Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – XI
Module-V
Optical OFDM

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Hello and welcome to the mook on optical communications. In this module we will discuss and complete the discussion of optical OFDM that we started in the last module. And then we take up some non-linear propagation effects or propagation effects when you have non-linear refractive index in the optical fiber okay.

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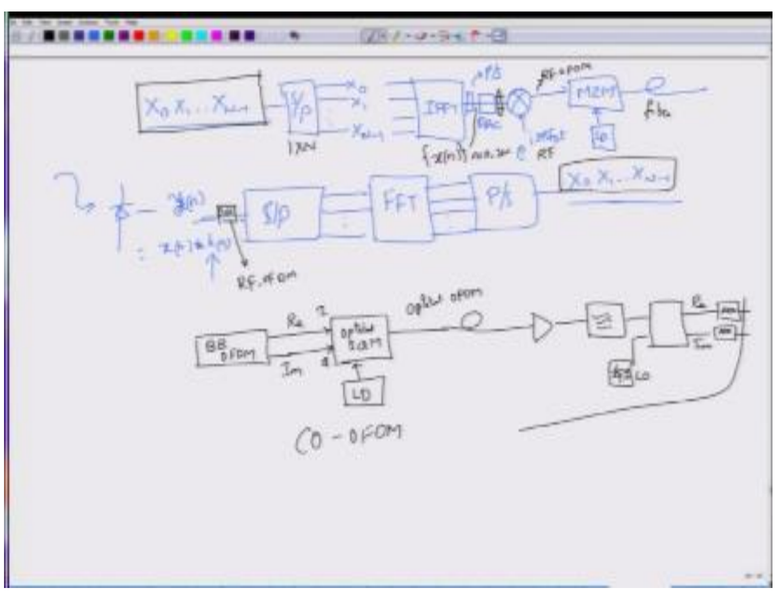

So if you remember the block diagram for the OFDM system that looks something like this which we wrote at the end of the last class. So here you had the symbols which were X0, X1, X and -1 corresponding to one particular OFDM frame okay. There are n such symbols these symbols are of course, the complex data that corresponds to the symbol. So if it is a BPSK then each of those X values that we have, each of those X symbols that we have would be +1 or -1.

If it is QPSK then we would have from four possible states and so on and so forth. These are usually arriving serially at the transmitter side and these bits which are generated serially either from a source or from a computer are then converted into parallel form using a serial to parallel converter. So you have a 1 to n converter over here which then puts up the n symbols onto the parallel form.

Once you have the symbols in the parallel form the symbols are actually the data at this point right. So these complex data then IFFT that is we take out inverse Fourier transform and offering the Fourier transform we convert them again back into the serial data format. So what you get at this point after the parallel to serial conversion is again the IFFT samples for the sequence of samples X(n) where N goes from 0 to n-1 right.

So 0, 1 all the way up to n-1, these are converted into a digital wave form using a deck, usually you will have a real part as well as an imaginary part and in one of this type of a OFDM systems is called as direct OFDM system, you first modulate this onto an RF carrier okay. So this is an RF carrier, so what you generate here would be the RF OFDM okay. So this RF OFDM signal is further modulated on the intensity of the optical carrier and launched into the fiber.

At the receiver side you put a photo detector convert the optical signals into electrical signal, so what you get over here would be the RF OFDM signal which is then sampled using an analog to digital sampler okay, or analog digital converter and then convert it back into parallel form, you take the FFT of this operation.

So if everything has gone alright, then from the point where you have taken the IFFT and the point where you take the FFT these two effects will cancel with each other and what you get after you have converted the parallel outputs of the FFT block into serial will again be the OFDM frame X0 to Xn-1. So this is one possible realization of a OFDM optical OFDM system okay. It is of course possible to have a slightly different type of an OFDM system and this is called as coherent optical OFDM.

Here what we do is, we take the baseband OFDM signal, so the baseband OFDM signal is the one that is produced after the digital to analog converter okay. So this baseband wave form is converted into its real and imaginary components, that is you take the real part and the imaginary part separately. And then give this one to the two inputs of an optical IQ modulator, of course you need an optical carrier for this which is applied by a laser diode, the real and imaginary parts go into the I and the Q inputs of the optical IQ modulator.

And what you get at the output of the optical IQ modulator will be the optical OFDM signal v okay so the there is no conversation intermediate into the RF domain here rather the base band OFDM signal is directly converted to the optical OFDM signal this is then transmitted through the fiber at the output after you have amplified and then put nice band pass filters okay you mix the incoming signal the optical signal with the local oscillator signal okay.

So you mix it with the local oscillator signal and the you get the real and imaginary components okay you subtract or you get the real and imaginary components which are then combined or which are sometimes combined or does not combine you but then through the analog to digital converters in order to generator the base band samples okay so there is no intermediate RF conversation in this type of systems and these are called as co OFDM systems this is coherent optical OFDM system okay.

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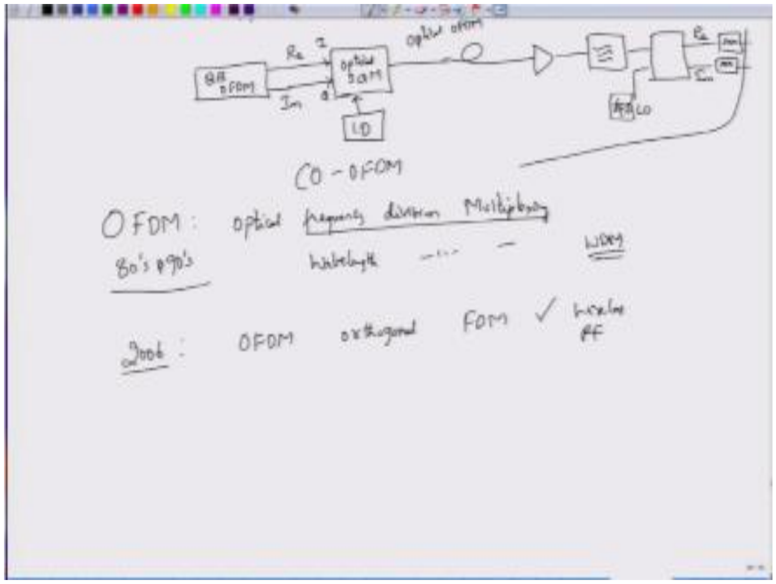

Before we talk about one additional aspect of OFDM it might be interesting to just tell you what this OFDM stands for in the earlier 80's and earlier 90's in that decade this OFDM actually stood for optical frequency division multiplexing this is something that was not done okay so in the optical domain we do not usually do a frequency division multiplexing or at least what we do we not call it as frequency division multiplexing we call this as wave light divisor multiplexing okay.

So what we have is a WDM system in the optical domain of course wave length is essential frequency because they are related through the speed of light but the term OFDM in optical community in the 80' and 90's meant optical frequency division multiplexing however after about 2006 when optical OFDM systems where you know started to be proposed and implemented.

Okay by couple of groups in the world OFDM, stands for orthogonal frequency division multiplexing which is what the name that is there in the wireless and RF domains okay so in the wireless and RF world OFD means orthogonal frequency division multiplexing where as in the optical domain it meant once up on a time in the 80's and 90's it meant optical frequency division multiplexing.

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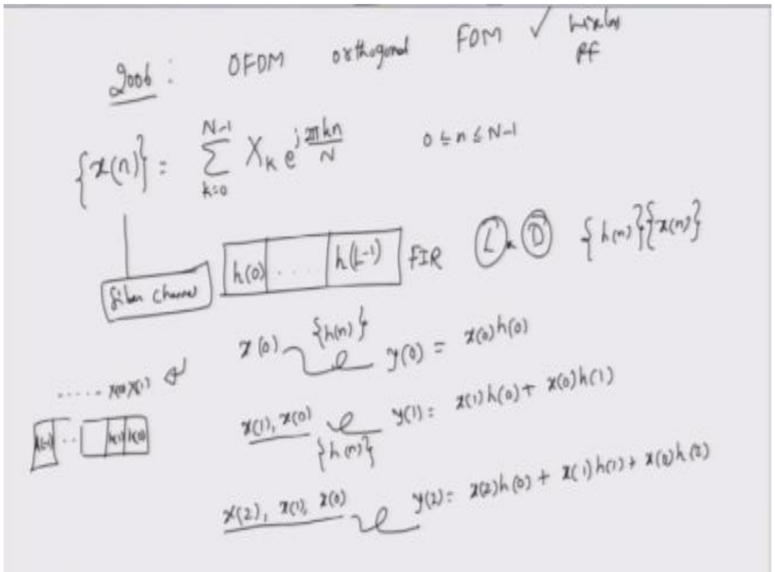

Any way after this k v hat let us come back the OFDM as we have discussed in the two modules here so you might remember that when we wrote down the OFDM samples you know the samples x9n) that is coming out of the OFDM transmitter after the IFFT block this x(n) was the IDFT or the IFFT of the symbols x_k right so you had $e^{j2\pi\ kn/}$n where k went from 0 to N-1 of course N was also from 0 to N-1 there are this N samples which make up the block correct.

So this was a discrete time version of that if this x(N) pass through the channel let us assume that you are looking at the fiber channel and although the fiber channel in theoretically request and infinite number of tabs or infinite number of coefficients to properly specify that one can assume that this fiber channel okay for a large number of problems we can assume that this fiber optical channel itself is molded as FIR filter and FIR is finite impulse response filter and the filter length is the number of coefficients that are present in the model.

So let us assume that you have the fiber optical channel molded as a L tap filter so you have h (0) to h (L-1) okay so this is the impulse response of the fiber which has been modeled the length here actually depends on the dispersion coefficient it has to be chosen in certain relationship between L and D so we are not going to look at this relationship but I will develop the relationship in the problem sheet that I will given you, okay. So for now let us assume simply that this L is large but this is not really infinite okay.

And L is of course not really large then you will have to wait until the samples arrive at the output and this delay will be quite large, so it is not too large but it is not too small either and whatever the length L is determined by the dispersion of the fiber, okay. So larger the dispersion in the fiber the larger will be the value of L, so what would be the output of this channel when you have an input sequence x(n) as input to this.

Well you might guess right so initially x(0) enters into the channel okay so this is the channel x(0) is entering and then you have this finite impulse response model of the channel there has to be a convolution between the sequence h(n) and the sequence x(n) right, so that is what we would assume and what you get at the output let us call the output as y(0) = x(0) h(0) right, so when x(1) enters into the channel.

You now have An input sequence which is two bit long or two sample lag which is then again going through the convolution with the impulse response of the fiber h(n) sequence which is L tab filter, so what you get is y(1) as x(1)h(0) okay plus x(0) h(1) the way to understand this one is to write down your h(0)h(1) all the way up to h(l-1) and then start putting in x(1)x(10) … right so you have this sequence that goes in like that.

So x(n) h(0) + x(0) h(1) next as the inputs enter here so I am sorry I took a right to left kind of a system but you could actually take in the other way wrong does not matter, so in the next sample when it enters you got x(2) you got x(1) and x(0) these three samples are entering to the fiber right, and what you get at y(2) will be x(2)h(0) + h(1) here, h(1) + x(0) h(2) so you can generalize these relationships and then write.

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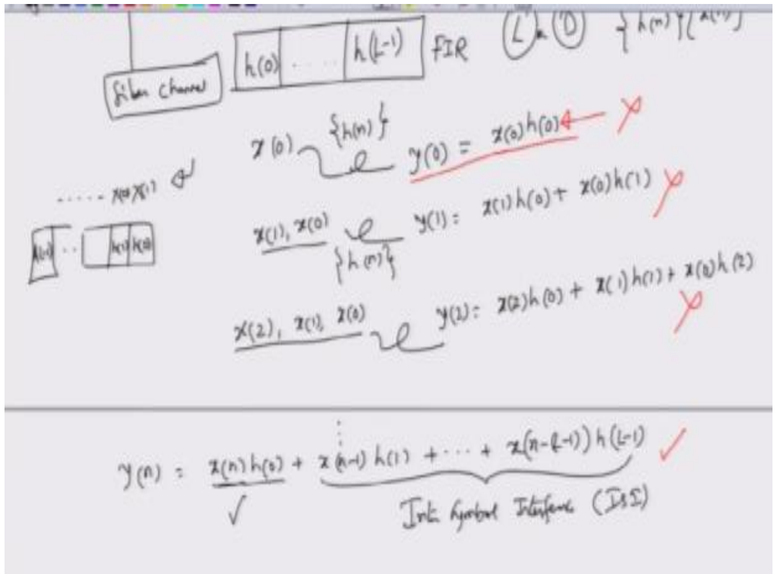

That the nth sample y(n) that would be coming out of the fiber the nth sample over here where n goes from 0 to n-1 will be x(n) h(0) + x(n-1) h(1) + all the way up to x(n-l-1) correct times h(l-1) why do we stop it h(l-1) because the impulse response of this sequence is only l tap long and then that would then be multiplying the l length sequence, right. So the l length sequence that we have considered is x(n) through x(n-l-1).

Of course x(n-l-1) can be re-written as x(n-l+1) okay, so this is what you are going to get, and if you look at y(n) which is the sample value at n you see that this is actually not just equal to x(n) which is what you would have hoped to obtain but rather there are all these terms which are coming from the previous symbols getting multiplied by the co-efficient and then getting summed up, okay.

So there is a contribution from the present sample x(n) which is what you are interested in okay, there is some multiplication factor that but that is not really big deal out of this so if you had y(n) = x(n) h(00 that would have been the ideal case because in that channel would simply have been just a multiplicative channel it would have simply multiplied by a co-efficient value and that was not a big deal right, in the sense that the samples would have not been distorted.

Here the samples are now getting distorted because of the presence of all the additional terms, okay these additional terms which will impact the present sample okay, si called as inter symbol interference, okay so this is called as inter symbol interference and this is actually an important thing in OFDM so you can see that this is what would have obtained. But let us actually revise our assumption a little bit or let us revisit our assumption are we really correct in saying that y(0) will be x(0)h(0) well we will be wrong, this is not exactly correct, this is also not correct, this is also not correct.

While this is true what we must have missed in getting this generalization is that the equation that we wrote here which is y(0) sample is equal to x(0)h(0) is strictly speaking not true, why because we forgot that the OFDM symbols.

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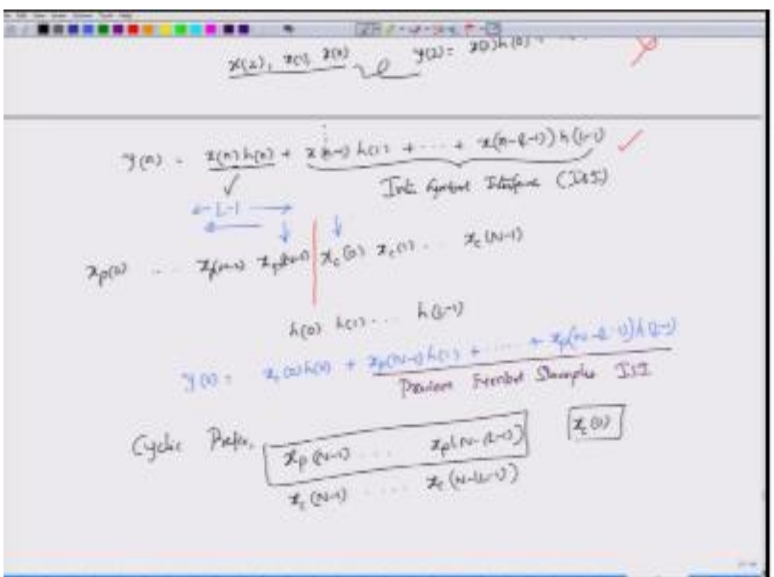

You know you do not just have OFDM symbol in the word right, you actually have a current symbol let us call this as x_c the c standing for the current sample value so you have $x_c(0)$ you $x_c(1)$ all the way up to $x_c(n-1)$ these are the current ODFM symbols. But then you have a previous symbol as well so you have $x_p(n-1)$, $x_p(n-2)$ all the way up to $x_p(0)$, right so let us just put a boundary between the two so this one is the current symbol this is the previous symbol, right.

And whenever you are convolving this with the sequence h(0), h(1) all the way up to h(L-1) you have to look for the previous L-1 samples plus the current sample. For example, when I am looking at y(0) my sample that will be interacting with the fiber would not just be $x_c(0)$ it would be this one and the previous L-1 samples, okay so there would be L-1 samples over here which in addition to $x_c(0)$ would be interacting with the fiber in order to generate y(0) which is given by $x_c(0)h(0)$ plus the previous symbol $x_p(n-1)h(1)$ plus all the way up to $x_p(n-L-1)$, okay, so $x_p(n-L-1)$ I suppose yeah, so this is $x_c(0)$ so there are L-1 terms here times h(L-1), okay.

So this is what you would actually see and it is very clear that these terms which are coming from the previous sample or the previous symbol samples, right these are the samples from the previous symbol they are talking to the present symbol and giving rise to an ISI, I can avoid this problem of having this previous symbols talking to the present symbol or the current symbol by actually doing what is called as cyclic prefix, okay.

In the cyclic prefix what we do is instead of taking this $x_p(n-1)$ all the way up to $x_p(n-L-1)$ symbols okay, whenever you are current symbol is $x_c(0)$ instead of having these previous symbols you replace this previous symbols by the current symbols themselves, so you have $x_c(n-1)$ all the way of $x_c(n-L-1)$, okay.

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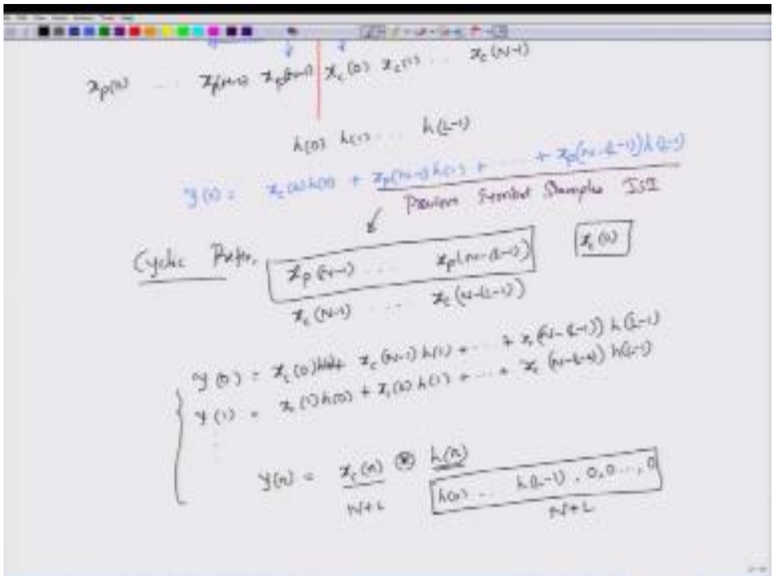

So when you do this then at the point where you are in right, so at the point where you are looking at $x_c(0)$ what you get is y(0) right, so you can see that y(0) has L-1 ISI samples, right so you can actually write down y(0) as $x_c(0)$ okay, plus so you can see here that when you have x you know you have the y(0) sample you have previous symbol samples which are l-1 samples of the previous symbol contribute in to the inter symbol interference, now in place of the previous symbol if you replace them with the current symbols okay.

Then you can see that the sample y(0) which earlier would have previous symbol samples ISI will now be rewritten or will now be written as y90) is xc (0) + xcx(n-1) h(1) + xc(n-l-1) h(l-1) look at eh sample y(1) will be xc(1)h(0) here this should be h(0) is there + xc (0) h(1) + all way up to xc(n-l-2) right h(l-1) and so on.

If you remember your dsp then you can you know dsp principles then you see that the sequence y (n) that you are generating is actually obtained by circular convolution okay so this is circular convolution of the sequence xc of which is the current symbol itself with the channel response which is h(n) okay so you see that y(n) is actually given by the circular convolution of xc(n) only catch is that h(n) was actually non 0 only from h(0) to h(l-1).

What we done is whenever the value here goes beyond that we have substituted this in to 0 so you have 0 padded so you have padded s7uch of the length if this h(0) sequence is equal to n whereas the length of xc of n is also = n okay so while we have done this rather the length of this one would be equal to n+ l and the length of this one is also n+ l.

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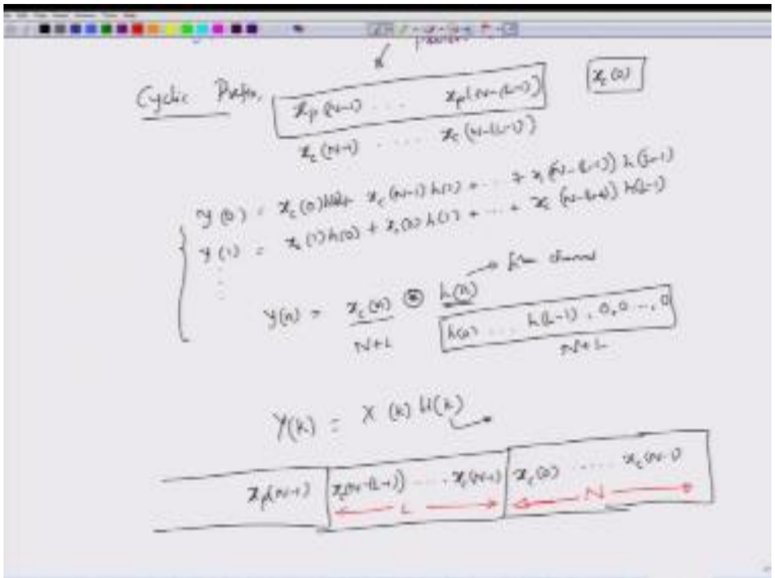

So what we have done is we have equated the length of xc(and the length of h(n) together in such a way that we have meet them equal lengths and we have managed to shoe that the samples that are coming out of the linear fiber channel right or in the fiber is linear is given by the circular convolution of x(n) with the x(n) sequence of the channel itself this h(n) represents the fiber channel okay.

Now this is in the frequency doming if you take the furrier doming or you take the f(t0 of the dft of this you will see that the circular convolution will you know in the times mind will be converted in to multiplication in the frequency doming so what you get is y(k) = xc(k) x h(k)right h(k0 is the frequency doming transfer function of the fiber channel xc(k) is the current symbol. Since the previous symbols have all gone away and what you have is only the current symbol we can now remove the subscript c that we were using.

Okay so the new structure what you get will be xp9n-1) this is the previous symbol okay and then you have a sequence of l value over her which is x(n-1) the current value x(n-1) or rather yo start here with x(n-l-1) all then up to xc(n-1) and then you have the current symbol itself xc(0) going on the way uyp to xc(n-1) so this si the OFDM structure that you are now looking at you have this as the symbol values right so length of this one is about n and these are the complex you know the sample value that we had actually transmitted after the IFFT operation.

The once that we have added here there are about l values here which we have obtain from the present symbol itself and then take and out it back at the beginning okay so you take the last once okay you have the OFDM structure you take the last l samples pad it on to the top or at the beginning of the current symbol, right and that order when you do that this is called as cyclic prefix, okay, there is no specific thing that you have to add a cyclic prefix, you could have done the same operation okay, by having the current symbol, which is

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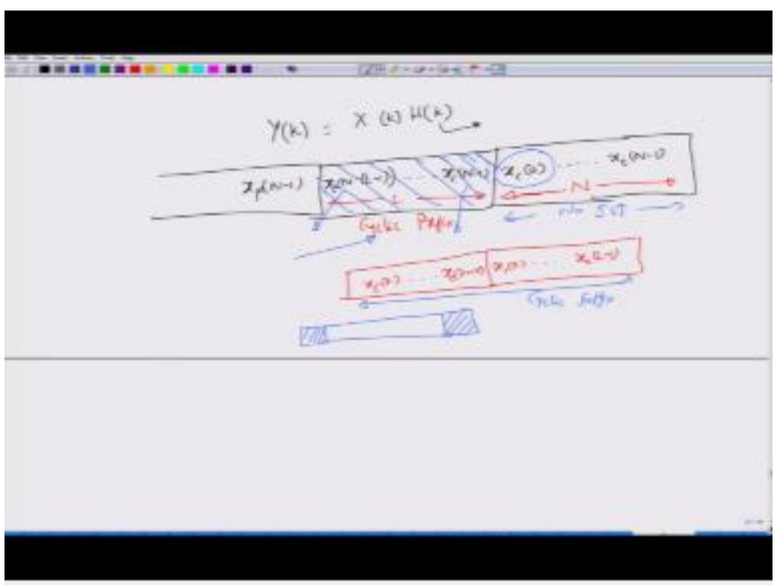

$X_c(0, X_c$ n-1) and then taken the first l sample, so you have $X_c(0)$ to $X_c(l-1)$ or may be the order is slightly different, I am not telling very important at this point, but you could had this part, the first L samples that you have taken and then pad it in the front of the symbol, okay so this could completely be the one OFDM symbol, and in this case you would have call this as cyclic suffix, okay.

It is also possible as you have mightily guessed, to have a prefix part this is the symbol, followed by suffix part, although for operational simplicity, and for general case what we will normally do is we just go for the cyclic prefix case, okay, the cyclic prefix has a an advantage, when you receive the OFDM symbols you know the first L samples have actually being in terms of these fellows right.

So this first l samples are going to be in error, because this X_C (n-l)-1would have talk the previous values, so this values in the higher, is affected by the ISI, this is also affected by the ISI right?, so these are all affected by the ISI because of the previous symbol values, and if you ignore this values, right the only time when they don't really contributed the ISI.

The first ISI free sample is going to be the $X_c(0)$ thing, because $X_c(0)$ would involve only the present symbols right, and then this would be coming out as the circular convolution. So if this is little easy don't worry too much, if you ignore the first L samples of what you have received, right which is the cyclic prefix then the remaining samples are actually without any ISI.

So there is no ISI in these received samples, off course the received samples will be Y_P, Y_C and Y(0), right. So there won't be any ISI, what is the drawback of this system? The drawback of this system is that while earlier you had only n samples to send, now you have to send n+l, samples, so when you send n+l samples what it means is that, you are taking up that extra space.

You know of the L samples which otherwise, you would have use to send only the data, so the effective data rate has now become n/ n+l, when l=0, their effective data rate was 1, but because

$l>0$, the data rate has actually come down, of course this the ratio of L to N, all depends upon the dispersion in the fiber, the larger the dispersion the larger will be the value of L.

And lower will be the throughput of the system, okay so this is one of the problem, well with OFDM there are additional thing that one has to consider when you are implementing in them with the optical communication system, while optical communication system is you know already then demands for the laser line width id is pretty small.

With OFDM the major impairment, there are two major impairment one is that, it is very sensitive to phase noise, as well as the frequency and timing offsets, if there is a frequency offset it shows up as a phase cheater, if there is a timing offset, it shows up as a frequency offset term need and both of these things will reduce the performance of the system, okay.

If the phase noise is pretty large and there are many methods to mitigate the those phase noise, if the phase noise is not mitigated then it will lead to inter carrier interference, even the other two things the timing offset under frequency offset will lead to what is called as inter carrier interference, the details of that is not important but this is a group of defects that will happen.

The other impairment optical OFDM system offer is the high peak average power ratio, because each of these symbols will be at different values and the average power will be different from the peak power, when you give such a OFDM symbol to the erbium doped fiber amplifier, the particular frequency band which has the peak value will eat up the gain of the amplifier, which will reduce the gain that is available for the other frequency bands or the other symbol or the sample points.

So because of this fact that the high peak to average power ratio, the amplifier have to be designed in such a way that linear dynamic range, the dynamic range should b very, very large and that is not very easy to realize and this problem I of course very severe in RF and wireless system, so much severe in the optical communication systems, but the effects of phase noise and the timing and frequency offsets I very important.

Now phase noise, you can't keep pushing the phase noise value as small as possible, because phase noise depends on two factors, right? One you have the line width Δν of the laser and others is only so much you can do minimize the line width. If you start putting the line width value, I mean required line width value to be very small and small, and then the expense associated with the let also starts going up.

And the other thing is that it depends on the bit rate, the phase noise variance depends on the bit rate and it usually inversely proportional to the bit rate and never the less, you can't simply increasing the bit rate, there are problems with increasing the bit rate later on. You can't simply say, okay the phase noise variance might be low at 1 terabyte per second, so why not run the OFDM system at 1 terabyte per second? The answer is not so simple, because if you run the system at 1 terabyte per second, while the phase noise can be reduced, there are whole lot of other problems that will through up.

So how do you receive the signal, how do you ample the signal, are there enough, things at the electronic side, the DSP side to mitigate all the other factors, so there are lot of things that will go wrong when you simply increase the data rate and that would again of course not possible. There are people, people who methods developed in order to overcome all these perhaps that would be the discussion for different module and the difference course all together. So we will stop here and continue with the fiber effects in the next module. Thank you very much.

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