Chapter 1

INTRODUCTION

There are few things in nature more unwieldy than the power-limited, space-varying, time-varying, frequency-varying *wireless channel*. Yet there is great reward for engineers who can overcome these limitations and transmit data through such harsh environments. The explosive worldwide growth of personal communications services through the 1990s is a testament to the business opportunities that result from conquering the wireless channel. However, given the emergence of newer wireless systems that require more and more bandwidth, the task of conquering the wireless channel is becoming more difficult. This task requires a thorough background in wireless channel modeling.

Furthermore, understanding and modeling the wireless channel provides beautiful insight into a number of other problems in the physical sciences. This book presents the basic principles for describing the random fading that plagues space–time wireless channels. Although most of the examples and discussions are in the context of commercial radio applications, it is possible to apply the theory to a wide range of problems in any field that involves dynamic wave propagation.

This chapter presents an overview of channel modeling history in the context of wireless communications and motivates the need for studying the full space–time wireless channel. This chapter includes

- Section 1.1: Historical context of wireless channel modeling.
- Section 1.2: Importance of the spatial channel interface.
- Section 1.3: Trends in wireless influencing channel modeling.
- Section 1.4: Content summary of this book.

Indeed, the current state of wireless communications points to a coming epoch when understanding the space–time channel is not a luxury, but an absolute necessity.

1.1 Perspectives in Propagation

To understand the importance of radio channel modeling, it helps to understand some history and background in the development of wireless communications. This section shows how the material presented in *Space–Time Wireless Channels* fits into the historical context of wireless technology development.

1.1.1 Early Years of Radio

The world's first digital radio system was actually the world's first radio system. Guglielmo Marconi's first wireless transmission in 1897 used Morse code (a digital representation of text) to communicate from ship to shore. He soon commercialized his technology by installing wireless systems in transatlantic ocean vessels. These Marconi wireless systems were first used to send distress calls to other nearby boats or shoreline stations, even in the famous luxury liner *Titanic*.

This first wireless system used a spark-gap transmitter, a glorified spark plug that sprayed electromagnetic waves in all directions at all frequencies. The spark-gap transmitter could be wired to send simple Morse code sequences, but the real challenge of the system was to receive the radio signal. For that, Marconi used a *coherer*, a device that could only detect the presence or absence of strong radio waves. This form of detection - coupled with the fact that only mechanical switching forms of signal amplification existed - meant that Marconi's wireless was only capable of digital transmission.

Note: What Is a Coherer?

A coherer is a glass tube that contains loose metal filings resting on the bottom, as illustrated in Figure 1.1. Two contact wires are placed on opposite ends of the tube, allowing an external apparatus to measure the overall resistance to electrical current through the tube. Normally, resistance across loose metal filings is large due to the loose, jagged contact points between the small shards of metal. If a strong electromagnetic wave (i.e., from a nearby radio transmitter) travels across the filings, they *cohere*; the overall resistance drops and the radio wave is detected. To repeat detection, a coherer must be shaken mechanically to return the filings to their uncohered state.

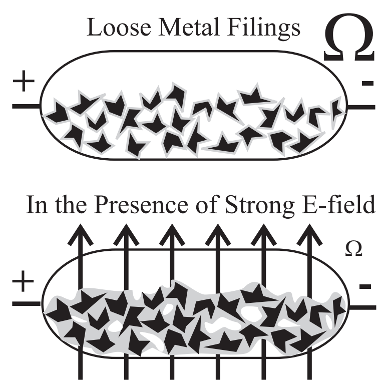

Figure 1.1 In the presence of a strong electric field, metal filings cohere and their overall electrical resistance drops.

The Marconi wireless was heavily limited in range and data speed by the power required to send and receive signals. However, radio communications - as well as every other electronic technology - changed in 1906 when Lee de Forest invented the first vacuum tube. The vacuum tube amplifies *analog* waveforms, so radio communication was liberated from its low-rate, on-and-off keying. It was now possible to transmit high-fidelity analog signals, such as voice and music, over amplitude modulation (AM). Commercial AM radio stations proliferated across the world in the 1920s, as marked on the timeline in Figure 1.2.

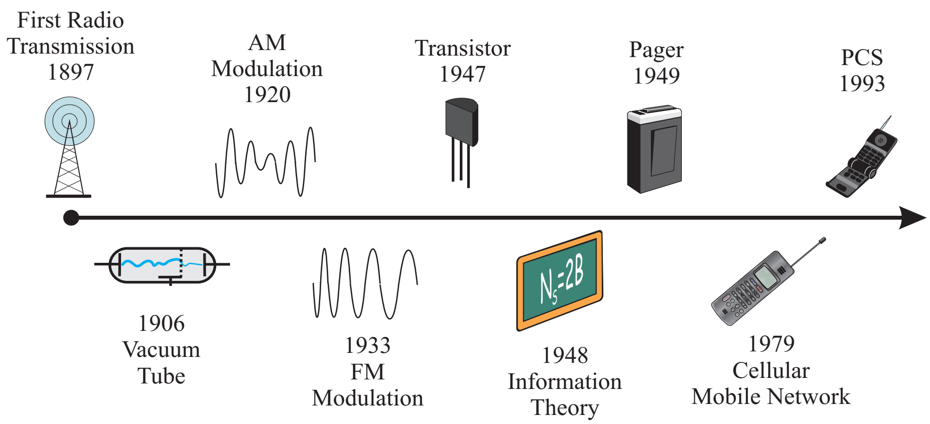

Figure 1.2 Some important milestones in radio communications.

The next great milestone in radio came in 1933, when E. H. Armstrong invented frequency modulation (FM). FM radio was the first example of signal-processing used to overcome the noisy, deleterious radio channel. In this case, the nonlinear modulation scheme of FM was capable of trading usable bandwidth for signal fidelity. For once, engineers could design radio links with a degree of freedom other than transmit power.

Many other wireless devices followed (television, military radios, radar, etc.), but perhaps the most important and sublime milestone occurred in 1948 with Claude E. Shannon's publication of his famous "A Mathematical Theory of Communications" [Sha48]. There are two extremely important principles outlined in this paper that revolutionized the design of communication links:

- All analog signals can be represented by sets of discrete digital symbols to a controllable degree of precision.
- The fundamental rate at which digital symbols may be sent through any channel is a function of bandwidth, signal power, and noise power.

In essence, Shannon's theory predicted that *digital* communications, rather than analog communications, was the best way to send data through any link. It was only a matter of time before most radio communications would use digital modulation. It turned out to be a *long* time, however.

1.1.2 Cellular on the Scene

Digital communications may have been *preferable* to analog communications, but with the technology of 1948 it was still not *possible*. Any type of digital communications requires discrete signal-processing operations that simply were not possible (commercially) with the vacuum tube technology of the day. Only with the advent of solid-state devices, such as the transistor in 1947, could engineers implement the signal processing required for digital communications. Even this was not possible overnight, as solid-state electronics had to undergo years of research and development before producing integrated circuits (IC) that were fast enough and cheap enough to implement signal processing. In the meantime, the wireless industry continued developing analog radios.

The modern cellular phone and paging industry was birthed in the post-Shannon period using analog radio technology. In 1949, Al Gross (the inventor of the walkie-talkie) introduced the first mobile pager, for use by hospital doctors. In 1979, the first commercial cellular phone market opened in Tokyo using a type of analog FM modulation to send voice signals to users. Similar systems in North America and Europe followed. By the late 1980s, analog cellular communications was a commercial success, and companies were pressing government regulatory agencies to open up new radio spectrum for more voice services.

Cellular telephony presented wireless engineers with a uniquely different design challenge. Previously, most radio systems operated in a *noise-limited* radio channel, where thermal noise was the sole source of signal degradation. As a mobile receiver moved in such a channel, fading would cause the signal power to fluctuate in space as the average noise power remained nearly constant; performance of the radio link depends on maintaining an adequate *signal-to-noise* ratio. Cellular networks, however, have *interference-limited* channels, because nearby cells reuse the same frequency spectrum. As illustrated in Figure 1.3, the interfering signal fluctuates in space along with the desired information signal. Careful spatial modeling becomes much more crucial for the noise-limited case.

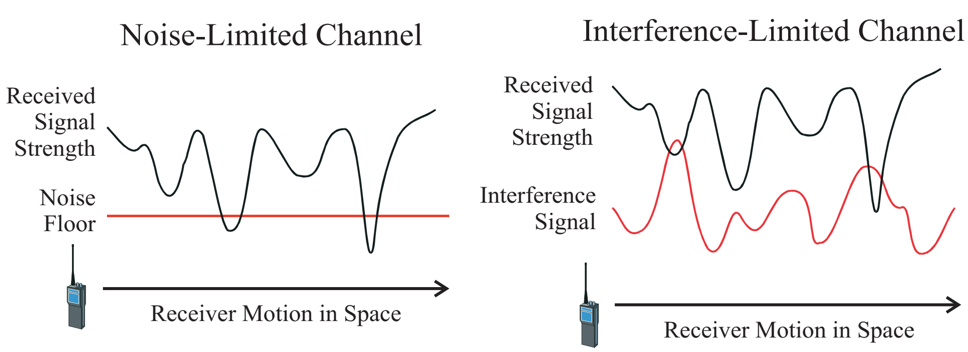

Figure 1.3 Fading for mobile communications causes sporadic moments of poor signal-to-interference+noise ratio (SINR) levels.

In 1993, the second generation of cellular telephone networks, called *Personal Communications Services* (PCS), were launched and rapidly spread throughout the world in just several years. Unlike their predecessors, these PCS networks were true digital communications systems, enabled by the cheap, fast, solid-state devices for signal-processing and radio-frequency (RF) electronics that became available at the end of the 1980s. Finally, the prophetic ideas of Shannon and digital information transmission had become a reality in the commercial wireless industry. In fact, the whole story of wireless communications is a story of great ideas followed by decades of incubation until the intellectual and industrial forces governing hardware development enabled implementation. Indeed, one must only look at recent vintages of proposed signaling techniques to understand the future of commercial wireless.

1.1.3 Origins of Channel Modeling

Most engineers are aware of the great inventions made at Bell Laboratories (the transistor, the laser, the communications satellite, to name just a few). Less appreciated, however, is the laboratory's enormous contribution to the theory of channel modeling and statistical communications analysis. The stochastic modeling work by Bell Laboratories researcher Stephen O. Rice stands out as one of the crucial achievements in describing radio communications. In 1944, Rice published a theory of random noise, which has since become a foundation of statistical analysis in communications [Ric44], [Ric45]. This work, originally used to characterize the noise in large-carrier AM and some FM signals, had extensive application for the description of fading signals, including level crossing rates, fade duration statistics, and the Rician envelope distribution that bears his name.

Still, the type of random processes described by Rice were signals with a single time dependency. In the early post-war period, there was little need for other types of analysis in radio communications. However, work began on the concept of mobile cellular telephony in the mid 1940s. As work progressed, it became obvious that newer channel descriptions were necessary - models that described the concept of *spatial multipath fading*. Unlike point-to-point microwave or satellite links, the cellular telephone user would operate receiver terminals buried within the clutter of a dense scattering environment, such as a cityscape or a neighborhood. In these types of propagation environments, objects such as terrain, buildings, and trees would block direct contact between a user terminal and a tower-top base station, but would instead provide a link between the two by scattering numerous low-powered radio waves from one to the other. These *multipath* waves arrive at the receiver from many different directions and, as illustrated in Figure 1.4, create pockets of constructive and destructive interference in space. As a receiver moves through space, it rapidly experiences the peaks and nulls of multipath fading, often losing a signal momentarily, even though there is a large amount of average signal power propagating through the immediate area.

Spatial fading is, perhaps, not a novel concept to most engineers. The first experience with spatial fading is usually encountered in a basic engineering or physics

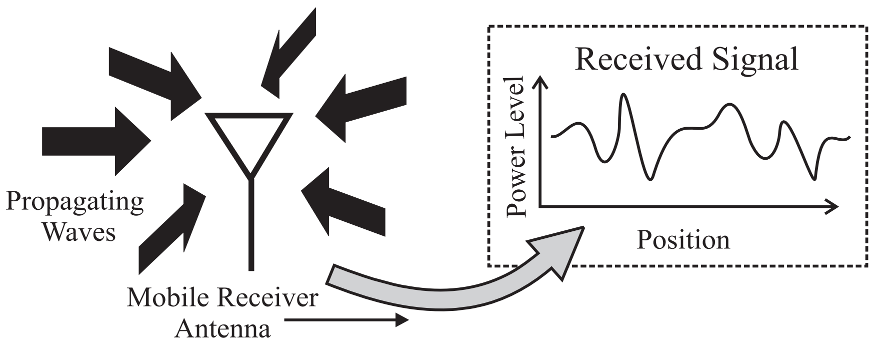

Figure 1.4 Small-scale fading for a mobile receiver in a multipath environment.

course on electromagnetism. The classic example is the transmission line, as shown in Figure 1.5. Recall that, unless the load is matched perfectly to the impedance of the transmission line, a wave sent down the line will partially reflect so that the net wave propagation is the superposition of two waves traveling in opposite directions. If we used a "mobile" power meter to measure the power along the transmission line, we would observe a standing wave interference pattern with peaks and nulls, each occurring at half-wavelength intervals.

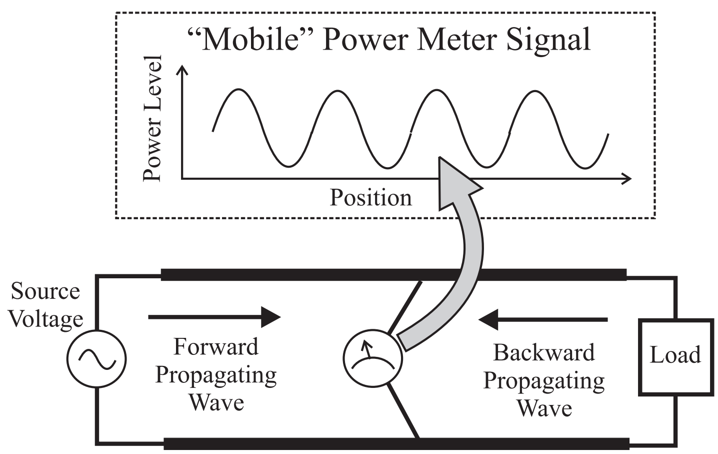

Figure 1.5 Signal fluctuation across a time-harmonic transmission line.

The transmission line example is a simple one. There are only two discrete waves. These waves, which are also scalar in the analysis, create a standing wave interference pattern that is regular and predictable. Contrast this to the case of multipath fading for a mobile wireless receiver. The multipath channel may have numerous waves of vastly differing magnitudes that obey *vector* wave propagation laws.

Yet the transmission line example is still a useful analogy. For example, as the frequency of the voltage source is increased, the wavelength of radiation decreases and the distance between peaks and nulls across the transmission line shrinks proportionally. The same effect is true of spatial multipath fading for a wireless mobile receiver. Modern cellular telephones operate in the upper UHF and microwave bands. In these bands, the wavelength of radiation is less than 1 m. At these wavelengths it is possible for a mobile receiver to receive a signal with a high-powered peak in one region of space and then, with just a few centimeters of movement, to receive virtually nothing.

As research on mobile telephony accelerated at Bell Laboratories during the 1960s, some important innovations in channel modeling were made. Researchers proposed the sum-of-waves model for spatial multipath [Oss64]. Clarke later extended this work to several basic scattering distributions, applying much of the Rician random process theory to the spatial fading for mobile receivers [Cla68]. Gans published a method for constructing a *Doppler spectrum* from the angles-of-arrival of multipath waves [Gan72]. Jakes published seminal work on the concept of *space diversity* - using multiple antennas to avoid deep signal fades [Jak71], [Jak74].

An important result in all of this research was the emergence of the omnidirectional Rayleigh fading model. This model assumes that radio waves arrive at the mobile receiver with equal power from all directions. This spatial channel models a fluctuating received signal strength with *Rayleigh statistics*. When a constant velocity is assumed by the mobile receiver, the model provides useful analytical expressions for channel coherence and fading statistics. This simple model is still a de facto standard in mobile radio system design.

1.1.4 Rayleigh Pessimism

The omnidirectional Rayleigh model is also unrealistic, but it is unrealistic in a way that endears it to engineers. It is a *pessimistic* channel model for conventional mobile receivers. There are two important characteristics of a mobile wireless receiver affected by small-scale channel fading: fade margin and update rate. The omnidirectional Rayleigh is useful for calculating both of these parameters.

Fade Margin

Fade margin is a critical parameter in the site design of a cellular radio system. The mobile handset requires a minimum signal-to-interference+noise ratio (SINR) to maintain the specified data rate and not drop calls. This minimum SINR is most difficult to achieve when the handset is operating on the fringe of a cell, where the distance between mobile unit and base station is the largest and received power is the weakest.

Because of small-scale fading, it is not enough to simply design a cellular network based on *average* power at the fringe of cells. If this were the case, a handset would drop a call at even the slightest signal fade, since the received signal power fluctuates over space. Instead, wireless engineers add anywhere from 12 dB to 18 dB of extra fade margin to the radio power link budget to ensure that small-scale fading does not drive the received signal below an acceptable level. On the business side of wireless, dB's translate into dollars, so the fade margin cannot be made arbitrarily high. The actual amount depends on the modulation scheme and the distribution of signal fades.

At this point, fading with Rayleigh statistics becomes a useful benchmark for a link design. Rayleigh statistics are considered by many to be a worst-case scenario of signal fading because the received signal strength experiences such deep fades (as we will see in Chapter 5). If a wireless receiver works in a Rayleigh fading channel, then it is likely to work in other types of channels. Thus, the fade margins of all systems are based on Rayleigh spatial fading statistics.

> *Note: Even More Pessimistic Statistics*
>
> Many have thought that worse-than-Rayleigh fading statistics were only possible in contrived mathematical analysis, but not in physical practice. In Chapter 5 we show a class of fading statistics that often leads to even deeper and more frequent signal fades than the Rayleigh fading channels. See Section 5.4 for a discussion of the *TWDP* fading distribution.

Update Rate

A narrowband receiver in a fading channel must apply some type of *automatic gain control* (AGC) to counter the unpredictable fading in received signal strength. An AGC unit in a handset is basically an amplifier with variable gain that increases when signal strength is low and decreases when signal strength is high. The key issue for an engineer designing AGC is update rate, the maximum speed that the receiver must change the gain in a realistic fading channel. To calculate this, we have to consider the worst-case scenario where fading is changing the fastest. The most pessimistic estimate would be the highest possible mobile user velocity in the propagation with the multipath arriving from all directions in space.

Once again, the omnidirectional Rayleigh model provides the pessimistic result. Since the angle-of-arrival is omnidirectional, it is impossible to generate fading with closer peaks and nulls in space (the reason for this becomes clearer in Chapter 6). A user talking in a car on the highway in an omnidirectional Rayleigh propagation environment will experience the fastest signal fading and will require the highest update rate. The update rate of most adaptive equalizers (of which the AGC is a simple example) are designed with this philosophy.

Changing Paradigm

Of course, Rayleigh pessimism is predicated on a purely passive design philosophy; the wireless engineer designs a communications system for worst-case fading scenarios and accepts whatever penalties are imposed upon a receiver by spatial fading. Emerging digital radios take more proactive efforts to overcome channel fading with dynamic modulation, diversity, and channel coding schemes. Furthermore, wireless systems of the future may employ *space–time processing* to further combat the fading channel. In fact, as we will see in Chapter 9, these wireless systems exploit the presence of multipath to *enhance* the transmission of data through a wireless link - a far cry from the design philosophy of early mobile radio. Ironically, Rayleigh fading becomes an optimistic, best-case scenario of operation for these future systems - and it is very bad engineering practice to design with optimism.

1.1.5 Channels with Multiple Dependencies

Despite the advances in spatial channel modeling in the 1960s, the treatment of the wireless channel was still usually restricted to a single scalar dependency. Since the analysis of fading channels requires some elegant random process theory, there was difficulty in characterizing channels with full space, time, and frequency dependencies. The seminal contribution to this part of the puzzle comes from work performed at MIT's Lincoln Laboratories during the 1950s. A research group performed groundbreaking research in the field of radio astronomy, where a theoretical framework for studying stochastic signals of multiple dependencies was first developed [Gre62].

Out of this work came a brilliant piece of scholarship by P. A. Bello in 1963, which was the first research to describe stochastic communication channels that were combinations of time-varying and frequency-varying random processes [Bel63]. The work itself may have been a little ahead of its time, however, since broadband communications were not in widespread use (thus, no need for the frequency-varying aspects of channel models). As time marched onward, bandwidths became larger and joint channel dependencies became more important. The work by H. Hashemi in the late 1970s was some of the first to study truly random wideband temporal channels in the context of wireless communications [Has79].

Extensions of the original Lincoln Lab theory to joint spatial modeling of wireless channels were absent as late as the year 2000. R. G. Vaughan presented joint-dependency Fourier analysis techniques for space in [Vau00], and B. H. Fleury presented the first description of joint space–time–frequency wireless channels in [Fle00]. Clearly, the field of space–time wireless channel modeling is still in its infancy, with a great deal of work and innovation left to be done.

1.2 The Case for Space

This book places particular emphasis on *spatial* channel modeling, because this is both the most complicated aspect of the wireless channel and, not surprisingly, the least understood. This section provides several arguments for why space is crucial in the future study of wireless communications.

1.2.1 Complexities of Wireless Channels

The wireless channel is often neglected in texts and courses on communications. Rarely does an engineer ever study anything more complicated than the *additive* *white Gaussian noise* (AWGN) channel. In AWGN channel modeling, the received signal is set equal to the transmitted signal with some proportion of Gaussian white noise added. The AWGN model, pictured in Figure 1.6, works well for very simple communications through band-limited channels corrupted mostly by thermal noise.

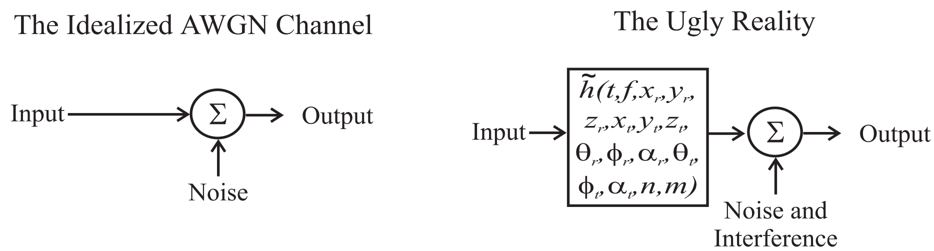

Figure 1.6 In contrast to the idealized additive white Gaussian noise (AWGN) channel, the true wireless radio channel has numerous dependencies.

For realistic wireless channels, however, there will be signal distortion that is described by a *channel transfer function*. Many engineers have working knowledge of "black-box" transfer functions that represent linear, time-invariant channel effects - those described by a single time dependency using the operation of convolution. The wireless channel, on the other hand, has multiple dependencies. In fact, some channels may have up to 16 different dependencies! Consider the following dependencies (we will discuss some of these in detail in the next chapter):

- **Frequency:** The wireless channel depends on the transmitted frequency.
- **Time:** The wireless channel is time-varying.
- **Receiver Translation:** The wireless channel depends on the position movement (called *translation*) of the receiver antenna. In three-dimensional space, translation is actually three different scalar dependencies in the wireless channel.
- **Transmitter Translation:** What is true for the receiver is also true for the transmitter. The freedom to change transmitter position in three-dimensional space adds another three dependencies to a wireless channel representation.
- **Receiver Orientation:** Translation is only one type of spatial dependency. A receiver antenna may be reoriented in any direction in space, which changes the polarization and gain pattern interaction of the receiver antenna with incoming radio waves. An antenna may be rotated in azimuth or elevation or be tilted laterally. Changes in orientation add up to three dependencies to a wireless channel representation.
- **Transmitter Orientation:** The radio channel also depends on the transmitter antenna orientation. This adds three more dependencies to the wireless channel.

- **Multi-Element Receiver:** The use of multiple antenna elements at the receiver adds one discrete dependency to a wireless channel.

- **Multi-Element Transmitter:** The use of multiple antenna elements at the transmitter adds another discrete dependency.

So there are the 16 total radio channel dependencies. A characterization of the realistic wireless channel can be overwhelming.

Note that most of the dependencies can be categorized as spatial aspects of the wireless channel, summarized in Figure 1.7. Translation, orientation, and multi-element dependencies all influence the spatial filtering of the channel. They also happen to be the least-understood aspects of the wireless channel. Indeed, space really is the final frontier for channel modeling.

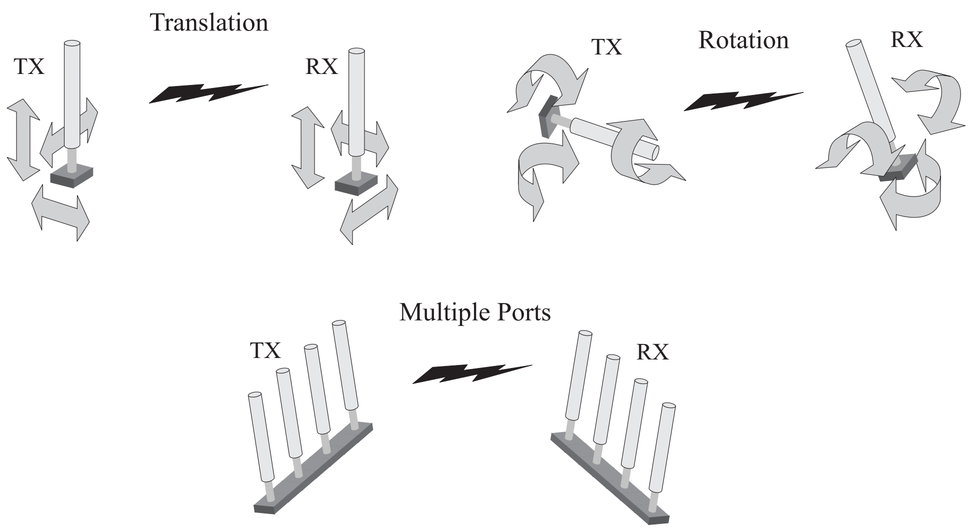

Figure 1.7 There are many types of spatial dependencies in a wireless channel: antenna translation, antenna rotation, and multiple ports for both transmitter (TX) and receiver (RX).

There is both a pessimistic and optimistic way of viewing all of these dependencies. Each dependency is another layer of complexity for understanding the transmission of wireless information. Each dependency is also a potential source of fading and unpredictability. On the other hand, each dependency may be viewed as an opportunity to increase channel capacity. Just as bandwidth or transmission time can be increased to send additional data, the spatial dimensions of a wireless channel may also be exploited similarly to increase capacity, so the 16 dependencies implies 16 potential opportunities to increase channel capacity. There are many fascinating design issues involving wireless channels with multiple dependencies.

1.2.2 Channel Primacy in Communications

When Shannon derived channel capacity equations, he showed that the fundamental limit on data rate in a communications system depended almost solely on the amount of power (in proportion to noise) delivered to a receiver. This limit is universal, independent of any of the signal-processing operations that may occur at either the transmitter or the receiver. The principle of the Shannon limit has key implications for wireless system design.

The modern approach to digital communication design requires wireless engineers to use a baseband block-diagram approach for building transmitters and receivers that span a radio link [Skl01]. In this scheme, the transmitter performs operations such as source coding, channel coding, multiplexing, modulation, and multiple access operations on a stream (or streams) of information. Each of these operations is represented by a functional block in Figure 1.8. The operation of the receiver is functionally the inverse of the transmitter, performing block operations in the reverse order to recover the original information.

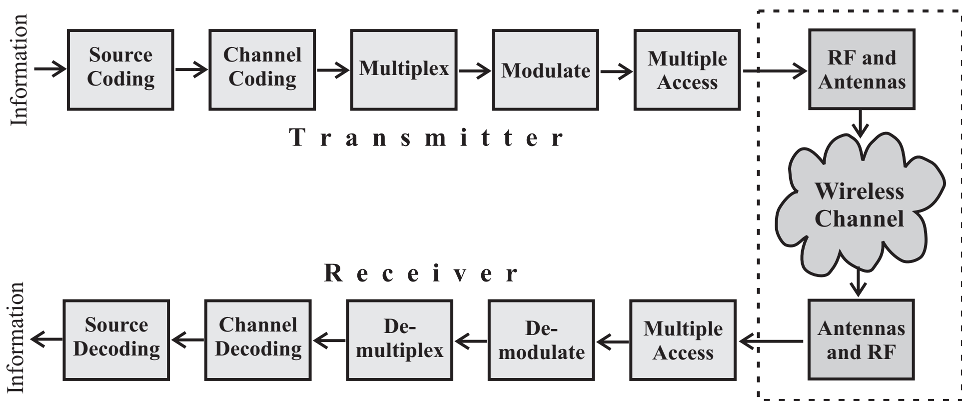

Figure 1.8 Some basic operations of a digital wireless communications system may be broken into functional blocks. (See B. Sklar's textbook [Skl01] for an outstanding, exhaustive block-diagram analysis of digital systems.)

In between the baseband block operations of transmitter and receiver, the signal passes through the wireless channel and the radio-frequency (RF)/antenna hardware that physically interacts with this channel. It is this part of the transmission, on the right side of Figure 1.8, that determines Shannon channel capacity. Thus, the communications engineer is at the mercy of whatever happens in this part of the link. The engineer selects appropriate blocks from an arsenal of signal-processing schemes and, upon success, has designed a system that approaches the available channel capacity. Engineering the baseband blocks of a digital communications link is a very close-ended problem: We know that an optimum design is achieved if the link performance approaches the Shannon limit.

Not so for the RF engineer, who works with the hardware and antennas that interface with the wireless channel. The physical and spatial interface with the radio channel is an *open*-ended problem, with no guarantee that even a successful solution is an optimal solution. From this viewpoint, studying the wireless channel interface has some of the richest design possibilities.

1.2.3 Wasted Space

Commercial wireless has mostly operated under the single-port paradigm: A single antenna element - usually a metal loop or whip - is attached to a user terminal. The first AM and FM radios, walkie-talkies, and pagers all used a single antenna. Despite all of the vaunted advances in signal processing and radio portability, a survey of digital handsets and wireless LAN terminals at the start of the 21^{st} century would show the exact same single-port architecture. The single antenna element for radio terminals is a lot like the lead-acid battery for cars: A century of innovation has passed them by.

The single-port architecture has two Achilles' heels that make it terminally unattractive for radio design. First of all, a single-port receiver is always susceptible to *catastrophic fading*. In a spatial fading channel, there are receiver positions in space that cannot accommodate wireless communications. These "blind spots" occur unpredictably, even in environments with high average signal strength. Thus, all receivers operate in the fading equivalent of a mine field, encountering sporadic pockets of fades that threaten to sever the wireless link.

Space itself is not the only source of catastrophic fading. The immediate environment of the single antenna element can be problematic, as coupling with the human body, close-in objects, and even the casing and circuitry of the receiver itself can skew the pattern and radiation impedance of the antenna. There is no bullet-proof radio design for a single, static antenna element. When multiband operation is considered - using multiple, noncontiguous frequency bands - the antenna problem can seem hopeless.

Without an additional spatial port, the receiver is stuck with a single channel. The inability to overcome deep fades with a single-port receiver is the main reason cellular phones drop calls in mid-conversation. If there were additional spatial ports, the phone could at least employ some form of *selection diversity* (discussed in Chapter 10) and use an alternative signal if one port experiences a catastrophic fade.

The second critical problem with the single-port architecture is the wasted opportunities for power coupling into the receiver. Consider the case of the simple whip antenna fixed to the typical cellular handset. The effective electromagnetic aperture - roughly the area of space from which an antenna can sink radio power - is small compared to the handset itself. Most of the propagating radio power that impinges upon a handset is unused, reflected off into free space.

As Figure 1.9 shows, it would be much more desirable to design a handset that could somehow absorb radio power across its entire body. Furthermore, multipath radio waves have a polarization that cannot couple completely into any single antenna. From the electric-field point of view, there are three distinct polarizations (due to the three-dimensionality of space). Moreover, researchers have even shown benefits from separate sensing of the three magnetic-field components of propagating multipath waves *in addition to* the three electric-field components [And01].

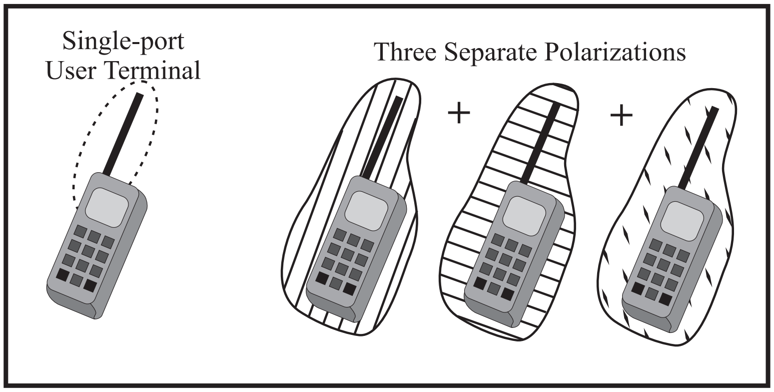

Figure 1.9 In a multipath channel, a single-port radio wastes much of the impinging signal power.

Clearly a lot of potential radio power and opportunity is going to waste in a single-port radio. More power and multiple spatial ports can overcome the thermal noise and in-band interference that signal processing alone cannot remove.

Needless to say, space-wasting receivers have persisted for good reasons. There are two major challenges facing multiport receiver designs. First, multiplying spatial ports on a receiver also multiplies complexity in the radio-frequency hardware - a critical expense in the production of user terminals. Second, it is difficult and expensive to incorporate more than one low-profile antenna into a terminal. This problem is particularly acute for handsets, where aesthetics is important for user-acceptance. Nobody wants to carry around a pin cushion of antennas.

Still, multiport receivers are a certainty for wireless communication that desires to maximize data transmission. If the goal is to develop a receiver that can sustain a reliably high data rate, then the goal must be a power-stingy receiver that wastes no space.

1.3 Trends in Wireless Communications

The theory that engineers use to measure and model wireless communications has changed very little over the last 30 years. The main reason for this stagnation of development may be summed up as follows: The current theory still works for wireless systems that have been deployed to date. Do not expect this to hold much longer. There are six trends in wireless communications that emphasize the need for improved and expanded channel modeling theory.

1.3.1 Higher and Higher Data Rates

The capacity for data transmission of current wireless systems is still tiny when compared to wired forms of communications. But wireless data rates continue to increase. To understand the push for higher and higher data rates, it is useful to consider an analogy involving the trends of memory size and processor speed in the personal computer market. In the early 1980s, a typical personal computer had about 64 kilobytes of RAM and operated with a processor that clocked at speeds less than 1 MHz. In 2000, the typical personal computer had a processor that operated at a clock frequency close to 1 GHz and required as much as 100 MB of RAM. In short, as soon as computer hardware is enhanced, new commercial software applications are developed that exploit the newfound capacity for storing and manipulating data.

The computer hardware illustration provides a valuable lesson for the wireless industry. There is a basic rule that applies to all information technology: Technology that increases the capacity to store or manipulate data is eventually (and sometimes rapidly) followed by new applications that exhaust the resources. For wireless, this means that the current technology will continue to gravitate towards higher transmitted data rates [Rap02b].

Of course, higher data rates imply wireless systems that operate with wider bandwidths. Future wireless systems will operate with bandwidths that greatly exceed conventional channel models. New systems will require new channel models and measurements.

1.3.2 Ubiquity of Wireless Devices

Wireless personal communications has permeated nearly every environment on earth. It is now possible to use a wireless handset in a city, in a car, in the home, in an office building, on a boat - the list goes on. Future applications will involve wireless sensors and impersonal communications between engines, machinery, and appliances.

The wireless channel is heavily dependent on the environment in which it operates. Since future wireless applications will operate in nearly every imaginable environment, there will be an incredibly diverse variety of channels that require characterization. In fact, many of these new environments will defy characterization by the older paradigms of wireless channel modeling.

1.3.3 Smart Antennas

Adaptive arrays and other types of smart antenna techniques are emerging technologies for improving the wireless link and mitigating interference in a multiple access system [God97], [Win98]. Many multiuser communication systems such as cellular radio networks had, until the end of the 20th century, operated below their designed capacity. As the market for these systems has grown and matured, the network traffic has grown as well. Smart antenna technology is seen as a cheap and effective solution for mitigating the problem of network congestion.

A directional antenna at a receiver or transmitter drastically changes the channel characteristics. Channel models that once applied to omnidirectional antennas must be modified and improved to account for the new space–time distortion of the channel by the directional antenna.

1.3.4 Faster, Smaller, Cheaper Hardware

Over the years, basic research in wireless communications has produced a plethora of modulation, multiple-access, and signal-processing innovations that combat the distortions introduced by a wireless channel. Only a small subset of these innovations are used in practice, since many algorithms and techniques do not have a feasible realization in hardware.

Radio frequency and digital signal-processing technology continues to develop, however. The computational power of baseband chipsets is increasing. The radio-frequency integrated circuits are operating at higher power levels and at higher frequencies. Above all, these transmitter and receiver components are becoming cheaper and cheaper to fabricate. As a result, many algorithms and techniques that are not feasible to implement today will become feasible tomorrow.

The added capabilities of future radio receivers, therefore, will be able to combat the detrimental effects of the multipath channel in new and innovative ways. With added functionality, receivers of the future need more than just an ad hoc approximation about the radio channel. Future receiver designs will require models that mimic the detailed dispersion, time-varying, and space-varying characteristics of a realistic wireless channel.

1.3.5 Frequency Congestion

Bandwidth is a finite resource. As wireless systems with wider and wider bandwidths continue to deploy, frequency congestion becomes a problem. One solution is to move outside of common frequency bands and into higher, uncrowded frequency in the upper microwave and mm-wave bands. Propagation at these higher frequencies presents an entirely different set of problems. Channel models developed around the 1 GHz microwave bands are inadequate to characterize wireless systems where both the carrier frequency and signal bandwidth are one or two orders of magnitude greater.

1.3.6 Multiple-Input, Multiple-Output Systems

Perhaps one of the most interesting trends in wireless communications is the proposed use of multiple-input, multiple-output (MIMO) systems. A MIMO system uses multiple transmitter antennas *and* multiple receiver antennas to break a multipath channel into several individual spatial channels. Such a system employs *space–time coding* to increase the link capacity [Fos96].

New MIMO systems represent a huge change in how wireless communications systems are designed. This change reflects how we view multipath in a wireless system:

> **The Old Perspective:** The ultimate goal of wireless communications is to combat the distortion caused by multipath in order to approach the theoretical limit of capacity for a band-limited channel.
>
> **The New Perspective:** Since multipath propagation actually represents *multiple channels* between a transmitter and receiver, the ultimate goal of wireless communications is to *use* multipath to provide higher total capacity than the theoretical limit for a conventional band-limited channel.

This philosophical reversal implies that many of the engineering design rules of thumb that were based on pessimistic, worst-case scenario channel models have now become unrealistically optimistic. Design of such systems will require new space–time channel models.

1.4 About This Book

This section presents an overview of the content in *Space–Time Wireless Channels*.

1.4.1 The Basic Disciplines

The primary purpose of this book is to provide a unique instruction or research reference for wireless researchers who require knowledge of the space–time wireless channel. The target reader is a researcher with limited exposure to the three basic disciplines of space–time channel modeling: random process theory (probability theory), electromagnetic propagation, and communications. Any reader with an undergraduate degree (or equivalent) in electrical engineering should have little difficulty understanding the mathematics and physics presented throughout the book.

All space–time channel concepts grow out of the three theoretical disciplines, listed in Figure 1.10. Communication theory, besides providing the general theory of information transmission, is the primary field of application in this text. All of the modulation, multiple access, coding, and signal processing algorithms of wireless communications depend, in part, on the space–time channel description.

Some basic concepts in random process theory are also vital to the study of space–time wireless channels. Since the type of channels experienced by a real radio link are varied and unpredictable, only stochastic modeling with random processes provides the engineer with a bridge from analytical description to realistic performance. Basic electromagnetic theory, one of the most neglected areas in practice, is important for understanding the physical properties of a space–time wireless channel.

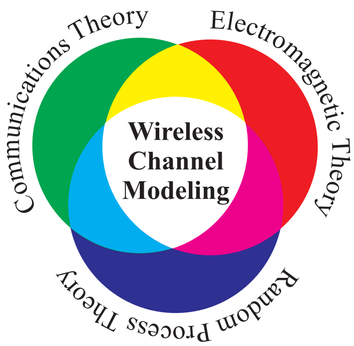

Figure 1.10 Wireless channel modeling theory is an amalgam of three different theoretical disciplines.

1.4.2 Contents

This book conveniently divides into three roughly equivalent parts. Chapters 2 to 4 are the basic principles of the three disciplines (communications, electromagnetics, and random process theory), presenting the basic framework of *Space–Time Wireless Channels*. Chapters 5 to 7 present the development of theory based on this basic framework. Chapters 8 to 10 present an overview of space–time applications, focusing on multiple antenna techniques for wireless communications. The following summarizes the contents of each chapter:

- Chapter 1: Introduction to the field of channel modeling.
- Chapter 2: Theory of transmission through space, time, and frequency.
- Chapter 3: Random process theory for space, time, and frequency.
- Chapter 4: Electromagnetic description of space–time channels.
- Chapter 5: First-order statistics of fading channels.
- Chapter 6: Angle spectrum concepts and applications.
- Chapter 7: Second-order statistics of fading channels.
- Chapter 8: Overview of diversity techniques.
- Chapter 9: Overview of space–time signal processing.
- Chapter 10: Design rules for antenna arrays in multipath channels.

In addition to the main text, the following appendices are included:

- Appendix A: List of special functions used in the text.
- Appendix B: Tables and examples of Fourier transforms.

- Appendix C: Review of definitions and concepts in random process theory.
- Appendix D: Glossary of mathematical conventions and acronyms.

By the conclusion of the book, the reader should have an understanding of general information transmission through many types of space–time wireless channels.

1.4.3 Features of This Book

In matters of scholarship and presentation, this text attempts to be as practical and as readable as possible. Since communications, stochastic process theory, and electromagnetic wave theory are vast subjects in themselves, advanced topics are introduced with thorough background information. Extensive mathematical derivations have been removed from the main text and placed in appendices at the end of the chapters. Important *theorems* are proven with pragmatic methods that emphasize understanding instead of mathematical rigor. *Examples* are used to illustrate concepts wherever possible. Each subsequent chapter is concluded with a set of problems, many of which relate theory to practical issues in wireless link design.

> *Note: Supplemental Information*
>
> Throughout this book there are *noteboxes* (like this one) that supplement technical concepts in the main text. These noteboxes are used to clarify possible points of confusion, to justify a certain type of notation, to alert the reader to misconceptions that exist in the research literature, or even to provide some history behind a useful concept and its inventor. Such "editorials-in-miniature" help break up long (and admittedly tedious) technical expositions.

This book is meant for more than just a treatment of various channel modeling issues in wireless communications. More broadly, the text is really a grass roots introduction to the principles of *stereostochastics*, the study of random processes as functions of both time and space. The principles of *Space–Time Wireless Channels* have numerous applications outside the field of commercial wireless engineering, including radar, optics, acoustics, quantum mechanics, and any other field of study involving dynamic wave interactions.