1 Short-range wireless communications and reliability

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Even though there is no universally accepted definition, *short-range wireless communications* typically refers to a wide variety of technologies with communication ranges from a few centimeters to several hundreds of meters. While the last three decades of the wireless industry have been mostly dominated by cellular systems, short-range wireless devices have gradually become a more integrated part of our everyday lives over the last decade. The Wireless World Research Forum (WWRF) envisions that this trend will accelerate in the upcoming years: by the year 2017, it is expected that seven billion people in the world will be using seven trillion wireless devices [1]. The majority of these devices will be short-range wireless devices that interconnect people with each other and their environments.

While the reliability of wireless communication systems has been studied in detail in the past, a comprehensive study of different factors affecting reliability for short-range wireless systems and how they can be handled is not available in the literature, to date. The present book intends to fill this gap by covering important reliability problems for short-range wireless communication systems. The scope of the contributions in the book is mostly within the domain of wireless personal area networks (WPANs) and wireless sensor networks (WSNs), and issues related to wireless local area networks (WLANs) are not specifically treated.

Due to the differences in application scenarios, quality of service (QoS) requirements, signaling models, and different error sources and mitigation approaches, the high-rate and low-rate systems will be addressed in separate parts of the book. For the high-rate systems covered in Part I, multiband orthogonal frequency division multiplexing (OFDM) and millimeter wave communication systems will be the main focus owing to their significant potential for achieving high throughputs. On the other hand, Part II of the book will be focusing mostly on ZigBee and pulse-based ultrawideband (UWB) communications owing to their benefits for low-rate, low-power, and low-complexity operation. In addition, a third set of chapters within Part III will be addressing some selected topics related to the reliability of short-range wireless communication systems, where the chapters are written from a broader perspective without specifying a certain technology or standard.

The rest of this chapter is organized as follows. First, in Section 1.1, enabling factors for short-range wireless communications are discussed, and differences from long-range wireless systems are summarized. In addition, a comparison of low-rate and high-rate systems in terms of application scenarios, typical transmitter/receiver characteristics, and reliability requirements is provided, and globally available frequency bands for short-range wireless systems are reviewed. In Section 1.2, reliability problems observed at different layers of the protocol stack are defined, and possible solutions to address these are discussed along with references to different chapters in the book. Section 1.3 provides a brief review of certain short-range wireless communications standards, leaving the detailed treatment of more established standards to Chapter 2 and Chapter 6.

1.1 Short-range wireless communications

1.1.1 Enabling factors

There are three significant factors that play an important role for the widespread use and adoption of short-range wireless communications devices in today's world: (i) advancements in the solid-state devices, (ii) developments in the digital communication and modulation techniques, and (iii) developments in related standardization activities.

Advances in the solid-state technology have been an important factor enabling the widespread use of short-range wireless technologies. First, the mass production of devices became possible, decreasing the production cost per unit device. Second, with the new developments, higher center frequencies have become operational for short-range devices. This implies access to the previously inaccessible frequency bands such as the 2.4 GHz, 5 GHz, and 60 GHz bands of the industrial, scientific, and medical (ISM) bands that will be discussed in more detail in Section 1.1.4. Using higher center frequencies also enables the use of very small antenna elements, of which multiple may easily be embedded within the same device [2]. Today, circuit miniaturization and small-size antennas make it possible to manufacture extremely small radio frequency integrated circuits (RFICs) on chips that contain all the essential system components. For example, CMOS RFIC-on-chip antennas are available for short-range wireless technologies utilizing central frequencies as high as 60 GHz and having chip sizes of less than 1 mm^2 [3, 4].

Another enabling factor that has an important role in the success of short-range wireless communication systems is the recent developments in digital modulation techniques and transceiver algorithms. For example, direct sequence spread spectrum (DSSS) technology has been used successfully in systems such as the IEEE 802.15.4 WPANs and the IEEE 802.11 WLANs. Through spreading the frequency content of a transmitted signal, DSSS provides advantages such as interference resilience, low-power spectral density, resistance to jamming, and mitigation of multipath effects [5]. Frequency-hopping spread spectrum (FHSS) is another spread spectrum transmission technology that has commonly been used in short-range wireless devices due to its interference resilience. Because of its important advantages in multipath environments, OFDM has recently been a key technology for achieving higher throughputs in short-range wireless communication systems [6, 7]. Advantages of OFDM over other relevant competitive technologies include the following: (i) there is no need for time-domain equalization, and much simpler frequency-domain equalization techniques can be utilized efficiently,[1] (ii) it is robust in frequency selective channels owing to the use of a cyclic prefix (CP), and (iii) multiple-input multiple-output (MIMO) is easily implementable with OFDM due to frequency-flat fading at each tone. Due to such advantages, OFDM has been adopted by recent standards such as ECMA-368 (high-rate UWB PHY and MAC [6]) and ECMA-387 (high-rate 60 GHz PHY, MAC, and HDMI PAL [7]). Other recent developments that may impact the future of short-range wireless communications include the advances in MIMO techniques for achieving higher data rates and better reliability [9–13], and cognitive radio methods for more efficient and reliable utilization of the wireless spectrum [14–17].

The critical role of standardization bodies in the widespread use of short-range wireless devices should also be emphasized here. Through standardization, related companies and research organizations actively work towards obtaining a well-defined technical specification for a given wireless technology. This brings with it a high potential for the realizability and interoperability of the technology; a better understanding of the application scenarios, potentials, and limitations is achieved, and a consensus is reached on how to implement it in a good way. Several successful short-range wireless devices that we use in our everyday lives today such as WiFi, Bluetooth headsets, wireless keyboards, and ZigBee devices are all the result of long years of standardization. Probably the most important standardization group working on short-range wireless communication technologies is the IEEE 802.15 Working Group for WPANs. As well as the already standardized short-range wireless technologies discussed before, IEEE 802.15 is also working on the standardization of some recent technologies such as wireless body area networks (WBANs), radio frequency identification (RFID) systems, mesh networks, and visible light communications (VLCs). Other standard bodies related to short-range wireless communications include ISA-100 and ECMA standards. A more detailed discussion on related short-range wireless communication standards will be presented in Section 1.3 as well as in other chapters of the book.

1.1.2 Short-range versus medium/long-range communications

While short-range wireless technologies span a wide range of application scenarios, they typically have some common characteristics that are significantly different from medium and long-range wireless technologies, such as WLANs, cellular systems, wireless metropolitan area networks, and satellite communication systems. Some of the common features of short-range wireless devices include low-power operation, communication ranges from several centimeters up to a hundred meters, principally indoor operation, omnidirectional built-in antennas, low-complexity and low-price devices, battery operated transmitter/receiver, and unlicensed operation [18].

Short-range wireless devices typically have very low or no mobility, which implies simple and low-complexity receiver architectures compared, for example, to cellular

[1] Note that frequency domain equalization is also possible for single-carrier frequency domain multiple access (SC-FDMA) systems [8].

systems. On the other hand, multihop and cooperative communications may be considered as important operational modes for certain short-range wireless communications scenarios (e.g., as in WSNs). This is primarily due to dense deployment scenarios of wireless sensors that collect local information, aggregate it, and communicate to the intended receiver. Such wireless networks should have very low-power operation for extended network life, and overall power consumption may be decreased by transmitting the packets over multiple shorter distance hops rather than over a direct link with longer transmitter–receiver separation. Due to their critical importance for short-range wireless communication systems, multihop and cooperative communication techniques will be treated in detail in Part III of this book.

The QoS requirements (e.g., packet error rate, data rate, and latency) for short-range wireless systems are also quite different from long-range communication technologies and are closely coupled with the application scenarios. In reference [19], the top 10 design rules for short-range communications, which are different from the design rules of long-range networks, have been listed as follows: communication architecture (both point-to-point and point-to-multipoint communications capability), energy awareness, signaling and traffic channels, scalability and connectivity, medium access control and channel access methods, self organization, service discovery, security and privacy issues, flexible spectrum usage, and software-defined radio design.

1.1.3 High-rate versus low-rate communications

It is possible to have different sets of taxonomies and classifications for short-range wireless communication technologies. Among some other possible classifications, they may be classified with respect to their communication ranges, mobility characteristics, network topology, QoS requirements, indoor versus outdoor operation, operating frequency/bandwidth, and data rates. Communication ranges of short-range wireless systems may be on the order of several centimeters (e.g., for near field communications (NFCs)), fractions of a meter (e.g., for WBANs), several meters (e.g., WPANs), or from a few meters up to hundreds of meters (WSNs) [20]. The range of passive RFIDs are on the order of tens of centimeters, while active RFIDs may have ranges as large as a hundred meters. Even though short-range wireless technologies typically operate with no mobility or very low mobility, there may be scenarios in which the mobility may be a concern. For example, body movements in WBANs, or movement of the transmitter and/or the receiver in certain WSN applications may introduce mobility related problems that should be taken into account in receiver design. Centralized network topology or distributed network architectures are two common topologies for short-range wireless communication systems.

Despite the aforementioned classifications and several other possible taxonomies, it is difficult to classify different short-range technologies within different groups. The large diversity of application scenarios and requirements, differences in the air interface, and variations in operational ranges even for the same wireless technology are only a few of the factors preventing well-defined taxonomies. In this book, since it provides a relatively uniform and well-defined classification, we choose to study

Table 1.1 Example applications for short-range wireless communications.

Low-rate systems	High-rate systems
Tele-control for home and building	Wireless USB
Wireless microphones and headphones	Internet access and multimedia services
Wireless mouse, keyboard, etc.	Uncompressed high-definition video
Remote keyless entry, gate openers, etc.	Patient monitoring in hospitals
Wireless bar-code readers	Wireless surveillance cameras
Wireless sensor networks	Wireless video conferencing
Emergency medical alarms	Wireless ad-hoc communications
Wireless billing	Wireless peripheral interfaces

short-range wireless communications systems by grouping them into two categories: high-rate systems and low-rate systems.

While a clear-cut separation does not exist, high-rate systems are considered for data rates higher than 10 Mbps (up to several Gbps), and they have communication ranges smaller than 10 m. Example application scenarios for high-rate systems include wireless video streaming, wireless file transfer (e.g., wireless USB), wireless video conferencing, and wireless surveillance cameras. Also, as discussed in reference [1], high-rate technologies considered for short-range wireless communication applications are based on multiband UWB [21] and millimeter wave technologies [22, 23], and related wireless standards will be discussed in detail in Chapter 2.

Low-rate systems, on the other hand, are considered for low-power and low-complexity applications that do not have significant data rate requirements. While they do not necessarily have long communication ranges, the maximum ranges of low-rate systems may be significantly larger than those of the high-rate systems. Apart from application related requirements, two important reasons for this are as follows: (i) larger communication ranges mean lower levels of received power, which inherently prevent high data rates, and (ii) high-rate systems require a significantly large bandwidth, which is commonly available at higher central frequencies (e.g., 60 GHz spectrum) that are subject to a larger path-loss. WSNs are probably the most common applications for short-range low-rate wireless communication systems. Two important recent wireless technologies that are suitable for low-rate systems are ZigBee and low-rate UWB, and the wireless standards related to these technologies will be reviewed in detail in Chapter 6. Some examples for short-range wireless communications applications for high-rate and low-rate systems are summarized in Table 1.1, and more detailed discussions of the related applications are left to Chapter 2 and Chapter 6.

The QoS requirements as well as possible techniques and protocols for improving the reliability of low-rate and high-rate systems are considerably different. For example, primarily due to application scenarios and requirements, low-power operation becomes more relevant to WSNs, e.g., for environmental sensing applications, where the sensor nodes should operate with the same battery for extended durations. Power efficient routing techniques and cooperative communication methods may also gain more importance in such scenarios. While such techniques may also be applied to certain high-rate communication scenarios, one of the most common applications for high-rate systems is the wireless USB, which by definition is point-to-point, and routing and cooperative communications techniques become irrelevant. Due to multiple-antenna capabilities enabled by high-frequency operation of high-rate systems (e.g., for millimeter wave communications), beamforming techniques and protocols may be very important for certain scenarios in order to minimize the interference and improve reliability.

Signaling models utilized by low-rate and high-rate systems may vary greatly. For example, the high-rate ECMA-368 standard has adopted an MB-OFDM based physical (PHY) layer, which facilitates a simple equalization process in the frequency domain. On the other hand, the low-rate IEEE 802.15.4a standard uses pulse-based signal transmissions. It is an ideal signaling scheme, for example, for low-rate WSN applications, in which low-complexity transmitter/receiver architectures may be designed and highly accurate ranging/positioning is supported. Low-complexity transceiver architectures such as the energy detector and the transmitted-reference schemes become possible with pulse-based signaling, whereas FFT/IFFT operations in OFDM-based transmission may increase the transceiver complexity.

1.1.4 Review of frequency regulations and available frequency bands

The choice of the central frequency and communication bandwidth is critical for short-range wireless communication systems. As discussed earlier, high central frequencies may be preferable in many cases, because they facilitate small form-factors owing to small antenna sizes, and enable access to several license-free frequency bands at high frequencies (typically having fewer interference sources). On the other hand, since signal attenuation is directly proportional to the central frequency, wireless devices employing high central frequencies may not communicate reliably over relatively long distances owing to severe signal attenuation. Based on the application requirements of a certain short-range wireless system, before deciding on an operational center frequency, such trade-offs should be evaluated carefully by system designers.

The frequency bands in which short-range wireless devices may operate are in most cases limited to license-free bands. While certain license-free bands are globally available, there are also some license-free bands that are available in only certain regions of the world. The frequency bands that are globally available for short-range wireless devices are the 13.56 MHz band (typically considered for near-field communications), 40 MHz band, 433 MHz band, 2.4 GHz band, and the 5.8 MHz band [5]. Among these, the 2.4 GHz band is the most popular global license-free band, which is commonly used by WLANs and microwave ovens. Another band that is available and commonly used for short-range communications in Europe, the USA, Canada, Australia, and New Zealand is the 868 MHz/915 MHz band.

A part of the spectrum that can be used without a license in most countries is the ISM band [24], which also includes some of the frequency bands discussed above. For example, in the USA, popular ISM bands include the 902–928 MHz, 2.4 GHz, and 5.7–5.8 GHz bands. Similar to several other frequency bands for unlicensed transmissions,

Table 1.2 Review of the ISM/U-NII bands, and the spectrum used for UWB and 60 GHz systems in the USA.

ISM bands	Power limit	U-NII 5 GHz bands	Power limit
902–928 MHz		WiFi (802.11a/n)	
Cordless phones	1 W	5.15–5.25 GHz	200 mW
Microwave ovens	750 W	5.25–5.35 GHz	1 W
Industrial heaters	100 kW	5.47–5.725 GHz	1 W
Military radar	1000 kW	5.725–5.825 GHz	4 W
2.4–2.4835 GHz		**60 GHz band**	
Wi-Fi (802.11b/g)	1 W	57–64 GHz	0.5 W
Microwave ovens	900 W	**Ultra–wideband**	
5 GHz		3.1–10.6 GHz	−41.3 dBm/Mhz
5.725–5.825 GHz			
Wi-Fi (802.11a/n)	4 W		

the ISM bands are defined under the Part 15 rules of the Federal Communications Commission (FCC). Until 1985, the industrial, scientific, and medical (ISM) bands were not allowed to be used for radio communications in the USA. Together with the FCC Part 15.247 rules in 1985, the ISM bands have been opened for use by WLANs and mobile communications [24]. The Unlicensed National Information Infrastructure (U-NII) bands introduced by Part 15.401 to Part 15.407 of the FCC in 1997 added additional license-free frequency bands in the 5 GHz range.

In 2002, the FCC released the Subpart-F of its Part 15 rules, which defines the scope and operation of UWB devices (including communications, imaging systems, and ground-penetrating radar) under Part 15.501 to Part 15.525. Based on this new ruling, UWB devices can transmit at power levels up to −41.3 dBm/MHz in the frequency spectrum between 3.1 GHz and 10.6 GHz. This opens up a large amount of spectrum available for use by short-range UWB wireless devices. Another large spectrum that can be utilized by short-range wireless devices is defined by the Part 15.255 rules of the FCC, which allow transmission powers up to 500 mW within the frequency range 57–63 GHz. This spectrum is commonly referred to as the millimeter wave or the 60 GHz spectrum, and is another popular band for future short-range high-rate communication systems. The frequency bands and transmit power limits for the ISM/U-NII bands, UWB, and 60 GHz systems in the USA are summarized in Table 1.2. More details on the unlicensed frequency bands of the FCC can be found in reference [25], while further discussions about the sub-GHz frequency bands around the world for short-range wireless communication systems can be found in reference [5].

1.2 Definition of reliability

The focus of the current book is on reliability aspects of short-range wireless communication systems. Ultimately, reliability should be defined by the application itself. For some applications (e.g., data transfer), reliability is about data integrity and all the information sent by the transmitter must be accurately received at the receiver. For other applications such as audio and video, it is less about data integrity and more about tolerable distortion at the application layer which is a convoluted function of error rates, error burstiness, delay, error concealment techniques, etc. Traditionally, each layer of the communication stack addresses reliability at different timescales to fix errors that are not correctable, observable, or too costly to correct at the lower layers. In wireless systems, however, independent decisions at each layer often lead to an unreliable or inefficient communication environment. Therefore, some degree of cross-layer coordination/optimization has been proposed by numerous research papers and adopted in some systems (especially between the PHY and medium access control (MAC) layers). In different chapters, examples of such cross-layer optimization and coordination will be treated in their special contexts. In the rest of this section, we briefly overview how reliability is impacted by the decisions at different layers of the communication stack and discuss error sources from the perspective of each layer.

1.2.1 Reliability at the PHY layer

The PHY layer in a digital communication system is responsible for bit-level transmission/reception of signals between the nodes. It has to ensure that the transmitted bits are reliably reconstructed at an intended receiver. In order to understand better the basic principles of digital transmission/reception and related error sources involved at the PHY layer, a simple example of a transmitter/receiver architecture is illustrated in Figure 1.1. The chapters that will be addressing different aspects of reliability are illustrated in the figure. At the transmitter, data to be communicated to a target receiver is in the form of bits, composed of 0's and 1's. These bits are mapped onto signal waveforms after a modulation/coding stage. Through an RF oscillator, the transmit waveform is up-converted to the desired central frequency, amplified, and transmitted through the antenna. Before the transmit waveform arrives at the receiver, it propagates through the wireless channel, which may distort the transmitted signal in different ways as illustrated in Figure 1.1. Once the signal arrives at the receiver, it passes through the low-noise amplifier (LNA) and down-conversion stages, and gets demodulated/decoded to obtain the received bits. The transmitter structure of short-range wireless devices defined in specific standards will be discussed in more detail in Chapter 2 and Chapter 6.

Some of the important metrics that characterize reliability at the physical layer include the *signal to interference plus noise ratio* (SINR), bit error rate (BER), symbol error rate (SER), packet error rate (PER), and outage probability. Certain issues related to the reliability and relevant error sources at the PHY layer may also be explained through the help of basic channel capacity formulations. In reference [26], a reliable communication is defined as having an arbitrarily small error probability P_b, and the maximum data rate at which reliable communication is possible is defined as the capacity C of the channel. Achievable capacity for reliable communications may simply be written for additive

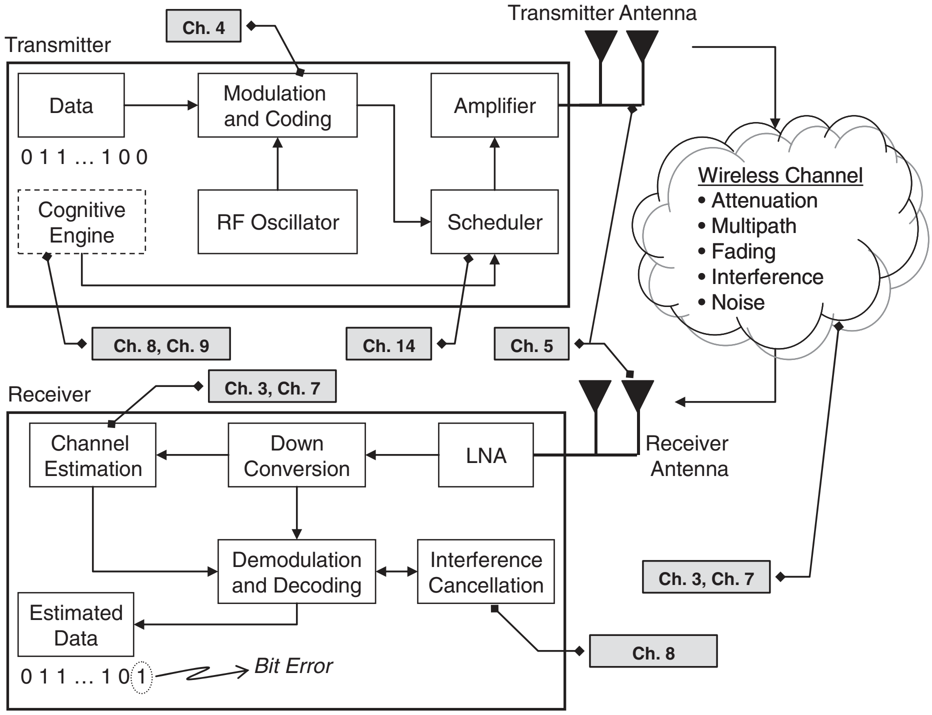

Figure 1.1 An example block diagram of a wireless transmitter/receiver and related error sources.

white Gaussian noise (AWGN) channels as[2]

$$C_{\text{awgn}} = B \log \left(1 + \frac{P_{\text{rec}}}{\sigma_{\text{I}}^2 + \sigma_{\text{n}}^2} \right), \tag{1.1}$$

where B is the communication bandwidth, P_{rec} is the received power of the signal, σ_{I}^2 captures the variance of different error/interference terms (which are assumed to be white Gaussian processes independent from the noise term), $\sigma_{\text{n}}^2 = BN_0$ is the noise variance, N_0 is the noise spectral density, and $\frac{P_{\text{rec}}}{\sigma_{\text{I}}^2+\sigma_{\text{n}}^2}$ is referred to as the SINR. Note that while the interference is assumed to be Gaussian in (1.1), this holds only with a sufficiently large number of interferers, which may not always be the case for short-range systems. As the channel capacity in (1.1) increases, reliable communications become possible at higher data rates. In order to increase the capacity, the bandwidth B can be increased (e.g., through scheduling algorithms), average interference power (σ_{I}^2) can be decreased (e.g., through interference cancellation techniques), or the received power P_{rec} can be increased (e.g., through power control algorithms).

In the rest of this subsection, Figure 1.1 and equation (1.1) will be used to discuss the major error sources that may impact the reliability at the PHY layer. Possible techniques that may be used in order to mitigate the undesired effects of these error sources will

[2] This may be easily extended to include different types of MIMO techniques, impact of multipath channels, cooperative communications, etc. [26].

also be explained, along with referrals to the related chapters in the book for a more complete treatment.

1.2.1.1 Attenuation

The received power P_{rec} in (1.1) should be sufficiently larger than the combination of noise and interference powers for the reliable detection of received bits. Due to path loss, the received power is less than the transmitted power. In free space, the Friis formula relates the transmitted and received powers as follows:

$$P_{\mathrm{rec}} = P_{\mathrm{t}} \frac{\lambda^2 G_{\mathrm{t}} G_{\mathrm{r}}}{(4\pi d)^2}\,, \tag{1.2}$$

where P_{t} denotes the transmit power, $\lambda = c/f_{\mathrm{c}}$ is the wavelength, c is the speed of light, f_{c} is the central frequency, and G_{t} and G_{r} are the antenna gains at the transmitter and the receiver, respectively. Since free-space propagation may not describe most environments accurately, a better approach is to use the empirical path loss formula

$$P_{\mathrm{rec}} = P_{\mathrm{t}} P_{\mathrm{o}} \left(\frac{d_{\mathrm{o}}}{d}\right)^{\alpha} \chi_{\mathrm{sh}}\,, \tag{1.3}$$

where P_{o} is the measured path loss at a reference distance d_{o} (typically well approximated by $(4\pi/\lambda)^2$ for $d_{\mathrm{o}} = 1$ [27]) and α is the path loss exponent. The path loss is also subject to shadowing effect due to several obstacles between the transmitter and receiver, that is captured by the multiplicative term χ_{sh} in (1.3). The shadowing is typically modeled using a log-normal random variable, where $10 \log_{10} \chi_{\mathrm{sh}} \sim \mathcal{N}(0, \sigma_{\mathrm{s}}^2)$, with σ_{s}^2 denoting the variance of χ_{sh} in the logarithmic scale.

It is obvious from both (1.2) and (1.3) that the path loss is directly proportional to the central frequency. Therefore, wireless communication systems operating at higher central frequencies (e.g., operating in the millimeter wave spectrum) may have significantly shorter communication distances than wireless devices operating at lower central frequencies. Similarly, the path loss is also directly proportional to the propagation distance. Therefore, the receivers that are closer to the transmitter will have larger received powers while far-away receivers will have lower received powers, implying lower reliability based on (1.1). A method to tackle this problem is to use adaptive modulation and coding (AMC) schemes, which adaptively select the modulation/coding scheme based on the received signal quality. When the received signal quality is good, higher order modulation schemes such as 64-QAM can be utilized to achieve higher data rates. If the receiver moves away from the transmitter, the received signal quality degrades and the receiver is no longer able reliably to demodulate the received bits with 64-QAM. Hence, a lower order modulation such as binary phase shift keying (BPSK) can be used, where the distance between the constellation points is larger, enabling reliable demodulation of the bits at the expense of lower data rates. The AMC schemes for high-rate systems will be discussed in more detail in Chapter 4.

Another possible way to improve the system performance in the presence of variations in the received signal power is to employ power control techniques. For users far away from the transmitter, a larger transmit power may be used to ensure sufficiently large