Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – VI
Module – IV
System Design-I

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Hello and welcome to mook on optical communications in this module we will give a brief introduction to system design of optical fiber communication system of course we still do not know much about various components of optical systems and how they will influence the overall system but this attempt of system design which have characterized as system design one.

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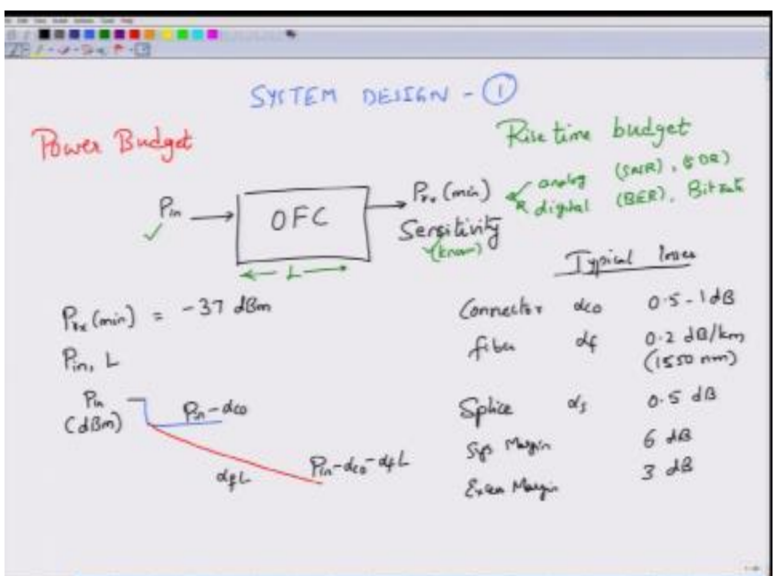

Is to essentially talk about two important effects we will modify the complicity of the problem as and when we talk about other components and other parts of the system throughout the course but for now let me introduce you to two topics which come in system design and whatever we have learned so far is sufficient for us to design a simple working optical fiber communication system okay.

So with that in mind system designers are typically interested in two quantizes one is called as the power budget and the other is called as the rise time budget now power budget in it is very simple sense is essentially budgeting the total power so let us say I have a receiver that usually is fixed having a certain sensitivity, sensitivity in our case can be thought of us what is the minimum optical power that the optical receiver requires so that it can detect optical signals, so if that is assumed to be fixed right then the question that power budget designers are looking at is what would be the minimum transmit power that is required.

So as to cover a given length on the other hand if someone as an ability of the power then one can talk about what would be the maximum length over which we can communicate so these interrelated quantities so you use a larger power you can go longer distance but increasing larger power brings with it is lot of problems which are not considering at this point we will consider them later okay so at for now we can consider that increasing the optical power makes the length of the fiber increase.

Of course it is not just an optical source of fiber and optical receiver that forms an optical communication system there are additional components the optical source would be a laser or an LED for a cheap and a simple and low transmission distance system but for long hole systems it is a laser so you have a laser emitting light this light as to be coupled into the connecter I mean to the fiber okay so there as to be a laser to fiber coupler okay.

And sometimes this comes in up with a package so you have laser diode actually most of the time it comes with the package so you have laser diode emitting light there is a micro lens which focus light on to a pigtail of the fiber so we call this as a fiber pigtail which then completes the laser diode that is say the optical source comes with a laser diode a lens and a fiber we are now connecting that fiber to the modulator or you are connecting that fiber to the actual transmission fiber.

So when you have to connect two fibers you have to use what is called as a connecter we will see some types of connectors later as we talk about them but for now connecters simply means I connect light from one to other okay then I have the transmission fibers through which the signal propagates as we know the fibers give some loss or a rather the fiber induces loss in the signal that is propagating so the power keeps going down at the out end you have to connect again light to the optical receiver where one more connecter.

In between you might have to also do something called as splicing up so splicing means that you are taking two optical fibers but you are not putting them through a connecter but rather fusing their cores together this process is a low loss process and that is used for that is used to couple many other components along the way so the point here is that you star with a transmitter then as you go until the receiver up to the receiver you will see various components you will encounter various components each of those components are going to give loss.

So after the total loss if you calculate what is the total loss then what ever the power that you receive at the receiver will be the power that you have to use in order to recover the data now the question is I have a receiver with a certain sensitivity of course which means that my received power should be at least equal to the receiver sensitivity in many case I cannot operate it with such a constrained.

I actually have to keep my received power at a slightly higher value compare to the sensitivity of the receiver the reason why I have to do this is that many optical components change you know during the course of operation they undergo ageing effects they slowly de-edurate the values drift, so all these things will contribute to additional losses which is the system designer does not think a head then operating it with such zero margin would lead us to a problem, any small change in the optical link will simply mean that the link becomes unusable.

So if you have to cope with reasonable number of values then you have to keep the received power of the slightly higher value compared to the received optical power, in addition to this sometimes the system designer has to take into effect the future upgradability of the optical link, so let us say I want to include an WDM router later on not today but may be once the traffic increases.

Then I want to include a WDM router may be I also want to include a WDM multiplexer may be a De-multiplexer may be a filter so I can include all these components but each of these components that I include in the link will give rise to more losses, so if I do not plan ahead so what are these losses that might happen for the future upgrade then I will not be able to use the link later on. So power budget is a very simple task seems to be a very simple task okay but it involves lot of intricate details, okay. For now we will consider a simplified power budget analysis, what we do is.

We assume that the goal of us is to either calculate. What is a minimum launch power or T_{in} as we will denote that one and also calculate what would be the length of the fiber, okay. So the receiver minimum sensitivity is something that is known this is mostly determined by whether we are looking at the analog transmission or digital transmission if it is digital transmission we are looking at what bit error rate we are operating in, okay. The lower the bit error rate the sensitivity actually goes up.

So if you want an operation at 10^{-9} the receiver sensitivity might be around -37dbm okay for a given bit rate, however if I want to operate with a bit error rate of 10^{-12} then my received power actually goes up, in other words the minimum received optical power goes up, okay. So it is a quantity that depends on the what BR is required, it also depends on what is the bit rate of the system, okay.

For now we will not worry about who calculate the sensitivity we will simply assume that this is known to us, okay. So this is known to us and we are going to work with this sensitivity now for analog the performance is characterized in terms of the single to noise ratio or sometimes it is characterized by the signal to distortion ratio, okay. But we are not going to consider analog systems at this point.

We will simply concentrate on digital optical links, okay. Now here in this table I have shown couple of optical elements okay we have a connector whose loss in dB is actually a range of 0.5 to 1 dB, 1dB is typical 0.5 dB is with very good connectors, fiber losses at 1550 nm this again is a variable for the system designer you have to choose which wavelength window that you are going to operate.

So that loss is 0.2dB/km the splice loss as I mentioned will be around 0.5 dB for each splice so if you increase a number of splices then the total splice loss also goes up, now what is a power budget, right So in addition to this we might also write down what would be the system margin which is the upgrade margin that you are looking for, let us call this as about 6dB okay and let us also call this excess margin.

Which incorporates system link failures, ageing, drift all these problems which induce losses so let us call this excess margin as 3dB, now the question is pick a value of P_{in} and pick a value of L such that you are able to operate this particular digital link, okay. So in order to do that one I need to tell you what is the sensitivity of the receiver assume that for a 10^{-9} BER that we are looking for the receiver sensitivity is -37DBM, okay.

And then you have all this other margins given what you have to find out is P_{in} as well as L, how would the loss vary, graphically you can say that at this point I am starting with some launch power P_{in} which I will measure in DBM, remember losses are better talked about in DB scale rather than in the linear scale, so let us say I convert whatever the input launch power in the linear scale in the watts, mille watts to DBM. And I start with that, the first loss that I encounter will be the connector loss, correct? So I will first encounter the connector loss therefore the power at this point would drop from P_{in} to $P_{in} – \alpha_{co.}$ So this is the launch power into the fiber but it has to be connected this launch power coming from the transmitter has to be connected to the fiber by a connector so connector will induce a loss of αco so the power drops to Pin-αc0. At this point the power actually starts decaying because the fiber introduces a loss and at the end of the transmission over a length l the total loss in the fiber is $\alpha_f(L)$.

Therefore, the power at this point will be Pin-αco-α_fL α_f is measured in dp per kilo meter and L is measured in kilo meter, okay.

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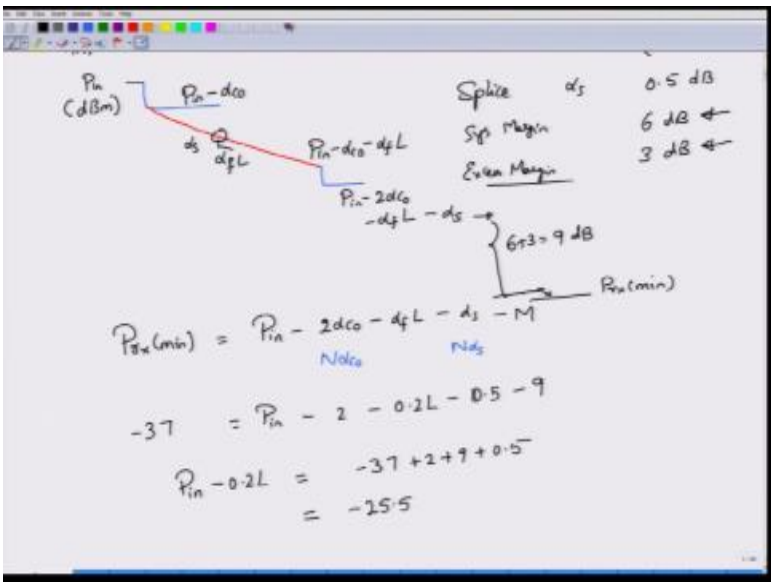

Now what happens next, I might actually have another connector here, okay which causes my optical power to drop down to Pin-2αc0 2 because you have two connectors here a more the number of connectors, the more the points that you have to include -α_fL, okay. you might also encounter a certain splice in between okay, at which point you where power would have dropped and then again decreases, okay so this would be the splice loss so let is assume that there is only one splice in this particular scenario and that would be –α_s this is power that you are receiving, okay this is the power that is receiving.

But we want to consider a system margin of 6 dp and excess margin of 3 dp. What it mean is that, if this is my Prx(min) which is the minimum received optical power then the optical power that I receive here must be above 6+3 which is equal to 9 dp. So in other words, if the link completely fails giving you a loss of 6 dp with respect to system failure and if that drift aging and everything happens there will be additional loss of 3 dp, so this 6+3 =9 dp loss will come into picture when either the link is completely falis or you are going to get excess margin as well, right.

So you are components all drifted and then you got a pretty bad components that you are working with. So this is the received power -9 dp would be the power that would at the edge over which we are operating the received optical power. If you want you can actually keep the total received power to be greater than received minimum received power, okay after considering the margins you might still have an excess margin of about 1 or 2 dp it is typical to do so. let us assume in this case that we are not going to use any excess margin over and top of the margin that we have already specified, okay.

So my goal would be to try and make the total power that I am receiving including the margin losses to go to Prx minimum, so the equation is very simple Prx minimum will be equal to this is the optical power that is required, minimum optical power required for the detection of the optical signals this is equal to launch power minus total losses in the system, losses come from 2αc0 which you will have to replace it by nαc0 if you have n connectors, if you have two connectors is 2αc0-α_fL which is the fiber losses –αs replaces –αs by Nαs if you have n number of splices minus margin which I am calling it as M, okay tis should be equal to the received optical power.

So substituting this for our case in the above situation what we get is Pin is the value which I do not know, α connector loss let us take it to be 1 dp so this would be 1x2 that would be 2, -α_fL is 0.2L I do not know what is the length of the propagation, right so I have to find that one out, minus assuming once splice loss is about 1, sorry 0.5 dp minus a margin of 9, okay so this received power must be -37 dp. So you can look at this equation so you actually have Pin-0.2L=-37+2+9+0.5 which turns out to be -37+2 is -35, -35+9 this is about -24, so it is about 9 and 1 which is 10, so -27, -26 and -25.5, okay. So this would be the power that you are looking at.

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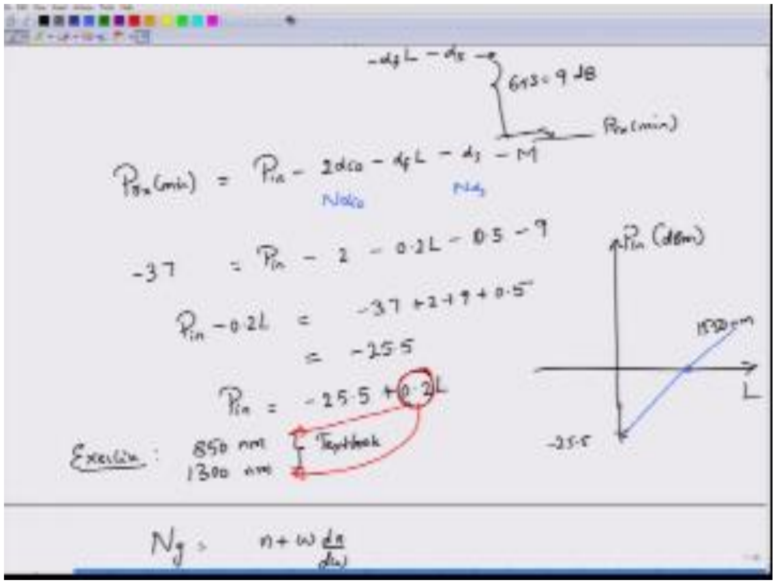

This equation is what you are looking at, now it is interesting I actually have two variables, okay so I can rearrange the variable slightly I can rearrange it in this way let me write this as so I will re write this as P_{in} = -25.5 +0.2 x L okay now I will plot L versus P_{in} if I want to propagate a certain distance L what should be my P_{in} of course with L = 0 which is the case there is no fiber then P_{in} can be at -25.5 let us put all this in dB_m right.

And then from here onwards it would be a straight line at some point you will see that the power or the P_{in} will be equal to 0 dB_m and that will happen when you are looking at 25.5 / 0.2 and this would be the graph that you are going to look at okay, now this graph is for a 1550 nm operating window here is an exercise which you can use you can actually write a small mat lap program to compute this one.

Exercise is that consider the losses for a 850nm fiber and a 1300nm fiber this values can be obtain from your text book find this values substitute in to this equations okay, so what quantity will change this quantity will change right this would not be 0.2 but rather it would be the value that corresponds to 850nm or 1300nm okay and this times L should be equal to this so calculate on the same graph right plot on the same graph the curves correspond in P_{in} versus L okay.

So this is the simple exercise that you can and then you can see that if you either fix P_{in} you can find the corresponding value of L or if you fix L you can find the corresponding value of P_{in}. So this completes our discussion of power budget.

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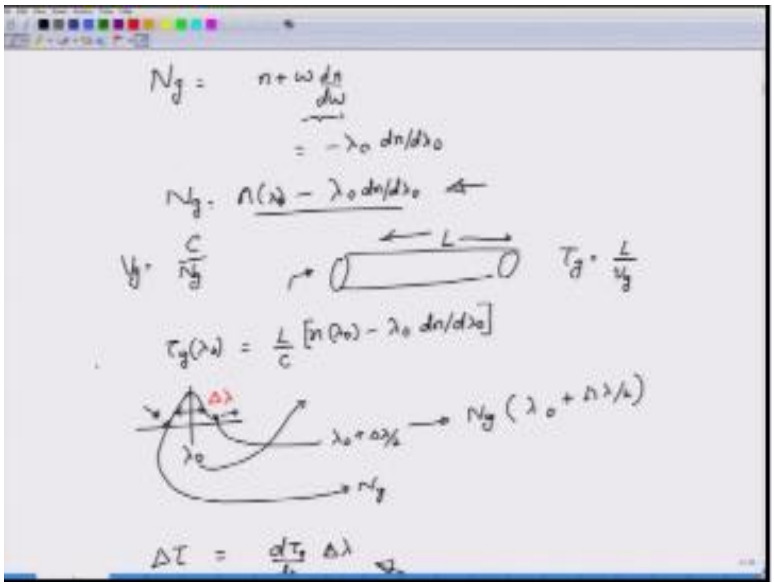

Now let us look at what is called as the rise time budget okay so in the rise time budget what I am looking at is.

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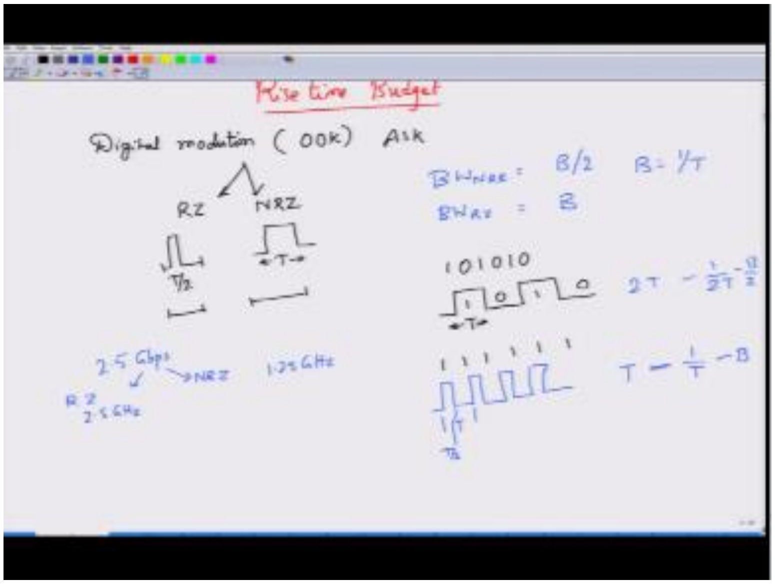

The effect of dispersion okay, so I know what is the main effect of dispersion, dispersion simply causes the pulse to spread out right so if I am performing digital modulation then I can perform modulation of the information on its amplitude or amplitude and phase which is the quad quadrature amplitude modulation that we talked about for now we will assume only on off keying type of modulation which is also the amplitude shift keying modulation okay.

Here I can actually transmit pulses in two different ways one is called as the RZ transmission the other is called as the NRZ transmission RZ stands for written to 0 here a bit one is considered bit one is represented by a pulse which loss for about half the period okay whereas for the NRZ case the bit 1 is represented by a full width pulse okay so the pulse loss all the way up to T seconds. For 0 you transmit nothing over the period similarly for 0 you transmit nothing over the bit period.

For the NRZ case if the bit rate is B okay then the band width requirement for the NRZ case is equal to B/2 whereas the band width requirement for the RZ case is equal to B and typically B is 1/T where T is the pulse width and B is the bit rate so you are sending 1 pulse every T seconds and that corresponds to a bit rate of B and the band width requirement is B/2 for NRZ and for RZ it is B.

You can see why this is so if you look at the NRZ transmission for bit sequence 101010 this is where get the maximum change of amplitude right, so for one will be duration of T seconds 0 is her T seconds so this is 1 this is 0 this is 1 this is 0 this duration is T seconds whereas for the RZ case you have maximum transmission I mean the maximum change of bits when you have transmitting all ones.

Because when you transmits all ones you have one half period then one more half period the one more half period and other half period and so on right, so this would be your total width T whereas this one is only about T/2 okay so the fundamental period here is 2T the fundamental period here is T therefore the band width requirement is 1/2T or B/2 whereas the band width requirement for the RZ case is 1/ T or B okay. So if I am looking at 2.5 GBPS transmission for NRZ the band width requirement is 1.25GHz,for RZ it would be 2.5GHZ,these are quite rough values a different way of expressing the same information is to talk about the rise time, okay, a rise time for a signal is specified by looking at its

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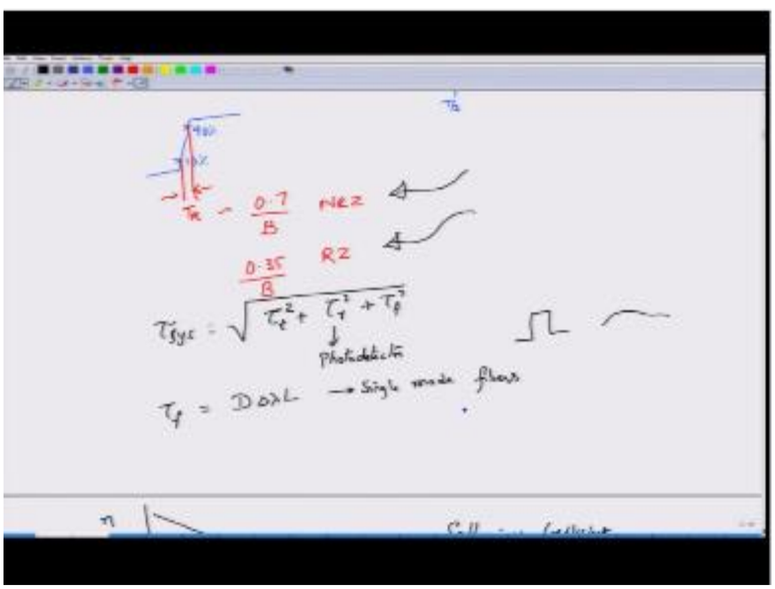

10% to 90% of the final value transition, what is the time required for 10% to 90% transmission and this is called as the rise time of the pulse, okay. For the Nrz this is about 0.7/B, this is for the Nrz case and for the Rz case this is only about half the time, okay, because Rz pulses has to rise up because they also have to fall down, right? In the half period they have to rise and then they have to fall.

Whereas for an Nrz case it has to rise and it has to fall at a much later time compare to Rz, now which kind of a modulation technique that you are going to use, will you use Rz or will you use Nrz, the answer to this question depends on various factors, with Rz scheme it is kind of easier to obtain the clock, which means I can synchronies them even if I am transmitting a sequence of once it of course does not work when I transmit the sequence of 0's but neither the Nrz scheme will work at that point.

So for Rz if you are transmitting a bit of I mean, a string of once it is still possible to recover the clock, okay, for Nrz scheme it is not possible or it is very difficult, because for contentious ones the power will be contentiously ON there are no boundaries that you can easily detect, well if you are looking for bandwidth occupancy Nrz occupy smaller bandwidth, because its period is larger time period is larger whereas, Rz occupies a larger bandwidth because its time period is smaller.

So if you looking for bandwidth conservation Nrz is the thing to go for, okay if you are looking at dispersion combating then Nrz is bad because the signal occupies the whole period, and once dispersion kicks in then the pulse will actually detonate and then cause inter symbol interference, so Nrz is not a very good option there.

Whereas Rz since it occupies only half the time slot even if it is expand a little bit no problem , in can infect expand for a another half period, before or rather 25% of the period so it doesn't really matter to us, because Rz still will remain within the time period as Nrz would exceed its time slots, okay.

In case you looking at no linear effects in the fiber something that we are going to discuss later, then Nrz bad because you are now transmitting full optical power for the entire duration, however Rz is even more worse because Rz corresponds to transmitting pulses and within pulses the peak power increases which will then cause higher non linear effects.

So there are lot of factor which are involved weather you transmitting Nrz or Rz, but for this we are interested in knowing what are the rise time requirements, okay. So my over all system raise time must be less then this quantity, it has to be less than 0.7/B for Nrz , it has to be less than 0.35/B for Rz, okay.

So let us see what and how we can look at? Rise time in optical communication system is given by three factor, so there is the total rise time let us write down which we call us the system rise time, this is given by τ_t^2 which is the transmit rise time, this quantity is not very important in modern optical communication systems, about 10 to 15 years ago, this was important because your lasers where directly modulated.

Today you use an external modulator as we discussed, so this quantity is not very important except for the legacy systems, and then you have receiver rise time which is very important, because this is directly coming from the photo detector, so if you don't have a high speed photo detector then it's simply won't respond, to your signals, okay, you might sending in a nice rectangular pulse but if the photo detector bandwidth is very bad and very small, then you will get a signal which if like this, which is very distorted and you won't be able to measure anything, okay.

So photo detector rise time is important but more or less the limitation comes from the fiber rise time, okay, so fiber rise time is denoted by τ_f^2 and this fiber rise time is actually dependent on the, the fiber rise time is basically the pulse spreading which depends on the dispersion co efficient d Δ λ *l, this is for the case of single mode fibers for multi mode fibers you have to consider the intermodal delay which is the main limiting factor.

Any way we will not consider multimode delay for as single mode fiber are more than sufficient so, for the single mode fiber the pulse spreading is given by d* Δ λ *l , so you can substitute that into this expression, let's consider a typical example and then see what happens, so let's us consider typical example in which my data rate R_B is about 400Mbps and I want to transmit over 100 kilometer by transmitter rise time I 1 nana second, My receiver rise time I something which I have to calculate. Fiber dispersion for a single mode fiber is given by 17 picoseconds per nano meter kilometer, if I'm working at 1550nm, with a 0 dispersion wavelength of the fiber at 1300 nm; remember we talked about it in previous module.

However this goes down to 2ps/nm-km, if I'm working with the same 1550 nm operation, but 0 dispersion wavelength has been shifted to 1500 nm, this fiber is called as the dispersion shifted fiber, this fiber is called as the standard single mode fiber. So this is the standard single mode fiber and this is dispersion shifted fiber. So depending on these two you can satisfy the overall rise time, let us now look at it, suppose I consider the standard single mode fiber, then the pulse spreading comes out to be, T is17 nm-km and my length is 100 km, what about the spectral width if I'm using the Fp laser that is Dfp laser but it is having multiple frequencies which is, if I'm using a laser with multiple frequencies this I called as Fp laser, fabric pero laser.

This laser has the spectral width of about 4 nm, anyway from 1 to 4 and modern Fp lasers have about 2nm one to 2 nm, this is the slightly older design so it has 4nm spectral width Δλ, whereas a single frequency laser or Dfp laser has a width of only 0.2 nm Δλ, so if I first operate with the Fp laser which correspond to 4nm, this will be around 6.8ns, whereas the same value will be at 17*100*0.2, so this value is about 0.34 ns not 3.4 n. So clearly the spreading due to the fiber is less here.

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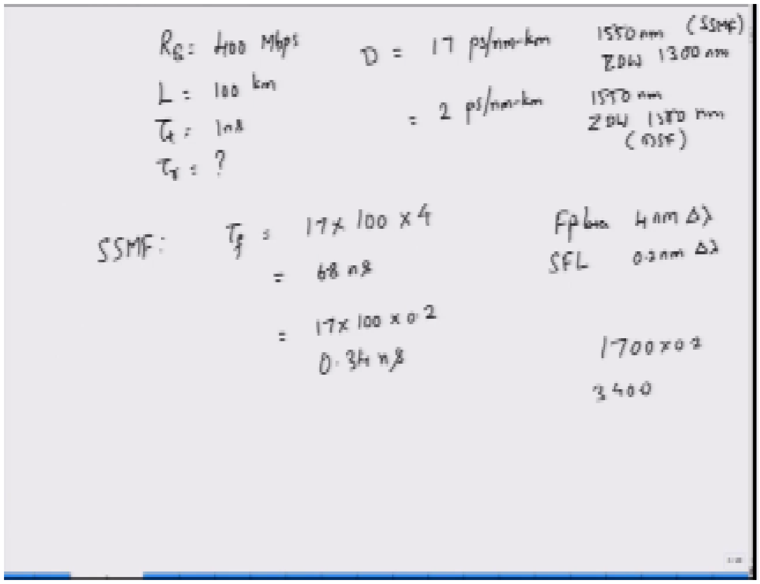

Bt what is the maximum allowed system rise time, I mean the maximum allowed system rise time basically comes from the bitrates, so we have seen that the bit rate R_B is 400 mega bits per second, so if you calculate what would be the system rise time assuming that we are looking at NRZ, so NRZ we have seen that there should be 0.7/ R_B which is, if you put in the values of 400 Mbps, this turns out to be 1.75 ns.

1ns is already coming from the transmitter, so if you look at the fiber for two cases, for 6.8 ns we are hopeless, because I cannot in anyway reduce 6.98 ns and top of it I'm going to add some rise time for the receiver and for the transmitter I will never be able to reach these 1.75 ns. However if I operate with the dispersion shifted fiber the pulse spreading because of the fiber is itself very small, so in this case if o calculate what is the receiver rise time which is given by square root of τNRZ^2- τS^2-τ transmitter square, so you can substitute all these values, it will turn out to b 1.42 ns, so the receiver rise time is around 1.421 ns which is much smaller than 1.75v ns.

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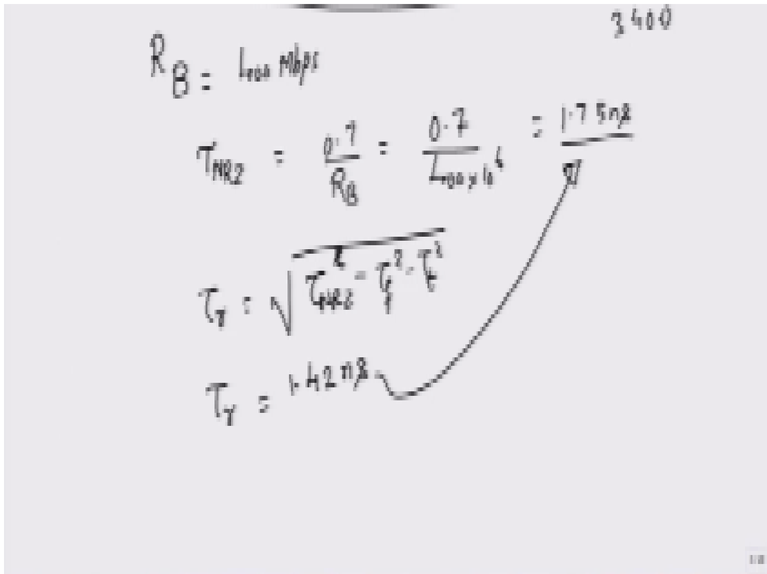

In this way you have to design the components in such a way that you are actually transmitting signals under given bit rate width, the overall goal of maintaining the rise time budget a well as maintaining the power budget. For different fibers different operating condition this budget, rise time budget will also change and you can use mat lab in order to calculate this values, so we will supply you with a small mat lab program which you will be able to see in order to come up with the maximum value for propagation distance and for the rise time of the system. Thank you very much.

Acknowledgement

Ministry of Human Resource & Development

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Co-ordinator, NPTEL IIT Kanpur

NPTEL Team

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Ashish Singh

Badal Pradhan

Tapobrata Das

Ram Chandra

Dilip Tripathi

Manoj Shrivastava

Padam Shukla

Sanjay Mishra

Shubham Rawat

Shikha Gupta

K. K. Mishra

Aradhana Singh

Sweta

Ashutosh Gairola

Dilip Katiyar

Sharwan

Hari Ram

Bhadra Rao

Puneet Kumar Bajpai

Lalty Dutta

Ajay Kanaujia

Shivendra Kumar Tiwari

an IIT Kanpur Production