CHAPTER 1

Introduction

Overview

On the night of April 14, 1912, the RMS *Titanic*, en route from Southampton, England, to New York, struck an iceberg and sank in the North Atlantic. Over fifteen hundred lives were lost when the ship went down, but fortunately for the more than seven hundred passengers and crew who were able to find accommodation in the ship's lifeboats, the *Titanic* was equipped with a wireless system. The *Titanic*'s wireless included a 5 kW rotary spark transmitter built by the Marconi Wireless Company. Distress calls were heard by a number of ships at sea, including the *Carpathia* that arrived on the scene of the disaster several hours later, in time to rescue the survivors.

The wireless traffic between the *Carpathia* and shore stations in North America was widely monitored. News was passed to the press even before the fate of the *Titanic*'s passengers was known. The widespread publicity given to this disaster galvanized public interest and propelled wireless communication into the forefront of attention. The age of wireless communication might be said to have begun with the sinking of the *Titanic*.

As social beings, humans have a fundamental need to communicate. As we grow and learn, so do our communication needs evolve. Dramatic advancements over the past century have made several facts about our evolving communication needs rather apparent: (1) The information that needs to be communicated varies widely; (2) the types and amount of information that needs to be communicated continuously change, typically toward higher complexity; and (3) current technology rarely meets communication demands, so technology evolves. These facts, along with a healthy worldwide economy, produced the wireless revolution in the late twentieth century. Wireless communication is here to stay, and the design principles used to create wireless technology differ enough from those used to create wired communication systems that a separate treatment is necessary.

In this text the process of designing a wireless communication system is presented from the perspective of a systems engineer. Two main goals of the text follow immediately: (1) to present the concepts and design processes involved in creating wireless communication systems, and (2) to introduce the process of systems engineering and the role of a systems engineer to provide an organizing framework under which to introduce the wireless system concepts. In the industrial world, the design process flows in an organized manner from problem definition, through conceptual and detailed design, to actual deployment. In this text, information from first principles to advanced topics is presented in a fashion compatible with systems-engineering design processes, which are required to manage the development of complex systems.

In Chapter 1 the problem of moving information wirelessly from any point A to any point B is introduced. In every engineering endeavor it is important to have a clear understanding of the problem to be solved before beginning, and so the system and its requirements are defined. The role of a systems engineer and the methods of systems engineering are introduced as the perspective for conducting our study and design.

Chapter 2 presents the most fundamental element of our wireless system, the radio link that connects points A and B. This chapter addresses two issues: how radio waves propagate in space, and how much power must be provided at point B to ensure a desirable quality of communication service. This chapter focuses on propagation in free space and the development of the **range equation**, a mathematical model familiar to both radio and radar engineers. We introduce the antenna as a system element and the antenna design engineer as a member of the design team. To answer the question of how much power is enough, we develop models and analysis tools for thermal noise and describe how thermal noise limits performance. Signal-to-noise ratio (SNR) is introduced as a measure of system performance. Finally, the concept of link budget, a fundamental tool for radio frequency (RF) systems engineering, is presented and supported with examples.

Chapter 3 focuses on signal propagation in the real world. Obstacles in the signal path and indeed the very presence of the Earth itself modify a signal as it travels between endpoints. Various terrestrial propagation models are presented and discussed. These models provide methods for predicting how a signal will propagate in various types of environments. The phenomena associated with shadow fading, Rayleigh fading, and multipath propagation are described as well as the effects of relative motion of a receiver and of objects in the environment. Statistical methods are developed that allow engineers to create robust designs in an unstable and changing environment. Receiver design and channel modeling are added to the list of design functions that a systems engineer must understand to competently interact with team members who specialize in these design disciplines.

Given a basic understanding of methods to ensure that an adequate signal can be conveyed between two endpoints, we discuss the concepts and complexities involved in allowing many users in a large area to share a common system. Geographic diversity and frequency reuse are discussed and used as the basis for developing the "cellular" concept in Chapter 4. The cellular concept is the fundamental basis for designing and deploying most wireless communication systems that must provide service for many users over a large geographic area. The chapter describes how engineers using cellular engineering techniques plan for growth in user capacity and coverage area. Traffic engineering and the use of the Erlang formula as tools for predicting and designing a system for user capacity are demonstrated. At this stage of the design, system-level concerns are well above the device or subsystem level.

In Chapter 5 we describe the methods used to convey information over the wireless link. The process for conveying information using a radio signal, called modulation, is described from a trade-off perspective. The characteristics of several digital modulation schemes are developed and their attributes are compared. The key design parameters of data throughput, error rate, bandwidth, and spectral efficiency are contrasted in the context of optimizing a system design. Also in this chapter we introduce spread-spectrum signaling. Spread spectrum is a modulation technique that broadens the bandwidth of the transmitted signal in a manner unrelated to the information to be transmitted. Spread-spectrum techniques are very effective in making signals resilient in the presence of interference and frequency-selective fading. Our study of spread-spectrum techniques continues in Chapter 6, as these techniques provide an important basis for multiple-access communications.

The first five chapters provide all of the fundamental elements of system design for providing radio coverage to many users over a large area and for designing the components that support the conveying of information at a given quality of service (QoS) across a wireless link between individual users. Chapter 6 introduces various methods that allow many users to access the system and to simultaneously use the resources it provides. In this chapter we introduce the classical methods of frequency-division and time-division multiple access, as well as spread-spectrum-based code-division multiple access which allows independent users to share the same bandwidth at the same time. In providing a multiple-access capability, a systems engineer unifies a variety of system-level design activities to make the system accessible to a varying number of users.

People wish to communicate different types of information, and the information they want to communicate comes from a variety of sources. Chapter 7 discusses several of the types and sources of information commonly communicated in contemporary wireless systems. The required QoS that is to be provided to a system's users must be accounted for in nearly every aspect of a system design. Users' perceptions of what constitutes good quality vary for different types and sources of information and always depend on how well a signal representing the information is preserved in the communication process. Chapter 7 discusses some of the fundamental relationships between the perceptual measures of QoS and specific system design parameters. Understanding these relationships allows a systems engineer to design for predictable QoS at minimum cost. As modern wireless systems are designed to carry information in digital form, a major part of this chapter is about efficient digitization of speech. We discuss two general categories of speech "coding": waveform coding and source coding. As an example of the waveform coding technique we examine traditional pulse code modulation (PCM). Our example of source coding is linear predictive coding (LPC). This latter technique has been extremely successful in providing high-quality, low-bit rate digitization of voice signals for cellular telephone applications. Following the discussion of speech coding, the chapter concludes with an example of coding for error control. Convolutional coding is used for this purpose in all of the digital cellular telephone systems. We introduce the coding method and the widely used Viterbi decoding algorithm.

Chapter 8 wraps up the presentation with a review of the lessons developed in the preceding chapters. This is followed by an overview of the generations of cellular telephone systems and a look into the future at the way wireless systems are evolving to provide an increasing array of services at ever-higher quality. As wireless systems evolve, they tend to become more complicated. Thus the role of the systems engineer in managing the design process and in understanding the myriad of design trade-offs and interactions becomes ever more important.

System Description

What Is a Wireless System?

In the most general sense, a wireless system is any collection of elements (or subsystems) that operate interdependently and use unguided electromagnetic-wave propagation to perform some specified function(s). Some examples of systems that fit this definition are

- Systems that convey information between two or more locations, such as personal communication systems (PCS), police and fire department radio systems, commercial broadcast systems, satellite broadcast systems, telemetry and remote monitoring systems
- Systems that sense the environment and/or objects in the environment, including radar systems that may be used for detecting the presence of objects in some region or volume of the environment and measuring their relative motion and/or position, systems for sensing or measuring atmospheric conditions, and systems for mapping the surface of the Earth or planets
- Systems that aid in navigation or determine the location of an object on the Earth or in space

Each of these systems contains at least one transmitting antenna and at least one receiving antenna. In the abstract, an antenna may be thought of as any device that converts a guided signal, such as a signal in an electrical circuit or transmission line, into an unguided signal propagating in space, or vice versa. We note in passing that some systems do not need to transmit and receive simultaneously. For example, the WiFi local area network computer interface uses a single antenna that is switched between transmitter and receiver. Specifically, a pulse of energy is transmitted, after which the antenna is switched to a receiver to detect the response from the network access point.

As the examples show, some systems may be used to convey information, whereas others may be used to extract information about the environment based on how the transmitted signal is modified as it traverses the path between transmitting and receiving antennas. In either case, the physical and electromagnetic environment in the neighborhood of the path may significantly modify the signal. We define a **channel** as the physical and electromagnetic environment surrounding and connecting the endpoints of the transmission path, that is, surrounding and connecting the system's transmitter and receiver. A channel may consist of wires, waveguide and coaxial cable, fiber, the Earth's atmosphere and surface, free space, and so on. When a wireless system is used to convey information between endpoints, the environment often corrupts the signal in an unpredictable[1] way and impairs the system's ability to extract the transmitted information accurately at a receiving end. Therein lies a major difference between wired and wireless systems. To provide a little further insight, we compare some of these differences.

The signal environment or channel characteristics of a single-link wired system are rather benign.

- At any instant of time, the path between endpoints is well known and many of its degrading effects upon a signal can be measured and compensated for.
- Signal dropout (signal loss), momentary or otherwise, is very rare.
- Random effects such as "thermal noise" and "interference" are fairly predictable and controllable and therefore less likely to corrupt the signal to the extent of unintelligibility.
- The signal environment does not change or changes very slowly with time.
- The endpoints do not move.

In contrast, the signal environment of a wireless system is hostile.

- The direction of the signal cannot be completely controlled, and the path between endpoints is not unique.
- The path between endpoints is time-varying.
- Signal dropouts are frequent.
- Noise and interference levels are often difficult to predict and time-varying.
- Objects in the path between and surrounding the endpoints affect the signal level and its content.
- Variations in the signal environment change with geographic location, seasons, and weather.
- For mobile systems, as in cellular and PCS systems, at least one of the endpoints may be moving at an unknown and sometimes significant speed.

As an everyday example, the differences between wired and wireless systems may be compared to the difference between carrying on a conversation with someone in the environment of your living room versus conversing in the environment of a busy airport runway. The same principles of communication theory apply to the design of both wired and wireless communication systems. In addition to those specific functions associated with the unguided propagation of signals, however, the most profound differences between the implementations of wired and wireless communication systems relate to overcoming the signal impairments introduced by a changing wireless channel and, for mobile systems, compensating for the possible motion of the endpoints.

1. The term *unpredictable* is used in the sense that the signal cannot be perfectly determined at any point in space. As we will see, however, we can infer a great deal about a signal using statistical modeling. These models are a fundamental basis for system design.

In addition to providing the fundamental basis for the design of wireless communication systems, the principles of communication theory, RF engineering, and propagation in real-world environments also apply to a host of other applications. As examples, these principles apply to a multitude of radar applications, including object or target detection, location and ranging, speed/velocity measurement, terrain mapping, weather monitoring, and navigation. In fact, many of the techniques used to develop modern personal communication systems were originally developed and proved for radar applications. In contrast to wireless communication systems that convey information between endpoints, radar systems analyze the way transmitted signals are reflected and modified by the presence of objects or variations along the signal path to extract information about the objects or the environment that the signal traverses. As a simple example, consider that a narrow pulsed-RF signal is transmitted in a given direction. Objects within the transmission path reflect some fraction of the signal incident upon them. If a receiver colocated with the transmitter detects an approximate replica of the transmitted signal sometime after the transmitted signal is sent, it is reasonable to assume that an object is located in the direction of transmission and the distance to the object is proportional to the time delay between transmitted and received signals. If no signal is detected within a specified period of time, it is assumed that there are no reflecting objects in the path of the signal, over a given range.

Clearly our general definition of a wireless system fits a vast range of seemingly unrelated applications. It is profoundly important, however, to recognize that all of these applications are founded on a common set of enabling principles and technologies encompassing communication theory, RF engineering, and RF propagation. Although the focus of this text is personal communication systems, the principles and techniques to be presented provide a strong foundation for study of other wireless system applications.

General Architecture, Basic Concepts, and Terminology

At a high level, every communication system is described by a common block diagram. In this section we present a basic functional description of each of the blocks to introduce some of the terminology of wireless systems and to help motivate later discussion of each of the functions.

We begin by considering the general block diagram of a wireless system for a generic application as shown in Figure 1.1. Many of the blocks and their functions apply to both wired and wireless communication systems. Note, however, that the blocks contained within the dashed outline are fundamental and necessary to wireless systems. With the exception of the antennas, all of the remaining blocks may also be found in wired system applications.

The box labeled "Information Source" includes all functions necessary to produce an electrical signal that adequately represents the actual information to be communicated between end users. The term **end user** refers to a person or device that is the source or recipient (sink) of the information to be communicated. The term **endpoint** refers to the location of the transmitters and receivers in the communication path. End users may or may not be colocated with the endpoints. The functions of the Information Source box might include

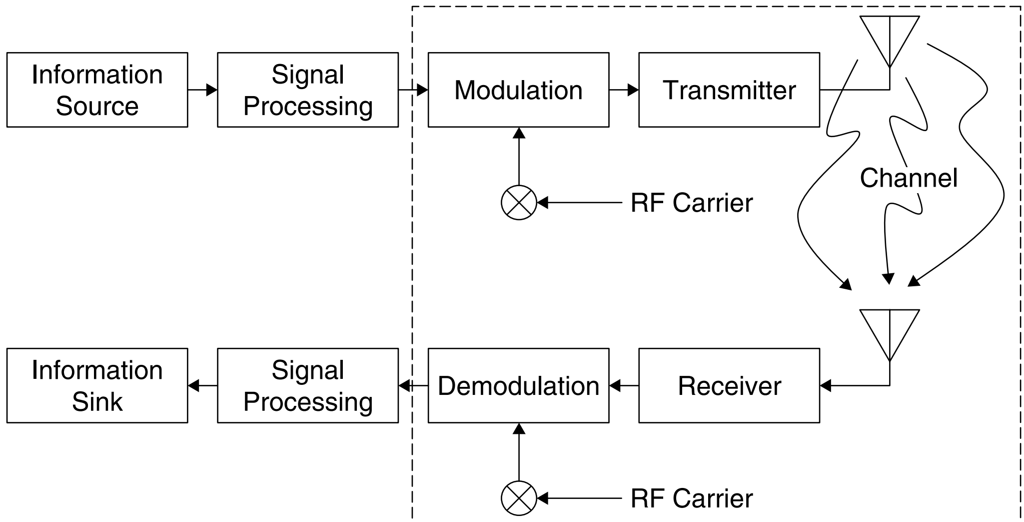

Figure 1.1 A Wireless System

- Creation of an analog waveform representing speech derived from a microphone, or creation of a digital bit stream resulting from sampling of an analog waveform
- Formatting digital information such as data, text, sampled audio, images, video, and so forth

The signals from information sources are typically bandlimited; that is, they contain frequencies from DC (or near DC) to some nominal cutoff frequency. They are termed **baseband signals**.

The box labeled "Signal Processing" encompasses all operations necessary to convert information signals into waveforms designed to maximize system performance. Signals may be processed to increase capacity, throughput, intelligibility, and accuracy and to provide other auxiliary functions. In modern wireless systems, many of the signal-processing functions are aimed at improving signal reception by mitigating the corrupting effects of the transmission medium or environment. Signal-processing functions on the transmitting end may include

- Converting analog signals to digital signals of a specific type
- Shaping signals to minimize the corrupting effects of the environment or transmission medium
- Compressing and coding signals to remove redundancies and improve throughput
- Coding signals to aid in the detection and correction of errors caused by the environment
- Encryption of signals for privacy
- Multiplexing information from several sources to fully utilize the channel bandwidth
- Adding information that simplifies or enhances access and control for the endpoints or end users

Signal processing may also include digital modulation, a technique used to spread the signal spectrum by coding one or more bits into a substantially longer bit stream. We will say more about digital spread spectrum and its benefits in a later chapter.

Signal processing, especially digital signal processing (DSP), has dramatically enabled rapid advances in the state of the art of communications in general and wireless personal communications in particular. The majority of topics to be covered in this text, as in any text on modern communications, will focus on some aspect of signal processing.

The efficient radiation of an electrical signal as an electromagnetic wave requires that the physical size of the antenna be comparable in size to the wavelength of the signal. This is also true for the reception of such an electromagnetic wave. This physical limitation renders the radiation of baseband signals impractical. As an example, consider the size requirement for radiating a 10 kHz signal. Recall from basic physics that the wavelength of a signal is related to its frequency by

$$\lambda = c/f, \tag{1.1}$$

where c is the speed of light in free space, 3×10^8 m/s. The wavelength of a 10 kHz signal is about 98,000 feet. If a typical quarter-wavelength ($\lambda/4$) antenna were used, it would be 24,600 feet or 4.7 miles in length. In contrast, $\lambda/4$ antennas in the cellular (900 MHz) or PCS (2 GHz) bands are 3.3 inches and 1.5 inches long, respectively. For this reason, practical wireless systems employ high-frequency or radio frequency sinusoidal signals called **carriers** to transport (or carry) information between endpoints.

The laws and regulations of the countries in which the systems are to be deployed govern and constrain the radiation of electromagnetic waves. Various frequency bands are allocated by law for specific applications; for example, there are AM, FM, and TV broadcast bands; public safety bands; airport communication, radar, traffic control, and maritime applications bands; and others. Furthermore, the laws may regulate transmitted power, transmitted spectrum and spectrum characteristics, modulation method, geographic location, tower height, and so on. Figure 1.2 shows some of the spectrum allocations in the ultra-high-frequency (UHF) band from 300 MHz to 3 GHz. A detailed chart of spectrum allocations in the United States is available from the National Telecommunications and Information Administration (NTIA).[2] In the United States, the Federal Communications Commission (FCC) is the agency entrusted with the responsibility for administering the use of the radio spectrum, granting licenses, and working with government and private industry to develop fair and equitable regulatory rules and standards.

Information signals are imposed upon a carrier signal by modulating (varying) its amplitude, frequency, and/or phase in direct relation to the variations of the information signal. At the receiving end, an information signal is extracted from the carrier by a process of demodulation. The boxes labeled "Modulation" and "Demodulation" refer to any of a wide range of techniques

2. National Telecommunications and Information Administration. Source: www.ntia.doc.gov/osmhome/allochrt.html, accessed August 8, 2006.

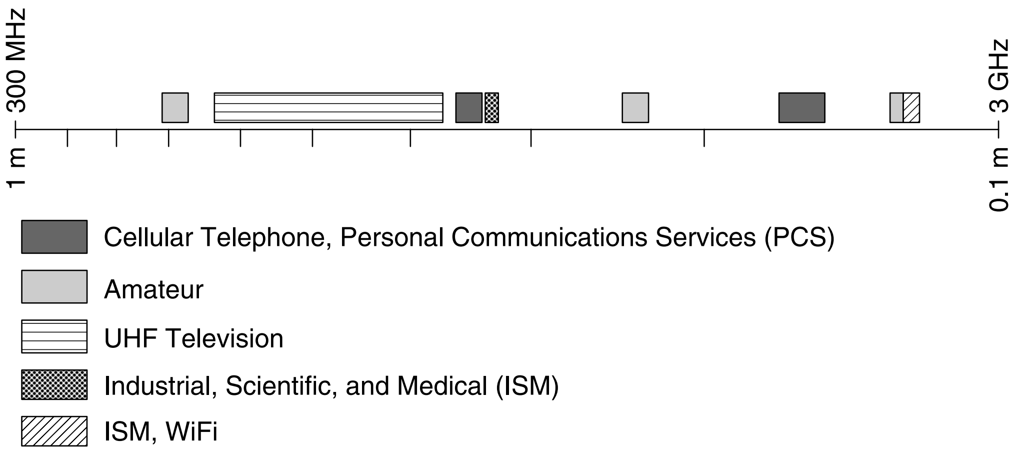

Figure 1.2 Some Spectrum Allocations in the UHF Band (January 2008)

that may be used to impose/extract an information signal upon/from a carrier. As we will discuss later, the choice of modulation scheme is strongly influenced by a number of factors, including available frequency spectrum, spectrum rules and regulations, required throughput, channel characteristics, and QoS requirements. In the context of a wireless system (or a "broadband" wired system that employs coaxial cable, waveguide, or fiber as a transmission medium), a modulator translates the spectrum of a baseband signal to a bandpass spectrum centered about some high "radio" frequency appropriate for the intended application and consistent with spectrum regulations.

Many wired systems (for example, "plain old telephone service" [POTS]) use transmission media that allow the system to operate effectively at baseband. For such systems, a modulator translates an information signal into waveforms (sometimes called line codes) that are optimized for the given transmission medium and application. For example, a line code may convert a binary bit stream (1s and 0s) into a bipolar or multilevel voltage waveform, or it may convert a bit stream to positive and negative voltage transitions.

For wireless systems, a transmitter is essentially an RF power amplifier and appropriate bandpass filter. A transmitter drives a transmitting antenna (often through a coaxial cable or waveguide) and ensures that the modulated RF signal is radiated at a power level, and within a bandwidth, specific to the application and applicable regulations. Wired systems, on the other hand, often use transmitters termed **line drivers** that ensure that transmitted signals have sufficient energy to overcome the line losses in the path to the receiving end.

The power intercepted and absorbed by a receiving antenna is usually much lower than the transmitted power. For example, when a cellular base station transmits with a power of one watt, the received signal two miles away may be only a few tenths of a nanowatt. In fact, a receiver may be located so far from the transmitter that the signal level is comparable to system noise. **System noise** is a random signal that arises from a number of sources such as galactic radiation, engine ignitions, and the very devices used to amplify a received signal. In particular, we will discuss **thermal noise**, which is a random signal arising from the thermal agitation of electrons in the receiving antenna and its downstream interconnections and circuitry. The difference between transmitted and received power is inversely related to the distance (raised to some power) between the transmitting and receiving antennas and is termed **path loss**.

A receiver is essentially an amplifier designed to optimally reproduce the transmitted signal and remove the carrier. As such, a receiver is matched to the characteristics of the transmitted signal. Receivers usually employ high-gain, low-loss front-end amplifiers that are designed to minimize the level of thermal noise that they will pass to downstream functional blocks.

Signal processing on the receiving end seeks to restore the signal originating at the source. It converts the signal from the receiver into the form required for the endpoint recipient, that is, the Information Sink. In modern digital communication systems, signal processing at the receiving end is aimed at the reliable detection of bits. This may include error detection and correction, depending on the coding used to transmit the original signal, and also may include digital demodulation of a spread-spectrum signal.

Historical Perspective

A hundred years ago, a radio "system" was a transmitter, a receiver, and a path that could be successfully traversed by the miracle of radio waves. Even then there were broader issues to resolve—trade-offs that could be made between one element of the configuration and another. A more powerful transmitter or a more sensitive receiver; a higher mast or a directive antenna—these were some of the potential design improvements that could extend the range of the system when needed. Which of these to adopt became an important question, affecting cost and having performance implications in other dimensions. Was the power demand excessive? Was range being limited by circuit noise within the receiver or by external environmental noise? Was it limited by a physical obstruction over which one might radiate?

Radio had evolved from the design of general-purpose transmitters and receivers to a variety of "systems" with specific applications. Broadcast systems created the wildly popular phenomena of radio and television entertainment, by creating a way to deliver that entertainment inexpensively to a mass market. The trade-offs shifted again; base transmitters could be extremely powerful and expensive, sited on tall buildings or hills, using tall masts and elaborate gain antennas, but the millions of home receivers had to be low-cost consumer products.

"Propagation engineers" now had a more difficult problem; rather than designing a single path from one radio to another, they were concerned with an "area of coverage" in which signal quality was likely (but not guaranteed) to be acceptable. Moreover, the demand for channels required channels to be reused in nearby areas, so that interference needed to be predicted and controlled in the service areas of systems. Probability and statistics had joined the sciences that contributed to system design.

The first mobile telephone systems emerged in the 1940s, quickly became popular, and introduced a number of new trade-offs. The mobile equipment, carried in the trunks of cars and powered from the car battery, needed to be smaller and lower in power (as well as cheaper) than the base station equipment; but coverage areas needed to be large, since cars would need to operate throughout large urban areas. A single high-powered base station could serve an entire urban area of more than a thousand square miles, but the lower-powered return paths from the vehicles could not, and satellite base station receivers became necessary. The higher cost of the (relatively few) satellite base stations could now be traded off for the (smaller) savings in power in the more numerous mobile units. This trade-off of expensive base equipment against more numerous mobile radios is characteristic of such systems.

In the major urban areas, a mobile telephone system would now consist of several radio channels, serving several hundred customers. This aggregation of radios and customers led to the incorporation of telephone traffic-handling probabilities into mobile system design—designers would now calculate the probability that an idle channel would be available. Because of the shortage of channels, however, service was very poor before the days of cellular systems. In the 1950s mobile operators who set up calls were replaced by equipment to automatically select idle channels, allowing the dialing of telephone calls in both directions. Signaling had been added to voice communication on radio channels, together with the first steps toward complex logic.

As early as the 1940s, when the first crude mobile telephone systems were going into service, AT&T had begun to propose a new concept in mobile radio system design. Rather than using a single high-powered base station to cover an entire urban area, they proposed to create a service area from a grid of smaller coverage areas, called “cells.” This had several important advantages. It allowed both base and mobile radios to operate at lower power, which would reduce radio costs. It also allowed larger service areas, since additional small coverage areas could always be added around the periphery to expand the system. Most importantly, although nearby cells required different channels to prevent interference, farther cells could reuse the same channels. In this way each channel could handle tens or even hundreds of calls in the same urban area, overcoming the limitations on capacity that were a result of spectrum shortages. These new systems would require a few hundred channels to get started, however, and the needs of the broadcasters were more persuasive in that period.

In 1968 the FCC finally opened the inquiry that ultimately led to cellular systems in the 1980s. For the advantages they provided, however, these systems demanded a new level of complexity. This time, the major complexity was not in the radio design, which saw few radical changes. With the introduction of small cells, calls could cross many cells, requiring mobile locating, channel switching during calls, and the simultaneous switching of wireline connections from one cell to another. Mobiles had to identify systems and find the channels on which calls could be received or originated, which required the introduction of microcomputers in mobile radios and made the technology of telephone switching machines an important element of radio system design. Moreover, with the introduction of so many disciplines in the design of a single system, and a variety of new trade-offs to be made, it was no longer practical for the many engineers to mediate these trade-offs, and the practice of systems engineering became a new and important discipline.

The introduction of cellular systems also marked the continuation of a long-term trend, in which spectrum shortages drove system designs to higher and higher frequencies. Frequencies such as 900 MHz (and later, 2 GHz) were used for such applications for the first time, and it became necessary to understand the propagation characteristics at these frequencies in real-world environments. Moreover, the old methods of the propagation engineer, in which terrain elevations were plotted to determine coverage, were no longer practical for hundreds of cells in a single system, and statistical coverage methods were developed to assure an acceptable quality of coverage. This trend has reversed once again more recently, as computers have allowed detailed terrain studies to be carried out for many cells.

Even as the first analog systems such as the Advanced Mobile Phone Service (AMPS) were being deployed in the early 1980s, efforts were under way to provide significant performance and capacity enhancements enabled by digital communications, advancements in digital signal-processing technology, and speech encoding. The Global System for Mobile Communications (GSM) was a cooperative effort of European countries to define an evolutionary system that provided increased capacity (or equivalently improved spectral efficiency), improved the quality of service, and allowed seamless roaming and coverage across the continent, and eventually around the world. The GSM standard was the first to encompass both the radio elements and the interconnection of serving areas to provide a holistic approach to ubiquitous service. As the first commercial digital cellular system, GSM demonstrated the power of digital signal processing in providing spectrally efficient, high-quality communications. GSM systems began deployment in the early 1990s.

By the mid-nineties, digital spread-spectrum systems were being introduced in North America under standard IS-95. Introduced by Qualcomm, Inc., a U.S.-based company, this system allows all cells to use the same frequency. Each channel is distinguished not by a distinct frequency or time slot but by a spreading code. The fundamental basis for this system is a technique called code-division multiple access (CDMA), a technique that has become the universal architecture for third-generation systems and beyond. CDMA systems have provided another technological leap in complexity, bringing additional enhancements to capacity, information bandwidth, quality of service, and variety of services that can be provided.

Each generation of wireless systems builds upon the technological advances of the prior generation. For each step in this evolution, the classical tools of the engineer remain, but they are honed and reshaped by each subsequent generation. The importance of system design and the role of systems engineering have grown substantially with each new technological generation. The continuing demand for new services and increased capacity, interacting with ongoing technological advancement, leads to new opportunities for system design, new problems to solve, and even the development of new engineering disciplines.

Systems Engineering and the Role of the Systems Engineer

Wireless communications, and communications in general, are specializations in the discipline of systems engineering. Our approach to the study of wireless communications from the perspective of a systems engineer is therefore a study in a specialized field of systems engineering. It is fitting, then, that we begin our study by discussing systems engineering at a general level.

Some type of system supports nearly every aspect of our daily life. Systems help us to travel anywhere on the Earth (and beyond), create memos, solve complex problems, store and retrieve vast arrays of information, cook our food, heat and light our homes, entertain ourselves and our friends, and of course communicate with each other. There is no universally accepted standard definition of a "system," but the purposes of this discussion are served by the working definition: A **system** is any collection of elements or subsystems that operate interdependently to perform some specified function or functions.

An automobile, an airplane, a personal computer, a home, a television or radio, an ordinary telephone, and a microwave oven are all common examples of systems. But at a lower level, an automobile engine or transmission, an airplane's hydraulic system, a computer chip or microprocessor, a home air-conditioning or heating unit, or the video circuitry of a television or audio circuitry of a radio are also systems by definition. Depending on the context of discussion, a system may often be referred to as a subsystem, since it may perform only a few of the intended or auxiliary functions of the overall system of which it is a part. For example, an automobile is a system that conveys passengers and/or objects to arbitrary geographic locations. Its subsystems are the engine, transmission, braking system, steering system, chassis, dashboard, and so on, all of which are necessary for an automobile to perform the functions we have come to expect. Likewise, an engine is a collection of other subsystems such as the ignition system, fuel system, and emission control system. At some level the terms *system* and *subsystem* become less relevant. For example, a passive circuit may be considered a system, but considering resistors, capacitors, and inductors as subsystems has little relevance. In such instances we may choose to use the term *component* or *element.*

In the previous sections we introduced a simplified block diagram for a generic wireless system. Each block may be considered a subsystem of the overall system. Furthermore, each block performs some direct or auxiliary function needed to meet the general requirements of the system application. Regardless of the intended wireless application, the designs of the various blocks and their functions are founded on principles derived from distinct specialty areas. To identify a few of these specialty areas:

- Antennas and electromagnetic wave propagation
- Microwave circuit theory and techniques
- Signals, systems, and signal processing
- Noise and random processes
- Statistical nature of the environment and its effects on a propagating signal
- Communication theory
- Traffic theory
- Switching and networking theory

Depending on complexity and scale, the design and development of a system usually require knowledge and professional expertise in a number of distinctly different disciplines. For example, the development of large-scale wireless systems, such as personal communication systems or advanced radar systems, requires the participation of specialists in such diverse disciplines as

- Antenna design
- RF propagation and radio environment modeling
- Microwave circuit design
- Transmitter design
- Low-noise amplifier (LNA) design
- Modulator/demodulator (modem) design
- Digital circuit/system design
- Signal processing
- Real-time, non-real-time, and embedded software development
- Power systems and power management
- Switching, networking, and transmission
- Mechanical structures and packaging
- Human factors engineering
- Manufacturing engineering
- Reliability and quality engineering
- And, last but not least, systems engineering

Successful development companies usually have processes (sequences of well-defined steps and procedures) and information systems that allow development teams to work and communicate effectively; track progress; manage schedule, budget, and other resources; control changes; and maintain and improve product quality. Highly successful companies also review their processes, constantly seeking ways to reduce development costs and schedule time while improving product quality, customer satisfaction, and cost competitiveness. In fact, process engineering and improvement is an important area of specialization. A strong and continuously improving development process is often vital to a company's ability to compete in a given market.

Development processes may vary among companies, but they all possess common phases of particular emphasis, for example,

- Product/system definition
- Design/development
- Integration and system test
- Manufacture
- Product life-cycle management

The specific activities in each phase may vary significantly, and many of the phases may, and often do, run concurrently.

One of the most important factors contributing to the successful development of a system is a complete, well-directed, and stable product definition. The product definition, sometimes called "functional product requirements" (FPR), is usually developed by a marketing or market research organization in concert with members of the technical development community, especially systems engineering. In addition to specifying the required attributes of the system from a customer perspective, an FPR also defines all the information necessary to ensure a viable financial return for the investors, including cost to manufacture the product, time to market, development budget, projected manufacturing ramp-up and life-cycle volumes, key competitive attributes, and so forth.

The design and development phase of any system usually begins with a system design. It is one of the most important products of a systems-engineering effort. A system design consists of all the requirements, specifications, algorithms, and parameters that a development team uses to design and develop the hardware and software necessary to implement and manufacture a product in accordance with an agreed-upon product definition. System-level documentation may include

- System-level requirements—a high-level technical document that translates the needs expressed from a customer perspective into technical constraints on system functions, performance, testing, and manufacture
- System architecture—a specification that defines all of the parameters and subsystem functions necessary to ensure interoperability among subsystems and meet system requirements, including distribution of system-level functions among the subsystems, definition of subsystem interfaces, and specification of system-level controls
- Supporting analyses—appropriate documentation of all analyses, simulations, experimentation, trade-off studies, and so on, that support the choice of key technical parameters and predict and/or verify system-level performance

As it relates to a system design, the responsibilities of a systems engineer are to

- Translate customer-level functional requirements into technical specifications at a system level
- Develop a system architecture and determine specific parameters to ensure that the system will meet the desired level of functionality and performance within specified constraints
- Perform trade-off analyses among the system elements to ensure that the implementation requirements can be met within the specified constraints and technology limitations
- Develop and negotiate specific requirements for each of the subsystems based on analysis, modeling, experimentation, and simulation

These functions are the focus of this text and are the basis for many other functions that systems engineers perform. These other functions might include

- Interacting with potential customers
- Developing human-interface specifications

- Developing plans, methods, and criteria for system integration and verification
- Interfacing with government and legal entities
- Specifying deployment, maintenance, and operations procedures
- Competitive analysis
- Supporting regulatory and standards development

Depending on the complexity of the system being developed, a team of systems engineers, each of whom has a particular area of expertise, may be required to fully perform all of the systems-engineering functions of a development.

Problem Statement

This text develops the major systems aspects of personal communication systems while demonstrating the application of relevant theory and principles and introducing students to some of the real-world aspects of the wireless systems-engineering profession. It is fitting, therefore, that the subject matter be presented in the context of a solution to a general systems-engineering problem. To be specific, we seek to design a wireless telecommunication system that will

- Support the communication of information of various types, including speech, text, data, images, and video, in urban, suburban, and rural environments and with quality approximating that of wired communications
- Be capable of expanding in geographic coverage
- Allow for virtually limitless growth in the number of users
- Support endpoints that are not geographically fixed and, in fact, may be moving at vehicular speeds

Many of the attributes of this system, as stated previously, were in fact the major objectives underlying the development of the very first cellular mobile telephone systems. Our discussions of principles and concepts are presented as motivation for solving this systems-engineering problem in particular. In view of the continued advances in digital technologies and the directions of modern communication systems, our emphasis will be on digital wireless communications, although many of the principles apply to both analog and digital systems.

Since the advent of the first mobile phone systems, the meanings of some commonly used terms have become blurred by marketing and advertising efforts to provide some level of distinction between early first and later generations of systems. Specifically, the terms *cellular* and *PCS* are often used to identify the cellular frequency (850 MHz) or personal communication systems (or services) (1.9 GHz) frequency bands. The term *cellular,* however, originally referred to the technology underlying nearly all of the systems that may be classified as personal communication systems. We will endeavor to ensure that the meaning is always clear in context; however, it is important to recognize that most modern systems are capable of operating in either band.