Principles of Digital Communication
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Lecture – 01
Introduction

Good morning. Welcome, to this course on Principles of Digital Communication. Today is the first lecture and we will start this course by introducing the objectives and the course outline.

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This is an era of communication systems. Communication systems rather than communication itself have become the need of mankind. Imagining life today without the internet, mobile phones, satellite TVs and what have you is very hard and rather impossible. Moreover, all these communication systems which I have just pointed out the internet, telephone systems, mobile systems or satellite systems are the examples of a digital communication system. Digital communication systems form the substratum of this course. In this course, we will learn the basic principles that govern the design of a digital communication system.

So, let us get started and see what the course outline is.

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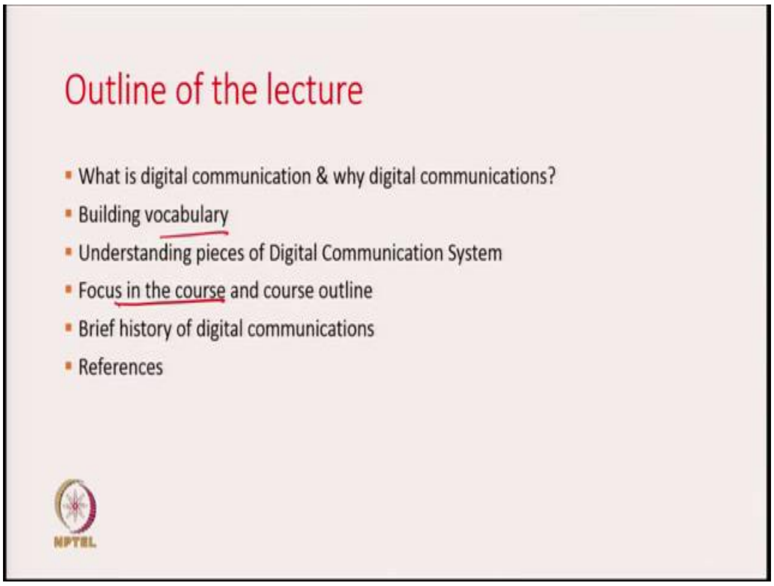

So, in this lecture we will see what digital communication is and why digital communications have become all pervasive, we will see and build the vocabulary that is that will help us to state things more precisely. We will understand pieces that are involved in the designing of a digital communication system, we will see what the focus in this course is and we will present the course outline. In fact, the scope of a digital communication system is quite wide, and thus it is safe to state the course upfront and point out where we will focus our energy in this course so, there are no surprises later on.

Then, we will present a brief history of digital communication systems and finally, we will present the references.

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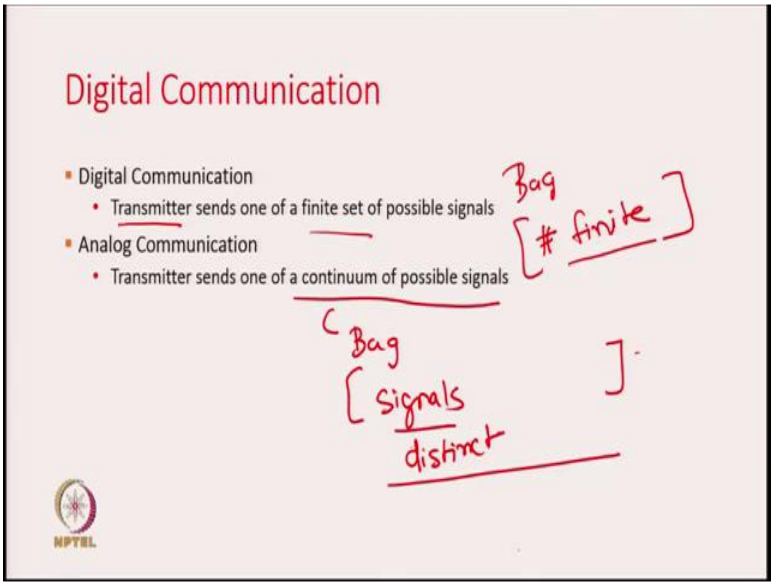

So, let us start with the question of what is digital communication and why digital communications have become all pervasive. So, to understand we would understand this digital communication by contrasting it with analog communication. Normally, the course under digital communication is preceded by a course in analog communication. However, if you have not done a course in any analog communication are not going to lose out anything.

Let us get back to the business and let us see what digital communication is. So, in digital communication transmitters has a finite set, it picks a signal from that finite set and it transmits that signal. So, for example, let us think it like this that the transmitter has a bag and in this bag the number of elements is finite, the transmitter picks a signal from this bag and sends it in the case of digital communication.

In case of analog communication, the transmitter sends one of a continuum of possible signals. So, in this pack the transmitter has signals and these signals are pretty close. These signals are so close that if you make an increment change in one of the signal then you wind up with another signal. These signals are not distinct signals and this set of signals may make a continuum whereas, in the case of digital communication the bag contains a finite number of signals and these signals are distinct signals, different signals. I know that at this point it is still uncanny and it will not be clear what are the differences between digital and analog communication and to sort it out let us relearn what we have learned about real numbers and integers.

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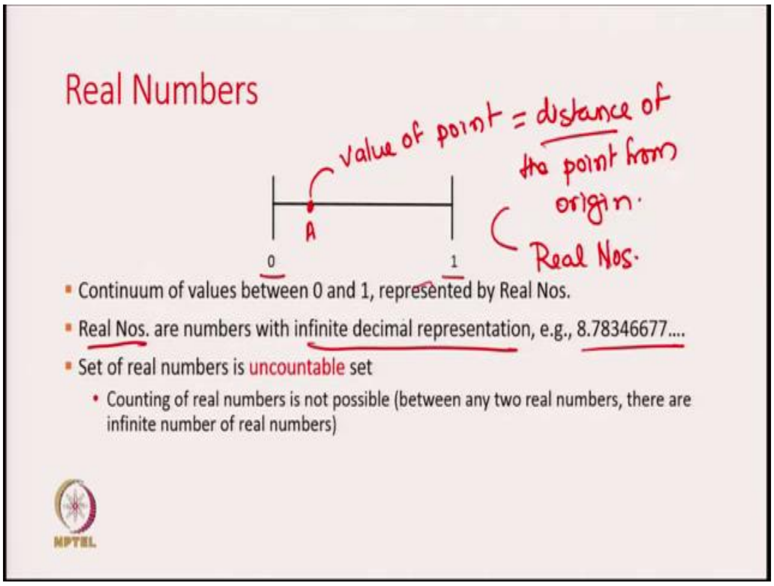

So, let us start by thinking about the real numbers first. So, to understand this real numbers, let us draw a line or let us look at this line between 0 and 1, if I focus on a point on this line let us say point A, the value of this point on this line corresponds to the distance of this point from the origin and distance in fact, is a continuous quantity. Why is this a continuous quantity, because if you change this value of the point even incrementally if you make an incremental change to the value of this point then you end up with another valid point and hence distance is a continuous quantity.

Now, how do we denote the distance of these points? By real numbers. So, real numbers are used to represent the distances of the points on this line and these real numbers are used in order to represent any continuous quantity, be it a distance, be it length, be it an area with volume and what have you. So, all continuous quantities are represented by real numbers. Mathematically we can also think about real numbers as the numbers with finite decimal representation; that means, these numbers run in forever. So, they go up to infinite decimal places. So, these are the two ways in which we can think about real numbers. The first picture is real numbers represent continuous quantity and the second viewpoint is real numbers come up with infinite decimal representation.

Now, last, but probably the most important the set of real numbers constitute what is known as an uncountable set. What is an uncountable set? An uncountable set is a set which you cannot count on two fingers. For example, if you start by counting set of real numbers if you pick a real number you will run into trouble because you will not know what is the real number preceding the chosen real number because between any two real numbers there are an infinite number of real numbers. So, we cannot count real numbers and hence the set of real numbers is referred to as an uncountable set.

Moreover, let us see, what we get when we go from real numbers to integers.

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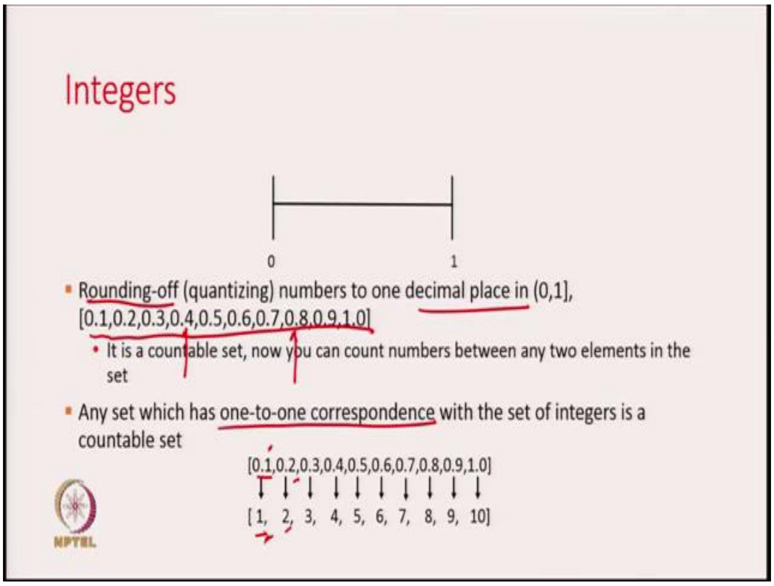

So, to think about that let us start by rounding of these numbers to one decimal place. Rounding off in engineering is referred to as quantization. So, in engineering, we want to show off and we rename the things that we have learned in high school. So, we instead of calling it as rounding of operations, we call it as quantization operations. So, let us assume that we have done the quantization of the numbers and if we quantize these numbers we get this set.

Now, this set is a countable set. Why is this a countable set? Because if I choose any two elements in this set can definitely tell you how many numbers lie between these two chosen numbers. For example, between 0.4 and 0.8 there are three elements and hence this a countable set. More precisely I can define a countable set which has a one-to-one correspondence with the set of integers.

So, let us see what I mean by one-to-one correspondence. So, for example, I can map this 0.1 to an integer 1, I can map this 0.2 to an integer 2 and so on so forth. So, I can have a mapping of each of these numbers with an integer. So, this is meant by one-to-one correspondence with the set of integers. So, any set which has a one-to-one correspondence with the set of integers is a countable set. So, once you quantize the real numbers what you end up with is a countable set.

So, let us summarize what we have learnt.

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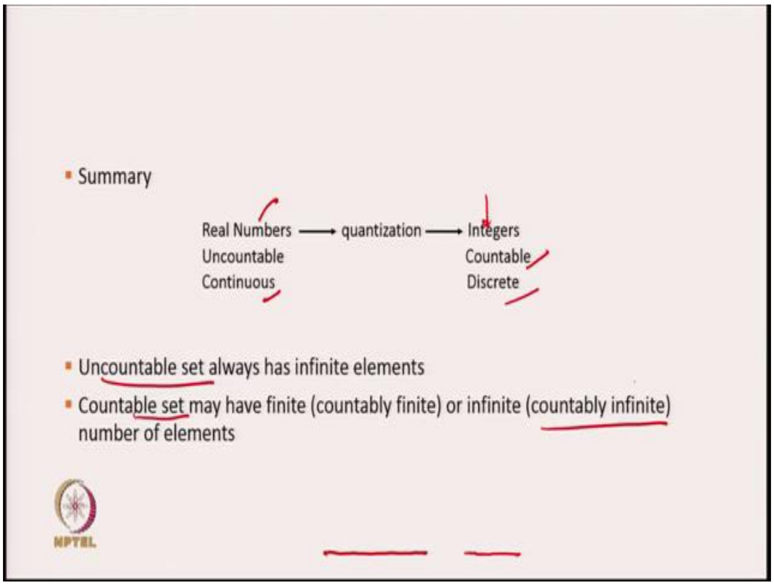

So, we said we start by real numbers we quantize the real numbers and we get the set of numbers which has one-to-one correspondence with a set of integers then we have said these real numbers are uncountable numbers because between any two real numbers there are an infinite number of real numbers in the case of integers the set of integers form a countable set. You can always tell me how many integers lie between any two integers. Real numbers are used to denote a continuous quantity; on the other hand, when we are talking about the integers, integers are used to denote a discrete quantity.

So, the uncountable set always has infinite numbers, whereas countable set may have a finite number of elements and then it is known as a countably finite set or it may have an infinite number of elements and then it is known as a countably infinite set. So, uncountable always comes with an infinite number of element countable may come with a finite or infinite number of elements.

Now, does this help us in redefining the differences between analog and digital communication? Let us see if we bring more clarity to this distinction between digital and analog communication.

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What we said before is digital communication. The transmitter sends one of a finite set of possible signals; that means, it selects a signal from a countably finite set. Something which can be mapped to which has one to one correspondence with the set of integers on the other hand in analog communication transmitter sends one of a continuum of possible signals; that means, it selects a signal from an uncountable set; that means, it is trying to send something like real numbers.

So, these are the main differences between digital and analog communication and I hope now this is clearer.

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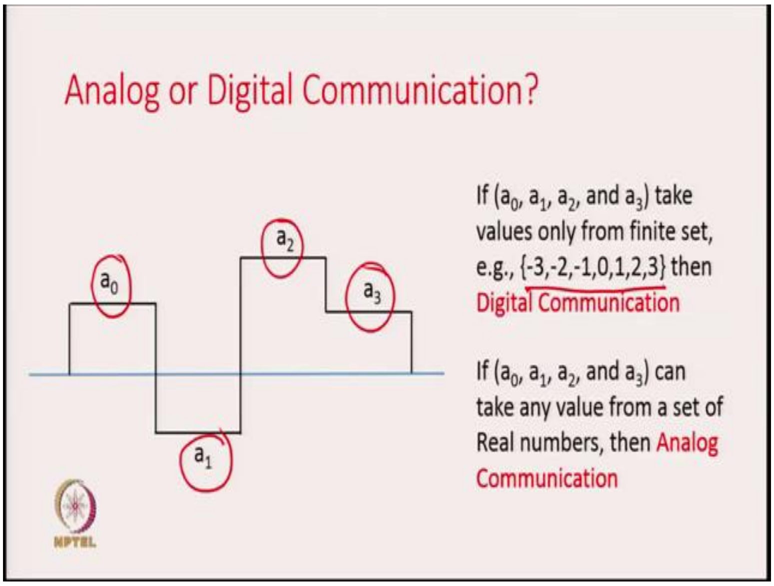

So, let us test you with an example. So, let us see this signal and let us assume that the information resides in these amplitude levels. So, that is given to us information resides in this amplitude labels and we have a signal like this. Can you guess whether the signal belongs to analog communication or digital communication? The answer is not in a straight forward manner because it will depend on these amplitude levels itself. If these amplitude levels have been taken from a finite set, for example, from a set like this then this signal.

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Belongs to the case of digital communication. On the other hand, if these amplitude labels have been drawn from a set of real numbers then we are in the world of analog communication. So, that is the main difference between analog and digital communication. Whether the set has been drawn from a finite set or whether you have this set of real numbers or you are having an uncountable set.

So, now we hope that this distinction is a little bit clearer.

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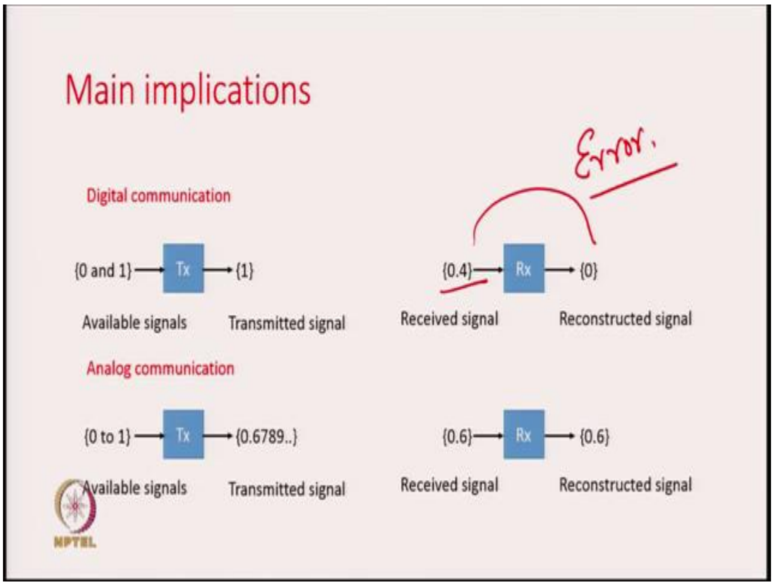

What it looks as if the difference between analog communication and digital communication is trivial, what are the main design implications does it give any benefit to this digital communication and to understand this let us see this. Moreover, what we have assumed is, this is an example of digital communication, and here we will be talking about analog communication.

So, in the case of digital communication let us assume that the transmitter can send either 0 or 1? Now, the set is a finite set. So, there are only two elements in this set and let us assume that the transmitter has transmitted 1. Let us assume that the receiver receives the signal with an amplitude level of 0.8, because of some noise and distortion we are not assuming any losses between transmitter and receiver so on and so forth.

Now, the receiver knows that the transmitter might have sent either 0 or 1 and by looking at 0.8 and by assuming that noise has not distorted the signal considerably, the receiver can make an intelligent guess that the transmitter might have sent 1. So, you can see in this case the receiver can reconstruct an exact replica of what was transmitted. So, in digital communication reconstruction of an exact replica what was transmitted is possible.

Now, let us see what happens in analog communication. In analog communication let us assume that a transmitter sends an amplitude level between 0 and 1 because it has to be a set of reals continuous set and let us assume that the transmitter has transmitted 0.6, 0.1, 0.8, 0.9 and so on and let us assume that the receiver receives 0.6 in the presence of some noise. Now, does the receiver has any way to reproduce an exact replica what was transmitted? The answer is no because there is an infinite possibility to choose from. Anything between 0 and 1 might have been transmitted and receiver would have had no knowledge of what was actually transmitted because there are infinite possibilities and hence the receiver would not be able to reconstruct an exact replica of what was transmitted.

So, an exact reconstruction is not possible in case of analog communication. So, these are the main design implications between digital communication and analog communication. Let us see this with one more example let us now assume everything remains the same. What has changed is that the receiver is receiving 0.4 instead of 0.8. So, now its amplitudes have been very large now. So, what would happen? The receiver would make a guess now that 0 might have been transmitted because 0.4 is closer to 0.

Now, in this case, what happens is an error has occurred. This leads to an error situation in a digital communication system and this is one of the main design objective of a digital communication system the design objective is to slash the error probabilities to make it virtually close to 0 so that it does not impact the performance of a digital communication system. So, one of the main design objectives is to keep error probabilities practically close to 0.

In the case of analog communication, can we talk about error probabilities? No, because if we define an error as the event when the receiver fails to reconstruct an exact replica of the transmitted signal, then that error probability is 1 because the receiver is never able to reconstruct an exact replica of what was transmitted and hence in the case of analog communication error probabilities are always close to 1. So, there is no sense in talking about error probabilities in the case of analog communication. In digital communication it makes sense.

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Let us see this the summary: In digital communication signal reconstruction is possible because the receiver has to make a guess from a finite number of possibilities. An important performance metric is error probabilities and you want to keep it as close to 0. In the case of analog communication signal reconstruction is not possible and there is no sense to talk about error probabilities.

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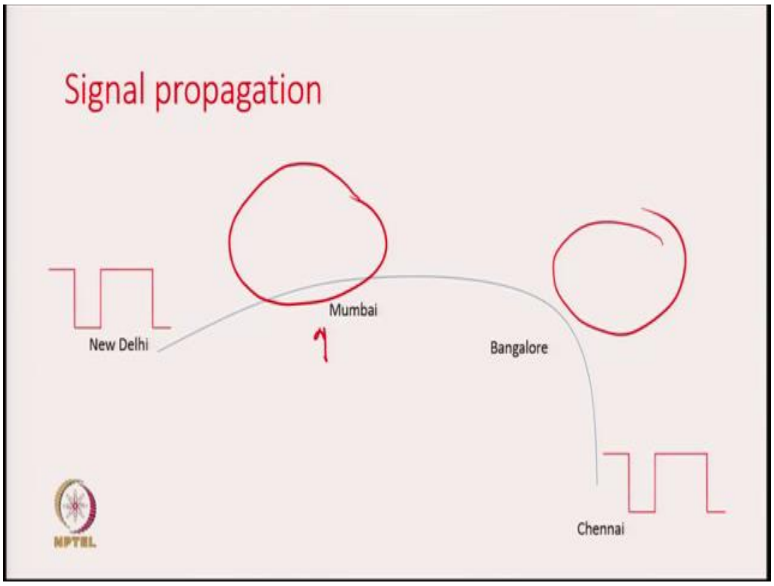

What does this lead to? Let us see this with an example. So, let us assume that we have a signal getting transmitted from New Delhi to Chennai and as the signal moves on the signal continuously picks noise as the signal travels. So, now, you can see that the received signal in the chain is completely different from the signal that was transmitted at New Delhi and there would be no way for the receiver to make an exact reconstruction of the signal. But, if you are employing digital communication what you can do is as the signal moves on, it picks noise. The noise levels are not so significant that it has degraded the signals considerably.

So, you can put a repeater or re-constructor in the middle of the signal transmission path and you can reconstruct the signal. So, you can have a repeater at Mumbai, you can reconstruct the signal. Similarly, as the signal travels it picks up some noise, but again the noise levels are not appreciably large. So, the signal has not degraded beyond a certain limit.

So, again you can reconstruct the signal exactly and similarly, what you can do by having these multiple stages of repeaters or re-constructor, you can facilitate the signal transmission over longer distances and this is what has happened. So, when we are using digital communication we can make the signal to travel over longer distances. So, digital communication facilitates longer distance transmission that is not the case in analog communication. So, there is one very important reason why digital communication is preferred over analog communication.

Now, if you think that is all in the kitty of digital communication that is not so. Digital communication is motivated or the growth in digital communication is motivated by several other important reasons and one important reason is the impact of computers. So, because of this computer now we have a lot of digital data as well. So, the growth in computers facilitates the growth in digital data. The second important reason which has led to significant growth in digital communication systems is that we want to go towards an integrated services network.

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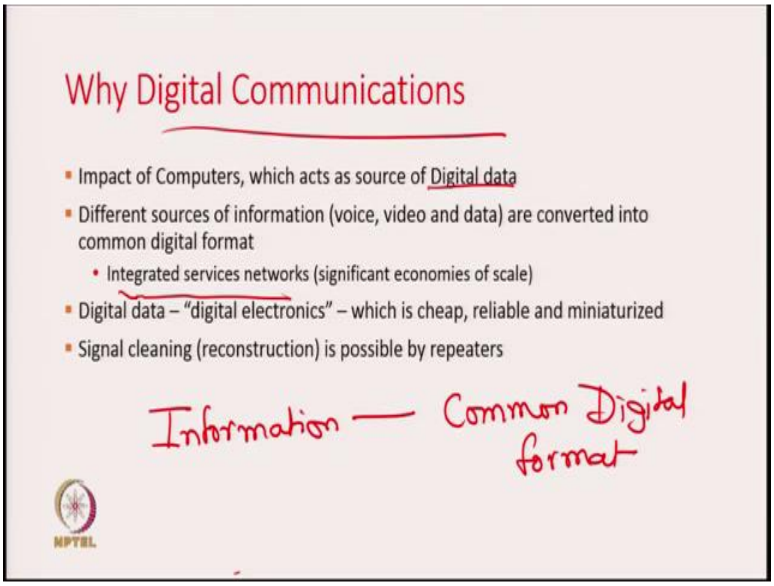

What is integrated services networks? In integrated services network we want to have a common infrastructure which facilitates the transmission of all kinds of information sources. So, for example, in internet basically we have three kinds of information sources. We have y sources to enable skype applications, we have video sources to enable you tube videos, we have data sources to do e-mails and things like that. So, these are the three important kinds of information sources.

In digital communication what we do is we take in the information source whatever is nature of the information source does not matter and we first convert it into common digital format. So, every information source is converted to a common digital format and once this information source is converted to a common digital format then the common network infrastructure can be used to carry this data.

So, it becomes invariant, the network itself becomes invariant to the kind of sources that it is dealing with and this is the main objective in the integrated services network that you can have all kinds of sources traveling simultaneously over the common network infrastructure and because of significant economies of scale this reduces the cost of the network per user. So, this is an important reason why digital communications have become all pervasive.

Third important reason is this digital data can be very conveniently processed by digital electronics. Digital electronics is pretty cheap, it is reliable, it is miniaturized and so on and so forth. So, that is also one important reason and as I have said the fourth important reason is signal cleaning is possible by repeaters.

So, all these things have favored the growth in digital communication. The proof of the cake is in eating and because all communication systems presently a digital communication system that itself speaks for the merits of a digital communication system. I think we have talked enough about what is digital communication and why digital communications have become so important.

So, let us now go to the second point where we will discuss the vocabulary which will help us to talk about things more precisely.

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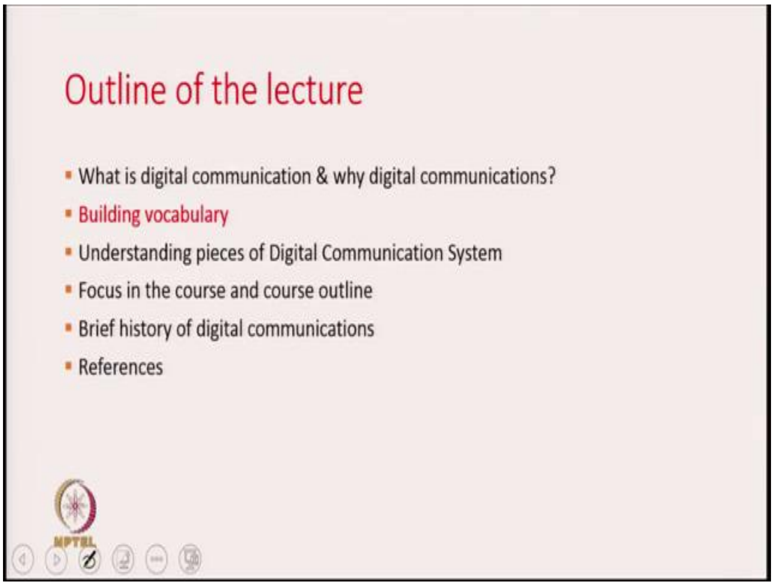

Unfortunately in literature these things are not stated precisely. The communication engineers have done in a parable job in choosing notation and picking up terminology and there is a conundrum that exists in what words mean. This meaning changes from context to context and from one book to another book. Thus I advise you not to lose your sleep if you find words meaning differently. In this course, however, what we will try to do is we will try to be as consistent as possible and that is why we are stating things afferent what these things mean to us.

So, let us get started and let us learn the words one by one. First of all let us defined what a signal is.

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Signals, in this course always means that a function of time. So, whenever we are saying signals it will always mean that is a function of time. If it does not mean so we will state it explicitly. So, if I am just saying signal, it will mean that it is a function of time easy.

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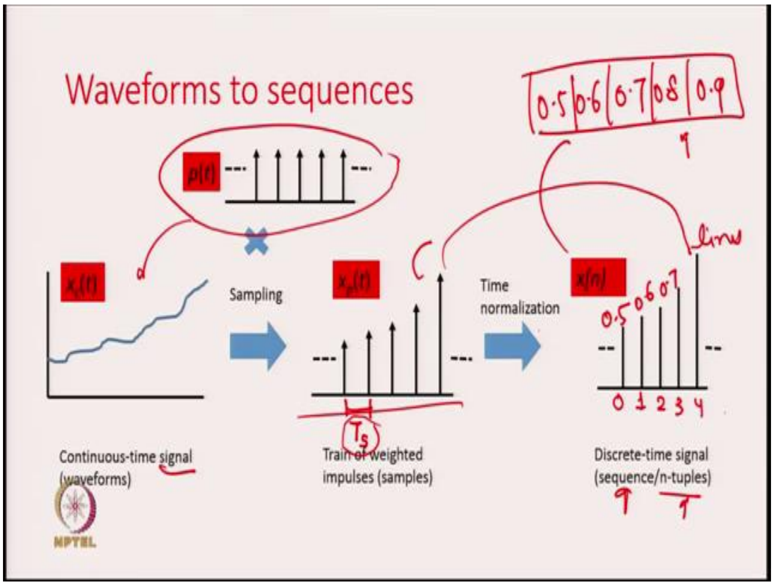

Now, let us look at what is a waveform. So, waveform is a continuous time signal. So, you know from signals and system course that you have two kinds of signals you have continuous time signals and the discrete time signals. So, when I am saying wave form I simply mean that it is a continuous time signal.

Now, you know also you must have read before that you take in a continuous time signal and you sample the continuous time signal to get what is a train of weighted impulses. So, there are these impulses and the weights of these impulses is varied. So, you have a train of weighted impulses. We will call this strain of weighted impulses as samples. This is how we would talk about the train of weighted impulses we will call either it as sample or we will call it as train of weighted impulses itself.

And, this procedure of going from a continuous time signals to train of weighted impulses is known as sampling and this is just done by multiplying the signal with the train of impulse. So, you must have seen this, you take in a train of impulse, you multiply a train of impulse with a signal and you get a way to train of impulse this is how you do sampling.

Now, after you have got this train of weighted impulse you can do time normalization to get a discrete time signal. So, for example, between these two impulses, these two impulses are separated by the sampling time interval let us call this as T_s. So, T_s denotes the sampling time interval. So, now, we get a discrete time signal where instead of T_s the samples are separated by one unit. So, n goes from 0, 1, 2, 3, 4. So, we do not have this sampling time anymore. So, you store the signal in array or whatever.

And, also you convert these impulses to lines with lines I mean that you just store the values of the weights of these impulses. So, this is basically a discrete time signal which you can store in array and you can store the values of these weights. So, signal like this. Now, this is a discrete time signal and this discrete time signal is also known as a sequence and it is also known as n-tuple; n means that you if you have n numbers you call this as n-tuples. So, we call it sometime sequence we call it sometimes n-tuples we call it sometimes discrete time signals. So, these are different ways in which you can talk about the signal.

So, remember the three words important words that we have just see it is a waveform which is a continuous time signal, you sample the waveform, you get samples, and you convert these samples to a discrete time signal. You call it sequence or you call it n-tuples

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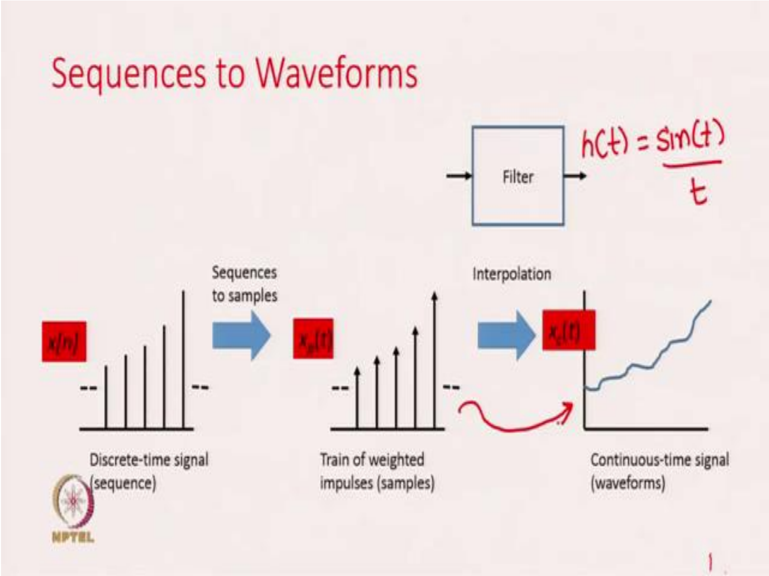

Now, you can go in the other way around as well you can start with discrete time signal you can convert this discrete time signal to sequence of samples and then you can do interpolation where you pass this system through a filter. So, if you pass this through a filter LTI filter you can do interpolation to create a continuous time cycle. And, normally we use a filter with impulse response h_t of the form of $\frac{\sin t}{t}$ and using this filter we can go from train of weighted impulses to continuous time signals. You must have seen this in a basic course on signals and systems and if you have not seen this need not worry, we will see this in lot more details later on.

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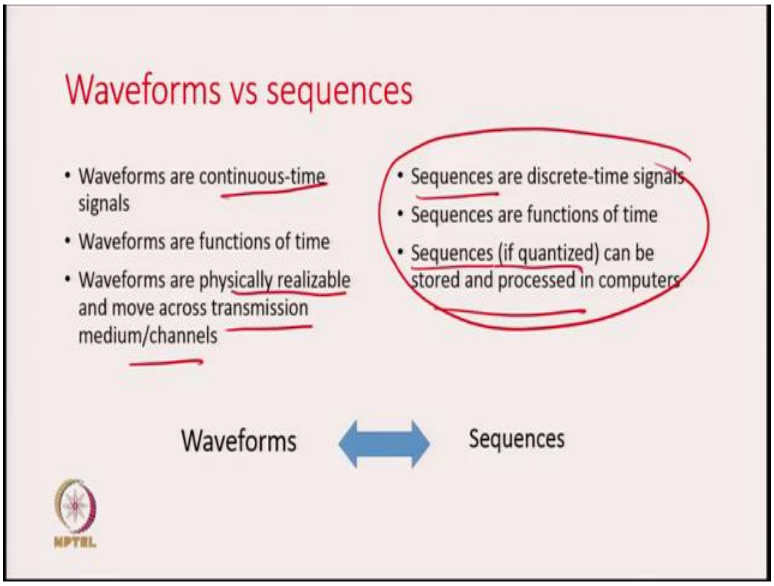

So, let us revise and summarize what we have said about waveforms and sequences. Waveforms are continuous-time signals. Waveforms are always functions of time. Waveforms are physically realizable; that means, if you have an electrical circuit you can produce these signals and the waveforms only move across transmission media. So, you know in digital communication systems or in any communication system the signal moves from one point to another point and the signal moves as a waveform. It is the waveform only that can move from one point to another point. It is the waveform only that could be physically realized.

On the other hand, what are sequences? The sequences are discrete time signals. There are also functions of time and sequences if quantized that is important; because when I am just saying sequence it can mean analog sequence; that means, it can be a sequence of real numbers. If it is a sequence of real number one real number would take a lot of memory because this real number comes with infinite precision. So, if you can quantized your sequence you can store and process this sequence in computers and this what happens in digital signal processing and so on and so forth.

So, this is how we want to process the signal. When we want to process the signal we want to process it using computer and to process this we have to convert the waveform into sequences or quantized sequence let us say.

So, in this course we like to discuss a lot about what is the relationship that exists between waveforms and sequences. Remember, waveforms are something which can travel over a channel whereas, the sequences are something that can be processed using a computer and we want to use both; for the transmission of information we would be using waveforms for processing of information we would be dealing with sequences and this relationship is important to understand.

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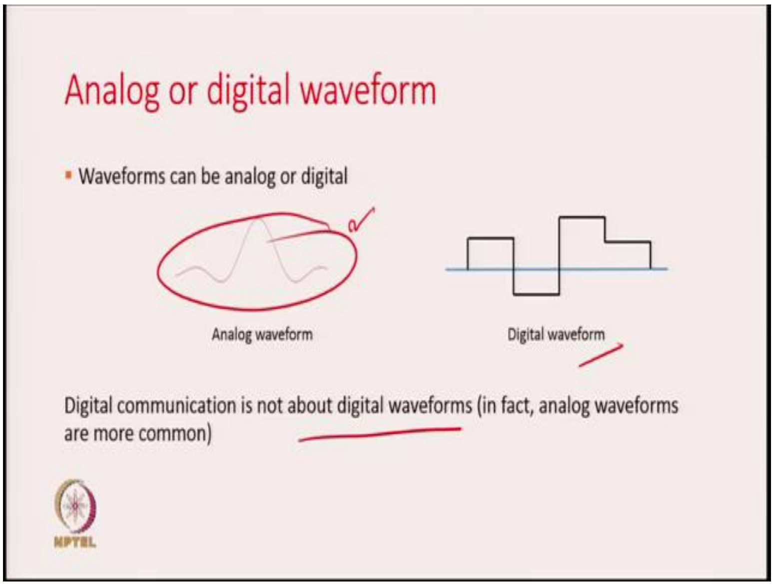

Let us continue with this waveform. Waveform can be analog waveform or digital waveform. Example of analog waveform is a signal like this which takes in all amplitudes, and example of a digital waveform is a signal like this which let us say takes on the amplitude levels from a finite set. Remember a digital communication is not about digital waveforms. This is a common misconception that lies in the head of students that digital communication is about digital waveforms, it is not. In fact, is in the digital communication analog waveforms are more common. We use these kind of waveforms more than these kind of waveform.

Digital communication deals with whether the transmitter has a finite set of amplitudes to send or is a finite set of signals to send or it whether it is sending an uncountable set. So, that is that is where the differences between analog and digital communication lies. It does not have to do anything with the waveform. Waveform can be analog or waveform can be digital.

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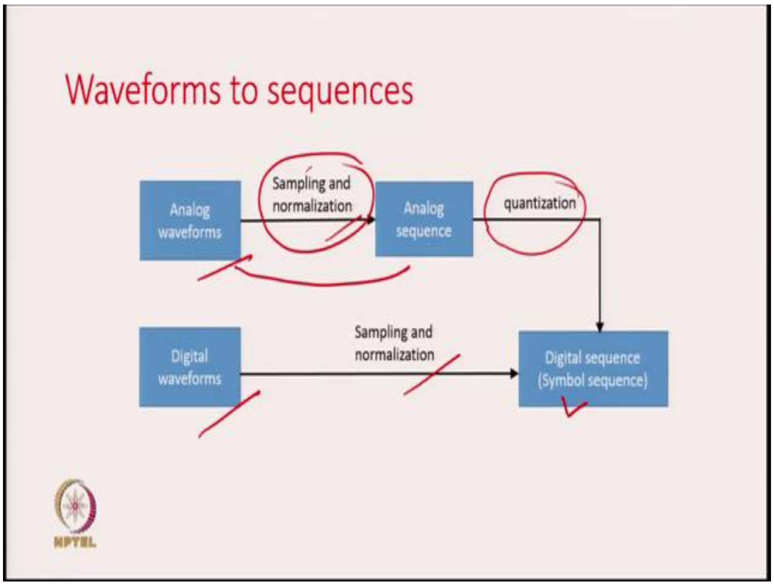

So, let us now see something more concerning these waveforms. So, if you start with analog waveform, you sample it as I have said you can sample a waveform and you normalize it then what he would get is an analog sequence. So, I can go from waveform to sequence by having these two steps, sampling and normalization. Now, once you have got this analog sequence you can quantize these analog values and what you can get is a digital sequence. Digital sequence is basically quantized sequence. We also call this as a symbol sequence that is important new word that we have learn.

So, you can start from analog waveform, sample normalize, get analog sequence, quantize it, and get a digital sequence or a symbol sequence. You can also start with digital waveforms you can sample and normalize it and you would find out with our digital sequence. So, this is the relationship that exists between waveforms, sequence, symbol sequence, analog sequence, digital sequence, and digital waveforms. So, these are the kind of words that you would be keep hearing too often and it is very important that you keep the terminology straight from a starting.

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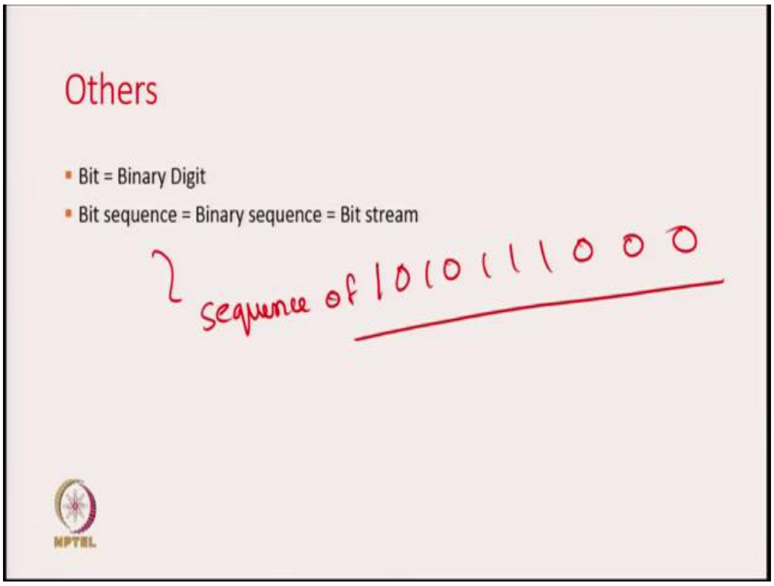

Something more bit you know stands for binary digit sometimes we say bit sequence; that means, it is a sequence of 1's and 0's 1's and 0's. For example, is signal like this? This is a sequence; sequence means is a discrete time signal and what is contained in the sequence is bits. So, 1's and 0's we can also call this as a binary sequence or we also call this as a bit stream. So, these three terms mean one and the same thing, do not get confused.

I think we have enough with building up the vocabulary. Let us now get to the main stuff and there is understanding pieces that are involved in the designing of a digital communication system.

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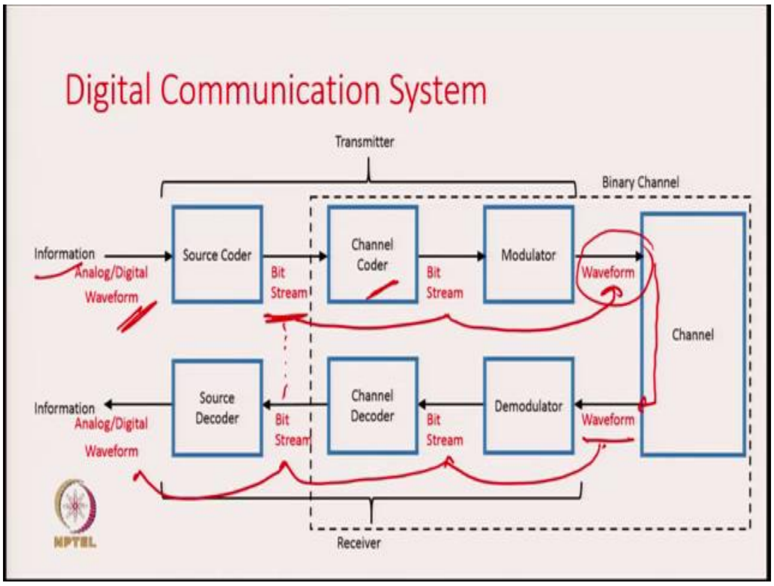

Let us start by looking at the block diagram of a digital communication system. So, information source is the first thing that we see. Information source can produce either analog or digital waveform. These waveforms are converted to bit stream by source coder. So, there is a source coder which sits in here, it takes in these waveforms and converts it into a bit stream. What is the bit stream? It is a sequence of 1's and 0's, right. What is a waveform? It is a continuous time signal. It is a continuous time signal.

Now, then you have a channel coder which takes in this bit stream and it converts it into a modified bit stream. So, takes in bit stream gives out a bit stream. This modification is done to increase the liability of your communication system by adding redundancy in the bit stream. Then you have a modulator which takes in the bit stream and converts it into a waveform. This waveform passes through the channel; it gets out of the channel with some noise. So, this gets slightly corrupted if you are lucky then you end up with a waveform. Remember the channels can only carry waveforms they cannot carry with stream.

So, they want a physically realizable signal to carry information. So, this channel can only take in the waveform. You have got a noisy waveform, then you pass this through a demodulator, the job of the demodulator is to convert this noisy waveform into bit stream. The channel decoder takes this bit stream, converts it into original bit stream this one. So, it strips off the redundancy that was added, then the source decoder converts this bit stream back into analog or digital waveform. So, this is what goes in a digital communication system. These are the building blocks of a digital communication system.

Now, there are two – three important issues if you look at this block diagram. Let us take it one by one.

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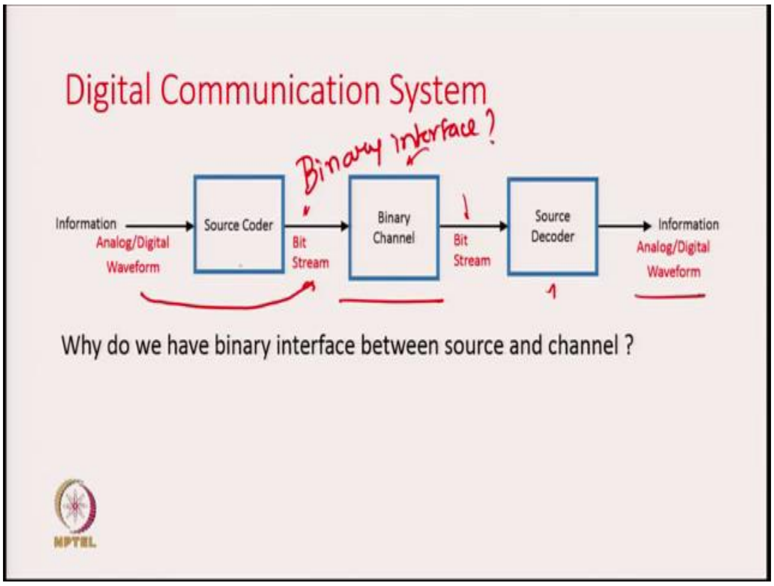

The first question is if you if you are careful you must have seen this that we said that the source coder takes in analog waveform and converts it into a bit stream and then we have a binary channels.

So, let us go back to this picture. So, this entire thing we call this as a binary channel. So, we have a binary channel. Binary channel means it takes in a bit stream and it spits out a bit stream. So, that is what a binary channel is. So, if you look at this we have a source coder, we have a binary channel, takes in a bit stream, spits out a bit stream and the then we have a source decoder which takes in this bit stream and converts this back into analog or digital waveform.

The question that you can ask is why do we have a binary interface here? Why is this binary interface sitting? This binary interface is anyway so popular that if you want to talk about the speed of this network a common way to do that is in terms of bits per second. So, you want to say my internet speed is 10 Mbps or 1 Gbps or whatever the case may be.

So, this is because of these binary interfaces. So, popular all digital communication systems have caught this.

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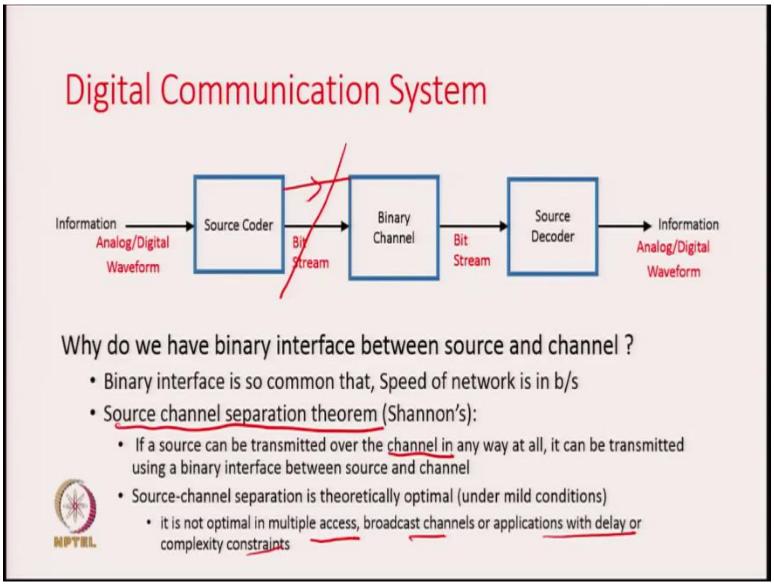

So, the question is why do we have this bit in binary interface? Are there other ways to do that and answer comes from Shannon's information theoretic idea which states that, if a source can be transmitted over the channel in any way, it can be transmitted using a binary interface between source and channel ok. So, that is you can separate the source from the channel, source-channel separation theorem and it says that you can transmit the information between source and channel using a binary interface and binary interface is the most optimal way to do this in most conditions.

So, it might not be optimal in the cases like multiple access, broadcast channels or applications with delay or complexity constraints. We are not interested in these kinds of applications in this course, we are just interested in simple point to point digital communication system and once you are considering a point to point digital communication system a binary interface is mostly an optimal thing to do. So, this comes from information theoretic ideas of Shannon. You would not be spending time on that, but it is a very good thing to note.

So, that if you are interested you see the proof for this. This goes by the name of source channel separation theorem.

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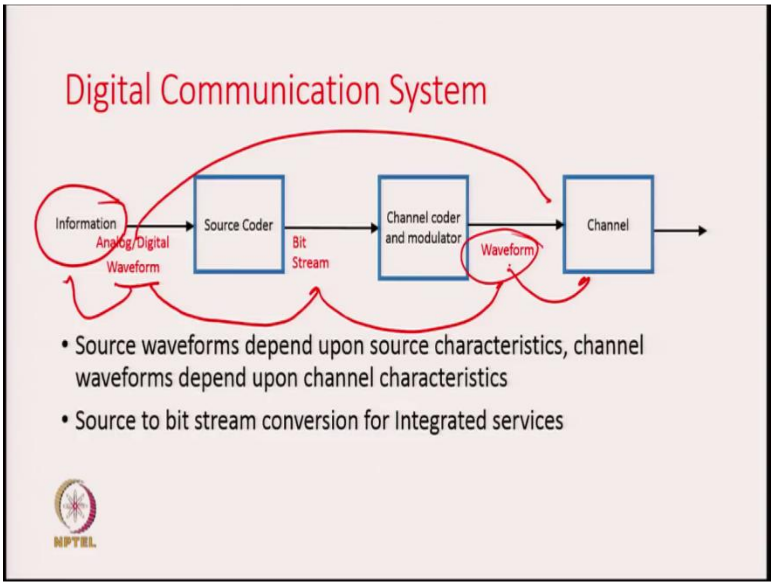

The second thing that you might worry about is if you look at this digital communication system design, we started with analog digital waveform. The source coder converts this into bit stream, channel coder and mode converts back this bit stream into waveform. Why cannot I simply transmit this waveform directly into this channel? Why do we are doing it in two steps? It seems as if we are doing we are duplicating the efforts.

The answer to this question is also simple. First, this waveforms depends upon the nature of the source. Given the kind of source you have these waveforms would be dictated by the nature of that source. These waveforms that we want to transmit on the channel are the waveforms which are most efficient for the transmission over the channel. So, these waveforms are not same as these waveforms. These waveforms are optimal for the transmission of a channel. These waveforms we do not have any control over, these waveforms are dictated by the source characteristics. So, that is one reason.

Second reason is as I have already stated about this integrator services network and what was the main idea there? The main idea there was you taken any kind of the source and you convert this source into bit stream generator, so that you do not worry about the source characteristic the channel deals only with the bit stream. So, this idea about integrated services network is facilitated by first having a source coder which deals with the complexity of the source converts all kinds of sources into a bit stream or a binary sequence. So, that is the second idea.

Third idea is about layering. So, layering is the idea which is very often used in computer networks and digital communication system. The idea of layering is you have a complicated problem, you break this complicated problem into smaller chunks of problem and then you solve smaller problems individually.

So, this is also really important once we are dealing with a complicated network.

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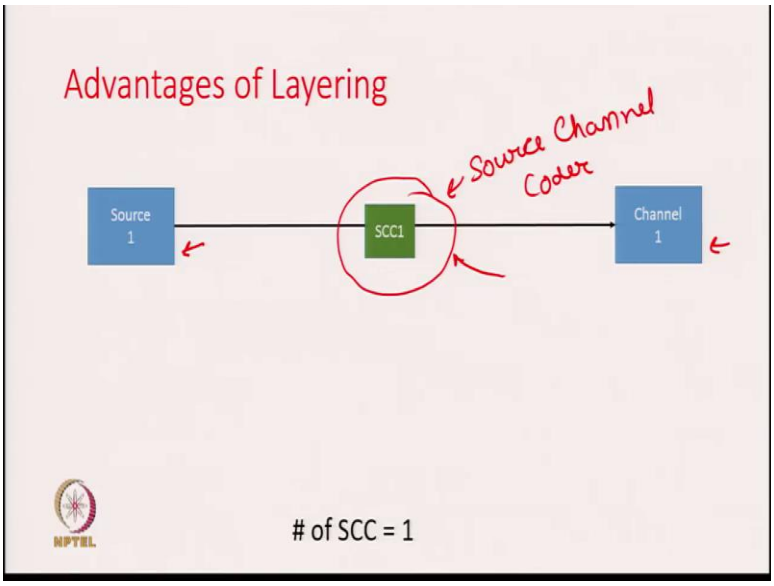

Let us see why that case is. So, to understand layering let us look at this picture and what I am assuming is that I have one kind of a source and I have a one kind of a channel. Now, to enable data transmission over one kind of a source and one kind of a channel what I need to have is a source channel coder. So, this I am assuming is a source channel coder. So, source channel coder here implies that I have put all this blocks into one block. So, earlier I had source coder, I had channel coder, I had modulator, I have put all these blocks into one block and I am designing one block to enable data transmission over our source and a channel pair.

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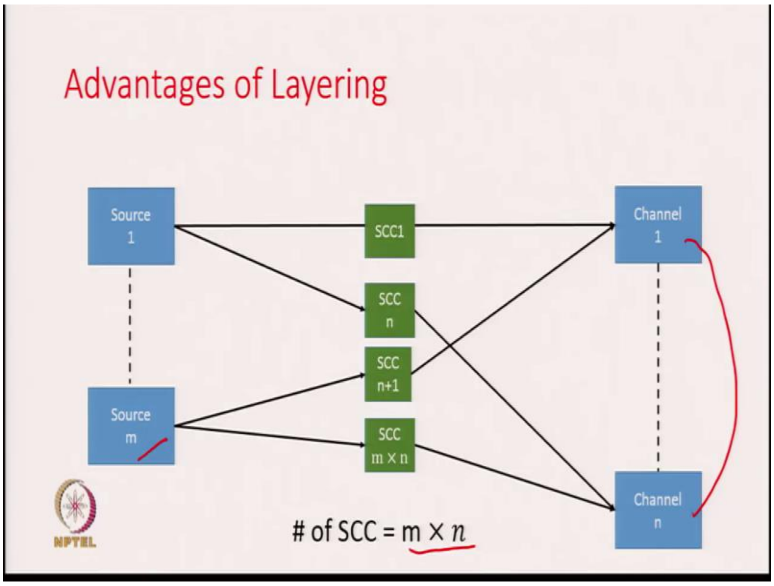

Now, suppose I need to transmit one kind of a source over n kinds of channels I need to design n kinds of source channel coders. So, research effort involved in designing such block is proportional to n. Now, let us imagine that the number of sources that I have is m. So, number of sources means number of different kinds of sources that I am having is m and number of different kinds of channels that I am having is n. So, the number of different kinds of source channel coder that I need to design is m times n. So, the research effort that is required in this case is m times n.

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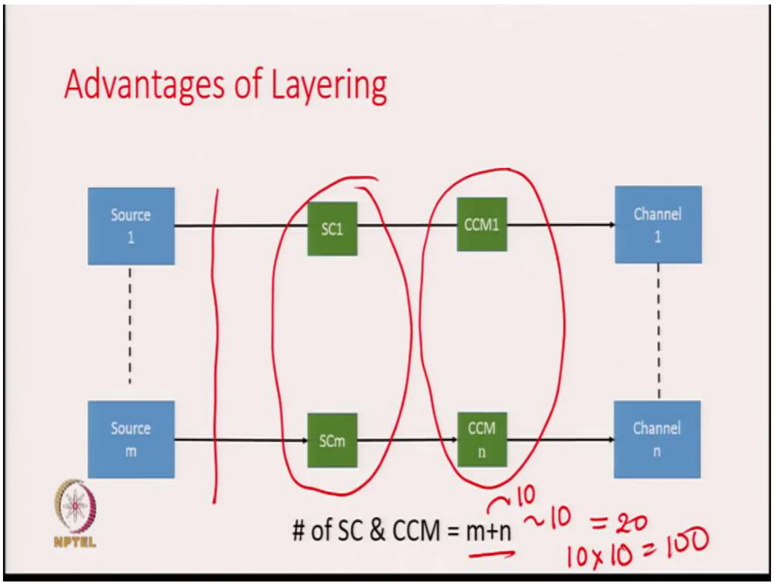

Now, let us invoke the concept of layering. So, I have broken down that complicated block into smaller blocks and this block let us assume deals with the complexity concerning this part and this block deals with the complexity concerning this part. Now, number of source coder that I need to have to tackle one kind of source is one, number of channel coder and modulator that I need to have to tackle one kind of channel is also one.

Now, if I have m kinds of sources m kinds of sources can be treated with m kinds of source coder and n kinds of channel can be treated using n kinds of channel coder and modulator. Thus the research effort needed in this case is m + n, and assuming that m is 10 and n is also 10 the research effort is proportional to 20 whereas, in the previous case research effort would have been proportional to 10 times 10, which is 100. Thus when you invoke the concept of layering that is breaking down a complicated thing into a smaller things, the research effort generally reduces significantly and that is why we love layering.

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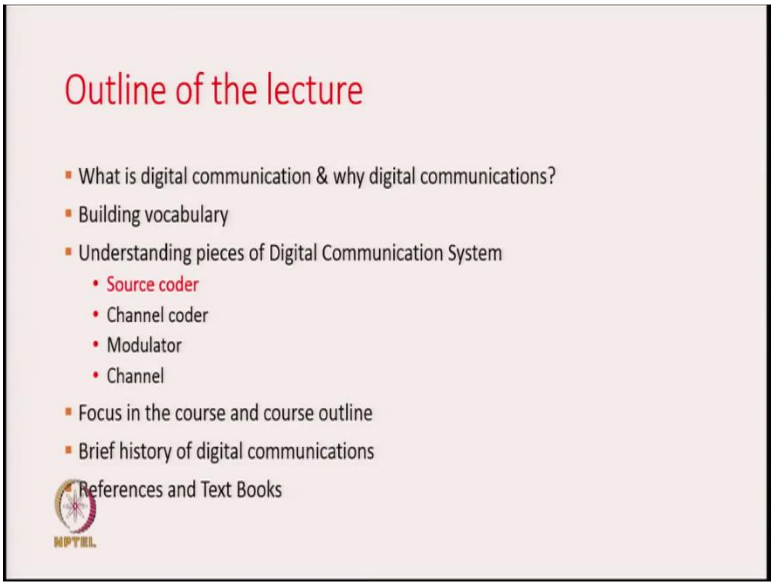

So, let us understand the pieces that are involved in the designing of a digital communication system.

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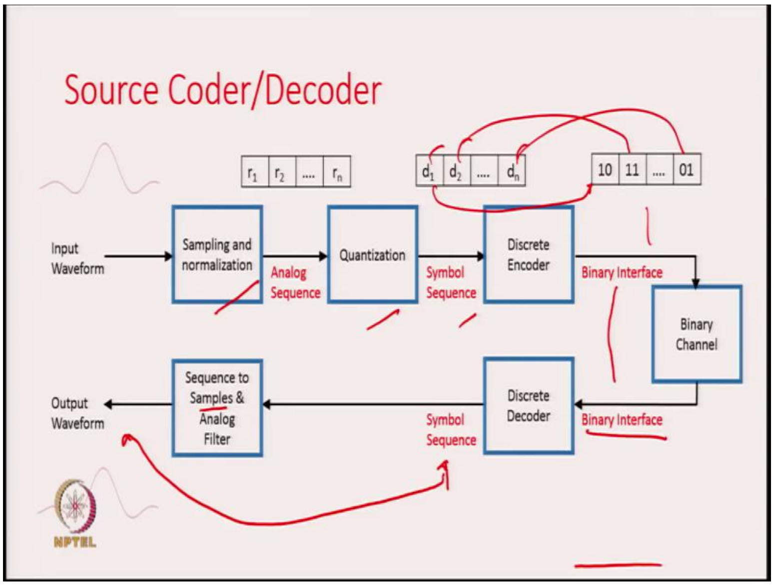

Let us start with source coder. Remember the high level objective of a source coder was it takes in waveform and it converts it into bits stream. The first step is, it takes in a waveform, and then it does sampling and normalization. The sampling and normalization will produce analog sequence. Analog sequence is quantized what you have is a symbol sequence. Remember these symbols are the quantized numbers.

So, we have this d_1, d_2, $d_n$which we call as symbol. So, we have a sequence of symbols. Then we have a discrete encoder which takes in a symbol and maps it to a binary numbers. So, for example, this d_1 is mapped to 10, d_2 is mapped to 11, d_n is mapped to 01 and so on so forth. Then you have a binary interface this moves this bit stream moves through a binary channel, then a binary channel produces a binary stream.

Most probably it should produce the same binary stream as was fed to a binary channel, then we have a discrete decoder which takes in this binary stream produces a sequence of symbol then the sequence of symbol is converted back to an output waveform by what we already have seen by having first a sequence to samples converter and then by having an analog filter. So, that is the way how you can go from symbol sequence to an output waveform.

So, these are the steps involved in this source coder and decoder design.

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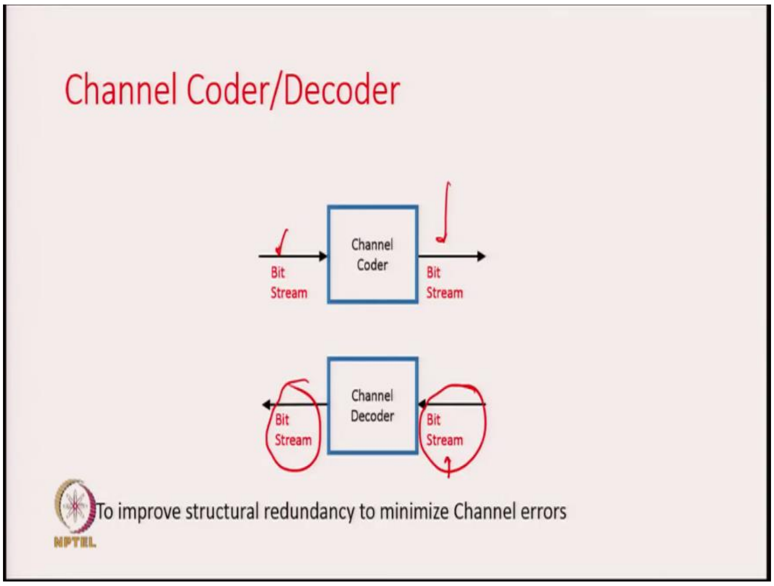

Let us look have the second block this channel coder. Channel coder takes in a bit stream and it produces a modified bit stream. A decoder does the same thing, it takes in the modified bit stream and it produces original bit stream and this modification as I have already pointed out happens in order to improve the redundancy and to minimize channel errors.

Let us see one example of how it can be done.

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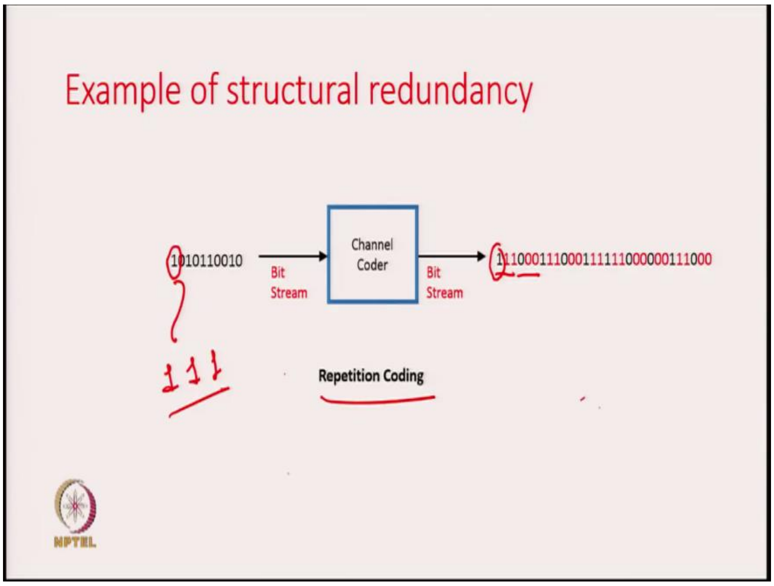

So, what I am showing to you is an example of a repetition coder. So, repetition coder takes in a bit and repeat this bit in this case, let us say three times. So, one is repeated three times and you have this bit. Similarly, it takes in 0, 0 is repeated three times and so on and so forth. Now, what you hope is if an error happens error impacts at most one bit out of the three bits. So, that you can use the majority rule at the decoder and you can minimize errors.

Repetition coding is a very simple example in order to show how you can increase the reliability of the system, but it is not the most efficient way to do that. You need to transmit a lot more bits now. So, it comes at some cost there are better ways to increase the reliability of your system.

So, now, let us try to understand the modulator and the demodulator.

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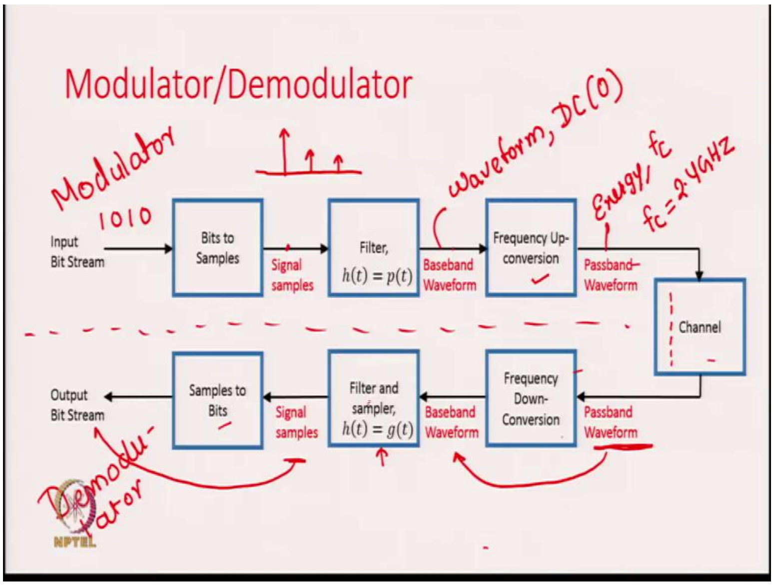

So, this part corresponds to modulator and this part corresponds to demodulator. So, add the modulator, bit stream comes in. Bit stream is a sequence of 1 and 0's. This bit stream is converted to signal samples. As I have said already signal samples is nothing, but it is a train of weighted impulses. So, at this point we have signal samples. These signal samples pass through a filter having an impulse response of p_t. At this point, we get a baseband waveform.

Baseband waveform is a waveform which has most of its energy centered at around DC or zero frequencies. This baseband waveform is then converted to passband waveform by this block frequency up conversion. This passband waveform has its energy centered at around some high frequency which is usually referred to as f_c. For example, in conventional Wi-Fi systems f_c is 2.4 GHz.

This passband waveform then moves through the channel. Channel corrupts this passband waveform, add some noise. So, we have a modified pass band waveform at the output of a channel. This passband waveform is down converted to baseband waveform by frequency down conversion. This then passes through a filter and a sampler and again we get signal samples. These signal samples are converted to output bit stream by using what is known as samples to bit converter. So, this is typically what goes in a modulator and demodulator.

So, this is a very high level overview of several blocks that are used in modulator and demodulator. We will study each block in lot more detail while going through the course.

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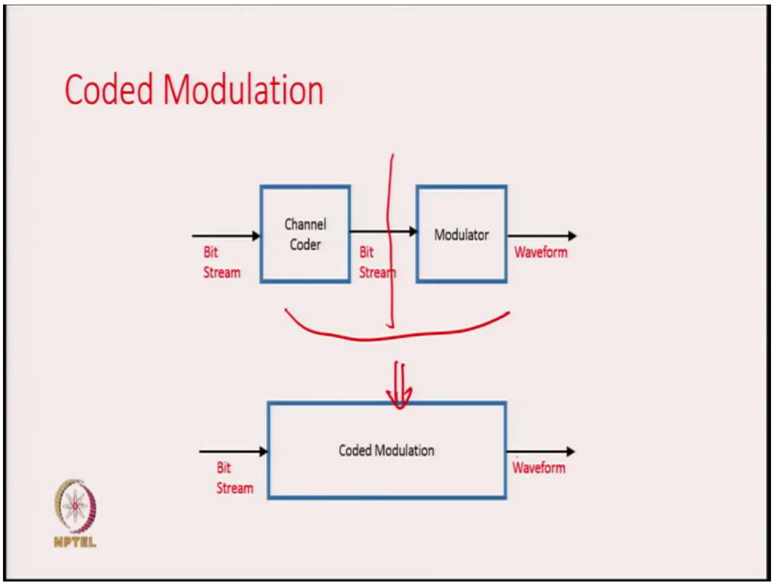

Now, though we I have said that we have two blocks, one for channel coding and one for modulator, but it is more efficient usually to combine these two things together and this is the modern viewpoint you try to combine this channel coding and modulate it together and you call this as coded modulation. So, this is the way things are happening nowadays.

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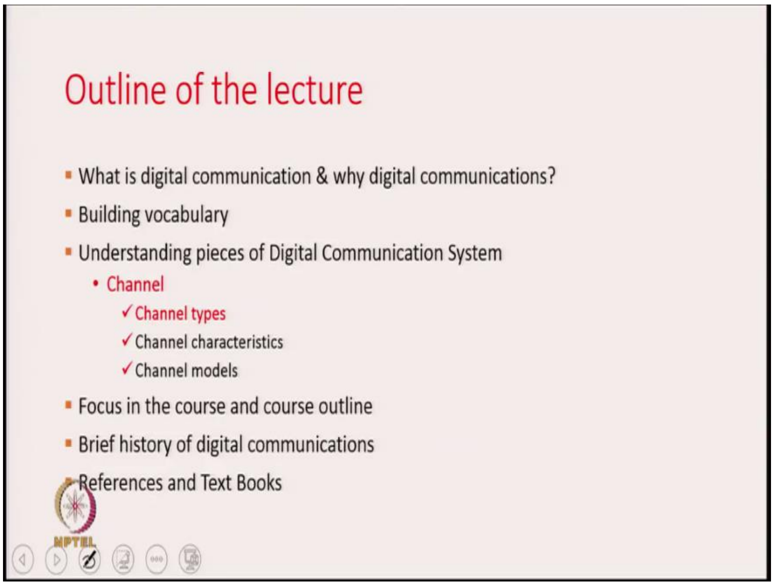

So, we have learned enough about modulation. Let us see the last thing that is a channel and in channel we will quickly see what are various kinds of channels, channel characteristics and channel models that we can use.

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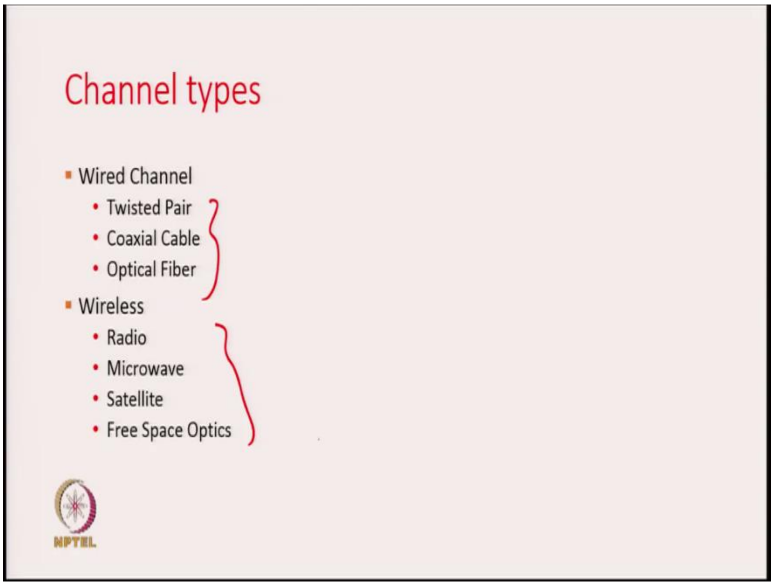

So, starting with channel types we have a wired channel and a wireless channel. So, examples of wired channels are twisted pair, coaxial cable, and optical fiber. In wireless, we have radio channels, microwave channels, satellite channels, free space optical channels.

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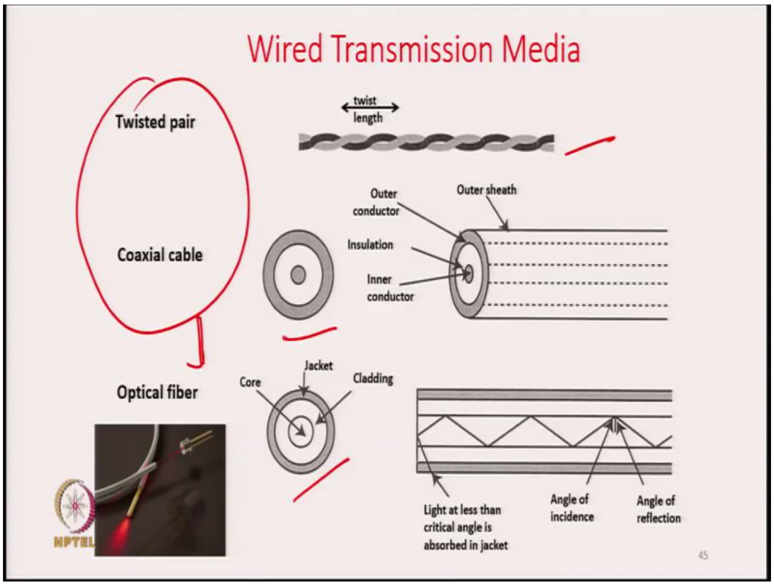

So, let us look at the wired channels first. So, these are the diagrams of these channels, you must have seen them before. So, you have this twisted pair. Twisted pair is what is used in telephone cables. So, if you want to see it just take the telephone cable out and see this. Coaxial cable is what is used in cable TV and then we have this optical fiber which is the next generation transmission media. All this transmission medium should be replaced by optical fiber because of its several advantages.

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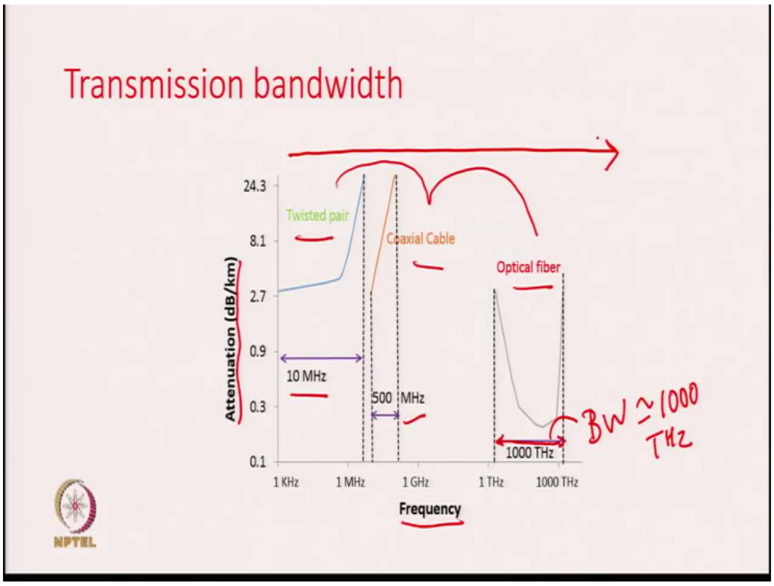

So, transmission media that we have just seen are normally characterized using transmission bandwidth. To identify transmission bandwidth we usually plot attenuation versus frequency.

So, here I have shown the attenuation versus frequency profile of three wire transmission media that we have just discussed. So, we have twisted pair, we have coaxial cable and we have optical fiber. From this attenuation versus frequency profile we can estimate the transmission bandwidth which is the range of frequencies for which attenuation is low.

So, for example, optical fiber has a low attenuation for the frequency range of about 1000 THz. So, optical fiber has got a bandwidth of around 1000 THz. Now, if you look at this bandwidth optical fiber has got much larger bandwidth than twisted pair whose bandwidth is around 10 MHz and coaxial cable, which has got a bandwidth of around 500 MHz.

You can also see the trend that as the frequency of operation increases, so, we have an increasing frequency of operation when we go from twisted pair to coaxial cable to optical fiber. So, as the frequency of operation increases the offered bandwidth also increases. Communication engineers love this high transmission bandwidth because high transmission bandwidth means higher capacity and; that means, higher bits per second and; that means, we can download movie faster and it also means more business for operators.

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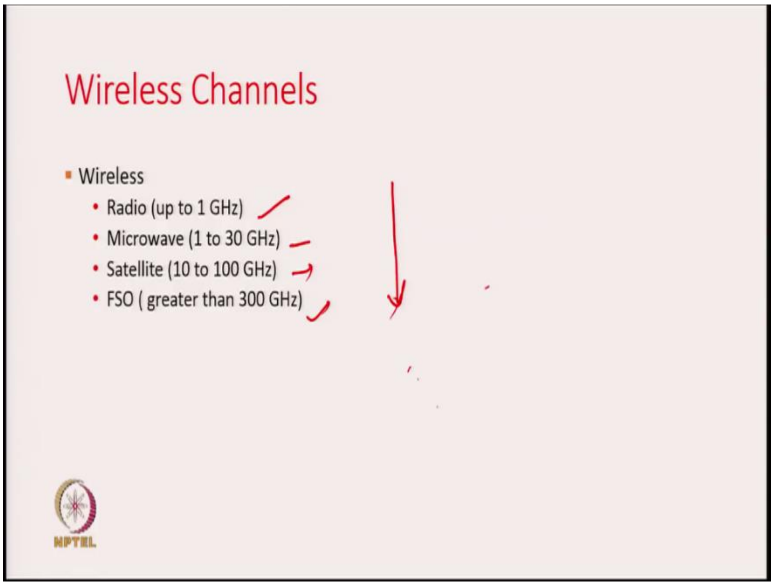

In case of wireless channels so, radio works up to 1 GHz, microwave works up to between 1 to 30 GHz, satellite communication is around 10 to 100 GHz, free space optical communication is greater than 300 GHz.

So, you can expect that the bandwidth would be highest in free space optical communication and it will be lowest in a radio communication.

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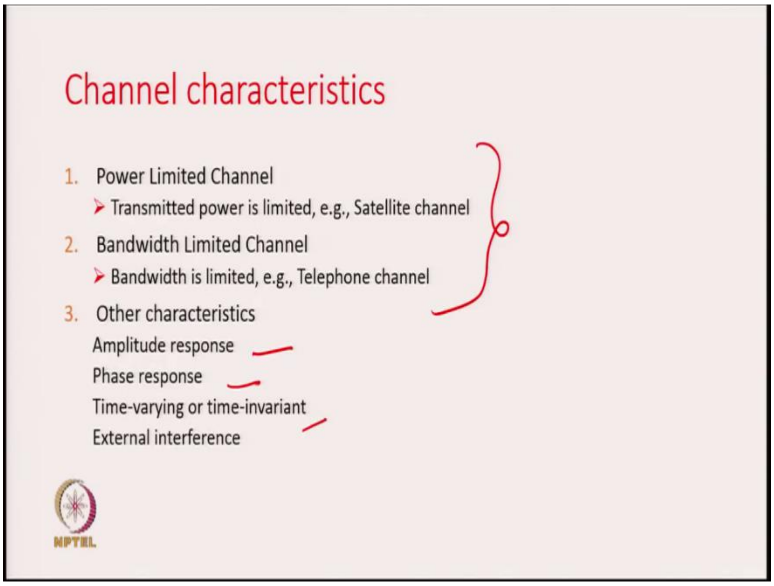

So, what are the important channel characteristics? The two important channel characteristics that we talk about is whether a channel is power limited channel or whether the channel is bandwidth limited channel. For example, satellite channel is an example of a power limited channel and satellite communication it is very important that you minimize the power expenditure in modulation in demodulation schemes because otherwise the battery will drain fast and you need to replace the batteries in satellites and replacing the batteries of a satellite is very expensive operation and hence what you want to do is use modulation and demodulations schemes which spends less power.

On the other hand, in case of telephone channels what you want to do is safe bandwidth. Bandwidth is more precious resource. You do not care about power in telephone channels because you have kind of unlimited power for telephone cables.

Other important characteristic is what is the amplitude response of the channel, is it flat or not, what is the phase response, it is also important whether the channel is time varying channel or it has time invariant characteristics, what kind of external interferences influences your channel.

So, these are various things that you need to look into when you are designing a communication system.

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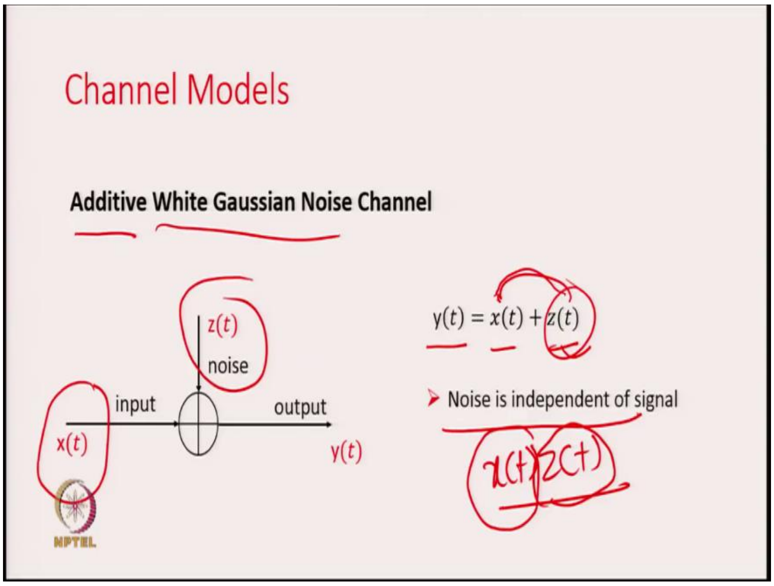

What are the typical channel models that we use? The first simplest model is additive white Gaussian noise channel. So, what is that? What this says is, you have an input, and you add noise to this input. So, this is the output; input plus noise. So, because noise adds to the input we say this as an additive noise. It is a white Gaussian noise what is a white Gaussian noise? We will spend several lectures on trying to explain what is a white Gaussian noise and this moment it is not important, but it is important to appreciate that there is a noise addition and this noise has a white Gaussian profile.

Once you are saying that the noise adds to the signal it means that the noise is independent of signal. For example, if I would have had this situation x_t time z_t. Now, the amplitude of the signal would influence the amplitude of the noise. So, noise in this case is multiplicative. So, noise additive means that noises independent of signal. So, additive white Gaussian noise channel is a very simple model to start modeling your communication channel.

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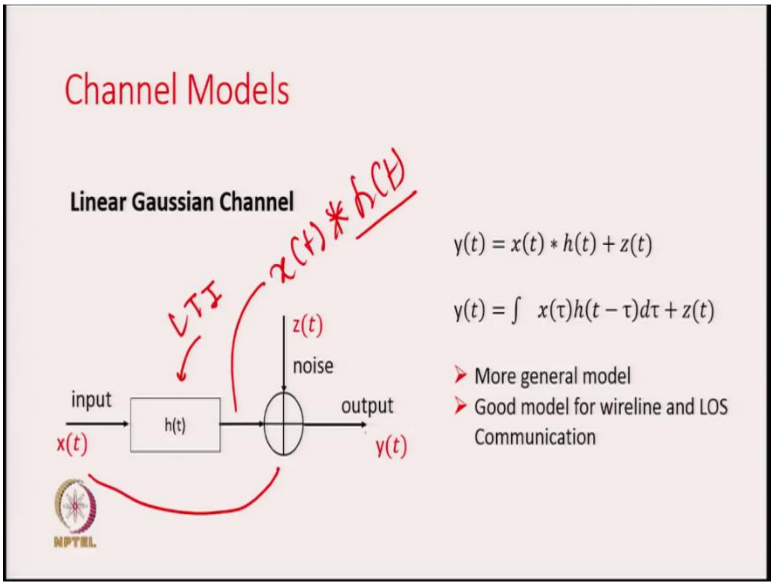

Then we have linear Gaussian channel which extends this concept of additive white Gaussian noise channel by having an LTI filter in between input and adder. So, this makes the thing more generic. You know if this input passes through a filter then at the output of the filter we would have x_t convolution with impulse response of the filter. So, this is a good model for wireline and line of sight communication.

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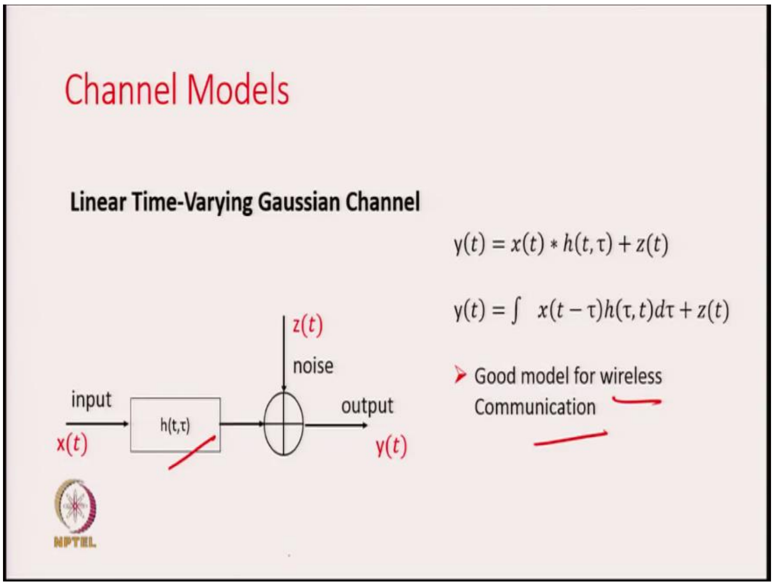

We have a third kind of a channel which is linear time varying Gaussian channel. In this channel the impulse response is time varying. The impulse response itself is time varying and this is a good model for wireless communication because wireless communication the distance between mobiles and receivers, the transmitters and receivers changes there are the factors that changes overtime, atmospheric conditions changes and so on and so forth and because of this the impulse response is also a function of time. So, this is a model which you can use for modeling wireless communication.

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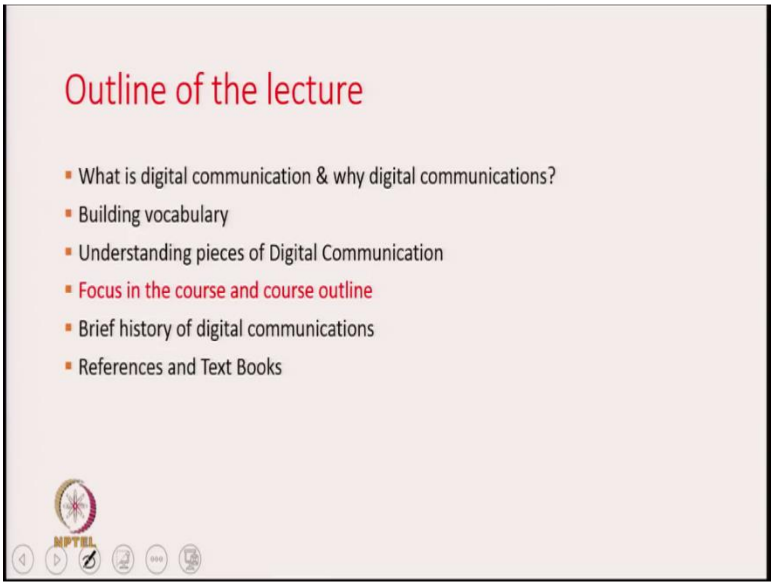

So, what is the focus in the course and what is the course outline?

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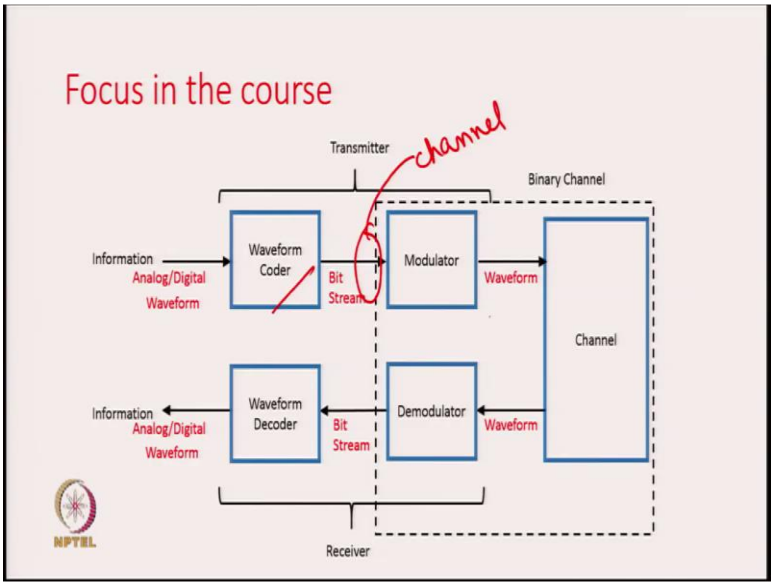

In this course we will not be talking about the channel coder. So, remember there was a block of channel coder here; we would not be dealing with channel coder. We have stripped it off because the subject of channel coder is a subject in itself. So, you need to spend at least twenty – thirty lectures just talking about channel coder. There are the courses on NPTEL on coding theory where you can refer to channel coder.

Also we have replaced the source coder with waveform coder. What is the difference between source coder and waveform coder? When we are talking about the source coder it means that you associate different probabilities to different symbols and you try to do encoding in such a way that you avoid any redundancy. When we are talking about the waveform coding what we assume is that all symbols have equal probabilities. So, we treat all symbols to be equal probable symbols.

So, we get over this issue of how to improve efficiency of coding and so on so forth. So, waveform coding is easier, it is a sub-set of source coding we will just be focusing on waveform coding without worrying about the probabilistic model of the sources.

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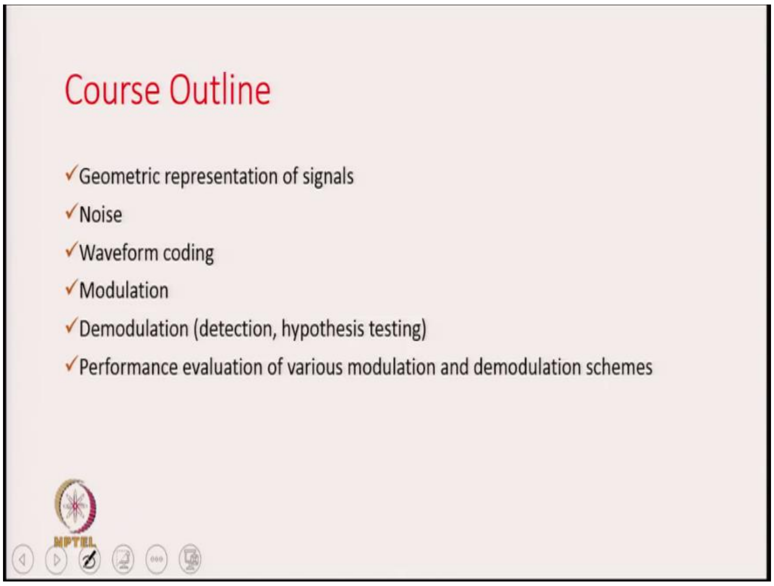

Course outline; so, we will start with geometric representation of signals. As I have said is the most interesting thing if you have understood this part really the course is easy. We will follow this up with discussion on noise; we will talk about waveform coding how to convert an analog waveform or a digital waveform into a binary sequence. We will deal with modulation which deals with starting from a bit stream, how are you going to get waveforms. Then we have demodulation going from waveform to binary stream. Demodulation is also known as detection hypothesis testing with several names for this. Finally, we will study how to evaluate the performance of various modulation and demodulation schemes.

We will like to finish this course by pointing out to the history of digital communications. Let us credit the right people who have led to the growth of this digital communication.

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We will start with Francis Bacon, who developed binary code in 1605.

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We have telegraphy from Samuel Morse in around 1837.

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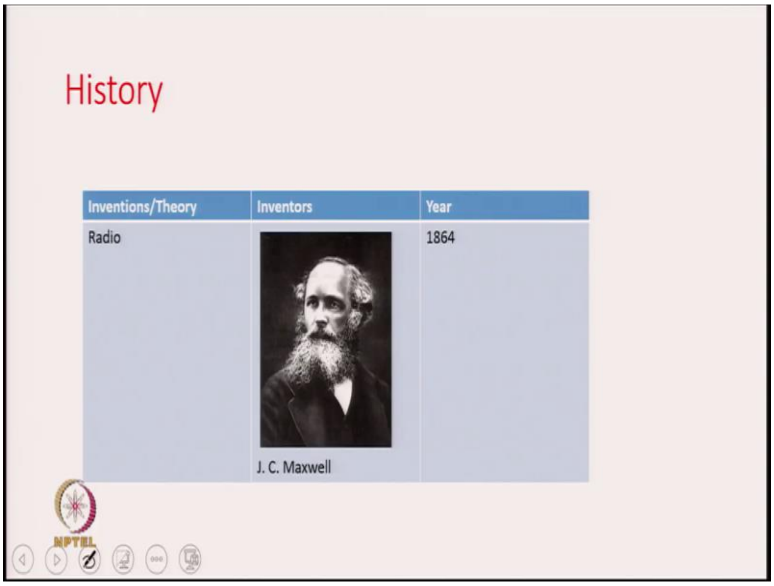

We have radio from Maxwell in 1864.

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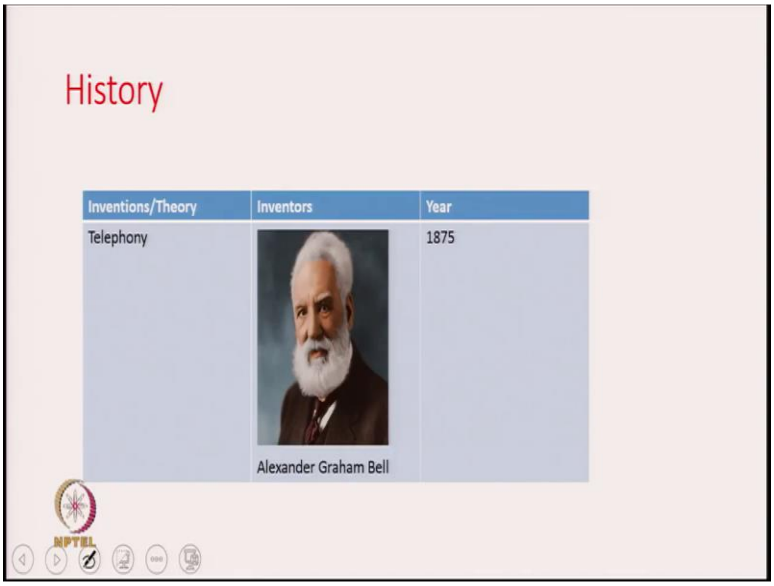

We have telephony from Graham Bell in 1875.

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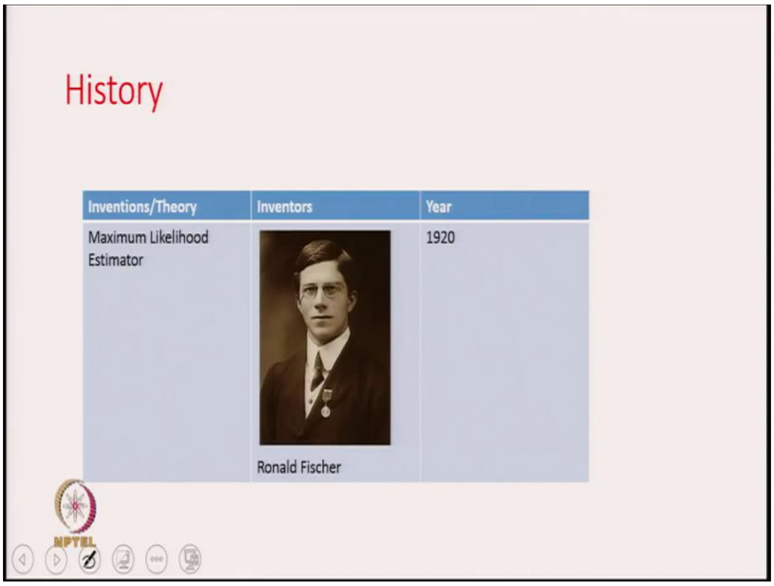

We have maximum likelihood estimator from Ronald Fisher in 1920. We will also talk about this maximum likelihood estimator.

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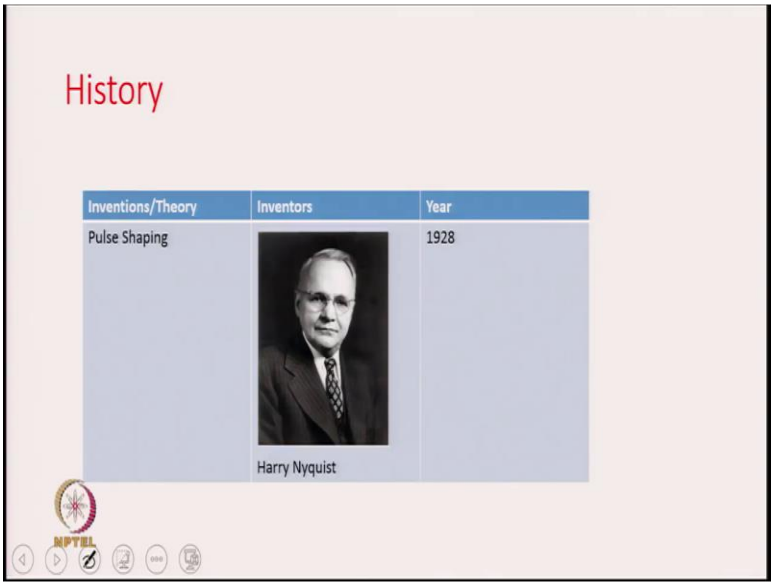

Then we have pulse shaping contributions from Harry Nyquist in 1928. There will be lecture or so which would be dedicated to the issues of pulse shaping in this course.

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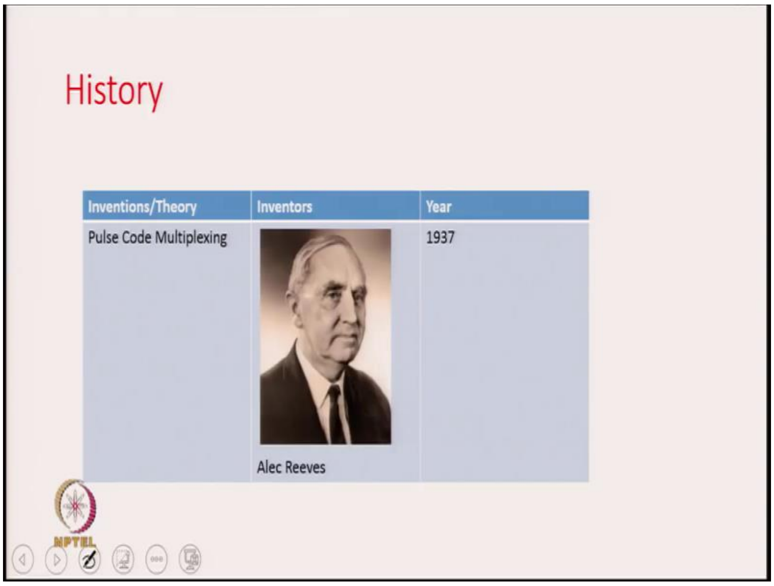

We have this pulse coding multiplexing from Alec Reeves in around 1937. We will also talk about this.

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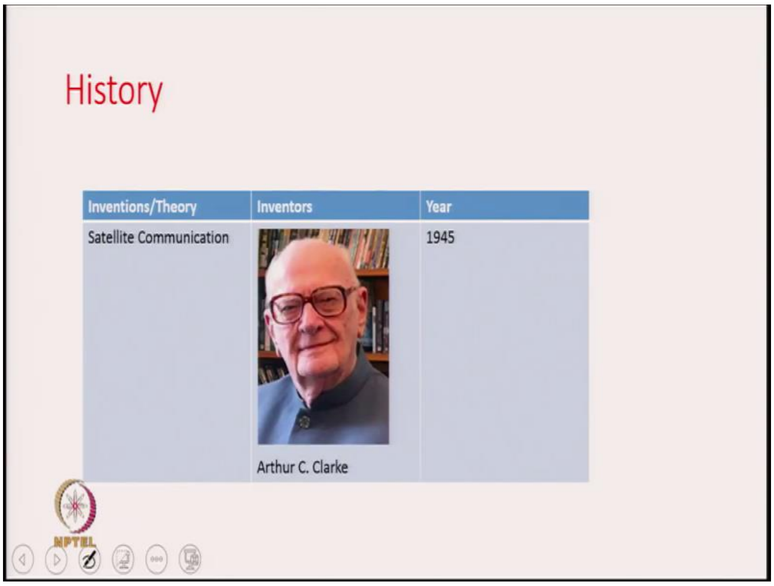

Then the work of Arthur Clarke has spurred the growth in satellite communications in arrow 1945.

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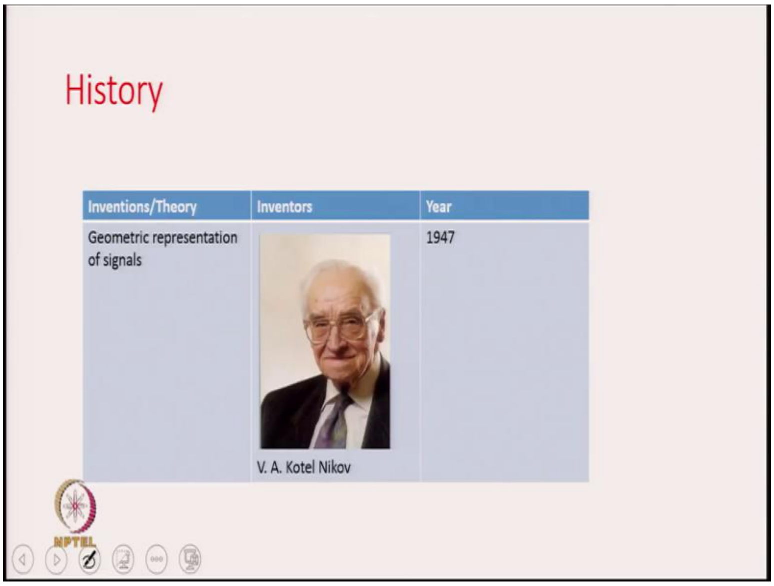

We have PhD dissertation of Kotel Nikov on geometric representation of signals in around 1947, this key thing simplifies digital communication to a large extent.

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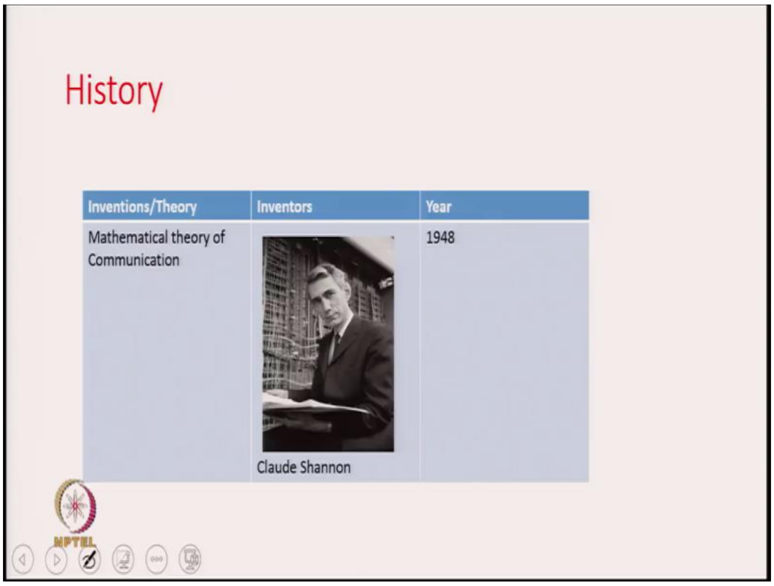

Then we have celebrated mathematical theory of communication from Claude Shannon in 1948. So, this has led to the revolution in communication theory. It has kind of unified communication and information theory.

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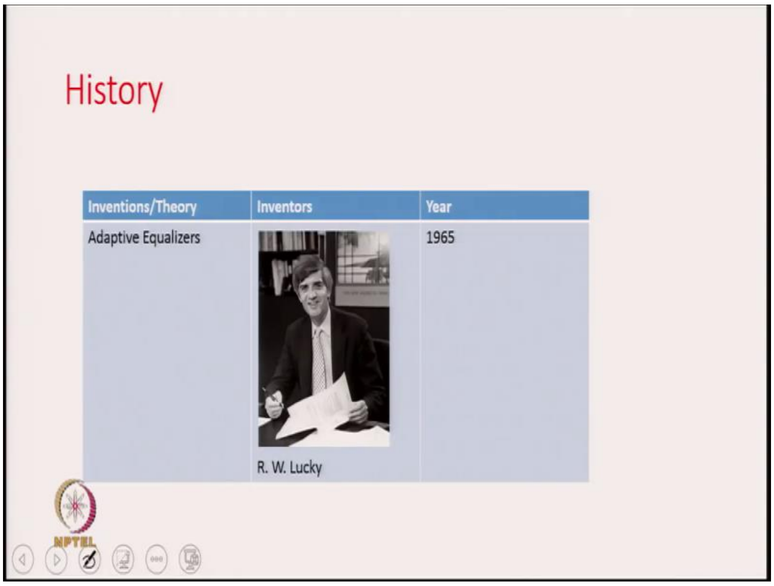

Then we have work of R W Lucky on adaptive equalizers. So, adaptive equalizers give you flat amplitude and phase response, improves channel characteristics. This work has been done by him in around 1965.

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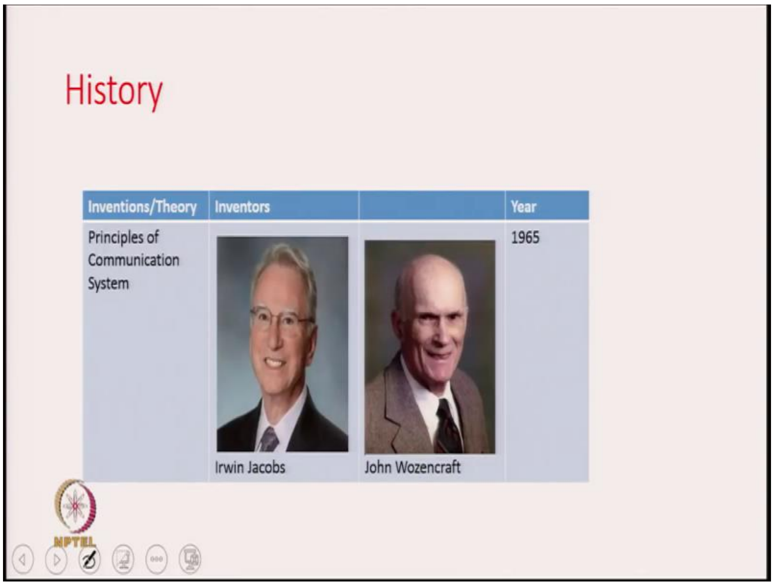

Then we have a very celebrated book, a classical book on Principles of Communication System from Irwin Jacobs and Wozencraft in around 1965. This is my personal favorite, is still is the best book to read, I believe.

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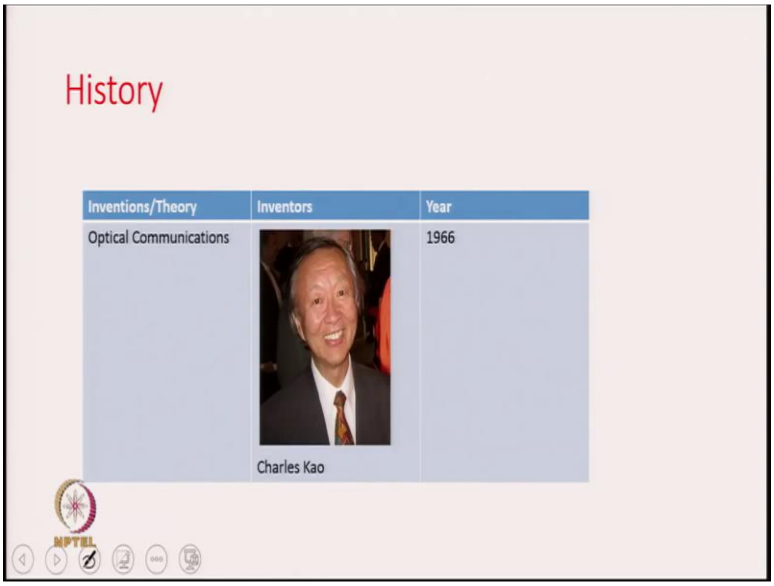

Then we have Charles Kao. He has basically worked on reducing the losses in fiber. This work has led to the growth spurt the growth in the area of our optical communication. He did this work in around 1966.

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Finally, the references. I would advise you that you for the study of this course you refer to my lectures and lecture notes. However, their classical books have available in this area. We have book from Robert Gallager titled Principles of Digital Communication. Professor Gallager himself has contributed significantly to the coding theory and this book talks about digital communication concepts in a lot of depth and so, a very good book to it. Then we have book by Upamanyu Madhow, titled Fundamentals of Digital Communication. It is a simple book to read. Simple, but it has unsacrificed depth that is very elegant book to read.

Then, my favorite book is book by Wozencraft and Jacobs on Principles of Communication System, 1965. It is the best book to read about signal spaces and detection theory. Then we have book from Proakis and Salehi which provides the widest coverage of digital communication concepts. Book from Simon Haykin is a good undergraduate book.

We have book from Amos Lapidoth, A Foundation in Digital Communication which is a newer addition to the kitty of books of digital communication. If you are looking for a mathematical proof and if you do not find it anywhere this is the book where you can find probably. Then we have book from Bernard Sklar a titled Digital Communications which is also a good book to read.

So, this concludes today’s lecture. From next lecture we will be talking about geometric representation of signals, how can we treat signals as vectors?

Thank you.