# Module 7
# Bandwidth and Maximum Data Rate of a channel

## Introduction

Data communication is about how the bits sent across the wire. Bits cannot be sent without converting them to signals that the media carries. Electromagnetic (EM) signals are used to generate different codes which represent zeros and ones. When the receiver receives those signals, it can interpret back as zeros and ones. There are two general methods to use EM signals. One is to use different voltage levels, which is a practice in copper cables and another to use photons (light pulses), which is used in fiber optic cables. Wireless transmissions also use both forms of transmission.

Every media that we use for communication, be it a copper cable or fiber optic cable or even wireless, has typical characteristics which affect the signal propagation process. As a result, the signal shape and speed and ability to travel intact for some distance changes. Apart from the inherent properties (like the shape and strength of the signal) of the media, the signal is also affected by a few external factors. In this module, we will look at those factors and solutions to avert signal distortion and weakening problems. We will also see how the media bandwidth (amount of frequency it has) is related to maximum data rate (amount of data it carries for a unit period of time) for a given media channel.

## Bandwidth and data rate

We have already learned that there are two types of channels through which data transfer takes place, wired and wireless. The quality of the communication is highly influenced by the characteristics of the medium it passes through. Bandwidth and data rate are two important parameters of us to consider. Bandwidth is the inherent property of the media which is analogous to the width of the road[1]. The data rate is the amount of data passing through, which is analogous to a number of people passing through the highway (which depends on a number of vehicles passes through which in turn depends on the width of the road). Thus, they are not independent to each other. The data rate has some dependency on the bandwidth.

The bandwidth of a **media** is the range of frequencies that can pass through that medium. The bandwidth of the **signal** is the range of frequencies that signal carries. The media bandwidth is analogous to the width of the road, wider the road more vehicles can pass per

[1] The bandwidth of the media is its physical property. That is natural and cannot change. For example, copper cables are used because they are better conductors than other metals.

unit time (usually per second) and thus larger the range, more the bandwidth. The maximum data rate also depends on the width and length of the wire.

Let us take an example to understand, a copper cable of category 6A (which is currently in vogue) can provide 500 Mbps for 100-meter distance. The same wire can provide speeds in excess of 10 Gb if the distance is reduced to 1 meter. If we increase the distance to say 500 meters, the capacity may reduce to 100 Mb or less. Category 5 cable was able to provide 100 Mbps for the same range of 100 meters. The ability of Category 6A cable to provide higher bandwidth for the same range depends on many things including better width.

Let us analyze the relation between bandwidth and data rate in little more detail. Data rate depends on the amount of data that the user is sending and thus, is a variable thing. It can increase, decrease and may become zero if the user is not sending. On the contrary, the bandwidth depends on the natural property of the media and thus, a fixed value. The maximum data rate is the maximum amount of data that one can send over that communication channel, the value, that depends on the bandwidth, and thus a fixed value.

Let us revisit the analogy. The data rate, a number of people traveling over the highway, is varying and can be zero if nobody is traveling on the highway right now. On the other hand, the capacity of the road is a fixed amount. Similarly, a maximum number of people traveling over the road, is also a fixed amount, depending on the capacity of the road.

Drivers cherish the widest possible road; similarly, the network users prefer large bandwidth. Drivers expect no obstacles and network users prefer no delay while accessing data. This demands very wide roads and fast media pipes. However, the administrators, who are concerned about the cost, would like the roads and the network cables to be utilized optimally so striking some balance is essential. One would like to have enough bandwidth that every user can work satisfactorily. However, one would also like to squeeze the maximum amount of data rate given the bandwidth.

Let us learn about one more critical aspect of communication, the signal. A signal is an EM wave of some type. The data is encoded in the signal; i.e. the typical type of signal represents typical data. For example, one may represent 1 as a wave with frequency (explained later) 10 Hz and 0 as a wave with frequency 20 Hz. Thus there are two different things, signals, and data. The data is 1 or 0 and signals are EM signals.

We will throw some light on how one gets maximum data rate in this module.

Let us first of all list some factors on which the data rate depends.

1. Data can be sent using either analog or digital signaling. Analog signals are continuous curved signals produced by people like us when we speak. Digital signals are discrete in nature and are square in shape. We will discuss both types of signals in little more detail in the next module. Analog signals require less bandwidth to travel and digital signal requires more bandwidth. The data rate depends on different factors based on which type of signaling is used.

2. Apart from signaling, the data rate depends on how signals code the data. Continuing with our analogy of highway traffic, vehicles are signals and people are data[2]. The road capacity determines the maximum amount of vehicles that can pass at any given point of time. Thus the bandwidth of the media determines the number of signals that can pass through. However, the number of people passing through depends on both, the number of vehicles that can pass through and the number of people carried by a single vehicle. Thus if a single signal can carry multiple bits (which is usually done), the maximum data rate also depends on how many bits a signal can carry, apart from the bandwidth itself.
3. If analog signals are used, the data rate depends on how the data is modulated. There are few methods of modulation used in practice. For example, in the case of cable TV, transmission from the server to the TV, it is possible to use the type of modulation known as QAM (Quadrature Amplitude Modulation) 256 which allows 8 bits per signal. The same cable TV, while uploading data from TV to server, uses a type of modulation called QPSK (Quadrature Phase Shift Keying) which only carries 2 bits per signal. Number of bits a signal carries depends on constellation point value, which in above QAM256 case is 256. In case of QPSK, it is 4.
4. If Digital signal is used, the data rate depends on how many numbers of digital levels are used. We will soon see what is the meaning of it.
5. In either case, the data rate is proportional to $\log_2(L)$ where L is a number of constellation points a signal can carry in the case of analog and L is the number of signal levels used in case of digital signaling. This is a normal way while you deal with binary numbers. If we have n bit to store a binary value, we can have $2^n$ total such values. On the other hand, for L are total such values, we need a $\log_2(L)$ bits long value.
6. The data rate also depends on how sensitive the receiver is. The communication media, for natural and environmental reasons, introduce noise. The noise distorts the signals to some extent. When the signal travels longer, it is more likely to encounter some noise. Due to natural characteristics, even without a noise, the signal tends to distort based on the distance covered. In the case of digital signaling, noise is possible to be removed to some extent, but it is impossible in analog signals. The problem with digital signaling is that the distortion also increases with the data rate. Thus, the receiver, in no case, receives the signal intact. One of the critical components is determining the data rate is the ability of the receiver to sustain distortion. The high-data-rate signal is more distorted than low rate signal and thus there is always some data rate, beyond which the signal is distorted to a point that receiver cannot decide what is the original signal is. One cannot send beyond that point, which is decided by the sensitivity of the receiver. In

[2] The difference between signal rate and data rate must be noted. Bandwidth decides the signal rate, i.e. number of signals which can be sent per second. The data rate, on the other hand, depends on how many bits one can send with one signal. Here we provide an analogy; signals as vehicles, people as data, and the road as media.

short, if the receiver is more sensitive and can recover from the higher level of distortion, it is capable of managing higher data rate.

7. Media like copper cables which are used in practice offer some resistance to the passing EM waves. The amount of resistance offered depends on a number of stray electrons in the copper cable. A number of stray electrons depend on the temperature of the cable. Like the sensitivity of the receiver, the amount of noise introduced by these stray electrons impacts the flow of waves depends on the data rate, higher the temperature, more the resistance. Thus temperature determines the resistance and thus influence the data rate. Over a typical data rate limit, it is impossible to increase the data rate for any given media. This discussion is not applicable to fiber optic cables as they carry photons and not electrons.
8. The data is also affected by external noise. The devices which work in vicinity, interferes with the communicating devices if they happen to work on the same frequency. When a scooter or a mixer starts in vicinity and our TV starts showing snowy images, or radio starts reflecting that noise, it is due to this phenomenon. The data rate can be improved by reducing the external noise. That is done by properly shielding and structuring the wires. When properly shielded, the external signals have reduced effect on the signal being propagated.

## The frequency and frequency band

So far, we have discussed the media bandwidth. In fact, the signal also has a bandwidth. The bandwidth of the signal is represented by the range of frequencies of a given signal. The difference between highest and lowest frequencies of the signal, in other words, is a bandwidth of that signal. Sometimes the range is also referred to as a frequency band.

Let us go back to our analogy of the highway. The bandwidth of the signal is the bandwidth of the caravan of few vehicles that we would like to pass on the highway together. If a number of vehicles in a caravan is more than the capacity of the highway, they cannot travel together. Same way, if the signal frequency is more than the media frequency, only those frequencies which can pass through the media, goes through, rest are filtered out. Unlike the highway case, we cannot carry that part of the signal in the second cycle. For two reasons, first, there is no way of cutting and pasting signals which can be practically used here, and second, the second cycle is not empty, the next signal is scheduled in next cycle.

Another analogy we can provide is a swimming pool. If we have 8 lanes in a swimming pool (the capacity of the pool), and the competition has 9 registrations, only 8 swimmers can swim at a time, the $9^{th}$ swimmer is not included (cut off).

Carrying on with our swimming pool analogy, we can also see that it is not possible for two swimmers to swim just next to each other, they need some space between them. Similarly, two frequency bands cannot stay just next to each other, they need guard bands in between. The reason is, the transmission on a specific frequency band cannot be confined to that band, some part of it 'spills over' the adjacent frequencies. For example, if you try listening radio Mirchi on 98.4 instead or 98.3, you will be able to listen to a few bits of the transmission. It is because the transmission on 98.3 also affects adjacent frequencies. Running another radio station at 98.4 will result in a lot of disturbance in the transmission of 98.3. We will have to run it much further apart. Another analogy is to have two different groups communicating in adjacent rooms, both will feel disturbance if their voice goes out of the room. The question is, can we make sure that even with disturbance, they can still communicate? One clever trick of using orthogonal frequencies for adjacent channels. It is possible for the receiver to listen only on the frequency intended to and omit the frequencies orthogonal to it, thus enabling to pack the frequencies much tighter. That trick is popularly known as Orthogonal Frequency Division Multiplexing and is used by a few versions of Wi-Fi.

A number of frequencies available in band determine the number of users who can send and receive at a given point of time. For example, Wi-Fi uses an ISM band between 2.4 GHz and 2.48GHz. As each Wi-Fi channel need 22 MHz[3], it is possible accommodate 14 channels (out of which 13 are available in India and 11 in the US, as two of them are used for low powered device communications) out of which 3 are non-overlapping and can be used together. That means between two channels, we need to keep 3 to 4 channels to avoid interference. Another version, 802.11g uses OFDM and thus can use number of channels compared to 802.11b, which result into better bandwidth from the same frequency band[4].

## The media affects the signal

When a signal passes through media and signal has higher frequencies than the media can pass, those frequencies are cut off and the signal is said to be distorted. In simple terms,

The resultant signal = original signal – frequency components which are cut off by media

However strange it looks like, another problem with media is, it favors some frequencies than others. Let us extend our swimming pool analogy to understand. Assume all 8 swimmers indicate the signal. Also, assume all 8 swimmers have the same speed. What if all of them starts swimming at the same point in time? Middle lanes offer less resistance and thus provide better movement for swimmers while the lanes at the outmost edge are comparatively harder. That means swimmers on the edge will lag behind others and middle lane swimmers forge ahead. The original shape (a straight line) now distorts into a shape like a > sign. Same thing happens with different frequency components of a signal. Some of them travel faster than others and thus when they reach at the receiver, the shape is not

[3] The actual requirement is 20 MHz but additional 2 MHz are needed as guard band
[4] 802.11b offers 11 Mb while 802.11g offers 54 Mb

the same as they start with. If we represent the starting position of the swimmers as the original shape of the signal and the final position of the swimmers as the shape what the receiver receives, the difference represents the distortion.

## The composite signal and harmonics

All signals used in data communication contains multiple frequencies, and thus a combination of multiple signals. Such a signal, which is a collection of other signals of different frequencies, is known as a composite signal. Jean Fourier, a French scientist, proved that a square signal is a composite signal and made up of an infinite number of components, each of which being an analog periodic sine wave (explained later). The first components of a given square signal are of the same frequency and amplitude of the square wave itself. The second component is of three times the frequency of the first component and has 1/3$^{rd}$ of the amplitude of the first component. The third component has 5 times the frequency of the first component and has the 1/5$^{th}$ amplitude of the first component, and so on. This means that the second component completes three cycles and the third component completes five cycles while the first component completes one. These components are also known as harmonics.

The frequency of the first component is known as the fundamental frequency, let us call it *f*, the amplitude of that first component is highest, let us call it *A*. In a mathematical form, a frequency of $n^{th}$ component is (2n+1) * f while the amplitude is $\frac{1}{2n+1} * A$. Closely observe figure 7.1.

First three rows describe the components combined to generate the signal are depicted. The fourth signal is the addition of first three components. If such infinite components are collected, we have a square signal. What can we learn from this figure? Here are some observations.

1. In a square signal, which is basically a composite signal, the frequency of the components increases and the amplitude decreases, in the linear fashion.
2. Only first few components contribute to the shape of the signal in a significant way. The rest add very little. In our figure, when we only add three components, the signal looks quite near to square.
3. These components are called harmonics or Fourier components. Signal, its shape and components are critical to understanding the relation between the bandwidth of a given medium and maximum data rate.
4. When the signal has n components and the media can only pass m components, the resultant signal is a signal with n-m components and thus is a distorted signal. For example, in the case of 7.1, if only three harmonics pass through, we will have a signal which is the combination of first three harmonics and looks like last but one signal. However, with a human eye, it is not difficult to judge their original value. If

the receiver is sensitive enough, it can only reconstruct the signal from the first three components in this case and do not mind if other components are cut off. The reason is that the higher frequency parts also have smaller amplitude and contribute little to the final shape of the signal.

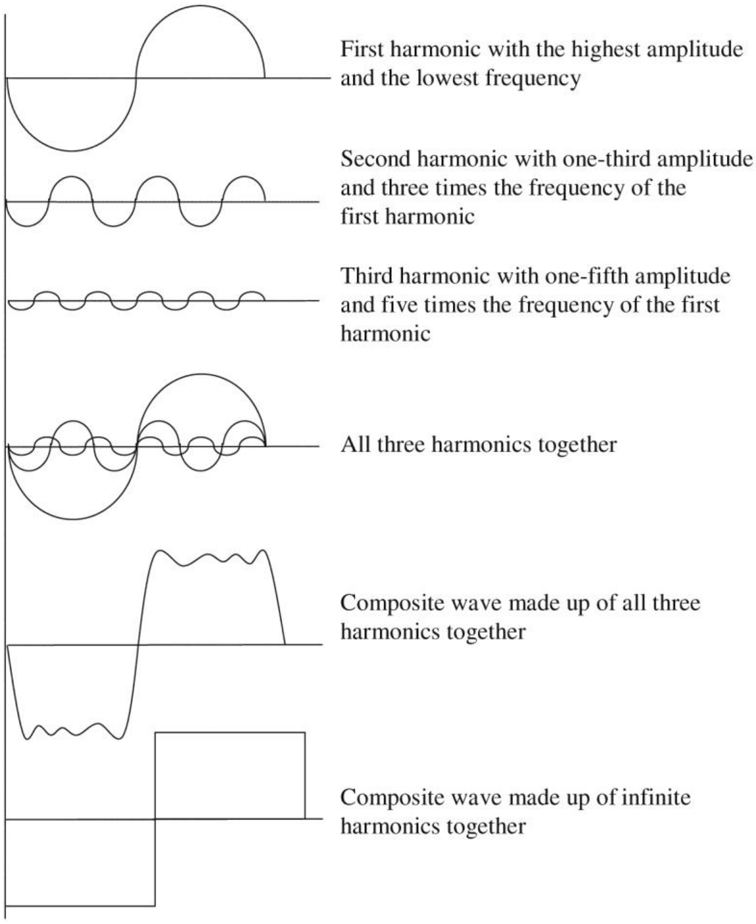


*Figure 7.1 Combining multiple harmonics*

## Properties of a channel

We have hinted about two rules of thumb for communication.

1. More the bandwidth of the media, more components pass through the media
2. Higher the data rate, lesser components pass through the media

What is the significance of the second rule? When we have higher data rate, the first or the fundamental frequency is higher and thus each subsequent component has higher frequency value than the previous one. That means given a cap, the media will be able to pass less number of components when data rate increases. As a consequence, when we increase the data rate continuously, lesser and lesser harmonics pass through and eventually no harmonic passes through once a limit is reached. Based on the sensitivity of the receiver, some number of harmonics must pass through and that puts a cap on the data rate.

In a way, this cap is on a number of signals and not bits. That means we are fixing a number of vehicles passes through the highway and not the number of people. Interestingly, our aim is not to increase the signal rate but the bit rate, (number of people passes through and not the number of vehicles that carry them). If we increase the number of people per vehicle, we can still increase the number of people passing through highway in unit time. The same approach is used here. Let us try to understand.

Suppose the signal has the binary state; thus have two different types of signals passing through the channel. Consider two types are +5V and -5V signals. Also assume that +5V indicates 0 and -5V indicate 1. Thus each of the signal carries one bit each.

Thus for sending 101101000110, We will be sending

+5V, -5V, +5V, +5V, -5V, +5V, -5V, +5V, -5V, -5V, -5V, +5V, +5V, -5V

Now assume the signal to contain four different states (or consider four different signals). Each signal contains 2 bits now. How? Assume we have a square signal represented by +5V, -5V, +10V, -10V; thus four different states (you can also call them four different signals with these values). Each signal, now, can represent two bits. One of the possible mappings is as follows.

+5V <-> 00, -5V <-> 01, +10V <-> 10, and -10V <-> 11

So, while we are sending 101101000110, We will be sending

+10V, -10V, -5V, +5V, -5V, +10V

Now let us assume the signal has eight states, +5, -5, +10, -10, +15, -15, +20, -20. How many bits can each of the states contain? 3 bits. Here is one typical mapping.

+5V <-> 000, -5V <-> 001, +10V <-> 010, and -10V <-> 011
+15V <-> 100, -15V <-> 101, +20V <-> 110, and -20V <-> 111

now, while we are sending 101101000110, We will be sending
-15V, -15V, +5V, +20V

In a way, we need less number of vehicles if we accommodate more people in the single vehicle, to carry the same number of people. On the other hand, if we are sending the same number of symbols (when each signal can carry multiple bits), we can send more and more bits, without really increasing the number of signals. Thus, having more bits per symbol helps us achieve arbitrary bit rates, irrespective of a number of symbols possible to be sent based on the bandwidth of the media. Great! Isn't it? If we extend the analogy, we can send as many people as we want across, if we can accommodate arbitrary number of people in the vehicle. However, there is a limit that we can accommodate people for a vehicle[5]. Similarly, we cannot accommodate an arbitrary number of bits in a symbol because of noise in the channel. Above discussion holds true only when the channel is noiseless.

Nyquist realized what we have discussed here and gave a simple equation for calculating Maximum Data Rate (MDR) of a *noiseless* channel.

MDR = 2 * Bandwidth * $\text{Log}_2$L where L is levels or states of signals.

When we have only two signals, $\text{Log}_2 2 = 1$ and thus MDR is calculated as
MDR = 2 * Bandwidth

Claude Shannon, a well-known scientist, furthered this work for noisy channels and proved that when a signal to noise ratio is S/N, the Maximum Data Rate (MDR) of a noisy channel, is

MDR = 2 * Bandwidth * $\log_2$(1 + S/N)

Signal to noise ratio of any channel is fixed for a given temperature. For example, conventional telephone lines use cat-3 and cat-5 copper wires, at room temperature, has 30 dB S/N value. (Signal to Noise ratio is measured in dB, decibel). Given that, we cannot have arbitrary levels. If the Shannon equation gives us the MDR to be 50 Mb, we can increase signal levels to the extent it reaches 50 Mb. Increasing signal levels after that do not yield higher data rate.

The S/N ratio represented in dB, which is 10 log (Ps/Pn) where Ps is the signal strength and Pn is noise strength. An interesting observation can be made when both these quantities are equal. The Ps/Pn ratio is 1. In that case, the MDR is calculated as

MDR = 2 * Bandwidth $\log_2$ (1 + 10 * $\log_2$ 1)
= Bandwidth * $\log_2$ (1 + 0) (as $\log_2 1 = 0$)
= Bandwidth * $\log_2$ 1
= 0

The meaning is, when the noise is as strong as the signal itself, nothing will pass through, irrespective of everything else. Quite logical.

Let us look at the figure 7.2. What do you understand of it?

---

[5] sometimes, we are surprised to find people being accommodated during marriages etc. in India, however, there is a limit still.

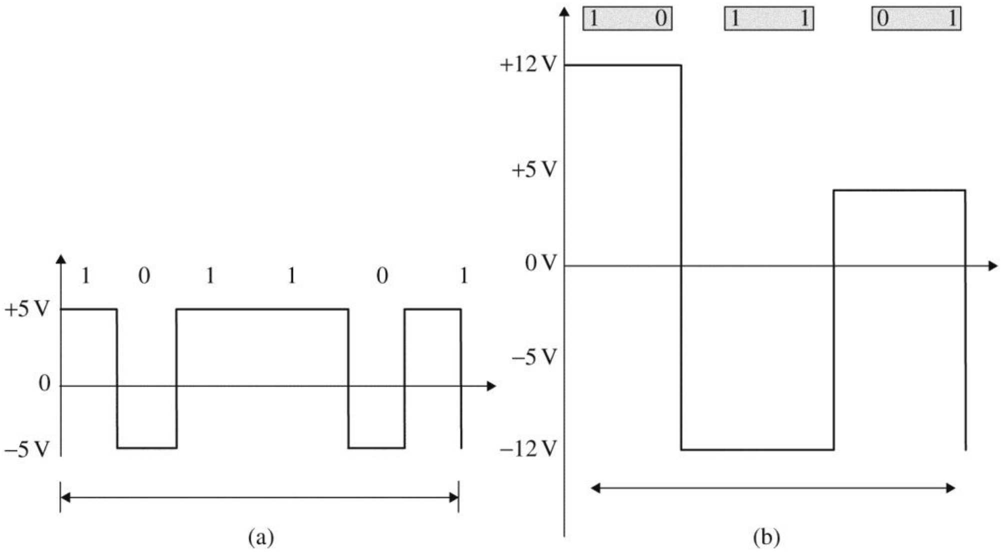


*Figure 7.2 Using multiple signal levels*

The 7.2(a) use two levels while 7.2(b) use four levels. Thus it is possible in 7.2(b) to accommodate two bits for a symbol. Thus we only need to send three symbols for the same data as compared to 7.2(a). Looking at the Shannon limit, we can continue increasing the signal levels and increase the bit rate only till we reach the Shannon limit. Reference-2 contains a more detailed discussion on this matter and some additional examples to illustrate this issue further.

## Summary

The module began with describing some terms like bandwidth of the media and signal, signal levels, bit and baud rates, data rate and maximum data rate of the channel etc. We have seen the relation between bandwidth and maximum data rate of a noiseless channel and a noisy channel. We have looked at two different equations, from Nyquist and Shannon, describing that relation.