Fiber- Optic Communication Systems and Techniques
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Lecture - 51
Intensity modulations/ Direct Detection

Hello, and welcome to NPTEL MOOC on Fiber- Optic Communication Systems and Techniques. In this module we will begin to look at various modulation formats and how can we analyze the performance of the system. We will begin with a very simple modulation technique, but nevertheless very important modulation technique which has been used in optical fiber communications from the 1970s till about last 5 or 6 years. And, this modulation technique although I am calling it as a simple is only a relative term because it has its own challenges that need to be overcome.

But this particular modulation technique is simple in the sense that the optical intensity will be directly proportional to whatever the information content that is being used as the modulating signal. And then at the receiver side you do not have to worry about the incoming signals face, if you match the polarization then on your looking at is the intensity variations which can be captured by a well designed photo detector. And, if possible or if required most of the time it is required that you also shape the output after the photo detector by a receive filter and then recover the data.

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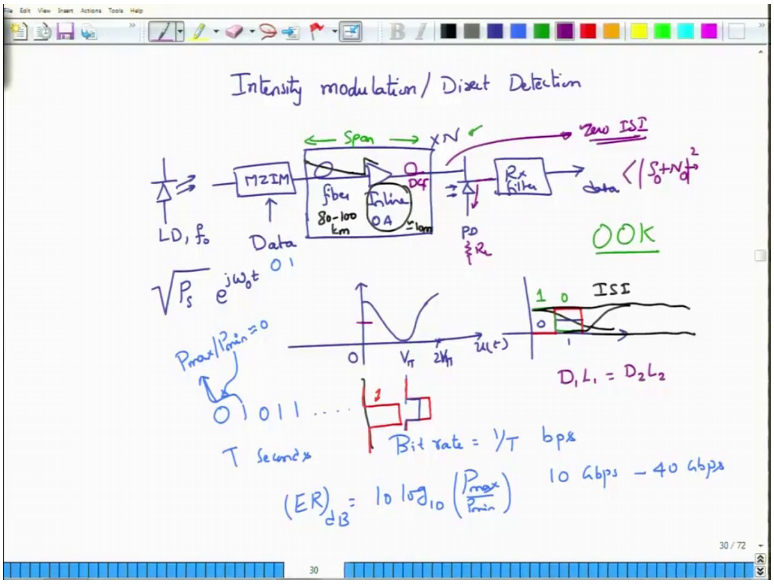

So, this is system schematic diagram of a single channel single polarization optical communication system that employs intensity modulation and direct detection. So, you can see that we start off with a laser diode here which provides us with a carrier. And, if you remember that the way we have return of the carrier is square root P s e power j omega 0 t where, omega 0 is 2 pi f phi f 0 is the carrier frequency of the laser diode. For now, we will neglect all noises that are associated with the lasers we will assume that this laser is producing or generating a pure tone at a frequency f 0 with the power of P s ok.

So, this is a complex representation and then we use a Mach-Zehnder interferometric modulator. Now, we have talked about Mach-Zehnder interferometric modulator. And we said that if you recall the transfer function in this way which is given for a Mach-Zehnder modulator. So, this is as a function of the applied signal u of t to the Mach-Zehnder modulator, it has it is a periodic function. The output power to the input power ratio, if you were to plot on the y axis and then as a function of the input voltage, you see that when the input voltage is about V pi the output would have dropped to 0 and then it will be maximum output will be maximum when it is 0 in the input voltage is 0 or it is equal to 2 V pi ok.

If you were to bias Mach-Zehnder modulator at this point which is called as the quadrature point which occurs u of t is equal to V pi by 2. And then have whatever the signal that you want to transmit as a small signal variation around this bias point. Then the output power will be faithful reproduction reasonably faithful reproduction which is centered at this particular power. So, this is about half. So, it will be centered in a normalized scale to about half. And, then any changes that you have applied or any time varying modulation signal that you have applied will be generated at the output ok.

And, this type of modulation as we have emphasized many times is called as a amplitude modulation and it is one of the classes of what is traditionally called as continuous wave or traditional called as linear modulation or analogue modulation technique ok. But we are not interested in this analogue modulation technique, but what we are interested in a digital modulation technique. For the digital modulation technique we need to determine what kind modulation that we are going to do. For example, if you want to only very the intensity as a function of the input data sequence ok. We will assume that the input data sequence of the binary sequence is actually given by a sequence of 0 1 1 1 whatever that is right.

So, it is actually a sequence which consists only of 0's and 1's arranged in this one of course, these sequences occur every T second so, which means that each modulation period or each data symbol period is about T seconds. And, because one symbol if occurring at every T seconds the symbol rate or the bit rate in this particular case will be equal to 1 by T ok. So, this will be usually measured in bits per second for optical communication systems that employs this modulation technique. The bit rate is typically from 10 Gbps to 40 Gbps, where Gbps stand for Gigabits per second. So, it is a reasonably large data rate, but as we will see later on even this data rate is small compared to the current data rates of a single channel system, that is actually implemented today ok.

So, these symbols occur every T seconds and what will to do is to associate 2 levels of optical power to each of these bits. So, to for this 0 bit; we may associate a maximum optical power or we may associate minimum optical power, minimum optical power being approximately equal to 0. The ratio of max power in this system to the maximum (Refer Time: 05:40) transmitted power to the minimum transmitted power which would correspond to either 1 power 0 ok is called as extinction ratio and you want this extinction ratio to be as high as possible ok. And extinction ratio is usually defined in terms of its dB values which is given by extinction ratio in dB; is given by 10 log of P max to P min ok. Ideally the extinction ratio will be infinite because P min will be exactly equal to 0, now whether you associate P max to 0 or P min to is up to you ok. Traditionally we associate P min to 0 and then we associate P max to 1.

So, if you want to so, now when you send out this data which is 0 and 1 you want the output power to fluctuate between 2 values which is P max and P min. Now how do we go about implementing that system? One way would be to bias the modulator at V pi. So, when you have a bit 0 so, let us say this is a bit 0 over whatever the duration T seconds that we have; since the modulator is bios and input voltage is 0 the output voltage will also be equal to 0. And so, the output voltage will be 0 in this particular case and it is going to mirror whatever the input data that could be looking like.

So, this is 0 to 0 mapping in practice this will not be exactly (Refer Time: 07:07) output power will not be exactly 0. So, the extinction ratio is not going to be infinite, but it will be less than some quantity, but still reasonably high. So, that we do not really have to worry about this extension ratio in most of our practical systems ok. Now when you want to transmit a bit 1 that what you do is you apply a voltage pulse or u of t pulse with a maximum value of V pi ok. So, your input is actually switching between V pi to 2 V pi, which is 1 way of implementing this binary modulation on to this one and we can see when the output voltage amplitude is 2 V pi not V pi it is output voltage output voltage amplitude is 2 V pi then the output power will also be maximum.

So, it would be half, but it would be maximum finite extension ratio means you are going to reduce the amplitude here. So, instead of going all the way up to 2 V pi obtain the maximum. If you want to just go to this height you know you apply an amplitude which is lesser than V pi or two V pi then you will be seeing an output which would be lesser. So, now the ratio of P max to P min in this case of course, it is still infinite because for 0; we are assuming that we actually have 0 output power. But, in practice as I told you this is slightly about 0 and therefore, the extinction ratio is smaller for this blue case compared to the extinction ratio for the red case ok.

So, this is one way of modulating, the disadvantage of this one is that your input u of t must have a dc value which is reasonably high in this case because; when you want to transmit bit 0 u of t should be bias at V pi and when you want to transmit 1 you want your u of t to be equal to 2 V pi. So, what you can do is you can instead of working this way you can full down this u of t down to 0 and then have a max change of up to V pi ok. So, how would that goes to this is 0 this is 1 which goes up to V pi and then be back.

So, DC content of this waveform is actually smaller compared to the DC content of the previous biasing scheme, but in this biasing scheme the natural choice would be that a 0 at the voltage u of t will actually produce 1 at the output and 1 at the input would produce 0 at the output. But, if you were to make this logical connection of interchanging what you call as 0 and 1 and you do not worry about how u of t is going to be mapping to that output and you simply call what we get here as 1 and 0, then it will be all right. I mean this is after all some connection abstract connection that we are making at our end.

So, this is how you can actually generate what is called as on off keying; why is it called on off keying because; either the laser output is on which means that it is transmitting some output power or the transmitter is off which means actually giving out 0 power.

So, this is exactly what we call as on off keying and this is modulation scheme in which the input data happens to be binary or a bit sequence. Now, after modulation what we do is we actually put this one through the fiber depending on the distance between the transmitter and receiver your fiber may have multiple spans; span being the length of the fiber before you put in the inline optical amplifier. And I have put this cross to the power N here as you can see and this cross to the power N indicates that there N such reputation of this span.

So, this entire thing is 1 span and the optical amplifier that we put in here will be the erbium doped fiber amplifier for which we talked about in the earlier module. And erbium doped fiber amplifier will have its gain exactly equal to the loss of the fiber. So, the input signal which is whatever is launched here will start to decay because, of that attenuation in the fiber and then as it approaches the input optical meaning line of optical amplifier. And after it passes through the inline optical amplifier output would be pulled back to its original position.

So, you can see that it would go back to original position and thereafter of course, it will again decrease because of the fiber that is kept also please remember the fiber is roughly about 80 to 100 kilometer in 1 span and the inline optical amplifier is just about 10 meters. So, as far as the span is concerned the inline amplifier in just 1 lumped element which is which has negligible special content compared to the amplifier. So, now, we have propagate this optical pulses of course, this optical pulses are not going to stay in their time slot what will happen is because of the inevitable dispersion this optical pulses will start to mix each other or rather broaden and then interact with each other; so, that the outside would essentially have lot of dispersion.

So, and because of dispersion you will have what is called as inter symbol interference and you want to compensate this inter symbol interference. Now, that can be done at the output and that is at the receiver side or it can be done by placing strategic amplifiers sorry strategic fibers called as fibers strategically place. And this fibers are called as dispersion compensating fibers. The only condition that you normally want to satisfy is that if the forward fiber has dispersion coefficient of D 1 and has a length of L 1 then this should be equal to D 2 times L 2, where D 2 is the dispersion coefficient of the dispersion compensating fiber, but its fine will be opposite of D 1. And, then L two is the length of a dispersion compensating fiber and one is the length of the forward fiber that is used.

So, this is how a typical span would look like; for most legacy systems, most legacy systems employs DCF to compensate dispersion. So, that when you receive the optical pulses at the receiver side where is almost zero ISI they will still be some ISI; because of the last span which is not being compensated, but that is usually too small for us to worry really about that. So, you can imagine or you can take it that the input optical pulses that are received at the receiver will be almost highest ISI. Now, you have this optical pulses of course, what would have happened in addition would be that each of these amplifiers would have given out some amount of noise that is added some noise to the input. And, the signal that you received will be noisy version of the input signal that has been transmitted.

So, if the binary data whatever that you are transmitted the optical pulses that you receive here will be noisy. And, further even you convert this optical signal into electrical signal by putting up of photo detector, the output would have output of photo detector would have been additional noise which comes from couple of sources. One source is the load resistor that we keep and the load resistor will have its thermal noise which we have talked about. And, there will also be what is called as shot noise because of the fluctuations of the source itself I and R the fluctuations in the way this semiconductor photodiodes actually work.

So, you have short noise you have thermal noise and then there will also circuit noise which comes by putting upper filter in after the photo detector. But, in this course will not worry about the circuit noise because that is a subject of entirely of its own which is very deep subject we will not go to text that one, but we will assume that the signal that comes out the electrical signal that comes out of the photo detector will have additional noise in addition to whatever the noise that the inline optical amplifiers are added we were all. There is a important difference that is rate to observe here, the optical amplifiers would have added noise in the optical domain, but you will not be looking at the optical domain directly.

So, you will be looking at the optical domain only with the help of a photo detector. So, when you convert that optical are the noise which is signal plus noise in the optical domain back into the electrical domain you will be seeing that signal plus noise which is both in the optical domain. So, let me call this. as the S o and N o, o standing for the optical domain. When you convert this one into the electrical domain by putting up of photo detector what your actually seeing is the magnitude square of this rather you would be seen the magnitude square and the average of this month.

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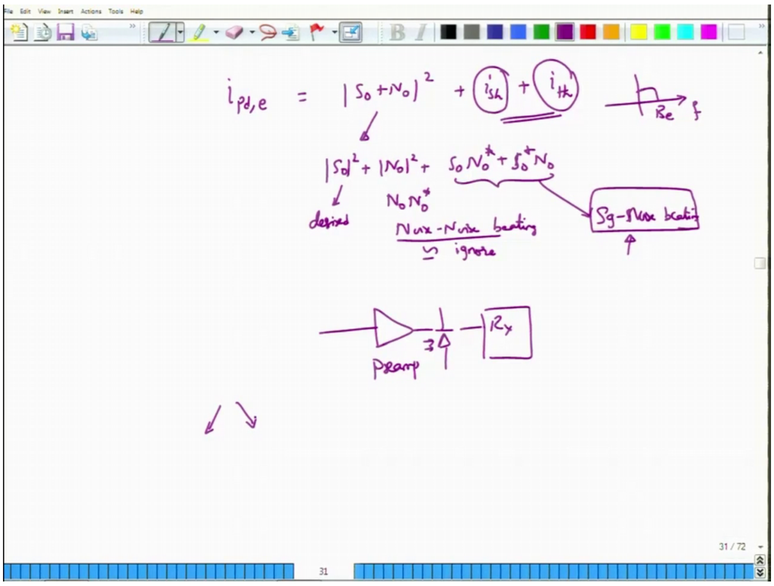

$$i_{pd,e} = |S_0 + N_0|^2 + \boxed{i_{sh}} + \boxed{i_{th}}$$

$$|S_0|^2 + |N_0|^2 + \underbrace{S_0 N_0^* + S_0^* N_0}$$

$$N_0 N_0^*$$

So, what you get from the photo detector output. So, photo detector output which would be electrical would be signal, plus noise plus whatever the additional noise that the photo detector would provide plus the thermal noise that you are going to get because of the register that has been employed (Refer Time: 15:55) that has been employed ok. All of this must occur in electrical bandwidth of about B e which is the bandwidth the single sided bandwidth of filter that we have kept ok. So, this entire noise must be accounted over the bandwidth of B e because, that is where the signal of interest is kept and the filter actually cuts of at B e ok. Now you look at this S 0 plus N 0 square and when you expand this out you will get S 0 square plus N 0 square plus S 0 N 0 right.

So, if S 0 and N 0 are complex then you will get S 0 N 0 conjugate plus S 0 conjugate N 0 right. So, you are going to this 3 terms, this is your desired signal because this is the output photo current is proportional to the power anyways. So, and this is the input power the optical power which comes from the desired data or by the actual launch signal. So, this is my desire optical power ok, but to this optical power I have this term which is N 0 square which can be thought of as N 0, N 0 conjugate and this is called as noise to noise beating ok.

The noise spectrum beats with itself to generate this additional noise called as noise to noise beating and usually this is quite small that we can ignore. The actual statistics of this noise to noise beating depends on the kind of filter receiver filter that we have employed and whether we have amplifier it before and if the amplifier is there: what is the characteristic of the amplifier itself. So, it depends on mainly on the inline optical amplifier for at least the pre amplifier that we are going to place we have not talked about it yet, but you can assume or you can kind of now idea get an idea that noise itself will beat with itself because of this square law demodulation that we are doing or rather square law detector that we are doing. Then there are these two additional terms these additional terms will of course, be something like two times real part of S 0 N not conjugate are called as signal and noise beating.

Usually if you place a pre amplifier so, this preamplifier would be at the receiver frontend and follow this preamplifier with the photo detector and whatever the received filter that you have. This preamplifier will be responsible to generate most of the signal noise beating and noise beating which any way we are can still ignore to the major without affecting the output very much. So, but you cannot ignore the signal to noise beating and because of the signal to noise beating you can in fact, ignore the short noise and the thermal noise ok. So, whenever you employer preamplifier you can ignore the short noise and the thermal noise that is given by the or that is the result of being the short noise in the photo detector. And, the source as well as the thermal noise because of the (Refer Time: 18:52) you can ignore these two affects because, you have a signal to noise beating because of the pre amplifier.

So, that would be the dominant noise source in all of your pre amplifier based direct detection receivers ok. So, whether we you we have a preamplifier or not depends on the kind of application that you have for most long haul application we almost always use a preamplifier and this preamplifier has a noise which is which contributed dominant noise which is the signal to noise beating ok. Now we will analyze are on off key in system in 2 cases 1 without preamplifier 1 with preamplifier because, the noise statistics with preamplifier without preamplifier are different they are radically different. So, we will see what these differences are.

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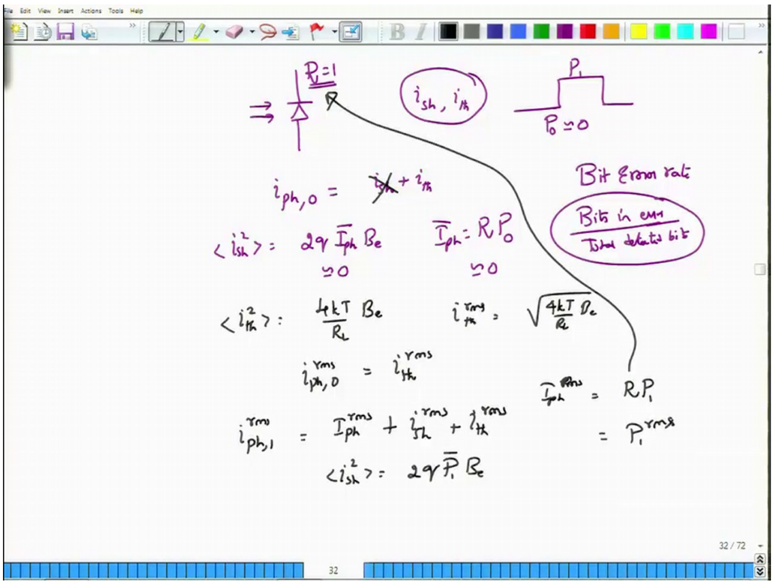

$R = 1$

i_{sh}, i_{th}

P_1

$P_0 \simeq 0$

Bit Error rate

$\frac{\text{Bits in error}}{\text{Total detected bit}}$

$$i_{ph,0} = \cancel{i_{sh}} + i_{th}$$

$$\langle i_{sh}^2 \rangle = 2q \bar{I}_{ph} B_e \simeq 0 \qquad \bar{I}_{ph} = R P_0 \simeq 0$$

$$\langle i_{th}^2 \rangle = \frac{4kT}{R_L} B_e \qquad i_{th}^{rms} = \sqrt{\frac{4kT}{R_L} B_e}$$

$$i_{ph,0}^{rms} = i_{th}^{rms}$$

$$\bar{I}_{ph}^{rms} = R P_1 = P_1^{rms}$$

$$i_{ph,1}^{rms} = I_{ph}^{rms} + i_{sh}^{rms} + i_{th}^{rms}$$

$$\langle i_{sh}^2 \rangle = 2q \bar{P}_1 B_e$$

So, first consider the case of no preamplifier you have a photo detector out there. So, the short noise and thermal noise are the only noises that come and the total photo detector output; I am writing the shorter I here to indicate that this is actually the time varying signal ok. So, this time varying photo current will be whatever the input files that has been launched. Now, if you achieve a infinite extinction ratio then P 0 that is power that is launched when bit is 0 is almost 0 whereas, power when you launch a bit 1 will be which we will P 1 will be whatever the maximum value of that that you have used ok. So, P 0 is approximately 0 P 1 can be reasonably large that is sufficient. So, you need to worry about how small P 1 can be above P 0, but that consideration has to come from observing whatever the total noise in the system ok, we will talk about that.

So, we will quantify the performance of these systems by what is called as bit error rate, which is term that we use to characterize digital communication systems which essentially gives you the ratio of bits in error to the total detected bits. Some bits may not be detected, but to the total detected bits whatever the bits that are there in error write will determine the bit error rate ok. So, this is in fact, not error rate, but rather error ratio, but the term bit error rate is usually used in this sense. So, do not worry about the bit error ratio or bit error rate. They both essentially mean the same as the traditional usage goes ok. So, now you look at the output photo current output photocurrent would; obviously, have we will also make an additional assumption that R is equal to 1 where R is the responsivity of the photodiode otherwise the input current has to be or the photo current has to be reduced by that amount that we use for R less than 1 ok.

So, to simplify the map you will use R equal to 1 and the output photocurrent would therefore, b of 2 types rights. So, when you launch a bit 0 or when you send in a bit 0 you have i p h 0. This is my notation to tell you that the bit that I am received is obtained are the current that obtain the through the photo detector is whenever launched bit 0 and this will be i s h plus it h. What is i s h variance? i s h is a 0 mean process or assume to be zero mean and the i s h square or this is a variance of the short noise which will actually be given by 2 q the average photo detector i p h times B e, B e being the electrical bandwidth at we are implying. So, clearly sorry of course, when the photo current I ph itself will be equal to R times P whatever that we have launched. If we have launched with 0 this would be RP 0 which is approximately equal to 0 so, which means that the short noise also can be neglected.

So, it is interesting that the short noise does not occur when you launch very low optical powers or when you send out the bit 0. So, you can ignore short noise here and thermal noise is the current noise who is variance is given by 4 k T by R L over the same bandwidth B e. And, this thermal noise variance will be present or the thermal noise will be present regardless of what bit you have transmitted. If you transmitted 0 or you transmitted 1 it does not matter the thermal noise will always B e present because that is independent of the beat that is transmitted. So, to summarize i p h 0 the photo current that is generated when you launch a bit 0 is purely because, of the thermal noise. The rms value of the thermal noise is given by square root of 4 kT by R L times B e ok. So, this you need to remember. So, what you will get in the rms value if you are looking at will be the rms thermal noise ok. When you launch bit 1; so i ph 1 rms that you would receive will be both because of the photo current that has been launched.

So, you have I ph rms where I ph rms corresponds to the signal to I mean the rms value of the input signals. So, which is R P 1 says R is equal to 1 so, this would be P 1 the value of rms ok. So, you can write this is rms you can just write it in terms of the value peak values. It is all up to you how you would like to proceed, but I am just writing them down to indicate that we are looking at rms values ok. Then to this you need to have short noise again I am writing rms value here; and then you have thermal noise. Short noise in this case will be non-zero because, short noise variance for this case will be 2 q

P 1 the average value of P 1 that you have received times B e, again please remember R is equal to 1. So, all of these calculations that we are considering R is equal to 1. So, this is what the 2 photo currents that you are going to receive when you launcher bit 0 and a bit 1.

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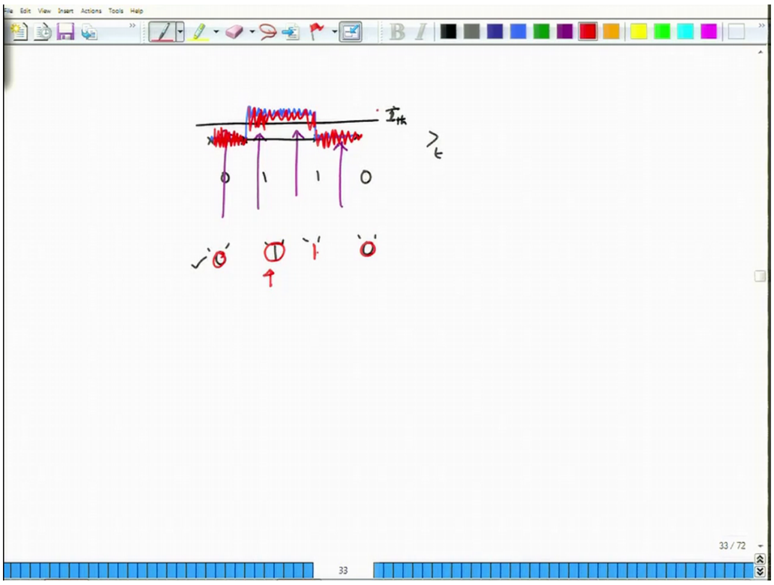

So, if you observe a sequence of pulses. So, you may actually have launched 0 1. So, let us assume so we have launched a 0 1 1 and 0 ok. So, there the 4 bits that we have launched and what is the received R current that you would see that there will be some amount of noise. So, notice that the photo current is almost 0 when you launch bit 0, but then when you go to bit 1 depending. So, this height here depends on whatever the power P 1 that we have used. So, if you used visibly large value of P 1 then this height will be large, but there will also be increased noise because you have higher value of P 1 which means that short noise will also increase. Now, on top of shortness you have thermal noise right again you are you will still have a short I mean you have a bit 1 here.

Because so, this is what you had; now when you to go back to being bit 0 you will have only thermal noise. But, this is the case which is actually very good you know that is the system is actually very good because, what you can do is you can put up a threshold here call this threshold as I t h and put a capital I over there. And, this threshold is constant all the line that have drawn does not really show a constant. And what you now do is to sample the signal at the midpoints of the symbols. So, you sample the signals at the midpoints, this midpoint was actually a 2 slots. So, this is 1 slot and this is 1 slot, you sample this signals here. What do you get after sampling?

So, what you get is this is the I threshold. Now, if you look at the sample current here, the sample value is actually quite small compared to the threshold value. So, you can the assume that the input that has been transmitted, the data that is transmitted was actually bit 0. Here the sample values above threshold, next time also the sample also above threshold. Here the sample values below threshold therefore, you can put the received symbols as 0 1 1 0 and in this case you manage to detect every bit and you detected every bit without any error here ok. Now you can make errors in various ways, one when the noise actually gets too large. So, for example, if this is your thermal noise and then to this if you add lot of short noise as well and then you have this lot of thermal noise up there; for 0 you still are not receiving any error. So, 0 is alright 1 instead of 1 because, when you now sample here or maybe you know the noise level was not exactly like this. So, let us say noise level is like this. the sample value actually becomes less than 1.

So, you know revise your big decision instead of 1 to 0 and here the noise was ok, but it was not so, large therefore, this bit was still 1 this was 0 0 1 and the other last output could have also 0. So, now you manage to detect all 4 bits, but 1 bit was actually in error and this error happened because, of the noise that was present. Now, you can overcome this problem by moving the threshold up. So, you can overcome the problem by moving threshold up, but that again what is the optimum value of the threshold depends on the statistics of the noise itself. We are going to look at couple of expressions and then tell you how the threshold value can be obtained in the next module.

Thank you very much.