1

INTRODUCTION

We begin with a brief historical account of some of the major contributors to wireless communications. We then list background material on *multiple-input, multiple-output* (MIMO) communications, MIMO channel models, and *software defined radio* (SDR) and include some important references. The chapter concludes with a brief summary of the remainder of the text.

1.1 HISTORICAL PERSPECTIVE

In retrospect, wireless communications in its current form is the result of many discoveries made by many people over hundreds of years. In the literature, a handful of people is credited with the most important discoveries in wireless communication theory. The origins of wireless communication can be traced back to the first experiments on electricity and magnetism.

1.1.1 Electromagnetism

The eighteenth century saw the discovery of electricity, including Benjamin Franklin's famous kite-flying experiments, and the invention of the battery by Alessandre Volta in 1800. In the latter half of the eighteenth century, some people began to suspect that there might be a connection between electricity and magnetism. In 1820, the Danish physicist Hans Christan Øersted first made the observation that he could force a

Multiple-Input, Multiple-Output Channel Models: Theory and Practice. By Nelson Costa and Simon Haykin

compass needle to deflect at right angles to a current-carrying wire. This was perhaps the first concrete evidence that electricity and magnetism were somehow linked (1). Later that same year, a week after hearing about Øersted's discovery, the French physicist André-Marie Ampère presented a detailed paper on the phenomenon.

From that point forward, physicists such as Michael Farady, André Ampère, and Joseph Henry tried to define the mathematical relationship between electricity and magnetism. Defining this relationship proved to be a difficult task. It was the Scottish mathematician and physicist James Clerk Maxwell who is largely credited with discovering the laws of electromagnetism. Maxwell presented his work over the course of three publications.

In the 1861 publication "On Physical Lines of Force" (2), Maxwell first presented what would eventually be known as *Maxwell's equations.* Arguably, the most important contributions of the paper were the following four laws of electromagnetism:

1. *Gauss's law*, defining the relationship between an electric field and free electric charge;
2. *Gauss's law of magnetism*, which states the net flow of a magnetic field at any point is zero, implying the nonexistence of magnetic monopoles;
3. *Faraday's law of induction*, showing how a changing magnetic field can induce an electric field; and
4. *Ampère's circuital law*, showing how a changing electric field can produce a magnetic field. Except for Ampère's circuital law, the first three laws had already been stated elsewhere. In Ref. 2, using Faraday's *lines of force* and his own model, Maxwell rederived the above relations (3).

In 1864, Maxwell published "A Dynamical Theory of the Electromagnetic Field" (4). In this paper, he expanded on Ref. 2, and presented a set of eight equations, which would become known as Maxwell's equations. In addition to this, Maxwell also correctly predicted that light was an *electromagnetic wave* and followed the same laws as electromagnetic fields. He then presented a wave equation that described the propagation of electromagnetic (EM) waves through a medium. Maxwell implied that, using a time-varying current, it was possible to generate electromagnetic waves that traveled at the speed of light.

In 1873, Maxwell brought all his previous work together in a single book entitled *A Treatise on Electricity and Magnetism* (5). This book is most often cited as Maxwell's most important contribution. The book contained a series of 20 equations that defined the relationship between electric fields, magnetic fields, electric charge, and electric current (3). The book also provided a comprehensive review of Maxwell's findings in EM theory.

Maxwell's discoveries were so advanced that it took more than a decade for people to realize their importance. In 1884, the English electrical engineer Oliver Heaviside, after reviewing Maxwell's work, selected four of Maxwell's original equations and rewrote them using modern differential notation. The revised equations are sometimes referred to as *Heaviside equations* to differentiate them from the original eight equations given in Ref. 4. Heaviside's simplification brought Maxwell's discoveries to the forefront and led to the development of the first wireless transmitters and receivers.

1.1.2 The Hertz Transmitter

The person most often credited with building the world's first wireless transmitter was the German physicist Heinrich Hertz in the late nineteenth century. From 1885 to 1889, Hertz was a professor of physics at Karlsruhe Polytechnic. During this time, Hertz was trying to find proof of EM waves, as predicted by Maxwell. In 1886, Hertz developed the *Hertz antenna receiver*, which is illustrated in Fig. 1.1. Hertz built his transmitter using a Ruhmkorff-type induction coil connected to a center-fed dipole equipped with a spark gap. Capacitive elements at the transmit antenna helped to tune the frequency of the transmitted energy. The induction coil caused sparks to appear at the transmit antenna gap. The receiver consisted of a simple loop antenna, equipped with a similar spark gap. During operation, the transmitter would cause sparks to appear at the receive-antenna gap when the transmitter was separated from the receiver by a small distance. Over the course of numerous experiments, Hertz was able to measure the wavelength and velocity of the EM waves. He demonstrated that the EM waves traveled at the speed of light, despite having a much larger wavelength than light. Hertz also experimented with EM propagation through different media and showed that the EM energy would transmit through some media and would reflect off others. He demonstrated that the *refraction* and *reflection* properties of EM waves were similar to those of light, as predicted by Maxwell. This discovery also formed the bases for *radar* technology, among other things (6).

Not even Hertz realized the practical implications of his invention. He is quoted as saying that his apparatus was "of no use whatsoever [. . .] this is just an experiment that proves Maestro Maxwell was right—we just have these mysterious electromagnetic waves that we cannot see with the naked eye" (6). Despite his apparent lack of vision, Hertz's discoveries inspired an entirely new field of research. He demonstrated that EM waves could be used to induce an action-at-a-distance but failed to see the

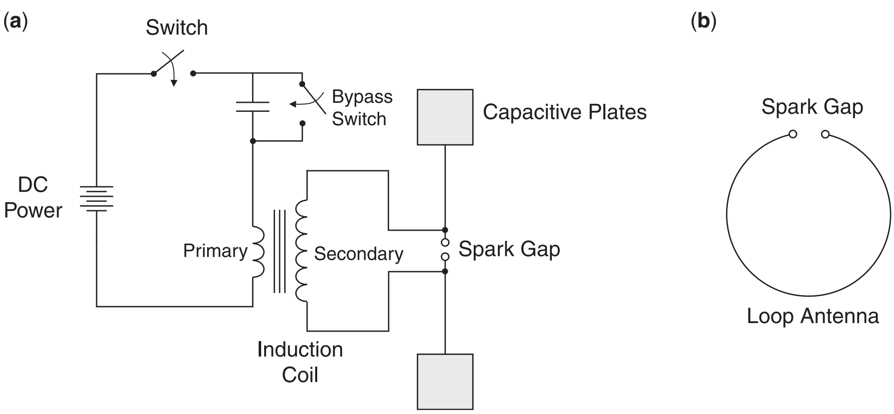

Figure 1.1 Hertz's spark-gap experimental setup showing (a) transmitter and (b) receiver.

significance of this discovery. Hertz's discoveries led directly to the development of the first wireless telegraphing devices.

1.1.3 Tesla and Wireless Power

It took another decade for people to make the connection between Hertz's work and wireless communications. Motivated primarily by his research into wireless power transmission, in 1891 Nikola Tesla demonstrated the wireless propagation of power to vacuum tubes. He constructed several different alternators that generated AC power between 15 and 18 kHz. He used the alternators to wirelessly power phosphorus-lined vacuum tubes and cause them to glow. In 1892, at a meeting of the Institution of Electrical Engineers of London, Tesla stated that this technology could be used to convey information from one point to another wirelessly (7). As early as 1896, Tesla transmitted a continuous-wave signal from his Houston St. lab in New York City to West Point, a distance of approximately 48 km. The transmitter consisted of an alternator, which generated a continuous wave at approximately 5 kHz. The receiver was made up of a steel wire, two condensers, and a strong electromagnet. The receiver was tuned to the transmitter by placing the wire within the magnetic field, thus forming a resonant circuit in conjunction with the condensers (7). In 1943, soon after Tesla's death, the Supreme Court of the United States overturned one of Marconi's patents and named Tesla "the inventor of the radio" (8).

1.1.4 Lodge and Tunable Circuits

In 1890, French physicist Édouard Branly showed that metal filings in a glass tube would "cohere," or clump together, when under the influence of EM waves. The English physicist Oliver Lodge improved on Branly's radio detector by including a "trembler" that would dislodge the filings between cycles, thus maintaining the receiver's sensitivity. He named the device a *cohere*. Lodge connected the cohere to a receiver circuit that included an inker to record the received signals. In 1894, at a meeting of the British Association for the Advancement of Science at Oxford University, Lodge used his apparatus to transmit and receive Morse-encoded signals across a distance of 150 m, thus demonstrating its usefulness in wireless communications.

Perhaps Lodge's greatest contribution was in the area of tunable resonant circuits for communications. While at University College, Liverpool, Lodge experimented with tunable circuits using inductors and capacitors. He showed that untuned circuits would respond to EM waves at almost any frequency, but that their response would fall off quickly. Conversely, a tuned circuit would respond to waves whose frequency corresponded with the circuit's natural frequency. Furthermore, the response would not decay as quickly as for an untuned circuit. In 1898, Lodge submitted a patent for a tunable transmitter and receiver set. The transmitter antenna was equipped with an adjustable induction coil that could be tuned to the receiver. The receiver used his version of Branly's cohere. His "syntonic" patent showed the importance of tuning the transmitter to the receiver. This patent was later acquired by the Marconi company in 1912 (9).

1.1.5 Marconi and Trans-Atlantic Communication

At the beginning of the twentieth century, the wired telegraph was already a widely accepted form of communication. Trans-Atlantic cable had already been laid, making telegraph communication possible between North America and Europe. The disadvantage of cable, however, was that it was difficult and expensive to lay and maintain. Also, the fact that it required both users to be linked by wire precluded its use on ships. Guglielmo Marconi is one of the first people credited with proving the practicality of wireless communication. Marconi took ideas from visionaries before him, such as Hertz and Tesla, Branly and Lodge (among others), and refined them to increase the distance between transmitter and receiver. He was interested in developing a telegraphing apparatus for commercial and military use.

Marconi started doing experiments in his parents' attic in Pontecchio, Italy, at a young age. By 1895, he demonstrated the wireless transmission of a Morse-encoded message across a distance of 1.5 km. At this point, Marconi concluded that he needed more funding to extend the range of his apparatus. In a bid to solicit financial support, Marconi traveled to London, England, in 1896. It was there that Marconi first demonstrated his apparatus to the British Post Office, thereby gaining the attention of the British government. From 1896 to 1899, the British government funded a series of wireless experiments. With each new experiment, Marconi refined his apparatus and increased the distance between the transmitter and receiver. In 1897, Marconi was the first to transmit a signal successfully over a body of water. The Morse-encoded signal crossed the Bristol Channel, from Lavernrock Point in South Wales to Flat Holm Island, a distance of approximately 14 km. By 1899, Marconi had successfully broadcast signals across the English Channel, from Wimereux, France, to the South Foreland Lighthouse in England, a distance of more than 45 km (10, 11).

In 1901, Marconi made his famous trans-Atlantic transmission, in which the Morse-encoded letter "S" was broadcast from Poldhu, England, to St. Johns, Newfoundland, Canada, across a distance of approximately 3500 km. At the time, some questioned the validity of Marconi's experiment. Because Marconi's device used a cohere detector at the receiver, the transmitter used a low spark rate (estimated later to be of the order 2–3 sparks/s); this ensured that the detector could reset itself between cycles. At the receiver, Marconi was barely able to hear the transmitted signal above the background atmospheric noise. Critics claimed that the low spark rate, combined with the very low signal-to-noise ratio, made it impossible to distinguish the transmitted signal from background noise. They concluded that Marconi had, in fact, only heard the latter. In a bid to silence critics, Marconi set up a mobile experiment to measure the maximum distance of the receiver. In 1902, he set up his cohere receiver on the S.S. *Philadelphia* and sailed west from the Poldhu station, recording the received signal as he went. He found that the maximum range of the transmitted signal was 2496 km at night and only 1125 km during the day, less than half the distance from Poldhu to St. Johns. The St. Johns–Poldhu experiments had been conducted during the day. Although this experiment cast an even bigger shadow over his 1901 claim, Marconi did prove that signals could propagate hundreds of kilometers. Until then, the prevailing view was that signals could only travel within line-of-sight (10, 11).

Despite doubts about his most famous claim, Marconi was very successful at convincing the public of the importance of wireless communications. He leveraged his influence with the British and American governments to build high-power transmission stations on both sides of the Atlantic and to build at least two successful companies. In 1904, he established a news telegraph service for seafaring ships, and 1907 was the first year that his company provided regular telegraph service across the Atlantic. In 1909, in conjunction with Karl Ferdinand Braun, Marconi won the Nobel Prize for Physics "in recognition of their contributions to the development of wireless telegraphy" (11).

1.2 MIMO COMMUNICATIONS

The field of wireless communications has grown since the days of Marconi's first wireless transmission across the Atlantic. Wireless devices are now ubiquitous in our society. From cell phones to satellite links, they have become a necessary part of everyday life. Wireless technology allows us to communicate across large distances, such as in satellite communication. It also allows the wireless devices themselves to communicate with each other, such as a Bluetooth handset with a cordless ear piece. With the proliferation of wireless devices, the goal has shifted from making wireless communication work to making it more efficient. Given the proliferation of communication devices and a limited set of network resources, we wish to increase the number of *users* sharing the network while increasing the reliability of each user's link to it.

Perhaps the most precious resource in a given radio channel is the amount of available *bandwidth*, or the frequency range that it occupies. Regardless of the communication scheme, the number of users one can place within a given bandwidth is limited. Government bodies strictly regulate the allotment of bandwidth to civilian entities, such as cell phone service providers. Given a constant transmission rate for each user in a network, providers want to maximize the number of users within their allotted bandwidth. Thus, the issue then becomes one of *bandwidth efficiency*.

Since the time of Marconi, it was found that, typically, the signal strength at a receiver varies greatly with small changes in its position. The prevailing view is that the received signal is composed of many signals arriving from many different directions. Each signal is formed when the transmitted energy takes a different *path* from the transmitter to the receiver. Through propagation mechanisms such as reflection, diffraction, and scattering, objects in the channel create multiple paths from the transmitter to the receiver. We collectively refer to these objects as *scatterers*. The paths are of different lengths, and thus the signals arrive at the receiver with different amplitudes and phases. This is illustrated in Fig. 1.2. In some cases, the multiple signals add destructively at the receiver, creating points in space where the composite received signal is greatly attenuated. This is referred to as *multipath interference*. To combat the effects of multipath interference, we can employ an array of antennas at the receiver, with each antenna separated by some distance in space. This is illustrated in Fig. 1.3 for the case where the receiver employs a two-element *antenna array*.

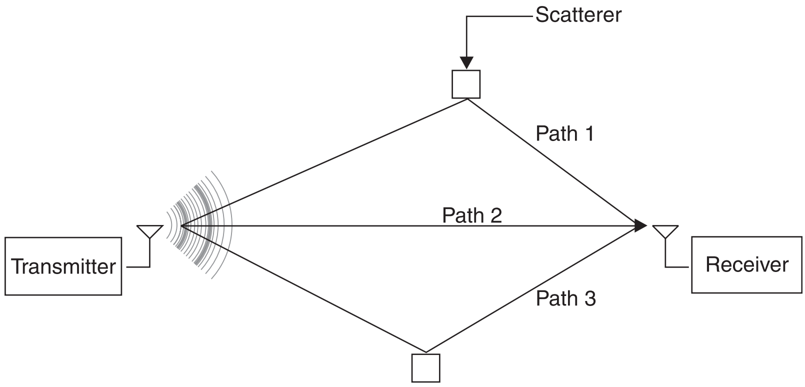

Figure 1.2 Abstraction of a multipath channel.

In this way, we increase our chances that at least one antenna at the receiver does not suffer from multipath fading. By increasing the number of antennas at the receiver, we better the odds. Also, if we combine the signal from both antennas intelligently, we can increase the overall signal strength at the receiver. This is an example of *receive-diversity*. We can also increase the number of antennas at the transmitter to combat multipath fading. This is an example of *transmit-diversity*. In general, diversity techniques greatly improve the average received signal strength in multipath channels. Diversity systems are a fairly mature topic in wireless communications. Jakes (12) provides one of the best introductions to multipath fading and diversity systems. A more recent review of diversity system techniques is given in Refs. 13 and 14.

Work in diversity systems naturally led to the inception of MIMO systems. In channels with rich multipath, the probability that we have more than one independent path increases. This independence is the key to diversity systems; if one path exhibits a deep fade, rich multipath ensures that the likelihood of the other paths doing so at the same

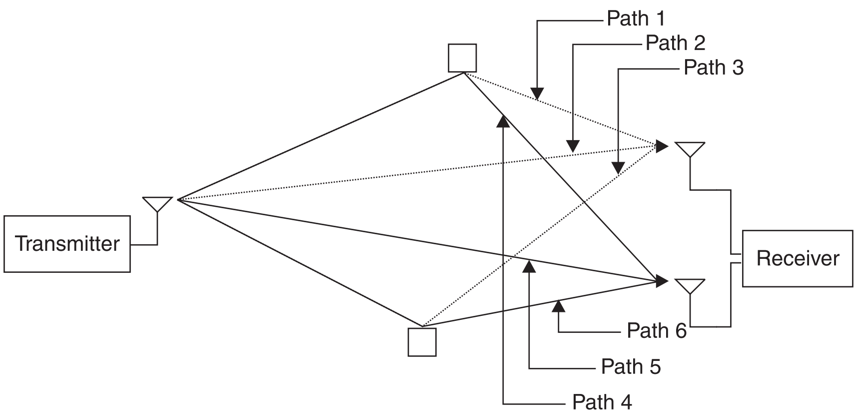

Figure 1.3 Example of a 2 × 1 receive-diversity system.

instant is small. Having the ability to resolve independent paths in the channel also implies that we can increase the amount of information we transmit by sending multiple signals into the channel *within the same bandwidth.* In this way, MIMO systems add another degree of freedom; whereas diversity systems use multipath to increase the *reliability* of a link, MIMO systems can trade reliability for an increase in link *capacity.* Consider the case shown in Fig. 1.4, where the transmitter and receiver are both equipped with a two-element array.

At the transmitter, each antenna broadcasts an independent signal on the same bandwidth. The two signals are combined in the channel. Each receive-antenna captures an independently faded version of the combined signals. Until about 20 years ago, because the signals were combined in the channel, it was impractical to separate them at the receiver. It was Winters who first suggested that, by employing multiple antennas both at the transmitter and receiver, we could increase the number of transmitted signals to increase the capacity of a given channel (15). He did not, however, indicate a coding method by which we could separate the transmitted streams at the receiver.

It was not until 1996 that Foschini introduced a coding algorithm that took advantage of the added capacity in a MIMO channel (16). The algorithm encoded data across time and across all transmit antennas. The result was one of the first *space–time algorithms*. The algorithm was later dubbed *Bell LAbs layered Space–Time* (BLAST). It was also in this paper that Foschini first presented the now-famous capacity formula for MIMO channels,

$$C = \log_2 \det\left[\mathbf{I}_{M_{\mathrm{Rx}}} + \frac{\rho}{M_{\mathrm{Tx}}}\mathbf{H}\mathbf{H}^H\right] \text{ b/s/Hz}, \tag{1.1}$$

where $\mathbf{I}_{M_{\mathrm{Rx}}}$ is the $M_{\mathrm{Rx}} \times M_{\mathrm{Rx}}$ identity matrix, ρ is the *system signal-to-noise ratio* (SNR), $(\bullet)^H$ is the Hermitian transpose, M_{Rx} and M_{Tx} denotes the number of receivers and transmitters, respectively, and $\mathbf{H}$ is a matrix whose entries are the $M_{\mathrm{Rx}} \times M_{\mathrm{Tx}}$ channel gains, often referred to as the *H-matrix*. In Ref. 17, Telatar gives a detailed analysis of the capacity in multiantenna Gaussian channels. Perhaps the simplest space–time algorithms is the Alamouti space–time code (18), which is applicable to the 2×2 case shown above. In the Alamouti scheme, information is coded across both antennas, and over two symbol periods, thus across both time and space.

Foschini showed that, under ideal conditions, the data rate of his algorithm approached the capacity limit of the MIMO channel. These limits were investigated more thoroughly in Ref. 19. Foschini's BLAST touched off an entirely new field of

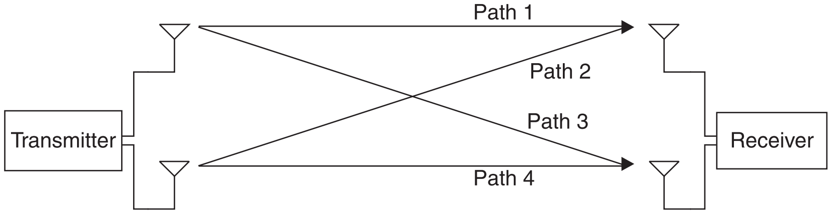

Figure 1.4 Example of a 2×2 MIMO system.

study in space–time coding. Since then, many other space–time algorithms, such as vertical BLAST (V-BLAST) (20) and Turbo-BLAST (21), have been developed. MIMO theory has also had far-reaching consequences in other areas of communications, such as multiuser wireless networks (22) and even optical fiber communications (23). MIMO is arguably one of the most important single advances in communications in the past decade.

Around the time of Foschini's landmark paper, MIMO was largely touted as a method by which we could increase the capacity of a given link without increasing the bandwidth; that is, we increase the *spectral efficiency* of the channel. As discussed above, multiple antennas at the transmitter or receiver can also be used to increase the *reliability* of a wireless link via diversity. More recently, it has been shown that we can trade capacity for diversity to increase the reliability of the wireless link. This trade-off represents an added degree of flexibility and is known as the *diversity-multiplexing trade-off* (24, 25).

1.3 MIMO CHANNEL MODELS

In the past, the increased capacity of a MIMO versus *single-input, single-output* (SISO) channel was often shown using the assumption that individual paths in the MIMO channel are *independent*. Over the course of many experimental studies, it was found that, in many practical cases, this assumption was not accurate. Experimental data have shown that, depending on the environment, the capacity of a measured channel often falls short of the limit given by Foschini (26–28). Space–time algorithms that focus on approaching the MIMO capacity bound rely heavily on the multipath diversity of the channel. As a result, their overall performance is highly dependent on the environment. Thus, there is need to accurately model the MIMO channel to evaluate properly the performance gains of MIMO versus diversity or single antenna systems.

With respect to MIMO system development, MIMO channel models serve a twofold purpose. First, a MIMO channel model can be used in the design of a MIMO system. This includes the design of an optimal signaling scheme, detection scheme, and space–time code. The same model can often be used to test a given system. In this case, the model acts as a *channel simulator*. We can generate exemplar channels using the model and use them to test the performance of a given system. The second and perhaps most important purpose of a MIMO channel model is to gain some insight into the underlying physics of the channel. At a higher level, an accurate channel model can tell us a lot about the behavior of a given channel. It imposes a structure that allows for a deeper understanding and can indicate what assumptions can safely be made to optimize system design.

1.3.1 The Channel Model Spectrum

In general, most wireless channel models fall somewhere in the spectrum indicated in Fig. 1.5. Models on the left of the spectrum are closely related to the channel physics. They rely on EM propagation techniques to solve for EM field values given specific

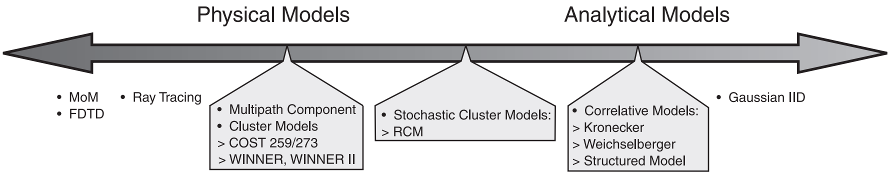

Figure 1.5 The spectrum of channel models, indicating where a few of the MIMO channel models discussed in this text fall.

geometries. These models are often the most accurate but are by far the most complex. *Finite difference time domain* (FDTD) (29, 30) models solve for Maxwell's equations given specific boundary conditions and are most often used on small scales. *Ray tracing models* are based on EM propagation mechanisms such as free-space propagation, reflection, diffraction, and scattering (31). They require a complete description of every object in the channel, including doors, walls, desks, and so forth. This includes each object's geometry, location, and scattering properties.

Cluster models are a compromise between stochastic and ray-tracing models. They use rays, called *multipath components*, to simulate reflected energy in a channel. The multipath components are stochastically modeled using a number of parameters measured from real-life channels. To simplify the model, the multipath components are grouped into *clusters*, with multipath components in each cluster having similar statistics. Clusters, in turn, simulate the behavior of objects in the channel.

Scattering models use the concept of virtual scatterers and simplified ray tracing to capture the statistical properties of the channel (32–34). Many of these models begin with a simple EM ray-based propagation model, such as that described by Jakes (12), choose a scatter geometry that approximates the behavior of scatterers in a real environment, and then derive relationships for the correlation or capacity as a function of physical parameters. Prior geometries include a ring of scatterers around the receiver only (31), one line of scatterers at the transmitter and receiver (32), and layers of scatterers (33). Emphasis is usually placed on correlation between antennas and the resulting capacity distribution of the channel given some antenna spacing.

Further to the right-end of the spectrum, *correlative models* attempt to approximate the *spatial structure* of the channel by modeling the correlation between paths in a MIMO channel. These models bias a "white" channel matrix with correlation matrices at the transmitter and receiver to approximate the correlation between scatterers at both link ends. The white channel matrix consists of uncorrelated complex-Gaussian elements (35–37).

In general, channel models for wireless systems have been primarily concerned with modeling the effects of the following parameters on the transmitted signal: path loss, delay spread, shadowing, Doppler spread, and Ricean *K*-factor. Parameters of specific interest to the MIMO channel are the joint antenna correlations and channel matrix singular-value distribution. Also of interest in the MIMO channel is the spatial diversity, which can be measured by analyzing the H-matrix singular-value distribution (38). In this way, the MIMO channel can be decomposed into a number of parallel SISO channels whose channel gains are directly related to the singular values of the H-matrix. By analyzing the distribution of the singular values in different environments, we can assess the performance gain of MIMO over other signaling techniques.

1.3.2 Wideband MIMO Channel Models

Increasing the bandwidth of a wireless channel often means that it begins to affect a given signal differently at different frequencies. When *fading* is *frequency dependent*, we refer to the channel as being *wideband*. Wideband channel characterization, in the case of single antenna systems, is a fairly mature topic. The first characterizations of the wideband channel appeared in the works of Kailath (39) and Bello (40). Both describe the wideband channel as a linear time-varying filter and apply linear theory to its characterization. *Bello's model* characterizes both the time and frequency variation of a wideband channel. Since then, there have been many experiments to validate his model and measure the parameters of different real-life channels. See, for example, Refs. 41–44, among others.

In contrast, the characterization of wideband MIMO channels is a relatively new field of study. To date, only a handful of wideband MIMO test beds exist. Some examples are given in Refs. 45–49. There are even fewer wideband MIMO channel models. Due to the complexity and difficulty of building a wideband MIMO channel sounder, fewer still test their channel model with real-life data. One of the most notable works in the field of wideband MIMO channel modeling is that of Yu et al., in which a known narrowband correlative model, called the *Kronecker model*, is extended to the wideband case (36). Yu et al. show the Kronecker model to be fairly accurate in predicting the correlation between paths in a MIMO channel. However, more recent work suggested weaknesses in the Kronecker model, especially as the number of antennas at the transmitter and receiver is increased (50, 51).

To reduce the number of model parameters, the Kronecker model assumes that scatterers at the transmitter are not correlated with those at the receiver. We refer to this as the *separability assumption*, as, in effect, it implies that the effects of scattering around the transmitter can be separated from those around the receiver. In Ref. 50, Özcelik et al. argue that this assumption is a source of modeling error. They also imply that, for many real-life channels, the scatterers at either link end are indeed coupled in some way.

In Chapter 3, we present a relatively new wideband MIMO channel model, called the *structured model*. The model is unique for the following reasons. It models the coupling between scatterers at either link end. It models the correlation between scatterers at different delays. The model also recasts the wideband MIMO channel gains as a third-order tensor. The model was derived using *tensor decomposition*. In Chapter 6, using real-life data, we compare the performance of the structured model versus the Kronecker model. We show that the structured model better approximates the spatial structure of a given channel versus the Kronecker model.

1.4 SOFTWARE DEFINED RADIO

Over the past decade, the number of wireless communication standards has grown. Currently, there are many competing cellular telephone standards, such as *Code Division Multiple-Access* (CDMA) and *Global System Mobile* (GSM); wireless computer networks such as the IEEE 802.11n and Bluetooth; as well as a host of military standards. Different standards have different hardware requirements; the carrier frequency and the method by which the signal is encoded will differ across standards, requiring different antennae, filters, mixers, and so forth. Often, a single device will be designed to work across a variety of network standards. For example, many cell phones are designed to work in both North American and European standards. In many cases, it would be advantageous for a single device to have the ability to communicate using multiple standards. Traditionally, doing this meant that we had to increase the hardware complexity of the device, thereby increasing its development time and unit cost.

Most communications devices nowadays perform their task with a combination of hardware and software. The hardware translates analog signals in the channel to digital signals that can be processed in software. Its functionality is fixed; once implemented, it is difficult to alter its specifications. By contrast, the software functionality is often more malleable and can be changed by simply writing more software. Thus, the goal of SDR is to reduce the amount of hardware by increasing software functionality, thereby increasing overall flexibility.

The dichotomy between hardware and software is best illustrated by way of example. Figure 1.6 shows a block diagram of a typical digital receiver. Radio frequency (RF) signals are captured by an antenna and fed to a *RF conversion* block. The output of this block is connected to an *analog-to-digital converter* (ADC), which converts the analog signals to digital form. Once in the digital domain, the signals can be processed in many ways using software. In practice, the input frequency and amplitude range of ADCs are limited. The RF signals, on the other hand, are usually centered at a relatively large frequency, which we refer to as the *carrier frequency*. Furthermore, there are many other signals adjacent to the signal of interest in the frequency domain. Therefore, the RF conversion block consists of all *hardware* responsible for converting the frequency and amplitude range of the RF signal of

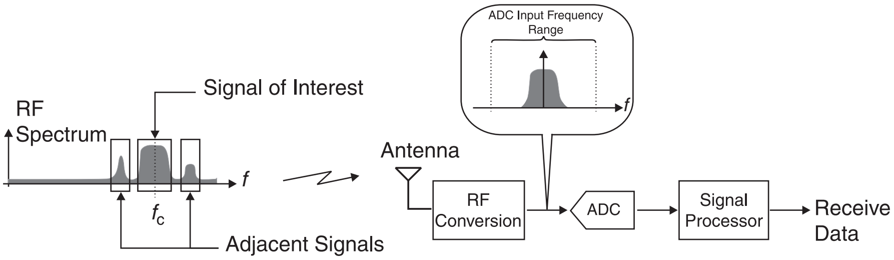

Figure 1.6 A typical digital receiver, highlighting the division between the analog and digital domains.

interest to a range that is compatible with the ADC and filtering out the undesired signals. The signal processor block is responsible for decoding the signal and estimating the transmitted message. Depending on the capability of the hardware before this block, including the ADC, and depending on the capabilities of the signal processor itself, we can decode just about any type of signal using software.

In the above example, the input range of the ADC determines, to some extent, the specifications of the RF conversion-block. That is to say, if the ADC input range is small, we must increase the complexity of the RF conversion block to decode a given signal. In Ref. 52, Tuttlebee distinguishes between *pure* and *pragmatic* SDR. In its purist form, a software defined receiver would consist of an antenna, ADC, and signal processor block, as shown in Fig. 1.7. In this case, the input range of the ADC is such that it would capture the entire frequency spectrum, including the signal of interest, and convert everything to the digital domain. That is to say, the input amplitude and frequency range would be large enough to capture all signals in the entire RF spectrum. In this way, we can write software to isolate and decode the signal of interest, regardless of where it lies in the RF spectrum.

In most cases, implementing a pure SDR is impractical, if not impossible. Even with the ever-increasing capabilities of data conversion technology, the RF spectrum contains many undesired signals. Government regulations force providers, such as cell phone and wireless data providers, to occupy relatively small, well-defined segments of spectrum. Also, converting the entire spectrum to the digital domain requires enormous computing power. For example, consider the case where we have a 32 kHz signal, centered at 5 GHz. To capture this signal, an ADC would have to operate at a sample rate greater than 10 GHz. Assuming 8-bits/sample, a computer would have to process greater than 10 MB/s just to capture a 32 kHz signal. This data rate increases linearly as we increase the number of antennas; for example, in MIMO systems. Furthermore, the received signal power can vary widely, especially in mobile applications. The dynamic range of the ADC, determined by the number of bits at its output, is often much smaller than the range of the received signal. The received signal is lost while its power falls outside of the ADC input range.

For these reasons, pragmatic SDR tries to strike a balance between pure hardware radios with limited functionality and pure SDRs, which are impractical. As technology advances, more and more functionality is moved to the signal processor. Practical considerations such as portability, battery life, and cost determine exactly where the line is drawn between hardware and software functionality.

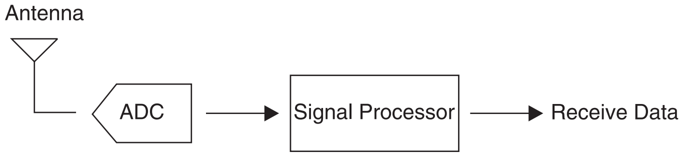

Figure 1.7 The purist SDR.

Mitola (53) is the person most often credited as having coined the term "software radio." In Ref. 54, he gives a detailed vision of SDR in the context of a cellular network. Mitola describes all the necessary functions that a software radio would have to perform to communicate with the network. His vision is that of a pragmatic SDR; the device would consist of RF conversion hardware and a signal processor. Every stage of the RF conversion is controlled by the signal processor in real time. The requirements of each function block, from the RF signal to the decoded message, are described in detail. The requirements are mostly derived from cellular standards such as CDMA and GSM.

One of the more intriguing contributions of the paper involve the idea of quantifying the *total available resources*, like computing power, and dividing these resources quantitatively between different functions, depending on the task. For example, an analog voice signal requires different resource allocation versus a CDMA signal. These resources are dynamically allocated by the signal processor in real time. Mitola states that this is one of the distinguishing features of a software radio versus a "software-controlled" radio, although he does not quantify the distinction.

Since Mitola's paper was first published, the definition of SDR has undergone many changes. The ideas contained in Ref. 53 have also led to the creation of the *SDR Forum*, whose body is "dedicated to promoting the development, deployment and use of software defined radio technologies for advanced wireless systems" (55). The forum is composed of individuals from many different companies, universities, and government bodies all over the globe. Specifications for software radio development have already been included in some standards, such as the *3rd Generation Partnership Project* (3GPP) (56).

Although the definition has changed, the goal of SDR remains the same; to implement a SDR, we want to move as much functionality as possible to the digital domain and give the signal processor as much control over the remaining RF conversion as possible. In the following, we present an example of a pragmatic SDR, the *Wideband MIMO Software Defined Radio* (WMSDR). The WMSDR was built at McMaster University for the purpose of characterizing outdoor wideband MIMO channels. It consists of a separate transmitter and receiver. The transmitter is equipped with four independent transmit chains. Each chain can be controlled in software. The receiver is similarly equipped with four independent receive chains. We use software to record and process the information from each chain. In this way, the WMSDR is a highly versatile 4×4 SDR, capable of many tasks.

1.5 OVERVIEW

The following section outlines the contents of the remainder of the text.

1.5.1 Chapter 2: Multiple Antenna Channels and Correlation

Chapter 2 describes some of the fundamentals of multiple antenna channels. Most wireless channels can be characterized using linear system theory. This chapter defines the different classes of channels, including the time-invariant narrowband channel, leading through to the time-varying wideband channel. It is here that we introduce the tensor system model for the wideband MIMO channel. The third-order *H-tensor* is an elegant way of describing the complex gains in a wideband MIMO channel and leads to channel tensor decomposition.

Of importance to MIMO channels in general is the concept of *channel correlation*. We define correlation in narrowband and wideband MIMO channels and discuss its *eigenvalue decomposition* (EVD). We extend the definition of correlation to include the wideband MIMO channel using tensor calculus. Using the *azimuth power spectrum* (APS), we define the *spatial structure* of the channel and show how this relates to the channel correlation. Both the channel correlation and its EVD are fundamental to the correlative models covered in the next chapter.

1.5.2 Chapter 3: Correlative Models

Chapter 3 describes the first class of MIMO channel models, correlative models. Specifically, we review the *Kronecker*, *Weichselberger*, and *structured* models. We first outline the fundamentals of correlative modeling, including how correlation can be used to generate an ensemble of new channels with the same spatial structure as a given channel. The concept of *one-sided correlation* is used in all three models to reduce the number of parameters needed to describe the channel. The Kronecker model gets its name from the fact that it approximates the full correlation as the Kronecker product of the one-sided correlation matrices. Both the Weichselberger and structured models use the EVD of the one-sided correlation as parameters. The structured model is the wideband extension of the Weichselberger model. In deriving the structured model, the concept of one-sided correlation is extended to include the wideband channel.

The Kronecker model assumes that fading at the transmitter is not linked to that at the receiver. The Weichselberger model (57) suggests the opposite; scatterers at both link ends are coupled in some way. It characterizes this coupling as the average energy coupled between the eigenvectors of the one-sided correlation matrices. Using tensor algebra, the structured model extends this concept to the wideband MIMO channel. The structured model uses a *coupling tensor*, in addition to the eigenbases of the one-sided correlation matrices as input parameters.

1.5.3 Chapter 4: Cluster Models

Chapter 4 provides some of the fundamentals behind cluster models, another class of MIMO channel models. Cluster models address an important shortcoming of correlative models, namely time-variation. They are also more prominent in wireless standards than correlative models.

The chapter covers several important cluster models, leading from the simplest to more complex. Thse include the Saleh–Valenzuela model, the extended Saleh–Valenzuela model, the *European Cooperation in the field of Scientific and Technical Research* (COST) 273 model, and finally the *random cluster model* (RCM).

The Saleh–Valenzuela model was the first to describe the arrival of energy in the delay domain using clusters. Subsequent cluster models extended the Saleh–Valenzuela model to include the *angle of arrival* (AoA) and *angle of departure* (AoD). In this way, clusters were located in space as well as time. The COST 273 model is complex, consisting of many parts. The chapter focuses the discussion on the model implementation. This allows some insight into the many mechanisms that make up the model and explores the reason behind some of its parameters. The RCM is an extension of the COST 273 model. It greatly reduces implementation complexity by characterizing the channel using a multivariate probability density function (PDF). This PDF includes a characterization of time-variation in the channel.

1.5.4 Chapter 5: Channel Sounding

To estimate the impulse response of real-life channels, we employ a technique called *channel sounding*. This chapter presents the theory behind a few channel sounding techniques used to sound narrowband and wideband channels. One of these, *correlative channel sounding*, is used to measure the wideband channel. A discussion of the role of *maximal-length sequences* (ML sequences) in correlative channel sounding is provided. The technique of *digital matched filtering* and how it can be used to estimate the impulse response of a wideband channel is discussed. We then extend digital matched filtering to include the MIMO case. Using real-life data, we show that MIMO matched filtering provides very accurate estimates of the channel gains.

Because of the proliferation of cheap RF signal generators, sampled spectrum sounding is a popular technique for sounding the wideband channel. Switched array sounders are also popular, because they reduce the bandwidth requirement for MIMO channel sounders. We list advantages and disadvantages of both.

To sound the channel, we employ the use of a *channel sounder*. The chapter discusses the WMSDR, an example of a 4×4 wideband MIMO channel sounder. In any digital communication system, including PN-sequence sounders such as the WMSDR, there are several steps required at the receiver to recover the transmitted signal. This involves *timing* and *carrier recovery*. The chapter discusses a few existing timing and carrier recovery algorithms that were implemented in the WMSDR. Examples of their performance are provided.

1.5.5 Chapter 6: Experimental Verifications

Chapter 6 contains a performance analysis of two correlative channel models; namely, the structured and Kronecker models. The chapter begins with a discussion of several important metrics used in the literature to validate MIMO channel models. Using real-life data is an important step in validating any channel model because it shows how useful a given model is in approximating real-life channels. In addition to the WMSDR data, we test both models with data from *Brigham Young University's* (BYU's) 8×8 wideband MIMO channel sounder. We use data from these very different apparatuses gathered in very different environments to highlight some of the shortcomings of the Kronecker model and the robustness of the structured model.

The chapter describes the BYU sounder architecture, specifications, and theory of operation. It highlights the differences between the WMSDR and BYU data sets. The experimental setup for the WMSDR and BYU data sets is described. We compare the performance of the structured model versus the Kronecker model using several important metrics. In the end, we show that the structured model outperforms the Kronecker model when predicting the capacity of a given channel and in approximating the spatial structure of the channel. In all cases considered here, the structured model uses fewer parameters than the Kronecker model. This implies that the channel structure imposed by the structured model is accurate for a wide variety of channels.

We comment on the importance of modeling the correlation between channel gains at different delays by comparing the wideband correlation matrices of real-life channels. We discuss a metric that quantifies the correlation between paths at different delays. This becomes significant, especially as we increase the system bandwidth, and thus should not be ignored when modeling the channel.

1.5.6 Appendixes: Background and Definitions

The text contains additional material, divided into three appendixes. Appendix A provides a short primer on tensor calculus. Appendix B provides proofs used in the derivation of the structured model. This is closely related to material covered in Chapter 3. Finally, Appendix C summarizes the COST 273 channel model, which is discussed in Chapter 4.