Module 1

Introduction to Digital Communications and Information Theory

Lesson
1

Introduction to Digital Communications

After reading this lesson, you will learn about

- ***Lesson-wise organization of this course***
- ***Schematic description of a representative digital communication system***
- ***Milestones in the history of electronic communications***
- ***Names and usage of electromagnetic bands***
- ***Typical transmission loss for several physical media***

Preamble

Usage of the benefits of electrical communications in general and digital communications in particular, is an inseparable part of our daily experience now. Innumerable applications due to developments in digital communications have already started influencing our day-to-day activities directly or indirectly. Popularity of the Internet and television are only two of the most obvious examples to prove the point. In fact, it may not be an overstatement today that 'information highways' are considered as essential ingredients of national infrastructure in the march of a modern society. It is, however, pertinent to mention that isolated developments only in the field of electrical communications have not caused this phenomenon. Remarkable progresses and technical achievements in several related fields in electronics engineering and computer engineering have actually made applications of several principles and theories of communication engineering feasible for implementation and usage. The purpose of this web course, however, is narrow and specific to the principles of digital communications.

This web course on 'Digital Communications' is primarily intended for use by undergraduate students who may be preparing for graduate level studies in the area of electrical communications engineering. A teacher, offering an introductory-level course on digital communications, may also find several topics suitable for classroom coverage. The field of Digital Communications is reach in literature and there is no dearth of excellent text books and research papers on specific topics over and above the bulk of tutorial material, technical standards and product information that are available through the Internet. Hence, the onus is clearly on the present authors to justify the need and relevance of this web course on 'Digital Communications'. To put it humbly, the present authors believe that any 'web course' should primarily cater to the quick requirements of the prime target audience (in our case, an undergraduate student preparing for graduate level studies in the area of electrical communications engineering). The usual requirements are believed to be of the following types: a) exposition to a relevant topic or concept, b) examples and problems to highlight the significance or use of certain principles and c) specific data or information in relation to a topic of study in the area of digital communications. Our teaching experience says that some or all of these requirements are indeed met in several textbooks to a good extent. For ready reference, a consolidated Bibliography is appended at the end of this course material. What stand out, probably, in favour of a 'web course' are the flexibility in using the material may be covered and the scope of continuous upgradation of the material to cater to specific needs of the audience in future.

The general structure of '40-Lesson course' is an indication to the implicit limits (of 'time to read' and 'storage'); hence a balance among the reader requirements a) – c), mentioned above, should be worked out. The present version of this web course is designed with more emphasis on exposing relevant topics and concepts [requirement a)] which may supplement classroom teaching.

The course is split in seven Modules as outlined below.

The first module consists of four lessons. The present lesson (Lesson #1) gives an outline of major historical developments in the field of research in telecommunications engineering over a period of hundred years. Materials on radio spectrum should help recapitulate a few basic issues. The lesson ends with a general schematic description on a digital communication system. Lesson #2 gives a brief classification of signals and emphasizes the importance of sampling theory. Lesson #3 presents some basic concepts of information theory, which helps in appreciating other central principles and techniques of digital transmission. The concept of 'information' is also outlined here. Needs and benefits of modeling an information source are the topics in Lesson #4.

The second module is devoted to Random Processes. The module starts with a simple to follow introduction to random variables (Lesson #5). It is often necessary to acquire the skill of defining appropriate functions of one or more random variables and their manipulation to have greater insight into parameters of interest. The topic is introduced in Lesson #6 wherein only functions of one random variable have been considered. A powerful and appropriate modeling of a digital communication system is often possible by resorting to the rich theories of stochastic processes and this remains an important tool for deeper analysis of any transmission system in general. The topic has been treated at an elementary level in Lesson #7. A few commonly encountered random distributions, such as binomial, Poisson, Gaussian and Rayleigh are presented in Lesson #6. An emerging and powerful branch in electrical communication engineering is now popularly known as statistical signal processing and it encompasses several interesting issues of communication engineering including those of signal detection and parameter estimation. The basic backgrounds, laid in Lessons #5 to #8 should be useful in appreciating some of the generic issues of signal detection and parameter estimation as outlined in Lesson #9.

The third module on pulse coding focuses on the specific tasks of quantization and coding as are necessary for transmission and reception of an analog electrical signal. It is however, assumed that the reader is familiar with the basic schemes of analog-to-digital conversion. The emphasis in this module is more on the effects of quantization error (Lesson #10) while different pulse coding schemes such as Pulse Code Modulation (Lesson #11), Log-PCM (Lesson #12), Differential Pulse Code Modulation (Lesson #13) and Delta Modulation (Lesson #14) are used for possible reductions in the average number of bits that may have to be transmitted (or stored) for a given analog signal. The example of speech signal has been considered extensively.

Appropriate representation of bits (or information bearing symbol) is a key issue in any digital transmission system if the available bandwidth is not abundant. Most of the physical transmission media (e.g. twisted copper telephone line, good quality coaxial cable, radio frequency bands) are, in general, limited in terms of available frequency band (a simple reason for this general observation: demand for good quality digital communication system, in terms of bits to be transferred per second, has been rising with newer demands and aspirations from users). So, it makes sense to look for time-limited energy pulses to represent logical '1'-s and '0'-s such that the signal, after representation, can be transmitted reliably over the available limited bandwidth. The issue is pertinent for both carrier less (referred as 'baseband' in Module #4) transmission as well as modulated transmission (with carrier, Module #5). Several interesting and relevant issues such as orthogonality amongst time-limited energy pulses (Lesson #15), baseband channel modeling (Lesson #17) and signal reception strategies (Lessons #18 - #21) have, hence, been included in Module #4.

Module #5 is fully devoted to the broad topic of Carrier Modulation. Several simple digital modulation schemes including amplitude shift keying, frequency shift keying (Lesson #23) and phase shift keying (Lessons #24 - #26) have been introduced briefly. Performance of these modulation schemes in the background of additive Gaussian noise process is addressed in Lesson #27 and Lesson #28. If appreciated fully, these basic techniques of performance evaluation will also be useful in assessing performance of the digital modulation schemes in presence of other transmission impairments (e.g. interference). The basic issues of carrier synchronization and timing synchronization have been elaborated with reasonable illustrations in Lesson #31 and Lesson #32.

Module #6 is on error control coding or 'Channel Coding' as it is popularly known today. Basics of block and convolutional codes have been presented in three lessons (Lessons #33 - #35). Two more lessons on turbo coding (Lesson #37) and coded modulation schemes (Lesson #36) have been added in view of the importance of these schemes and procedures in recent years.

Spread spectrum communication techniques have gained popularity in last two decades in view of their widespread commercial use in digital satellite communications and cellular communications. A primary reason for this is the inherent feature of multiple access that helps simultaneous use of radio spectrum by multiple users. Effectively, several users can access the same frequency band to communicate information successfully without appreciable interference. Basic spread spectrum techniques have been discussed in Lesson #38 of Module #7 before highlighting the multiple access feature in Lesson #40. It is interesting to note that a spread spectrum communication system offers several other advantages such as anti-jamming and low probability of interception. In such non-conventional applications, the issue of code acquisition and fine tracking is of utmost importance as no pilot signal is usually expected to aid the process of code synchronization. To appraise the reader about this interesting and practical aspect of code synchronization the topic has been introduced in Lesson #39.

A short Bibliography is appended at the end of Lesson #40.

Block Schematic Description of a Digital Communication System

In the simplest form, a transmission-reception system is a three-block system, consisting of a) a transmitter, b) a transmission medium and c) a receiver. If we think of a combination of the transmission device and reception device in the form of a 'transceiver' and if (as is usually the case) the transmission medium allows signal both ways, we are in a position to think of a both-way (bi-directional) communication system. For ease of description, we will discuss about a one-way transmission-reception system with the implicit assumption that, once understood, the ideas can be utilized for developing / analyzing two-way communication systems. So, our representative communication system, in a simple form, again consists of three different entities, viz. a transmitter, a communication channel and a receiver.

A digital communication system has several distinguishing features when compared with an analog communication system. Both analog (such as voice signal) and digital signals (such as data generated by computers) can be communicated over a digital transmission system. When the signal is analog in nature, an equivalent discrete-time-discrete-amplitude representation is possible after the initial processing of sampling and quantization. So, both a digital signal and a quantized analog signal are of similar type, i.e. discrete-time-discrete-amplitude signals.

A key feature of a digital communication system is that a sense of 'information', with appropriate unit of measure, is associated with such signals. This visualization, credited to Claude E. Shannon, leads to several interesting schematic description of a digital communication system. For example, consider **Fig.1.1.1** which shows the signal source at the transmission end as an equivalent 'Information Source' and the receiving user as an 'Information sink'. The overall purpose of the digital communication system is 'to collect information from the source and carry out necessary electronic signal processing such that the information can be delivered to the end user (information sink) with acceptable quality'. One may take note of the compromising phrase 'acceptable quality' and wonder why a digital transmission system should not deliver exactly the same information to the sink as accepted from the source. A broad and general answer to such query at this point is: well, it depends on the designer's understanding of the 'channel' (**Fig. 1.1.1**) and how the designer can translate his knowledge to design the electronic signal processing algorithms / techniques in the 'Encoder' and 'decoder' blocks in **Fig. 1.1.1**. We hope to pick up a few basic yet good approaches to acquire the above skills. However, pioneering work in the 1940-s and 1950-s have established a bottom-line to the search for 'a flawless (equivalently, 'error-less') digital communication system' bringing out several profound theorems (which now go in the name of Information Theory) to establish that, while error-less transmission of information can never be guaranteed, any other 'acceptable quality', arbitrarily close to error-less transmission may be possible. This 'possibility' of almost error-less information transmission has driven significant research over the last five decades in multiple related areas such as, a) digital modulation schemes, b) error control techniques, c) optimum receiver design, d) modeling and characterization of channel and so forth. As a result, varieties of digital communication systems have been designed and put to use over the years and the overall performance have improved significantly.

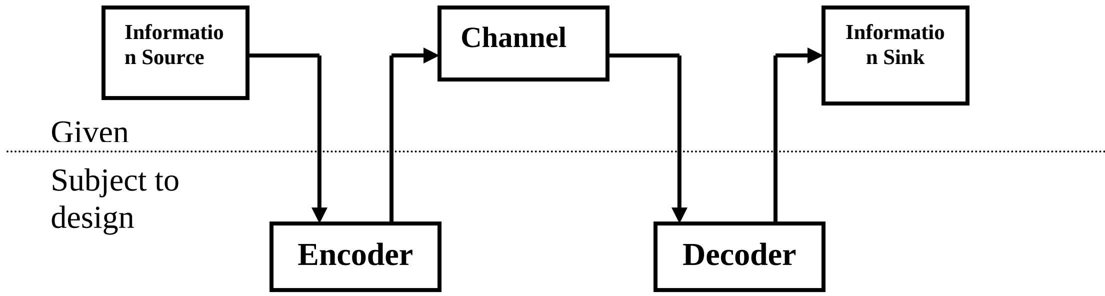

Fig. 1.1.1 *Basic block diagram of a digital communication System*

It is possible to expand our basic 'three-entity' description of a digital communication system in multiple ways. For example, **Fig. 1.1.2** shows a somewhat elaborate block diagram explicitly showing the important processes of 'modulation-demodulation', 'source coding-decoding' and 'channel encoding – decoding'. A reader may have multiple queries relating to this kind of abstraction. For example, when 'information' has to be sent over a large distance, it is a common knowledge that the signal should be amplified in terms of power and then launched into the physical transmission medium. Diagrams of the type in **Figs. 1.1.1** and **1.1.2** have no explicit reference to such issues. However, the issue here is more of suitable representation of a system for clarity rather than a module-by-module replication of an operational digital communication system.

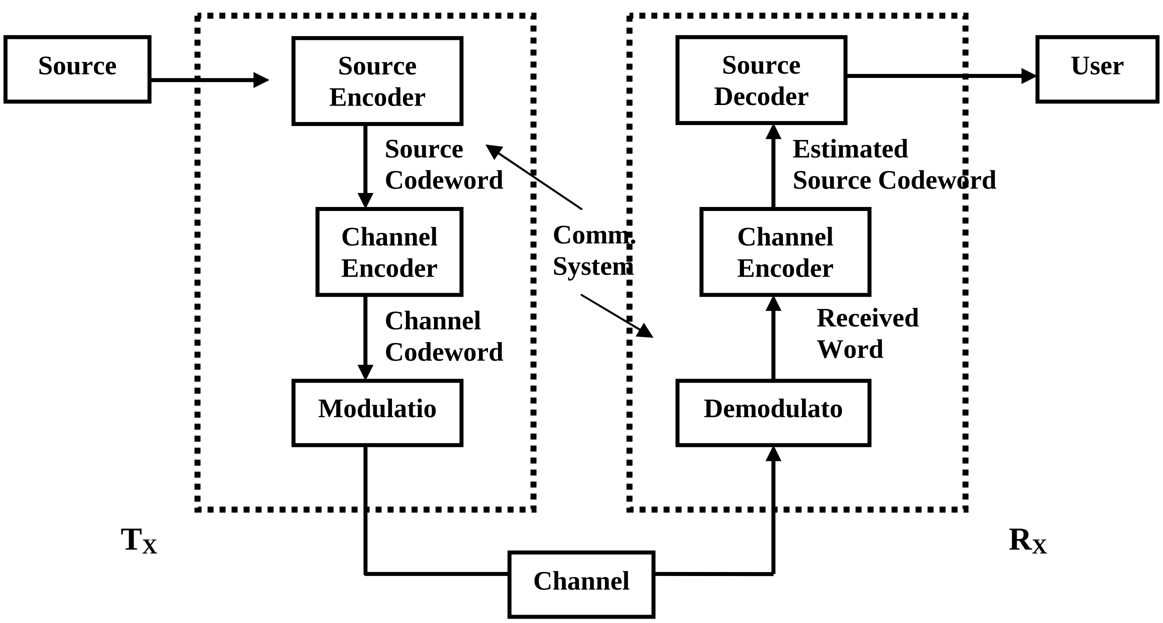

Fig. 1.1.2 *A possible break up of the previous diagram (following Shannon's ideas)*

To elaborate this potentially useful style of representation, let us note that we have hardly discussed about the third entity of our model, viz. the ‘channel’. One can define several types of channel. For example, the ‘channel’ in **Fig. 1.1.2** should more appropriately be called as a ‘modulation channel’ with an understanding that the actual transmission medium (called ‘physical channel’), any electromagnetic (or other wise) transmission- reception operations, amplifiers at the transmission and reception ends and any other necessary signal processing units are combined together to form this ‘modulation channel’.

We will see later that a modulation channel usually accepts modulated signals as analog waveforms at its inputs and delivers another version of the modulated signal in the form of analog waveforms. Such channels are also referred as ‘waveform channels’. The ‘channel’ in **Fig. 1.1.1**, on the other hand, appears to accept some ‘encoded’ information from the source and deliver some ‘decoded’ information to the sink. Both the figures are potentially useful for describing the same digital communication system. On comparison of the two figures, the reader is encouraged to infer that the ‘channel’ in **Fig. 1.1.1** includes the ‘modulation channel’ and the modulation- demodulation operations of **Fig. 1.1.2**. The ‘channel’ of **Fig. 1.1.1** is widely denoted as a ‘discrete channel’, implying that it accepts discrete-time-discrete-amplitude signals and also delivers discrete-time-discrete-amplitude signals.

In the following, we introduce a few short tables, which may help a reader to recapitulate some relevant issues of electrical communications. **Table 1.1.1** lists some of the important events which have contributed to the developments in electrical communication. **Table 1.1.2** presents different frequency bands with typical applications that are commonly used for the purpose of electrical communications. This table is very useful for our subsequent lessons. **Table 1.1.3** mentions frequency ranges for a few popular broadcast and communication services. **Table 1.1.4** gives an idea of typical centre frequencies and the nominal bandwidths that are available for five frequency bands. It is important to note that larger bandwidths are available when the operating frequency bands are higher. **Table 1.1.5** provides an idea of typical power losses of several physical transmission media at representative operating frequency. It may be noted that all transmission media are not equally suitable at all frequencies. An important factor other than the power loss in a physical medium is its cost per unit length.

Year / Period	Achievements
1838	Samuel F. B. Morse demonstrated the technique of telegraph
1876	Alexander Graham Bell invents telephone
1897	Guglielmo Marconi patents wireless telegraph system. A few years earlier, Sir J. C. Bose demonstrated the working principle of electromagnetic radiation using a ‘solid state coherer’
1918	B. H. Armstrong develops super heterodyne radio receiver
1931	Teletype service introduced
1933	Analog frequency modulation invented by Edwin Armstrong
1937	Alec Reeves suggests pulse code modulation (PCM)
1948-49	Claude E. Shannon publishes seminal papers on ‘A Mathematical Theory of Communications’
1956	First transoceanic telephone cable launched successfully
1960	Development of Laser
1962	Telstar I, first satellite for active communication, launched successfully
1970-80	Fast developments in microprocessors and other digital integrated circuits made high bit rate digital processing and transmission possible; commercial geostationary satellites started carrying digital speech, wide area computer communication networks started appearing, optical fibers were deployed for carrying information through light., deep space probing yielded high quality pictures of planets.
1980-90	Local area networks (LAN) making speedy inter-computer data transmission became widely available; Cellular telephone systems came into use. Many new applications of wireless technology opened up remarkable scopes in business automation.
1990-2000	Several new concepts and standards in data network, such as, wireless LAN (WLAN), AdHoc networks, personal area networks (PAN), sensor networks are under consideration for a myriad of potential applications.

Table 1.1.1 *Some milestones in the history of electrical communications*

Frequency Band	Wavelength	Name	Transmission Media	Some Applications
3 – 30 KHz	100–10 Km	Very Low Frequency (VLF)	Air, water, copper cable	Navigation, SONAR
30–300 KHz	10 Km- 1 Km	Low Frequency (LF)	Air, water, copper cable	Radio beacons, Ground wave communication
300KHz – 3 MHz	1 Km – 100 m	Medium Frequency (MF)	Air, copper cable	AM radio, navigation, Ground wave communication
3 MHz – 30 MHz	100 m– 10 m	High Frequency (HF)	Air, copper and coaxial cables	HF communication, Citizen's Band (CB) radio, ionosphere communication
30MHz- 300 MHz	10 m – 1 m	Very High Frequency (VHF)	Air, free space, coaxial cable	Television, Commercial FM broadcasting, point to point terrestrial communication
300 MHz – 3 GHz	1m – 10 cm	Ultra High Frequency (UHF)	Air, free space, waveguide	Television, mobile telephones, satellite communications,
3GHz – 30 GHz	10cm–1cm	Super / Extra High Frequency (SHF / EHF)	Air, free space, waveguide	Satellite communications, wireless LAN, Metropolitan Area network (WMAN), Ultra Wideband communication over a short distance
30 GHz – 300 GHz	1 cm – 1 mm			Mostly at experimental stage
30 Tera Hz – 3000 Tera Hz	10 µm – 0.1µm (approx)	Optical	Optical fiber	Fiber optic communications

Table 1.1.2 *Electromagnetic bands with typical applications*

Any radio operation at 1GHz or beyond (upto several tens of GHz) is also termed as 'microwave' operation.

Name / Description	Frequency Range	Application
AM Broadcast Radio	540 KHz – 1600 KHz	Commercial audio broadcasting using amplitude modulation
FM Broadcast Radio	88 MHz – 108 MHz	Commercial audio broadcasting using frequency modulation
Cellular Telephony	806 MHz – 940 MHz	Mobile telephone communication systems
Cellular Telephony and Personal Communication Systems (PCS)	1.8 GHz – 2.0 GHz	Mobile telephone communication systems
ISM (Industrial Scientific and Medical) Band	2.4 GHz – 2.4835 GHz	Unlicensed band for use at low transmission power
WLAN (Wireless Local Area Network)	2.4 GHz band and 5.5 GHz	Two unlicensed bands are used for establishing high speed data network among willing computers
UWB (Ultra Wide Band)	3.7 GHz – 10.5 GHz	Emerging new standard for short distance wireless communication at a very high bit rate (typically, 100 Mbps)

Table 1.1.3 *A few popular frequency bands*

Frequency band	Carrier frequency	Approx. Bandwidth
Long wave Radio [LF]	100KHz	~ 2 KHz
Short wave [HF]	5MHz	100 KHz
VHF	100MHz	5 MHz
Micro wave	5GHz	100 MHz
Optical	5×10^{14} Hz	10 GHz – 10 THz

Table 1.1.4 *Some Carrier frequency values and nominal bandwidth that may be available at the carrier frequency*

Transmission medium	**Frequency**	**Power loss in [dB/km]**
Twisted copper wire [16 AWG]	1 KHz 100KHz	0.05 3.0
Co-Axial Cable [1cm dia.]	100 KHz 3 MHz	1.0 4.0
Wave Guide	10 GHz	1.5
Optical Fiber	$10^{14} – 10^{16}$ Hz	<0.5

Table 1.1.5 Typical power losses during transmission through a few media

Problems

Q1.1.1) Mention two reasons justifying the source encoding operation in a digital communication system.

Q1.1.2) Give examples of three channels, which are used for purpose of communication

Q1.1.3) Give three examples of types of signals that a source (Fig 1.1.2) may generate.

Q1.1.4) Signaling in UHF band allows higher bit rate compared to HF band – criticize this comment.