Advanced Optical Communications

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Lecture No. # 23

Optical Receivers - II

We have been investigating optical receivers. We saw that in photo detectors, there are various mechanisms, by which the noise is created. For example, there is a shot noise, because of the random fluctuations in the photon flux and the interaction of the photons with the matter. And there is a noise, because of thermal movement of electrons inside the resistor. And then in the last lecture, we saw that because of this noise, we have deterioration in the system performance. And for a digital communication system, we measure the deterioration by parameter, what is called the bit error rate.

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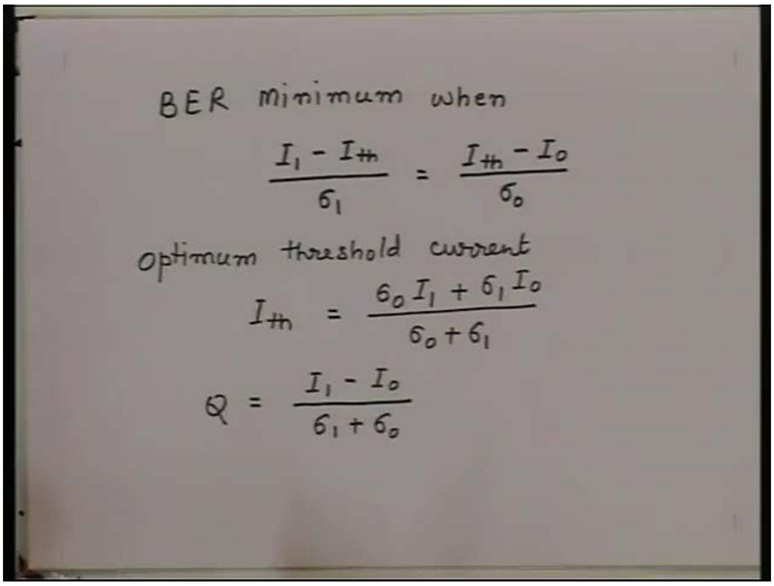

So, we had defined a quantity what is called the Q of the data, and which we have said is defined by this; where I 1 is the photocurrent corresponding to the level 1 of the data, I 0 is the level 0 of the data and sigma 1 and sigma 0 are the standard deviations of the noise, when the level is 1, and when the level is 0. We are also seen that this quantity is related to the noise margin of the data, because I 1 minus I 0 essentially gives you the swing between the two levels, and sigma 1 plus sigma 0 that gives you essential the encroachment in the swing, because of the noise. So, this quantity Q essentially determines the quality of the data, which you measure in terms of the bit error rate. And we have seen that assuming that the noise is distributed in a Gaussian fashion, we can calculate the bit error rate.

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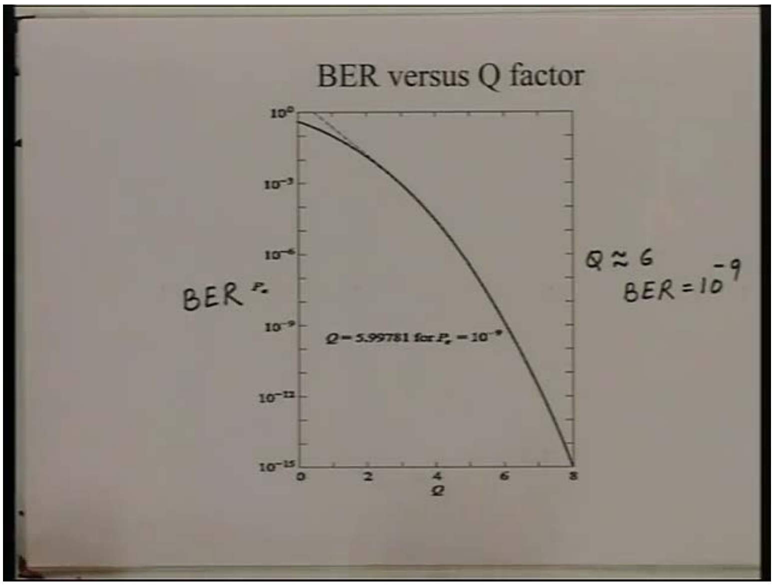

And we saw that if you plot the bit error rate as a function of this parameter Q, then the bit error rate decreases very rapidly as the function of Q. And if you take a standard number for bit error rate which is 10 to the power minus 9, then we require the Q atleast to be 6. So, for a satisfactory performance of a receiver, this parameter Q has to be greater than or equal to 6. Today, essentially we are going to look at the aspects what is called the minimum average power required in the data. We will also talk about what is called the quantum noise of the signal detection. And then we also talk about what is called the eye diagram, which gives you the quality of the data.

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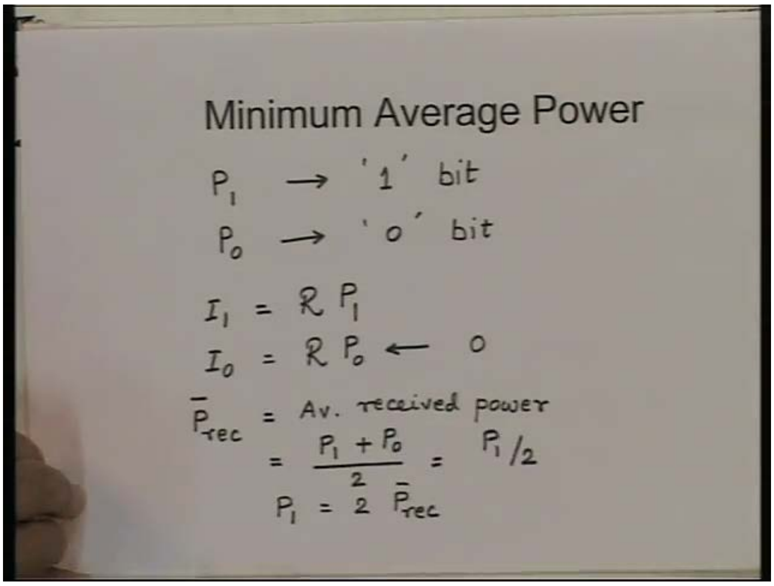

So, essentially what we are doing here is we want to ask if you are getting a random data with a equal probability of 0 and 1, then what is the minimum average power required; because that is what essentially one can measure. one When one is receiving signal from an optical fiber, one can put an optical meter to measure the power which is coming and this is essentially the average power, which you received in the signal. So, without losing generality if we say that corresponding to the 0 level, no power is received and corresponding 1 level, we have a certain power received. Then the average of these two levels essentially gives me the power, which the power meter will measure.

So, let us say to calculate the minimum average power, let us say we have some power received corresponding to 1 level and let us say for 0 level, there is no power received. But without losing generality, let us say some p 0 power is received, when level 0 is received. So, let us say I have power p 1 corresponding to 1 of the bit and I have a power p 0 corresponding to 0 level of the bit and the corresponding currents which you are going to get for these two levels are let us say given by I 1 and I 0. So, we have here I 1 that will be equal to the responsivity of your detector multiplied by this power which is p 1. Similarly, we can have I 0 that will be responsivity of the receiver multiplied by this power p 0 and for a ideal receiver, we are saying that since no power is received during 0 bit, this quantity is 0.

Then one can define the average received power, which your power meter measures which we can call as p bar received. So, this is the average received power and which is the mean value of the two powers which you are receiving. So, that is p 1 plus p 0 upon 2 and in this case, since we are assuming that the power corresponding to 0 level is 0, this quantity is p 1 upon 2. So, that means we have now the p 1 power received is 2 times the average power received, p received. So, we have form here p 1 that is equal to 2 times p average received power. We can calculate the noises corresponding to these levels. So, when we have a 0 bit reception, that time since there is no optical power incident, only thermal noise is present.

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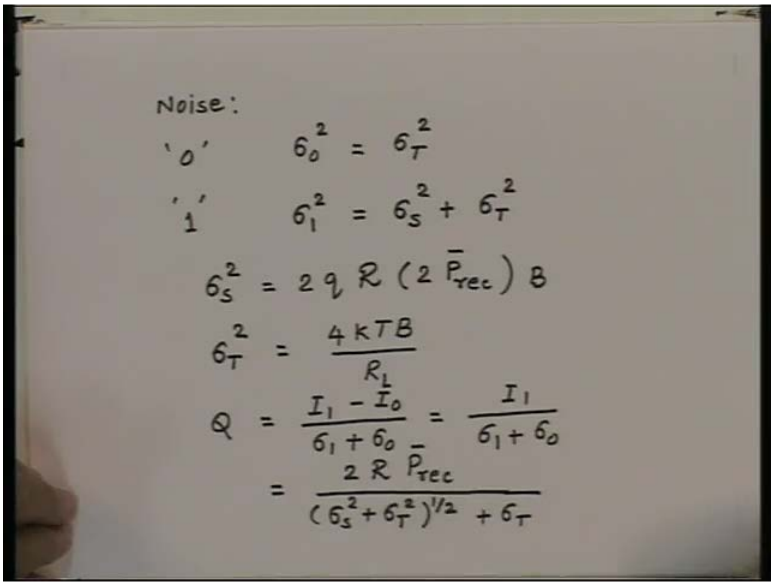

So, we can write down noise. For 0 level, we get the noise variance which is sigma 0 square; that is nothing but equal to sigma T square, which is thermal noise variance. Well in this case, the optical signal is 0. Then for the 1 bit, the variance sigma 1 square; that will be equal to the sum of the variances because of the thermal noise and because of the shot noise. So, essentially this will be equal to the shot noise square plus sigma T square. Ofcourse, depending upon the power level which you are receiving in bit 1, the sigma T may be negligible compared to sigma S or may not be negligible.

So, in general we can write down the variance of level 1; that will be sum of the variances of the shot noise and the thermal noise. And we have seen that this quantity here sigma S square that is given by 2 times q, where q is the the carrier charge into responsivity into p 1. But we have seen that the p 1 now is 2 times this p average received. So, we can say that this is 2 times p average received and the bandwidth of the receiver and as we have seen sigma T square, which is a thermal noise. This is given by 4 KTB divided by R L, where R L is the load resistance connected to the photo detector and K is the Boltzmann constant, T is the temperature.

Once we get these quantities now, so we know these levels (Refer Slide Time: 03:41) I 1, I 0 and I 0 is 0 and we also know this quantity sigma S and sigma T. So, we can now define the quality factor is Q that is equal to I 1 minus I 0 divided by sigma 1 plus sigma 0 and since I 0 is 0, this is essentially I 1 divided by sigma 1 plus sigma 0. Substituting for I 1 and sigma 0 and sigma 1, we get this is 2 times responsivity to p received average divided by sigma 1, which is sigma S square plus sigma T square to the power half plus sigma T. We can reverse this expression to get the received power in terms of this factor Q.

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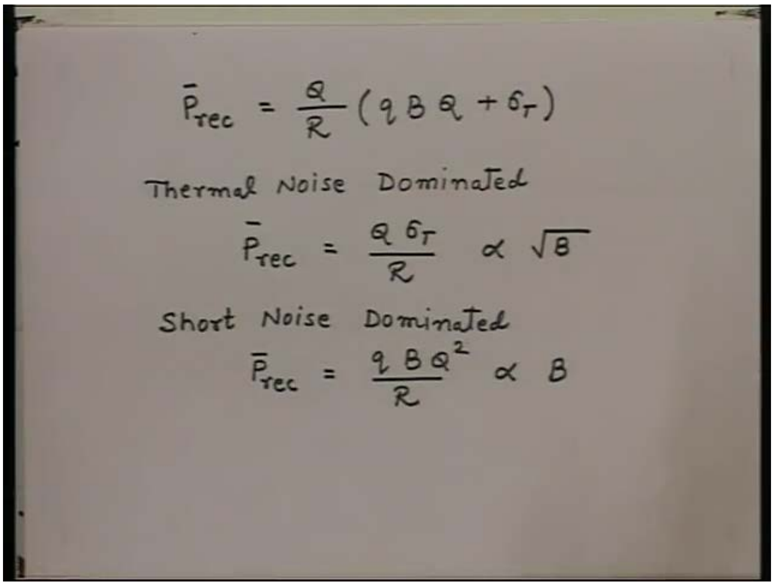

So, we can get this quantity average p received that will be equal to Q divided by the responsivity into q B Q plus sigma T. Note here, in this quantity (Refer Slide Time: 07:01) sigma S square when we are talking about, we are already having a p received. Say, essentially you have to solve for p received and that is what we have done to get this quantity p received. So, now we are having the p received, which is expressed in terms of this parameter which is k and we have seen for the acceptable bit error rate, the Q has to be greater than 6. So, now we can substitute the value of Q. But essentially we can calculate what is the minimum average power required in the data to achieve the required bit error rate.

That is ofcourse we can do depending upon the parameters, one can do the quantitative calculation. But the thing which we see from this expression, the interesting thing is that now as we saw in the last lecture, we can have the two regimes. One regime which we call as the thermal noise dominated regime; that means, if the optical power is not very high, then the shot noise is negligible compared to the thermal noise. And then we say that this regime is the thermal noise dominated regime. In second case, when the optical power is significantly high and the variance of the shot noise is much larger compared to the variance of the thermal noise, then thermal noise can be neglected and then we can say that regime is the shot noise limited regime.

So, same thing we can do here. So, in this case if we take the thermal noise dominated regime, (No audio from 12:50 to 13:00) then we can this quantity now is very small. So, we are assuming only thermal noise, which is present there. So, we can calculate the minimum p received p r e c; that is equal to Q into sigma T divided by responsivity R. And by substituting for sigma T which is (Refer Slide Time: 07:01) proportional to square root of B, essentially we can get the p r e c which is proportional to square root of the bandwidth. And since the bandwidth is directly proportional to the data rate, essentially what we are saying is that in the thermal noise dominated regime; as the data rate increases, the minimum power required to achieve the required bit error rate has to be increased and the increase in that power is proportional to square root of the bandwidth.

So, the requirement of the power increases. But it is not very rapid; because it is going to increase as the square root of the bandwidth. So, if you are having a optical communication system and if the signal has travelled over a significantly long distance, so that the detected power is much smaller compared to the thermal noise contribution. Then we can make this approximation that now the regime is thermal noise dominated regime. And in that situation for long link, the minimum required power to achieve a given bit error rate would scale as square root of the data rate or the bandwidth. Whereas if you go to other extreme, where the receiver is reasonably close to the transmitter and in that case, there is no significant attenuation of the optical signal in the optical fiber.

Then the power which is detected by the optical receiver is relatively large and in that case, we may get the shot noise which may not be negligible compared to the thermal noise and in that case, this regime will be applicable. So, we have the second limit which will be shot noise dominated and in this case, this term is negligible now. So, we can get this quantity. So, which is p received that is equal to a q B Q square divided by the responsivity R. So, what do you find this case now that the p received for a given value of Q is proportional to the bandwidth; this quantity now is proportional to bandwidth. So, for the low optical powers, the minimum required power scales as square root of the bandwidth.

Whereas, if the optical power is large, then the minimum required power will scale proportional to the bandwidth; that means as the bandwidth increases, you have to increase the power in the same proportion to achieve the same bit error rate. So, infact what this analysis is telling you is that when the different data rates are transmitted on the optical communication system. Depending upon the separation between the transmitter and the receiver, the minimum required power scaling will vary as a function of bandwidth. So, for the receivers which are separated by a large distance from the transmitter, the minimum required power will scale as square root of bandwidth.

Whereas, if the receiver is nearby to the transmitter, then there is a good possibility that now the shot noise will dominate. And in that case, the minimum required power will scale as the bandwidth. So, infact in this case, now what is happening is that the power which is to be transmitted and the bandwidth they are related now. So, we cannot arbitrary increase the bandwidth without increasing corresponding power. Otherwise, we will not get the required bit error rate or the system performance. Now, one can ask a question that if we had designed a receiver the best possible receiver; that means, if it makes a receiver where thermal noise is negligibly small and whatever noise is going to be there is going to be purely because of only the photon fluctuation.

Then what kind of minimum power I require or minimum number of photons we require per bit to get a required bit error rate. So, this is the ultimate performance on the limit one can get on the optical receiver that it in the absence of any external noise. That is the noise created by the amplifier or by the registers; that is thermal noise just because of the intrinsic nature of the photons, which is statistical. What is the minimum number of average photons required per bit to achieve a required bit error rate and that limit is what is called the quantum limit of detection. So, idea here is as follows.

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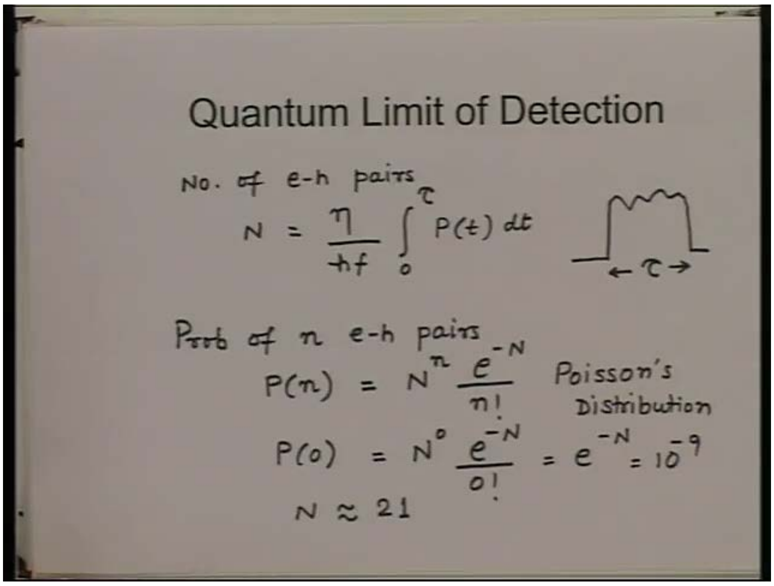

We simply now take the statistics of the photon in to consideration and that is the poisson statistics. And then you ask that if the thermal noise was not present, then what is the average number of photons required? So, that there is no bit error. So, since we are assuming now that the thermal noise is completely absent; when 0 level is transmitted, no power is transmitted optically; also there is no thermal noise present. So, no power was transmitted; no power is received. So, there is no possibility of having now error in detection of the 0 level. However if certain power is transmitted by the transmitter; but no power is received and in this case, we are saying since thermal noise is absent even if one photon was received during the bit 1, then we say the bit is detected.

Because now there is no error in detection of 0; that means if no photon is detected, we say that level is 0. So, even if one photon was detected in 1 bit, then we say that the bit is present. That means, now what we are saying is if some average number of photons are transmitted per bit, what is the probability that not even one photon is received during 1 bit duration. Because if that happens, then the 1 bit will not be detected as 1 bit; it will be detected as 0 and then we will have a bit error. So, in this case when we are assuming there is no thermal noise present in to the system, there is no bit error corresponding to 0 level and there is a bit error corresponding to only 1 level. So, now let us say we have a power transmitted during 1 bit and as we have seen the power might fluctuate as a function of time during the 1 bit.

So, we can say that if some p(t) power was transmitted during 1 bit, the number of electron hole pairs generated N that is equal to some parameter which we call quantum efficiency divided by energy of one photon, which is h into f; where f is the frequency of the photon and to integrate the power over the bit duration, which is 0 to tau. And this is the power which you are getting as a function of time during the bit. So, we are assuming in general, the bit is not necessarily rectangular which you may have some variation like this and that is what is represented by 1 level. So, if you integrate now, the power over this duration tau of the bit that gives us the total energy in this bit.

You divide by the energy of one photon that gives you number of photons, which are received by the detector and multiplied by the quantum efficiency that gives you the number of electron hole pairs generated. Now, as we have seen that this quantity N is essentially telling you the average number of electron hole pairs, which will be generated during this time; that is because the photon flux has random fluctuations. The photon arrival process itself is the statistical process and as you have seen that this process is the poisson process. So, now one can ask a question that if on average N photons were received by the detector or was supposed to be received by the detector, what is the probability that not even a single photon is detected by the receiver?

Because if that happens as we said, there will be bit error in detection of the bit 1.So, the probability function for the poisson distribution is given as… see I have a probability of n small n e-h pairs generated during certain time. Let us say that is given by p(n) that is given by the poisson distribution, which is N to the power n e to the power minus N divided by factorial n. This is the poisson process. So, now as we said that the 1 level will not be detected as 1 level, if no photon is received during this time. Even if one photon is received, you will declare the bit is present. That means the bit error will be committed, only when no photon is received during a given time period for the bit.

So, now we can ask a question what is the probability that when n average photons were supposed to be received by the receiver. No photon actually was received; that means n is equal to 0. So, for quantum limit we are saying that what is the probability of receiving 0 photon or no photon in that bit duration; which is p(0) that is equal to N to the power 0 e to the power minus N divided by (( )) which is e to the power minus N. And we have defined a standard that our bit error rate should be less than 10 to the power minus 9 and with this quantity now should be less than 10 to the power minus 9. See if we equate this to 10 to the power minus 9 to the power minus 9, we get this average number of photons which must arrive during 1 bit duration and that will be approximately equal to 21.

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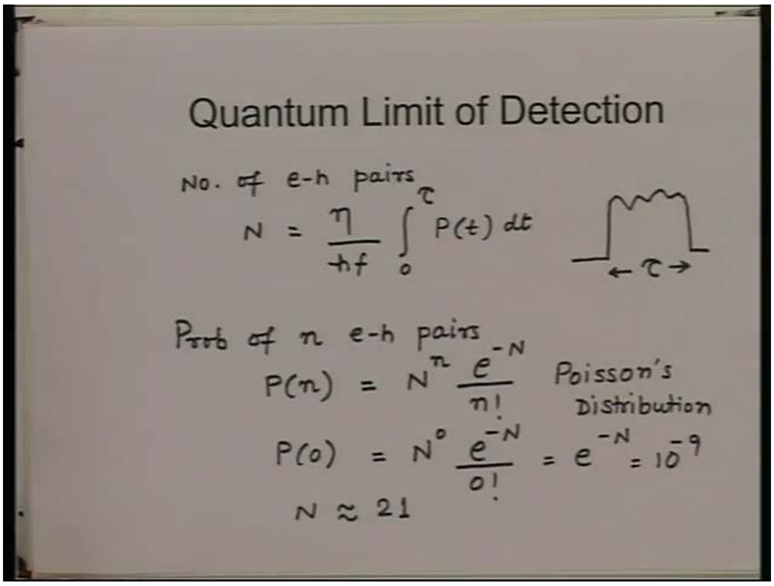

So, what we are essentially saying is that if the thermal noise is absent; if the fluctuations are because of the statistical nature of the photons, then there must be at least 21 photons on average guaranteed per bit. Then there will be a chance one in one billion that no photon will be received during the 1 that bit duration. Of course, in practice we do not work very close to this number; number n is rather large. Typically, it could be of the order of about few hundred to thousand. But this is the ultimate limit which one can get on the receiver performance. So, even if you make the best possible receiver, which does not contribute any additional noise because of the thermal nature.

Even then just because of the statistical nature of the photon arrival, we need to guarantee 21 photons per bit to get a bit error rate of 10 to the power minus 9. And there is a very interesting result; because what then it saying is it is not saying that the average number of photons in the data should be so and so. It is saying that in the bit duration, the number of photon must be equal to 21. Or in other words, as the data rate increases, the bit duration becomes smaller and smaller. And for getting the 21 photons on average during 1 bit period, you get more and more number of photons per second.

Because there are now more and more number of bits are going to be per second, as the data rate increases. So, essentially what we are saying is as the data rate increases, now we are having now proportionality between the number of photons per second and the bandwidth. And that is what we saw in the in this case here that when we are having a shot noise dominated regime and that is what we are talking about. Because in this case, we assume that the thermal noise is practically absent. And in that case, then we get proportionality between the number of photons required and the data rate; number of photon required per second and the data rate.

And number of photons required per second, if you multiply by the energy of the photon, essentially we get the average power which is going to be there in the data. So, this is what is called the quantum limit of detection and for data rate, let us say about 100 megabits per second. The typically the quantum limit would be very very small. It will be typically of the order of about minus 70 dbm or something like that. But in real system, the thermal noise is of the order of about minus 60 dbm. So, normally we do not really go in to the regime of really the quantum limit of detection. But if it happens in future, if you go to make better receivers, then we would be dealing with the quantum limit of the detection.

So, this is one of the important aspects of the detection of the data and the corresponding bit rate. Another aspect which you have for the optical receiver is what is called the inter symbol interference. Now, inside optical receiver as we have seen, there are resistances and capacitances. So, essentially optical receiver behave like a low pass filter; that means if you receive a very sharp transition in the optical signal, your optical detector will not be able to respond to that sharp transition. It will blur the transition; because you have a finite bandwidth and because of that the raise time of the system is limited. Also because of this finite bandwidth in the time domain, we have the repel in the signal.

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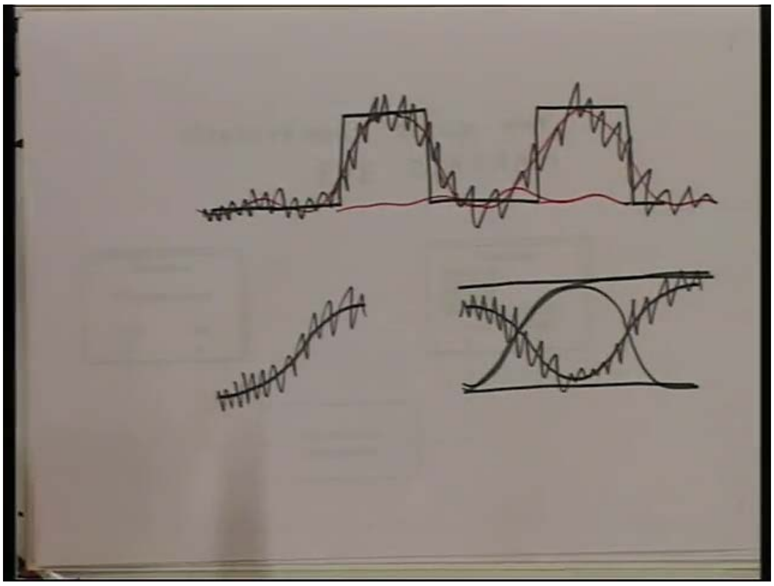

So, what we are saying is if ideally if we had transmitted a pulse optical pulses which are like this and if the bandwidth of the system was infinite, you would have got a current pulse also which would look like that. However because of the finite bandwidth of the receiver, the pulse firstly will get blurred. So, you will get slow transition like that. But in addition to that, you will also see that there is some fluctuation of the signal which is going to be taking place. So, the actual data pulse which we receive is going to typically look like that. Obviously, this signal which ideally should have been 0 now is having these fluctuations.

So, if you have another bit present at this location, this signal is going to superimpose on this. This phenomena is what is called the inter symbol interference. So, we are transmitting this bit and this bit is now going to create interference at another bit, which is separated in time. So, if you are having now the random bits received by the receiver, then we will not get the data which will look as clean as this; but which will be superposition of this. Again, this beta also is going to get distorted in a similar fashion like this. So, essentially we are going to get some fluctuation even at 0 level, which ideally framed in 0 plus some deformed pulses in the data.

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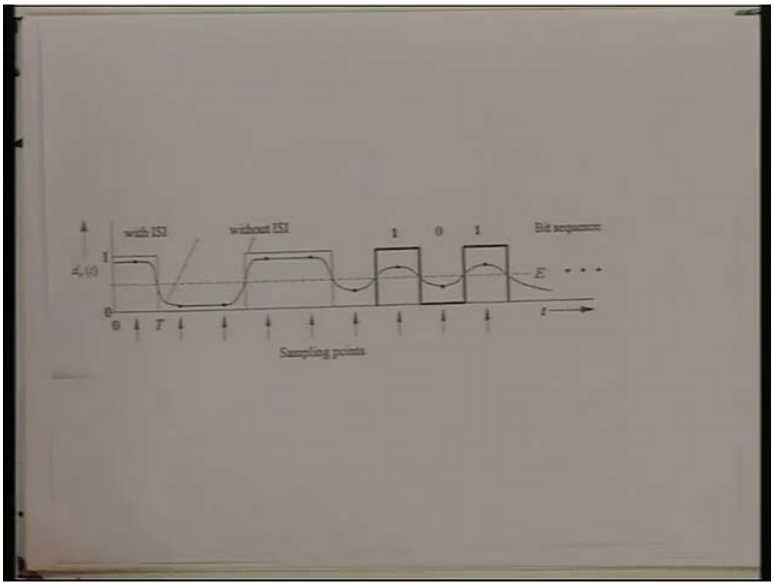

So, when arbitrary data is transmitted, essentially we are having a situation which would typically like that. And now what we are saying is here, we do not really integrate the optical power received inside a pulse. The pulses are converted in to corresponding photocurrent and the corresponding voltages and then you are having the duration or the location in time, where we are expecting a bit. So, what the receiver essentially does is that at that instant of time, it simply checks the value of the voltage or current. If that value is greater than the threshold value, then it declares that the bit is 1. If that value is less than the threshold value, then it declares the bit is 0. So, these are the locations where the samples are tested for the signal level and depending upon the amplitude of the signal at that instant of time, the bit is either declared 0 or the bit is declared 1.

So, now in the presence of this distortion which you are going to get in the pulses; essentially if you are having the pattern, which looks ideally like that. The actual signal which we will receive will be something like this. Say as you can see here, even that 1 level could not be reached; because before it could really rise to this value, the bit is already gone to 0. So, signal start decreasing again. Similarly, before this signal could reach to 0 level again the 1 next bit is coming, so again signal start rising and so on. So, actually signal which we receive from the receiver; that signal essentially will look something like this. So, we want to create now a mechanism. By which, we can measure this distortion which is going to be there in the data. So, let us now consider all possible transitions, which the data can go through.

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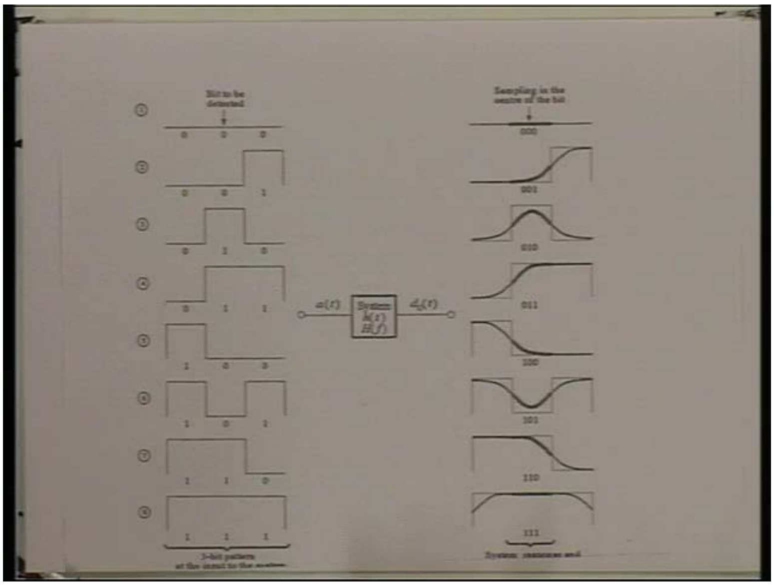

So, let us consider let us say three consecutive bits. So, we have various possibilities either we can have 0 0 0 bit or we can have 0 0 1 bit or we can have 0 1 0 bit or we can have 0 1 1 pattern and so on. So, these are the 8 possibilities, if you consider a pattern of 3 bits. And if this pattern is passed through the optical receiver, then at the output we will get a signal which will look something like this. So, if the bit pattern is 0 0 0, then the level will remain 0 like this. If the bit pattern is 0 0 1, then it will remain 0 here; but then it will start rising. So, you will get a function, which will look like that. If we have a pattern which is 0 1 0, then you will have this edge; then you will have this edge. So, you will get signal which will look like that.

If you are having 1 0 1, then this is 1; this is 1. So, signal will decrease; but before it reaches to 0, again the 1 is come. So, you will get a thing which will look like that. And if you are having pattern which is 1 1 1, then it will remain practically flat on the top of this. So, if you assume that now the data is coming randomly and any of these patterns let us say is present with equal probability in the data, essentially sometime we will have this; sometime we will have this; sometime we will have this and so on. That is what essentially we are going to get. So, if you look at now the data stream in general, it may look something like this.

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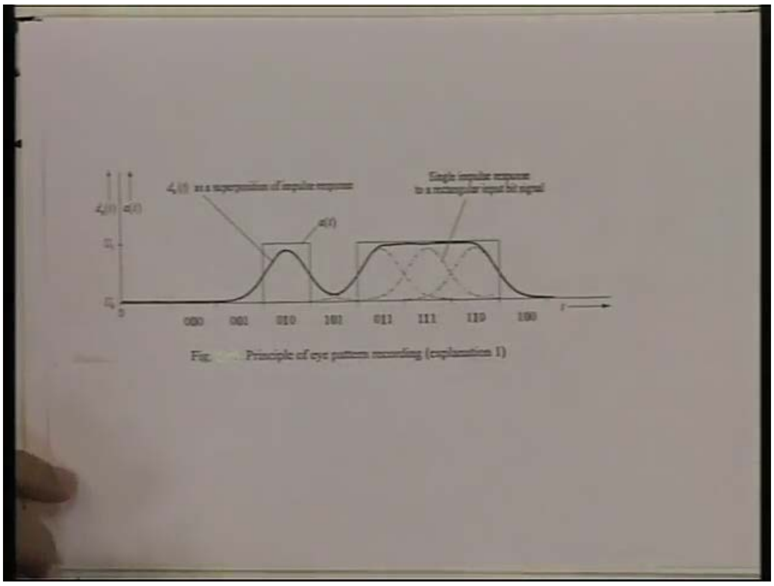

So, here this is the bit pattern which is 0 1 0; this is 1 0 1 and this is 0 1 1; this is 1 1 1; this is 1 0 1. So, actual data which you are received will look something like this and these are the blocks of 3 3 bit patterns. Now, you want to find out the quality of the data; that means, how much distortion has taken place because of the finite bandwidth of the receiver and also due to the presence of noise. So, in this case we saw that the bit is distorted because of the finite bandwidth. (Refer Slide Time: 31:15) But now the bit is going to have additional noise also which is present on this.

So, actually the signal which will go something like that; that is the way the pattern will be received. So, when we are talking about a pattern which looks like that or a pattern which looks like this, the noise also is going to be superimposed on this. And in general, the noise would be a function of the amplitude, if the short noise is playing a role. So, you will have a signal which we receive which will look something like this. So, now to measure the quality of the data, we use the technique what is called the eye diagram of the data and here the idea is as follows.

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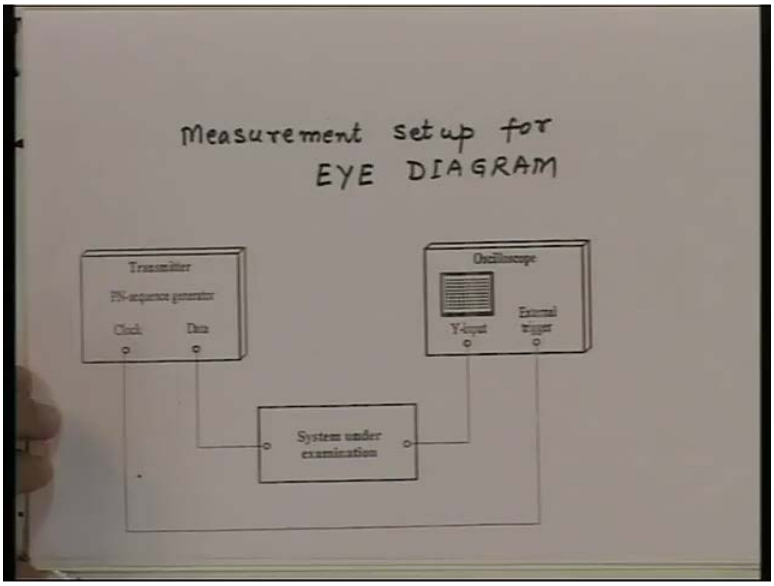

We have a simple setup. So, this is the measurement setup for what is called eye diagram. (No audio from 39:22 to 39:42) So, what we are essentially doing here is that we have a transmitter here, which generates the data in a random sequence. This data is supplied to the optical receiver, which we want to test. The output of this receiver is given to the oscilloscope and the clock with which the data was generated is supplied as a external trigger to the oscilloscope. So, essentially now this data which we are recording on the oscilloscope is synced with the clock of the data. As a result, what will happen now is that (Refer Slide Time: 31:15) we get now the folding of this data over 1 bit period or let us say 3 bit periods.

So, as the data stream is coming, (Refer Slide Time: 37:24) we have this pattern which is there. If the data is synchronized with the clock, we essentially see superposition of all these blocks; this block, this block, this block, this block and so on. So, sometime we have a variation which will be like that; sometime we will have a variation which will be like this; sometime we will have a variation which will be like that; sometime we will have a variation which will be like this; sometime we will have variation which will be like that. So, if we synchronize the oscilloscope with the clock, then essentially we get the output on the oscilloscope which would typically look like that.

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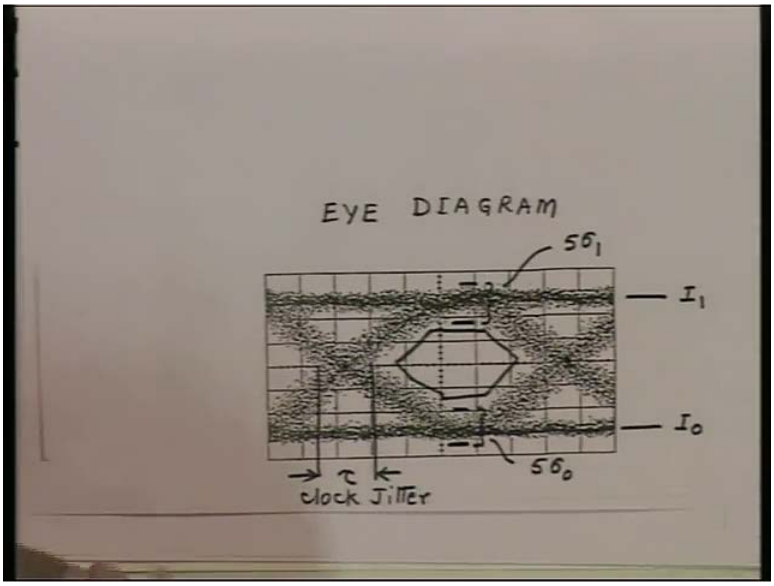

This is what is called the eye diagram of the receiver. (No audio from 41:32 to 41:45) And why it is called eye diagram that if we look at this pattern, it looks similar to the eye and that is the reason this pattern is what is called the eye pattern of the data. Say we saw there, we have all possible transition (Refer Slide Time: 31:15) which are going to take place. So, you may have signal which will be continue like this or you may have a signal which may make a transition this one or we may have a transition which is like this and so on. So, that is what is shown here; that if the data received from the optical receiver and if it is synchronized with the bit, then we get a pattern which will typically look like that.

So, you will have this is the thing which is going from 0 0 1, the pattern will look like that. If I consider 1 1 0, the pattern will look like this; if I consider 0 1 0, pattern will be this; if I consider 1 1 0, 1 0 1 the pattern will be like that and so on. And now this dot which you see here are just the fluctuations in the optical intensity because of the noise which is present there. So, this pattern essentially gives the visual feel for the quality of data. So, now the parameter which you want to extract from the eye diagram is the parameter which essentially can be used for calculating the bit error rate. And we have seen that the bit error rate can be calculated by using a parameter, which is Q which depends upon the difference between the two levels 1 and 0 and also the noises which are present.

Now, if I take the mean value of this level here, this essentially correspond to the level I 1. Similarly, if we consider this level here, this level mean level essentially corresponds to level I 0. So, measuring now the average value of this and average value of this, we can calculate this quantity I 1 minus I 0. Also knowing now the maximum deviation which we get from here to here, we can calculate now the variance of the noise corresponding to level 1. Well if we assume that this distribution is almost Gaussian, then the peak to peak spread will be typically about 5 to 6 sigma. So, if we measure this peak to peak deviation from here, one fifth of that approximately gives the value of sigma 1.

So, measuring now from the oscilloscope the peak to peak deviation, we can calculate the quantity sigma 1. So, we are saying that this quantity here this one, this is approximately equal to 5 times sigma 1. Similarly, if we consider the peak to peak level here this one, would correspond to 5 times sigma 0. So, from the eye diagram, we can calculate this quantity I 1 minus I 0. We can also calculate the quantity which is sigma 1 plus sigma 0. And once I get that, then we can calculate the parameter Q and then we can go to the plot for BER and then calculate what the BER is for this optical receiver. Invariably, what people do essentially is they define some kind of a mask which fits in to this eye diagram.

And they run the receiver for a very long time and this measure how many times the noise has fallen inside this mask and that essentially gives the measure of how good the data quality is. Because ideally it should have remaining noise should not have enclosed in to this region and wider this range, better is the quality of the data; because lesser will be the probability of the better. So, now we see that as the signal to noise ratio which is a essentially the quantity Q. As the signal to noise ratio reduces, this level essentially reduces; I 1 minus I 0 reduces. So, the r starts closing vertically. So, any reduction in the amplitude of the eye or the closing of the eye vertically, reflects the reduction in the signal to noise ratio.

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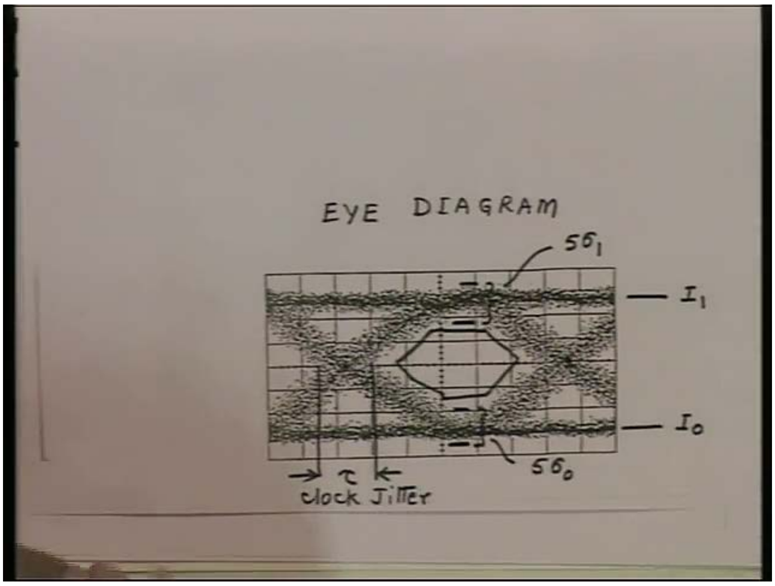

What more the eye diagram gives? We see that since we have synchronized the data with the clock, essentially this period from here to here will be 1 bit duration or 3 bit duration. So, if this clock or the data is coming with absolutely constant clock or on the receiver side when the data is received, we generate the clock from the data. We will see later and then if this clock is perfectly stable, we will see that these points are very steady points. They do not change as a function of time. But suppose there is a small jitter in the clock; that means, the two frequencies of the data and clock are not same, then these points will slightly wander around this point. So, the width which we see in the horizontal direction for the eye diagram; that is the measure of the clock jitter in the data.

So, you can take the deviation this direction and that essentially is what is called the tau, which is the clock jitter. Clock jitter is the random fluctuation of the clock with respect to the data and because of that when we try to sync the data with the clock, this period is not perfectly synced, and because of that we have a random fluctuation in this point. So, essentially eye diagram gives two parameters. One is the signal to noise ratio, which is related to the bit error rate. And also it gives is the clock jitter; because the clock jitter tells me how precise my sampling point should be ideally sampling point should be in the middle. But if the clock jitter increases, then essentially this region becomes wider and because of that, the eye starts closing horizontally.

So, we see the eye diagram essentially gives the quality of the data for signal to noise ratio and vertical closing of the eye indicates the reduction in signal to noise ratio. Whereas, horizontal closing of the eye indicates the clock jitter; and any of these situations when happen inside a receiver, you have essentially performance deterioration. So, eye diagram is one of the very important diagrams. After the system is designed completely and commissioned, essentially one has to perform final test on the data which is what is called the eye diagram. And then only, one can satisfactorily say that there is optical receiver is performing satisfactorily. So, these are certain tests which are conducted on optical receiver and the parameters are extracted to calculate the quantitative parameter what is called the bit error rate.

Now, up till now what we have done is we have assumed the optical receiver to be ideal in the sense that; when we say 0 level, no power is received by the optical receiver. So, there is no what is called the extension ratio is 0; whereas in real data, when we talk about this quantity will not be there. Also the pulses, which we transmit will not be rectangular pulses, they will be deformed because of various factors and that will have a simplication for the bit error rate. So, up till now we have considered the ideal systems. When we meet in the next lecture, essentially we will discuss, what are called the power penalties that means, if the receiver is not ideal, then how much extra power has to be supplied by the transmitter to account for those non idealities in the receiver to achieve the same bit error ratio.