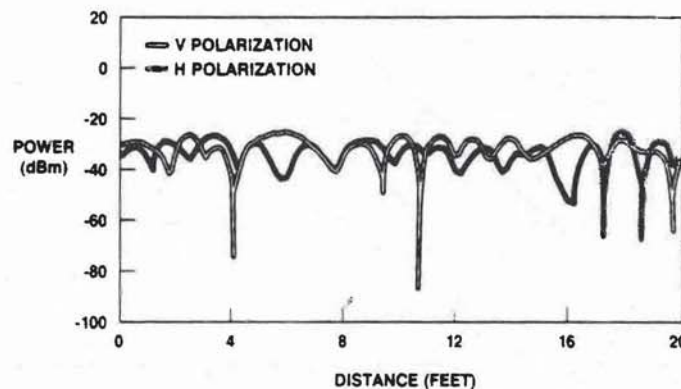


Figure 8.27 Measured 800 MHz Multipath Signal Variations.

Source: Cox, et al., *IEEE Proc.*, 1987.

Frequency diversity involves the transmission of the same circuit on two different frequencies sufficiently separated such that again their fading characteristics are uncorrelated. For the frequencies under discussion here, the separation between the two frequencies would have to be on the order of 1–2 MHz [30]. Frequency diversity is employed on wideband microwave point-to-point systems. The use of multiple frequencies to transmit the

same message to a mobile user, however, would be intolerably wasteful of spectrum in a mobile-radio application. The concept of frequency diversity, however, is relevant in discussion of wideband spread-spectrum systems, some of which employ an ingenious form of frequency diversity. (See Chapter 12.)

8.4.3 Supplementary Base Stations

To fill in large holes caused by shadowing from hills or buildings, the conventional answer has been to deploy a satellite base station to radiate the same signal from a different angle. (See Figure 8.28.) The principle of what is in effect base-station diversity has been built into today's cellular architecture through the use of corner-sited antennas with directional transmission to provide alternative paths for reaching subscribers in shadowed areas within the cells [31]. (See Figure 8.29.) The advantage of this architecture is that the number of cell-sites is not greatly increased, which holds down costs. According to calculations presented by Jakes *et al.*, the use of multiple base stations, with the ability to select and hand off the mobile within the cell to the best one, should improve average signal-to-noise ratio by something on the order of 10 dB. It should also eliminate the truly deep shadows. A penalty associated with this approach, however, may be an increased likelihood of hand-off which overburdens the central system processor. Given the fuzziness of cell boundaries for an FM system in a fading environment, we now face the prospect of a fuzzy zone at the center of every cell, where the signals from competing corner-sited base stations may be very close in average strength, and stationary vehicles finding themselves in a temporary but deep fade may undergo an undesirable hand-off [32].

8.5 DIGITAL COUNTERMEASURES

In a digital system, the inherently robust format and the opportunity to apply intelligent signal processing open up new avenues for counteracting the effects of the mobile environment. The most important of these are:

1. Robust voice coding;
2. Robust modulation;
3. Adaptive equalization;
4. Error correction.

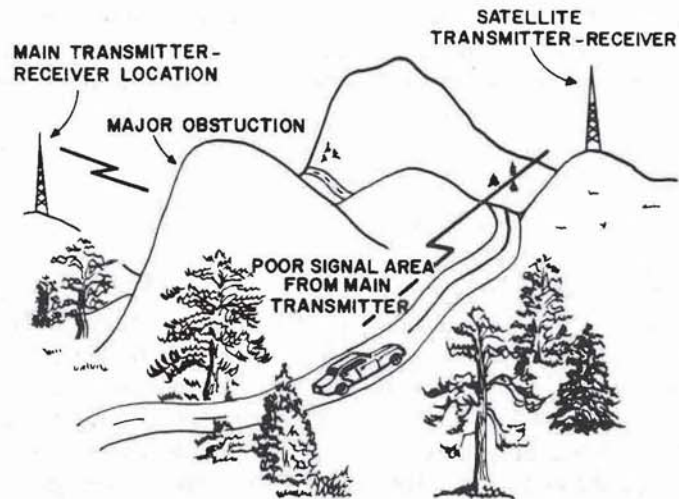


Figure 8.28 Use of Supplemental Base Stations to Fill-In Blocked Coverage.
 Source: William C. Jakes, *Microwave Mobile Communications*, p.378.

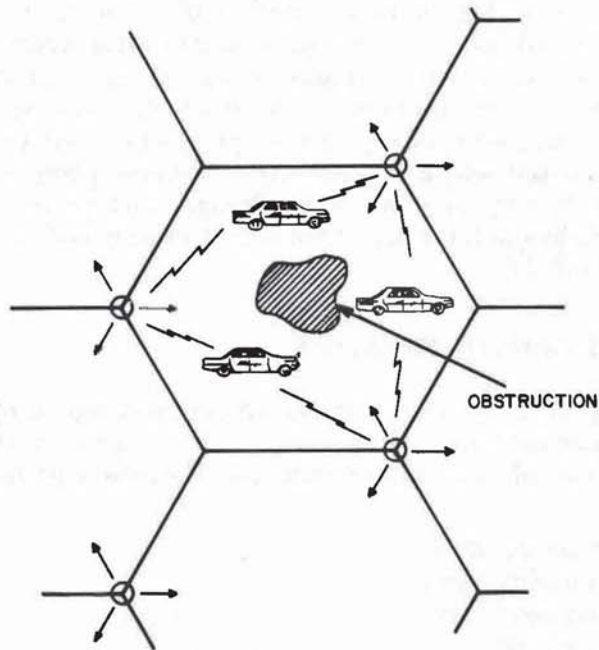


Figure 8.29 Corner-Siting of Cell-Site Transmitters.
 Source: William C. Jakes, *Microwave Mobile Communications*, p.379.

The use of robust techniques is based on the principle of making the transmission more error-resistant by limiting the damage caused by errors. As noted in Chapter 6, adaptive equalization is a generic signal processing technique designed to help recover the physical level of the code. Error correction is another generic technique which focuses on recovering the logical level of the code.

8.5.1 Robust Voice Coding

Conventional PCM was designed for wireline digital systems where the system engineer can employ regenerative repeaters to assure virtually error-free transmission. PCM is actually rather vulnerable to transmission errors. Some bits are relatively more important than others. This means that some errors can have a much greater effect than others.

In the dirty mobile-radio channel, regenerative repeaters are not feasible and error-free transmission is not a practical design goal. In fact, the mobile channel often operates at error rates that would overwhelm an ordinary PCM coder. There are other coding strategies, however, which are inherently more robust. For example, delta modulation, which is not a form of modulation as we have used the term here but a voice-coding technique (see Chapter 12), uses only 1-bit words, and each bit is equal in weight to all other bits. In an error-filled environment, delta modulation should outperform standard PCM.

The digital mobile-radio designer, however, is constrained by another opposing objective: the search for lower bit rates to reduce the signal bandwidth. Today's most advanced coding strategies use complex algorithms to reduce the bit rate dramatically. These methods, however, actually increase the relative importance of certain bits and thus could heighten the vulnerability to errors. The consideration of coder robustness is intimately bound up with the question of error correction.

The search for robust voice coders is aided by the characteristics of the human speech processor itself, i.e., the ear and the brain. We are all able to communicate in very noisy acoustic environments — for example, an individual listening to a conversation at a crowded cocktail party. As researchers have developed an understanding of the mechanisms underlying speech production and interpretation, many clues have emerged for the design of coders that will simultaneously satisfy both objectives of the digital mobile-radio designer — imperviousness to errors and low bit rates. We will delve more into this area in Section 12.2.2.

8.5.2 Robust Modulation

The same general considerations apply to the second coding stage, or modulation. The vagaries of the mobile channel impact some modulation schemes much more than others. We have already noted that the violent oscillations in signal amplitude due to Rayleigh fading render amplitude modulation schemes almost inoperative. The relative size of multipath-induced frequency variations is considerably less than amplitude or phase alterations: hence the superiority of FM to AM in a mobile environment.

Digital modulation schemes — which are quite numerous, as we shall see in Section 12.2.1 — face the same winnowing. Some techniques which work well and are highly spectrum efficient in fixed radio applications are simply unable to cope with the mobile channel conditions. Again, the digital mobile-radio designer must satisfy two conflicting criteria, spectrum efficiency *versus* robustness in an error-dominated channel. For example, as noted earlier, 16-level phase modulation is capable of transmitting twice as much information in a given bandwidth as 4-level phase modulation. The 16-level demodulator, however, is required to detect phase differences of only 22.5° , while the 4-level demodulator works with 90° differences. Since the phase alterations produced by the mobile environment are the same for either case, the relative error rate for 4-level modulation is much lower than for 16-level at a given signal-to-noise ratio.

8.5.3 Adaptive Equalization

The digital demodulator is designed to detect the incoming pulses, which in radio systems are usually discrete variations in some characteristic of the carrier, and to assign them their proper value to allow subsequent processing to proceed. The detection process is fundamentally quite simple. At regular intervals the demodulator samples the received waveform and quantizes it, assigning it to one of a small number of possible values. For example, in a 4-level phase modulation scheme, each sample must be assigned to one of four values. If the receiver is properly synchronized, it should see the samples clustering at these four levels. In between samples, the value of the incoming waveform varies over the entire range. The universe of possible waveforms, such as will be seen if a random data stream is transmitted and a large number of pulses superimposed, is usually drawn in a characteristic diagram known as an *eye pattern*. Figure 8.30 shows an eye pattern for 4-level modulation. The sample is taken and the pulse measured at the middle of the eye pattern, where, in principle, the decision will always be fairly easy.

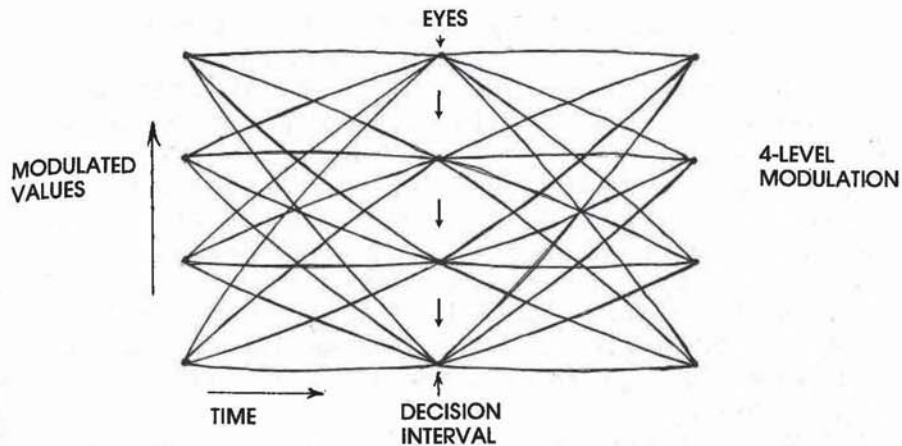


Figure 8.30 Four-Level Eye Pattern.

Source: William C.Y. Lee, *Mobile Communications Engineering*, p.381.

As we have seen, the hazards of the mobile environment often produce an increase in intersymbol interference, smearing the pulses together. (See Figure 8.31.) This tends to close the eye pattern and to make the demodulator's decision much less accurate. In the 1960s, R. W. Lucky of Bell Labs was the first to devise a signal-processing technique — known as *equalization* — capable of counteracting this problem [33]. In the following decades, the study of equalization techniques has grown into a vigorous field with a rich literature [34].

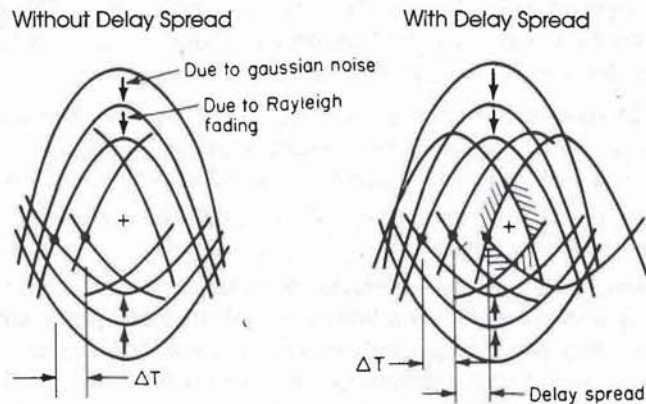


Figure 8.31 Degradation of the Demodulator's Eye Pattern Due to Factors in the Mobile Environment.

Source: William C.Y. Lee, *Mobile Communications Engineering*, p.381.

The fundamental principle of adaptive equalization is to obtain, prior to the commencement of transmission, certain information about the distortion and attenuation characteristics of the channel, and then to employ this information to correct the received signal, to reshape the incoming pulses, so as to improve the resolution of the eye pattern and the error performance of the demodulator. A typical way of accomplishing this is to begin the transmission with a brief "training" sequence: a known data sequence is transmitted, and the demodulator compares the actual received signal with what it knows to be the original input sequence. The observed error is therefore channel-induced. From these data, the system derives sufficient information to characterize the channel and uses this information to set its processing algorithms to subtract the expected error from all subsequent samples.

If the channel characteristics are expected to be fairly stable over the duration of the transmission, as they may well be for most wireline channels, the initial training may suffice. If, however, the channel characteristics are expected to continue to change during the course of the transmission — as in mobile radio — then the initial training must be supplemented by an ongoing adaptive equalization algorithm that is capable of measuring the channel characteristics and continuously tuning the equalizer parameters to maintain good pulse shaping and low error rates. The basic idea of *decision feedback equalization* (DFE) is also quite simple. The equalizer is assumed to start out with the right setting — a correct analysis of the expected error — immediately after training is completed. The first sample will be analyzed and extracted from the incoming signal. Once the first pulse has been decided and its value is known, the error between that value and what was actually received can be recomputed. This actual error is now compared with what had been the expected error. *This* difference — between expected error and observed error — can now be used to update the settings of the equalizer circuitry.

The basic idea is that if the value of the symbols already detected are known (past decisions are assumed to be correct), then the ISI [intersymbol interference] contributed by these symbols can be canceled exactly, by subtracting past symbol values with appropriate weighting from the equalizer output [35].

The concept of using past decisions to aid in the making of future decisions is the central concept for all adaptive signal processing and can be generalized beyond equalization *per se* [36]. It is one of the overarching advantages of digital transmission in dirty environments. As the official AT&T history of engineering in the Bell System observes:

Feedback control information was obtained by comparing decided bits against the receiver's incoming, distorted analog pulse train in order to ascertain an error component. This technique of using prior decisions to determine an ideal upon which to base adaptation became known as decision direction; it subsequently became the basis not only for equalization but for the recovery of timing and other necessary receiver parameters [37].

The effects of equalization properly applied can be dramatic. Figure 8.32 is derived from a study by Bell Labs of the effects of using equalization on an 8-level signal. The chief challenge in designing equalization algorithms for mobile-radio applications appears to be the requirement for continuous adjustment to very rapid and large magnitude changes in the channel characteristics. The trend today is toward fully digital software implementations of equalization algorithms on new, fast digital signal-processing chips.

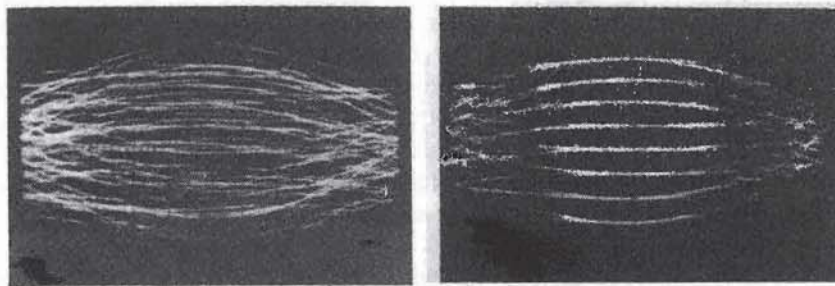


Figure 8.32 Eight-Level Eye Pattern: Before and After Equalization.

Source: AT&T Bell Labs, *A History of Engineering and Science in the Bell System: Communications Sciences, 1925–1975*, p.423.

8.5.4 Error Correction

Once the incoming pulses have been sampled and decided to the best of the demodulator's and the equalizer's capabilities, there is still the possibility that errors in detection may have occurred. In the mobile channel, it is likely that even post-equalization bit-error rates of 10^{-2} to 10^{-3} may be experienced in some link conditions. At this stage, it is possible to cleanse the received bit stream further by means of *forward error correction* (FEC) techniques.

FEC is a *very* complex field, and it is neither possible nor necessary here to present even a conceptual survey of different approaches [38]. All FEC techniques are based on the principle that by encoding the bit sequences prior to transmission in such a way as to introduce certain redundant information, the presence of errors can be detected by the receiver, which knows the coding principles, and in many cases actually corrected at the receiver by making use of this redundant information. In this sense, the simplest form of FEC is gross multiple transmission of the same information more than once. This is done in some of today's cellular signaling, for example. The enormous ingenuity of the field of error coding, however, has been expressed in the ideal of finding more efficient techniques that will allow the maximum error correction with the minimum additional information.

The desire to minimize the additional information is very appropriate in the bandwidth-limited radio environment. All FEC techniques increase the bandwidth of the transmission. Indeed, the hypothetical coding gain is related to the amount by which the bandwidth is increased. The coding gain is the amount by which the signal-to-noise ratio may be *reduced*, or the amount of noise increased, while still maintaining a desired BER criterion, assuming FEC is employed. For example, Bhargava calculates that a coding gain of 11.2 dB in SNR is "theoretically possible" for binary phase modulation (BPSK) [39]. While such a gain cannot be realized with current algorithms, Bhargava nevertheless feels that "it is safe to say that coding systems (delivering 2–6 dB) will be used routinely in digital communication links [40]."

In short, FEC techniques are promising, but, like robust voice-coding and modulation techniques, their use in mobile-radio systems is constrained by (1) the computational complexity of implementing advanced algorithms, which is a function of the contemporary hardware, and (2) the bandwidth limitations we have referred to throughout.

REFERENCES

- [1] John C. Bellamy, *Digital Telephony*, New York: Wiley, 1982, p. 71.
- [2] Bell Laboratories, *Engineering and Operations in the Bell System*, AT&T Bell Laboratories, 1977, pp. 604 ff.
- [3] William C. Jakes, ed., *Microwave Mobile Communications*, New York: Wiley, 1974, pp. 11, 189.
- [4] *Ibid.*, p. 161.
- [5] *Ibid.*, p. 201.
- [6] *Ibid.*

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- [7] *Ibid.*, pp. 112 ff.; also David R. Smith, *Digital Transmission Systems*, New York: Van Nostrand Reinhold, 1985, pp. 361 ff.
 - [8] Jakes, *op. cit.*, p. 65.
 - [9] Jules LeBel, "Mobile Radio Signal Statistics in Non-Urban Environments," *Proceedings of the 37th IEEE Vehicular Technology Conference*, Tampa, June 1-3, 1987, p. 135.
 - [10] Jakes, *op. cit.*, Chapter 2.
 - [11] *Ibid.*, pp. 105-106.
 - [12] *Ibid.*, p. 107.
 - [13] *Ibid.*, p. 110.
 - [14] *Ibid.*, p. 298.
 - [15] *Ibid.*, p. 110.
 - [16] Donald C. Cox, Hamilton W. Arnold, and Philip T. Porter, "Universal Digital Portable Communications: A System Perspective," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-5, No. 5, June 1987, pp. 764-773.
 - [17] *Ibid.*
 - [18] Jakes, *op. cit.*, p. 46.
 - [19] *Ibid.*, p. 162.
 - [20] *Ibid.*, p. 383.
 - [21] *Ibid.*, pp. 215-217.
 - [22] Bellamy, *op. cit.*, pp. 193, 489-493, 295.
 - [23] William C. Y. Lee, *Mobile Communications Engineering*, New York: McGraw-Hill, 1982, p. 17.
 - [24] See Smith, *op. cit.*, pp. 381 ff.
 - [25] Stan Roelefs, "Fade Margin Requirements for Microwave Systems," *Mobile Radio Technology*, December 1986, pp. 52-61.
 - [26] Lee, *Mobile Communications Engineering*, *op. cit.*, p. 276.
 - [27] Jakes, *op. cit.*, p. 379.
 - [28] *Ibid.*, p. 362.
 - [29] Cox *et al.*, *op. cit.*
 - [30] Jakes, *op. cit.*, p. 312.
 - [31] *Ibid.*, pp. 377-386.
 - [32] Richard C. Bernhardt, "Macroscopic Diversity in Frequency Reuse Radio Systems," *IEEE Journal on Selected Areas in Communications*, Vol. SAC-5, No. 5, June 1987, pp. 862-870.
 - [33] S. Millman, ed., *A History of Engineering and Science in the Bell System: Communications Sciences (1925-1980)*, AT&T Bell Laboratories, 1984, pp. 422-424.
 - [34] Shahid Qureshi, "Adaptive Equalization," *IEEE Communications Magazine*, March 1982, pp. 9-16; Thomas J. Aprille, "Filtering and

Equalization for Digital Transmission," *IEEE Communications Magazine*, March 1983, pp. 17-24; T. A. C. M. Claasen and W. F. G. Mecklenbrauker, "Adaptive Techniques for Signal Processing in Communications," *IEEE Communications Magazine*, November 1985, pp. 8-19; Curtis A. Siller, "Multipath Propagation," *IEEE Communications Magazine*, February 1984, pp. 6-15.

- [35] Qureshi, *op. cit.*, p. 13.
- [36] Claasen and Mecklenbrauker, *op. cit.*
- [37] Millman, *op. cit.*, p. 424.
- [38] Vijay K. Bhargava, "Forward Error Correction Schemes for Digital Communications," *IEEE Communications Magazine*, January 1983, pp. 11-19.
- [39] *Ibid.*, p. 12.
- [40] *Ibid.*, p. 13.

Chapter 13

ALTERNATIVE SYSTEM ARCHITECTURES: CELL LEVEL

In the previous chapter, we dealt with the alternatives for the transmission link between the cell-site and the mobile unit. This may be referred to as the *circuit-level architecture*. The next higher level in the cellular architecture encompasses the creation of a *cell-level* operating system. The cell-site manages the communication traffic with a large number of mobile units operating more or less independently of one another. There are two broad questions to be addressed at this level:

1. *Spectrum management*. How is the total spectrum allocation divided into individual mobile-telephone circuits?
2. *Access*. How are individual mobile-telephone circuits assigned on demand to specific users?

The first question is of greater interest because there are several viable alternatives. The techniques of access *per se* — call setup, circuit assignment, exclusion of other users from occupied channels — are less controversial, primarily because today's cellular systems have established certain operating standards which are not likely to change.

All of the cell-level architectures we shall consider in this chapter are *multiple-access* systems, which means that every radio-telephone circuit is a *trunk* [1]. In other words, it is shared among all users and may be accessed by any user for any given telephone call. Full trunking is an essential requirement for a modern mobile-telephone system.

Older radio-telephone systems did not employ multiple access. Instead, specific users were preassigned to specific channels; originally, each mobile unit was tuned to one and only one frequency, which was shared like a party line among a number of mobiles. Obviously, like party lines,

such systems had their limitations. Later, tuning elements were incorporated into mobile units and manual scanning of a set of channels was allowed. This brought the question of access to the fore.

Older systems also approached the access question in a very makeshift fashion, by comparison at least with the operating procedures in the wire-line network. In the precellular era, access was generally under the control of the mobile unit. The basic technique was simply *contention*: mobile units would attempt to transmit on an unoccupied channel without any pre-clearance from the base station, and would continue transmitting unless interference from another user was detected. In the event of such a collision, certain back-off routines were instituted, designed to stagger the new access attempts by different users so as to allow them all to get through, ultimately. This is sometimes called *carrier-sense multiple access (CSMA)* — a rather fancy term for what one author defines as follows: "Each terminal must listen to the channel first before transmission. If the channel is idle, it sends; otherwise, it waits [2]." In older systems, the carrier sensing was done by the human user; the user could tune his unit to the various channels, like turning the channels of a TV set, until he found an empty channel on which to transmit. Later the process was automated. One type of automatic scanning involved the transmission by the base station of a tone on all idle channels; the mobile units would home on this tone to find a usable circuit. The advent of such relatively primitive multiple-access systems is recent; as late as the late 1970s, trunking was being heralded as a major new advance in spectrum efficiency.

The benefit of such crude access control was that it did not require very much *system-level* control. The penalties included: reduced throughput, potential lack of privacy, and potential for mobile units to transmit on unauthorized channels, thereby creating uncontrolled interference.

Analog cellular radio brought out what may be termed the first modern multiple-access system. Separate control channels were used to initiate the call requests to and from the mobile units, greatly improving system efficiencies and reducing collisions, attempts by two or more users to access the same channel at the same time which occur frequently in heavily loaded — i.e., efficient — systems. Contention was limited to the call setup request, which is a much shorter data burst; access to voice circuits is strictly controlled by the base station. A key feature of modern multiple-access systems is that all mobile units are under the direct and continuous control of the cell-site base station. Their transmissions are under system control, which makes possible system-level optimizations, like hand-offs, that cannot be easily accomplished in less sophisticated architectures. It also means that the system can enforce privacy and police unauthorized emissions with much greater effectiveness.

The various proposals for the next generation of cellular telephone systems will all retain these access features. Where they differ is in the area of spectrum management. In general, there are three types of cell-level architecture, based on three different types of spectrum management:

1. Frequency-division multiple access (FDMA);
2. Time-division multiple access (TDMA);
3. Code-division multiple access (CDMA).

Two terminological notes: First, TDMA systems may also encompass FDMA simultaneously and are, therefore, sometimes referred to as TDMA-FDMA. It is the TDMA characteristic, however, that differentiates them from conventional FDMA architecture. Second, some writers persist in applying the terms TDMA and FDMA in their original context only, where they referred to systems in which specific frequencies or time slots were in fact preallocated to individual users [3]. This is now an obsolete usage. TDMA and FDMA as used here refer to fully trunked systems, where there is no preassignment of frequency or time slots.

13.1 FDMA ARCHITECTURE

In an FDMA architecture, the total number of channels available within a particular cell are assigned on demand, on a first-come, first-served basis, to users asking to initiate a call, or to those for whom an incoming call has been received. Each frequency carries one single call at any one time. Any given mobile user may be assigned to any of the available voice channels for any call. Over time, any given user may expect to use all of the available frequencies at one time or another. (See Figure 13.1.)

In modern FDMA systems, including analog cellular radio, one or more of the available channels is set aside as a *control channel*. In the case of a mobile-initiated call, the call setup request, including transmission of dialed digits and sometimes other initiation information, is transmitted over this channel from the mobile to the base. The base transmits instructions to the mobile unit to move to a particular voice frequency to carry out the call. This frequency assignment is carried out rapidly and automatically; it is transparent to the mobile user.

At this time, several of the more important industry players in the United States, including AT&T and Motorola, are apparently backing digital FDMA architectures for the next generation of mobile telephony [4]. Some of the important features of digital FDMA are:

Single circuit per carrier. Each FDMA channel is designed to carry only one telephone circuit.

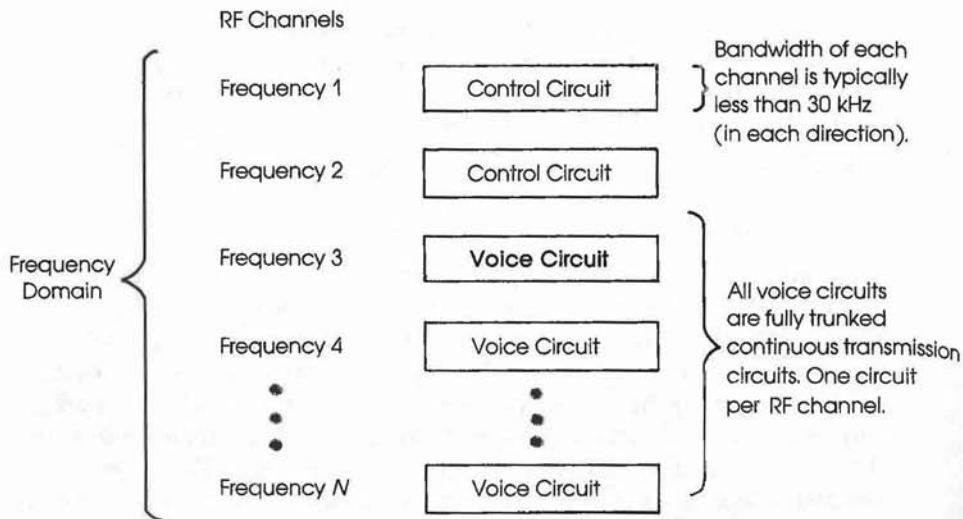


Figure 13.1 FDMA Architecture.

Continuous transmission. Once the voice channel has been assigned, both the mobile unit and the base station transmit continuously and simultaneously.

Bandwidth. FDMA channels are relatively narrow, usually 30 kHz or less, since they carry only one circuit per carrier. In fact, the trend is toward narrower bandwidths: some recently proposed digital FDMA systems have called for channels of 10 or 15 kHz [5].

Bit rates and symbol durations. Using constant-envelope digital modulation, bit rates equal to about 1 b/Hz are anticipated in most FDMA proposals [6]. In a 25-kHz channel, with 25 kb/s transmission and one bit per symbol, the symbol time would be about 40 microseconds. This is quite a long symbol time compared to the average delay spread, typically a few microseconds at most, depending upon the environment. (See Figure 13.2.) In the traditional view, this is a very important advantage for FDMA systems, because it means that the amount of intersymbol interference is likely to be quite low and little or no adaptive equalization may be required [7]. In actuality, however, the processing overhead associated with adaptive equalization is likely to loom less and less as digital signal processors become faster and cheaper.

Lower mobile-subscriber unit complexity. Along the same lines, it is sometimes claimed that FDMA mobile units will be less complex and,

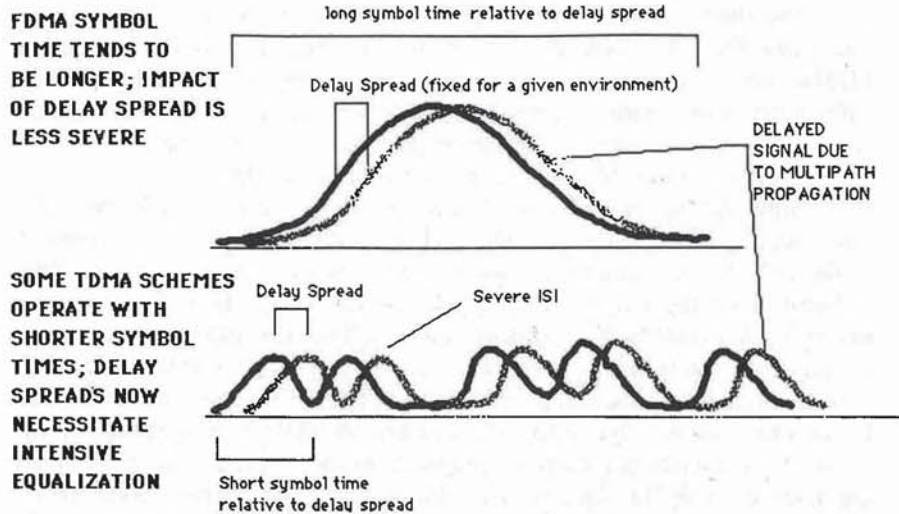


Figure 13.2 Delay Spread in an FDMA Channel versus Some TDMA Channels.

therefore, perhaps less costly than TDMA units, since they may not require equalization or the complex framing and synchronization associated with burst transmission in TDMA systems. I believe this is a transitory consideration; TDMA subscriber units are being designed today to operate on a single digital signal-processor chip, and the fact that the chip may be operating at 90% capacity, in a hypothetical TDMA implementation, instead of at 60% capacity, in a hypothetical FDMA implementation, should have virtually no impact on recurring product cost. The real mobile-unit cost drivers lie elsewhere, mainly in the radio subsystem of the unit, as opposed to the digital baseband processors.

Low transmission overhead. In an FDMA channel, the transmission to or from the mobile unit is continuous, much like T-carrier transmission on wireline or in point-to-point microwave radio. As in T-carrier, a few overhead bits may be inserted into the bit stream to allow for synchronization, framing, and certain control information, such as hand-off instructions, which have to be transmitted in the voice channel, since they occur when the call is already in progress. Because the transmission is continuous, however, the FDMA system should maintain good synchronization fairly easily with fewer bits devoted to overhead than in TDMA

systems which operate in the burst mode and are constantly starting and stopping transmission. In wireline systems, the amount of overhead ranges from less than 1% for North American T-1 transmission to 6.25% for European CCITT 32-channel PCM [8]. In some proposals for digital FDMA for cellular radio, the overhead is projected at about 2% [9]. Effectively, this means that more bits are available to the voice transmission or to error-correction coding to improve signal robustness. This is considered to be one of the chief advantages of FDMA.

High shared-system costs. A critical shortcoming of all FDMA designs, analog or digital, is that they require substantially more equipment at the cell-site base station to handle a given number of subscribers. This is because of the single channel per carrier design. If we assume, for example, that 1000 mobile users in a given cell require 100 telephone trunk circuits to provide adequate service, an FDMA system will require 100 channel elements at the cell site, 100 transmitters, 100 receivers, 200 codecs (2 for each circuit), 200 modems, *et cetera*. A TDMA system that multiplexes four circuits per carrier, however, would require only 25 channel elements to serve the same population, only 25 transmitters, 25 receivers, 50 codecs, and 50 modems — one-fourth the amount of base-station radio equipment compared to the FDMA system. The TDMA equipment would probably be somewhat more expensive, but the cost of shared-system equipment per subscriber would be much less. (The economics of this very important point will be discussed in greater detail in Chapter 15.)

Duplexer required. Because the transmitter and the receiver must operate at the same time — both are on continuously during an FDMA call — the FDMA mobile unit must incorporate a duplexer to prevent the mobile transmitter from overwhelming the mobile receiver. The duplexer circuitry, which may be taken here to include more stringent filter requirements, imposes a cost penalty of perhaps as much as 10% upon the FDMA mobile unit compared to a TDMA mobile unit, which does not need a duplexer for reasons discussed in the following section. This is a moderate disadvantage for FDMA systems.

Hand-off complexity. Because the FDMA transmission is continuous, the accomplishment of the hand-off to another channel in another cell is somewhat more difficult than in a TDMA system, where the shift can be made during an idle time slot [10]. In today's cellular systems, this has led to the awkward "blank and burst" technique, which creates difficulties for superimposed data transmissions [11].

13.2 TDMA ARCHITECTURE

In a TDMA system, each radio channel carries a number of telephone trunk circuits which are time division multiplexed. The structure of the TDMA channel is considerably more complex than an FDMA channel. Figure 13.3 portrays a typical TDMA channel structure. This TDMA system creates four time slots on each channel. A mobile unit that has accessed one of these channels transmits in a buffer-and-burst fashion; transmission from or to an individual mobile unit is not continuous. The mobile transmits on slot 1; holds for slot 2; receives on slot 3; holds for slot 4; and then transmits again on slot 1, and so repeats the cycle. This burst-transmission mode has a number of implications.

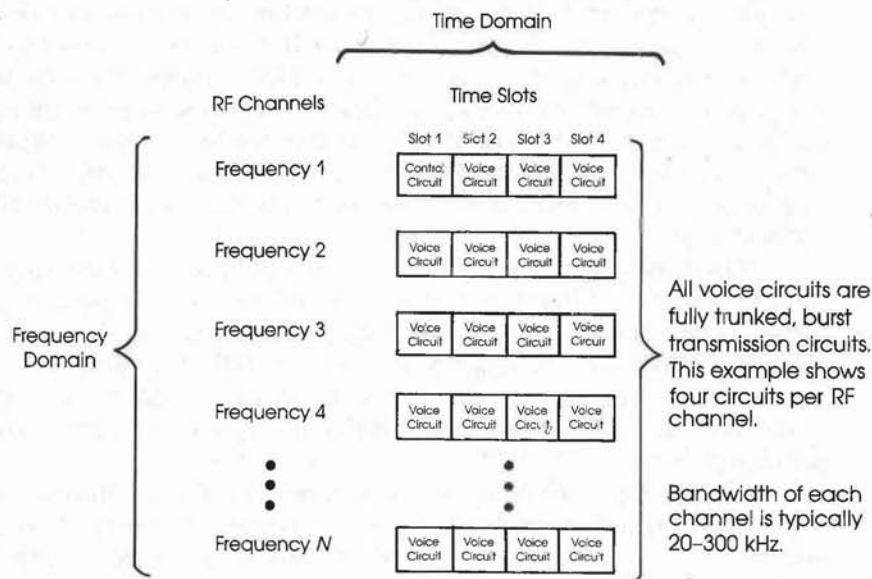


Figure 13.3 TDMA Architecture.

For example, the channel-transmission rate is no longer equal to the coding rate, or even the coding-plus-overhead rate. The channel rate is faster by a factor equal to the number of time slots in the frame. For example, in the system described above, the voice-coding rate, including overhead, is 16 kb/s. Voice coding is continuous. Since the radio transmitter

only burst-transmits during one time slot out of four, however, the transmission rate during that burst must be *four times faster*, or 64 kb/s. If there were eight time slots per frame, as contemplated by the European standard, the transmission rate during the slot-burst would have to be eight times the coding rate.

How is multiple access achieved in TDMA? The TDMA system creates a frequency-time matrix: on each frequency it creates four time slots, or eight, or whatever number may be chosen by the system architects. Each of the cells in this matrix is a telephone trunked voice circuit, which can be accessed by any mobile user on any given call. As in FDMA, the assignment of users to circuits takes place on a call-by-call basis under the control of the base station. Call setup is performed over a separate *control slot*, which corresponds to the control channel or channels in an FDMA system. While the mobile unit is on hook, it monitors the control slot continuously, listening for a page indicating that it has an incoming call. If a page is detected, the mobile unit acknowledges the page to the cell-site base station over the control slot, and then the base station transmits another message over the control slot to instruct the mobile unit to move to a given frequency and a given time slot to take the call. (The mobile-initiated sequence is virtually the same.)

TDMA proposals have gained considerable support, especially in Europe, where the GSM standard has focused upon an eight-circuit per carrier TDMA format. In the United States, TDMA has also been championed by some [12]. The significant features of TDMA systems include:

Multiple circuits per carrier. As indicated, all TDMA formats seek to multiplex at least two, and more often four, or eight, or more, circuits per carrier.

Burst transmission. As noted, the transmission from the mobile units is not continuous, but occurs during specified time slots only. This has many implications for circuit design and system control. It may also impact, positively, the cochannel interference equation, since at any given moment only a percentage of the mobile units in operation are actually transmitting. (See Chapter 15.)

Bandwidth. The bandwidths of proposed TDMA systems range from around 20–30 KHz, equivalent to today's analog channels [13], to more than ten times that wide. Bandwidth is determined in part by the choice of modulation technique [14]. Spectrally inefficient modulation approaches require a wider bandwidth to transmit the same bit stream. For example, the European standard appears to be heading toward a 200-KHz channel, multiplexing eight circuits of about 30 kb/s each, for a total channel rate of about 240 kb/s. This is a little more than 1 b/Hz, about the same as

FDMA approaches. By comparison, the IMM TDMA architecture multiplexes four circuits per carrier, but by using higher-level modulation is able to transmit the required 64 kb/s, for 16-kb/s voice circuits, within a 20-KHz occupied bandwidth, equal to about 3.2 b/Hz [15].

Bit rates and symbol durations. The higher channel rates proposed for some TDMA systems — up to 300–400 kilosymbols per second, one bit per symbol — can create a much more severe intersymbol-interference problem than FDMA systems. For a 300-kilosymbol rate, for example, the symbol time is 3.33 μ s, which is approximately the same as the delay spread that might be expected in dense urban centers. Even using four-level modulation to attain 2 b/Hz would only increase the symbol time to 6.67 μ s. Adaptive equalization would be absolutely necessary. For TDMA systems with lower channel rates, however, the equalization requirement may be no more severe than for FDMA systems. The IMM system, for example, with a 16-kilosymbol rate, four bits per symbol, has a symbol time of 62.5 μ s, and is relatively impervious to the average delay spread. It is important to remember that TDMA is *not inherently more vulnerable to the delay spread*; the degree of vulnerability in any digital system depends not upon the form of access, but upon the symbol rate in the channel, which in turn rests upon the degree of spectral efficiency of the modulation scheme.

Higher mobile-unit complexity. The TDMA mobile unit has more to do than the FDMA unit, at least on the digital-processing side. Whether this is a crucial difference depends upon the processing-device technology that is assumed. As time passes, the added processing for TDMA grows less and less significant in the total picture. Some TDMA units may also be required to do slow-frequency hopping, to improve resistance to multipath fading [16]. Slow FH circuitry would complicate the mobile design. Other TDMA proposals, however, do not call for frequency hopping; this can be treated as a separate design requirement.

Higher transmission overhead. A TDMA slotted transmission forces the receiver to reacquire synchronization on each burst. Also, guardbands may be necessary to separate one slot from another, in case unequalized propagation delay causes a far user to slip into the adjacent slot of a nearby user. Because of this, TDMA systems usually need much more overhead than FDMA systems. The conventional view is that TDMA overhead requirements can run to 20–30% of the total bits transmitted, which is indeed a significant penalty [17]. With proper design, however, this can be lessened. The IMM TDMA system today utilizes less than 9% for overhead. Nevertheless, it is true that TDMA overhead will always exceed

FDMA overhead, which means that fewer bits will be available at a given bit rate for voice coding or error correction. The significance of this inefficiency depends upon the scope of the TDMA overhead requirement, and upon the choice of coding schemes.

Lower shared-system costs. As already indicated, the major advantage of TDMA systems over FDMA arises from the fact that each radio channel is effectively shared by a much larger number of subscribers. The cost of the central-site equipment is reduced dramatically. A more detailed analysis of these savings is presented in Chapter 15.

No duplexer required. An additional cost advantage for TDMA over FDMA arises from the fact that by transmitting and receiving on different slots it is possible to eliminate the duplexer circuitry entirely, replacing it with a fast switching circuit to turn the transmitter and receiver on and off at the appropriate times. This should lead to a reduction in the cost of the mobile unit [18].

Hand-off complexity. Because the TDMA transmitter is turned off during idle slots, TDMA units have the opportunity to carry out a more efficient hand-off procedure [19]. In particular, the blank-and-burst problem can be avoided to maintain data-transmission integrity.

Openness to technological change. TDMA systems have another edge over FDMA which may outweigh everything else, at least in the eyes of the system architect or regulator who looks to the long-term technological viability and flexibility of the system. As bit rates fall for coding algorithms, a TDMA channel is more easily reconfigurable to accept new techniques. Within the existing channel rate, the slot structure can be redefined to support lower bit rates or variable bit rates. For example, if the channel rate is 64 kb/s, divided into four 16-kb/s slots, an 8-kb/s coder may be accommodated by redividing the channel into eight slots instead of four. This modification, if carried out with careful attention to other architectural constraints, should be implementable by means of ROM (*read only memory*) changes in the digital circuitry. That is, existing radio hardware can most likely be utilized at the base station. Retrofitting existing mobile units may or may not make economic sense; a TDMA format, however, can be designed to accommodate different bit rates, different slot lengths. Since the channel rate, bandwidth, and other features of the radio transmission remain the same, such changes can be introduced without disrupting the cellular network frequency plan.

Although not as straightforward, modifications in modulation techniques can also potentially be accommodated in TDMA systems through software upgrades or options. For example, the IMM system previously referred to possesses the ability to adapt modulation levels from 4-level PSK to 16-level PSK, depending upon channel conditions [20]. The same

hardware is used; the option is built into the system and mobile-unit software. It is possible to envision future modulation adaptations that could be implemented through stored program changes to digital circuitry without affecting radio-channel characteristics significantly.

By comparison, incorporating new technology into an FDMA would appear far less straightforward. To realize the potential spectrum-efficiency gain from, say, a reduction in coding rates, it would be necessary to redesign the FDMA to operate on still narrower channels. Aside from the system-wide implications, including changed carrier-to-interference ratios and reuse patterns which could be disrupted by rechannelization, much of the radio hardware at the base station would have to be substantially altered or replaced. This would involve a considerable investment.

In short, TDMA systems leave the door open wider to continuing technological improvements. Since they operate fully in the digital domain, many upgrades can be implemented "in software" — which is to say, with minimal impact upon expensive radio hardware. FDMA systems, which can only be upgraded through overhauling the radio channel itself, are much less flexible.

13.3 CDMA ARCHITECTURE

Spread-spectrum techniques have been described in detail in Section 12.3. The characteristic form of multiple access for spread-spectrum systems is known as code division multiple access. Each mobile unit is assigned a unique randomized code sequence, different from and orthogonal to, i.e., uncorrelated with, all other codes. In an FH/SS system, this code is used to generate a unique sequence of frequency hops. In a DS/SS system, the code is used to generate the randomized noiselike high-bit-rate signal that is mixed with the information signal to spread the spectrum.

"Unlimited" circuits per carrier. SS systems utilize single, or very few, wideband carriers to transmit a great many individual telephone circuits. Where FDMA systems transmit only one circuit per carrier, and TDMA a handful, CDMA systems could potentially transmit hundreds. In fact, as noted in the discussion of spread-spectrum methods, there is no hard limit on the number of circuits that may be transmitted.

Bandwidth. Proposed SS channels are very wide — typically 1–10 MHz — compared to TDMA and FDMA systems.

Bit rates and symbol durations. Because of the very high bit rates in the SS channel, the symbol times are very short. In a DS/SS system, with a one-megabit channel rate, each symbol would be only one microsecond in length, assuming BPSK or some other 2-level modulation. This is less than the average delay spread. Intensive equalization would be required.

Lower mobile complexity (?). Some writers have suggested that the mobile units in a CDMA system would be very simple, compared to TDMA and FDMA units. If so, this simplicity would appear to benefit chiefly the radio portion of the subscriber unit by relaxing or eliminating filter requirements. The digital portion of the mobile unit would likely be as complex as TDMA units, if not more so. Certainly the requirement for frequency hopping in FH/SS systems is no simple task.

Overhead (?). I am not sure that it is meaningful to discuss overhead for CDMA SS systems in the same way we have discussed overhead for FDMA and TDMA. The concept of overhead as bits expended for channel administration, bits which cannot be used for voice communication, is difficult to apply here. The entire SS concept is in effect a way of building in a massive overhead which, paradoxically, improves the ability of the signal to coexist with other transmissions and with environmental noise and multipath.

Shared-system costs. Presumably, an SS system ought to enjoy relatively low system costs per subscriber, since a very large number of subscribers are sharing the cost of the base-station channel equipment. This indeed may prove to be a decisive future advantage for SS, once the costs are better known.

Unfortunately, as noted in Section 12.3, there are still too many unknowns for most people, this author included, concerning the actual implementation of SS techniques and their performance in the field. It is still difficult to draw conclusions about CDMA SS architectures in comparison to better understood alternatives like FDMA and TDMA.

REFERENCES

- [1] Victor O. K. Li, "Multiple Access Communications Networks," *IEEE Communications Magazine*, June 1987, pp. 41-48.
- [2] *Ibid.*, p. 43.
- [3] *Ibid.*
- [4] Joseph Tarallo and George I. Zysman, "A Digital Narrowband Cellular System," *Proceedings of the 37th IEEE Vehicular Technology Conference*, Tampa, June 1-3, 1987, pp. 279-280.
- [5] *Ibid.*
- [6] Jan Uddenfelt and Bengt Persson, "A Narrowband TDMA System for a New Generation Cellular Radio," *Proceedings of the 37th IEEE Vehicular Technology Conference*, Tampa, June 1-3, 1987, pp. 286-292.
- [7] *Ibid.*

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- [8] John C. Bellamy, *Digital Telephony*, New York: John Wiley and Sons, 1982, pp. 206-208.
 - [9] FCC Seminar on "The Future of Cellular Radio," Washington, D. C., September 2, 1987.
 - [10] Uddenfelt and Persson, *op. cit.*
 - [11] Z. C. Fluhr and P. T. Porter, "AMPS: Control Architecture," *Bell System Technical Journal*, January 1979, pp. 43-69.
 - [12] D. Ridgley Bolgiano, "Spectrally Efficient Digital UHF Mobile System," *Proceedings of the 38th IEEE Vehicular Technology Conference*, Philadelphia, June 1988.
 - [13] *Ibid.*
 - [14] Uddenfelt and Persson, *op. cit.*
 - [15] Bolgiano, *op. cit.*
 - [16] Uddenfelt and Persson, *op. cit.*
 - [17] James Mikulski, Remarks at the FCC Seminar on "The Future of Cellular Radio," Washington, D. C., September 2, 1987.
 - [18] Uddenfelt and Persson, *op. cit.*
 - [19] *Ibid.*
 - [20] Bolgiano, *op. cit.*