Chapter 1

Digital Communication

The advent of data transmissions over physical channels has transformed the modern communication landscape. The term *digital communication* broadly refers to the transfer of information using digital messages or bit streams. There are notable advantages to transmitting data using discrete messages. It allows for enhanced signal processing and quality control. In particular, errors caused by noise and interference can be detected and corrected systematically. Furthermore, digital communication makes the networking of heterogeneous systems possible, with the Internet being the most obvious such example. These advantages, and many more, explain the widespread adoption and constantly increasing popularity of digital media.

1.1 System Components

The operation of a typical digital communication system can be represented by the functional block diagram depicted in Figure 1.1. It is composed of five basic components. The input block contains the source, which produces data such as voice, emails, or images; and it also includes all the operations that are required to convert the original signal waveform into a format suitable for transmission. The transmitter takes bits from the input block and sends them over a channel using electromagnetic signals or some alternate means. It may add a protective layer to the intended message to shield it from noise and interference. Communication channels come in many flavors. For instance,

a transmission can take place over an ethernet cable, a coaxial cable, or free space (wireless communication). There are also more esoteric channels like a hard drive platter, a compact disc, or a memory stick. The role of the receiver is to recover the sent message from a collection of measurements. This unit may need to extract the signal from noise and, possibly, correct errors that may have occurred during transmission. Finally, the output block takes the received information and puts it back into a format that is appropriate for the end-users.
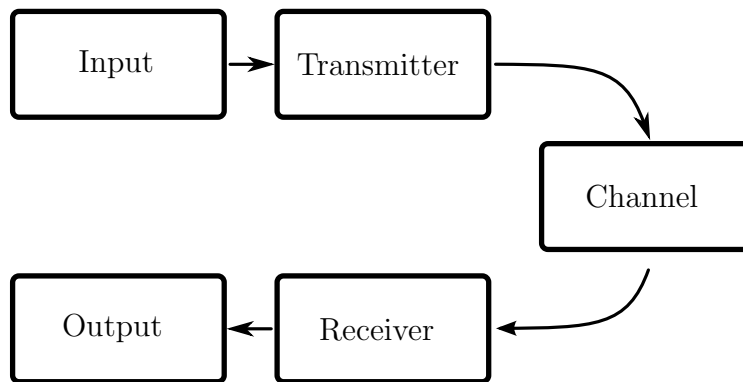

Figure 1.1: A digital communication system contains five basic components. These building blocks appear in this diagram.

Figure 1.1 also alludes to the natural symmetry present in digital communication systems. Operations that take place on the transmitter side must often be undone at the destination. As such, complementary steps are frequently studied in pairs. Our treatment of digital communication follows this general approach.

1.1.1   The Input-Output Blocks

The role of the input block is to take information in its original form and to convert it into a digital format. Depending on the nature of the source, two operations may be necessary to digitize the information waveform. *Sampling* is a signal processing technique that transforms a continuous-time function to a discrete-time signal. The conversion of a sound wave into a sequence of samples is a common application of sampling. The second action that may be

needed is *quantization*, which maps a continuous-space signal into a discrete set of possible values. The combination of these two operations will transform an analog signal into a digital message.
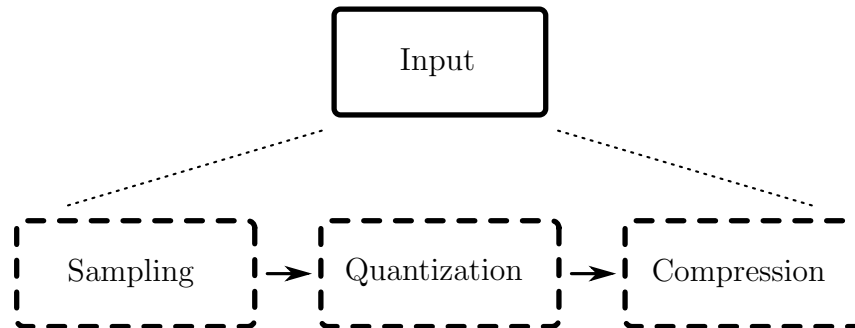

Figure 1.2: The input block can be further divided into three operations: sampling, quantization and data compression. The first two operations are necessary to transform an analog waveform into a digital signal; whereas the last block is optional and provides a means to reduce the size of a digitized message.

The optional step of *data compression*, or source coding, is often employed at the origin to reduce the size of the message to be transmitted. This, in turn, brings down the consumption of expensive physical resources such as power, spectral bandwidth and hard disk space. On the downside, data processing entails additional computations and delay, and the compressed data must be expanded before being accessed. This involves using extra processing on the receiver side as well. Some compression schemes reduce the quality of the data. These schemes usually feature better compression ratios at the expense of introducing small variations in the data. The MPEG standards, including the MP3 audio layer, provide examples of lossy compression schemes.

At the output of the system, the data must be put back into a format that is acceptable to the end-user. The received message must be decompressed. Note that for the destination to be able to recover the original data, it must understand the encoding scheme utilized by the sender. In other words, the decoding method must be known at the receiver. If the original signal is a continuous-time waveform, then an interpolator can be used to reconstruct the waveform from its sample values. The quantization block present at the input
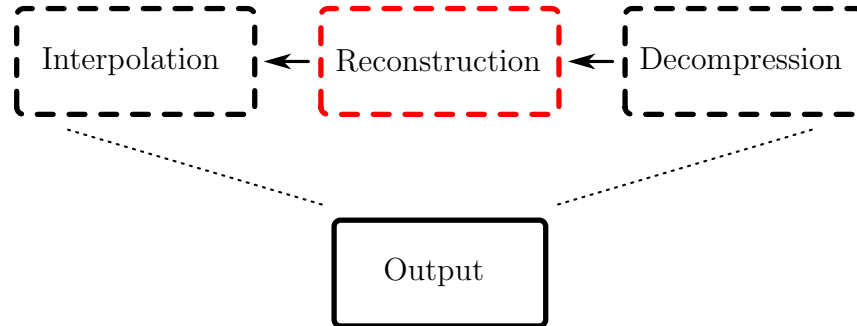
Figure 1.3: The operations executed at the transmitter must typically be undone at the destination. When passed through the output block, the received data is first decompressed and put in a format that suitable for signal processing. Furthermore, an analog signal must be reconstructed from the sampled data point. While these two steps can reversed without any loss, the quantization step cannot. This is because quantization loses a small part of the original information. Instead, the reconstruction step reverses quantization step in an approximate way to minimize the distortion.

does not have an exact counterpart at the output. This deficiency follows from the fact that quantization cannot be perfectly undone because information is typically lost when a continuous-valued signal is discretized. The level of *distortion* associated with quantization can, however, be controlled by choosing an appropriate scheme and reconstructing the signal in a sensible way. In most cases, the impact of quantization is minimal; indeed, quantizers are often designed to induce negligible distortion.

1.1.2 The Transmitter-Receiver Pair

A channel code is used at the transmitter to shield data sent over the channel against errors due to noise and interference. This level of protection is achieved by adding redundancy to the information bits in a structured manner. Audio compact discs make use of a *Reed-Solomon code* to protect digital music from scratches and dust, whereas a low-latency *convolutional code* is employed in cellphones to carry voice signals. The second task of the transmission unit is to modulate the digital bit-stream onto an analog carrier prior to transmission.

The possible waveforms emitted by the transmitter are chosen from a finite number of symbols. The transmitter must produce a signal that remains confined to its assigned spectral bandwidth.
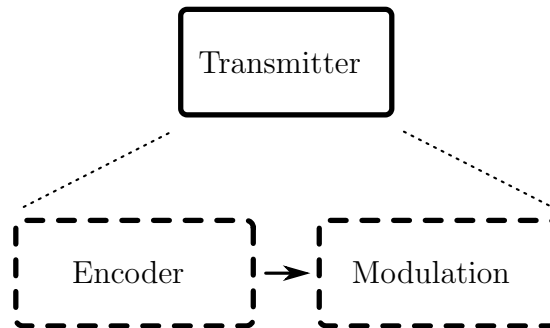

Figure 1.4: At the transmitter, redundancy is added to the digital message to protect information bits against noise and interference. Once this is completed, the bit stream is modulated onto an analog carrier and transmitted to the destination.

The message then propagates through the communication channel. This is the physical medium that bridges the gap between the transmitter and the receiver. In most applications, the channel acts as to transfer the data to a different place. However, in hard disk drives and compact discs, the information is stored simply to be accessible at a later time. Most communication channels cause signal degradation. The message may be subject to attenuation, interference and noise corruption. That is, the communication channel may be unreliable; and its environment, hard to characterize. Recovering the original data from a set of measurements available at the receiver is one of the many challenges of digital communication systems.

The receiver is tasked with extracting the original symbols from noisy measurements. The first step consists of estimating which symbols were sent by the transmitter over the channel. This procedure is termed *demodulation*. These symbol estimates are then translated back into information bits by the decoder. Redundancy is removed from the data, and the original format of the information bits is restored. When channel conditions are harsh and the local measurement noisy, this process may fail and the corresponding data is lost. Scratching a compact disc repetitively will illustrate this point well; after sub-
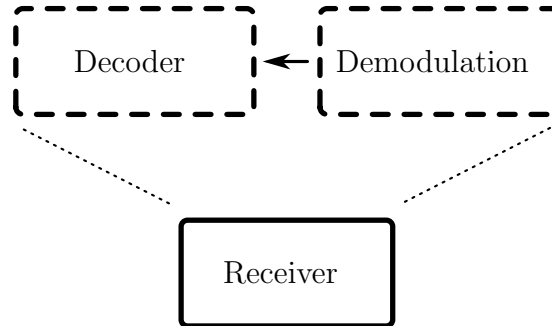
Figure 1.5: On the receiver side, the sent symbols are extracted from the received signal. Error-correction techniques are then applied to insure the integrity of the acquired data. Finally, the digital message is restored to its original format.

stantial disc abuse, a player is no longer able to reconstruct the music. At this point, the receiver may elect to notify the sender and request a retransmission of the desired message.

1.2   Common Channels and Applications

Various communication channels can provide a connection between a transmitter and its destination. Common wireline channels include coaxial cables, ethernet cables, and twisted-pair wires. Optical fiber offers a high-capacity solution for heavy applications. Compact discs and DVDs are also based on optics and they can be employed to store information on discs. Finally, wireless electromagnetic channels are popular for their convenience and broadcast capabilities.

Digital communication occupies a central role in almost every aspect of contemporary life. Most businesses rely directly or indirectly on networked computers and the Internet for day-to-day operations, and digital technologies have become a staple of the entertainment industry. Below, we provide a few examples of digital communication systems that you may be familiar with.

Cable Modem: A cable modem enables point-to-point communication over the cable television infrastructure. They are primarily employed to deliver

broadband Internet access, taking advantage of unused bandwidth on a cable television network. With the emergence of voice over Internet protocol (VoIP) telephony, cable modems can also be used to provide telephone service.

Wi-Fi Technology: Wi-Fi is a global set of standards that allows wireless inter-networking. In particular, it includes the IEEE 802.11 protocol suite (e.g., 802.11b, 802.11g and 802.11n). Wireless access points, also called *hotspots*, often provide users access to the Internet. Wi-Fi products can be used as an enabling technology for *mesh networks*, which offer connectivity to large urban communities.

Bluetooth: Bluetooth is a wireless protocol designed specifically for short-range communication. It is used primarily to create personal area networks. Bluetooth provides a means to exchange information between devices such as mobile phones, personal computers, digital cameras, and a myriad of small accessories.

Hard Disk Drive: A hard disk drive is a non-volatile storage device that keeps digitally encoded data on rapidly rotating platters with magnetic surfaces. Today, hard drives can be found in computers, digital audio players, personal digital assistants, game consoles and other embedded computing devices. Data on a hard disk drive is recorded by magnetizing ferromagnetic material directionally, and is read back by detecting the magnetization of the material.

Compact Disc: The compact disc (CD) is an optical disc used to store digital data, and remains one of the popular playback media for commercial audio recordings. A standard compact disc can store approximately 650 Megabytes of data. The data is stored on the disc as a sequence of bumps that are stamped into the polycarbonate during production. A reflective layer is added so that the data can be read by using a laser to distinguish between *pits* and *lands*.

In a recordable compact disc (CD-R), a photosensitive dye is used instead. The write laser of a CD recorder changes the color of the dye to allow a

standard CD player to read the data, just as it would with a standard stamped disc. A re-recordable disc medium (CD-RW) uses a metallic alloy instead of a dye. The write laser in this case is used to heat and alter the properties of the alloy, and hence change its reflectivity. A CD-RW does not possess as great a difference in reflectivity as a stamped compact disc, and so many earlier audio players cannot read CD-RW discs, although most later CD audio players and stand-alone DVD players can.