Module
2
Data Communication Fundamentals

Lesson 3

Transmission Impairments and Channel Capacity

Specific Instructional Objectives

At the end of this lesson the students will be able to:

- Specify the Sources of impairments
- Explain Attenuation and unit of Attenuation
- Specify possible types of distortions of a signal
- Explain Data Rate Limits and Nyquist Bit Rate
- Distinguish between Bit Rate and Baud Rate
- Identify Noise Sources
- Explain Shannon Capacity in a Noisy Channel

2.3.1 Introduction

When a signal is transmitted over a communication channel, it is subjected to different types of impairments because of imperfect characteristics of the channel. As a consequence, the received and the transmitted signals are not the same. Outcome of the impairments are manifested in two different ways in analog and digital signals. These impairments introduce random modifications in analog signals leading to distortion. On the other hand, in case of digital signals, the impairments lead to error in the bit values. The impairment can be broadly categorised into the following three types:

- Attenuation and attenuation distortion
- Delay distortion
- Noise

In this lesson these impairments are discussed in detail and possible approaches to overcome these impairments. The concept of channel capacity for both noise-free and noisy channels have also been introduced.

2.3.2 Attenuation

Irrespective of whether a medium is guided or unguided, the strength of a signal falls off with distance. This is known as *attenuation.* In case of guided media, the attenuation is logarithmic, whereas in case of unguided media it is a more complex function of the distance and the material that constitutes the medium.

An important concept in the field of data communications is the use of on unit known as **decibel** (dB). To define it let us consider the circuit elements shown in Fig. 2.3.1. The elements can be either a transmission line, an amplifier, an attenuator, a filter, etc. In the figure, a transmission line (between points P_1 and P_2) is followed by an amplifier (between P_2 and P_3). The input signal delivers a power P_1 at the input of an communication element and the output power is P_2. Then the power gain G for this element in decibles is given by $G = 10\log_2 P_2/ P_1$. Here P_2/ P_1 is referred to as absolute power gain. When $P_2 > P_1$, the gain is positive, whereas if $P_2 < P_1$, then the power gain is negative and there is a power loss in the circuit element. For P_2 = 5mW, P_1 = 10mW, the power gain G = 10log 5/10 = 10 × -3 = -3dB is negative and it represents attenuation as a signal passes through the communication element.

Example: Let us consider a transmission line between points 1 and 2 and let the energy strength at point 2 is 1/10 of that of point 1. Then attenuation in dB is $10\log_{10}(1/10) = -10$ dB. On the other hand, there is an amplifier between points 2 and 3. Let the power is 100 times at point 3 with respect to point 2. Then power gain in dB is $10\log_{10}(100/1) = 20$ dB, which has a positive sign.

Figure 2.3.1 *Compensation of attenuation using an amplifier*

The attenuation leads to several problems:

Attenuation Distortion: If the strength of the signal is very low, the signal cannot be detected and interpreted properly at the receiving end. The signal strength should be sufficiently high so that the signal can be correctly detected by a receiver in presence of noise in the channel. As shown in Fig. 2.3.1, an amplifier can be used to compensate the attenuation of the transmission line. So, attenuation decides how far a signal can be sent without amplification through a particular medium.

Attenuation of all frequency components is not same. Some frequencies are passed without attenuation, some are weakened and some are blocked. This dependence of attenuation of a channel on the frequency of a signal leads to a new kind of distortion *attenuation distortion*. As shown in Fig. 2.3.2, a square wave is sent through a medium and the output is no longer a square wave because of more attenuation of the high-frequency components in the medium.

Figure 2.3.2 *Attenuation distortion of a square wave after passing through a medium.*

The effect of attenuation distortion can be reduced with the help of a suitable equalizer circuit, which is placed between the channel and the receiver. The equalizer has opposite attenuation/amplification characteristics of the medium and compensates higher losses of some frequency components in the medium by higher amplification in the equalizer. Attenuation characteristics of three popular transmission media are shown in Fig. 2.3.3. As shown in the figure, the attenuation of a signal increases exponentially as frequency is increased from KHz range to MHz range. In case of coaxial cable attenuation increases linearly with frequency in the Mhz range. The optical fibre, on the other hand, has attenuation characteristic similar to a band-pass filter and a small frequency band in the THz range can be used for the transmission of signal.

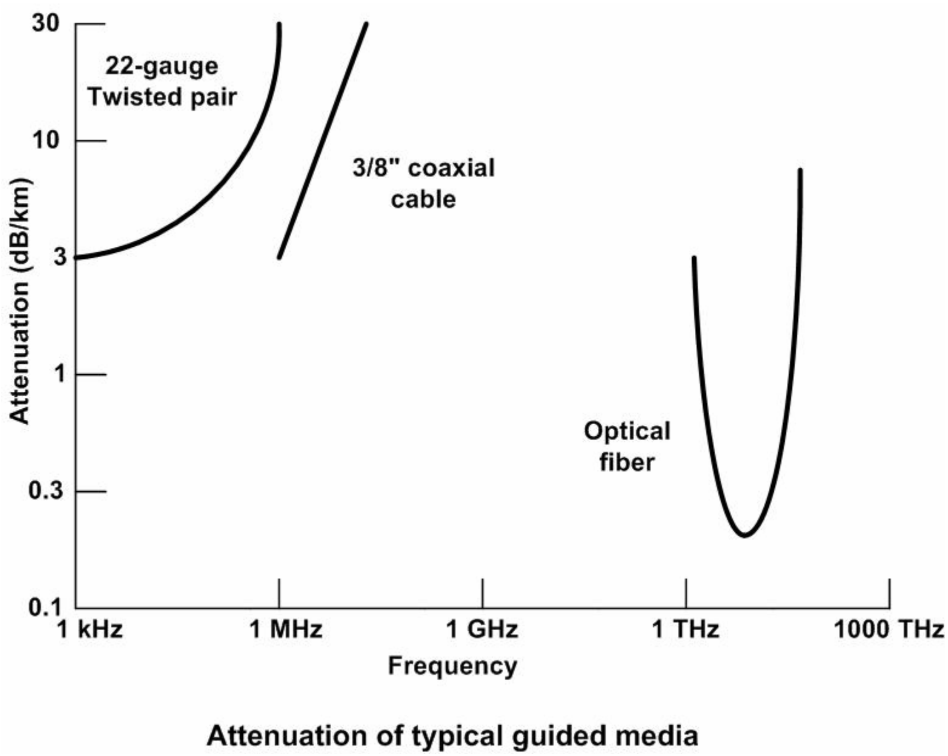

Figure 2.3.3 *Attenuation characteristics of the popular guided media*

2.3.3 Delay distortion

The velocity of propagation of different frequency components of a signal are different in guided media. This leads to delay distortion in the signal. For a bandlimited signal, the velocity of propagation has been found to be maximum near the center frequency and lower on both sides of the edges of the frequency band. In case of analog signals, the received signal is distorted because of variable delay of different components. In case of digital signals, the problem is much more severe. Some frequency components of one bit position spill over to other bit positions, because of delay distortion. This leads to intersymbol interference, which restricts the maximum bit rate of transmission through a particular transmission medium. The delay distortion can also be neutralised, like attenuation distortion, by using suitable equalizers.

2.3.4 Noise

As signal is transmitted through a channel, undesired signal in the form of noise gets mixed up with the signal, along with the distortion introduced by the transmission media. Noise can be categorised into the following four types:

- Thermal Noise
- Intermodulation Noise
- Cross talk
- Impulse Noise

The ***thermal noise*** is due to thermal agitation of electrons in a conductor. It is distributed across the entire spectrum and that is why it is also known as *white noise* (as the frequency encompass over a broad range of frequencies).

When more than one signal share a single transmission medium, ***intermodulation noise*** is generated. For example, two signals f_1 and f_2 will generate signals of frequencies ($f_1 + f_2$) and ($f_1 - f_2$), which may interfere with the signals of the same frequencies sent by the transmitter. Intermodulation noise is introduced due to nonlinearity present in any part of the communication system.

Cross talk is a result of bunching several conductors together in a single cable. Signal carrying wires generate electromagnetic radiation, which is induced on other conductors because of close proximity of the conductors. While using telephone, it is a common experience to hear conversation of other people in the background. This is known as *cross talk.*

Impulse noise is irregular pulses or noise spikes of short duration generated by phenomena like lightning, spark due to loose contact in electric circuits, etc. Impulse noise is a primary source of bit-errors in digital data communication. This kind of noise introduces burst errors.

2.3.5 Bandwidth and Channel Capacity

Bandwidth refers to the range of frequencies that a medium can pass without a loss of one-half of the power (-3dB) contained in the signal. Figure 2.3.4 shows the bandwidth of a channel. The points F_l and F_h points correspond to –3bB of the maximum amplitude A.

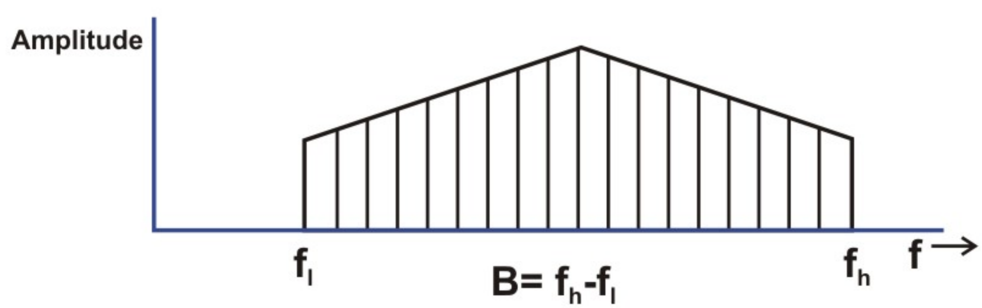

Figure 2.3.4 *Bandwidth of a channel*

Bandwidth of a medium decides the quality of the signal at the other end. A digital signal (usually aperiodic) requires a bandwidth from 0 to infinity. So, it needs a low-pass channel characteristic as shown in Fig. 2.3.5. On the other hand, a band-pass channel characteristic is required for the transmission of analog signals, as shown in Fig. 2.3.6.

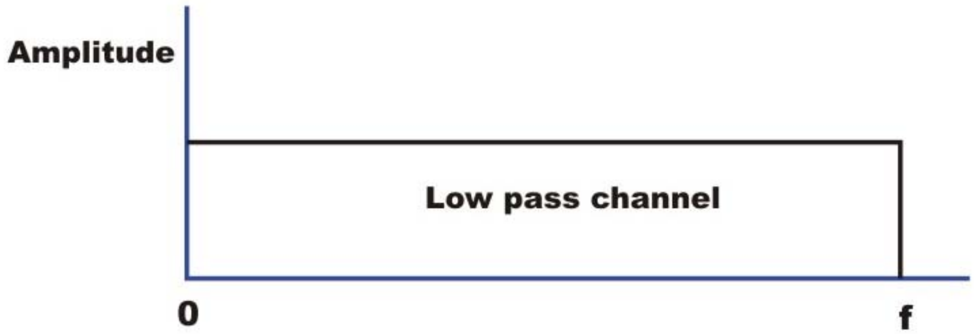

Figure 2.3.5 *Low-pass channel characteristic required for the transmission of digital signals*

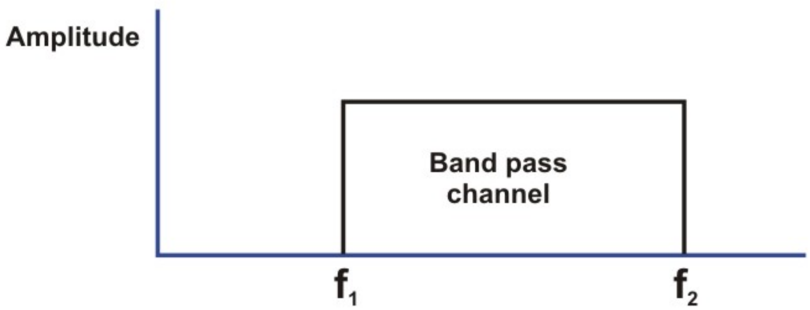

Figure 2.3.6 *Band-pass channel characteristic required for the transmission of analog signals*

Nyquist Bit Rate

The maximum rate at which data can be correctly communicated over a channel in presence of noise and distortion is known as its channel capacity. Consider first a noise-free channel of Bandwidth B. Based on Nyquist formulation it is known that given a bandwidth B of a channel, the maximum data rate that can be carried is 2B. This limitation arises due to the effect of intersymbol interference caused by the frequency components higher than B. If the signal consists of m discrete levels, then Nyquist theorem states:

Maximum data rate $C = 2 B \log_2 m$ bits/sec,

where C is known as the channel capacity,
B is the bandwidth of the channel
and m is the number of signal levels used.

Baud Rate: The baud rate or signaling rate is defined as the number of distinct symbols transmitted per second, irrespective of the form of encoding. For baseband digital transmission m = 2. So, the maximum baud rate = 1/Element width (in Seconds) = 2B

Bit Rate: The bit rate or information rate I is the actual equivalent number of bits transmitted per second. I = Baud Rate × Bits per Baud

= Baud Rate × N = Baud Rate × log2m

For binary encoding, the bit rate and the baud rate are the same; i.e., I = Baud Rate.

Example: Let us consider the telephone channel having bandwidth B = 4 kHz. Assuming there is no noise, determine channel capacity for the following encoding levels:
(i) 2, and (ii) 128.

Ans: (i) C = 2B = 2×4000 = 8 Kbits/s

(ii) C = 2×4000×log2128 = 8000×7 = 56 Kbits/s

Effects of Noise

When there is noise present in the medium, the limitations of both bandwidth and noise must be considered. A noise spike may cause a given level to be interpreted as a signal of greater level, if it is in positive phase or a smaller level, if it is negative phase. Noise becomes more problematic as the number of levels increases.

Shannon Capacity (Noisy Channel)

In presence of Gaussian band-limited white noise, Shannon-Hartley theorem gives the maximum data rate capacity

C = B log2 (1 + S/N),

where S and N are the signal and noise power, respectively, at the output of the channel. This theorem gives an upper bound of the data rate which can be reliably transmitted over a thermal-noise limited channel.

Example: Suppose we have a channel of 3000 Hz bandwidth, we need an S/N ratio (i.e. signal to noise ration, SNR) of 30 dB to have an acceptable bit-error rate. Then, the maximum data rate that we can transmit is 30,000 bps. In practice, because of the presence of different types of noises, attenuation and delay distortions, actual (practical) upper limit will be much lower.

In case of extremely noisy channel, C = 0

Between the Nyquist Bit Rate and the Shannon limit, the result providing the smallest channel capacity is the one that establishes the limit.

Example: A channel has *B* = 4 KHz. Determine the channel capacity for each of the following signal-to-noise ratios: (a) 20 dB, (b) 30 dB, (c) 40 dB.

Answer: (a) $C= B \log_2 (1 + S/N) = 4\times10^3\times\log_2 (1+100) = 4\times10^3\times3.32\times2.004 = 26.6$ kbits/s

b) $C= B \log_2 (1 + S/N) = 4\times10^3\times\log_2 (1+1000) = 4\times10^3\times3.32\times3.0 = 39.8$ kbits/s

(c) $C= B \log_2 (1 + S/N) = 4\times10^3\times\log_2 (1+10000) = 4\times10^3\times3.32\times4.0 = 53.1$ kbits/s

Example: A channel has B = 4 KHz and a signal-to-noise ratio of 30 dB. Determine maximum information rate for 4-level encoding.
Answer: For B = 4 KHz and 4-level encoding the *Nyquist Bit Rate* is 16 Kbps. Again for B = 4 KHz and S/N of 30 dB the *Shannon capacity* is 39.8 Kbps. The smallest of the two values has to be taken as the Information capacity I = 16 Kbps.

Example: A channel has B = 4 kHz and a signal-to-noise ratio of 30 dB. Determine maximum information rate for 128-level encoding.

Answer: The *Nyquist Bit Rate* for B = 4 kHz and M = 128 levels is 56 kbits/s. Again the *Shannon capacity* for B = 4 kHz and S/N of 30 dB is 39.8 Kbps. The smallest of the two values decides the channel capacity C = 39.8 kbps.

Example: The digital signal is to be designed to permit 160 kbps for a bandwidth of 20 KHz. Determine (a) number of levels and (b) S/N ratio.

(a) Apply *Nyquist Bit Rate* to determine number of levels.

$C = 2B \log_2 (M)$,

or $160\times10^3 = 2\times20\times10^3 \log_2 (M)$,

or $M = 2^4$, which means 4bits/baud.

(b) Apply *Shannon capacity* to determine the S/N ratio

$C = B \log_2 (1+S/N)$,

or $160\times10^3 = 20\times10^3 \log_2 (1+S/N) \times10^3 \log_2 (M)$,

or $S/N = 2^8 - 1$,

or S/N = 255,

or S/N = 24.07 dB.

Review Questions

Q-1. Distinguish between attenuation distortion and delay distortion.
Ans: Attenuation distortion arises because the attenuation of the signal in the transmitting media. Attenuation distortion is predominant in case of analog signals. Delay distortion arises because different frequency components of the signal suffer different delay as the signal passes through the media. This happens because the velocity of the signal varies with frequency and it is predominant in case of digital signals.

Q-2. How the effect of delay distortion can be minimized?
Ans: Delay distortion can be minimized by using an equalizer (a kind of filter).

Q-3. What is intermodulation noise?
Ans: When a signal (having different frequency components) passes through a transmitting media, then due to non-linearity, some of the frequency components may combine to generate a different frequency component. This leads to distortion in the signal, which is known as intermodulation noise. For example, a signal may be having frequency components f_1 and f_2, and due to non-linearity of the media they may generate a frequency component (f_1+f_2). Further a frequency of (f_1+f_2) may be already present in the original signal. This causes intermodulation noise.

Q-4. Why does impulse noise have more effect on digital signals rather than on analog signals?
Ans: Impulse noise is random in nature and arises due to random events like lightning, electrical sparks, etc. In case of digital signal, it makes a significant effect, as ‘0’ may become ‘1’ and vice versa. In analog signal the effect is not that serious as some portion of the signal gets affected.

Q-5. What is crosstalk?
Ans: Crosstalk refers to the picking up of electromagnetic signals from other adjacent wires by electromagnetic induction.

Q-6. Let the energy strength at point 2 is $1/50^{th}$ with respect to the point 1. Find out the attenuation in dB.
Ans: Then attenuation in dB is $10\log_{10}(1/50) = -16.9$ dB.

Q-7. Assuming there is no noise in a medium of B = 4KHz, determine channel capacity for the encoding level 4.

Ans: $I = 2\times4000\times\log_2 4 = 16$ Kbps

Q-8. A channel has *B* = 10 MHz. Determine the channel capacity for signal-to-noise ratio 60 dB.
Ans: $C = B$ ´ $\log_2(1 + S/N) = 10 \text{ x } \log_2(1 + 60)$

Q-9. The digital signal is to be designed to permit 56 kbps for a bandwidth of 4 KHz. Determine (a) number of levels and (b) S/N ratio.